EFFICIENT REFRIGERATORS: MARKET AVAILABILITY AND POTENTIAL SAVINGS

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ABSTRACT: Refrigerators are the largest consumers of electricity among home appliances in the United States. Cost-effective ways of reducing their energy consumption by 75% are described, based on engineering studies. Refrigerators currently marketed in Japan are noted to achieve most of this conservation potential. The most efficient mass-produced Japanese refrigerator uses 40% less electricity than the most efficient comparable American model. The market has been slow to achieve efficiency improvements in refrigerators in the United States. Changes in the distribution function of refrigerator efficiencies are reflective primarily of changes in California efficiency requirements. Efficiencies of the best American refrigerators (which are not affected by regulations) have increased to a much lesser extent than average efficiencies (which are strongly influenced by state standards).

1. INTRODUCTION

Home refrigerators are the largest consumers of electricity among residential appliances, and account for a significant fraction of total electricity use in the United States.1/ They presently consume over 17,000 MW of electric power,2/ or almost half the output of all the nuclear power plants operating in the United States in 1981.3/ The potential has been identified to improve refrigerator efficiency fourfold.4/ This report discusses technological and public policy options for increasing the efficiency of refrigerators. Refrigerators are being marketed in 1981 that achieve most of the potential savings. However, these high-efficiency models are not available in the United States at present.

2. CONSERVATION POTENTIAL

Refrigerator energy consumption grew from about 350 kWh/year in the post-World War II period to 1600 kWh/year for an average new refrigerator in 1975.5/ Part of this increase was a result of the shift to larger, more feature-laden models -- the typical 1975 refrigerator was a 15 cubic foot (425 liter) automatic defrost model with a relatively large and cold (0°F or -18°C) freezer compartment, while the earlier units were about 7 cubic foot (200 liter) manual defrost units with less freezing ability (15°F or -9°C). However, the energy consumption of the remaining small manual models increased to 600 kWh/year by 1975, while that of the popular top-freezer automatic defrost type grew to 1800 kWh/year.6/

This report focuses on top-freezer automatic defrost refrigerators, because they account for about half of refrigerator sales,7/ and have been most extensively analyzed. The other half of sales is split among manual defrost refrigerators, which have only one door and a small, relatively warm (15°F or -9°C) freezer inside the refrigerator compartment and account for about

10% of sales, partial automatic defrost units with separate, cold (0°F or -18°C) manual defrost freezer compartments and frost-free refrigerator compartments, and side-by-side units, with fully frost-free, cold freezers (about 25% of sales).

Figure 1 summarizes the data on energy consumption for mid-sized top-freezer automatic defrost refrigerators. The units described in the figure are all in the size range 14.5-17.5 ft^3 (400-500 liters), although empirically energy consumption varies only very weakly with size for a given feature class.[8/] The left bar represents the average energy consumption for 1975, before there were any regulations affecting efficiency and before the impact of electricity price increases could be felt.

California began regulating the minimum efficiency of refrigerators in 1976. Current regulations limit the consumption for a 15 cubic foot automatic defrost model to 1400 kWh/year, as shown in Figure 1. This maximum level is 22% below the average 1975 level; it results in a savings of 33% on the average, since not all models will conform to the bare minimum required.[9/] Manufacturers have complied with California requirements in all fifty states: noncomplying models have disappeared from national retail store catalogues and industry-wide compilations of available refrigerators.[10/] Several manufacturers claim that the California standard became a *de facto* national standard.

Despite the removal of the lower efficiency models from the market, there is still a considerable extent of variation between the efficiencies of different refrigerators. The most efficient top freezer frost-free model currently sold in bulk in the United States in 1981, for example, used 914 kWh/year.[11/] This level is forty percent below the California standard for the unit's size of 17 ft^3(480 liters).

Several studies indicate that considerably more conservation is both technically feasible and cost-effective. Two studies by David Lee at A. D. Little, Inc. (ADL) have explored alternate methods of reducing energy consumption in refrigerators.[12,13/] The first was more general in specification -- it looked at generic improvements to a typical 16 ft^3 refrigerator. Most of the improvements studied had extremely rapid paybacks: typically one year. The most dramatic gains in efficiency were obtained from three types of measures: reductions in heat transfer from the room to the refrigerator, improvements in motor and compressor efficiency, and improvements to the evaporator.

The first category of conservation measures included thicker insulation, or the replacement of fiberglass insulation with urethane foam to reduce heat gain. Insulation thickness was not precisely optimized, however. Improvements were made to the door closure area, reducing infiltration of room air into the refrigerator, and the interchanger was better insulated. Taken as a package, this category provided 29% energy savings from the base case.

The second category of measures included increasing the motor efficiency through the use of a capacitor-run motor and the substitution of copper for aluminum wiring. Motor efficiencies were increased to 81-83% compared to a baseline of 68-70% using these measures. Compressor efficiency improvements involved decreasing the mechanical friction of moving parts and reducing fluid friction losses by redesigning valves and ports. In addition, reductions were made in the magnitude of waste heat from the motor/compressor entering the refrigerant. The set of motor/compressor measures saved 29% of the energy of the base case refrigerator.

