BENEFITS OF REPLACING RESIDENTIAL CENTRAL AIR CONDITIONING SYSTEMS*

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ABSTRACT

The energy efficiency ratios (EERs) of marketed residential air conditioning equipment have increased during recent years. This investigation examined the benefits of replacing a unit having an EER of 6 with a unit having an EER of 10 in a prototypical two story house located in 32 U.S. cities. The DOE-2.1A building simulation model was used to predict the energy savings associated with this action. The reasonableness of the model for this study was confirmed by comparing the DOE-2.1A predicted energy use data with measured energy use data for the ACES control house in Knoxville, Tennessee, and four specially metered houses in Little Rock, Arkansas.

It is predicted that the seasonal efficiencies (SEERs) of correctly sized units will vary from 0.6 of the rated EERs in the northern part of the country, to 0.8 of the rated EERs in the middle part of the country, and to about the rated EERs in the lower southern part of the country. Oversized units were predicted to have lower SEERs.

Using 1982 capital and electrical energy costs, simple payback periods were calculated to be as low as 5 years in the lower south regions to about 10 to 15 years in the upper south regions. If the air conditioning unit needs replacement, the simple payback period for the incremental cost of installing a high-efficiency unit was calculated to be about 2 to 5 years in these regions. Further savings would be realized if existing oversized units were replaced with properly sized high-efficiency units.

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INTRODUCTION

The ever increasing cost of energy has had a marked effect on the efficiency of residential air-conditioning equipment that is marketed. Demand for higher efficiency equipment is reflected by industry shipments, which show increasing EERs with time. The average EER of these units has increased from about 7 in 1977 to 8-9 in 1982. Prior to 1977, an average EER of about 6 was predominant. Today, there are air-conditioning units on the market with EERs in excess of 12; however, these are limited. There is a wide range of units having EERs of 10 or greater.

The purpose of this study was to investigate the cost and benefits of replacing a central air-conditioning unit in a residence with a new high-efficiency unit.[1] It was assumed that a unit having an EER of 10 would be used to replace an existing unit having an EER of 6. Three different situations that must be considered for replacing an existing unit are: (1) the existing unit is economically beyond repair and must be replaced in any case, (2) the existing unit has limited life expectancy and needs major repair, such as compressor replacement, and (3) the existing unit continues to operate with a history of little or no failures, but has a low EER value (<6). A corollary of this effort was to evaluate the impact of oversized air conditioning units on seasonal efficiency and operating costs.

The approach used to evaluate the benefits of replacing the air-conditioning units was to use the DOE-2.1A building energy use program[2] to predict the seasonal air-conditioning energy savings. This was done for a prototypical house located in 32 cities representing different climate areas.

The reasonableness of the DOE-2.1A program for this study was confirmed by the analysis of air-conditioning energy use data for the ACES control house located in Knoxville, Tennessee[3] and four occupied houses located in Little Rock, Arkansas.[4]

DOE-2.1A SIMULATION MODEL AND CONFIRMATION

DOE-2.1A Simulation Model

The DOE-2.1A program describes the flow of heat in a building and the associated HVAC equipment on an hourly basis. The program uses detailed data for the building geometry and construction, for the HVAC system, and for the weather to predict the energy flow in the building. Solar radiation, internal heat loads in the form of people, lights, and equipment, as well as any air infiltration or ventilation, are incorporated in the energy flow description. Heat flow through all the internal and external building surfaces is assumed to be one-dimensional.[2]

The program uses a sequential approach to calculate the energy use by the HVAC equipment. It first determines the heating or cooling loads in each zone of the building, assuming the interior temperature in each zone is fixed. This part of the program is called LOADS and a time series approach, called the weighting factor method, is used to account for delays in heat transfer. These fixed temperature loads are then passed on to the next part of the program, called SYSTEMS, where the actual zone temperatures and the amount of heat added or extracted by the HVAC systems are calculated. The weighting factor method is used again, together with the HVAC equipment characteristics, to predict these values.[2]

The DOE-2.1A program is designed to accept detailed input data regarding building geometry and construction and HVAC equipment design and performance characteristics. Many of these data do not have to be specified in order to use the program. The program can draw upon its library of default data and routines to fill in the missing data. In this study, the total HVAC system capacities and circulating air flow rates at design conditions were specified, but the program's default relations were used to modify these quantities at other conditions.

