EER & SEER AS PREDICTORS OF RESIDENTIAL SEASONAL COOLING PERFORMANCE

Updated Report of Residential Research

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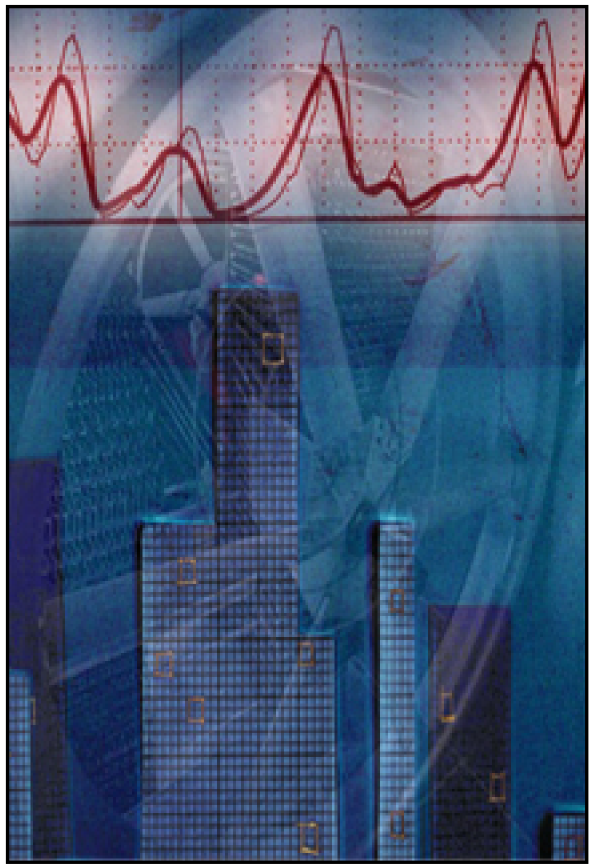

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ACKNOWLEDGEMENTS

This study was prepared by James J. Hirsch and Associates under contract to Southern California Edison Company as a portion of a project to investigate value of SEER and EER as seasonal energy performance indicators, as described herein. The work was conducted under the direction of Carlos Haiad of Southern California Edison Company. The principal investigators for this study were Marlin Addison, John Hill, Paul Reeves, and Steve Gates, James J. Hirsch and Associates. In support of this project, a new two-speed cooling system performance algorithm was designed and implemented in DOE-2.2 by Steve Gates.

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EXECUTIVE SUMMARY

This study evaluates the efficacy of using SEER (Seasonal Energy Efficiency Ratio) when making efficiency investment decisions and recommendations. All direct expansion cooling systems having a cooling capacity below 65,000 Btu/hr are required by federal regulations to be given an energy efficiency rating using SEER. Prescribed steady-state and cycling tests provide the information used to calculate a system's SEER (e.g., Air-Conditioning and Refrigeration Institute Standard 210/240). The SEER rating is, theoretically, the ratio of seasonal cooling electric consumption to the cooling load, thus providing an indicator of season-long cooling efficiency. Since its inception over 20 years ago, SEER has become the codified standard by which small electric HVAC cooling systems are compared. In California, the current Title 20 and Title 24 standards mandate air conditioner efficiency levels using SEER, electric utilities have until very recently designed their efficiency programs based on SEER, and consumers are typically guided to make energy-wise purchases based on these ratings.

Accordingly, this analysis seeks to answer the following specific questions regarding the efficacy of using SEER to make efficiency investment decisions and recommendations:

- How effective is SEER as a predictor of expected cooling *energy use*?
- How effective is SEER in estimating cooling energy *savings*? For example, based only on the difference in magnitude of SEER, upgrading from SEER 10 to SEER 12 represents a 20% improvement in SEER ([12/10]-1), and suggests a 17% reduction in annual cooling energy use (1-[10/12]). Will a 17% savings in annual cooling energy be realized?
- How effective is SEER in estimating the *relative* seasonal cooling efficiency of different cooling systems, i.e., *rank ordering* seasonal performance? Like the EPA gas mileage label, "mileage may vary", actual annual energy use or savings may vary due to user effects such as thermostat set point and climate effects due to location. Not withstanding this, is SEER a reliable indicator of *relative* cooling efficiency of cooling system? As an example, for a specific house and climate zone, will a SEER 11 system reliably use less annual cooling energy than a SEER 10 system? Alternatively, will upgrading from a SEER 10 system to SEER 11 system reliably provide savings?
- How effective is SEER as a predictor of expected cooling *peak demand* and demand savings? This question has become all the more important since ARI (Air-Conditioning and Refrigeration Institute) decided in November of 2002 to stop listing EER for SEER-rated systems in its directory of certified equipment.

The challenge in developing the SEER rating has always been to provide a useful estimate of season-long cooling efficiency using only one, or at most, a very few laboratory tests, i.e., the testing must be affordable and reliable (repeatable). Necessarily, several fundamental assumptions were made in the original development of the SEER rating. The most fundamental of which is an assumed seasonal coil load profile representative of a nation-wide average. The national average seasonal system coil load profile was developed using the following key assumptions:

1) The building overall shell U-value, solar gains, internal loads, and thermostat cooling set point yield a 65°F balance point for the building, i.e., cooling is required above outdoor air temperatures of 65°F; no cooling is required below 65°F;

2) The distribution of outdoor temperatures coincident with cooling is such that 76°F is the median outdoor temperature;

3) All cooling coil load is a linear function of outdoor temperature only.

4) The previous three assumptions results in a U.S. average seasonal average coil load distribution with a seasonal cooling *mid-load* temperature of 82°F. The mid-load temperature is the outdoor temperature above and below which exactly half of the seasonal cooling coil load occurs.

5) The sensitivity of capacity and efficiency to outdoor temperature for individual HVAC systems tends to be linear. This is significant because hour-by-hour operational performance for DX cooling systems will always vary with outdoor temperature (less efficient in warmer outdoor temperatures and more efficient in cooler temperatures). Even systems with equal SEER ratings will tend to differ in their sensitivity to outdoor temperature, i.e., some systems will be more sensitive to changes in outdoor temperature than others. If the sensitivity to outdoor condensing temperatures is linear, systems with equal SEER but differing efficiency at other temperatures (e.g., EER at 95°F) can still have equal annual cooling energy consumption. As an example, a system with high temperature sensitivity will be less efficient at hotter outdoor temperatures than a system with low temperature sensitivity. If sensitivity to temperatures is linear, then the system with high temperature sensitivity will also tend to be more efficient at cooler temperatures than the other system. Over an entire cooling season, this will tend to balance out, i.e., the two systems will have the same season-long energy use. Hence, if temperature sensitivities are linear, seasonal cooling system efficiency can successfully be predicted based on a steady-state test at the mid-load temperature (82°F).

6) The previous assumptions imply linearity of cooling energy use in outdoor temperature. This includes at least two important assumptions regarding indoor (evaporator) fans and outdoor (condenser) fans:
   - The energy from both fans is included in the overall SEER rating and is generally assumed to be a relatively small and relatively constant fraction of the total system energy requirements.
   - More importantly, both fans are assumed to cycle with the compressor; hence, fan energy is also a linear function of outdoor temperature.

This analysis examines the validity of these assumptions for typical California residential and non-residential buildings across all sixteen California climate zones. The overall motivation of this study is to assess whether SEER can accurately guide California consumers, designers, and builders in making efficiency investment decisions, and whether SEER can serve as an adequate regulatory basis for Title 20, Title 24, and statewide efficiency programs.

This study uses the DOE-2 energy analysis program to better understand the factors that affect SEER and its efficacy when used to make efficiency investment decisions and recommendations. Specifically, DOE-2 thermal models were developed for building types likely to be served by SEER-rated air conditioners and heat pumps (<65,000 Btu/hr). For heat pumps, only the cooling energy was considered. These prototypes include: single-family residential, small office, small retail, and school classroom (including portable classroom) building types.

A broadly representative range of seasonal cooling coil load profiles was examined for each building type by varying key operational and design features of each prototype and by examining performance in each of the California climate zones. Operational and design features include envelope insulation levels, window area and properties, occupancy and equipment densities, and thermostat schedules and set points, among others. Title 24 requirements were used to determine median values for prototype characteristics, where applicable (i.e., some prototype characteristics varied by climate zone). Maximum and minimum values (and median values for prototype characteristics not governed by Title 24, e.g., building size) for the various features examined were obtained from the *2000 Residential New Construction Market Share Tracking* (RMST) Database. DOE-2 prototypes included as many as twenty variable building features used to describe and vary the thermal characteristics and operation of each building prototype.

This analysis also examines a representative range of SEER-rated cooling systems that varied by SEER level, application (i.e., building type), and performance characteristics (e.g., sensitivity to outdoor operating temperatures and cycling effects). Residential simulations were executed using split-system single and two-speed air conditioners and heat pumps. The systems that were examined ranged from nominal SEER-10, SEER-12, SEER-13, SEER-14, and SEER-15 single-speed systems to nominal SEER-16, SEER-17, and SEER-18 two-speed systems.

Prior experience has shown that DOE-2 can reliably reproduce manufacturers' measured performance when manufactures extended ratings data are used to define system performance curves in DOE-2. In this analysis, <u>all</u> simulation runs were conducted using actual cooling systems currently available from major manufactures, i.e., all performance curves used in DOE-2 were based on manufactures extended ratings data for each system.

The cooling systems used in the analysis were selected from a database of over 570 systems based on their SEER rating and sensitivity to changing outdoor temperature and their cycling losses. Each system was selected to be representative of the range of performance characteristics typical of available systems, e.g., within each type of equipment (i.e., split or packaged air conditioner or heat pump) and SEER level. Systems were identified as having high, median, and low levels of sensitivity to operating temperatures (capacity and efficiency effects), and cycling losses. In all, 119 cooling systems, representative of the range of currently available systems were used in the analysis.

Findings

This work attempted to develop adjustment factors to be applied to standard SEER ratings, using only readily available data, in order to improve the predictive power of SEER. The more complex adjustment models that were investigated did not offer significant improvements over a less complex method using empirical simulation-based corrections for climate zone; these are included below.

Rated SEER as a predictor of expected cooling energy use

SEER rating alone is a poor predictor of expected cooling energy use and consequently, cooling utility costs in residential applications.

> **Across all California climate zones, one should expect errors in estimated cooling energy and utility costs predictions between -25% and +33% when using rated SEER as the cooling system seasonal efficiency. One-half to two-thirds of this error is associated with climate effects. The remaining error is approximately equally due to variations in building characteristics (i.e., operational and design features) and system effects (e.g., differences in sensitivity to outdoor temperature effects).**

Expressed in terms of the key SEER rating conditions assumptions, approximately half of the total error in SEER-predicted energy use in California residential applications result from the assumed distribution of cooling season outdoor temperatures. Assumptions regarding cooling coil entering air conditions appear to account for much of the remaining climate-related error. The assumptions regarding building balance point and the linearity between cooling load and outdoor temperature in the SEER ratings process accounts for fifteen to twenty percent of the total error. The remaining error (approximately fifteen percent of the total) is related to system effects. These include the variability in sensible capacity from system-to-system, variation in system capacity and efficiency to coil entering conditions and outdoor temperatures, and the effect of these issues on cycling losses.

Errors associated with climate effects can be reduced by applying the climate zone multipliers in Table ES-1. These multipliers represent the ratio of DOE-2-simulated SEER and rated SEER for typical single-family residences.

> **Using the climate zone SEER multipliers in Table ES-1 to estimate seasonal cooling energy reduces the error to ±10% (±8% for single-speed units) for a typical single-family residence when compared to DOE-2 estimates.**

One should expect the possible error to expand to ±15% when considering the typical variation in home construction and cooling system operation.

Climate-based SEER multipliers provided in Table ES-1 provide different SEER estimates than provided by current 2005 Title 24 ACM method. The ACM method (when using actual EER values instead of the default EER of 10) improve seasonal cooling system efficiency estimates by 30% when compared to rated SEER. On average, the method under predicts seasonal cooling system efficiency by 8% for single-speed units and 2% for two-speed units. Differences between the Title 24 ACM method and those provided via Table ES-1 are typically within ten to fifteen percent.

Rated SEER as a predictor of energy savings

> **On average rated SEER provides a reasonable prediction of the energy savings**

associated with moving from a lower SEER to higher SEER system for cooler climates. It over-predicts savings for warmer climates by 10% to 20%. On a unit-by-unit comparison, system efficiency upgrades will fall short of expected levels 45% to 98% of the time (expected levels based on rated SEER).

For single-speed systems, this over-prediction ranged from effectively 0% to 20%, where the lesser error tends to be associated with cooler climate zones and the larger error tends to be associated with warmer climate zones. In these same cases, only 17% to 55% of the upgrades exceeded expected levels of savings. For upgrades from single-speed systems to two-speed systems, the over-prediction ranged from 0% to 55%. In these cases, only 2% to 29% of the upgrades exceeded expected savings.

SEER-related savings are also of interest in estimating the cooling energy-related savings associated with any building efficiency measure that reduces cooling load. These cases rely directly on the accuracy of SEER. Therefore, to estimate the uncertainty associated with this type of use for SEER, it is appropriate to rely on the estimates regarding the prediction of cooling energy, i.e., up to ±25% total variation across all climate zones and approximately half of that for variation in estimates with a particular climate zone where the tendency would be to over predict cooling related benefit in the milder climate zones and under predict benefit in the hotter climate zones.

Using rated SEER to rank order the relative efficiency of two cooling systems

If rated SEER can yield ±25% error in predicting seasonal cooling energy, can a home owner or home builder at least use SEER to reliably select the more efficient system when applied to a specific house in a specific climate zone? As an example, although, like the EPA gas mileage label, “your mileage may vary”, for a specific application (i.e., for a specific house and climate zone), will a SEER 13 system reliably use less annual cooling energy than a SEER 10 system?

In residential applications, SEER cannot rank the relative efficiency of two cooling systems with any more precision than approximately two SEER rating “points”. This analysis indicates that one should expect that differences in the way cooling systems respond to outdoor and indoor conditions, along with cycling rates, will mean that there will be a ±5% variation in seasonal cooling efficiency among like-SEER products for a given house in a specific climate zone. That is, a nominal SEER 13 system could produce seasonal cooling energy values equivalent to a SEER as low as 12.4 or as high as 13.7. Because of this uncertainty, one could not be certain that purchasing the next higher SEER-rated system (e.g., SEER 14 instead of SEER 13, or SEER 15 instead of SEER 13, etc.) would actually realize seasonal energy savings.

In broad terms, for residential applications, <u>on average</u> one can expect a higher SEER-rated system to require less energy than a lower SEER-rated system. However, given the variability among the systems this work sampled, to assure savings, one may require a two-SEER point upgrade from the 13 SEER code minimum and two-to-four if considering an upgrade from a unit that exceeds the minimum.

Table ES-1 Residential SEER Climate Zone Multipliers

	Single-Speed SEER Rating						Two-Speed SEER Rating				All Units
	10	12	13	14	15	All	16	17	18	All	
CZ01	1.20	1.16	1.19	1.16	1.23	1.19	0.98	1.11	1.08	1.11	1.10
CZ02	0.96	0.95	0.94	0.92	0.94	0.94	0.83	0.90	0.92	0.87	0.90
CZ03	1.08	1.06	1.08	1.07	1.09	1.08	0.95	1.06	1.03	1.03	1.04
CZ04	1.06	1.04	1.06	1.04	1.06	1.05	0.93	1.00	1.00	0.98	1.00
CZ05	1.08	1.07	1.08	1.07	1.10	1.08	0.96	1.08	1.06	1.05	1.06
CZ06	1.10	1.07	1.10	1.07	1.11	1.09	0.97	1.08	1.06	1.06	1.07
CZ07	1.08	1.06	1.07	1.06	1.08	1.07	0.95	1.05	1.04	1.03	1.04
CZ08	1.08	1.06	1.02	1.00	1.02	1.02	0.90	0.98	0.98	0.95	0.97
CZ09	0.97	0.97	0.95	0.94	0.95	0.96	0.85	0.92	0.94	0.88	0.91
CZ10	0.94	0.94	0.91	0.90	0.91	0.92	0.81	0.86	0.88	0.83	0.86
CZ11	0.91	0.90	0.87	0.86	0.87	0.88	0.78	0.82	0.84	0.80	0.82
CZ12	0.95	0.95	0.93	0.91	0.92	0.93	0.82	0.88	0.90	0.84	0.87
CZ13	0.91	0.91	0.88	0.87	0.87	0.88	0.79	0.83	0.84	0.80	0.82
CZ14	0.86	0.85	0.84	0.81	0.84	0.85	0.75	0.79	0.80	0.75	0.78
CZ15	0.81	0.81	0.78	0.77	0.78	0.79	0.72	0.74	0.74	0.70	0.73
CZ16	1.05	1.03	1.03	1.02	1.03	1.03	0.84	0.91	0.95	0.89	0.91

Note: Climate zone and SEER specific multipliers used in all presentation graphics and summary findings. Values noted as "All" are for the reader's interest only.

Climate zone SEER multipliers provided in Table ES-1 should be used (not nominal SEER rating) to determine expected benefit associated with moving to a higher SEER-rated system in a specific climate zone. More work is needed (e.g., an estimate of the penetration of specific systems in the California market) to estimate the probability of failure if one assumes that a higher SEER system will use less energy than a lower SEER system.

The 2005 Title 24 ACM method produces SEER values that differ from climate zone and unit specific SEER obtained through the use of Table ES-1. Consequently, they provide estimates of the energy benefits associated with moving to a higher SEER-rated system that, at times, differ from the findings of this research. Differences vary from climate-zone to climate-zone and from one SEER level to another.

Rated SEER as a predictor of peak demand and demand savings

SEER is a poor predictor of cooling system electric demand in residential applications. For typical single-speed compressor systems, one has to move four SEER points (e.g., from SEER 10 to SEER 14) to be assured of cooling system demand reductions.

Using climate zone SEER adjusters provided in Table ES-1, does not yield substantially improved estimates of demand reduction.

The demand performance of typical two-speed compressor systems tends to be similar to the demand performance of single-speed systems two SEER points lower. Therefore, while moving from a SEER 13 single-speed system to a SEER 16 two-speed system will typically yield demand reductions, but, for most cases, moving from SEER 14 single speed system to a SEER 16 two-speed system will yield no demand benefit.

> **Moving from single-speed SEER 15 systems to two-speed SEER 16 systems will typically result in a demand penalty**.

Demand impacts can be predicted much more reliably using cooling systems' rated EER.

> **EER can distinguish relative (percent reduction) demand benefits associated with moving to a higher EER system to within ±10%.**

For a typical house, absolute demand improvement can be estimated to within ±8% if Table ES-2 is used to produce climate-adjusted EER.

Table ES-2 Residential EER Climate Zone Multipliers*

	Single-Speed SEER Rating						Two-Speed SEER Rating				All Units
	10	12	13	14	15	All	16	17	18	All	
CZ01	1.24	1.30	1.30	1.26	1.32	1.29	1.35	1.34	1.41	1.37	1.32
CZ02	1.08	1.04	1.03	1.02	1.01	1.04	1.03	1.02	1.00	1.02	1.03
CZ03	1.16	1.17	1.16	1.15	1.15	1.16	1.16	1.15	1.16	1.16	1.16
CZ04	1.10	1.10	1.08	1.06	1.05	1.08	1.07	1.06	1.06	1.06	1.07
CZ05	1.18	1.19	1.18	1.16	1.17	1.18	1.19	1.19	1.19	1.19	1.18
CZ06	1.18	1.20	1.20	1.18	1.19	1.19	1.20	1.22	1.22	1.21	1.20
CZ07	1.15	1.18	1.17	1.16	1.15	1.16	1.21	1.20	1.21	1.21	1.18
CZ08	1.15	1.18	1.08	1.07	1.07	1.09	1.09	1.09	1.08	1.08	1.10
CZ09	1.06	1.07	1.01	1.01	0.99	1.03	1.00	1.00	0.99	1.00	1.02
CZ10	1.05	1.01	0.99	0.98	0.96	1.00	0.99	0.99	0.98	0.99	0.99
CZ11	1.03	0.98	0.96	0.94	0.93	0.97	0.96	0.96	0.94	0.95	0.96
CZ12	1.04	1.01	0.99	0.98	0.96	1.00	0.98	0.98	0.96	0.98	0.99
CZ13	1.03	0.99	0.97	0.96	0.94	0.97	0.95	0.95	0.93	0.94	0.96
CZ14	1.02	0.97	0.95	0.93	0.92	0.96	0.95	0.94	0.92	0.94	0.95
CZ15	0.97	0.89	0.88	0.86	0.85	0.89	0.88	0.88	0.87	0.88	0.89
CZ16	1.10	1.09	1.06	1.04	1.05	1.07	1.06	1.06	1.03	1.05	1.06

Note: Climate zone and SEER specific multipliers used in all presentation graphics and summary findings. Values noted as "All" are for the reader's interest only.