The third category of rapid-payback measures involved improvements to the evaporator. In a frost-free refrigerator, the evaporator is isolated from the food compartments so that it can be defrosted without unduly increasing the temperature of

REFRIGERATOR ENERGY CONSUMPTION

top-freezer, frost-free, 14.5 - 17.5 cubic feet

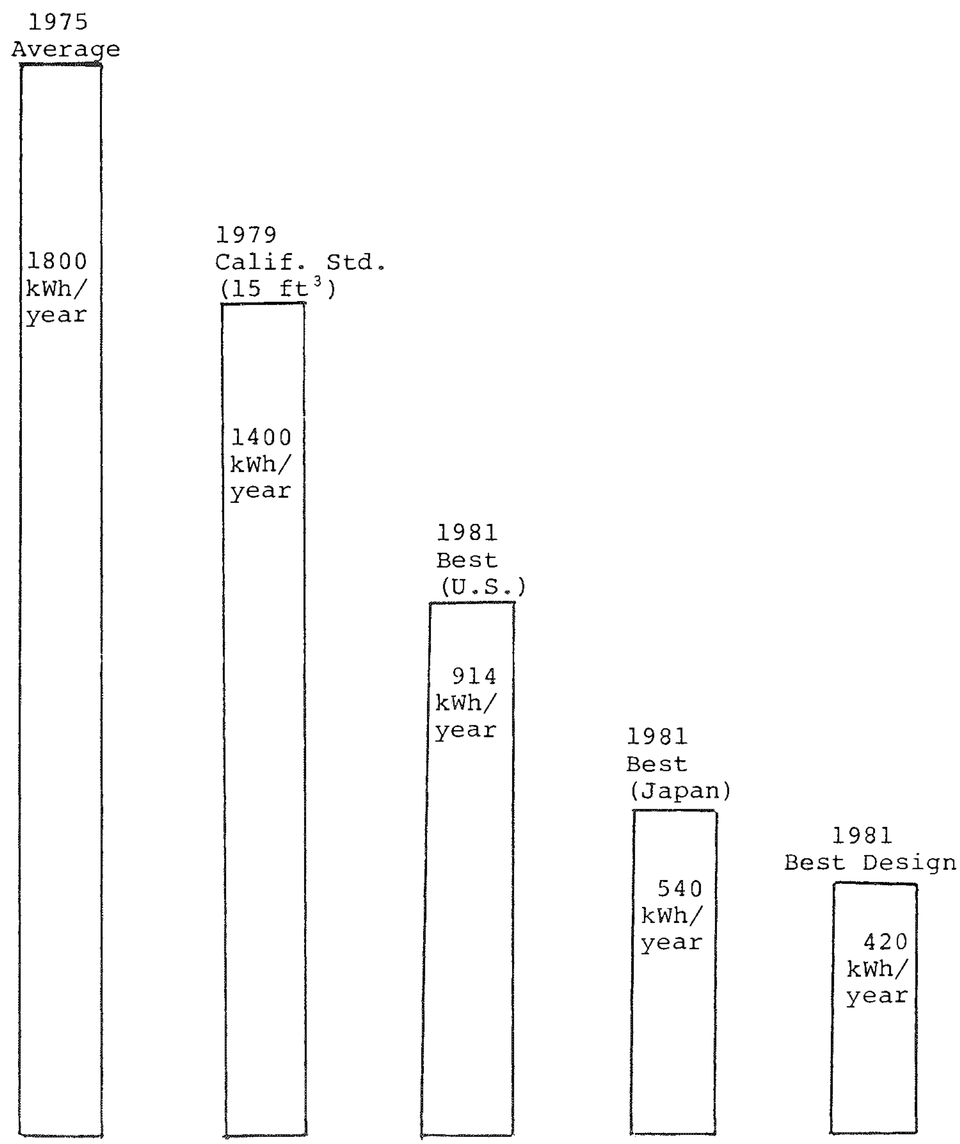

FIGURE 1. Refrigerator energy consumption for the class of top-freezer, automatic defrost refrigerators between 14.5 and 17.5 cubic feet.

the food storage areas. Heat transfer from the cold evaporator must therefore occur by forced convection, using a fan. Increasing the fan/motor efficiency not only reduces direct energy consumption, it also reduces the heat load on the food. Further reductions in heat load were obtained by placing the fan motor outside the cold areas. Finally, an evaporator with improved heat transfer was employed. Savings from this package were approximately ten percent. Combining these three packages produced a 63% savings from the base case (1975 average), for a consumption of 620 kWh/year. The additional cost to the consumer was $125. This combination did not include all of the measures studied: it omitted consideration of using hot refrigerant gas for defrost, initiating defrost only when needed rather than with a timer, reducing compressor speed to cut friction losses, and several other technically feasible measures. Several of the additional measures that were cost-effective on the base case model and will probably remain so on the 620 kWh/year model could reduce this usage by 5-10% more.