Simulation Model Confirmation

Although DOE-2.1A is a highly detailed computer program, it is still a simplified model of the complex building and HVAC system behavior. It was thus felt desirable to confirm its use for this specific application of residential structures and air-conditioning equipment behaviors. The lack of detailed air-conditioning system performance data, and, in some cases, housing construction data was a special concern in this study. Reliance on many of the program's default relations to describe the air-conditioning system's performance had to be proven viable.

To achieve confidence in the program, the predicted residential cooling energy use was compared with measured values. Two sources of measured data were used: (1) the Annual Cycle Energy System (ACES) control house[3,5] and (2) four occupied houses selected from the Little Rock DOE Electric Energy Systems Load Management Demonstration program.[4] The ACES control house had the limitation of being only a single sample, but it was very well described for accuracy of input data to the simulation model. The Little Rock houses provided a greater number of samples and degree of variety of house type.

The comparison of the ACES control house data with the DOE-2.1A simulated data were done for the winter of 1977-1978, and the summer of 1978. The house had a medium efficiency heat pump to heat and cool the house, but during the winter of 1977-1978, only the electric resistance heaters were used to heat the house.[3] The construction data for this house are well defined, and the internal loads were artificially added on a precise schedule. On-site weather data, except for the cloud cover and solar radiation data, were used in this comparison. Cloud cover data measured at the Knoxville airport, located within five miles of the test site, were assumed to be valid for this simulation.

The comparisons for the 1977-1978 winter heating season and the 1978 summer cooling season are presented in Figures 1 and 2. The number of days of each month when the experimental data were recorded are noted on these figures. Good agreement was obtained for the cumulative energy use for both seasons, about 3%. Agreement of the monthly average energy use rates were also generally very good for both seasons. The exceptions were those for January and June. The reasons for this were not investigated, but it should be noted that the data were collected in January for only six days. Factors such as a higher than normal number of door openings during this period could have a marked effect on the measured energy use. The difference of 10% in the cooling energy use during June was felt to be within the accuracy required for this study. There were no trends observed here which would lead to a conclusion that the DOE-2.1A predicted values that are in suspect.

The comparisons for the four Little Rock houses were done for the summer of 1981. The air-conditioning units (heat pump for House 2) were separately metered for their energy use. Days with missing data were excluded and other days were also excluded due to a combination of missing data and other anomalies, such as obvious vacation periods. Details of the house construction, shading, and internal heat loads were not known with the accuracy of those for the ACES control house. Therefore, some assumptions had to be made, and there was some iteration in comparing the predicted and measured data to estimate parameters such as natural ventilation due to window openings and vacation periods. The weather data for these simulations were assumed to be those measured at the Little Rock airport.

Results for Houses 1 and 2 are shown in Figures 3 and 4. The importance of lifestyle on cooling energy use can be seen clearly. The comparison for House 1 is very good. Here, the best agreement was obtained by assuming that the windows are opened during the daytime hours only when the outside air enthalpy was sufficiently low to cool the house. The overall agreement using this assumption is 1.2% compared to 2.7% when neglecting any window openings. The greatest improvement is for the month of May (the coolest of the three months evaluated), where the assumption of window opening improved the agreement from 46% to 4%.

The importance of the lifestyle assumptions is further illustrated in the House 2 comparisons. Neglecting any window opening, the predicted seasonal energy use is about 16% higher than the measured value. The greatest disagreement occurred during the months demanding less air conditioning, such as September, where the values differed by 79%. (The May comparison includes some heating energy, and thus is of limited value here.) Assuming that the windows were opened during the cooler hours resulted in better agreement, within 12% for the total season. Further agreement was obtained by assuming that the shading coefficient[6] for the windows was reduced from 0.86 to 0.55 (by the use of shades and blinds). In this case, the seasonal energy use is predicted to be 6% lower than the measured value. Here the agreement for September is somewhat better, the predicted value being about 36% higher than the measured value.

