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Environmental Program

The Room Air Conditioner as an Energy Consumer

John C. Moyers

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ABSTRACT

As a part of the ORNL-NSF Environmental Program's effort toward conservation of energy, large differences in the efficiency with which room air conditioners consume electricity to provide cooling are pointed out and examined. Efficiencies range from 4.9 to 12.2 Btu/watt-hr. An improvement in average efficiency from 6 to 10 Btu/watt-hr is estimated to result in a total saving of 212 billion kW-hr during the 1973-80 period and a reduction in connected load to the electrical utilities in 1980 of almost 58,000 MW. A method for predicting the change in efficiency due to a change in design is developed and used to estimate the additional cost entailed in providing higher efficiency. A simple method for evaluating the monetary worth of the power saving at higher efficiency, from the individual's standpoint, is presented.

TABLE OF CONTENTS

THE ROOM AIR CONDITIONER AS AN ENERGY CONSUMER

Introduction

A doubling time of 10 years for our nation's power consumption is a historical fact and a widely-accepted prediction for the near future. The growing recognition of the environmental effects of such an expansion of the fuel extraction, power generation, and transmission sectors of the power industry has provided the impetus for a wide range of technical, judicial, and legislative activities aimed at reducing the environmental degradation associated with each of the sectors.

Another way to diminish the environmental impact of power production is to reduce the consumption. This avenue, as it applies to the residential portion of the total consumption, is being explored as a part of the Oak Ridge National Laboratory-National Science Foundation Environmental Program. A previous report[1] presented estimates of reductions in energy consumption achievable by the use of additional thermal insulation in residential construction.

In all-electric homes, air conditioning ranks third as a major electricity-consuming function, behind space heating and water heating. In air-conditioned homes having non-electric space heating and water heating, air conditioning is by far the largest single electricity-consuming function. Air conditioning is particularly important as a power consumer because of its contribution to (or cause of) the annual peak load that occurs in the summertime for many utility systems. The popularity of room air conditioners for use in upgrading existing dwellings and in new construction, either as window or through-the-wall units is evidenced by a sales doubling time of five years and a doubling time for the number of homes equipped with room air conditioners of six years over the 1960-70 decade.

This study was undertaken to determine the range of operating efficiencies offered by the many models of room air conditioners available on the market, to determine the extent to which adequate information is available to the prospective air conditioner purchaser, and to develop a method for comparing differences in purchase price with differences in performance. A conjectural estimate of the effect on the nation's power consumption of a change in the average efficiency of room air conditioners was also developed.

Sales and Market Saturation Statistics

Data for the number of room air conditioners shipped by manufacturers, market saturation level (expressed as the percentage of wired homes having room units), and the number of homes having room units, as extracted from Merchandising Week,[2] are given for the 1960-72 period in Table 1.

Table 1. Room Air Conditioner Shipments and Market Saturation Data*

Year	No. Shipped	Saturation Level	No. of Equipped Homes
1960	1.580×10^6	12.8%	6.48×10^6
1961	1.500×10^6	15.1%	7.80×10^6
1962	1.580×10^6	17.0%	8.91×10^6
1963	1.945×10^6	18.8%	10.09×10^6
1964	2.755×10^6	19.4%	10.65×10^6
1965	2.945×10^6	20.2%	11.40×10^6
1966	3.345×10^6	24.2%	13.93×10^6
1967	4.129×10^6	27.9%	16.42×10^6
1968	4.026×10^6	30.7%	18.44×10^6
1969	5.459×10^6	33.5%	20.53×10^6
1970	5.887×10^6	36.7%	23.01×10^6
1971	5.438×10^6	40.6%	25.99×10^6
1972	—	44.5%	29.17×10^6

*Data adapted from Merchandising Week, "Statistical and Marketing Report Edition," February 23, 1970, February 22, 1971, and February 28, 1972.

The rate of growth of shipments is essentially exponential through the period, with the number shipped doubling about every five years. The rate of growth of the number of homes with room air conditioners is also essentially exponential, with a doubling time of approximately six years.

Multiple-unit installations, retirement of older units, and non-residential purchases probably account for the discrepancies between yearly shipments and the increase in homes with air conditioners.

The growth in number of shipments and homes equipped with room air conditioners is shown in Figure 1. Also shown for comparison is the growth in number of shipments of color television sets. No other major appliance has shown such a consistently strong growth in popularity as the room air conditioner over the last 12 years. The growth was sustained through 1970, even though the downturn in the national economy caused slight decreases in shipments of kitchen and laundry appliances and a 10% decrease in shipments of home electronics (phone, radio, and TV). An 8% decrease in air conditioner shipments occurred in 1971, probably as a delayed result of the economic downturn. However, it appears that air conditioning is becoming a necessity in the view of the American consumer.

The size distributions of units shipped during the first nine months of 1969 and of 1970 are as follows:

Btu/hr	Under 7,000	7,000 - 11,000	11,000 - 20,000	Over 20,000
1969	34.1%	24.8%	29.2%	11.9%
1970	31.5	26.6	30.4	11.5

The Industry Certification Program

The Association of Home Appliance Manufacturers (AHAM) sponsors a certification program for air conditioners in which practically all manufacturers and marketers of the units participate. In order to participate, the participant must agree that all models manufacturer or marketed by him and offered for sale in the United States must be certified for cooling capacity and electrical input (volts, amps, and watts).

The manufacturer establishes the cooling capacity and electrical input ratings for his units at test conditions of:

Room air temperature	80°F dry bulb, 67°F wet bulb
Outside air temperature	95°F dry bulb, 75°F wet bulb

The ratings are listed on the nameplate and an AHAM certification seal is affixed to each unit.

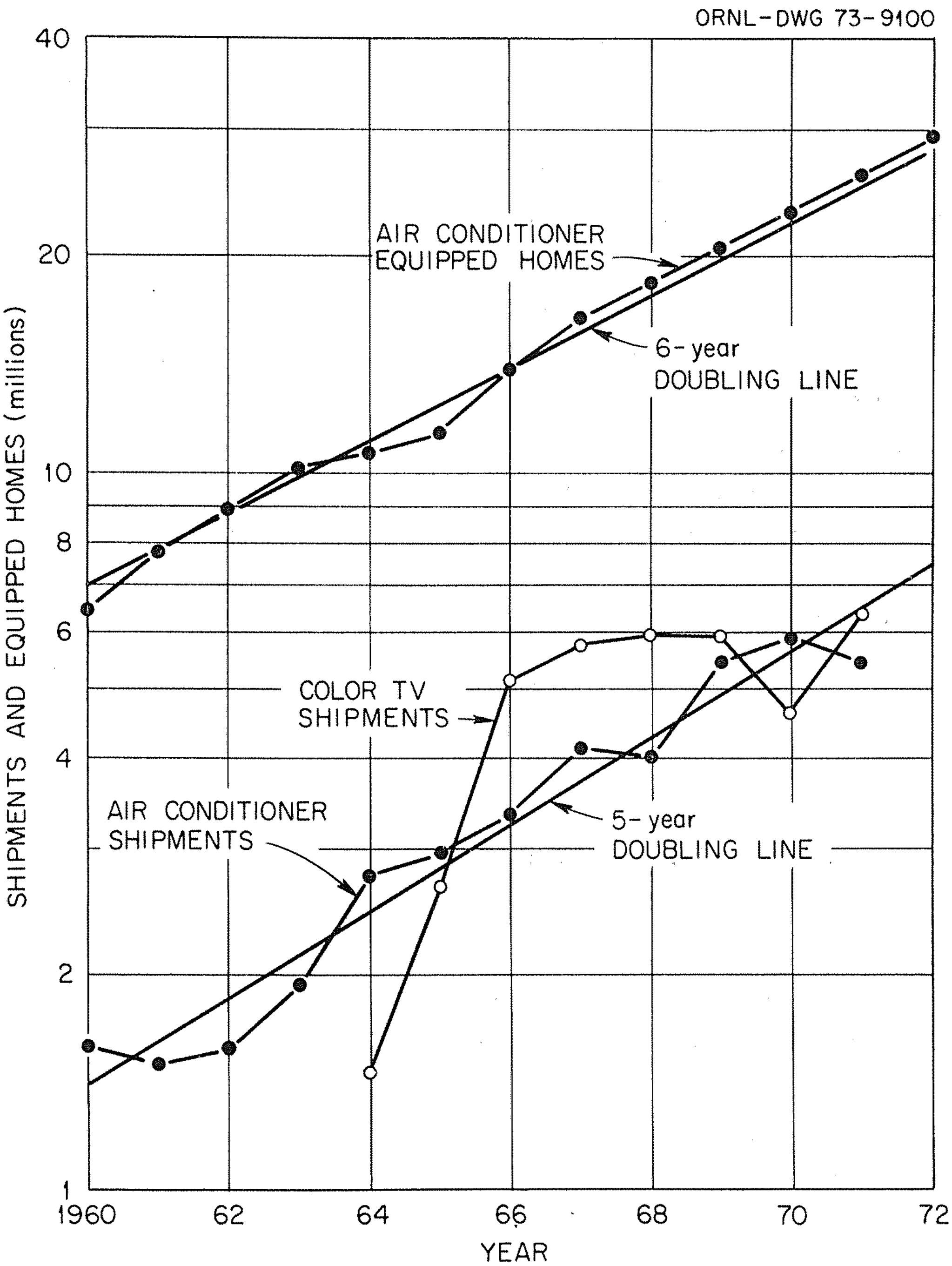

Figure 1. Room Air Conditioners Shipments and Equipped Homes.