The more recent ADL study focused on an existing 16 ft^3 refrigerator that was already one of the most efficient on the American market. A number of conservation measures were studied and ranked according to criteria of first cost, rapid payback, noise, effect on the storage volume of the refrigerator, and effect on its lifetime. Only those features that were felt to be competitive benefits in the current U.S. consumer market were accepted. This screening eliminated many of the measures in the 1977 study from consideration. The measures incorporated into the prototype were:

- Removing the evaporator fan motor from the refrigerated area;
- Using a separate, natural convection evaporator in the refrigerator compartment, as is done in current partial-automatic defrost units. This change reduces the volume of air dehumidified by the colder evaporator, cutting latent heat load, and reduces fan usage. It also reduces the frequency of defrosting;
- Employing an improved condenser;
- Increasing insulation levels, with more insulation in the freezer compartment than in the fresh food compartment;
- Adding a double gasket to the door;
- Optimizing the air flow past the evaporator to minimize energy use.

The resulting energy consumption was measured at less than 650 kWh/year, using an ADL test procedure that is more realistic than the U.S. Department of Energy test procedure.[14/] The extra cost of the unit is on the order of $50, as some of the measures save first cost along with operating cost.

Both ADL studies involved the analysis of how manufacturers would be able to reduce energy consumption in mass-produced appliances. The costs included both retooling costs and operating costs, as well as an assumed 200% to 250% markup. Measures that were demonstrably feasible on prototypes were rejected if they were felt to be too speculative in realistic mass merchandising circumstances, either because of technical uncertainties or because of potential marketing problems.

Results from the two ADL studies can be combined because of the non-overlap of the measures. The earlier ADL study showed that the motor and compressor improvements alone would produce a savings of 29% of base case energy use. These changes were not incorporated into the 1980 design, possibly because the manufacturer co-funding the study did not produce its own motor/compressor units. Since the savings from this type of improvement should scale very close to proportionally with total load, we can predict that the application of these improvements to the 1980 ADL prototype would yield a total energy consumption 29% lower than that of the prototype, or 460 kWh/year. The 29% reduction in energy use from compressor improvements is also demonstrated by Nelson.[15] Since the compressor efficiency measures are overwhelmingly cost-effective in the base case refrigerators, they will also be cost-effective on the improved prototype; thus the 460 kWh/year unit is cost-effective.[16] Its increased cost relative to the base case 1975 model is approximately $100.

Similar analysis is presented by Pine,[17] except that an even greater improvement in compressor efficiency is assumed. Instead of the 29% savings from increasing compressor efficiency modelled by ADL, a 45% reduction in energy use is assumed, as a result of the lower amounts of compressor waste heat dumped into the refrigerant.

Stoecker[18] estimates that a further 12% reduction in compressor energy can be achieved by changing from a single refrigerant to a mixed refrigerant. The 12% reduction in compressor energy predicted by Stoecker would result in a 10% reduction in overall refrigerator energy,[19] thus lowering energy consumption to 420 kWh/year. Stoecker does not estimate costs, but the changes involved in implementing his proposal, other than compressor changes that would simply substitute for those already needed to raise efficiency, appear to cost less than $40 or $50, based on the two ADL studies. Thus, this measure would also be cost-effective. The overall increase in first cost would be approximately $150.

This estimate of 420 kWh per year is by no means a lower bound on the energy required by a cost-minimizing frost-free refrigerator, but rather the lowest figure currently possible to document using published studies. All but the last 10% is derived from reports that compute both costs and savings. Conservation measures not studied by ADL and not already incorporated into current efficient designs or some of those rejected as too speculative may become possible to implement in a cost-effective manner. It is reasonable to expect that further research will lead to even lower energy consumption than the 1981 "best design." For example, improved insulating materials may be developed, or new refrigeration cycles with better thermodynamic properties may become feasible. Better systems for automatic defrosting could be developed.

High-efficiency refrigerators in other size or feature classes have already been demonstrated to consume much less energy than 420 kWh/year. Schlussler has designed and constructed a prototype 13 ft^3 partial automatic defrost refrigerator that uses 250 kWh/year[20] and is currently working on a 100 kWh/year model. Nørgård has described a small (130 liters or 4-1/2 ft^3) manual defrost refrigerator using 80 kWh/year.[21] These non-automatic models use 40-80% less than the "optimum" top freezer frost-free model.

How close does the market come to this "best design"? As we have seen, the best 1981 American unit comes in at more than double the consumption of the "optimum." But the state-of-the-art American refrigerator has hardly improved since 1975, when the most efficient top-freezer model used 1130 kWh/year. Energy use of the best top-freezer model declined only 20% in six years.

In contrast, the energy consumption of the best Japanese refrigerators (which are not currently imported into the United States) has been reduced by half from 1975 to 1981, and has continued to decline at about 10% per year in recent years. A brief shopping trip to a Japanese department store will reveal refrigerators of comparable size to American models which surpass the best efficiency of American units by a wide margin.

The most efficient large (14.5 ft^3 or 411 liters) Japanese refrigerator that the author was able to locate in 1981 consumed 540 kWh/year based on a test procedure that included door openings and reasonable ambient temperatures and humidities.[22]

This is only 30% above the "optimum" for an automatic defrost unit. (The Japanese model -- a Toshiba GR411 -- is frost-free and comparable in amenity and appearance to American refrigerators.)