Similar comparisons were obtained for Houses 3 and 4. While the exact lifestyle cannot be pinpointed in any of these scenarios, it can be seen that the DOE-2.1A program input data can be specified to approximate the lifestyle effects on the predicted energy use rates to the precision required in this study.

COST/BENEFITS EVALUATION

Methodology and Results

The DOE-2.1A program was used to predict the air-conditioning system's seasonal energy use for the prototypical Hastings two-story house[7] in 32 United States cities. The typical meteorological year (TMY) weather data were used to represent the weather conditions in each of these cities. The proper size (no excess capacity) of the air-conditioning unit was determined in each city by trial and error using the DOE-2.1A program, assuming that the indoor temperature would not exceed 80°F for more than 1% of the cooling season. The thermostat setpoints were assumed to be 70°F for heating and 78°F for cooling. It was assumed further that the windows would not be opened during the cooling season.

Results of these simulations for 6 of the 32 cities are summarized in Table I. (The results for all 32 cities are summarized in Reference 1.) For the cities listed in column 1, column 2 identifies the percent that the air-conditioning unit is oversized. Columns 3 and 4 list the seasonal energy consumption to handle the cooling load for two air-conditioning unit efficiencies; an original unit with an EER = 6 and a new replacement unit with an EER = 10. The seasonal cooling load for each size unit is shown in column 5. The cooling loads for the oversized units are slightly greater since they maintain slightly lower interior temperatures during the peak load days. Columns 6 and 7 list the calculated seasonal energy efficiency ratio (SEER) for both the low- and high-efficiency units. These values, of course, vary with the climatic conditions. The difference between the energy consumptions for the low- and high-efficiency units is shown in column 8. Column 9 represents the maximum energy savings that would occur if the original low-efficiency unit was 50% oversized and was replaced by a properly sized high-efficiency unit.

Columns 11 and 12 reflect the annual dollar savings for the respective energy savings in columns 8 and 9, based on the 1982 average electricity prices (column 10) for the state in which the city is located.[8] The air-conditioning unit ratings, shown in column 13, are those for the properly sized units and for the 25% and 50% oversized units. Column 14 shows the installed costs for new replacement units having rated EER = 6, and column 15 shows the installed costs for new replacement units having rated EER = 10. The following equations were used to estimate these costs:

for EER = 6, cost (\$) = 250 + (0.025) (Btu/h rating),
for EER = 10, cost (\$) = 400 + (0.04) (Btu/h rating).

These equations were developed from a regression of 1982 dealer costs for units having a variety of efficiencies, doubled to include installation costs. Keep in mind that it is only the air-conditioning unit which needs replacing, not the ducting, wiring, etc.

The final results of this evaluation are the cost vs benefit for replacement air conditioners, shown as simple payback in columns 16 and 17. Simple payback, as used here, is defined as the installed cost divided by the first year energy savings. Column 16 shows the payback of replacing a low-efficiency air-conditioning unit with a high-efficiency unit when both the existing and replacement units are properly sized for the load (zero percent oversized). The upper number is based on charging the full installed price for the replacement unit. The lower number is based on the difference between the installed cost of a new high-efficiency unit and the cost of installing a replacement low-efficiency unit, assuming the original in-place unit needed replacing (not functioning or high maintenance costs).

Column 17 shows the payback of replacing an existing low-efficiency unit that is 50% oversized with a high-efficiency unit which is properly sized. The upper number of column 17 is based on charging the full installed cost of the replacement unit. The lower number is based on the difference between installing a new properly sized high-efficiency unit and the cost of installing a replacement 50% oversized low-efficiency unit, again assuming the original in-place unit need replacing.