Findings Summary

- Neither SEER nor EER is a sufficiently reliable indicator of cooling energy performance (consumption or demand) to meet the needs of California stakeholders. In residential applications, system efficiency upgrades will fall short of expected levels 45% to 98% of the time. Non-residential applications are more complex and require substantial additional research, but indications are that an even larger fraction will fall short of expected savings.

- Most of the basic assumptions implicit in the SEER rating process were found to be a poor match for typical California applications. As a results, the overall error or bias associated with using rated SEER to anticipate seasonal energy efficiency in California residential applications is from approximately +22% (in milder climates) to –30% (in warmer climates) for single speed equipment and from +25% to –33% for two-speed units. This overall bias was partitioned into the following effects.
  - Climate effects: The climate profile assumed in the SEER rating process is a poor match for most of the California climates. As a result, climate effects provide the largest source of bias in the reliability of rated SEER in California residential applications, approximately +15% to –27% or one-half to two-third of the total bias. Dryer conditions in the state will lead to a 5% to 10% reduction of seasonal cooling efficiency across all climate zones. Tabular correction factors were developed that were able to significantly reduce error in SEER to approximately ±8% for single-speed units and ±10% for two-speed units.
  - Building effects: The cooling load distribution and resulting mid-load temperature assumed in the SEER rating process (82°F) is poorly suited for California residential applications. As a result, building effects (i.e., typical variation found among California single-family residences) provide the second largest source of compromise in the reliability of rated SEER in California residential applications, approximately ±7%, or one-fourth to one-fifth of the total bias.
  - System effects: Differences between HVAC systems not accounted for in the SEER ratings process combined to provide the third largest source of compromise in the reliability of rated SEER, approximately ±5%, or $^1/_5$ to ¼ of the total bias. These differences include the effects of outdoor temperature and indoor coil conditions on capacity, impact of cooling efficiency on coil entering conditions, and the units' sensible cooling capacity.

- This study demonstrates that significant variation in annual cooling efficiency exists amongst equally rated cooling equipment (using only rated SEER as an indicator of cooling efficiency). To assure savings, one may require a two-SEER point upgrade from the 13 SEER code minimum and two-to-four points if considering an upgrade from a unit that exceeds the minimum. In November of 2002, ARI decided to no longer include EER in its equipment performance listings of SEER-rated equipment. Having at least two ratings points, i.e., SEER and EER, is critical to the energy efficiency industry in California.

Additional Research

This research has demonstrated that individual differences between identically rated HVAC systems, combined with simplifications implicit in the SEER ratings process, can significantly compromise the ability of a SEER rating to be a reliable predictor of cooling system performance in California. While the research summarized here has done much to characterize the scope of the problem with SEER ratings and demonstrate effective climate based SEER corrections, much more needs be done. The items below are suggested as important follow-on research.

- This work should be extended as follows.
  - Update systems rated as SEER 14 to include a representative sample range from the large number recently introduced units at this rating point;
  - Add HVAC equipment penetration rates and apply statistical methods to more accurately characterize the California statewide impacts of performance variability on expected savings and demand.
  - Performance testing of cooling systems to verify expanded ratings data.
- More study is needed to explore how the inherent performance variability of SEER-rated HVAC systems, as characterized by this research, can be applied to:
  - the future development of the California energy efficiency standards to better ensure resultant savings;
  - utility incentive programs to improve efficiency realization rates.
- Additional research is required to more effectively correct for:
  - building effects, e.g., varying mid-load temperatures;
  - system effects, e.g., especially off-rated coil entering conditions.

1.0 INTRODUCTION

1.1 BACKGROUND

The air conditioning industry has long relied on the Energy Efficiency Ratio (EER) and the Seasonal Energy Efficiency Ratio (SEER) as indicators of cooling HVAC equipment efficiency and performance. EER is “a ratio calculated by dividing the cooling capacity in Btu/h by the power input in Watts at any given set of rating conditions, expressed in Btu/h/W” (ARI, 1984). Currently, all direct expansion (DX) air conditioners are rated using EER (also know as the EER_A rating point), a rating standardized by ARI, which reports steady-state efficiency at 95°F outdoor and 80°F dry-bulb, 67°F wet-bulb indoor temperatures. Smaller (i.e., residential-sized, < 65,000 Btu/hr) air-conditioners are rated using SEER, a rating developed by the U.S. DOE. SEER is “the total cooling of a central air conditioner in Btu’s during its normal usage period for cooling … divided by the total electric energy input in watt-hours during the same period…” (ARI 1984). It is intended to better indicate average seasonal performance, i.e., a season-long "average" EER.

The current California Title 20 and Title 24 standards mandate air conditioner efficiency levels using EER and SEER and consumers are typically guided to make energy-wise purchases based on these ratings. For example, “consumers can compare the efficiency of central air conditioners and heat pumps (in the cooling cycle) using the SEER. The higher the SEER, the more efficient the system…” [California Energy Commission Web site]. Additionally, California electric utilities desire a reliable energy and peak demand savings predictor that is effective across the state. State-wide efficiency programs have recently abandoned SEER in favor of EER as an indicator of both energy and demand benefit (www.savingsbydesign.com/system.htm).

SEER ratings for single-speed cooling systems are based on a steady-state single-point rating system similar to EER rating. Systems are rated at 82°F outdoor and 80°F dry-bulb, 67°F wet-bulb indoor temperatures (EER_B ratings point). Additional cycling tests provide an estimate of the system’s cycling losses which result largely from the time required after start-up to re-establish the operational pressure differences in the system. Results from the EER_B and cycling loss tests are used to calculate SEER. The equation is:

$$SEER = EER_B * (1 - 0.5*C_D) \qquad (1.1)$$

where EER_B is as described above and C_D is the system’s degradation coefficient determined from prescribed cycling tests. The 82°F outdoor temperature used in the EER_B rating point was selected as representative of a seasonal average outdoor temperature seen by the system. It also represents the mid-load temperature, i.e., half of the seasonal cooling coil load occurs above 82°F outdoor temperature, half below. The degradation coefficient multiplier, C_D, is adjusted for an assumed average 50% cycling over the course of the cooling season. The assumed load profile and mid-load temperature used to determine a SEER rating are shown in Figure 1.1.1.

Thus, the SEER ratings procedure replaces one steady-state rating point with another and accounts for load dynamics through a single loss calculation. The new rating point (EER_B) is based on an assumed system loading that may not be representative of actual conditions. Understandably, manufactures design their systems to maximize SEER ratings. However, there is no guarantee that SEER rating conditions reflect actual dynamic loading and temperature effects within the state of California. The question remains as to whether SEER can accurately guide the consumer or designer to make energy-wise equipment selections or the utility industry to design effective efficiency programs. Additionally, SEER may or may not serve as an adequate regulatory basis for Title 20 and Title 24.

The rating of two-speed systems differs somewhat from single-speed systems. Both rating procedures are based on the same assumed equipment loading and system entering air conditions. As such, neither may represent conditions found throughout the various California climate zones or reflect the range of common cooling system uses.

Figure 1.1.1
Cooling Coil Load Profile and Mid-Load Temperature
Assumed in the SEER Ratings Process

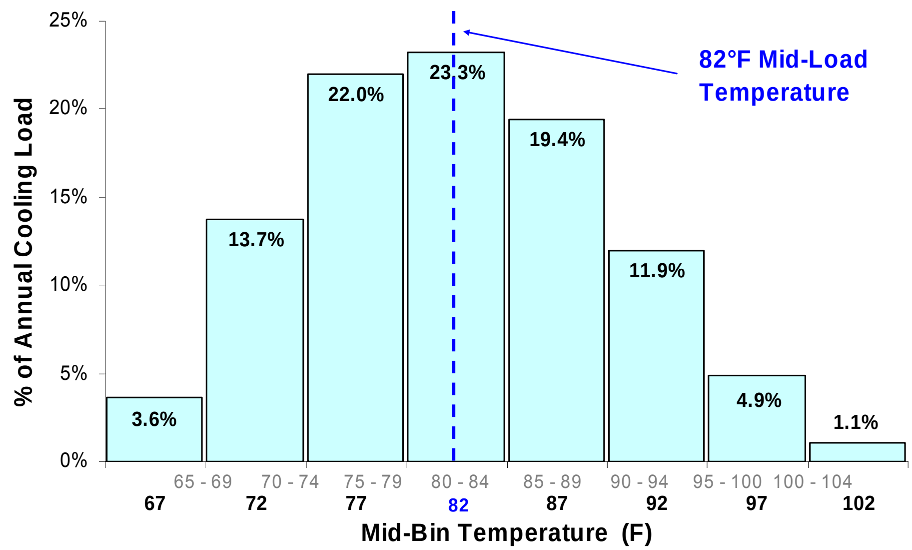
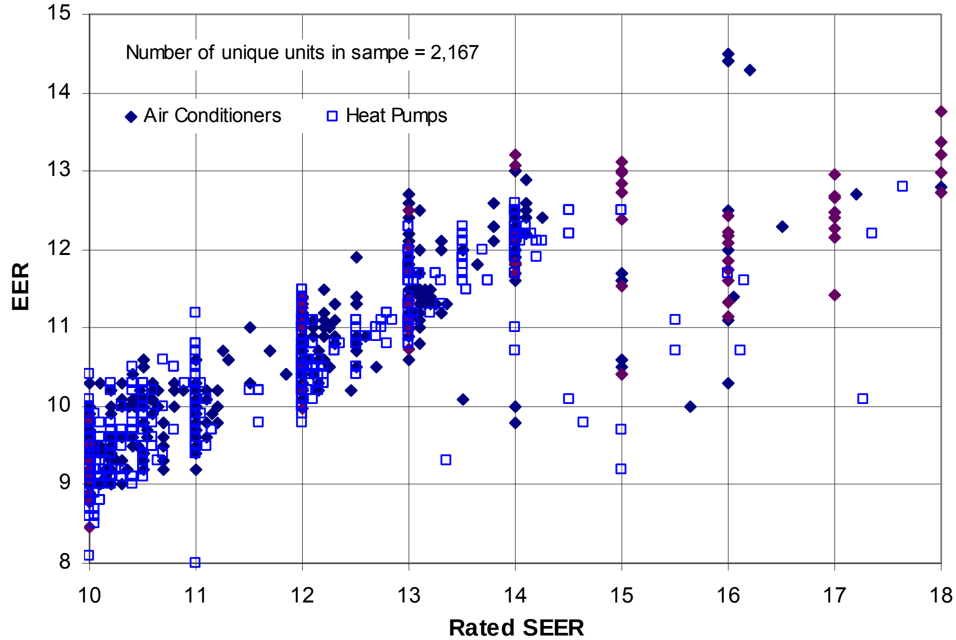


Figure 1.1.2 plots EER vs. SEER for approximately 2,200 unique, split-system SEER-rated cooling systems (< 65,000 Btu/hr) included in the CEC's listing of certified air conditioners. Note that for a given SEER level, there is a significant variation in EER (±15%), and for a given EER level, there is an even more significant variation in SEER (±25%). This variation results from the varied means manufactures use to obtain the highest possible SEER rating. It follows that these same systems will exhibit a great deal of variation in season-long performance under actual dynamic load and temperature effects.

Figure 1.1.2
Performance Characteristics of SEER-rated Cooling Systems
Rated SEER (at 82°F) versus Rated EER (at 95°F)



1.2 OBJECTIVES

This effort focuses on the general question — "All other issues being equal, which system should I choose for my application?" In this light, are there problems with the current SEER ratings system and are there reasonable solutions to the problem? Questions to be answered include the following:

- How effective is SEER as a predictor of expected cooling *energy use* or *utility costs*?
- How effective is SEER in ranking the seasonal cooling efficiency of different systems? Like the EPA gas mileage label, "your mileage may vary", actual SEER may vary due to various user effects such as thermostat set point. Not withstanding this, can SEER be used to compare the *relative* cooling efficiency of air conditioners and heat pumps? As an example, for a specific house and climate zone, will a SEER 11 system reliably use less annual cooling energy than a SEER 10 system?
- How effective is SEER in estimating cooling energy or utility *savings*? For example, based only on the difference in magnitude of SEER, upgrading from SEER 10 to SEER 13 suggests a 23% improvement in seasonal efficiency (1-[10/13]). All other things being equal (i.e., controlling for climate and user differences), will a 23% savings in annual cooling energy be realized?
- How effective is SEER as a predictor of expected cooling *peak demand* and demand savings? This question has become all the more important since ARI (Air-Conditioning and Refrigeration Institute) decided in November of 2002 to stop listing EER for SEER-rated systems in its directory of certified equipment.

- Can a California-specific SEER adjustment procedure be developed that uses the existing published manufacture's performance data to calculate an "adjusted" SEER with improved value for decision makers?

The specific objectives of this study are to

1) quantify the reliability of SEER in predicting annual cooling *energy use*, *peak demand*, energy and demand *savings*, and *relative* efficiency (the ability to reliably rank order systems based on their efficiency).

2) derive and demonstrate improved methods to collect and predict more accurate energy use indicators.

In order to accomplish these tasks, this study will be separated into the following two tasks:

1) <u>Phase 1: Part-Load Performance Evaluation</u>. Using available detailed part-load and temperature performance data from air conditioner manufacturers, detailed DOE-2 energy simulations are conducted across a variety of building types and across five climate zones within the state. These simulations are used to calculate SEER values from simulated cooling load and energy results. This portion of the research would estimate the magnitude of the potential energy impact due to improved consumer information on SEER. This effort will also attempt to identify the efficacy of SEER as a regulatory index, from both energy and demand reduction standpoints.

2) <u>Phase 2: Rating Development.</u> If Phase 1 results show significant potential improvement in energy and demand estimates might be available from better characterization of weather, part-load, and other dynamic effects, derive and demonstrate a SEER adjustment to be used to improve the utility of the SEER rating. Ideally, the rating should be usable both in a regulatory context (Title 20 and Title 24) and as a consumer/builder-directed rating and would require no additional data or test procedures by manufactures beyond that which is currently being used or provided.

1.3 TECHNICAL APPROACH

This effort is based on detailed DOE-2 simulations. The use of the DOE-2 energy analysis program significantly expands the level of detail at which cooling system performance is evaluated in comparison to the DOE-mandated SEER calculation. Details of the differences in the calculation approaches and assumptions used in the SEER ratings process and DOE-2 calculations are given in Section 3.1 and Appendix A. Appendix A also includes the process whereby the DOE-2 program reproduces the SEER rating for a given cooling system. Some of the more salient issues addressed by the DOE-2 program, that are ignored by the standard ratings process include, but are not limited to, the following:

- Cooling system performance is evaluated under a full range of climate and load conditions rather than an assumed single load profile.
- The use of cooling system performance maps captures the dynamic impact of outdoor and entering air conditions on seasonal efficiency.

- Latent cooling loads are allowed to float in response to system runtime based on available sensible cooling capacity and sensible cooling load.
- Cycling losses are applied to dynamic hourly coil loads rather than via an assumed annual average condition.
- Peak system loads (both coil loads and electric input) are captured in addition to seasonal energy usage.

Building types were selected and characterized based on a statistical evaluation of statewide residential new construction surveys. Prototype DOE-2 building models were created and parametric runs were conducted to determine typical expected performance of SEER-rated split single and two-speed cooling systems. Simulations also examined their performance sensitivity to a variety of building characteristics and building operating conditions. The parametric variations of the prototypes were performed using one-at-a-time sensitivity analysis methods to search for the combination of building characteristics that leads to the maximum variation in predicted seasonal energy efficiency.

Manufacturers' expanded ratings charts were used in conjunction with rated EER, SEER and degradation coefficients to produce performance maps usable by the DOE-2 program. The performance maps account for changes in cooling system total and sensible capacities and energy input over a wide range of outdoor temperature and entering conditions to the coil. Cycling losses were determined from the DOE-mandated cyclical test in conjunction with a detailed thermostat model. Part-load curves captured these losses in DOE-2 simulations.

1.4 LIMITATIONS OF THE STUDY

Limitations of this study include the following:

1) This study assumes cooling system performance over a range of conditions based on data from manufacturer's expanded ratings charts. As such, all operating conditions inherent in the charts are assumed to apply to an actual system. These conditions include standard refrigerant line sets, proper system charge, and design airflows. While some system-level effects are included in simulations (air leakage in the duct system, ductwork transience, and duct thermal losses), it is assumed that all cooling systems are installed properly.

2) The original SEER ratings concept is based on a simplified thermal/energy model of a cooling system. Use of the DOE-2 program greatly expands the complexity of the thermal model and more nearly replicates expected actual operating conditions. The DOE-2 simulation package is still a thermal model and cannot reasonably capture all variability's in the operation of the cooling system. These unquantifiable operational effects are expected to increase the variation in seasonal performance of cooling systems. Because of this, study findings are expected to be conservative in their comparison to rated SEER values. Variability in SEER predicted by the DOE-2 program should be less than that found in actual applications.

3) The off-design and part-load performance of the various cooling systems have been

developed from manufacturers' expanded ratings charts. It is important to note that (other than the ARI point) performance data in these charts are not from direct system tests, rather, they are computer-generated, and are not warranted by the manufacturer. However, this data does serve as the best available information on the cooling systems included in this effort.

1.5 REPORT ORGANIZATION

The overall organization of the report is divided into five sections:

Section One provides this introduction.

Section Two provides details of the project implementation including a description of building prototypes and cooling system performance maps.

Section Three discusses simulation results and presents the basis for SEER adjustment factors.

Section Four presents the detailed SEER adjustment factors based on findings from Section Three.

Section Five compares the adjusted SEER models to results from expanded DOE-2 simulations that cover all climate zones and a full range of cooling systems.

Appendices contain detailed and/or background data such as details on building prototypes, system performance maps and approaches, and DOE-2 source code listings.

2.0 ANALYSIS METHODOLOGY

2.1 SEER RATING METHODOLOGY

The principal challenge in developing the SEER rating is to provide a reliable estimate of season-long cooling efficiency using very limited steady-state laboratory testing that is both repeatable and affordable. Necessarily, several fundamental assumptions were made in the original development of the SEER rating. The most significant of which is an assumed seasonal cooling coil load profile representative of hotter areas with significant cooling loads. The seasonal coil load profile was developed using the following key assumptions:

1) The building overall shell U-value, solar gains, internal loads, and thermostat cooling set point yield a 65°F balance point for the building, i.e., cooling is required at and above outdoor air temperatures of 65°F; no cooling is required below 65°F.

2) A cooling season temperature profile was determined, in part by weighting the penetration of residential cooling in selected cooling locations. The resulting distribution of outdoor cooling temperatures (i.e., outdoor temperatures coincident with cooling operations as per the first item above) has a median temperature of 82°F (see Figure 2.1.1a).

3) All cooling coil load is a linear function of outdoor temperature only (see Figure 2.1.1b). This assumption, combined with the previous assumption, allows 82°F to also be considered the seasonal cooling *mid-load* temperature, i.e., the outdoor temperature above and below which occurs approximately half of the seasonal cooling coil load (see Figure 2.1.1c). Consequently, 82°F is selected as the outdoor temperature for the SEER rating, i.e., for the EER_B rating point.

