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Room Air-Conditioner Lifetime Cost Considerations: Annual Operating Hours and Efficiencies

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OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

The annual hours of air-conditioning compressor operation are calculated for two types of use: (1) a house that is naturally ventilated to temperatures between 75 and 78°F when the outdoor temperature and wind speed will permit, and air conditioned at 78°F when required, and (2) a house that remains closed-up and is air conditioned at 78°F. For the 10 cities investigated, compressor savings from natural ventilation ranged from 12% in Phoenix to 73% in San Diego. These results are generalized to estimate the compressor-operating hours for any U.S. location. Potential purchasers of air conditioners can use this information to estimate their operating costs.

The variation of an air conditioner's energy efficieny ratio (EER) with outdoor conditions is given. For units having continuously operating fans, the EER decreases dramatically at milder outdoor temperatures. For example, a high efficiency model is shown to suffer a 40% decrease in EER when the outdoor temperature is 75°F compared to that when temperatures are in the low 90's.

Seasonal EERs are given for four units in 10 cities. Units with continuously operating circulating fans have EERs that average 8.5% below the nameplate value. For the cities and four units investigated, the use of an automatic circulating fan that only operates during the cooling cycle would increase the EER from 12 to 34% over an identical unit using a continuous fan. If existing room air conditioners were converted to automatic fan operation, about 4.4 billion kilowatt hours would be saved in 1975.

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I. INTRODUCTION

The growth rate of energy usage for residential air conditioning has far exceeded that of other appliances. While this energy use amounts to only about 3.7% of the total household requirements, the air conditioner's near total reliance on electricity results in residential air conditioning consuming over 11% of overall residential electricity use.[1]

Room air conditioner energy requirements can be reduced by using more efficient units, increasing thermostat settings, increasing thermal insulation levels, increasing window shading, and decreasing a unit's on time by life style changes. For example, Moyers[2] found that room air conditioner efficiencies can differ by factor of 2.5 and that a 1°F increase in thermostat setting results in approximately a 10% decrease in air conditioning requirements.

Lifetime costs for a room air conditioner are a function of the unit's capital costs (including interest), capacity, annual hours of compressor operation, efficiency, maintenance costs, and the price of electricity. Because of historically low electricity rates, past purchasing decisions for air conditioners have probably been based on minimum first costs. As electricity prices increase, consumers will give more attention to operating costs. The rational individual will tend to minimize the lifetime costs for such an installation.

This report addresses two of the parameters necessary for such decisions. First, annual hours of compressor operation are calculated for 10 cities using a modified version of the National Bureau of Standards Load Determination (NBSLD) computer code. Predicted annual compressor-operating hours for any location in the U.S. are given for two cases: (1) a house that is naturally ventilated to temperatures between 75 and 78°F when the outdoor temperature and wind speed will permit, and air conditioned at 78°F when required, and (2) a house that remains closed-up and is air conditioned at 78°F (typical of central cooling units or an exhorbitant room-unit user).

Secondly, the question of seasonal efficiencies is discussed for four typical room air conditioners. Nameplate efficiencies or energy efficiency ratios (EERs) are now provided on many new models sold. These efficiencies are measured for a specific test condition and are not necessarily indicative of the actual use efficiency. The efficiency of a unit with a continually operating circulating fan is significantly less than it would be if the fan operated only during the cooling cycle.

An Appendix is included to discuss the more technical aspects of this study.

II. COMPRESSOR-OPERATING HOURS

The annual operating cost of an air conditioner can be written as follows:

$$\text{Operating cost} = (\text{cooling requirement}) \times \left(\frac{1}{\text{seasonal EER}}\right) \times (\text{price of electricity})$$

$$= (\text{air conditioner capacity}) \times (\text{compressor-operating hours}) \times \left(\frac{1}{\text{seasonal EER}}\right) \times (\text{price of electricity}) .$$

A unit's required capacity is installation- and location-dependent. Seasonally averaged EERs are discussed in the following section. The number of hours of compressor operation is very dependent upon the unit's geographical location and upon the behavior of the user. Other variables such as the match between the unit's capacity and the installation's maximum cooling load also affect the compressor-operating hours.

Room air conditioners are typically operated in a different manner than central units. Many consumers who cool with central air conditioners do not take advantage of natural ventilation cooling by opening windows during milder periods. Users of room air conditioners are more inclined to open windows when the outdoor wind speed and temperature are adequate to maintain a comfortable temperature indoors.

The National Bureau of Standards Load Determination (NBSLD) computer code was modified to calculate compressor-operating hours while also accounting for the ability of natural ventilation to provide cooling. These calculations are for a model home typical of early 1960's construction (see Appendix). The house is air conditioned at 78°F, when required.

It is assumed that windows are opened if the outdoor conditions can maintain the inside temperature below 78°F. Natural ventilation is restricted to maintaining an indoor temperature above 75°F. These assumptions are probably typical of room air conditioner use.