Results for a Little Rock, Arkansas House

The results in Table I are illustrated in Figure 5 for a house located in Little Rock, Arkansas. Electrical energy usage (before and after air conditioner replacement), energy and cost savings potential, retrofit costs, and paybacks are illustrated in this figure.

The seasonal energy consumption for properly sized units and 50% oversized units for the original (EER = 6) and replacement (EER = 10) systems are shown on the four corners of the quadrilateral. The corresponding dollar values in brackets are the estimated installed costs of the replacement air-conditioning units. For example, the upper left-hand corner of Figure 5 shows an annual cooling energy consumption of 3784 kWh for air conditioning the prototype house (properly sized unit with an EER = 10). The estimated installed cost of this replacement unit is $1520. Along the connecting lines between the corners are the kWh and corresponding dollar savings obtained by moving from any one point (percent oversized and EER) to any other upgraded condition. If an original 50% oversized air-conditioning unit having an EER = 6 was replaced with a properly sized unit having an EER = 10, 3207 kWh of electricity would be saved during an average cooling season, resulting in a seasonal cost savings of $241.

Finally, the simple paybacks in years are shown on the left vertical line of Figure 5 (upgrading the EER, assuming the original unit was properly sized) and on the diagonal line (upgrading the EER, as well as reducing the capacity from 50% oversized to properly sized). These results are for two means of estimating air-conditioner replacement costs:

(1) using the full cost of installing the new unit, and (2) using the difference between the full replacement cost and the cost of replacing the original unit without upgrading (shown in parentheses).

As indicated in Figure 5, a homeowner can realize the quickest payback by selecting a high-efficiency replacement unit that is properly sized for the residence design load. In many cases, the existing unit is oversized because of caution used in the size selection and reduced loads after implementation of other energy conservation measures. For a 50% oversized situation, the example here indicates a simple payback of 6.3 years, on the basis of a full retrofit cost, or 0.91 years, if the original unit has little expected life and needs replacement. It is noted that the additional cost for the higher efficiency unit is partially offset by selecting a smaller properly sized unit that has a higher SEER value.

Overall Trends

To illustrate the overall trends of the SEER values, as a function of seasonal climate conditions, the ratios of the SEER to the rated EER for the properly sized air-conditioning units were calculated from the predicted data for the 32 cities in this study. These ratios were plotted on a map of the contiguous 48 states, and contours of these were drawn, as shown in Figure 6. These ratios vary from 1.0 in south Florida to less than 0.6 in the very northern part of the country. These correlations do not extend to the west coast region because of the high variability of the weather in this region.

The predicted results also showed that there is about a 0.2% reduction in the SEER value for every 1% that the air-conditioning unit is oversized. This degradation of the SEER should be considered in evaluating the energy use of an air-conditioning unit.

It was found that the simple economic payback times for replacement central air-conditioning units varied from less than one year to over 100 years for the 32 cities evaluated. The trends can be illustrated with the use of Figure 7. In the south belt (Zone I), simple payback times for replacement units in good operating condition were calculated to be as low as 5 years in the lower part of the region to about 10 to 15 years in the upper part of the region. If the air-conditioning unit needs replacement, however, these payback times are reduced to 2 to 5 years. These payback times are reduced further if the existing failed units are oversized and are replaced with properly sized high-efficiency units. In this case, the payback time for most of the region is lower than 1 year, being as low as 0.5 year in some cities. The coastal areas of California are exceptions due to the high variability of the climate. In these areas, the air-conditioning unit SEER is often low due to the unit operating significantly below design conditions for extended periods of time.

In a large northern portion of the country (Zone II), the simple payback times are generally greater than 10 years. Only when a failed oversized, low-efficiency unit is replaced with a properly sized high-efficiency unit does the payback times become attractive (4-8 years) in the lower parts of this region. They still exceed 10 years for the very northern states (WA, MT, ND, and MD).