Most Japanese refrigerators displayed at the major department stores are in the size range of 200-300 liters (7-9 cubic feet) -- significantly smaller than American models. These units consume as little as 305-410 kWh/year. On a per-liter basis, the best of these small units is as efficient as the larger Japanese model; others are up to 20% less efficient. But for American refrigerators of a given class, efficiency declines rapidly with decreasing size. The decrease in efficiency that would be expected from a reduction in size comparable to this (i.e., from about 411 liters to about 235) would be 26%.[23] The observed decreases are less than this (or zero); thus, the smaller, more popular Japanese models demonstrate an even greater potential for energy savings.

Some of the techniques used by the Japanese manufacturers to increase refrigerator efficiency are similar to those identified in the ADL studies. Evaporator fan motors are placed outside the refrigerated volume. Waste heat from the compressor is vented to the air rather than released to the refrigerant. More highly efficient capacitor-run motors with lower-loss iron cores are employed. Reductions in friction losses and in fluid flow resistance, along with improvement in volume efficiency are used to improve compressor performance. Other conservation measures include a plastic chimney behind the refrigerator, which increases air flow past the condenser, and the use of condenser tubing for the anti-sweat heaters.

The efficient Japanese refrigerators are not substantially more expensive to manufacture than comparable American models. While their suggested retail prices are considerably higher than those observed in the United States, they are generally sold at a 15-20% discount.[24] In addition, some of the difference in price is due to differences in tax policies. The 540 kWh/year model, for example, carries a list price of 235,000 yen, or about $1025 in mid-1981. Adjusting for the 20% commodity tax that is included in the Japanese price yields a net list price of $855, and an estimated retail price (discounted and without tax) of $675-$725, compared to a typical retail price of about $600 for American models. The estimated retail price difference of $75-$125 is consistent with the engineering calculations cited above. Other reasons for the price differential include the smaller volume of refrigerator production in Japan; they may also involve different wholesale and retail markups or other practices. The price differential is not subject to direct interpretation as a cost of high efficiency, because low-efficiency Japanese refrigerators are comparably expensive, based on sales brochures.

If the Japanese refrigerators were imported into the United States and sold at prices $255 higher than American models (which is an upper bound on the actual cost differential), they would still be cost-effective to the consumer. The present value of the savings of substituting the 540 kWh/year Japanese refrigerator for the most efficient (914 kWh/year) American model would exceed the extra cost whenever the value of electricity exceeds 3.5¢ per kWh.[25] Retail electric rates are higher than this in most of the United States, and marginal costs are greater throughout the country.

3. POLICY CONSIDERATIONS

The potential reduction in electricity demand due to a shift to high-efficiency appliances is large. For the United States as a whole, we can project that after twenty years, 81 million new refrigerators will be in use. If we assume a savings of 900 kWh per year (i.e., reducing average energy consumption from about 1300 kWh/year to 400), the total reduction in electric power demand would be 10,000 MW of peak power.26/ To supply this amount of end-use electricity would require the construction of 16,500 MW of electric capacity, at a cost of about $50 billion (in 1981 dollars).27/ The construction cost of avoided power plants is equivalent to about $600 per refrigerator, compared to the $150 cost of additional efficiency. Thus, higher refrigerator efficiency is cheaper on a first-cost basis, without even considering fuel and operational costs of the supply alternative.

However, it is unlikely that the market will accomplish this savings without government intervention. There is surprisingly little evidence that higher energy prices induce consumers to purchase appliances of higher efficiency.

Observed increases in the energy efficiency of refrigerators from 1975 to 1981 can be attributed to one of three possible causes. They could be caused by a change in consumer preference, motivated by rising electricity prices. They could alternately be caused by state regulation, or threatened federal regulation. Or they could be biproducts of some technological improvement possibly unrelated to energy, as is the case with television receivers, whose energy consumption declined by 60% from 1970 to 1980 as a result of the introduction of solid-state components. There has been no systematic study that has measured the relative strengths of each of these possible causes of efficiency improvement. But the data currently available are most consistent with the hypothesis that appliance efficiencies increase not as a function of energy price, but as a result of state standards.

First, consider the distribution functions for refrigerator efficiency as a function of time. As noted above, the efficiency of the best American refrigerator in the 14.5-17.5 ft^3 top-freezer automatic defrost class increased by only 20% from 1975 to 1981. For other classes, the picture is even less encouraging. For the class of 18-21 ft^3 side-by-side-freezer refrigerators, there was no improvement in the highest efficiency model available between 1975 and 1981. But for both classes, the low-efficiency end of the spectrum was completely eliminated during those six years.

Figures 2 and 3 illustrate the approximate distribution function for refrigerator energy consumption for these two classes of refrigerators from 1975 to 1981. The height of the curve indicates the relative prevalence of each energy-use range of refrigerators in each year.28/ As seen in the figures, the curves shifted dramatically to the left (towards higher efficiency) and became substantially narrower over the past six years.

These results are inconsistent with the predictions of the "consumer preference" hypothesis. This paradigm predicts a widening of the distribution function, as follows: those consumers who purchase their own appliances and try to minimize life-cycle costs would be expected to buy more and more efficient refrigerators in response to energy price increases and technological improvements. Given the relatively low cost of increased efficiency in refrigerators, a significant fraction of the market should pursue this strategy. Those consumers who are more sensitive to first costs should also have demanded higher efficiency, although to a lesser extent. For refrigerators purchased under "market-failure" conditions, such as those bought for rental housing units or by consumers who are ignorant about energy efficiency, there should have been little or no change in energy consumption. Thus the "price-induced conservation" model predicts that the distribution functions should widen through the introduction of more energy-efficient models, but that the sales of inefficient ones should continue.