The certification program is administered by Electrical Testing Laboratories, Inc. (ETL), which schedules the testing of specimens to determine compliance with the certification standards. Specimen testing includes all models representing a majority of the manufacturer's production, including a sampling of at least 50% of the manufacturer's basic models. ETL determines which models to test; the manufacturer does not know which models are to be tested nor when any test will be conducted.

If tests by ETL show that the cooling capacity of a production model is less than 92% of the nameplate rating or that the amps or watts drawn are more than 110% of the nameplate data, AHAM requires that the model must be rerated and the manufacturer must inform his distribution outlets of the new rating.

Survey of Available Models and Their Efficiencies

All models of room air conditioners certified under the AHAM program are listed with their voltage, cooling capacity, amps, and watts in the Directory of Certified Room Air Conditioners,[3] issued quarterly by AHAM. The May 1972, edition lists approximately 1200 models that are marketed under 50 different brand names. Cooling capacities range from 4,000 to 36,000 Btu/hr. The brand name offering the largest number of models is Fedders, with 78 models.

The efficiency with which a unit uses electricity to provide cooling may be expressed in terms of Btu/watt-hr, which is determined by the ratio of cooling capacity to input watts. This efficiency is listed for each of the models included in the AHAM Directory edition intended for the New York area, as a part of the industry's program to help alleviate that area's chronic summertime power deficiency. Figure 2 shows the efficiencies for all models having ratings up to 24,000 Btu/hr.

The spread of efficiencies is quite large, ranging from 4.9 to 12.2 Btu/watt-hr (a factor of 2.5). The high-efficiency unit would consume only 40% as much power as the low-efficiency machine to accomplish the same amount of cooling. Although there are numerous exceptions, the majority of the units have efficiencies of less than 7 Btu/watt-hr.

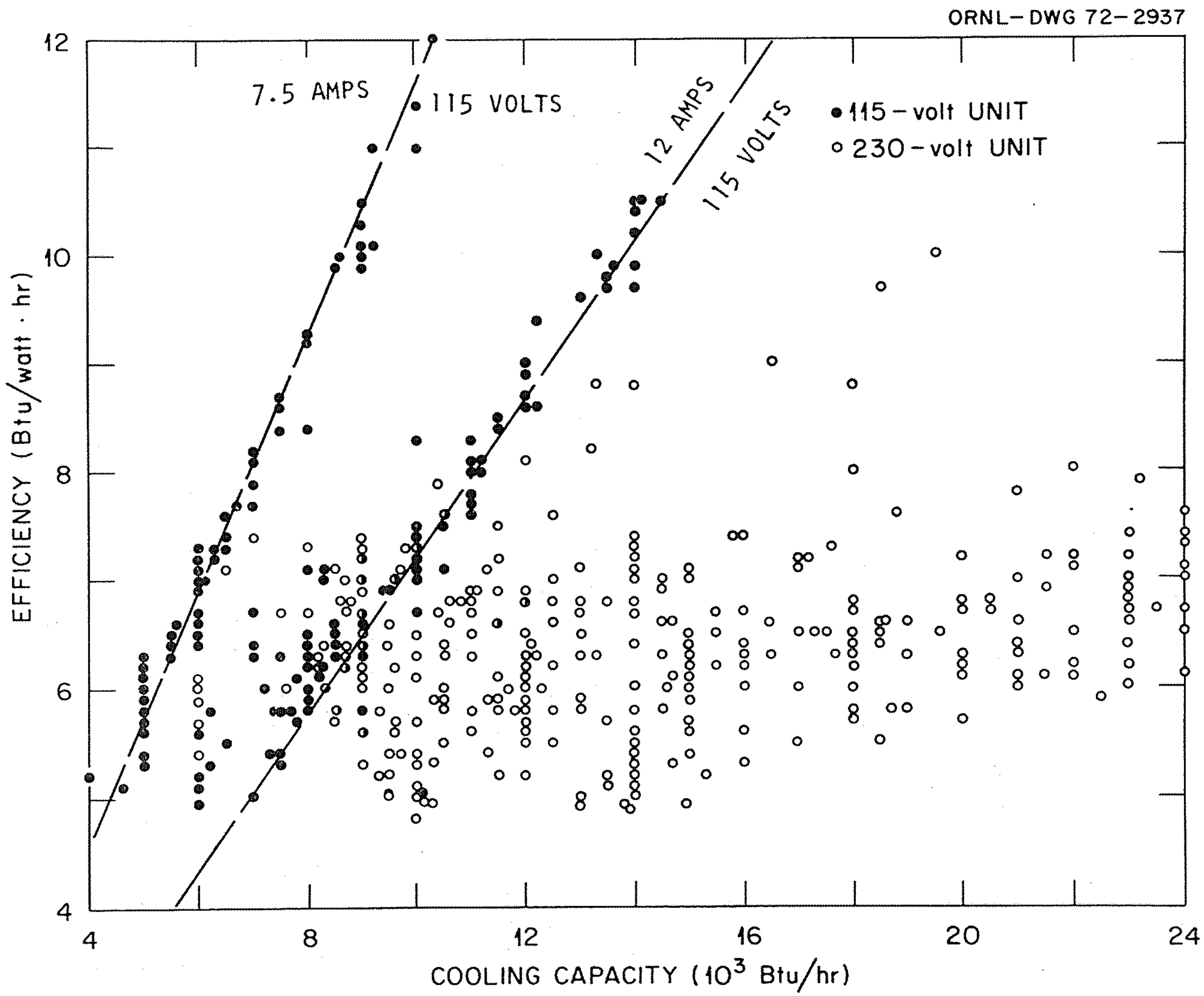

Figure 2. Efficiency of Room Air Conditioners.

There is no strong trend toward either higher or lower efficiency with increasing capacity, and except for two groupings of units, there is no marked difference in efficiencies for 115-volt versus 230-volt units.

Two groupings of highly efficient units are evident in Figure 2. These groupings follow the superimposed 7.5-amp, 115-volt, and the 12-amp, 115-volt, lines. The groupings result from the manufacturers' efforts to produce units having large cooling capacity ratings that can be used with existing or easily added electrical circuits and comply with the requirements of the National Electric Code (NEC).[4]

The smallest branch circuit rating permitted by the NEC is 15 amps. The NEC requires that the amp rating of an air conditioner shall not exceed 50% of the circuit rating if lighting units or other appliances are also supplied by the circuit, and that the amp rating of an air conditioner shall not exceed 80% of the circuit rating if the circuit supplies nothing else. Thus, the 7.5-amp units are intended for use with a general-purpose circuit and the 12-amp units for a single-purpose circuit. The only way the highly marketable, fairly large capacity units can be built to comply with the electrical requirements for commonly available circuits is to have a high efficiency. On either side of the 7.5-amp and 12-amp groupings, this reason for high efficiency does not exist. Smaller units don't overload the circuits and larger ones require 230-volt circuits.

Design changes that result in higher efficiency are discussed and the development of expressions that predict the magnitude of efficiency improvements is given in Appendix A.

The Prospective Purchaser's Dilemma

The expected choice between models of the purchaser of an air conditioner would be based on obtaining the lowest purchase price. Intuitively, it seems that this would rarely result in the purchase of a highly efficient machine. Selection of a unit having the lowest total cost, purchase plus operating, should result in a more efficient choice.

However, the problems facing the prospective purchaser are such that the possibility of his buying the one unit which will have the lowest total cost over its lifetime is very remote.