The payback periods for the intermediate area (Zone III), which are the mid-central and the mid-Atlantic states, vary between the extremes for the other two zones. They are always greater than 10 years for the replacement of an air-conditioning unit that is in good operating condition, but they drop to 5 to 8 years if the existing unit need replacement (short life expectancy). Again, if the failed existing unit is oversized, the payback times are reduced further (1.5 to 3 years) in this region.

Sensitivity Analysis

It was recognized in this study that various factors, such as internal loads, house construction, and window shading influence the cooling energy consumption. The influence of these factors on the replacement air conditioner SEER values were investiated for the prototype house located in Little Rock, Arkansas. Assuming that the air-conditioning unit had a rated EER of 10, the SEERs were calculated for this house assuming different internal loads and window shading coefficients. These calculations were also done for the Hastings ranch house,[7] which is smaller than the prototype house, and for a large ranch house with full basement exposed in back. For each of these cases, the air-conditioning unit was assumed to be properly sized, 25% oversized, and 50% oversized.

It was found in this analysis that the SEER value did not vary among the different scenarios more than 6%, and that the degradation of the SEER with oversize was essentially the same in all scenarios. It was concluded that the influence of these parameters on the SEER is small, and they should not have any pronounced effects on the conclusions of this study.

CONCLUSIONS

The primary purpose of this study was to evaluate the economic benefits of replacing an existing residential air-conditioning unit having a relatively low efficiency with a new high-efficiency unit. The effects of climate and other parameters on the SEER were evaluated using the DOE-2.1A computer program.

It was found that attractive economic paybacks could be realized in the southern part of the country. The shortest payback times, less than 3 years, could be realized in this region when the existing unit needs replacement. On the other hand, the payback times in the northern and northwestern parts of the country are not very attractive, varying from about 10 to over 100 years. In the mid-central and mid-Atlantic states, the payback times were predicted to be between these extremes, varying from 3 to 7 years, if the air-conditioning unit needs replacement. The results for the coastal area of California could not be readily generalized because of the variability of the climate in that area.

In all cases, it was found that oversizing the air-conditioning unit degrades the SEER. Replacing an oversized air-conditioning unit with a properly sized unit has the advantages of both lower initial capital cost and higher SEER value. It was determined that the SEER would be reduced about 0.2% for each 1% that the unit is oversized. Installing a high-efficiency properly sized replacement unit reduces the payback times. Payback times in this case were predicted to be 0.5 to 1 year in the southern states and 1.5 to 3 years in the mid-central and mid-Atlantic states.

In the course of this study, it was demonstrated that the DOE-2.1A program could predict the seasonal cooling energy use by comparing the predicted and measured data for the ACES control house and the four Little Rock test houses. The agreement for the ACES control house was very good. The agreement for the Little Rock test houses was generally good, recognizing the assumptions that had to be made regarding the lifestyles.

Lifestyle was shown to be very important in the evaluation of the summer cooling energy use in a home. In addition to the usual variation in internal loads, thermostat settings, etc., cooling requirements are affected by the manual control of the air-conditioning unit (when it is allowed to run) and by natural ventilation (opening windows) to satisfy the comfort of the occupants.

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Table I. Replacement air conditioner cost/benefits for six selected cities

①	②	③	④	⑤	⑥	⑦	⑧	⑨
		Seasonal Energy Consumption (kWh)		Seasonal cooling load	SEER		Energy Savings (kWh)	
City	Percent oversize	EER = 6	EER = 10	(MBtu)	EER = 6	EER = 10	EER_6-EER_{10}	50% EER_6-0% EER_{10}
Albuquerque, NM	0	5060	3148	26.471	5.23	8.41	1912	
	25	5387	3344	26.587	4.94	7.95	2043	2556
	50	5704	3534	25.634	4.67	7.54	2170	
Bakersfield, CA	0	7159	4385	37.115	5.18	8.46	2774	
	25	7621	4662	37.312	4.90	8.00	2959	3661
	50	8046	4917	37.370	4.64	7.60	3129	
Little Rock, AR	0	6160	3784	33.784	5.48	8.93	2376	
	25	6589	4041	34.048	5.17	8.43	2548	3207
	50	6991	4282	34.222	4.90	7.99	2709	
Minneapolis, MN	0	1488	1022	6.687	4.49	6.54	466	
	25	1581	1077	6.828	4.32	6.34	504	638
	50	1660	1125	6.883	4.15	6.12	535	
Orlando, FL	0	9895	5982	56.966	5.76	9.52	3913	
	25	10618	6415	57.450	5.41	8.96	4203	5324
	50	11306	6828	57.769	5.11	8.46	4478	
Washington, DC	0	3171	2014	16.787	5.29	8.34	1157	
	25	3398	2150	17.059	5.02	7.93	1248	1588
	50	3602	2273	17.179	4.77	7.56	1329	