4) The sensitivity of capacity and efficiency to outdoor temperature for individual HVAC systems tend to be linear in temperature. This is necessary if systems with the same EER at 82°F (EER_B) and therefore the same SEER (assuming equal cycling losses) but with differing EER at other temperatures (e.g., EER_A at 95°F) are to have equal total annual cooling energy requirements. Hour-by-hour operational performance for DX systems will always vary with outdoor temperature, less efficient in warmer outdoor temperatures, and more efficient in milder temperatures. Even systems with equal SEER ratings will usually differ in their sensitivity to outdoor temperature with some systems being more sensitive than others. As an example, imagine two systems with equal SEER (i.e., same EER at 82°F and equal cycling losses) but with differing sensitivity to outdoor temperature. The system with higher temperature sensitivity will tend to be <u>less</u> efficient at hotter outdoor temperatures than the other system. If the sensitivity to outdoor temperatures is linear for both systems, then the system with high temperature sensitivity will also tend to be <u>more</u> efficient at milder temperatures than the other system (see Figure 2.1.2). If 82°F is the mid-load temperature for both systems, then the efficiency penalty that the higher sensitivity system experiences above 82°F outdoor temperature, relative to the other system, will be balanced by increased efficiency at outdoor temperatures below 82°F. While

energy use measured at any temperature other than 82°F will differ between the two systems, over the course of the entire cooling season, this will tend to balance out and the two systems will have the same season-long energy use.

5) An important caveat for the previous assumption involves at least two assumptions regarding indoor (evaporator) and outdoor (condenser) fans:
   - The energy from both fans is included in the overall SEER rating and is generally assumed to be a relatively small and relatively constant portion of the total system energy requirement.
   - More importantly, both fans are assumed to cycle with the compressor, hence, fan energy is also assumed to be a linear function of outdoor temperature.

This analysis will examine the validity and consequence of these assumptions for typical California residential and non-residential buildings across all sixteen California climate zones.

Several of the fundamental assumptions used in the SEER rating calculation methodology are illustrated below in Figure 2.1.1.

Figure 2.1.1

Key Climate and Load-Related Assumptions Implicit in the SEER Rating Procedure
Derivation of the 82°F "Mid-Load" Temperature

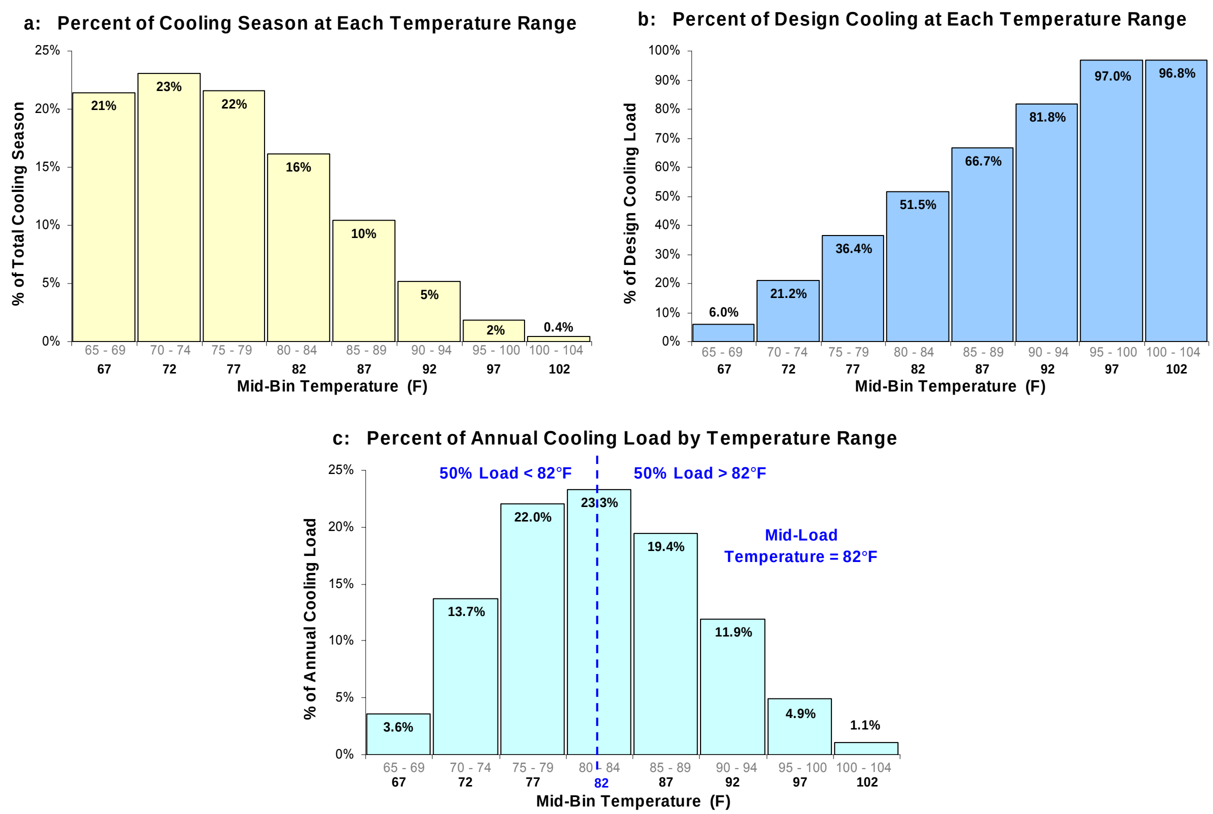
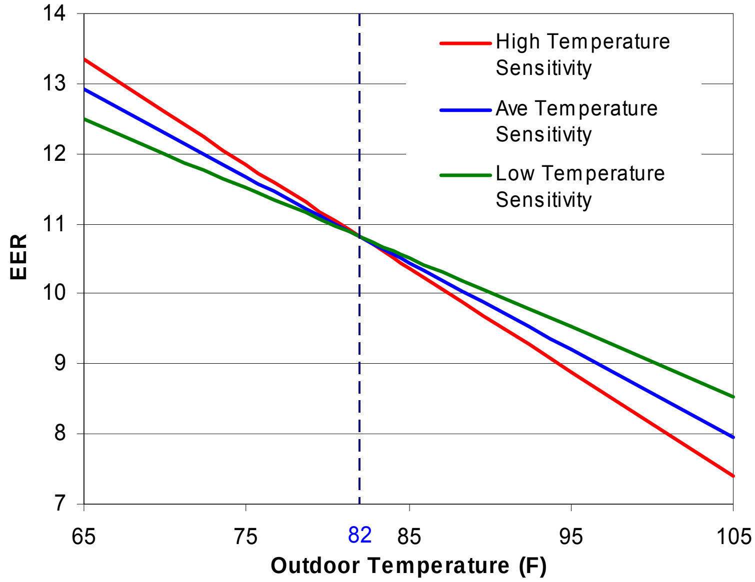


Figure 2.1.2
System Performance-Related Assumptions Implicit in the SEER Rating Procedure
Efficiency (EER) Sensitivity to Temperature



2.2 ENERGY ANALYSIS METHODOLOGY

2.2.1 Energy Simulation Package

Detailed computer simulations for this project were performed using the latest version of the DOE-2 building energy analysis program. DOE-2 calculates hour-by-hour building energy consumption over an entire year (8,760 hours) using hourly weather data for the location under consideration. The weather used for this analysis was the California Thermal Zone weather data, prepared by the California Energy Commission.

The version of DOE-2 used in this study, version 2.2, has been widely used and validated by public, private, and academic users. Much of the use of this version of DOE-2 is attributable to a number of widely used interfaces including eQUEST® and PowerDOE®. Version 2.2 is the latest enhanced version of DOE-2, which includes many new modeling features. It also improves and extends many prior capabilities, and corrects many previously existing bugs in the last version, more commonly known as DOE-2.1E. Driven by modeling requirements for this project, new capabilities were added to DOE-2 to allow the accurate modeling two-speed cooling systems. This new feature is an expansion of the staged-volume simulations additions recently added to DOE-2, properly capturing the high and low-speed operation of two-speed systems. The resulting version, including the new features used in this project, is available to the public as the currently posted freeware version 2.2.

2.2.2 Calculation Approach

The overall approach uses the DOE-2 program to calculate the seasonal energy performance of cooling system equipment when applied to typical building prototypes. The selected cooling systems are simulated within DOE-2 using detailed performance maps. These maps describe, in detail, the cooling systems' sensible and latent capacities, condenser unit energy, and fan energy under all operating conditions.

The operating conditions (i.e., operations schedules and coil loads) are calculated from building prototypes whose energy use characteristics are calculated from specific building features. These include detailed descriptions of the building components (walls, windows, building orientation, shading devices, floor area, number of floors, etc.) and building operating conditions (occupancy levels, thermostat settings, equipment use, lighting, and schedules that describe how these vary over the day). The building prototypes include those single-family residential applications in which SEER-rated equipment is most commonly found. The building component and operational details are obtained from new construction building surveys executed in California. These surveys provide median, minimum, and maximum values of the components and operational features of the various building prototypes, which are used to determine the effects of building characteristics on SEER.

2.3 COOLING EQUIPMENT SELECTION PROCEDURE

2.3.1 Equipment Databases

Figure 1.1.2 plots EER vs. SEER for approximately 2,200 unique SEER-rated split-system cooling systems (< 65,000 Btu/hr) included in the CEC's listing of certified air conditioners. This is actually only a fraction of available cooling systems on the market when one considers that the database only includes SEER-rated systems. SEER-rated systems are condensing unit and indoor coil (or fan coil) combinations that each manufacturer lists as its "most common" combination. There exist many more coil combinations that can be used with a given condensing unit. Some consistent and rational means was necessary to select among all of the available systems, to find a way to reasonably account for the range of equipment performance illustrated in Figure 1.1.2.

The selection mechanism began by expanding an equipment database put together by Hillier. This database sorted equipment by type (air conditioner or heat pump) and SEER rating. Only air-cooled systems are included in this effort. The databases were expanded and sorted to identify systems by the following metrics:

- System type - heat pump and air conditioner
- SEER level – 10, 12, 13, 14, 15, single-speed and SEER 16, 17, and 18 two-speed (SEER level is ±0.3 ratings points from levels shown, e.g. SEER 13 systems can range from SEER 12.7 to 13.3. See note on the following page)
- Single and two-speed compressor operation
- Degradation Coefficient for single-speed equipment (C_D in Equation 1.1) as obtained from the CEC's list of rated systems.
- EER sensitivity to changes in outdoor temperature for single-speed equipment, as determined from manufacturers' expanded ratings charts.
- EER level for two-speed equipment

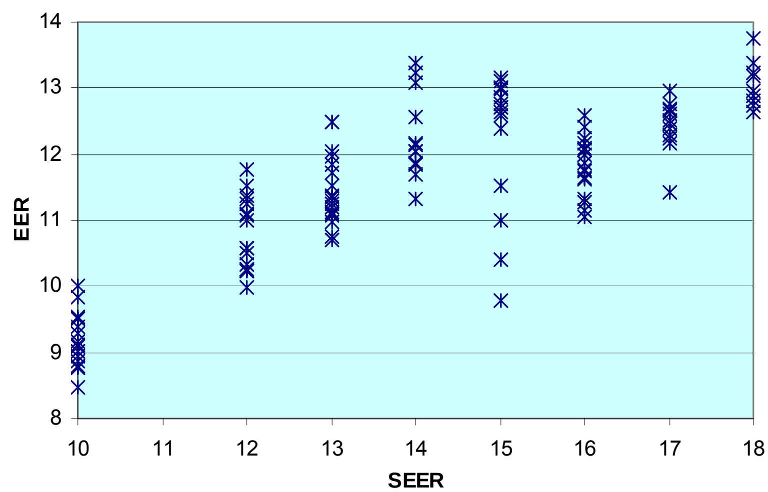
Since this effort is based on DOE-2 simulations, only equipment for which expanded ratings charts could be obtained was included in the database. The availability of expanded ratings charts tended to be manufacturer specific. Manufacturers included in the database include Carrier, Lennox, Nordyne, and Trane. This analysis only examined air-cooled SEER-rated cooling systems (heat pumps and air conditioners).

The system selection process was developed to account for the variation in cooling system performance illustrated in Figure 1.1.2. Figure 2.3.1 shows the performance characteristics of SEER 10, through 15 single-speed systems along with SEER 15 through 18 two-speed systems selected by this process. While the single-speed systems were not specifically selected by their EER, the selection process included systems that span the EER range given in Figure 1.1.2, as illustrated in Figure 2.3.1. Appendix B provides the details of the selection process.

Figure 2.3.1

Performance Characteristics of Selected Split-System Cooling Systems

(<65,000 Btuh Air-Cooled DX Cooling Units)



** Systems include both air conditioners and heat pumps*

This effort limits the systems examined to SEER 10, 12, 13, 14 and 15 single-speed systems, along with SEER 16, 17, and 18 two-speed systems. This was done both to reduce the number of DOE-2 simulations and to provide adequate differentiation between cooling system efficiency.

A specific system selected for simulation is identified by the six metrics listed above. For example, a system simulated could be a SEER-12, single-speed, split-system air conditioner, with a median EER temperature sensitivity and high degradation coefficient. All single-speed equipment was chosen by their EER temperature sensitivity and degradation coefficient (see Appendix B for details). The number of two-speed systems available is limited, so the database includes the SEER-rated heat pumps and air conditioners from as many product lines for which expanded ratings charts were available. Performance curves were created for the two-speed units that represented high, low, and median EER levels within a given product line. In all, detailed performance maps were created for over 119 cooling systems.

2.3.2 DOE-2 Performance Maps

DOE-2 performance curves were generated from manufacturers' expanded ratings charts and degradation coefficients from the CEC database for the systems selected for examination. Maps are based on rated cooling system values and off-rated and part-load adjustment curve fits. The information required by the DOE-2 program to fully simulate a cooling system includes design operating conditions and curve to adjust operating conditions from their design values. Design information includes the following:

- EIR – condenser unit energy input/ cooling system output at ARI rated conditions. Determined from expanded ratings charts and ARI rated conditions provided by manufacturer.†
- SHR – sensible heat ratio, or ratio of total to sensible cooling capacity at ARI rated conditions.
- Fan kW – fan energy in kW/cfm. Found or estimated from manufacturers' data
- Coil by-pass factor – ratio of actual temperature drop across the cooling coil to that if the air was fully saturated leaving the coil at ARI rated conditions. Calculated from manufacturers' total and sensible capacity at ARI rated conditions.
- Cfm – the air supply volume per Btu of cooling delivered by the system at ARI rated conditions. The DOE-2 program actually uses cfm directly, but program macros were used to match the required air volume to the system capacity (which varied from simulation to simulation).

Curve fits include:

- Total Capacity_*f*(ODB,EWB) – a bi-quadratic curve fit that adjusts the design total gross capacity for non-design outdoor dry-bulbs (ODB) and cooling coil entering air wet-bulbs (EWB). Curve fit to manufacturers' data found in expanded ratings charts.
- Sensible Capacity_*f*(ODB,EWB) – same as Total Capacity_*f*(ODB,EWB), except it adjusts the gross sensible cooling capacity. Curve fit to manufacturers' data found in expanded ratings charts.
- EIR_*f*(ODB,EWB) – same as Total Capacity_*f*(ODB,EWB), except it adjusts the energy input to the condenser unit (EIR). Curve fit to manufacturers' data found in expanded ratings charts.

† The databases of SEER-rated systems include cooling system with SEER ratings within ±0.3 ratings points of their nominal values. For example, the SEER-13 database includes systems with SEER ratings between 12.7 and 13.3. Where necessary, DOE-2 EIR values were adjusted to force all systems to their nominal SEER rating. This allows comparisons of systems with differing part-load and off-design characteristics in a consistent manner. The change in DOE-2 EIR is equivalent to replacing the existing compressor motor with one that is slightly more or less efficient (±5%). It does not change how a system responds to changes in coil entering or outdoor conditions, nor does it affect cycling losses.

- Coil By-pass Factor_*f*(EDB,EWB) – a bi-quadratic equation that adjusts the design coil by-pass factor to account for differing cooling coil entering air dry-bulb (EDB) and wet-bulb (EWB) conditions. Curve fit to manufacturers' data found in expanded ratings charts.
- EIR_*f*(PLR) – a cubic curve fit that adjusts the condenser unit efficiency (EIR) to account for system cycling (PLR). Used when the system's fan runs continuously. Curve fit is obtained through a detailed thermostat model (Appendix C) applied to the degradation coefficient determine via the SEER ratings cycling test.
- Cycling Loss__*f*(PLR) – a cubic curve fit that adjusts the condenser unit efficiency (EIR) to account for system cycling (PLR). Used when the system's fan runs cycles with the condenser unit. Curve fit is obtained through a detailed thermostat model (Appendix C) applied to the degradation coefficient determine via the SEER ratings cycling test.
- High and Low-speed Ratios – For two-speed units this includes high and low speed cooling capacity, airflow, and nominal coil by-pass factor. High and low efficiencies are accounted for by the EIR_*f*(PLR) curve.

The single-speed performance curves were examined to determine if they would reproduce the systems' rated SEER. Two comparison methods were used. First, the single-point method was used as given by Equation 1.1. In this comparison, ODB was set to 82, EWB 67, EDB 80, and PLR 0.5. This matches the outdoor, coil entering, and cycling conditions assumed in the ratings procedure. The resulting ratio of total electric input (condenser unit and indoor fan) to net cooling capacity matched the SEER rating (no difference at the first decimal level). In the second method, the performance maps were exercised against the assumed cooling load profile assumed in the ratings process (Appendix A). Again, the ratio of seasonal total electric to seasonal net cooling matched the SEER rating.

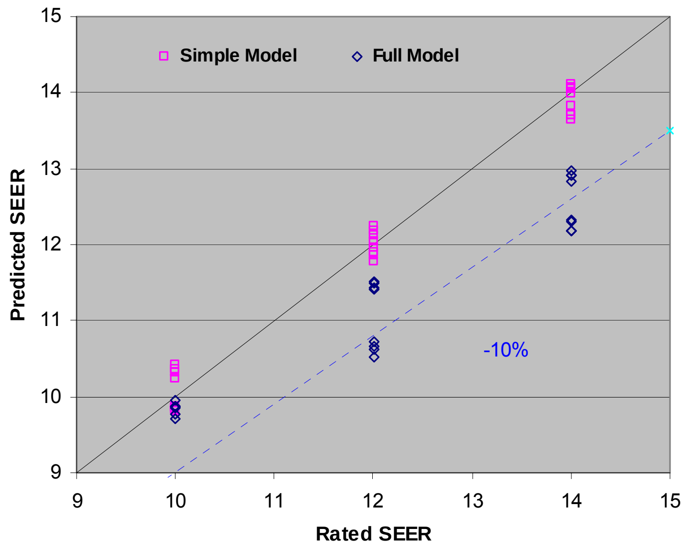
The question also arises as to whether or not the performance curves when used in the DOE-2 program will replicate SEER values. This is less straightforward as the SEER ratings process assumes a specific cooling load profile. The building loads simulation process would have to produce a load profile that matches that assumed in the ratings process. Some of the simulations run against climate zones 9 and 12 weather data did produce a load profile that was relatively close match to that used in SEER ratings.

Other problems include those associated with latent loads calculations in DOE-2. DOE-2 simulations maintain a fixed space temperature with floating (varying) space humidity. Consequently, simulation cooling coil entering conditions do not match conditions assumed in the ratings process (80 F dry-bulb and 67 F wet-bulb). This problem was resolved by altering performance maps so they were locked to 80 F dry-bulb and 67 F wet-bulb conditions. These and other issues relating to a comparison of the DOE-2 modeling process and assumptions used in the SEER ratings process are provided in Appendix A.

A comparison of simulated and rated SEER, once differences were resolved, are shown in Figure 2.3.2. Also included in Figure 2.3.2 are the results of the "full" DOE-2 simulations, i.e., do not include changes to performance maps needed to match the SEER ratings process assumptions.

The agreement between the SEER generated by the DOE-2 program and rated values for single speed (SEER 10, 12 and 14) systems is quite good. The scatter in the results is within ±5% of the rated SEER. This is on the order of the 10% variation Kelly and Parken reported in the development of the SEER ratings procedure when they applied the full bin method to real systems and compared results to the single point analysis. The scatter is associated with slight differences in the performance characteristics of the various systems. Some scatter in predicted SEER is to be expected as a result of differences in cooling equipment performance characteristics, load sequencing, and cycling losses.