The many models having a given capacity that are offered for sale make comparative shopping an onerous chore, with only a small chance that all units will be considered. For example, there are 130 window units rated at 6,000 Btu/hr in the AHAM Directory. There are many small differences between models, other than efficiency, that confuse the selection process. These include noise level claims, air distributer features, number of fan speeds, appearance features, ease of installation, component quality, etc.

All models marketed under AHAM certification (over 90% of all U.S.-made room air conditioners) provide reliable nameplate data on cooling capacity and power consumption. However, the nameplate is not visible on all models; in some cases, the front cover must be removed to find the plate.

The total cost of the air conditioner over its lifetime consists of the purchase price plus the present value of the power costs that will be incurred during the machine's lifetime. In addition, there may be significant but unpredictable maintenance costs.

It would be expected that a more efficient air conditioner, having lower power costs, would have a higher retail price because the higher efficiency is obtained through the use of larger or more expensive components. This was generally borne out by the cost studies described in Appendix B, although there are numerous exceptions.

A regression analysis of the relationship of price, efficiency, and size using data for 77 models produced by three manufacturers failed to produce a good general correlation. Among the three manufacturers, the analysis indicated an increase in price ranging from 13% to 29% accompanying an increase in efficiency from 6 to 10 Btu/watt-hr. A doubling of cooling capacity was accompanied by an indicated price increase ranging from 42% to 63%.

A rough estimate was also made of the additional manufacturing costs that might be incurred in increasing the efficiencies of two sizes of units from 6 to 10 Btu/watt-hr. The estimate was based on the additional costs of components required to effect the change in efficiency. These additional costs, assuming a 50% markup between manufacturing cost and retail price, would result in increases in retail price ranging from 15% to 22%. These retail price increases are equivalent to a range of $56 to $89 per kilowatt of reduced power rating.

Items of information needed to evaluate the present value of the power costs include: the wattage of the unit; the expected annual hours of operation; the unit cost of electricity; the discounting rate to be used; and the expected lifetime of the unit.

A nomograph that permits evaluation of the present value of all future power costs, assuming a 10-year lifetime, is included in Appendix C. By using the nomograph, the prospective purchaser can determine how much more he is justified in paying for the more efficient machine.

The complexity of the nomograph, or of any other accurate procedure for evaluating the present worth of future savings in operating cost, may discourage most shoppers from attempting the evaluation. Perhaps a labeling requirement, with prominent stick-on labels stating the nameplate data and approximate annual operating costs for different regions of the country and power prices, would be a more effective way of making the shopper efficiency-conscious. The present value of 10 years' operating costs would vary with the individual's appropriate interest (discounting) rate, ranging from 7.4 times the annual operating cost at 6% to 4.5 times the annual cost at 18%.

As an example of the magnitude of possible annual savings, the following case is cited. Of the 78 models of 10,000 Btu/hr capacity, the lowest-efficiency one draws 1900 watts and the highest-efficiency one draws 880 watts. If the Washington, D.C., area is assumed, the air conditioner would be expected to operate about 800 hours per year. The low-efficiency unit would use 816 kilowatt-hours more electricity each year than the high-efficiency unit, and at a rate of 1.8 cents/kW-hr, would have an additional operating cost of $14.69/year. The justifiable additional purchase price for the more efficient machine would be $66 for the 18% purchaser or $108 for the 6% purchaser.

Impact on Energy Consumption of an Improved Efficiency

An improvement in the average efficiency of room air conditioners would result in an appreciable reduction in the nation's energy consumption and required generating capacity. The following conservative estimate will serve to illustrate the magnitude of these effects.

The sales of room air conditioners doubled every five years between 1960 and 1970. Market saturation was estimated to be 40.6% at the end of 1970. Replacement sales accounted for 20% of the total sales in 1970.[2] An approach to full saturation will have a retarding effect on sales, but the replacement market will continue to grow. An assumption of a doubling in annual sales between 1970 and 1980 (i.e., half the rate of growth experienced between 1960 and 1970) appears reasonably conservative.

The average capacity of all units shipped in the first nine months of 1970 was 11,600 Btu/hr. A reasonable assumption is that this average will prevail through 1980. An annual operating time of 886 hours is assumed, in accordance with data published by the Edison Electric Institute.[5]

The estimated shipments, cooling capacity, and amount of cooling for the 1973-1980 period are given in Table 2. The amounts of electricity that would be consumed during the 8-year period, with several values for average efficiency, are also included.

By examination of Figure 2 and consideration of the fact that low-efficiency machines generally have lower selling prices and, as a result, appear to be better bargains to the casual shopper, a present-day average efficiency of 6 Btu/watt-hr can be assumed. An improved average efficiency of 10 Btu/watt-hr appears to be attainable without any technological breakthrough — this level is well below the maximum efficiency available today. Such an improvement would result in a cumulative saving of electricity consumption over the 8-year period of 212 billion kilowatt-hours. This is equivalent to 2.4 times the 1970 total electricity sales of the Tennessee Valley Authority or 6.5 times the 1970 sales of the Consolidated Edison Company.

The generation of 212 billion kilowatt-hours of electricity by modern coal-fired power plants at a heat rate of 9000 Btu/kW-hr would

Table 2. Estimated Shipments, Cooling Capacity, and Amount of Cooling — 1973-1980

Year	Shipments Millions	Capacity Shipped 10^9 Btu	Annual Cooling 10^{12} Btu	Cumulative Cooling 10^{12} Btu/yr
1973	7.25	84.1	74.5	74.5
1974	7.77	90.1	79.8	154.3
1975	8.33	96.6	85.6	239.9
1976	8.93	103.6	91.8	331.7
1977	9.57	111.0	98.4	430.1
1978	10.25	118.9	105.3	535.4
1979	10.99	127.5	113.0	648.4
1980	11.78	136.6	121.0	769.4
	Total cooling for 8-year period			3183.7
Total Power Consumed:				
	At efficiency of 6 Btu/watt-hr		530.6×10^9 kW-hr	
	At efficiency of 8 Btu/watt-hr		398.0×10^9 kW-hr	
	At efficiency of 10 Btu/watt-hr		318.4×10^9 kW-hr	
	At efficiency of 12 Btu/watt-hr		265.3×10^9 kW-hr	

consume 79.5 million tons of coal. At a strip mine yield of 5000 tons per acre, this is equivalent to 15,900 acres of stripped area.

The 1980 connected load of the room air conditioners sold during the 8-year period would be 145,000 MW with an efficiency of 6 Btu/watt-hr, or 87,000 MW with an efficiency of 10 Btu/watt-hr. Although not all of the air conditioners would ever be operating at the same time, this 58,000 MW reduction in connected load due to the efficiency improvement would surely result in an appreciable reduction in the installed generating capacity requirements for the nation's utilities.

Other Opportunities for Reducing Air Conditioning Energy Consumption

In addition to the potential for reducing the energy consumption by room air conditioners through improved efficiency introduced at the manufacturing level, there are opportunities for energy conservation that may be realized through action by the owner.

An adequately insulated home requires less energy for air conditioning than a poorly insulated one. For example, Reference 1 shows that an optimally insulated gas-heated home in Atlanta requires almost 22% less energy for air conditioning than a home built in compliance with FHA requirements prior to 1971 and originally without air conditioning (a common situation in which room air conditioners are used). If the home were electrically heated, storm windows would be included with optimal insulation and the energy consumption for air conditioning would be 31% less than that for the pre-1971 FHA-compliance home. Increasing the ceiling insulation thickness from 1 7/8 in. to 6 in., a step that can be taken quite easily in an older home, reduces air conditioning energy by about 8.5%, and storm windows, if left closed during the air conditioning season, will produce an additional reduction of more than 9%.

The efficiency of an air conditioner deteriorates somewhat with age and use. This deterioration is largely due to the accumulation of foreign material (dust, lint, leaves, spider webs, etc.) in the finned evaporator and condenser coils. This accumulation partially blocks the flow of air through the coils and also tends to insulate the surfaces against ready transfer of heat.

Frequent changes or cleaning of the filter retards the accumulation of dirt in the evaporator and allows free air flow through the filter itself. However, because the filters used in room air conditioners are generally not too effective at best, periodic cleaning of the evaporator as well as the condenser is beneficial. Preferably, the air conditioner chassis should be removed from its cabinet for cleaning. Cleaning may be accomplished by the application of a mild detergent solution with a soft, long-bristle brush, followed by a thorough flushing with clean water. Electrical parts and controls should be protected by covering with plastic, and the unit should be allowed to dry before use. Fins that have been bent should be straightened to allow free passage of air.