Using the above assumptions, air conditioning requirements were calculated for one year in 10 cities (Atlanta, Chicago, Dallas, Miami, Minneapolis, New Orleans, New York, Phoenix, San Diego, and Topeka). Multivariable regression relationships were found to correlate these requirements with weather information and latitude for each city. This provides a means of estimating the compressor-operating hours in any city (see Appendix).

The annual hours of compressor operation for a properly sized air conditioner, used in conjunction with natural ventilation cooling, are given in Fig. 1 for any U.S. location. For this study, a properly sized air conditioner is assumed to be one whose compressor operated continuously for no more than one hour during the entire year. Over-sized air conditioners have fewer compressor-operating hours but are poor dehumidifiers. For example, a unit that is oversized by 30% will require 23% fewer hours of compressor operation. Undersized units operate for longer periods than those given and are unable to maintain the desired thermostat setting.

Figure 2 gives the number of hours that a properly sized unit's compressor would operate if no ventilation were allowed. This is probably typical of most central air conditioning installations. For example, many homes with central cooling have fixed storm windows that make ventilation impractical. Again, a 78°F inside temperature setting is assumed.

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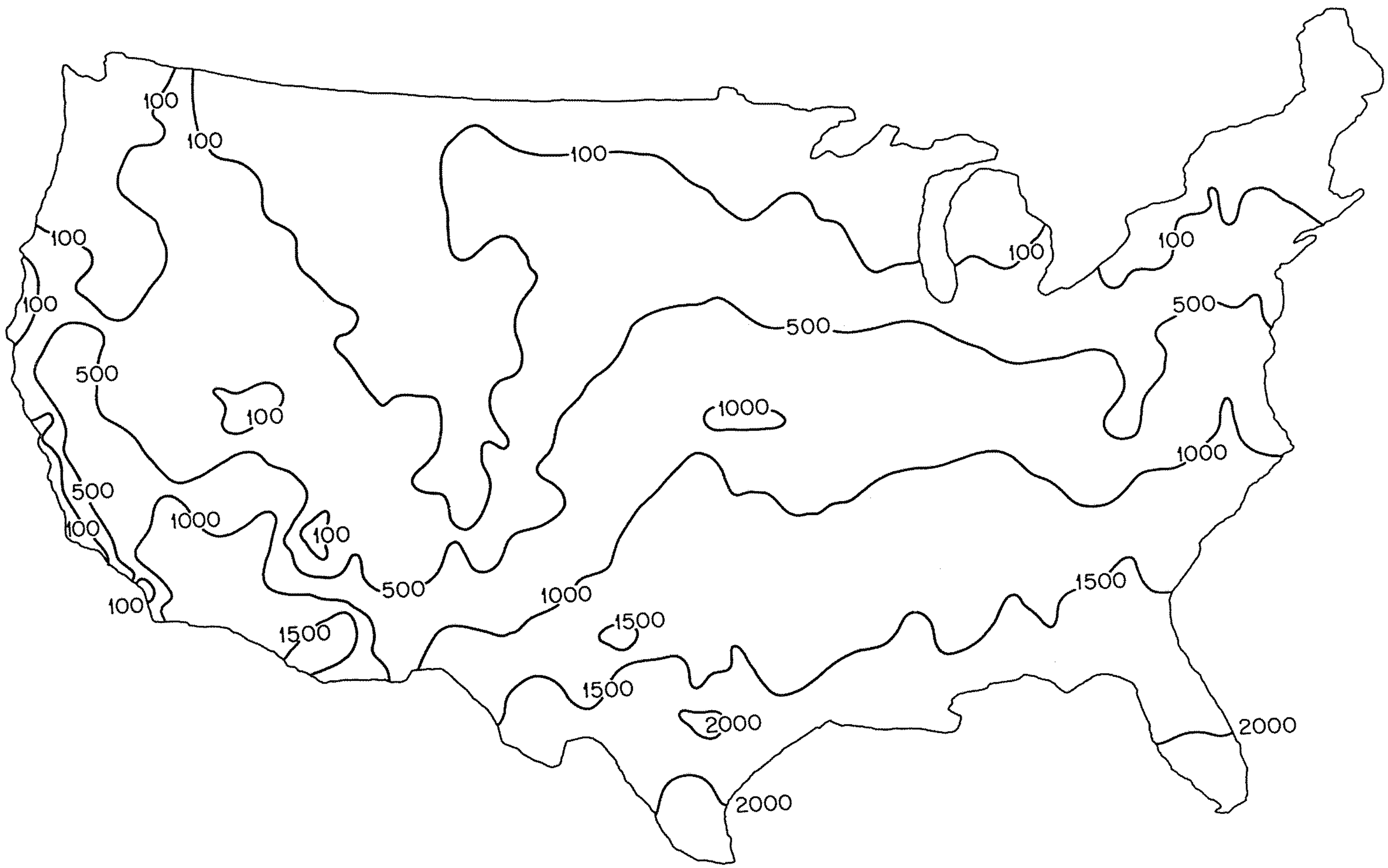

Fig. 1. Annual air-conditioner compressor-operating hours for homes that are also naturally ventilated.