Figure 2.3.2
Effect of Simplified HVAC System Assumptions of the SEER Rating Procedure
DOE-2 Predicted SEER vs. Rated SEER



Full Model *represents a detailed DOE-2 model using full manufacture's performance data to characterize HVAC system sensitivity to outdoor temperature and cooling entering conditions;*
Simple Model *represents a DOE-2 simulation with performance curves altered to better match the simplified assumptions used in the SEER rating process (e.g., constant 80°F DB & 67°F WB entering conditions).*

2.3.3 System Sizing

Systems are sized in a manner consistent with the SEER ratings process. That is, systems are sized at 90% of the peak cooling coil load. This is equivalent to the assumption in the SEER ratings process that the system has 10% excess cooling capacity at ARI conditions (95 F outdoor temperature). The load profile used in the ratings process assumes that the peak outdoor temperature seen by the system is 105 F. This results in a capacity shortfall during peak cooling conditions. The sizing approach used in the ratings process is roughly equivalent to sizing a cooling system to the ASHRAE 1% design condition. Details on the how this sizing procedure was developed from the SEER ratings process are provided in Appendix B.

The sizing process requires a preliminary DOE-2 simulation to determine the peak coil load. Once the coil load is known and the peak load captured for future runs, the system is sized to 90% of this value. The DOE-2 program assumes that the capacity given is at ARI conditions (95 F outdoor temperature). Equipment performance maps are used in conjunction with 1% design temperatures representative of each climate zone to translate the peak cooling coil load into its ARI equivalent.

It is recognized that the sizing process results in non-standard cooling system capacities. While this is the case, the approach is equivalent to that used for SEER ratings. The SEER ratings process assumes that the load on the cooling system is always a fixed fraction of its ARI capacity. This will obviously not be the case in a real application. It would be impractical when doing DOE-2 simulations to scale the building up or down to match the capacity of the system. Rather, the nominal capacity of the system was altered to match the size of the cooling load so that the system was exercised under the same sizing operational sequence as is inherent in the SEER ratings process. Additional studies were performed at higher sizing ratios to determine the impact of this sizing approach on SEER by using a much higher sizing ratio that would be representative of an over-sized system.

2.4 BUILDING PROTOTYPES

Key variables in the ability of the SEER rating to accurately predict energy performance include the load shape of the coil loads and how these loads relate to outside ambient temperature. In other words, identical SEER-rated single-zone air conditioners on the different buildings in the same climate may perform very differently, depending on the building balance point and load shape of the cooling coil loads (especially the building's mid-load temperature). For example, the loads of a home that includes a large amount of south-facing glass, a large amount of cooking and entertainment equipment, a low thermostat setting, and limited or no use of natural ventilation could affect SEER differently than a home with less solar gain, a higher thermostat setting, and more frequently used natural ventilation. Similarly, in an office setting, an core zone with no connection via the building envelope to the exterior conditions will be dominated by interior lighting and equipment loads. East or west-facing perimeter zones with significant fenestration may be dominated by morning or afternoon solar gains. In each of these cases, the fundamental relationship between cooling load and outside temperature, and hence, the mid-load temperature, is likely to be very different.

DOE-2 models were developed to examine these issues. They included variable building design and operational characteristics expected to impact the building balance point and mid-load temperature. Each was characterized using the 2000 Residential New Construction Market Share Tracking (RMST) Database. These databases provided typical and extreme values of features that affect cooling loads in buildings. A description of the building types and the features that were expected to impact building balance point and mid-load temperature for each building type follows.

To properly capture the loads seen by the residential HVAC system, DOE-2 models create realistic single-story and two-story models facing perpendicular directions, as shown below in Figure 2.4.1. The group of buildings has equal wall and window area facing each direction, but each individual building is dominated by east-west or north-south glazing. Typical characteristics for conditioned area, insulation levels, foundation type, etc. vary by climate zone, as defined in the RMST database. Details are provided in Appendix E. Twenty characteristics of single-family residences were varied in this study. These are listed in Table 2.4.1. Likely minimum (i.e., 10th percentile of the sample), maximum (i.e., 90th percentile), and median (i.e., 50th percentile) values for each characteristic were identified for each climate zone. See

Appendix E for details. Including changes in orientation, there are over 7,000 possible combinations of building features possible for examination in the DOE-2 simulations.

Figure 2.4.1
Single-Family Building Prototype

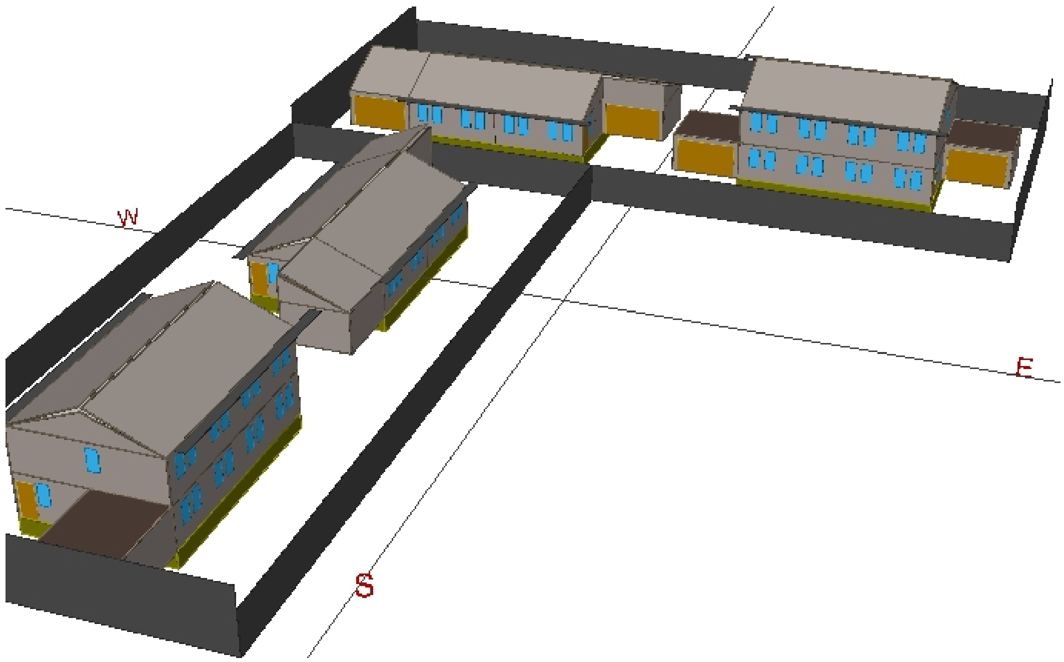


Table 2.4.1
Single-Family Building Characteristics Varied in DOE-2 Models

Total Floor Area	Conditioned floor area
Number of Stories	Typically a fraction that includes 1 & 2 stories
Aspect Ratio	Orientation of long axis varies
Occupancy	Includes number and schedule of use
Internal Gains	Net loads to the space
Glass Area (Fraction)	As a fraction of total wall area
Glass U-factor	NFRC U-factor
Glass SHGC	NFRC solar heat gain coefficient
Shading Level	Shading by overhang
Ceiling Type	Cathedral or attic
Roof Insulation	Roof overall U-value
Wall Construction Type	Construction and U-values varies
Floor Type	Crawlspace or Slab
Floor Insulation	U-value of floor or slab loss factor
Infiltration	Infiltration rate in air-changes/hour
Natural Ventilation	Varied by indoor temperature and ventilation rate
Cooling Thermostat	Consistent with natural ventilation
Cooling T-stat Setup	Consistent with occupancy schedules
Duct Loss (fraction)	Fraction of return and supply cfm lost to outside
Duct R-Value	Duct insulation value

3.0 ANALYSIS RESULTS

The possible combination of building prototype characteristics, cooling systems, and climate zones, provides a very large set of DOE-2 simulation results. A process was developed by which the impacts of each set of conditions were examined in a three step process:

1) Simulate median building prototypes and median system characteristics over the subset of climate zones chosen to represent the anticipated range of weather conditions. Compare simulated SEER (determined by detailed simulation) to rated SEER to identify the sensitivity of rated SEER to California climates.

2) Modify building characteristics in a sequential manner to determine the combination of characteristics that yield the highest and lowest simulated SEER values for each climate zone. Compare simulated SEER to rated SEER to identify the sensitivity of rated SEER to the typical variation in California buildings. Use these results to quantify the expected uncertainty in SEER based on the variation in building characteristics.

3) Simulate the building prototypes that produce the minimum, maximum, and median SEER values resulting from Step 2, using an expanded number of cooling systems, i.e., those that were selected to represent the expected range of performance (e.g., having minimum, maximum, and median sensitivity to outdoor temperature). Identify the sensitivity of rated SEER to the anticipated typical variation in cooling system performance characteristics, e.g., cooling system design features, fan power requirements, and system sizing criteria).

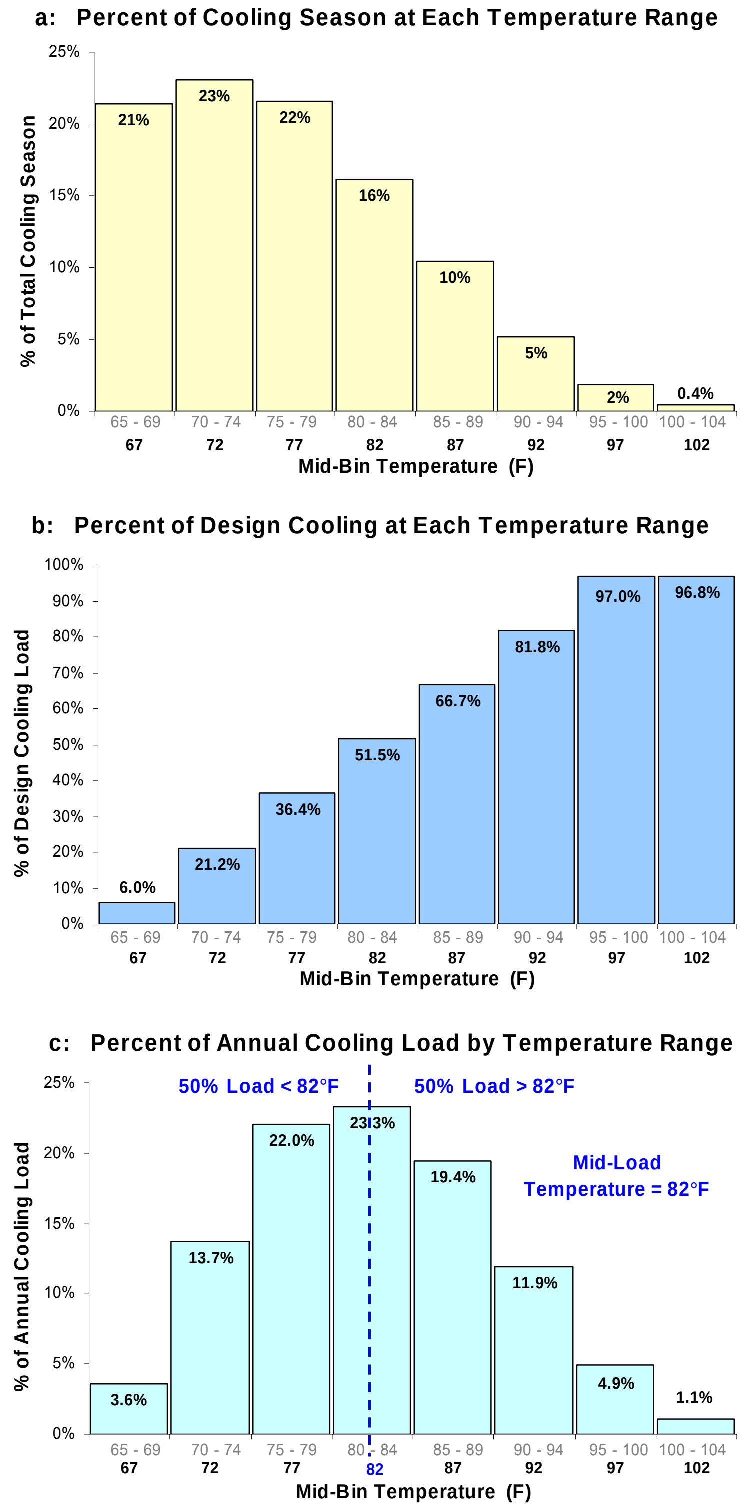
The process of sequential examination of the issues that affect SEER is expected to produce a set of SEER adjustments to be used to modify SEER to account for conditions not accounted for in the SEER ratings process. System demand information will be examined in parallel with SEER adjustments.

3.1 SEER RATING METHODOLOGY ASSUMPTIONS

Several assumptions implicit in the SEER rating process, described previously in Section 2.1, may not be realistic for California buildings and climates. Figure 2.1.1, which illustrates several of the key assumptions used in the SEER rating calculation methodology, is repeated below for convenience as Figure 3.1.1. This section examines the validity of these assumptions for typical California residential buildings across all sixteen California climate zones.

Figure 3.1.1*

Key Climate and Load-Related Assumptions Implicit in the SEER Rating Procedure
Derivation of the 82°F "Mid-load" Temperature



** same as Figure 2.1.1*

Figure 3.1.1a illustrates the assumed range and distribution of outdoor temperatures during the cooling season used as the basis for the SEER ratings methodology. The building balance point is assumed to be 65°F (the minimum temperature indicated in Figure 3.1.1). The SEER calculation procedure assumes no cooling is required below 65°F. Figure 3.1.1a also illustrates that the most extreme cooling temperature is assumed to be 104°F. This range of cooling season temperatures, from 65°F to 104°F, is divided into five degree bins with the midpoint temperature for each indicated. Note that the SEER rating procedure treats these temperatures as integers. For example, one of the five degree bins covers temperatures from 80°F up to and including 84°F (80°F ≤ bin < 85°F, not 80°F ≤ bin ≤ 85°F). This makes 82°F the midpoint temperature for that bin (i.e., not 82.5°F).

Figure 3.1.1b illustrates the assumed relationship between design cooling coil load and outdoor temperature, i.e., cooling load is a linear function of outdoor temperature, from 65°F (the building balance point) and 99°F, which represents the outdoor temperature for which the system's capacity was designed (more specifically, the system was assumed to be designed to have 10% excess capacity at 99°F). While this assumption of a simple and linear relationship between cooling coil load and only outdoor air and is consistent with the energy analysis methodologies in use at the time the SEER rating procedure was developed (i.e., "bin" methods), it ignores numerous other factors that contribute to cooling coil load, and which are included in detailed simulation tools such as DOE-2 (the simulation modeling tool used for this analysis).

Figure 3.1.1c illustrates the distribution of the seasonal (i.e., annual) cooling coil load assumed by the SEER rating procedure. Seasonal cooling coil loads in Figure 3.1.1c were calculated from the assumed distribution of outdoor temperatures in Figure 3.1.1a and the design cooling load represented in Figure 3.1.1b, i.e., number of cooling hours at each temperature bin (derived from Figure 3.1.1a) times the cooling coil load for each bin (from Figure 3.1.1b). The outdoor temperature that separates the total annual (seasonal) cooling coil load into two equal quantities is the "mid-load" temperature of 82°F. In other words, in the SEER rating procedure exactly half of the annual cooling coil load is assumed to occur at outdoor temperature below 82°F.

Figure 3.1.2 illustrates how well the assumed outdoor air temperature distribution from Figure 3.1.1a matches the distribution of long-term average outdoor temperatures for each of the sixteen California climate zones plus the overall California average and the average based on selected major urban centers, i.e., climate zones CZ 3 (Oakland), CZ 6 (Long Beach), CZ 7 (San Diego), and CZ12 (Sacramento). In Figure 3.1.2, the dark blue vertical bars represent the relative frequency distribution of outdoor temperatures in California climate zones. The orange curve represents the same relative frequency for outdoor temperatures assumed by the SEER rating procedure (i.e., in Figure 3.1.1a). While most of the vertical axes in Figure 3.1.2 use a constant scale, those that differ are shown in color (i.e., orange). These results suggest that climate zones 10 and 12 are closet to the distribution of outdoor temperatures assumed in the development of SEER.

Figure 3.1.3 illustrates how well the assumed annual distribution of cooling coil loads from Figure 3.1.1c matches distributions for each of the sixteen California climate zones and the overall California average. In Figure 3.1.3, the cooling coil distributions were prepared using the same assumptions as for Figure 3.1.1c, i.e., a simple linear relationship between cooling load and

Figure 3.1.2
Distribution of Cooling Season Outdoor Temperature
California Climate Zones vs. SEER rating assumption

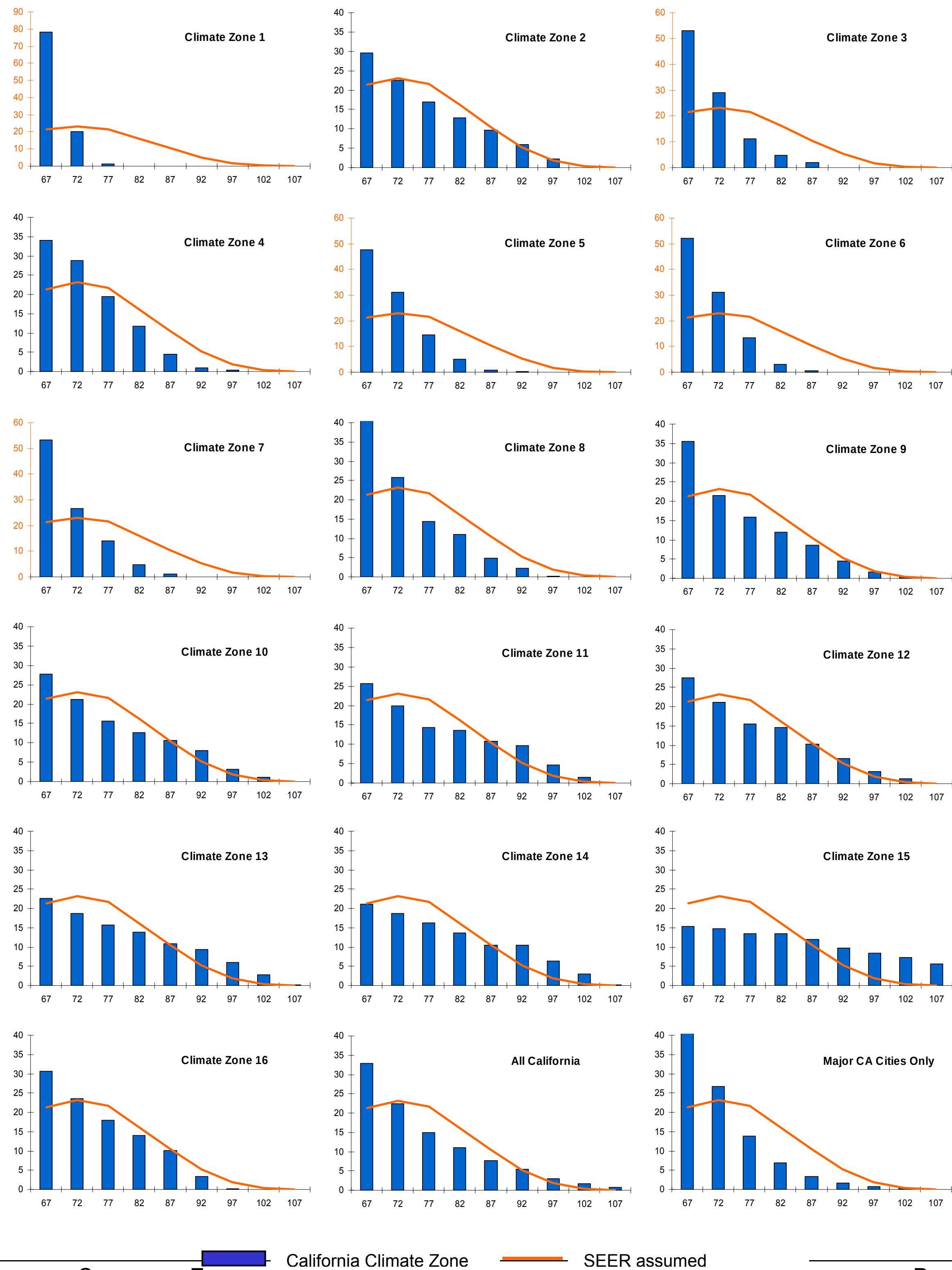
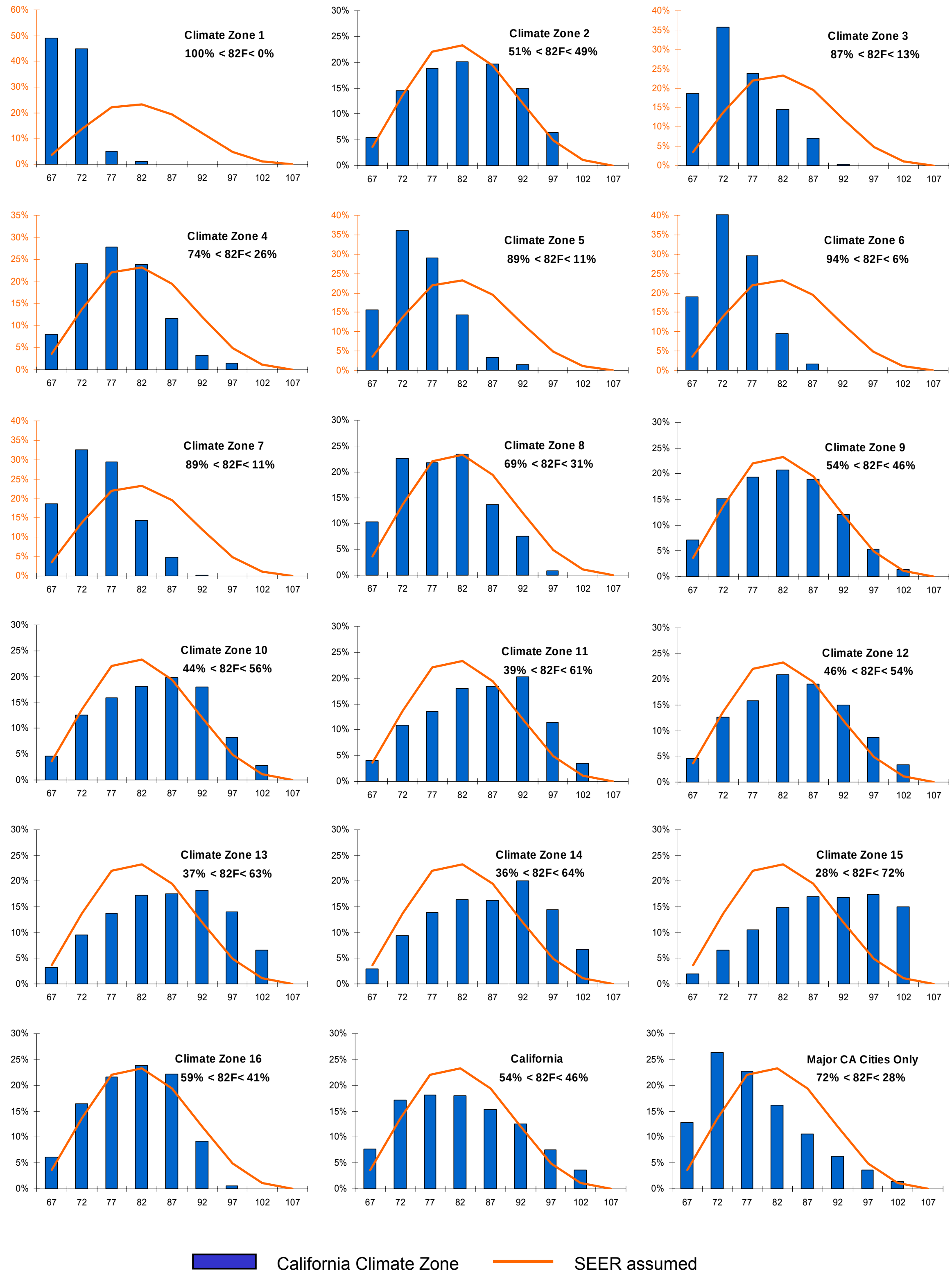