Perhaps the most significant energy-conserving action that can be taken by the user of an air conditioner is that of setting the thermostat at a higher temperature. Estimates of the annual energy consumption for air conditioning are usually based on the number of cooling degree-days* in the locale of interest. Weather Bureau data tapes giving hourly temperatures for several years in Atlanta, Philadelphia, and Minneapolis were scanned to determine cooling degree-days for a range of base temperatures. The results are given in Table 3.

Table 3. Cooling Degree-Days for Different Base Temperatures

Base Temperature °F	Annual Cooling Degree-Days		
	Atlanta	Philadelphia	Minneapolis
70	877	584	362
71	744	495	300
72	620	413	246
73	505	338	198
74	398	272	157
75	303	214	122
76	221	163	93
77	155	121	69
78	104	87	50
79	66	60	37
80	40	39	27

An increase in thermostat setting from 75 to 78°F, which might change the base temperature from 70 to 73°F, reduces the cooling degree hours by more than 42% in each of the cities. Assuming that 30% of the energy for air conditioning is consumed for dehumidification and fixed heat inputs that do not change with thermostat setting, the net reduction in energy consumption resulting from the 3°F increase in temperature setting would be 0.7 X 42 = 29.4%, or approximately 10% per degree of increase in setting.

*The contribution of each day to the annual cooling degree-days is that day's average temperature less some base temperature. The base temperature is usually the desired indoor temperature less about 5°F. For example, with a desired indoor temperature of 75°F, the base temperature would be 70°F and a day having a high of 90°F and a low of 72°F (average of 81°F) would contribute 81 - 70 = 11 cooling degree-days. If the desired indoor temperature were shifted upward to 78°F, the base temperature would become 73°F and the 90-72°F day would contritube only eight cooling degree-days.

Conclusions and Recommendations

The investigation has shown that there is a wide variation in the power consumption of room air conditioners that accomplish the same amount of cooling. Although an industry-sponsored certification program requires that cooling capacity and power consumption data be included on the nameplate, the data are probably not used effectively by the majority of prospective purchasers while deciding upon which model to buy. This is because the nameplate often is not readily accessible, the efficiency of an air conditioner usually is not an advertisement feature, and prospective purchasers usually are not aware of any great difference in power consumption between models.

In addition to long-term economic benefit that might accrue to the individual owner through the purchase of a more efficient machine, an improvement in the average efficiency of air conditioners would result in an appreciable reduction of the nation's electricity consumption and required generating capacity. This reduction would occur during the summer when so many utility systems are hard-pressed to meet the peak demand for power, and would reduce the need for the utilities' promotion of electric heat to balance their systems' winter and summer loads and improve the load factor.

Possible actions that could be taken to bring about improvement in the average efficiency of energy utilization of room air conditioners include:

1. Public education programs that point out the wastefulness of low-efficiency units, in terms of both resources and overall monetary cost. Consumers would be advised to make efficiency a criterion of the decision process. The need for frequent filter changes and periodic cleaning of the coils should be pointed out, and the energy savings realizable by maintaining a warmer thermostat setting should be stressed.
2. A requirement for promonent and informative labeling and advertising. A strip-off paper label that repeats the name-plate data and, in addition, states the efficiency in terms of Btu/watt-hr would be a reasonable requirement. Average yearly

operating costs for the various regions of the country and for a range of electricity costs might also be included. Advertisements should state the wattage and efficiency. (A recent development is the inclusion of efficiency in some advertisements by some manufacturers. However, this practice has not been generally adopted.)

3. A requirement that units meet some minimum efficiency level. This is a more drastic measure but is not without precedent. The air conditioner, via the plant that generates the power by which it operates, is a polluter as surely as is the automobile. The performance requirement could be introduced at the state level and apply to all units marketed in the state, or it could be a federal requirement applying to all units shipped in interstate commerce.

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2. Merchandising Week, "Statistical and Marketing Report Edition," issued during February each year, Billboard Publications, Inc., New York.

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4. National Electrical Code, 1971, NFPA No. 70-1971, ANSI C1-1971, National Fire Protection Association, Boston, 1971.

5. "Approximate Wattage Rating and Estimated Average kWhr Consumption of Electric Household Appliances Assuming Normal Use," issued biennially on odd years, Edison Electric Institute, New York, 1969.

APPENDIX A

EFFICIENCY AS A FUNCTION OF DESIGN

The efficiency of an air conditioner is influenced primarily by (a) the amount of heat transfer area built into the evaporator and condenser, (b) the air flows across those two heat exchangers, and (c) the efficiency of the motor-compressor. The heat transfer areas affect the temperature differences between the outside air and the refrigerant being condensed in the condenser and between the inside air and the refrigerant being evaporated in the evaporator. As a result, small areas cause a large temperature difference across which the refrigerant cycle must pump heat. Increasing the air flow rate through the heat exchangers has a dual effect. The air-side film coefficient for heat transfer increases with increasing velocity, decreasing the air-to-refrigerant temperature difference (which decreases the refrigerant cycle temperature difference for given inside and outside air temperatures). Increasing the air flow rate also decreases the temperature change of the air streams as they flow through the exchangers, resulting in an average air temperature for each stream that is more nearly equal to that of the inlet air and permits a refrigerant temperature more nearly that of the inlet air temperature for a given quantity of transferred heat. A more efficient motor-compressor results in lower frictional losses in the refrigerant circuit and, therefore a more efficient machine.

In the past, high-efficiency motor-compressors were usually 1800-rpm, 4-pole, units while the lower-efficiency ones ran at 3600 rpm (2-pole). The low-speed units were larger and more expensive. A recent development is the high-efficiency 3600-rpm compressor, which performs as efficiently as the older 1800-rpm type but is smaller and costs somewhat less.

The temperature levels that apply in considering the air conditioner are shown in Figure A.1. The outside air temperature usually specified for rating air-cooled units is 95°F. The hot refrigerant must dump the heat it has carried from inside the home to the outside air. Therefore, the hot refrigerant temperature is higher than the outside air temperature by some amount that depends upon the surface area of the condenser, the air flow through the condenser, the quantity of heat to be transferred, and the overall heat transfer coefficient. The inside air temperature is usually specified as 80°F for rating purposes. The cold refrigerant temperature must pick up heat from the inside air in order to cool the air. Therefore, the cold refrigerant temperature is lower than the inside air temperature by some amount that depends upon the heat transfer characteristics (surface area, air flow, quantity of heat, and heat transfer coefficient) of the evaporator.

The refrigerant cycle must pump the heat removed from the inside air across a temperature difference that consists of the sum of the inside-outside air Δt, the evaporator Δt, and the condenser Δt. The refrigerant cycle is assumed to perform in a manner similar to that of a Carnot cycle, with an efficiency that is some fraction of the efficiency of a Carnot cycle operating over the same temperature difference.

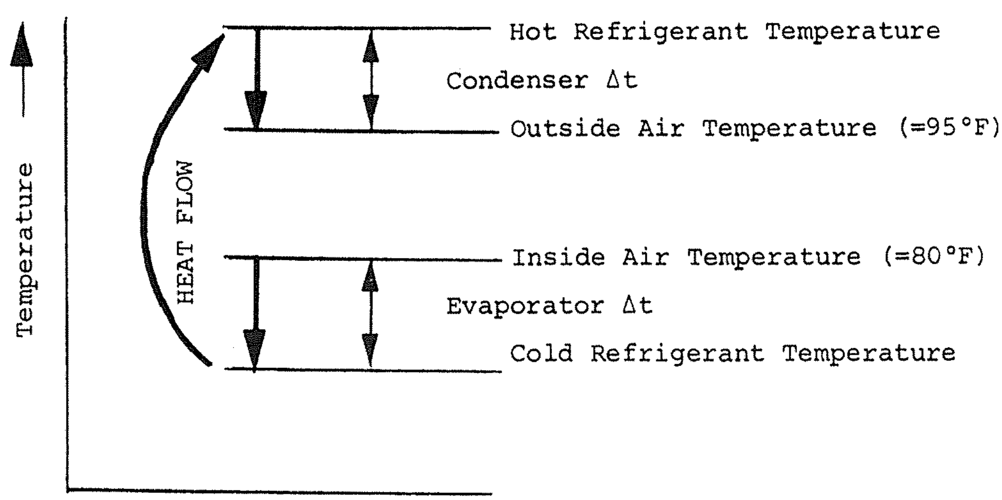

Figure A.1

In the ensuing development, considering first the two heat exchangers and then the complete machine, the following nomenclature will be used.