Table I. Replacement air conditioner cost/benefits for six selected cities (continued)

①	⑩	⑪	⑫	⑬	⑭	⑮	⑯	⑰
	Electricity price	Annual Savings ($)		A/C rating	A/C Cost ($)		Simple Payback (years)	
City	(¢/kWh)	0% EER_6-0% EER_{10}	50% EER_6-0% EER_{10}	(Btu/h)	EER = 6	EER = 10	0% EER_6-0% EER_{10} ($ Total/$)	50% EER_6-0% EER_{10} ($ Total/$)
Albuquerque, NM	9.91	189.48	253.30	26,000	900	1440	7.60/2.85	5.68/0.85
		202.46		32,500	1063	1700		
		215.05		39,000	1225	1960		
Bakersfield, CA	6.85	190.02	250.78	28,000	950	1520	8.00/3.00	6.06/0.88
		202.69		35,000	1125	1800		
		214.34		42,000	1300	2080		
Little Rock, AR	7.52	178.63	241.17	28,000	950	1520	8.51/3.19	6.30/0.91
		191.61		35,000	1125	1800		
		203.72		42,000	1300	2080		
Minneapolis, MN	5.31	24.74	33.88	18,000	700	1120	45.27/16.98	33.06/5.76
		26.76		22,500	812	1300		
		28.41		27,000	925	1480		
Orlando, FL	5.84	228.52	310.92	28,000	950	1520	6.65/2.49	4.89/0.71
		245.46		35,000	1125	1800		
		261.52		42,000	1300	2080		
Washington, DC	6.38	73.82	101.31	23,000	825	1320	17.88/6.71	13.03/2.04
		79.62		28,750	969	1550		
		84.79		34,500	1113	1780		

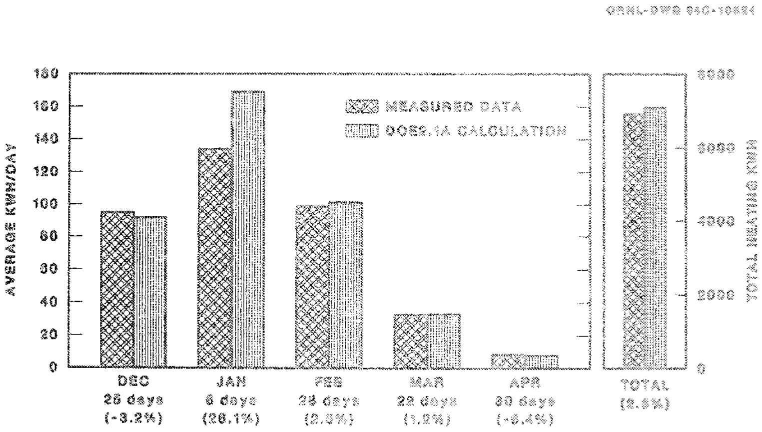

Fig. 1. Comparison of DOE-2.1A calculated to measured data for the ACES control house during the 1977–1978 winter heating season (resistance heaters).