Figure 3.1.3
Distribution of Cooling Coil Load by California Climate Zones
(simple linear cooling load function assumed in the SEER ratings procedure)



outside air temperature, but substituting the California-specific outdoor temperature distributions in place of the distribution illustrated in Figure 3.1.1a, to calculate the coil load profile. Under these assumptions, climate zones 9 and 12 most closely match the distribution of coil loads assumed in the development of SEER. In Figure 3.1.3, each climate zone's distribution is also annotated to indicate what percentage of the annual coil load occurs above and below 82°F. Ideally, the distribution would divide perfectly at 50/50%, above and below 82°F.

Figure 3.1.4 also examines the distribution of annual cooling coil loads but uses coil load distributions generated using DOE-2 where the prototype is a statistically typical single-family one-story house. While many of the characteristics are taken to be median values from the 2000 RMST database, they also vary by climate zone as necessary to meet 2001 Title-24 requirements. Consistent with the RMST database, windows are not evenly distributed on all four orientations. Rather, the glass is primarily located at the "front" and "back" of the house. In Figure 3.1.4, the windows are assumed to face east and west. As in the previous figure, climate zones 9 and 12 appear to most closely match the distribution of cooling coil loads assumed during the development of the SEER rating procedure.

Figure 3.1.5 is the same as Figure 3.1.4 except that the house is rotated 90 degrees so that the windows face north and south. Again, climate zones 9 and 12 appear to most closely match the distribution of cooling coil loads assumed during the development of the SEER rating procedure.

Figure 3.1.2 through 3.1.5 illustrate how reasonable the SEER assumed national average distribution of outdoor temperatures (Figure 3.1.1a) and coil loads (Figure 3.1.1c) is when applied in California's climate zones. These illustrate that the departures from the temperature and load distribution assumptions implicit in the SEER rating procedure can be significant.

Figure 3.1.1b above illustrated the simple linear relationship between outdoor temperature and load implicit in the SEER rating procedure. Figure 3.1.6 illustrates the role various climate factors, as well as building design features, has on cooling coil load. The data in Figure 3.1.6 are a full year of simulated hourly cooling coil loads plotted against the outdoor temperature at which each hourly load occurred. They were generated using the DOE-2 model of the median single-family one-story house used in Figure 3.1.5 (i.e., a north-south orientation). Climate zone 9 was selected for all cases illustrated in Figure 3.1.6 since it most closely matched the mid-load temperature assumptions implicit in SEER.

Figure 3.1.6A illustrates a simulation case in which there is demonstrated a significantly linear relationship between hourly cooling coil load and outdoor temperature. The slope of the line in Figure 3.1.6A represents the overall U-value for the house. The point at which the line meets the X-axis (zero cooling coil load) represents the balance point of the house.

Figure 3.1.4
Distribution of Cooling Coil Load by California Climate Zones
(median single family residence, DOE-2 cooling loads, East-West Orientation)

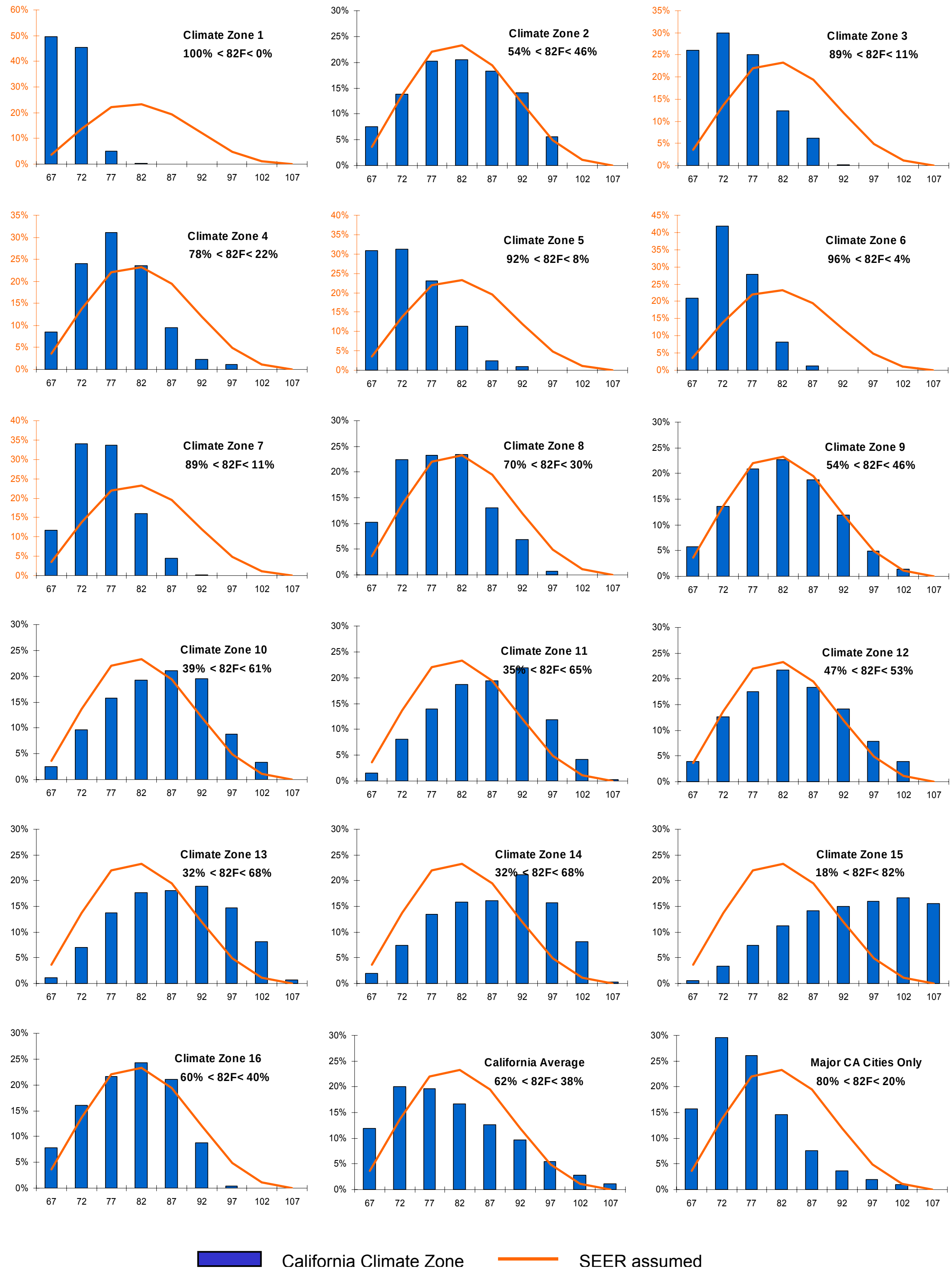


Figure 3.1.5
Distribution of Cooling Coil Load by California Climate Zones
(median single family residence, DOE-2 cooling loads, <u>North-South Orientation</u>)

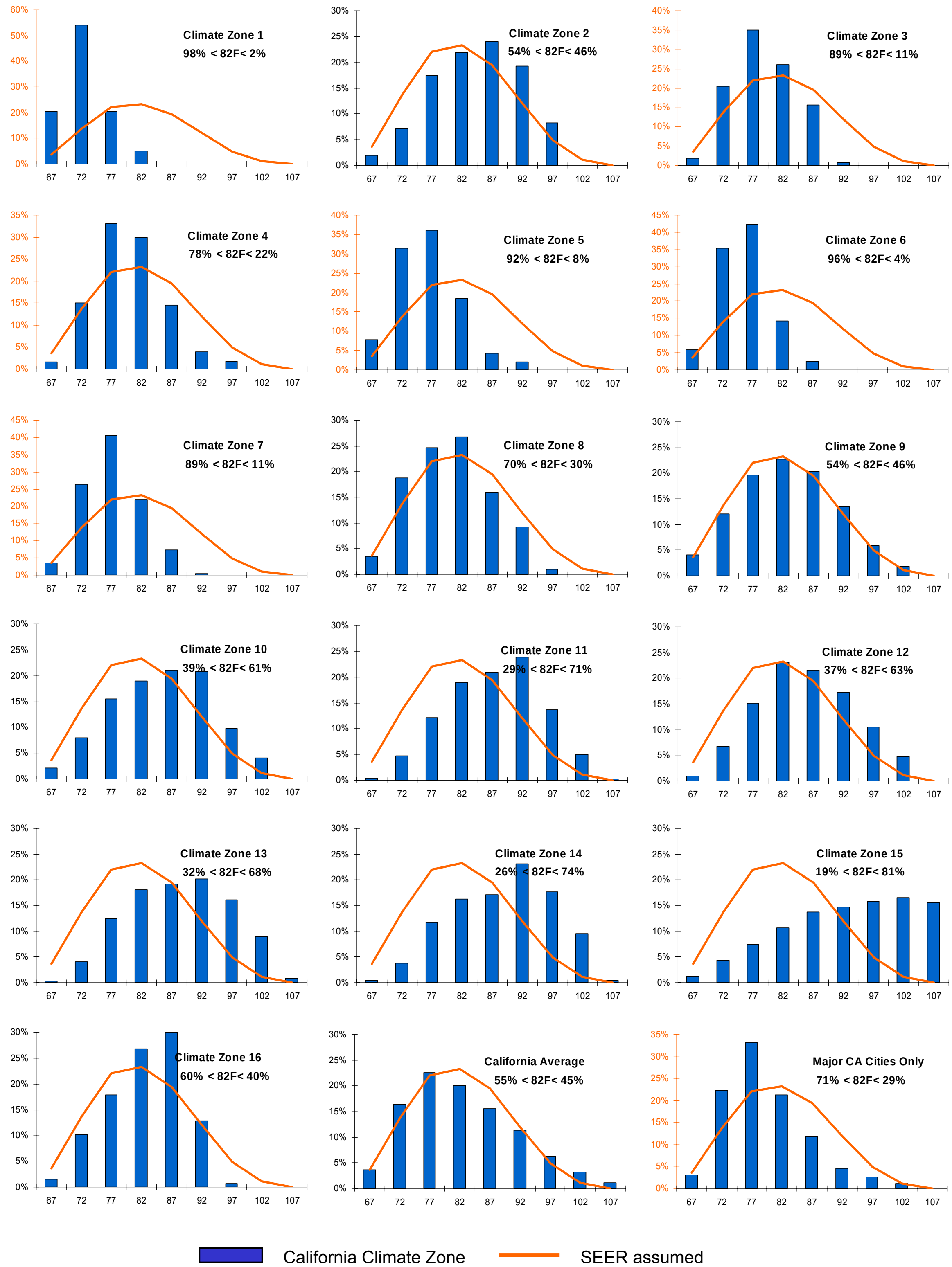
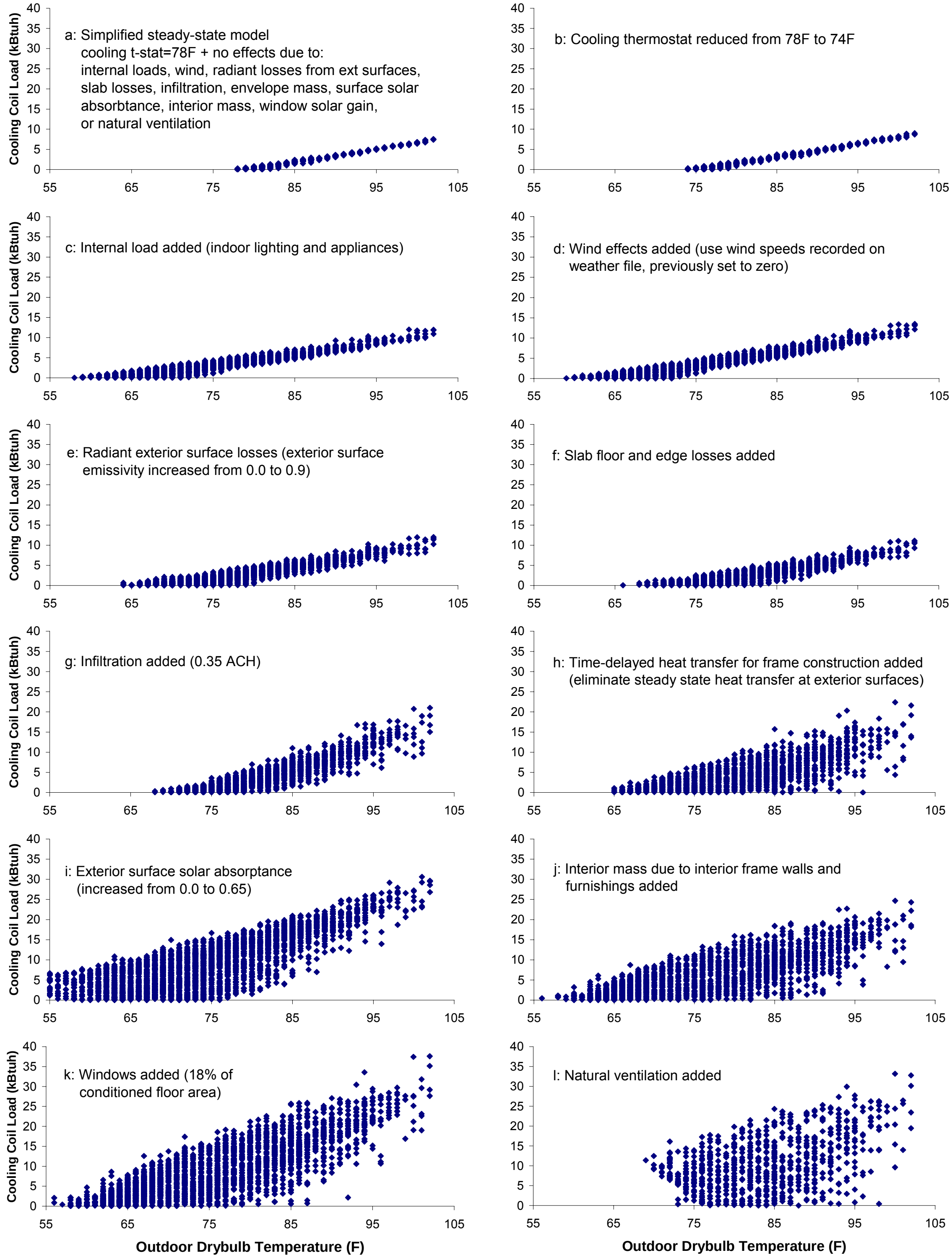


Figure 3.1.6
Cooling Coil Load as a Function of Outdoor Temperature
(median single family residence, DOE-2 cooling loads, North-South Orientation)



Obtaining the straight line relationship between hourly cooling coil load and outdoor temperature illustrated in Figure 3.1.6A required numerous simplifications to the DOE-2 prototype and simulation procedure. Each of the cases included in Figure 3.1.6, other than the first one, i.e., Figure 3.1.6B through 3.1.6L, represent separate annual simulation results in which one important climate or house design variable, omitted from Figure 3.1.6A was added back into the model. Each new run adds a climate or house design variable to the previous runs, i.e., the effects are cumulative, such that the last case, Figure 3.1.6L, includes all effects omitted from Figure 3.1.6A. Figure 3.1.6L represents a much more realistic representation of the relationship between outdoor temperature and hourly cooling coil load than does Figure 3.1.6A. Contrasting Figure 3.1.6A with 3.1.6L illustrates how differently cooling coil loads for typical house behave than is assumed by the assumptions implicit in the SEER rating procedure and suggests reasons to anticipate potentially large variability in the ability of SEER to accurately predict cooling energy use in California applications.