t_{CA1} - inside air temperature entering the evaporator (=80), °F
t_{CA2} - inside air temperature leaving the evaporator, °F
t_{CAm} - arithmetic mean air temperature in the evaporator, °F
t_{CR} - refrigerant temperature in the evaporator, °F
t_{HA1} - outside air temperature entering the condenser (=95), °F
t_{HA2} - outside air temperature leaving the condenser, °F
t_{HAm} - arithmetic mean air temperature in the condenser, °F
t_{HR} - refrigerant temperature in the condenser, °F
A_E - evaporator heat transfer area, ft^2
A_C - condenser heat transfer area, ft^2
FA_E - evaporator face area (normal to air flow), ft^2
FA_C - condenser face area (normal to air flow), ft^2
U_E - overall heat transfer coefficient for evaporator, Btu/ft^2-hr-°F
U_C - overall heat transfer coefficient for condenser, Btu/ft^2-hr-°F
V_E - air flow through the evaporator, ft^3/min
V_C - air flow through the condenser, ft^3/min
K - ratio, work input (real)/work input (Carnot)
Q - heat removed from the inside air, Btu/hr
I - input work to drive compressor, Btu/hr

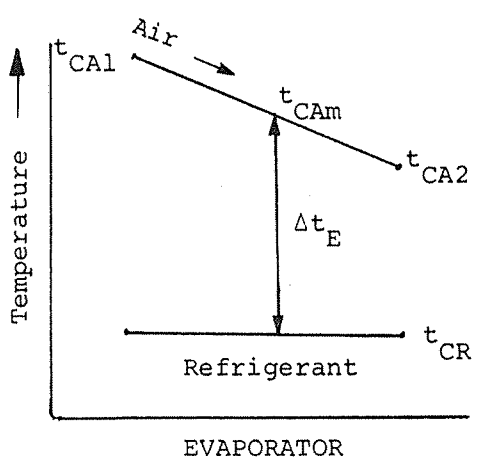

Figure A.2

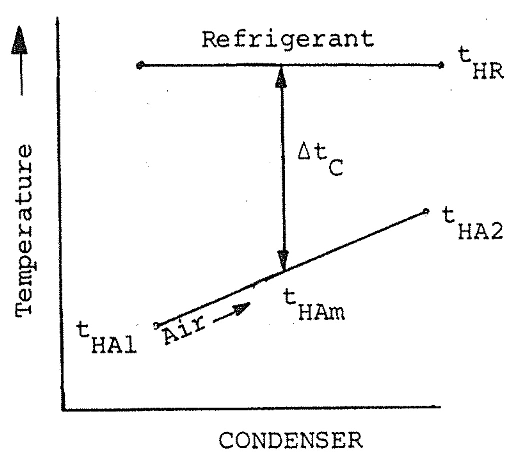

Figure A.3

<u>Evaporator</u> (Figure A.2)

$$t_{CA1} = 80°F$$

Assuming that 65% of heat removed from air is sensible, 35% latent,

$$\text{Air } \Delta t = 0.65Q/(1.08V_E) = 0.60Q/V_E$$

$$t_{CA2} = 80. - 0.60Q/V_E$$

$$t_{CAm} = 80. - 0.30Q/V_E$$

From $Q = U_E A_E \Delta t_E$,

$$t_{CR} = t_{CAm} - Q/U_E A_E$$

$$t_{CR} = 80. - 0.30Q/V_E - Q/U_E A_E$$

From examination of manufacturer's data for heat exchangers,*

$$U_E = 0.236(\text{Velocity, ft/min})^{0.603}$$

$$U_C = 0.212(\text{Velocity, ft/min})^{0.54}$$

Then,

$$t_{CR} = 80. - 0.30Q/V_E - 4.24Q/A_E(V_E/FA_E)^{0.603}$$

<u>Condenser</u> (Figure A.3)

$$t_{HA1} = 95°F$$

The condenser must transfer the heat transferred by the evaporator plus the heat equivalent of the compressor power input.

$$t_{HA2} = t_{HA1} + (Q + I)/1.08V_C$$

$$= 95. + 0.92(Q + I)/V_C$$

$$t_{HAm} = 95. + 0.46(Q + I)/V_C$$

$$t_{HR} = t_{HAm} + (Q + I)/A_C U_C$$

$$= 95. + 0.46(Q + I)/V_C + (Q + I)/[0.212A_C(V_C/FA_C)^{0.54}]$$

$$= 95. + 0.46(Q + I)/V_C + 4.95(Q + I)/A_C(V_C/FA_C)^{0.54}$$

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*"Heating and Cooling Coils," Bulletin B-1718, American Radiator and Standard Sanitary Corporation, 1962, Detroit.

Total Machine

For a Carnot machine,

$$\frac{I}{Q} = \frac{T_{HR} - T_{CR}}{T_{CR}} \quad ,$$

where T has same meaning as t except in °R.

For the real machine, input power is higher by some factor K (K > 1.0), or

$$\frac{I}{Q} = \frac{K(T_{HR} - T_{CR})}{T_{CR}}$$

$$= K[555. + 0.46(Q + I)/V_C + 4.95(Q + I)/A_C(V_C/FA_C)^{0.54} - 540.$$

$$+ 0.30Q/V_E + 4.24Q/A_E(V_E/FA_E)^{0.603}]/[540. - 0.30Q/V_E$$

$$- 4.24Q/A_E(V_E/FA_E)^{0.603}]$$

Solving for I,

$$I = \frac{15KQ + KQ^2\left[\frac{0.46}{V_C} + \frac{4.95}{A_C(V_C/FA_C)^{0.54}} + \frac{0.30}{V_E} + \frac{4.24}{A_E(V_E/FA_E)^{0.603}}\right]}{540. - Q\left[\frac{0.3}{V_E} + \frac{4.24}{A_E(V_E/FA_E)^{0.603}} + \frac{0.46K}{V_C} + \frac{4.95K}{A_C(V_C/FA_C)^{0.54}}\right]}$$

Applying a regression analysis technique to the design and performance data available for 31 machines (19 3600-rpm, 12 1800-rpm), values for K, which relates real to Carnot input power per unit of cooling, were determined. For the 3600-rpm machines, the value of K was 2.33. For the 1800-rpm machines the value of K was 1.96. In other words, the real efficiency, compared to Carnot efficiency, was 42.9% for 3600-rpm machines and 51% for 1800-rpm machines.

Substituting these values for K into the above expression for compressor input power, I, For 2-Pole, 3600-rpm, Machines

$$I = \frac{34.95Q + 2.33Q^2\left[\dfrac{0.461}{V_C} + \dfrac{4.95}{A_C(V_C/FA_C)^{0.54}} + \dfrac{0.30}{V_E} + \dfrac{4.24}{A_E(V_E/FA_E)^{0.603}}\right]}{540. - Q\left[\dfrac{0.30}{V_E} + \dfrac{4.24}{A_E(V_E/FA_E)^{0.603}} + \dfrac{1.07}{V_C} + \dfrac{11.53}{A_C(V_C/FA_C)^{0.54}}\right]}$$

For 4-Pole, 1800-rpm, Machines (or high-efficiency 2-pole machines)

$$I = \frac{29.40Q + 1.96Q^2\left[\dfrac{0.461}{V_C} + \dfrac{4.95}{A_C(V_C/FA_C)^{0.54}} + \dfrac{0.30}{V_E} + \dfrac{4.24}{A_E(V_E/FA_E)^{0.603}}\right]}{540. - Q\left[\dfrac{0.30}{V_E} + \dfrac{4.24}{A_E(V_E/FA_E)^{0.603}} + \dfrac{0.90}{V_C} + \dfrac{9.70}{A_C(V_C/FA_C)^{0.54}}\right]}$$

Figure A.4 shows the effects on compressor input power of varying condenser area, evaporator area, air flow rate, and type of compressor.