Fig. 2. Annual air-conditioner compressor-operating hours for homes that are not naturally ventilated.

The compressor-operating hours given in Figs. 1 and 2 are for maintaining the indoor temperature at 78°F (or below) for the entire year. Therefore, if a home were not cooled for some period during the warmer months, actual operating hours would be less. Turning air conditioners off during unoccupied periods will reduce energy requirements in a manner analogous to setting back heating thermostats at night.[3]

The cooling provided by ventilation can make a substantial difference in the cooling required by an air conditioner. For the 10 cities investigated, compressor savings from natural ventilation ranged from 12% in Phoenix to nearly 73% in San Diego. Therefore, significant reductions in air conditioning requirements can be achieved through adequate ventilation.

Fixed storm windows are energy consumers during the cooling season. They prohibit the use of natural ventilation cooling and should be discouraged during the cooling season if the occupants would otherwise ventilate.

Environmental conditions other than the air temperature and wind speed can limit the use of natural ventilation cooling. Outdoor noise, polluted air, and allergens are several examples. It should be noted that these conditions can (usually) be eliminated by means other than air conditioning.

III. ENERGY EFFICIENCY RATIOS (EERs)

A popularized measure of air conditioner efficiency is the EER, which is defined as the unit's cooling capacity (Btu/hr) divided by its power requirements (watts) at a specified test condition. The EER can increase in EER from higher humidity is due to the increased latent load from air infiltration to the cooled space. This results in a higher duty cycle than in the case where the outdoor humidity is lower.

Note the dramatic decrease in EER at lower outdoor temperatures. For example, the high efficiency model (unit B) operating in the drier climate (40% relative humidity) suffers a 40% decrease in EER when the outdoor temperature is 75°F compared to that when temperatures are in the low 90's. Air conditioner operation at outdoor temperatures below the thermostat setting is common due to the cooling required from internal loads (people, lights, and appliances) and solar input through windows. Therefore, it is expected that seasonal efficiencies will be less than nameplate values if the circulating fan operates continuously.

B. Continuous Versus Automatic Fan Operation

The vast majority of room air conditioners have fans that operate continuously once the unit is turned on. For example, only 2 of 17 room air conditioners recently tested by Consumers Union had automatic fans.[4] Figure 4 compares the effect of fan operation on EER variation with outdoor temperatures for the larger capacity air conditioners given in Table 1. The overall efficiency of units with automatic fans increases as the outside temperature decreases. However, units with continually operating fans suffer efficiency penalties at lower outdoor temperatures because of the fan energy requirements during the compressor-off cycle.