Each simulation case in Figure 3.1.6 is briefly described below.

a) This is the simplest modeled case. It was devised to obtain a significantly linear relationship between in cooling coil load and outdoor temperature, similar to that which is implicit in the SEER rating procedure (compare Figure 3.1.1a). Numerous features of the more detailed (and realistic) model (case L) are omitted in this case. These include: cooling t-stat = 78F + no effects due to: internal loads, wind, radiant losses from ext surfaces, slab losses, infiltration, envelope mass, surface solar absorbtance, interior mass, window solar gain, or natural ventilation. In this first case, note that since there is no internal heat gains and no solar gains, the balance point is equal to the indoor thermostat set point (i.e., 78°F). The slope of the line is related to the building overall U_0.

b) Cooling thermostat was altered from 78°F in case A to 74°F. As should be expected, this shifts the balance point lower by 4°F, to 74°F.

c) Internal loads due to interior lights and appliances are added to case B. Since these internal heat gains become “trapped” in the house, the balance point is shifted lower yet to approximately 57°F.

d) Wind effects are “turned on”, i.e., wind speeds from the CZ09 weather file are used in the simulation. In the previous cases, wind speed was set to zero for all hours. The impact if this is small. It provides some cooling effects that cause a slight shift in the balance point (i.e., to approximately 57°F). It also “blurs” slightly (i.e., introduces additional variability into) the linear relationship between coil load and outdoor temperature.

e) Long wave radiant exchange at exterior surfaces is “turned on”, i.e., the exterior surface emissivity for all exterior walls and roof surfaces are reset from 0 to 0.9. The impact of this is similar to the effect due to wind, but more significant, i.e., it provides some cooling effects that cause a slight shift in the balance point (i.e., to approximately 64°F). It also further “blurs” slightly the linear relationship between coil load and outdoor temperature.

f) Slab edge losses are “turned on”. Similar to the previous two effects, this adds a further source of heat loss slighting raising the balance point.

g) Infiltration, at a constant 0.35 air changes per hour, is added to case E. Due to the prior inclusion of internal loads, in case G, there are numerous cooling load hours when the outdoor temperature is cooler than the indoor temperature, hence, infiltration provides a cooling effect. Note that the general slope of the load-temperature relationship has increased (become steeper) due to a significant additional means of heat loss).

h) All exterior heat transfer surface constructions (i.e., walls and roofs) are converted from u-values (implies a steady-state $U \cdot A \cdot \Delta T$ calculation in the simulation) to use conduction transform functions (i.e., accounts for the time delay associated with the thermal mass of the roof and walls). All roof and wall construction are conventional wood frame. The u-values used in all previous cases were equivalent to the "delayed" constructions used in this and subsequent cases. The time delay of the heat gains through the envelope to the space further "blurs" the original straight line relationship between coil load and outdoor temperature.

i) Solar absorptance was "turned on" at each exterior heat transfer surface, i.e., exterior surface solar absorptance was reset from 0 to 0.6 for roof and 0.7 for walls. This had the effect of adding additional heat gain to the space, hence the balance point decreased. Since solar gain is only very loosely correlated with outdoor temperature, this modification further blurs the relationship between coil load and outdoor temperature.

j) Interior mass was "turned on" by using custom weighting factors in DOE-2 to calculate the unique contribution of the house interior walls and other surrounding surfaces plus furnishings to the overall capacitance (i.e., mass) of the spaces. In the previous runs, the DOE-2 "floor weight" was set to 1 lb/ft^2, thus providing virtually instantaneous response between surface heat gain and space cooling load.

k) Windows are added, predominantly on the north and south walls (18% of the conditioned floors area). This adds more heat gain, which both lowers the balance point (although more modestly due to the effect of internal mass) and further corrupts the original relationship between load and outdoor temperature.

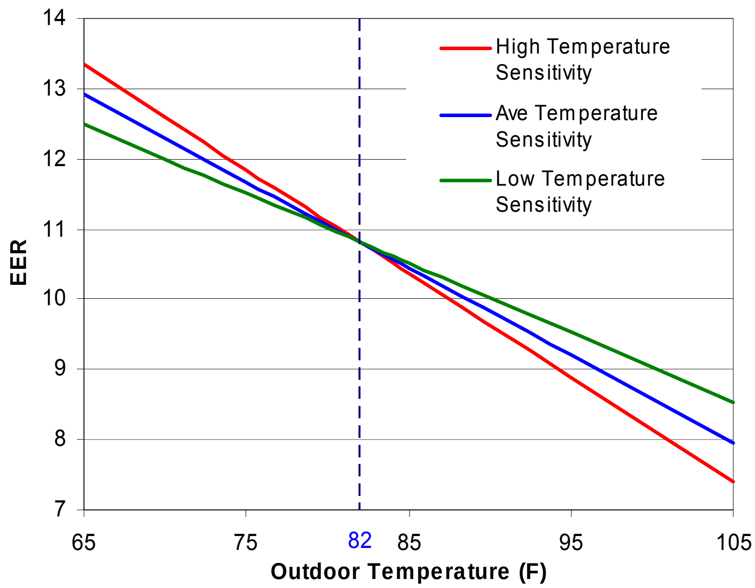
l) Natural ventilation is enabled via the operable windows. This assumes a constant air change rate of 3 ACH whenever the indoor cooling load could be met using natural ventilation. If the entire cooling load could not be met using natural ventilation, else the model assumed the windows were closed and the air conditioner was used to meet the cooling loads. The impact of natural ventilation is greatest on the coil loads that coincided with cooler outdoor temperatures, i.e., less than the 74°F thermostat temperature. The sloped boundary of the remaining cooling loads (i.e., starting at the X-axis near 74°F and toward the upper left) indicates that for hours with larger cooling loads, a greater temperature difference was necessary to provide the required cooling via natural ventilation to completely meet the load.

Figure 3.1.7 (same as Figure 2.1.2) illustrates another key assumption implicit in the SEER rating procedure, that the efficiency of the cooling process is linear with outdoor temperature. An important caveat for this involves at least two important assumptions regarding indoor (evaporator) and outdoor (condenser) fans:

- The energy from both fans is included in the overall SEER rating and is generally assumed to be a relatively small and relatively constant portion of the total system energy requirements.
- More importantly, both fan are assumed to cycle with the compressor, hence, fan energy is also assumed to be a linear function of outdoor temperature.

Figure 3.1.7

System Performance-Related Assumptions Implicit in the SEER Rating Procedure
Efficiency (EER) Sensitivity to Temperature



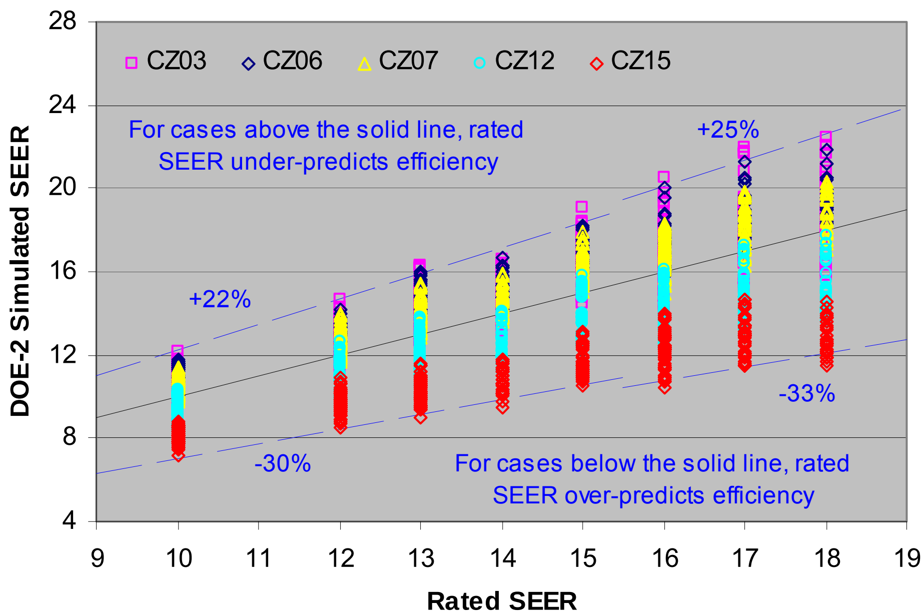
When the system fan is constant volume and cycles with the compressor, the typical case for residential applications, the fan energy is a relatively constant fraction of total system cooling energy. Actually, as compressor efficiency decreases with warmer temperatures, fan energy becomes a smaller fraction of the total, but the effect is small. Where system fans are constant volume and do not cycle with compressor operation (i.e., run continuously during occupied hours to provide ventilation), fan energy use has no relationship with outdoor temperature. While condenser unit energy (i.e., compressor + condenser fan) still tends to be linear with outdoor temperature, the continuous indoor fan represents a constant that represents a potentially very large fraction of the total system energy (e.g., in milder climates).

3.2 ANALYSIS FINDINGS

3.2.1 Results Across Range of Climate Zones, Building Configurations, and Systems

Results of the detailed computer simulations for the range of single-family building prototypes used in conjunction with a range of HVAC systems are shown in Figure 3.2.1. The figure compares the rated SEER with that calculated via DOE-2 simulations. The DOE-2 simulated SEER is equal to the net cooling provided by the system divided by the total cooling system energy consumption. Net cooling is the reported gross cooling load less fan heat. The total cooling energy is that consumed by the condenser unit, the indoor fan, and (if required by the cooling system) crankcase heat. Crankcase heat for heat pumps is not typically included, as the heaters are required for proper operation of the system as a heating system. It is included for air conditioners and/or heat pumps if it is included as part of the standard, or rated, cooling system configuration. Results are presented for the five climate zones (CZ03, CZ06, CZ07, CZ12, and CZ15) examined in this phase of the study. Simulations of the HVAC systems include both air conditioners and heat pumps in each SEER range (10, 12, 13, 14, and 15 single-speed units and SEER 16, 17 and 18 two-speed).

Figure 3.2.1
Calculated vs. Rated SEER
Single Family Building Prototype, Representative California Climates
Full Range of Building and HVAC System Characteristics



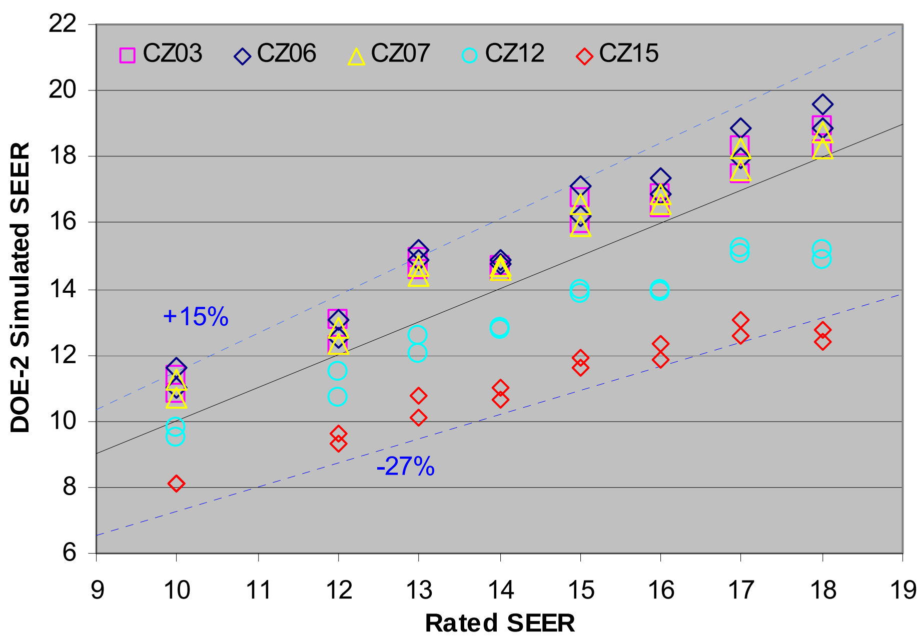
Figures 3.2.1 illustrates that rated SEER, without regard to location, building characteristics, or system details, is a poor predictor of annual residential energy use, even if seasonal loads are well known. One should expect that applying rated SEER to seasonal loads estimates could result in a 30% under prediction to a 22% over prediction of seasonal electrical energy consumption for single-speed equipment. This expands to +25% to –33% for two-speed equipment. The following sections identify and quantify the impact of various issues that lead to the variation in seasonal cooling system efficiency. This is done by looking at climate, building

characteristics, and system details in turn.

3.2.2 Median Building Configuration, Median Cooling System Performance

Results of the detailed computer simulations for single-family building prototypes used in conjunction with median system operation are shown in Figure 3.2.2. The figure compares the rated SEER with that calculated via DOE-2 simulations. The DOE-2 simulated SEER is equal to the net cooling provided by the system divided by the total cooling system energy consumption. Net cooling is the reported gross cooling load, less fan heat. The total cooling energy is that consumed by the condenser unit, the indoor fan, and (if required by the cooling system) crankcase heat. Crankcase heat for heat pumps is not typically included, as the heaters are required for proper operation of the system as a heating system. It is included for air conditioners and/or heat pumps if it is included as part of the standard, or rated, cooling system configuration. Results are presented for the five climate zones (CZ03, CZ06, CZ07, CZ12, and CZ15) examined in this phase of the study. Simulations of the single speed systems include both air conditioners and heat pumps in each SEER range (10, 12, 13, 14, and 15 single-speed units and SEER 16, 17 and 18 two-speed).

Figure 3.2.2
Calculated vs. Rated SEER
Single Family Prototype, Representative California Climates
Median Building Characteristics, Median System Characteristics



Simulation results indicate that a system's performance is highly dependent on climate conditions. A cooling system used in the same house, but located in different climate zones, should be expected to have seasonal efficiencies as much as 15% higher and 27% lower than rated values. Cooler climates (CZ03, CZ06, and CZ07) produce conditions that lead to higher SEER values. Hot climates (CZ15) produce significantly lower SEER values. Humidity conditions also affect SEER as they lead to coil entering conditions that differ from those assumed in the SEER ratings process. California is a relatively dry state (low ambient dew point temperatures). This will lead to seasonal performance that is lower than reflected in the rated SEER. Thus, the climate dependency of SEER shown in Figure 3.2.2 is a combination of outdoor temperature and coil entering conditions that differ from those assumed in the DOE ratings process.

Additionally, the difference between the sensitivity of the cooling systems to outdoor temperature and its sensitivity to coil entering conditions produces additional variation in simulated SEER. However, cooling system impact on SEER for systems used in this set of simulations is typically small in comparison to climate effects.

Figure 3.2.2 suggests that climate zone-specific SEER adjustments could correct for much of the difference between rated and simulated SEER. Adjustment factors based on median single-family building prototypes are provided in Table 3.2.1. The adjustments are rated-SEER multipliers. For example, a SEER 13 system being used in a single-family home in Climate Zone 3 could be expected to operate at a seasonal efficiency ratio of 14.4. The same system place on a typical home in Climate Zone 15 could expect to perform at a seasonal cooling efficiency ratio of 10.1. Different system load sequences affect different SEER-rated systems differently, and single-speed systems differently than two-speed systems. For this reason, climate zone adjustments are provided based on single or two-speed operation. Averaged multipliers are also provided for single-speed, two-speed and all systems. Given the lack of penetration of two-speed systems in the single-family market, the "All Single-Speed" multiplier should be used as a global adjustment factor for a given climate zone as opposed to that labeled as "All Units".

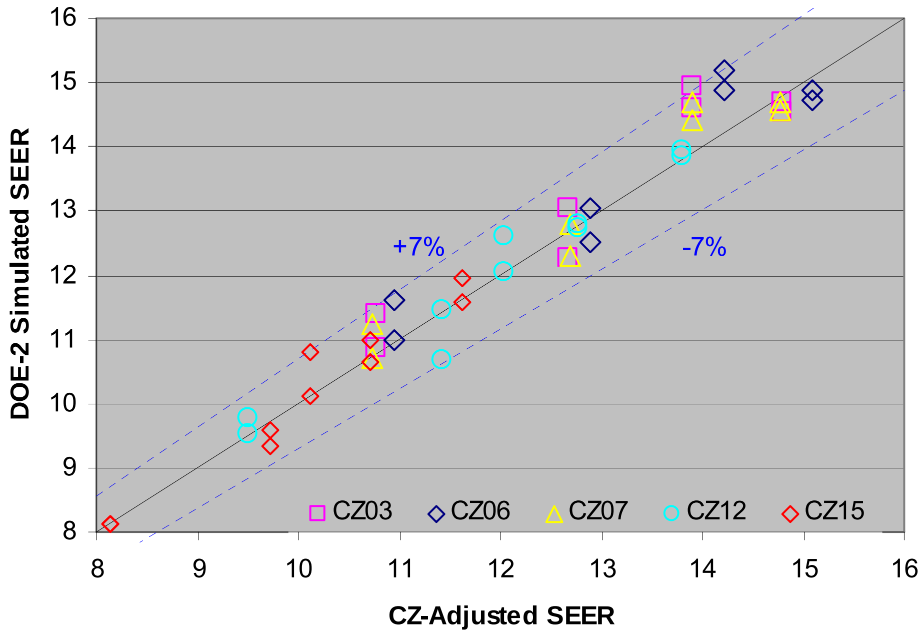
Table 3.2.1
SEER Climate Zone Multipliers
Single Family Prototype, Representative California Climates
Median Building Load, Median System Characteristics

	Single-Speed SEER Rating						Two-Speed SEER Rating				All Units
	10	12	13	14	15	All	16	17	18	All	
CZ03	1.08	1.06	1.08	1.07	1.09	1.08	0.95	1.06	1.03	1.03	1.04
CZ06	1.10	1.07	1.10	1.07	1.11	1.09	0.97	1.08	1.06	1.06	1.07
CZ07	1.08	1.06	1.07	1.06	1.08	1.07	0.95	1.05	1.04	1.03	1.04
CZ12	0.95	0.95	0.93	0.91	0.92	0.93	0.82	0.88	0.90	0.84	0.87
CZ15	0.81	0.81	0.78	0.77	0.78	0.79	0.72	0.74	0.74	0.70	0.73

** Multipliers assume rated fan energy and system sizing consistent with the SEER ratings procedure. Both issues are likely to impact SEER rating and are addressed later.*

Figure 3.2.3 illustrates the impact of climate zone and system specific multipliers on SEER. The rated SEER is adjusted by multipliers provided in Table 3.2.1 and compared to calculated values. Differences between climate zone-adjusted SEER and calculated values are reduced to ±7% from the +15% and -27% range that should be expected without the correction. Similar climate zone adjustments will be developed for the remaining climate zones later in this analysis process.

Figure 3.2.3
Calculated vs. Climate Zone-Adjusted SEER
Single Family Prototype, Representative California Climates
Median Building Characteristics, Median System Characteristics



3.2.3 Expanded Building Configuration, Median Cooling System Performance

The impact of building design on SEER was determined by varying the building features used to define the single-family prototype. These features, as described in Section 2.1.2, were varied through their minimum, median, and maximum values. Features that resulted in an increase in simulated SEER were noted, as were those that led to a decrease in simulated SEER. In this manner, a series of design features were found that produced minimum and maximum simulated SEER values for each particular climate zone. Table 3.2.2 provides a summary of features that produced an increase or decrease in simulated SEER resulting from an increase in their value.

As the table illustrates, features that increase SEER in one climate zone can cause a decrease in SEER in another. It is also important to note that the combination of features that leads to a higher SEER do not necessarily result in a reduction of annual cooling energy. Features that increase SEER can (and typically do) also lead to higher coil loads and higher seasonal energy consumption in spite of the increase in SEER.

The spread in SEER resulting from changes in building parameters is given in Figure 3.2.4. For clarity, results are given only for Climate Zone 6 (mild climate zone) and Climate Zone 15 (hottest climate zone) as these tend to bound the extremes of the total variation in results. Fiduciary lines indicating expected deviation from rated SEER as provided in Figures 3.2.1 and 3.2.2 are included for reference.

The median values shown in Figure 3.2.4 are the same as those given in Figure 3.2.2. The "Max" and "Min" SEER values represent building configurations that maximize and minimize

SEER for that particular climate zone. The scatter in simulated SEER about the median is similar for both climate zones and is representative of the other three climate zones examined in this phase of the analysis.