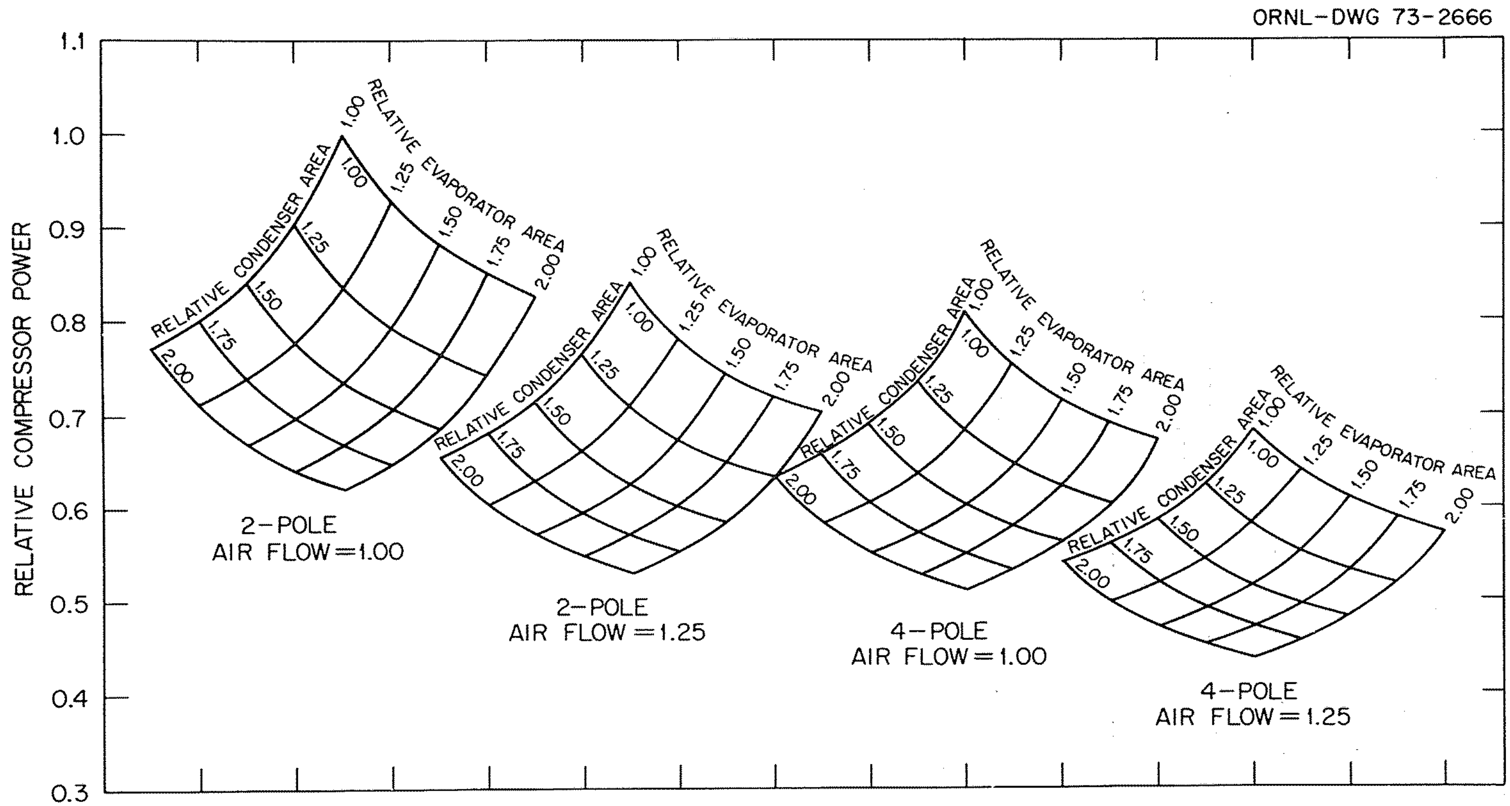


Figure A.4. Predicted Performance of Room Air Conditioners.

APPENDIX B

THE COST OF HIGHER EFFICIENCY

Analysis to determine the circumstances that make the purchase of a more efficient air conditioner economically justified requires knowledge of how purchase price is affected by efficiency. Two approaches to acquiring this knowledge were employed. In the first approach, suggested retail prices and performance data for various models on the market were examined, using a regression analysis technique. In the second approach, the design changes required to improve the performance of two mediocre units were determined and the manufacturing cost differences (and selling price differences) due to those changes were estimated.

Regression Analysis

Suggested retail prices and efficiencies for 77 room air conditioners produced by three manufacturers and ranging in size from 5,000 to 18,000 Btu/hr are given in Table B.1. The regression analysis technique was applied in an attempt to obtain a correlation of price with efficiency and size.

Each manufacturer produces more than one "line" of units. To accommodate the effect of the various lines on price, each unit was assigned to a line class using available descriptive material. The line classes were:

1. Deluxe
2. Standard
3. Specialty (for casement or sliding windows)
4. Portable and promotional

The correlation form that was used in the regression analysis for each manufacturer's units was:

$$\text{Price} = e^{A(\ell)} \times (\text{Efficiency})^{B} \times (\text{Size})^{C}$$

where

Price = \$/kBtu
Efficiency = Btu/watt-hr
Size = kBtu/hr
$A(\ell)$ = constant for a given line, ℓ, as listed above.

Table B.1. Efficiencies and Retail Prices of Air Conditioners

Btu/hr	Manufacturer	Efficiency	Price, $	$ per kBtu/hr
5,000	A	6.0	160	32.0
5,000	A	6.0	150	30.0
5,000	B	6.2	100	20.0
5,000	C	6.0	140	28.0
5,000	C	6.0	160	32.0
5,600	C	6.6	265	47.3
6,000	A	4.9	200	33.3
6,000	A	6.1	180	30.0
6,000	A	6.1	160	26.7
6,000	A	6.1	170	28.3
6,000	A	6.7	210	35.0
6,000	A	6.9	190	31.7
6,000	A	6.9	170	28.3
6,000	A	6.9	180	30.0
6,000	B	6.1	160	26.7
6,000	B	7.0	170	28.3
6,000	B	7.0	200	33.3
6,000	B	7.0	210	35.0
6,000	C	6.0	180	30.0
6,000	C	6.9	190	31.7
6,500	C	7.5	200	30.8
6,500	C	7.6	225	34.6
7,000	A	7.7	230	32.8
7,000	B	6.4	230	32.8
7,000	B	8.1	195	27.8
7,000	B	8.1	220	31.4
7,500	C	5.6	275	36.7
8,000	A	5.9	190	23.8
8,000	A	5.9	210	26.2
8,000	A	5.9	230	28.8
8,000	A	7.1	260	32.5
8,000	A	8.4	260	32.5
8,000	B	6.2	190	23.8
8,000	C	5.9	220	27.5
8,000	C	6.1	260	32.5
8,000	C	9.2	260	32.5
8,300	B	7.1	210	25.3
8,500	B	6.4	240	28.2
8,700	B	7.0	200	23.0
8,700	B	7.0	230	26.4
8,700	B	6.7	250	28.7

Table B.1 (continued)

Btu/hr	Manufacturer	Efficiency	Price, $	$ per kBtu/hr
8,800	C	6.8	250	28.4
9,000	C	6.7	230	25.6
9,500	B	11.1	300	31.6
10,000	A	5.4	250	25.0
10,000	A	6.7	280	28.0
10,000	A	7.2	280	28.0
10,000	A	7.4	260	26.0
10,000	A	11.0	350	35.0
10,000	C	7.3	260	26.0
11,000	A	7.6	280	25.4
11,000	B	5.8	260	23.6
11,000	C	8.0	280	25.4
12,000	A	5.8	250	20.8
12,000	A	6.0	270	22.5
12,000	A	8.6	310	25.8
12,000	B	7.1	250	20.8
12,000	B	8.7	310	25.8
12,000	C	5.6	260	21.7
12,000	C	5.8	290	24.2
12,000	C	6.0	290	24.2
12,200	C	8.9	310	25.4
12,300	C	6.0	280	22.8
13,200	C	8.3	330	25.0
14,000	A	5.1	310	22.1
14,000	A	5.5	290	20.7
14,000	A	8.8	350	25.0
14,000	A	9.9	370	26.4
14,000	C	6.0	300	21.4
14,500	C	5.4	290	20.0
15,000	B	5.9	275	18.3
16,000	C	5.3	320	20.0
18,000	A	6.4	360	20.0
18,000	A	6.4	390	21.7
18,000	A	8.8	400	22.2
18,000	C	6.0	350	19.4
18,000	C	6.0	320	17.8

The results are as follows:

Manufacturer	A(1)	A(2)	A(3)	A(4)	B	C	R^2
1	3.13	3.18	3.29	3.10	0.505	−0.376	0.899
2	3.14	2.99	3.25	2.97	0.417	−0.298	0.813
3	3.97	3.95	4.23	3.85	0.235	−0.497	0.941

Although the values for R^2 indicate a reasonably good fit with the data for each manufacturer's units, the large variations of values for the efficiency exponent, B, and the size exponent, C, between manufacturers make generalization hazardous. The results indicate that improving the efficiency from 6 to 10 Btu/watt-hr increases the price by 13 to 29%, depending upon the manufacturer. A doubling of cooling capacity would result in a price increase ranging from 42 to 63%.