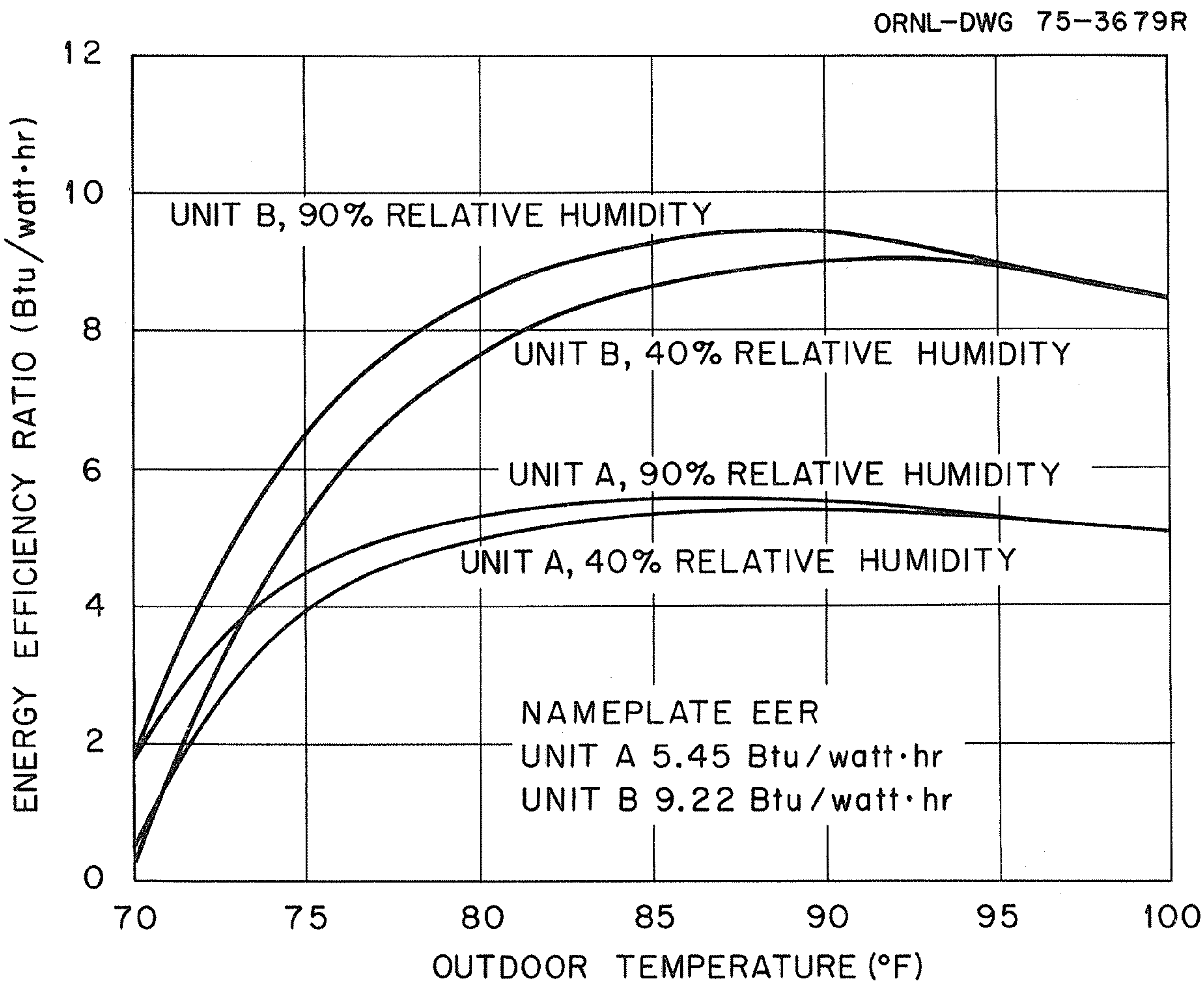

Fig. 3. EER variation with outdoor temperature and relative humidity (indoor conditions: 78°F and 50% relative humidity).