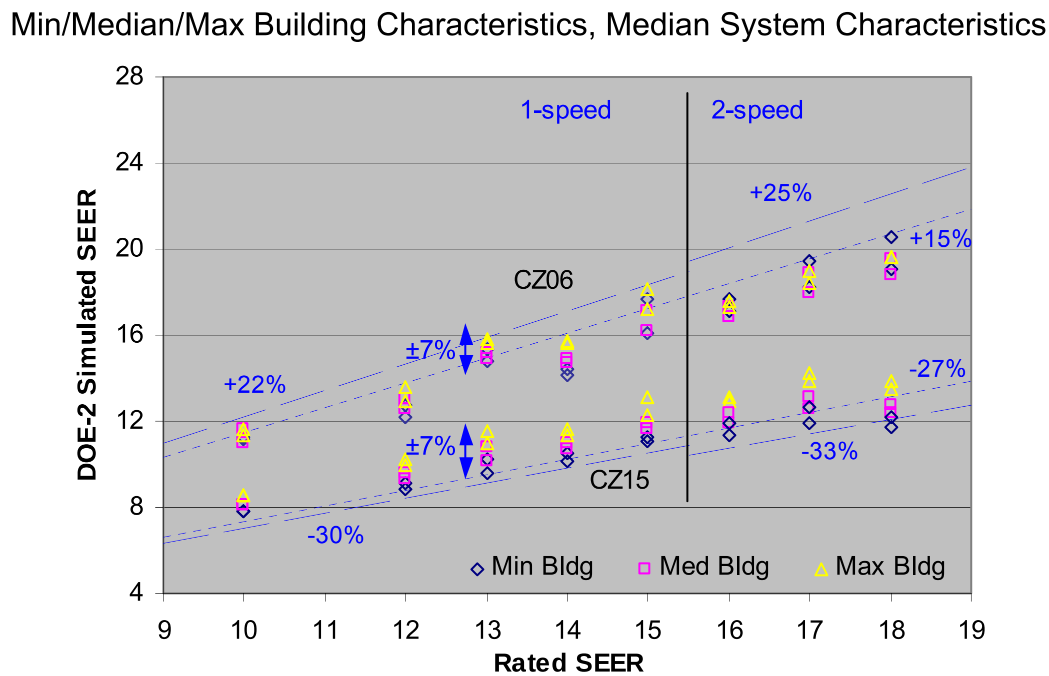
Table 3.2.2
Building Parameters Affecting SEER[1]
Affect on SEER Because of an Increase in Parameter Value

	CZ03	CZ06	CZ07	CZ12	CZ15
Total Floor Area	Lower	Lower	Lower	Lower	Lower
Number of Stories	None	None	None	None	None
Aspect Ratio	None	None	None	None	None
Occupancy[2]	Lower	Lower	Lower	Lower	Lower
Internal Gains	Higher	Higher	Higher	Higher	Higher
Cath Roof Frac	None	None	None	None	None
Floor Type	None	None	None	None	None
Glass Area	Higher	Lower	Lower	None	Higher
Glass U-value	Lower	Lower	Lower	Lower	Lower
Glass SC	Higher	Lower	None	Higher	Higher
Wall U-value	None	Higher	Higher	Higher	Higher
Roof Insul	None	None	None	None	None
Crawlspace Insul	None	None	None	None	None
Slab Insul	None	None	None	None	None
Duct Leakage	Higher	Higher	Higher	Higher	Higher
Duct Insul R-Value	Higher	Higher	Higher	Higher	Higher
Shading Level	Lower	Higher	None	Lower	Lower
Infiltration ACH	Higher	Higher	Higher	None	Lower
Natural Ventilation	Lower	None	Lower	Lower	Lower
Cool T'stat SP	Higher	Higher	Higher	Higher	None
Cool T-stat Setup	Lower	Lower	Lower	Lower	Lower

Notes:

1. *Changes in values that lead to an increase in simulated SEER do not necessarily result in lower total seasonal energy use.*
2. *Occupancy levels are given in terms of square foot per person. Thus, an increase in occupancy level results in fewer occupants in the space.*

Figure 3.2.4
Affect of Building Characteristics on Simulated SEER
Single Family Prototype, Representative California Climates



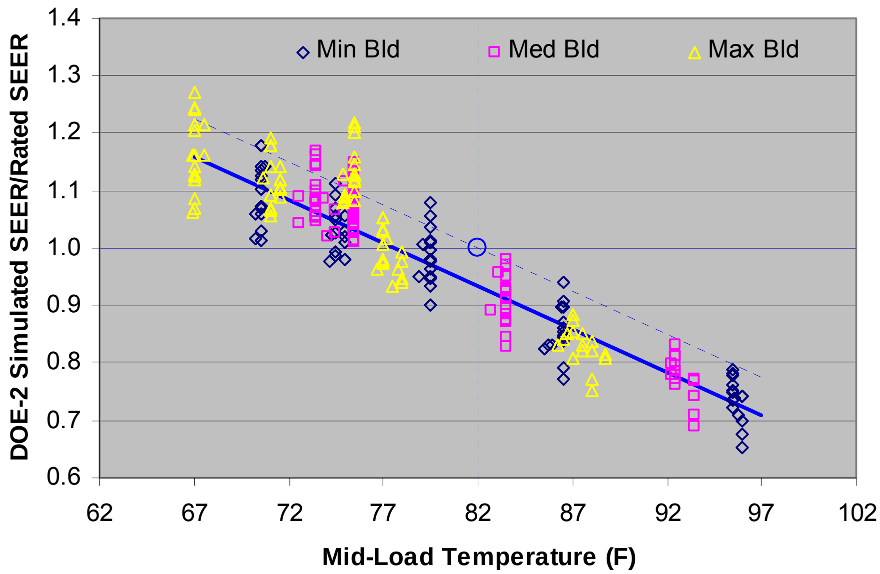
The impact of building features on SEER can also be illustrated via the mid-load temperature. The mid-load temperature is the outdoor temperature below and above which half of the seasonal cooling operation occurs (see Sections 2.1 and 3.1). For the SEER rating process, 82°F outdoor temperature is assumed to be the national average mid-load temperature. To mirror this approach, mid-load temperatures were captured for all DOE-2 simulations used to produce simulated SEER values. The relationship between simulated SEER and mid-load temperature is shown in Figure 3.2.5.

In Figure 3.2.5, the vertical axis is the ratio of simulated-to-rated SEER, which is equivalent to the SEER multipliers given in Table 3.2.1. Use of this ratio allows all systems in all climate zones to be presented in one figure. Simulation results are color-coded based on whether they are associated with building features that produce minimum, median, or maximum simulated SEER. All three graphs in Figure 3.2.5, (a), (b), and (c), present the same data. They differ only in how the data are color-coded.

The benefit of plotting the data in this way is that mid-load temperature includes both climate effects (i.e., the outdoor temperature portion of climate effects) and the effect of building parameters on SEER. The climate conditions and building features that lead to lower mid-load temperatures tend to result in higher SEER values. This is because, on average, the compressor is operating at a lower outdoor temperature over the cooling season. SEER increases since condensing is accomplished more efficiently at lower outdoor temperatures. Conversely, climate or building features that lead to an increase in the mid-load temperature tend to cause a decrease in SEER since the condenser, on average, is operating during warmer outdoor temperatures.

Figure 3.2.5
DOE-2 Simulated SEER / Rated SEER vs. Mid-Load Temperature
Single Family Expanded Prototype, Representative California Climates
Min/Median/Max Building Characteristics, Median System Characteristics

a: by Building Min/Median/Max Characteristics



b: by Climate Zone

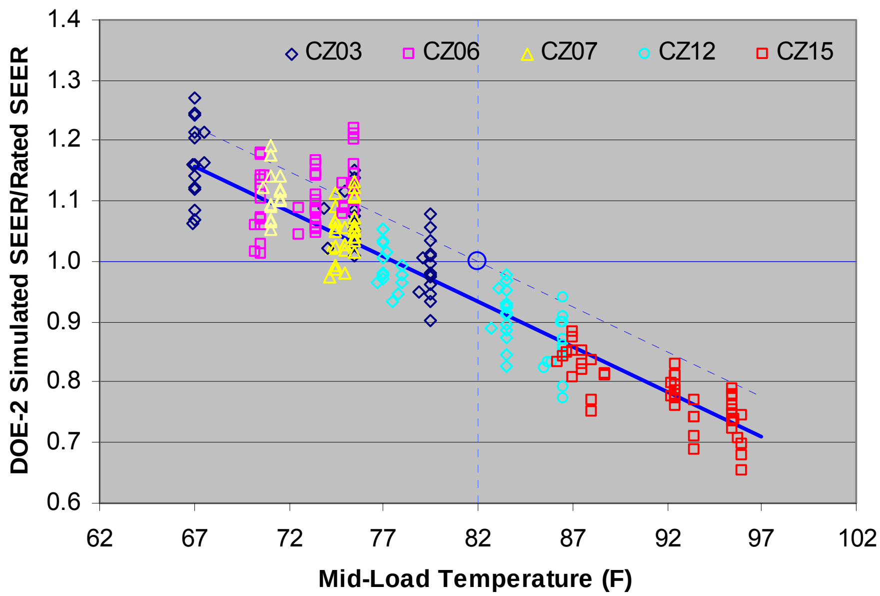
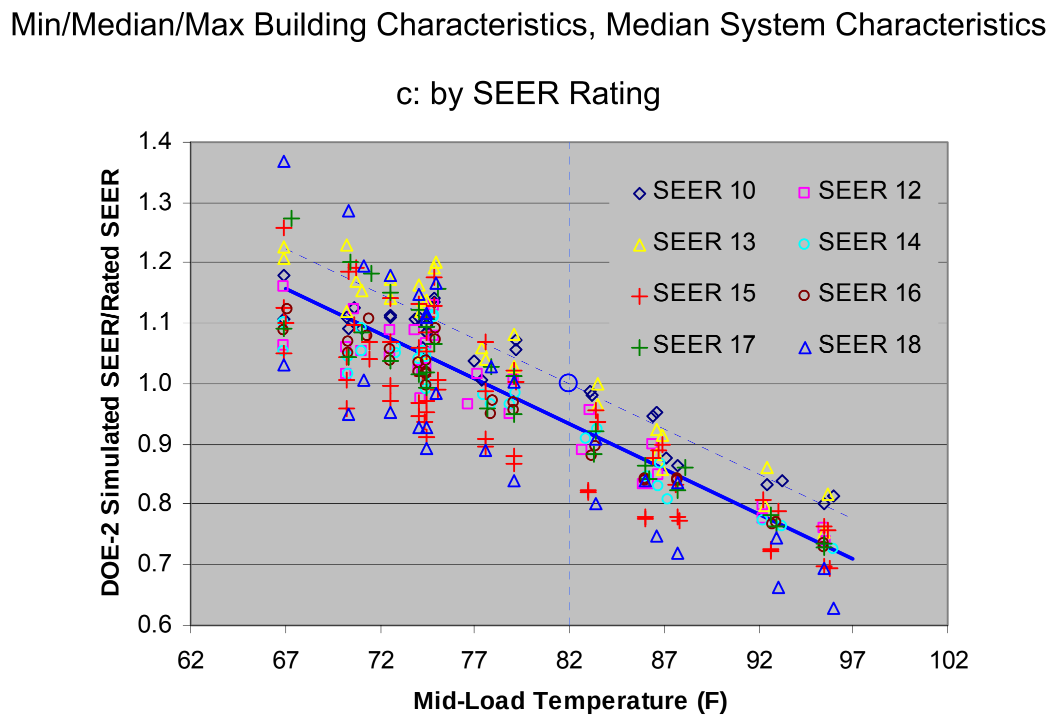


Figure 3.2.5 (continued)
DOE-2 Simulated SEER / Rated SEER vs. Mid-Load Temperature
Single Family Expanded Prototype, Representative California Climates



The scatter with respect to the x-axis (i.e., mid-load temperature) in Figure 3.2.5 is caused by climate and building characteristics. Figure 3.2.5b distinguishes the data by climate zone. Figure 3.2.5a distinguishes the data by building characteristics (high, medium, and low SEER-producing characteristics). For a given mid-load temperature, the vertical scatter in Figure 2.3.5 is caused by differences in the sensitivity of various cooling systems to outdoor temperature and coil entering conditions. This is a result of design features of each system and the refrigerant used (R-410 is inherently more sensitive to outdoor temperature changes than R-22).

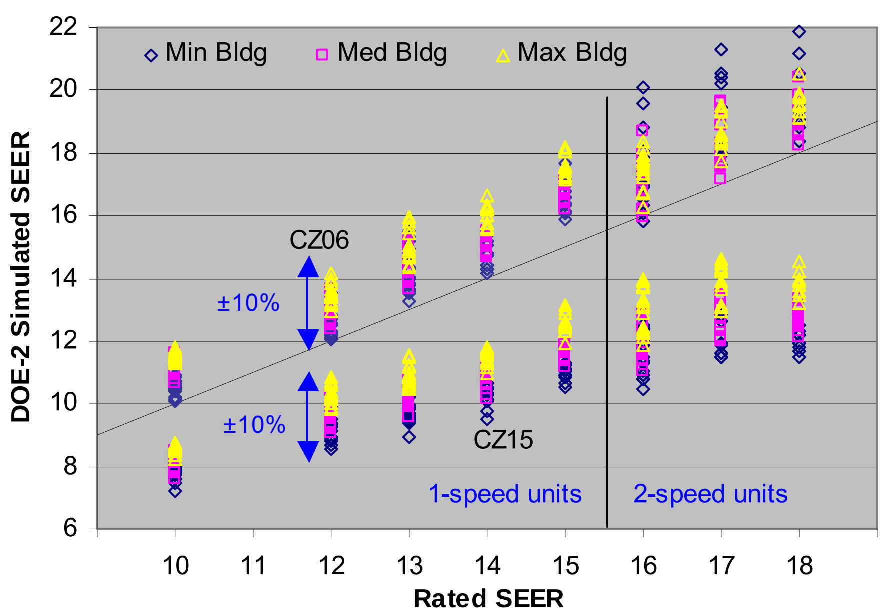
In Figure 3.2.5a, note that a best fit line (solid blue) does not pass through the point where DOE-2 simulated SEER divided by rated SEER equals 1.0 at 82°F. Rather, it passes through the simulated SEER = rated SEER horizontal line for a mid-load temperature of approximately 77°F. The downward shift of the best fit line, relative to the 82°F mid-load temperature point (the open blue circle in Figure 3.2.5a) is due, at least in part, to the influence of coil entering conditions, i.e., typical indoor wet-bulb temperatures lower than 67°F assumed in the SEER rating process. Cooling coil entering wet-bulb mid-load temperature was collected along with the outdoor dry bulb mid-load temperature. Typical cooling coil entering wet-bulb conditions in California are less that 62° F, not the 67° F used in ratings tests. For most residential cooling system, a 62° F coil entering wet-bulb is where dry coil conditions begin. System efficiency is 5% to 10% lower under dry coil conditions than at rated conditions (67° F coil entering wet-bulb). Lower humidity levels throughout the state leads to a 5% to 10% reduction in SEER. This is a statewide effect that is not particularly climate zone dependent.

3.2.4 Expanded Cooling System Performance

Median cooling systems used in prior two sections were selected because they were found to have mid-level performance characteristics of systems with like SEER. For example, the rated EER of the systems were near the middle of the range illustrated in Figure 2.3.1. The systems were not selected for their EER, but the selection criteria led to mid-range EERs. The actual selection criteria used to select the various systems were their EER sensitivity to outdoor temperature (EER Slope) and cycling loss coefficient (degradation coefficient C_D). The selection process is described in detail in Appendix B. The use of median values assures that a system selected at random will differ from the median system in an equal fashion. That is, a randomly selected system is as likely to have an EER temperature sensitivity that is higher than the median system than it is to have one lower. The same can be said of the likelihood of the system's C_D being higher or lower than the median system.

As a next phase in the analysis, the number of cooling systems was expanded beyond the median systems. DOE-2 performance maps were generated for additional systems to span the expected range of EER slope and C_D for a given SEER rating (from high to low temperature sensitivity in combination with high to low values of C_D). This selection process leads to the EER/SEER variation illustrated in Figure 2.3.1. The additional systems were then simulated using building features that produce minimum, median, and maximum simulated SEER values as described in Section 3.2.2. Simulation results for the minimum, median, and maximum building prototype and five climate zones are shown in Figure 3.2.6. Results for expanded building configurations are shown in Figure 3.2.7 (for comparison to Figure 3.2.4) for Climate Zones 6 and 15.

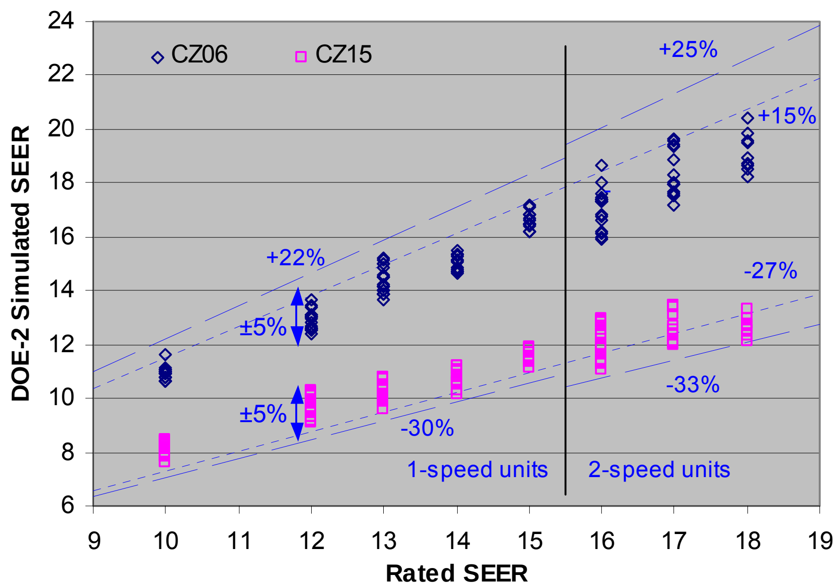
Figure 3.2.6
Simulated SEER vs. Rated SEER
Expanded Building and Equipment Prototypes – CZ06 & CZ15



The expansion of simulation cases to include different cooling systems leads to a further increase in the variation in simulated SEER. This is illustrated by comparing Figure 3.2.4 to 3.2.6. What was a ±7% variation in simulated SEER over the range of building characteristics expands to a ±10% to 12% variation. This variation is on the order of the difference from one rated SEER value to another (10 to 11, or 13 to 14, etc.). For higher SEER, two-speed units, this represents almost two SEER ratings points.

Figure 3.2.7 is a replication of Figure 3.2.6 with maximum and minimum SEER conditions caused by changes in building features removed. This allows a comparison of systems as if they were all applied to the same home operated under the same conditions. Figure 3.2.7 illustrates that the most widely held assumption related to SEER rating is incorrect. Those involved with the SEER rating process generally agree that SEER is not necessarily a good predictor of annual cooling energy consumption, even with reasonably accurate estimates of cooling loads. What is widely held is that SEER always reflects the relative efficiency of one system in comparison to another. That is, for a given application, a SEER 13 system is always more efficient than a SEER 12 system and less efficient than a SEER 14 system. Figure 3.2.7 indicates that this is not the case.

Figure 3.2.7
Simulated SEER vs. Rated SEER
Median Building and Expanded Equipment Prototypes



The expected scatter in simulated SEER resulting from differences in the performance characteristics of one system to another is approximately 5%. Thus, when selecting a SEER 13 rated system, one could only assume that it would operate at a seasonal efficiency between 12.4 and 13.7 (once climate and building operational effects are accounted for). A SEER 14 rated system applied in the same location to the same building could be expected to operate between a seasonal efficiency of 13.3 and 14.7. With only a standard SEER rating to differentiate the two, one could not be assured that the higher SEER-rated system would lead to lower annual cooling energy use as the expected SEER range overlaps between the two. Thus, SEER is neither an accurate measure of seasonal energy use nor a guaranteed ranking measure.

Previous results indicate potentially large uncertainties in using rated SEER to anticipate annual cooling energy use in residential applications in California climates. More frequently, SEER is used to anticipate the *reduction* in annual cooling energy when upgrading from an HVAC system with a lower SEER rating to a system with a higher SEER rating, e.g., from a SEER 12 system to a SEER 15. Table 3.2.3 and Figures 3.2.8 and 3.2.9 illustrate the results of upgrading from one SEER level to a higher SEER level. Five HVAC system upgrade cases were considered, e.g., SEER 10 to SEER 12, SEER 10 to SEER 14, etc.