Estimates of Incremental Manufacturing Costs

In order to gain some understanding of the magnitude of the differential costs involved in manufacturing more efficient air conditioners, with other design features held constant, a brief examination of component costs was made. Two units, rated at 8000 Btu/hr and 12,200 Btu/hr and having efficiencies of approximately 6 Btu/watt-hr, were selected as reference designs. Using Figure A.4, two alternate designs for each of the reference units were determined to provide an efficiency of approximately 10 Btu/watt-hr and the same cooling ratings as the respective reference units. In each case, the first alternate unit achieves the higher efficiency by using a high-efficiency compressor and additional surface area. The second alternate unit achieves the higher efficiency by using a high-efficiency compressor, a 25% increase in air flow through both the evaporator and the condenser, and a somewhat smaller amount of additional surface area.

The design characteristics and estimated performance of the six units are given in Table B.2.

Estimating costs for each of the condensers and evaporators were obtained from a large heat exchanger manufacturer and the differential cost between a normal and a high-efficiency compressor for the 12,200-Btu/hr machines was furnished by a compressor manufacturer.

The additional fan and motor cost for the second alternate units should be quite small; we estimate no more than $1.00. Differential costs are given in Table B.3.

Table B.2. Design Characteristics and Estimated Performance of Reference and Alternate Units

Unit No.	1	1A	1B	2	2A	2B
Cooling rating, Btu/hr	8000	8000	8000	12,200	12,200	12,200
Compressor type*	N	H	H	N	H	H
Evaporator						
Surface area, ft^2	48	84	74	65	101	86
Air flow, cfm	220	220	275	330	330	412
Condenser						
Surface area, ft^2	65	129	113	103	180	155
Air flow, cfm	325	325	410	600	600	750
Wattage						
Compressor	1150	610	560	1705	975	914
Fan	190	190	240	245	245	306
Total	1340	800	800	1950	1220	1220
Efficiency, Btu/watt-hr	6.0	10.0	10.0	6.3	10.0	10.0

*N = normal compressor; H = high-efficiency compressor.

Table B.3. Differential Costs of Alternate Units

Unit No.	1	1A	1B	2	2A	2B
Condenser differential cost, $	Base	17	12	Base	19	14
Evaporator differential cost, $	Base	9	9	Base	10	5
Compressor differential cost, $	Base	6	6	Base	7	7
Fan differential cost, $	Base	Base	1	Base	Base	1
Total differential manufacturing cost, $	Base	32	28	Base	36	27
Differential selling price, $*	Base	48	42	Base	54	41

*With an assumed markup on the differential manufacturing cost of 50%.

Units 1B and 2B, while providing the higher efficiency at less additional cost than Units 1A and 2A, would tend to be noisier due to the increased air velocity through their evaporators.

The present worths of the savings in power cost due to a load reduction of one kilowatt over a 10-year period are shown in Figure B.1 for an interest rate of 6% and in Figure B.2 for an interest rate of 18%, as functions of annual operating hours and the unit cost of electricity. Cities typically requiring the different annual air conditioner operating hours are shown. The incremental retail costs of the four high-efficiency units, normalized to a per-kilowatt power reduction basis, are also shown.

From these figures, the economic merit of purchasing the high-efficiency air conditioner, at a higher cost, can be determined for a particular area, power cost, and interest rate. For example, in an area having the summer cooling requirements of Chicago, the cash customer (6% interest) would realize an economic benefit by purchasing Unit 2B, instead of Unit 2, if his cost of electricity is greater than 1.9 cents/kW-hr. However, if he operates on a credit card economy (18% interest), Unit 2B is only justified if his cost of electricity is greater than 3.2 cents/kW-hr.

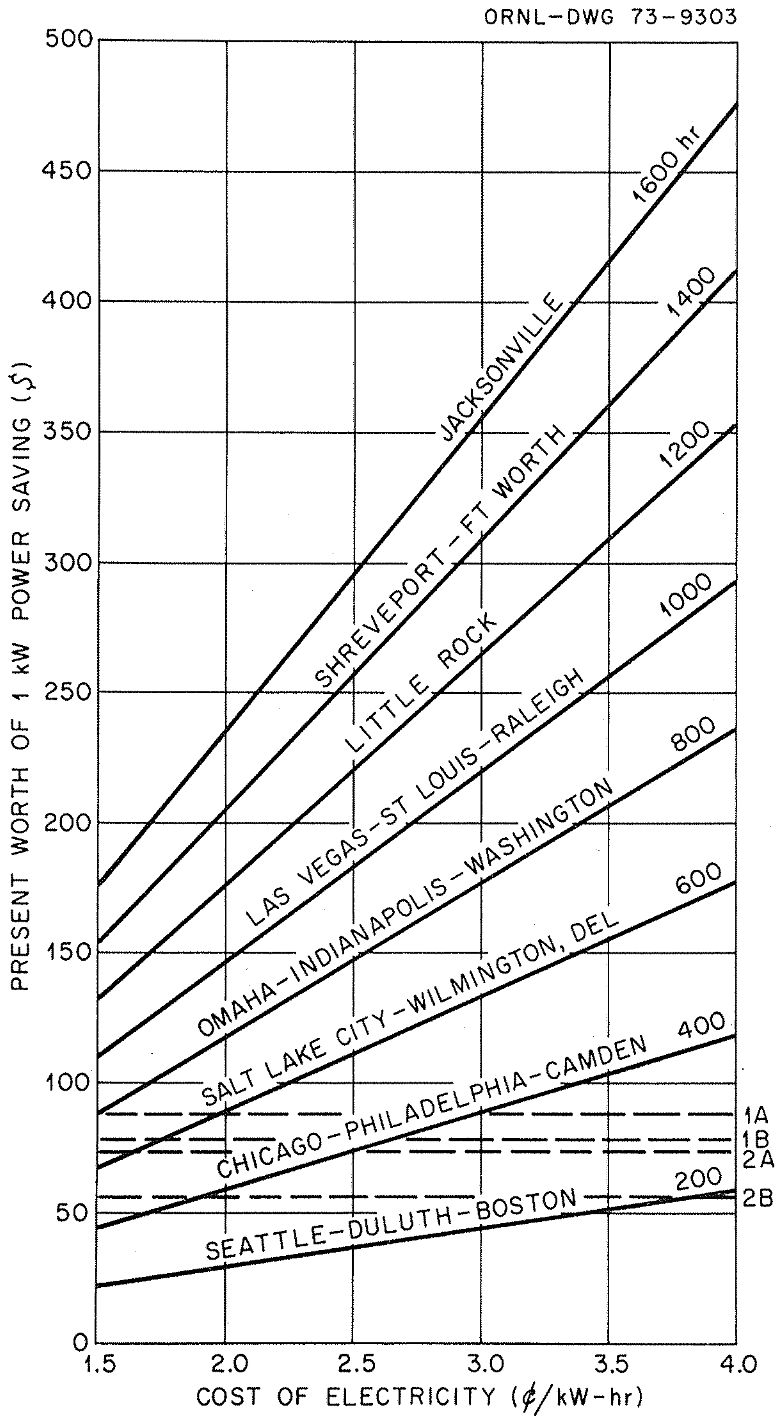


Figure B.1. Present Worth of 1 kW Power Saving as a Function of Annual Hours and Energy Cost (6% Interest Rate — 10 Years).