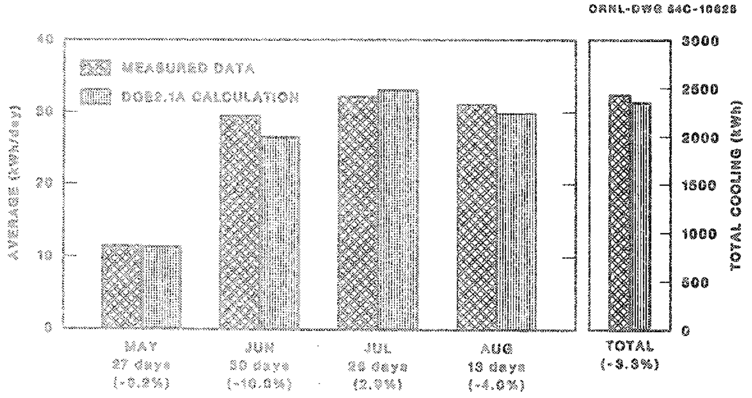

Fig. 2. Comparison of DOE-2.1A calculated to measured data for the ACES control house during the 1978 summer cooling season (medium-efficiency heat pump).

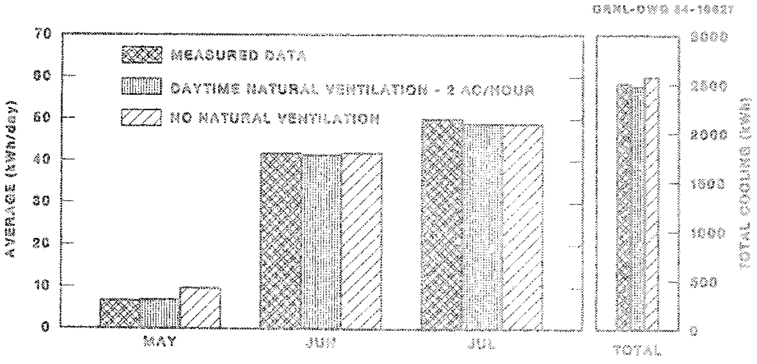

Fig. 3. Comparison of DOE-2.1A calculated to measured data for Little Rock House 1 during the 1981 summer cooling season.

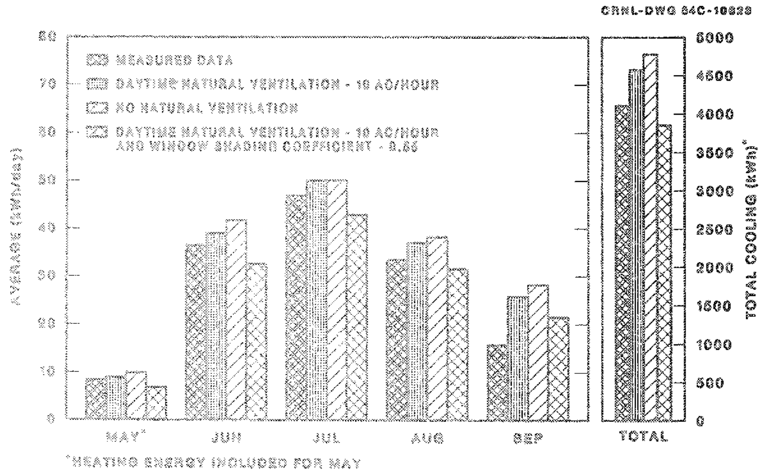

Fig. 4. Comparison of DOE-2.1A calculated to measured data for Little Rock House 2 during the 1981 summer cooling season.