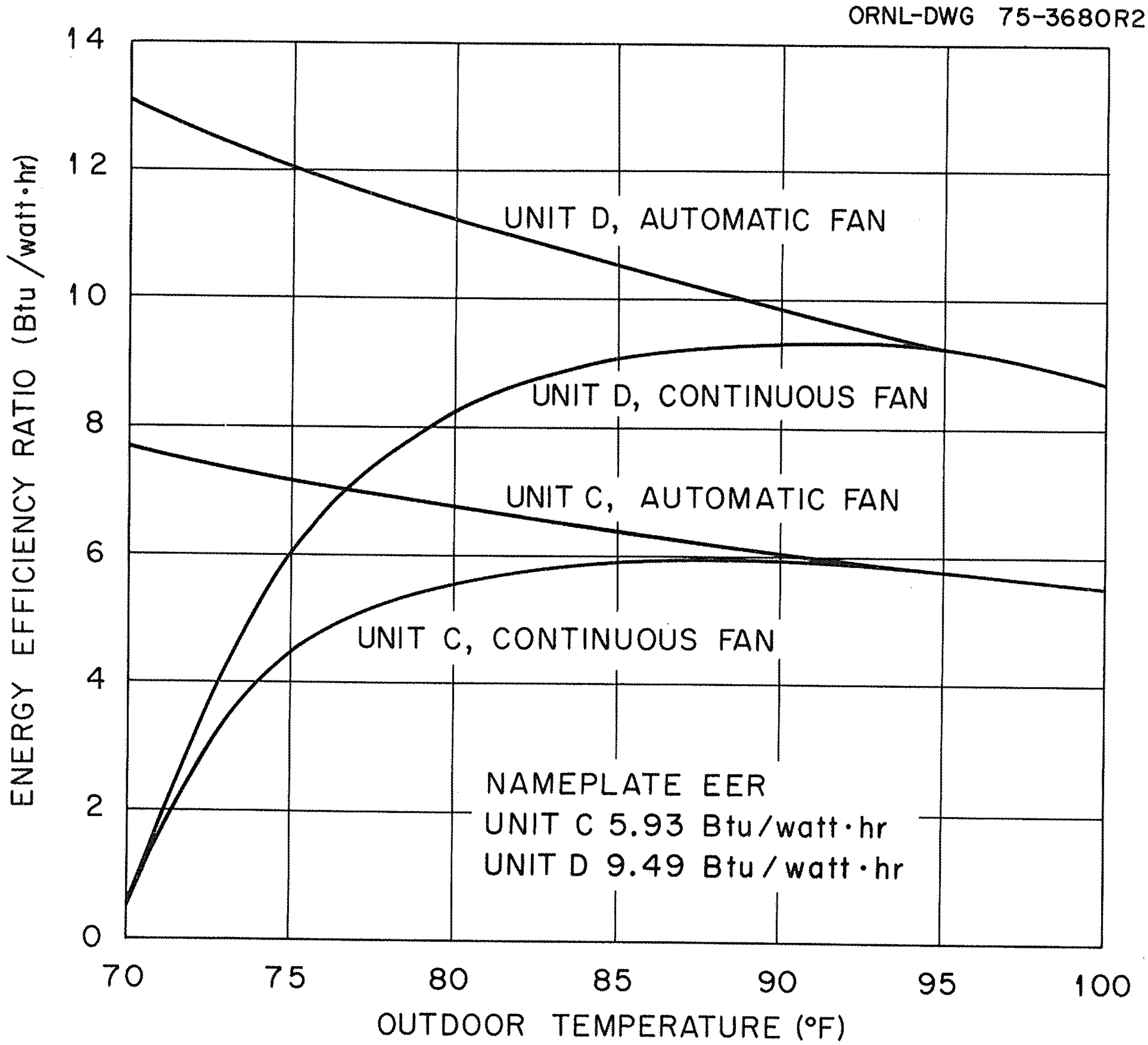

Fig. 4. EER variation with outdoor temperature for continuous and automatic fan operation (indoor conditions: 78°F and 50% relative humidity — outdoor relative humidity: 40%).

The efficiency penalty for having a continuously operating fan depends strongly on the EER of the unit. Efficiency differences between continuous and automatic fan operation at an outdoor temperature of 75°F are given in Table 2 for the four units.

Table 2. Percentage EER penalty for continuous operation at 75°F outdoor temperature

Unit A (low capacity, low efficiency)	39
Unit B (low capacity, high efficiency)	53
Unit C (high capacity, low efficiency)	37
Unit D (high capacity, high efficiency)	50

Units with high nameplate EERs are more adversely affected by the fan power requirements during the compressor-off cycle than lower efficiency models. This is due to the fact that the fan requirements for the high EER units are a greater percentage of the total energy use than for the low EER units.

C. Seasonal EERs

For estimating actual air conditioning energy requirements, the average and not the nameplate EER is required. To obtain the seasonal EER, computer simulations of 10 cities were used. These simulations are similar to those used to obtain compressor-operating hours.

Seasonal EERs for 10 cities are given in Table 3 for installations where the cooled space is naturally ventilated between temperatures of 75°F and 78°F and air conditioned at 78°F when ventilation is inadequate. The EERs are given for each of the four units described in Table 1 for both continuous and automatic fan operation.

Table 3. Seasonal EERs for several cities

City	Unit A (5.45)[a]		Unit B (9.22)		Unit C (5.93)		Unit D (9.49)	
	Continuous fan	Automatic fan	Continuous fan	Automatic fan	Continuous fan	Automatic fan	Continuous fan	Automatic fan
Atlanta	5.2	6.0	8.3	10.5	5.8	6.6	8.8	10.9
Chicago	5.0	5.9	7.8	10.2	5.5	6.4	8.3	10.5
Dallas	5.1	5.8	8.1	10.0	5.6	6.3	8.6	10.3
Miami	5.3	6.0	8.5	10.5	5.9	6.6	9.0	10.8
Minneapolis	4.9	5.8	7.5	10.1	5.4	6.4	8.0	10.4
New Orleans	5.3	6.0	8.5	10.5	5.9	6.6	9.0	10.9
New York	5.2	6.0	8.3	10.4	5.8	6.5	8.8	10.7
Phoenix	4.9	5.7	7.6	9.7	5.4	6.2	8.1	10.0
San Diego	5.1	6.1	8.0	10.6	5.7	6.7	8.6	11.0
Topeka	5.0	5.9	7.8	10.2	5.5	6.5	8.3	10.5

[a]Nameplate EER is given in parentheses.

For all cities and air-conditioning units considered, seasonal EERs for units with continually operating fans are less than nameplate values. However, if the circulating fan only operated during the cooling cycle, seasonal efficiencies would be greater than nameplate values. For the cities investigated, the use of a unit with an automatic fan would increase the EER from 12 to 34% over an identical unit using a continuous fan. Cities that experience their warmest temperatures for only short periods of time have the greatest potential for effecting seasonal EER improvements.

For the air conditioners and cities considered, the average increase in the seasonal EER above the nameplate value is 10.2%, if circulating fans were operated automatically. Continuous fan operation results in an average EER decrease of 8.5% below the nameplate EER.

Actual EER seasonal values depend on how the air conditioner is operated. The above values are for installations that also ventilate. Greater air-conditioning usage tends to decrease the average EER, if the unit's circulating fan operate continuously. For example, if unit B were operated without natural ventilation in the Atlanta area, the seasonal EER would be 7.8. This compares with an EER of 8.3 for the operation of a unit in that same location when natural ventilation is used.

The potential energy savings for converting all room air conditioner fans to automatic operation can be estimated. For the cities and the assumed behavior of using natural ventilation when possible, unit C's (most typical of present-day units) efficiency could be increased by nearly 15% if such a conversion were made. This reduction in seasonal efficiency is equivalent to a 13% increased in annual energy use. Because many room air conditioners are used infrequently, the actual savings might be about 10%. In 1975 this savings would be equivalent to about 4.4 billion kilowatt hours of electricity (see Appendix).