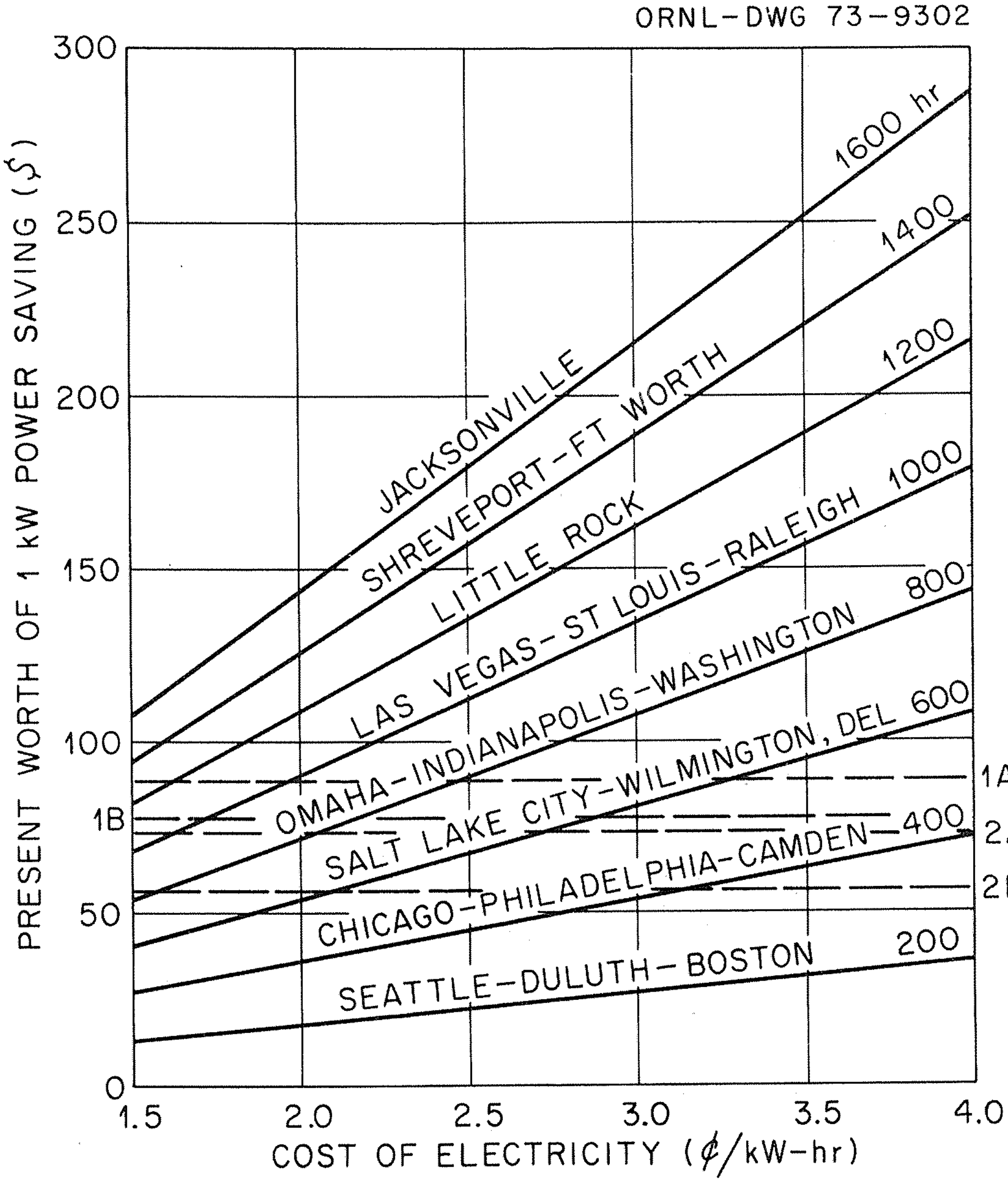


Figure B.2. Present Worth of 1 kW Power Saving as a Function of Annual Hours and Energy Cost (18% Interest Rate — 10 Years).

APPENDIX C

NOMOGRAPH FOR COMPARING VALUE OF REDUCED WATTAGE WITH DIFFERENCE IN INITIAL COST

Instructions for Using Nomograph

At Home

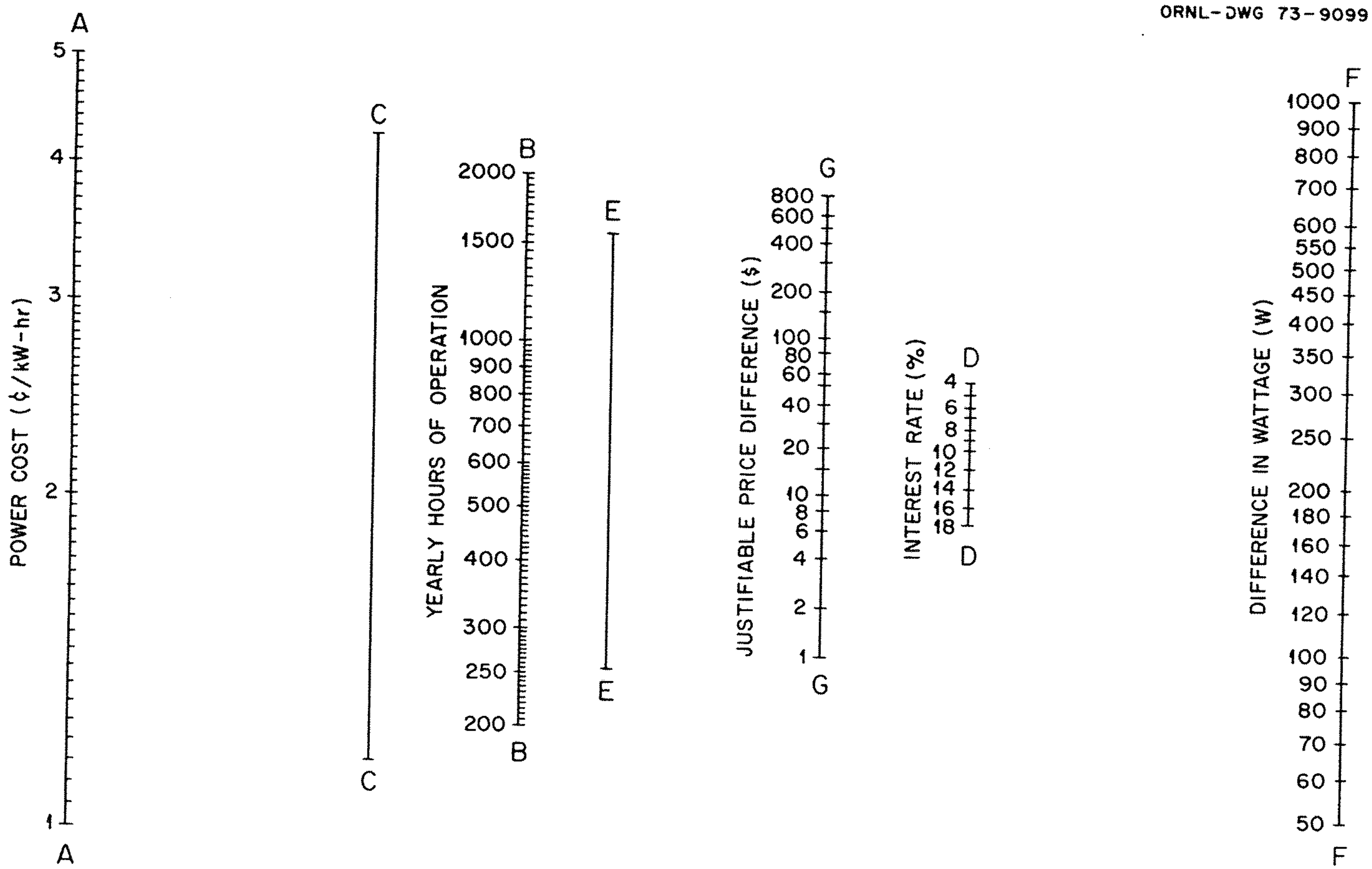
1. Check your power bill for a summer month to determine the amount of electricity you use without air conditioning. Obtain from your power company the cost of electricity for the next amount above what you have been using. Mark this on SCALE A.
2. From values given in Table C.1, estimate the hours the air conditioner must operate per year in your locality. Mark this on SCALE B. Draw a straight line between the mark on SCALE A and the mark on SCALE B. Mark where the line crosses SCALE C.
3. Determine the interest rate that applies to you. Do you regularly make time purchases by credit card or otherwise? If so, use the annual interest rate you pay. If not, do you have a savings account or investments? If so, use the yield from those. Mark the interest rate on SCALE D. Draw a straight line between the mark on SCALE C and the mark on SCALE D. Mark where this line crosses SCALE E.

While Shopping for Air Conditioner

4. For the air conditioner size that you need, determine for the different models you are considering the savings in wattage for each compared with the one having the highest wattage.
5. Draw straight lines from the mark on SCALE E to the wattage savings on SCALE F. The points where these lines cross SCALE G show the amount you can afford to pay extra for the more efficient models and still break even over the lifetime of the unit.

Table C.1

City	Hours per year
Atlanta	750
Atlantic City	500
Chicago	400
Knoxville	800
Little Rock	1200
Los Angeles	450
Miami	1700
Omaha	800
Phoenix	1300
Raleigh	1050
Seattle	200
Washington	800
Wichita	900



Nomograph for Evaluating Present Value of Future Electricity Savings.