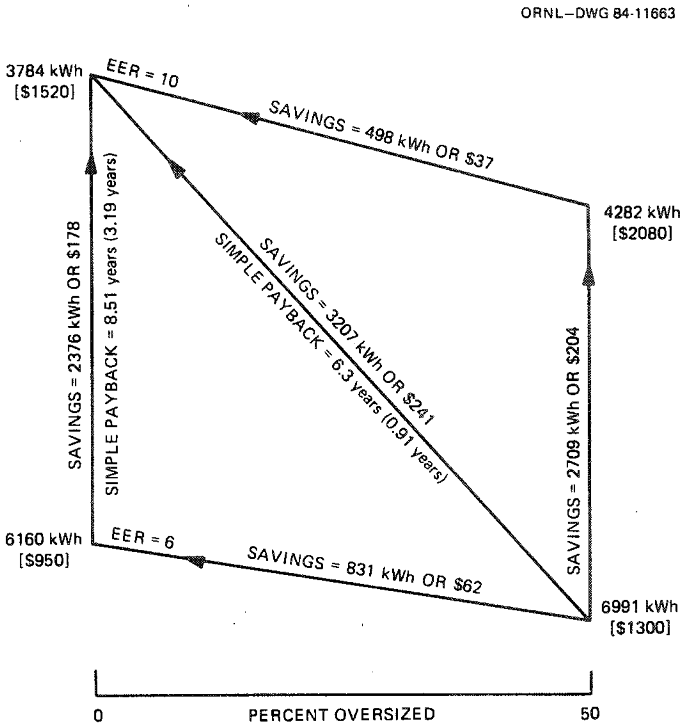

Fig. 5. Annual cooling energy and costs (7.52¢/kWh) for Hastings two-story house in Little Rock, Arkansas, with central air conditioning (two sizes and two EERs).

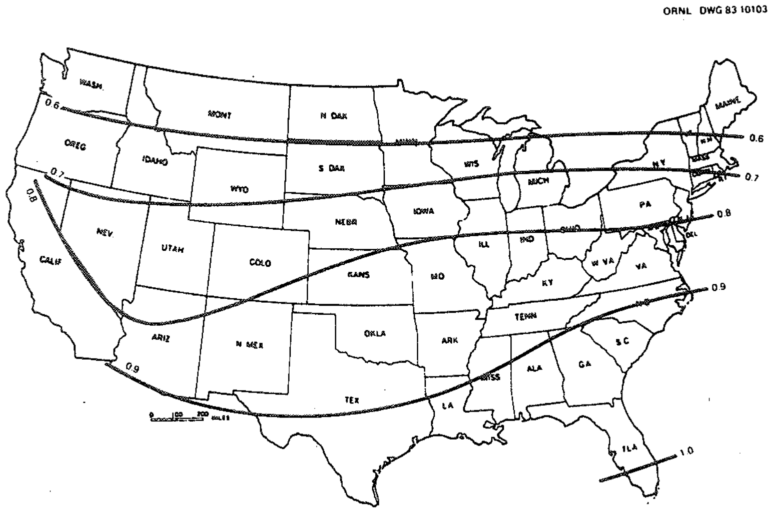

Fig. 6. Ratio of the SEER to the rated EER for properly sized air conditioning units.

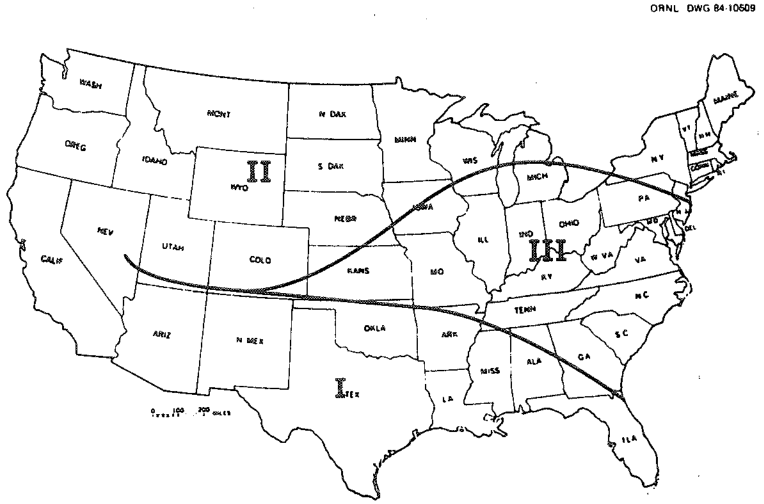

Fig. 7. Replacement air conditioner payback regions.