Another way to measure the decreased efficiency caused by continuous fan operation is to consider the number of hours the circulating fan operates when the compressor is off. The number of wasted fan hours for the cities and years investigated is given in Table 4. The circulating fan operated from 209 to 2207 hours while the compressor was off. For a typical fan power requirement of 250 watts, this results in 52 to 552 kilowatt hours of electric power. At 4¢ per kilowatt hour, this results in a cost of $2.08 to $22.08 per year. As electrical rates increase, this cost will likewise increase.

Table 4. Hours of fan operation while compressor is off

City (year)	Hours
Atlanta (1955)	1030
Chicago (1955)	579
Dallas (1955)	1565
Miami (1955)	2003
Minneapolis (1949)	537
New Orleans (1955)	1835
New York (1955)	405
Phoenix (1955)	2207
San Diego (1955)	209
Topeka (1959)	806

Automatic circulating fans offer a secondary benefit related to comfort. During the compressor-off cycle, continuously operating fans cause rapid evaporation of some of the water removed by the cold evaporator coil during the cooling cycle. By not operating the fan during the compressor-off cycle, this water would evaporate at a much slower rate. Therefore, use of automatic fan operation would reduce the time-averaged indoor humidity.

Continuous fan operation has been justified by the fact that an air conditioner's thermostat should sense the room air temperature. An enclosed thermostat on an air conditioner with an automatic fan might measure the temperature of the unit's body and result in uncomfortable room air temperatures. This problem can be alleviated by providing an external thermostat or one that detaches from the unit and is placed on a nearby wall.

IV. SUMMARY AND CONCLUSIONS

As electrical rates increase, consumers will give more attention to the operating costs of their electrical appliances. For an air conditioner, these costs (neglecting maintenance) are proportional to the price of electricity, the unit's capacity, the compressor-operating hours, and the inverse of the unit's seasonal EER.

Compressor-operating hours are primarily a function of the installation's geographical location and the behavior of the user. The annual operating hours for any U.S. location have been estimated for two types of usage: (1) cooling by natural ventilation when indoor temperatures can be maintained below 78°F and air conditioning at 78°F when necessary, and (2) air conditioning at 78°F with no natural ventilation. Potential purchasers of air conditioners can use this information to estimate their operating costs. Rational individuals should attempt to minimize their lifetime costs by purchasing more efficient (and, in general, more expensive[2]) units if high operating costs warrant it.

Natural ventilation cooling can maintain confortable indoor temperatures during milder periods and effect substantial decreases in air conditioning requirements. For the 10 cities investigated, air conditioning combined with natural ventilation reduced air conditioning requirements by 12% (Phoenix) to 73% (San Diego). Therefore, fixed storm windows that prevent natural ventilation should be discouraged during the warmer months.

Nameplate efficiencies or EERs are temporarily affixed to nearly all new air conditioners. However, the actual EER of an operating unit depends on the outdoor conditions. The vast majority of room air conditioners have continually operating circulating fans that result in severe efficiency penalties at milder outdoor temperatures. Room air conditioning power requirements could be reduced by about 10%, or about 4.4 billion kilowatt hours in 1975 if units were converted to automatic fan operation.

Continuously operating circulating fans more severely affect the efficiency of high EER units. Therefore, as more efficient models are manufactured, the detrimental effect of continuous fan operation will become increasingly important.

V. ACKNOWLEDGMENTS

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VII. APPENDIX

This section discusses the assumptions and calculations used in this study.

Model Home

All NBSLD calculations are based on a single-family detached house, typical of those built in the early 1960's. Such a house has about 1500 ft^2 of floor area, including three bedrooms, two baths, and a basement.[6] A floor plan of the model home is given in Fig. 5 and Table 5 presents the construction characteristics assumed for the house. The model home is identical to that used in Ref. 3, where the assumed hourly appliance use and home occupancy schedule are given.

Operating Hours

To calculate compressor-operating hours when natural ventilation is also used, the NBSLD computer code was modified to calculate both a ventilation and air conditioning situation each hour. It is assumed that 20% of the total window area can be opened with no obstructions. The natural ventilation rate is calculated according to Ref. 7, assuming a 0.425 effectiveness of openings. Ventilation is assumed if the ventilated indoor temperature is below 78°F and less than what the indoor temperature would be if the house were closed up. If the indoor temperature is below 75°F as a result of ventilation, the open-window area is assumed to be decreased to maintain an indoor temperature of 75°F.