In contrast, the "regulatory-effects" model predicts that models failing efficiency standards are dropped, while few new more highly-efficient models are introduced. As shown in Figures 2 and 3, this model best explains the data.

A further argument against the role of market forces in achieving efficiency improvements is the lack of any cross-sectional data to support such an argument. Since energy prices vary dramatically from state to state, one would expect to be able to show a variation in average refrigerator efficiency between states, with the more efficient models going to the states with the highest prices. No such evidence has been available to the public, although manufacturers probably could produce efficiency data by region. Some regional data on air conditioner sales have been provided by the Carrier Corporation; their results indicate that air conditioner efficiencies in the areas with the highest overall cost of air conditioning -- New York City (high electricity costs) and Florida (long cooling season) -- are no different from national average,[29] whereas California air conditioners (regulated) are significantly more efficient than average.

A theoretical study of consumer choice performed by Hausman[30] shows that consumers choose air conditioner efficiency improvements as if they have a discount rate of 25%. But even this weak responsiveness is likely to be an overestimate of the effect of electricity prices on consumer behavior, for a number of reasons. First, it is based on a biased sample, which covered only 56 households in 16 cities, and which included virtually no apartment or mobile home dwellers, and excluded people who expected to move within 16 months. Thus, it sampled those households who are likely to be most responsive to price. Second, the study asserts that all consumers maximize their economic welfare according to a specified equation, and assumes a fixed functional form for the equation. Thus, it is not able to test the hypothesis that consumers respond to price in their choice of efficiency -- it already accepts that result by assumption. And since efficiency is strongly related to price in air conditioners, some finite result for an effective discount rate (that is, a rate of tradeoff between increased first cost and decreased operating cost) is almost certain to emerge from the statistical analysis simply as a result of the cost/efficiency relationship of the air conditioners.

A third problem is revealed by Hausman's finding that higher-income consumers have a lower effective discount rate. Hausman interprets this result as meaning that higher-income people have a different rate of time preference. But an alternate interpretation is simply that high-efficiency air conditioners are more likely to be purchased by the affluent, perhaps because of their better features or greater status value.[31] This income effect suggests that energy costs may not be the major motivating factor behind the choice of high efficiency. As a result of these problems, Hausman's study does not provide conclusive evidence of any price effect on efficiency choice.

Thus the current evidence, while fragmentary, clearly supports the thesis that consumers do not respond in an economically rational way in their choice of refrigerator (or other appliance) efficiency. Cost-effective energy-efficient refrigerators are not chosen preferentially to inefficient models. The large improvement in refrigerator efficiency since 1972 is better explained by the existence of state standards than by direct electricity price response.

With a market composed of consumers who largely do not respond to higher efficiency, it is not surprising that American manufacturers have failed to incorporate the best engineering practices into their refrigerators. Improving efficiency involves making investments in research and development, retooling, and then changing marketing plans. Without evidence that such an investment will pay off in increased sales, it is not prudent for a manufacturer to make an investment beyond that necessary to ensure compliance with actual or expected mandatory standards.