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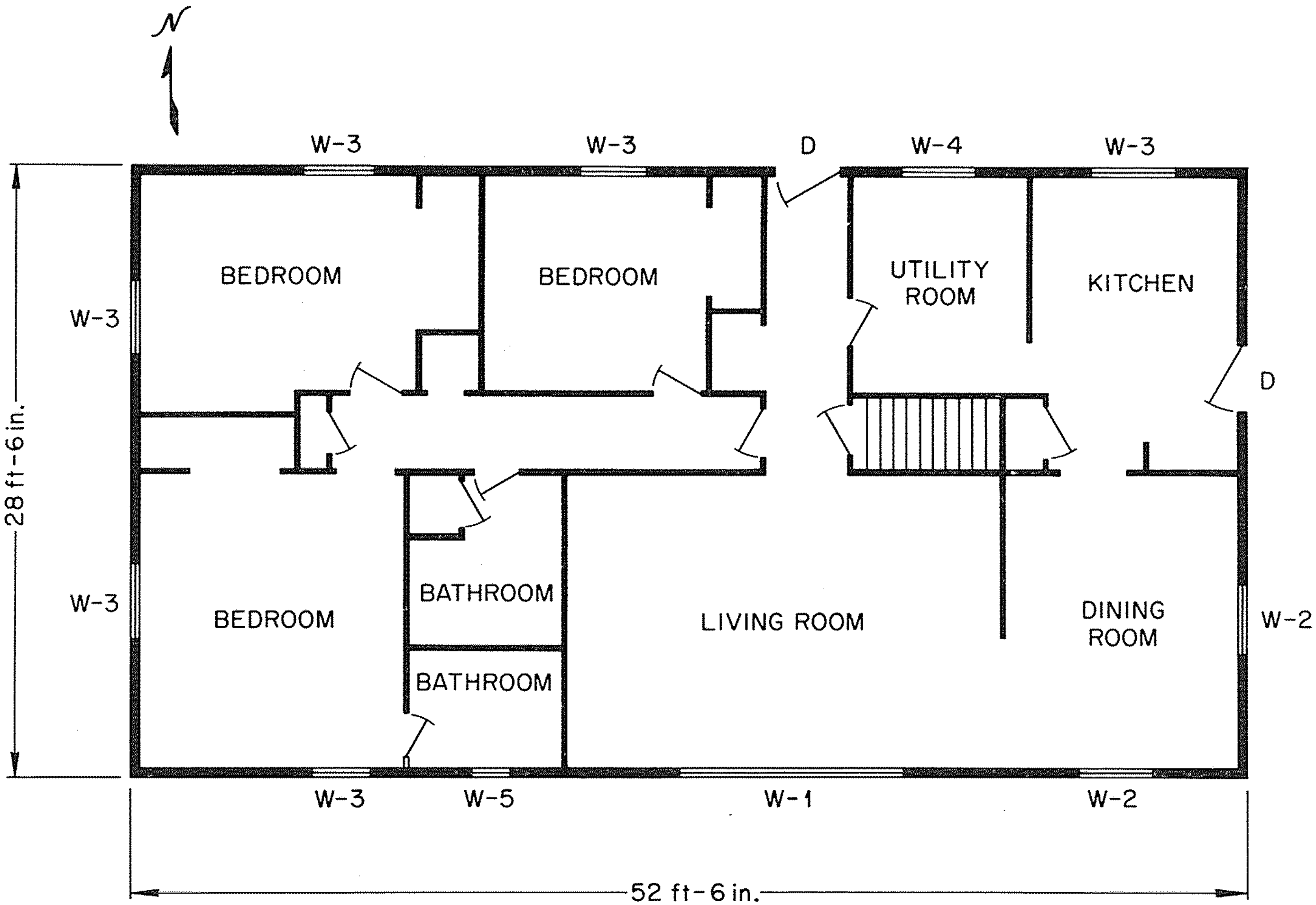

Fig. 5. Model home floor plan.

Table 5. Model home construction characteristics

Exterior wall	
	1/2-in. gypsum board
	1-7/8-in. fiberglass insulation (reflective backing)
	5/8-in. sheathing board
	4-in. face brick
Ceiling	
	1/2-in. gypsum board
	3-in. fiberglass insulation
Floor	
	3/4-in. hardwood floor
	Building felt
	25/32-in. subfloor
Roof	
	5/8-in. wood deck
	Building felt
	Asphalt shingles
Windows (all single glazed)	
	(W-1) — 112 in. × 51 in.
	(W-2) — 37 in. × 51 in.
	(W-3) — 37 in. × 38 in.
	(W-4) — 53 in. × 51 in.
	(W-5) — 19 in. × 38 in.
Exterior doors	
	34 in. × 80 in. × 1-3/4-in., solid core
Basement	
	Below ground level, unheated, concrete block walls, and concrete slab floor

Greater ventilation opening area increases the cooling ability of natural ventilation. An Atlanta home that increases the open area from 20% to 80% of the total window area will save 14% on air conditioning requirements.

Compressor-operating hours for the two types of behavior (air condition at 78°F; naturally ventilate between 75° and 78°F, air condition at 78°F when required) were calculated by NBSLD. Calculations were performed using hour-by-hour weather tapes for one year in 10 cities.

To generalize these results to other locations, the results are assumed a function of latitude and weather variables. This allowed the generation of the contour maps given in Figs. 1 and 2. The rest of this subsection outlines the methodology used.