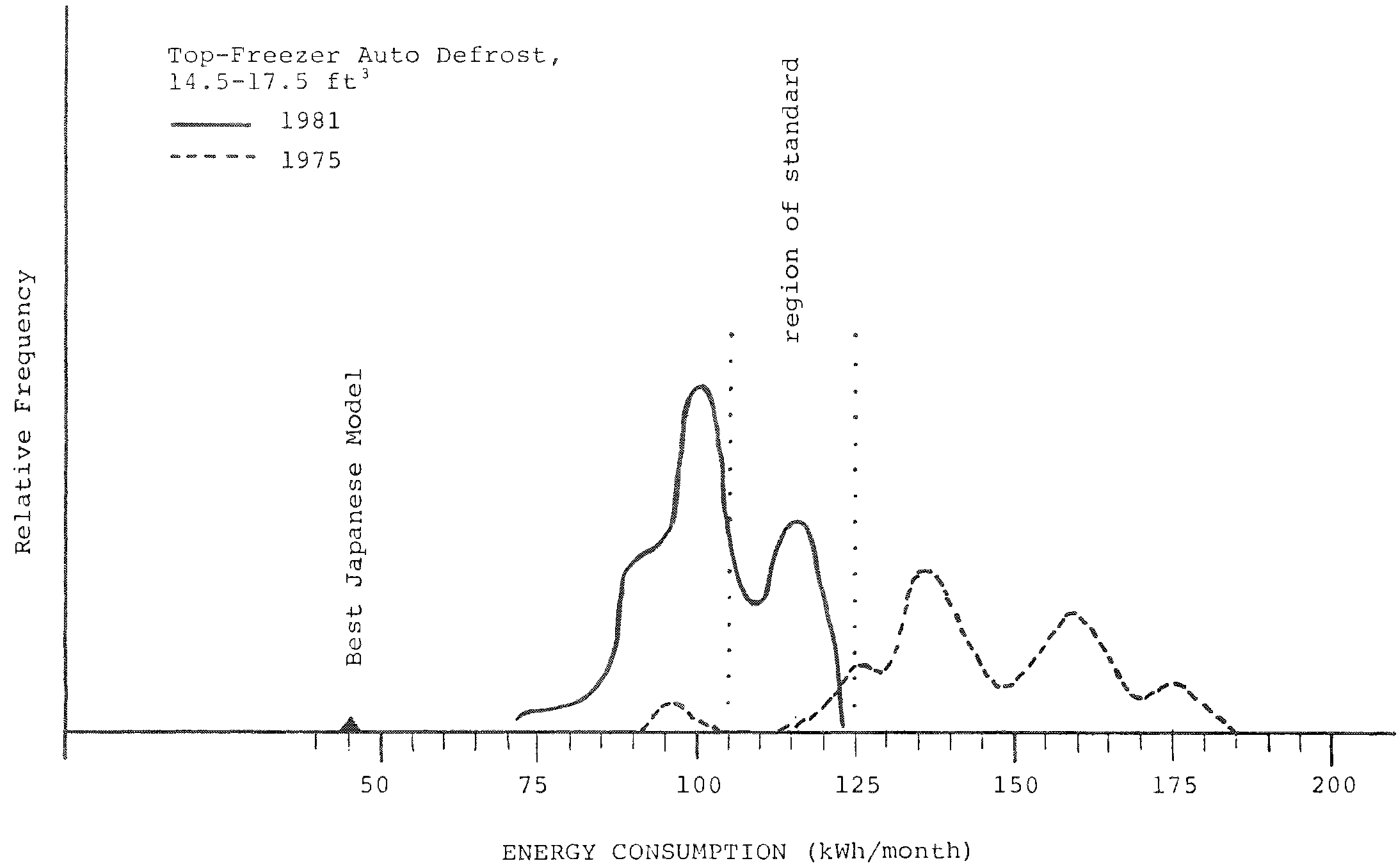

Figure 2. Distribution function for energy consumption of refrigerators in 1975 and 1981. Models are confined to the class of top-freezer automatic defrost refrigerators between 14.5 and 17.5 cubic feet. 1981 data (from Ref. 11) are for California only, but there are no high-energy-consumption models available elsewhere. 1979 California standard is indicated by the label "region of standards;" region is given because the exact standard varies with refrigerator size. Relative frequency is the approximate frequency of occurrence of models; sales weighting cannot be performed because data are proprietary. Source: Ref 11 and "AHAM Directory of Certified Refrigerator/Freezers 1975" (Association of Home Appliance Manufacturers, 20 North Wacker Drive, Chicago, Ill.)