To estimate the compressor operating hours for locations not calculated by NBSLD, a series of multivariable regression relationships was used. Annual cooling degree hours (70°F base) are obtained as a function of latitude and dry-bulb temperatures that are exceeded 1 and 5% of the time during the months of June through September for the 10 cities. Air conditioner capacity requirements are found as a function of latitude, dry- and wet-bulb temperatures that are exceeded 1% of the time during the summer months, and the difference between the average maximum and average minimum temperatures during the warmest month.

Annual cooling requirements are assumed a function of the predicted cooling degree hours (sensible load), the latitude (solar load), and the square of the difference between the 5% exceeded wet bulb temperature and 65°F (latent infiltration load; if negative, zero is assumed). For the assumed indoor conditions (78°F, 50% relative humidity), no latent infiltration load occurs if the outdoor wet-bulb temperature is below 65°F. For cooling requirements when natural ventilation is also used, an additional wind variable is included. The coincident wind variable from Ref. 7 is used as a proxy for the wind intensity.

Average values of the independent variables required to predict cooling degree hours, cooling capacity and annual cooling requirements are given in Ref. 7 for over 700 cities. The data for each city are used to calculate the compressor-operating hours (cooling requirement divided by capacity) and plot the contour maps in Figs. 1 and 2. Table 6 compares the predictions with the NBSLD calculations for the cities and years investigated.

Table 6. Comparison of NBSLD calculations and prediction equations for annual compressor-operating hours

	Ventilated house		Nonventilated house	
City (year)	NBSLD	Predictions	NBSLD	Predictions
Atlanta (1955)	983	993 (1.0)[a]	1521	1577 (3.7)
Chicago (1955)	455	596 (30.9)	727	868 (19.5)
Dallas (1955)	1604	1518 (5.3)	2003	1979 (1.2)
Miami (1955)	2169	2363 (8.9)	2901	2971 (2.4)
Minneapolis (1949)	374	319 (14.6)	590	462 (21.6)
New Orleans (1955)	1880	1663 (11.5)	2305	2157 (6.4)
New York[b] (1955)	393	357 (9.4)	755	765 (1.3)
Phoenix (1955)	1870	1826 (2.3)	2122	2102 (.9)
San Diego (1955)	162	150 (7.5)	592	583 (1.4)
Topeka (1959)	627	713 (13.8)	932	1023 (9.7)

[a]Percent error.

[b]Weather tape is for Kennedy Airport.

EERs

Reference 5 gives the number of room units shipped in the first five months of 1971 for four groups of capacities. All units under 7000 Btu/hr are assumed to be 6000 Btu/hr and all over 20,000 Btu/lb are assumed to be 24,000 Btu/hr. These assumptions result in an average capacity of 12,340 Btu/hr. (However, marketing pressure for the smaller portable units may have decreased this average for more recent shipments.)

Moyers[2] derived a general relationship for an air-conditioner's compressor requirements as a function of air temperatures and engineering parameters (such as heat transfer areas and air flow rates). This relationship, combined with data on four units described in Ref. 2 (units 1, 1A, 2, and 2A), gives the compressor power requirements (Btu/hr) as a function of indoor (T_{in}) and outdoor (T_{out}) temperature for the four units in this study:

Unit A

$$\frac{18640 \times (T_{out} - T_{in}) + 1,487,771}{T_{in} + 325}$$

Unit B

$$\frac{15680 \times (T_{out} - T_{in}) + 832,513}{T_{in} + 381}$$

Unit C

$$\frac{28426 \times (T_{out} - T_{in}) + 2,132,950}{T_{in} + 334}$$

Unit D

$$\frac{23912 \times (T_{out} - T_{in}) + 1,279,387}{T_{in} + 381}$$

To calculate the EER as a function of outdoor conditions in Figs. 3 and 4, the cooling requirement is separated into sensible and latent compontents. A 70°F base temperature is assumed for the sensible heat component to account for internal heat sources. The latent heat component is calculated assuming 0.75 air changes per hour and a 50% relative humidity indoors. Units A and B are assumed to cool a 12- by 15-ft room, and units C and D are assumed to cool a 16- by 18-ft room. The air conditioners are assumed to operate in the cooling mode with outside ventilators closed at all times. Hourly cooling requirements are divided by the hourly fan and compressor power requirements to give EER variations with outdoor conditions.

According to the cooling-load estimate form in Ref. 4, these units are well-matched to these room sizes for nominal conditions. (Comparisons with NBSLD results imply that the units are somewhat oversized for such installations.)

Seasonal EERs are derived from the given compressor power requirement relations, the fan power requirements, and the NBSLD calculations. The room air conditioner compressor-on time each hour is assumed the same as a central unit that is sized to meet the peak hourly demand for the model home.

Air conditioning power requirements for 1975 are estimated to be 44 billion kilowatt hours from a linear interpolation of electricity demand projections for room air-conditioners given in Ref. 8.