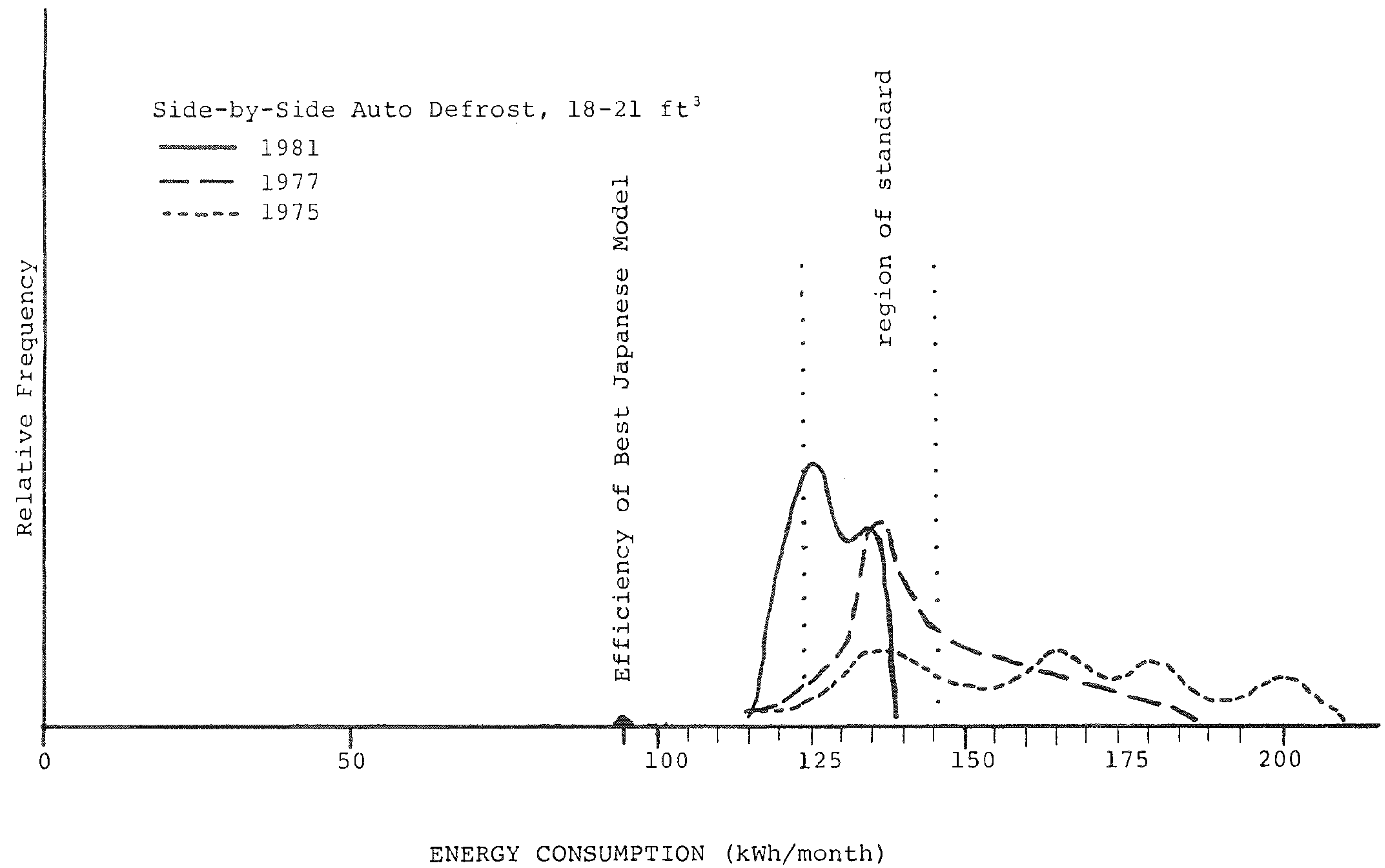

Figure 3. Distribution function for energy consumption of refrigerators in 1975, 1977, and 1981. Models are confined to the class of side-by-side automatic defrost refrigerators from 18 to 21 cubic feet. 1981 data (from Ref. 11) are for California only, but there are no high-energy-consumption models available elsewhere. 1979 California standard is indicated by the label "region of standards;" region is given because the exact standard varies with refrigerator size. Relative frequency is the approximate frequency of occurrence of models; sales weighting cannot be performed because data are proprietary. Source: Ref. 11 and "AHAM Directory of Certified Refrigerator/Freezers 1975 and 1977" (Association of Home Appliance Manufacturers, 20 N. Wacker Drive, Chicago, Ill.)

Efficiency standards are therefore the most reliable means of inducing changes in refrigerator efficiency. They have been demonstrated on the state level with considerable success. As seen by the response shown in Figures 2 and 3, efficiency standards have had a marked effect on the energy consumption of refrigerators currently offered for sale. The California Energy Commission has noted virtually no problems with the implementation of refrigerator standards. Since testing of appliances is already required for federal labelling, the administrative costs of standards would be low.

Incentive programs, such as a rebate offered by a utility on other entity for the purchase of high-efficiency models, may have a significant effect on efficiency as well. A utility whose marginal cost exceeded its average rate revenue could afford to pay the present value of this difference over the life of the refrigerator as a "bounty" for purchase of a high-efficiency unit. Several utilities already have such a program. Economic theory would indicate that this type of program could be very effective, although there are still few empirical results to confirm the hypothesis. Indeed, the failure of consumers to take advantage of the current variation in energy consumption, even when it is virtually free,[32] suggests that a policy of reliance on rebates alone would be very risky compared to a program of regulation. Of course, utility rebates and government regulation are not incompatible; rebates can reduce the first cost impact of compliance with standards, and help to share costs and benefits equitably.

4. CONCLUSION

A more than four-fold reduction in refrigerator energy use -- to about 420 kWh/yr for a typical top-freezer automatic defrost model -- is shown to be cost-effective based on engineering studies. Currently, refrigerators achieving an energy use of 540 kWh/yr are marketed in Japan. The extra cost of the efficient Japanese model can be justified by the present value of energy saved.

Market forces have failed to realize the bulk of the savings potentially available for American consumers. Observed increases in efficiency have been small in comparison to those justified by engineering and economic considerations, and are more reasonably attributed to the effect of regulation than to competitive forces.

5. BIBLIOGRAPHY AND FOOTNOTES

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3. Electricity production by the U.S. nuclear program was 273 billion kWh in 1981 (see Monthly Energy Review, U.S. Department of Energy, May 1982, p. 74) of which some 250 billion were transmitted to the customer. Refrigerator energy consumption was 121 billion kWh/year, following footnote 2.

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5. Berman, et al., "Electrical Energy Consumption in California: Data Collection and Analysis."

Lawrence Berkeley Laboratory, UCID-3847. Available at the California Energy Commission Publications Office, 1111 Howe Avenue, Sacramento, California, 95825.

6. Id.

7. Id.

8. See D.B. Goldstein and A.H. Rosenfeld, "Energy Conservation in Home Appliances Through Comparison Shopping," Lawrence Berkeley Laboratory, LBL-5910, 1978. Also, using the sales-weighted average energy factors published in Ref. 23, energy consumption increases only 22% as size increases 77% from 13 to 23 ft^3.

9. For example, the average top-freezer automatic defrost refrigerator meeting the standards used 112 kWh/month (see A.H. Rosenfeld, D.B. Goldstein, et al., "Saving Half of California's Energy and Peak Power in Buildings and Appliances Via Long-Range Standards and Other Legislation." Lawrence Berkeley Laboratory, LBL-6865, 1979). In contrast, the average California standard over the range of top-freezer automatics (13-23 ft^3) is 130 kWh/month. Thus, the average complying model used 14% less than the maximum permissible quantity of electricity.

10. "1982 Directory of Certified Refrigerators and Freezers," Association of Home Appliance Manufacturers, 20 North Wacker Drive, Chicago, Illinois.

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12. "Study of Energy-Saving Options for Refrigerators and Water Heaters,Volume 1 - Refrigerators." Arthur D. Little, Inc., Cambridge, Mass., 1977.

13. W. David Lee, "Development of a High Efficiency Automatic Defrosting Refrigerator/Freezer. Phase I - Design and Development." Arthur D. Little, Inc., for Oak Ridge National Laboratory, ORNL/Sub-7255/2, 1980.

14. The ADL test procedure involves door openings, where the DOE procedure tests the refrigerator in a 90°F room with no door openings. See Ref. 13, p. 47 for ADL test procedure results. Using the DOE test procedure produced an energy use estimate of 581 kWh/year, some 10% lower (see p. 51).

15. Richard T. Nelson and Marc G. Middleton, "The Development of Energy Efficient Compressors for Refrigerators and Freezers," Oak Ridge National Laboratory.

16. These measures cost $34.85 and save 477 kWh/year (see 1977 ADL study, Ref. 12, p. 57). Thus at 7¢ per kWh and adjusting the costs for inflation, the first cost is paid back in a little over a year. Assuming that the same measures applied to the 1980 ADL refrigerator would cost the same, costs would be about $50 in 1981 dollars, and savings of about 185 kWh/year would be worth a present value of about $250. Savings exceed costs by 5:1.

17. Gerald D. Pine, "Energy Consumed in 2010 by an Energy Efficient Building Sector," Oak Ridge National Laboratory, ORNL-5772, 1981, p. 30.

18. W.F. Stoecker, "Improving the Energy Effectiveness of Domestic Refrigerators by the Application of Refrigerant Mixtures," Oak Ridge National Laboratory, ORNL/Sub-78/55463/1, September 1978.

19. From Ref. 13, the compressor wattage was 187.4 while non-compressor uses accounted for 30.6 watts, for a total of 218 watts (during "on" periods). If this is reduced 29% due to motor/compressor improvements, the breakdown is 124.2 watts and 30.6 watts. A further 12% reduction in compressor power will save 14.9 watts, or 9.6% of the total.

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23. The reduction in energy use as a function of size can be calculated based on the Department of Energy proposed 1981 standard for frost-free refrigerators (which is based on current average efficiencies). "Energy Conservation Program for Consumer Products," U.S. Department of Energy, Office of Conservation, Solar Energy. 10 C.F.R. Part 430, Federal Register 45, 127, June 30, 1980.

24. See ref. 22.

25. This calculation is performed using a 2% real (inflation-free) discount rate (equal to the average rate of return on relatively low-risk investments) and a 2% real escalation in electricity prices, and the 20-year equipment lifetime given in Ref. 5. If the discount rate was 5% real, which is the approximate rate of return on stocks or real estate, the savings would be cost-effective for electricity costs exceeding 4.7¢.

26. This calculation includes a factor of 1.15 to account for higher peak-period consumption of refrigerators. (See Ref. 5.)

27. The power estimate was obtained by dividing the average power requirements of refrigerators by the average capacity factor of large base-load power plants (55%), and adding 9% for transmission losses. The costs and capacity factors are explained in NRDC's Statement In Response to the Bonneville Power Administration's Notice of Intent to Develop Policy Guidelines and a Methodology to Compute Billing Credits, June 29, 1981. They represent the avoided cost of electric power: the cost of the highest cost alternative that is being realistically considered for construction.

28. Lacking model-by-model sales data from manufacturers, which is considered proprietary, these distributions must be approximate; they are drawn by hand based on the number of different models within a 5 kWh/month bin of energy consumption. The hand drawing is for graphic clarity.

29. Carrier Corporation Position Regarding Central Air Conditioner and Heat Pump Federal Minimum Efficiency Standards, 1981.

30. J. Hausman, "Individual Discount Rates and the Purchase and Utilization of Energy-Using Durables," The Bell Journal of Economics, 10, 1, Spring 1979.

31. Testimony of Valair, Inc., Sacramento, California, before the California Legislature Joint Committee on the State's Economy, September 20, 1982. This wholesale heating and cooling equipment distributor noted that "high efficiency equipment [is] an upgraded item commanding premium pricing. [It is] sold ... based on the features and benefits of the offering." That is, high efficiency air conditioners are sold as a premium item to wealthier customers, so that a correlation between income and air conditioner efficiency is to be expected independent of any propensity of the wealthy to value energy savings.

32. The correlation between price and efficiency for existing American refrigerators is small or non-existent. See Ref. 8 for scatter-plots showing that price and efficiency are generally uncorrelated. Surveys by NRDC staff confirm that there is still no correlation. Evidence for a very weak correlation is given in R.H. Williams, "Marketing Energy Efficient Appliances," Center for Energy and Environmental Studies, Princeton University, June 4, 1981. Williams finds a first cost increase of $.166 per kWh/year of savings in 1981, but the r^2 for the equation is only 0.15 for 29 data points. A cost of $.166 per kWh/year results in a payback period of less than three years at 1981 electricity prices.