The calculation of rated SEER-predicted savings may seem counter-intuitive for at least two reasons. First, to achieve a *reduction* in cooling energy consumption, SEER value must *increase*. Second, the percentage increase in SEER (see Equation 3.1) does NOT indicate the anticipated percent reduction in cooling energy (i.e., savings) due to SEER upgrade (Equation 3.2).

$$\left(\frac{SEER14}{SEER10}\right) - 1 = 1.40 - 1 = 0.40 \text{ (or a 40\% improvement in SEER)} \quad (3.1)$$

$$1 - \left(\frac{\frac{1}{SEER14}}{\frac{1}{SEER10}}\right) = 1 - \left(\frac{SEER10}{SEER14}\right) = 1 - 0.714 = 0.286 \text{ (or a 29\% reduction in energy use)} \quad (3.2)$$

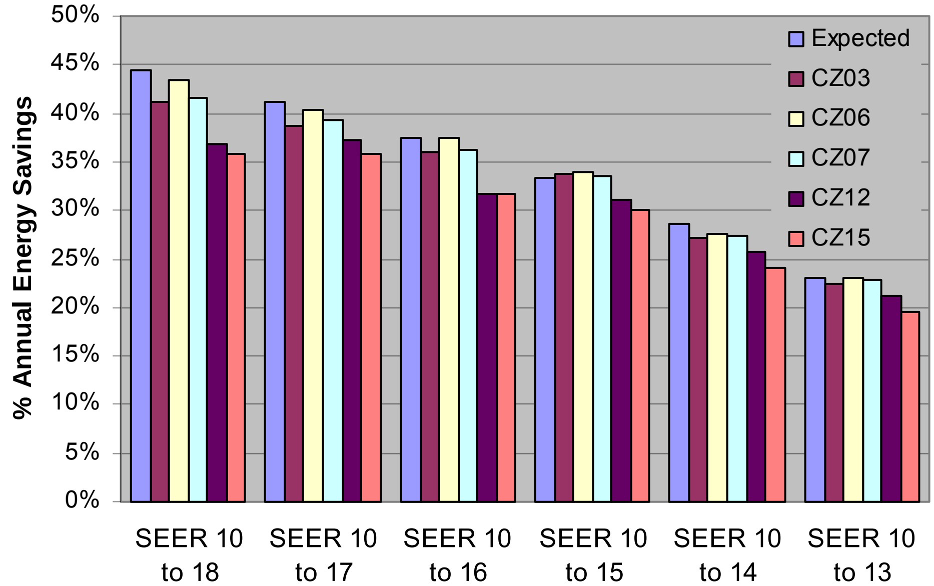
∴ a 20% improvement in SEER yields a 17% expected reduction in annual cooling energy use

Table 3.2.3 compares the maximum, median and minimum energy savings associated with moving to a higher SEER to that expected from the change in SEER rating. Values shown in the table are an average of savings from air conditioners and heat pumps. The upgrades assumed no fuel switching, i.e., no changing form air conditioners to heat pumps of visa versa. No consistent difference between savings for heat pump and air conditioners was evident. Savings in Table 3.2.3 are from simulation results based on the median building prototype. Subsequent figures illustrate the impact of expanding from median to maximum and minimum building prototypes.

Median annual energy savings associated with moving to a higher SEER-rated system are shown in Figures 3.2.8a and b, by climate zone. The figures illustrate the impact of climate zone on energy saving. Median energy savings tend to be slightly less for the hotter climate zones (CZ12 and CZ15) than for the cooler climates (CZ03, CZ06, and CZ07).

Figure 3.2.8
Percentage Savings Achieved by SEER Upgrade
Results by Climate Zone
Min/Median/Max Systems, Min/Median/Max Building Prototypes

a: Upgrade from a Vintage SEER 10 System



b: Upgrade from a SEER 13 System

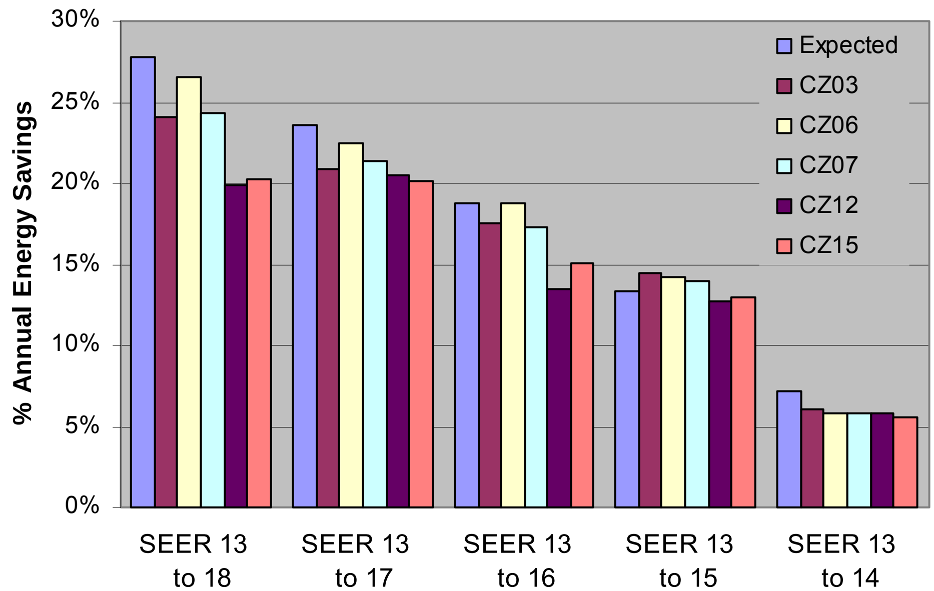


Table 3.2.3
Energy Benefits of Moving to a Higher SEER
Maximum, Median, and Minimum Building Type, All Systems

a: Climate Zone 03

CZ03

SEER Change	Percentage Decrease in Seasonal Cooling Energy			
	Expected	Maximum	Median	Minimum
SEER 10 to 18	44%	47%	41%	35%
SEER 10 to 17	41%	45%	39%	32%
SEER 10 to 16	38%	42%	36%	27%
SEER 10 to 15	33%	38%	34%	28%
SEER 10 to 14	29%	32%	27%	21%
SEER 10 to 13	23%	30%	23%	15%
SEER 10 to 12	17%	24%	15%	7%
SEER 12 to 18	33%	38%	31%	22%
SEER 12 to 17	29%	36%	28%	18%
SEER 12 to 16	25%	32%	25%	12%
SEER 12 to 15	20%	27%	22%	14%
SEER 12 to 14	14%	20%	14%	4%
SEER 12 to 13	8%	18%	9%	-2%
SEER 13 to 18	28%	32%	24%	15%
SEER 13 to 17	24%	29%	21%	11%
SEER 13 to 16	19%	26%	17%	3%
SEER 13 to 15	13%	20%	14%	6%
SEER 13 to 14	7%	12%	6%	-4%
SEER 14 to 18	22%	28%	19%	14%
SEER 14 to 17	18%	25%	16%	9%
SEER 14 to 16	13%	21%	12%	2%
SEER 14 to 15	7%	14%	9%	4%
SEER 15 to 18	17%	20%	11%	5%
SEER 15 to 17	12%	16%	7%	0%
SEER 15 to 16	6%	12%	4%	-8%
SEER 16 to 18	11%	22%	8%	-3%
SEER 16 to 17	6%	19%	4%	-8%
SEER 17 to 18	6%	16%	4%	-8%

b: Climate Zone 06

CZ06

SEER Change	Percentage Decrease in Seasonal Cooling Energy			
	Expected	Maximum	Median	Minimum
SEER 10 to 18	44%	48%	43%	37%
SEER 10 to 17	41%	46%	40%	34%
SEER 10 to 16	38%	43%	37%	27%
SEER 10 to 15	33%	40%	34%	28%
SEER 10 to 14	29%	31%	27%	21%
SEER 10 to 13	23%	31%	23%	15%
SEER 10 to 12	17%	22%	15%	6%
SEER 12 to 18	33%	40%	33%	26%
SEER 12 to 17	29%	37%	30%	22%
SEER 12 to 16	25%	34%	26%	14%
SEER 12 to 15	20%	30%	22%	16%
SEER 12 to 14	14%	20%	15%	7%
SEER 12 to 13	8%	20%	9%	0%
SEER 13 to 18	28%	34%	26%	16%
SEER 13 to 17	24%	30%	23%	12%
SEER 13 to 16	19%	27%	19%	3%
SEER 13 to 15	13%	23%	14%	4%
SEER 13 to 14	7%	12%	6%	-6%
SEER 14 to 18	22%	29%	22%	16%
SEER 14 to 17	18%	25%	18%	12%
SEER 14 to 16	13%	21%	14%	3%
SEER 14 to 15	7%	17%	9%	5%
SEER 15 to 18	17%	21%	14%	4%
SEER 15 to 17	12%	17%	10%	0%
SEER 15 to 16	6%	13%	5%	-11%
SEER 16 to 18	11%	22%	10%	-2%
SEER 16 to 17	6%	19%	5%	-6%
SEER 17 to 18	6%	14%	5%	-7%

c: Climate Zone 07

	SEER Change	Percentage Decrease in Seasonal Cooling Energy			
		Expected	Maximum	Median	Minimum
CZ07	*SEER 10 to 18*	44%	46%	42%	37%
	SEER 10 to 17	41%	45%	39%	33%
	SEER 10 to 16	38%	42%	36%	28%
	SEER 10 to 15	33%	37%	34%	29%
	SEER 10 to 14	29%	31%	27%	22%
	SEER 10 to 13	23%	29%	23%	17%
	SEER 10 to 12	17%	22%	15%	9%
	SEER 12 to 18	33%	37%	31%	25%
	SEER 12 to 17	29%	36%	28%	20%
	SEER 12 to 16	25%	31%	25%	14%
	SEER 12 to 15	20%	26%	22%	15%
	SEER 12 to 14	14%	19%	14%	7%
	SEER 12 to 13	8%	16%	9%	0%
	SEER 13 to 18	28%	31%	24%	17%
	SEER 13 to 17	24%	29%	21%	12%
	SEER 13 to 16	19%	25%	17%	6%
	SEER 13 to 15	13%	19%	14%	7%
	SEER 13 to 14	7%	11%	6%	-3%
	SEER 14 to 18	22%	26%	20%	15%
	SEER 14 to 17	18%	25%	17%	9%
	SEER 14 to 16	13%	20%	12%	3%
	SEER 14 to 15	7%	14%	9%	4%
	SEER 15 to 18	17%	19%	12%	6%
	SEER 15 to 17	12%	17%	9%	0%
	SEER 15 to 16	6%	12%	4%	-7%
	SEER 16 to 18	11%	20%	8%	-1%
	SEER 16 to 17	6%	18%	5%	-7%
	SEER 17 to 18	6%	14%	4%	-7%

d: Climate Zone 12

	SEER Change	Percentage Decrease in Seasonal Cooling Energy			
		Expected	Maximum	Median	Minimum
CZ12	*SEER 10 to 18*	44%	43%	37%	32%
	SEER 10 to 17	41%	43%	37%	30%
	SEER 10 to 16	38%	39%	32%	25%
	SEER 10 to 15	33%	36%	31%	27%
	SEER 10 to 14	29%	32%	26%	19%
	SEER 10 to 13	23%	29%	21%	15%
	SEER 10 to 12	17%	25%	17%	8%
	SEER 12 to 18	33%	33%	24%	17%
	SEER 12 to 17	29%	32%	25%	14%
	SEER 12 to 16	25%	28%	18%	8%
	SEER 12 to 15	20%	23%	17%	11%
	SEER 12 to 14	14%	19%	11%	1%
	SEER 12 to 13	8%	15%	5%	-4%
	SEER 13 to 18	28%	27%	20%	13%
	SEER 13 to 17	24%	26%	20%	10%
	SEER 13 to 16	19%	21%	14%	4%
	SEER 13 to 15	13%	17%	13%	6%
	SEER 13 to 14	7%	12%	6%	-3%
	SEER 14 to 18	22%	23%	15%	9%
	SEER 14 to 17	18%	22%	16%	6%
	SEER 14 to 16	13%	18%	8%	-1%
	SEER 14 to 15	7%	13%	7%	2%
	SEER 15 to 18	17%	15%	8%	4%
	SEER 15 to 17	12%	14%	9%	0%
	SEER 15 to 16	6%	9%	1%	-7%
	SEER 16 to 18	11%	18%	7%	-2%
	SEER 16 to 17	6%	17%	8%	-6%
	SEER 17 to 18	6%	12%	-1%	-8%

e: Climate Zone 15

	SEER Change	Percentage Decrease in Seasonal Cooling Energy			
		Expected	Maximum	Median	Minimum
	SEER 10 to 18	44%	43%	36%	30%
	SEER 10 to 17	41%	44%	36%	29%
	SEER 10 to 16	38%	41%	32%	23%
	SEER 10 to 15	33%	36%	30%	24%
	SEER 10 to 14	29%	32%	24%	16%
	SEER 10 to 13	23%	30%	20%	12%
	SEER 10 to 12	17%	26%	16%	7%
	SEER 12 to 18	33%	32%	23%	15%
	SEER 12 to 17	29%	33%	23%	14%
	SEER 12 to 16	25%	30%	18%	7%
	SEER 12 to 15	20%	24%	16%	8%
	SEER 12 to 14	14%	19%	9%	-2%
	SEER 12 to 13	8%	16%	4%	-8%
CZ12	*SEER 13 to 18*	28%	28%	20%	11%
	SEER 13 to 17	24%	29%	20%	10%
	SEER 13 to 16	19%	26%	15%	2%
	SEER 13 to 15	13%	20%	13%	3%
	SEER 13 to 14	7%	14%	6%	-7%
	SEER 14 to 18	22%	24%	15%	8%
	SEER 14 to 17	18%	25%	15%	7%
	SEER 14 to 16	13%	22%	10%	-1%
	SEER 14 to 15	7%	15%	8%	0%
	SEER 15 to 18	17%	16%	8%	1%
	SEER 15 to 17	12%	17%	8%	0%
	SEER 15 to 16	6%	14%	2%	-8%
	SEER 16 to 18	11%	17%	6%	-7%
	SEER 16 to 17	6%	18%	6%	-8%
	SEER 17 to 18	6%	10%	0%	-11%

Figure 3.2.9 illustrates the variation in energy savings from a SEER upgrade across all climate zones. Expected savings are shown in the left-most vertical bar (orange) for each upgrade case. This is the savings one would expect based on the SEER ratings, if SEER were a completely

reliable indicator of cooling energy consumption. Figure 3.2.9 also presents minimum, median, and maximum savings achieved (light blue, yellow, and green bars, respectively — read these bars against the LEFT axis). Figure 3.2.9a presents results considering upgrades from a vintage SEER 10 unit. In Figure 3.2.9b the upgrade cases are for an upgrade from a SEER 13 unit. The figures are based on median energy savings values over the 5 climate zones and building prototypes.

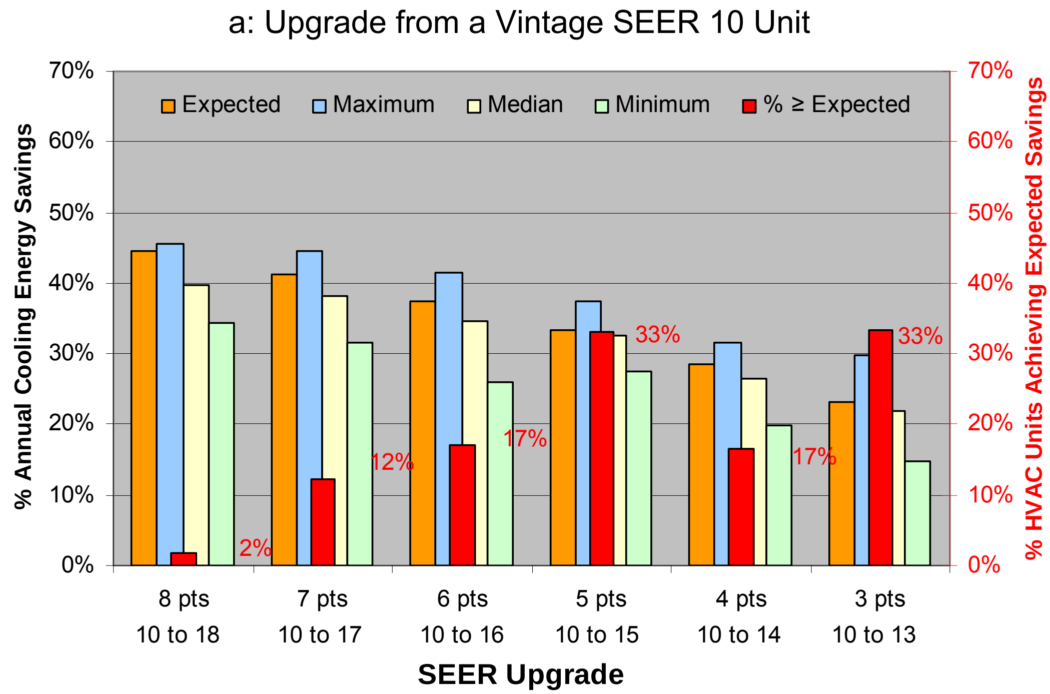
For all but a few upgrade cases, median simulated cooling energy savings falls short of the expected savings. The shortfall for upgrades of single-speed unit is typically less than 10% when averaged over the five climate zones. It is climate zone dependent as the warmer climates (climate zones 12 and 15) generate energy savings shortfalls as high as 20%. (see Figure 3.2.8a). Two-speed units are much less reliable in producing expected cooling efficiency with savings shortfalls typically double that of their single-speed counterparts.

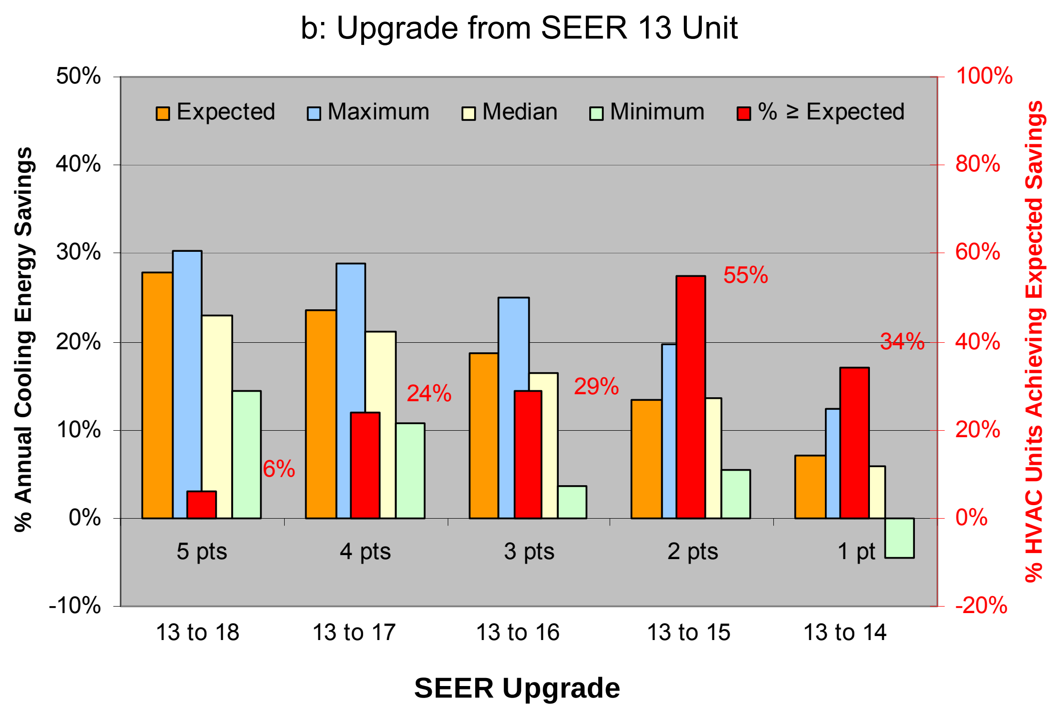
An additional result of particular interest in Figure 3.2.9 is indicated in red font and red vertical bars (read these bars against the RIGHT axis). These indicate the percentage of the simulated cases where the expected (i.e., SEER-predicted) level of savings was achieved or exceeded. Figure 3.2.9a indicates that, in upgrades from vintage SEER 10 units, 67% to 98% of the times consumers upgrade (one minus the red numbers reported in Figure 3.2.9a), their actual annual cooling energy savings will fall short of that indicated by changes in rated SEER. It is important to note that simulation results suggest that upgrades from a vintage SEER 10 unit to at least a SEER 13 unit will always produce energy savings, just not always the expected savings based the change in SEER rating. .

Figure 3.2.9b illustrates that upgrades beyond the current SEER 13 standard is not as reliable as upgrading from a vintage unit. Positive energy savings can be assured only for an upgrade to a SEER 15 single-speed unit (following the observation from above that it takes at leas a two SSER point upgrade to assure savings). Upgrading to higher SEER two-speed units can lead to significant energy savings for some units, but could cause a increase in cooling energy for others. Unfortunately, this effort hasn't identified a means of identifying beforehand which two-speed units offer the higher energy savings and which produce an increase in cooling energy.

It is important to note the simulation results presented in Figure 3.2.9 do not reflect statistically valid penetration rates. For example, the median savings for upgrades in Figure 3.2.9b implicitly give equal weight the savings results from the minimum, maximum, and median building prototypes cases. Similarly, for these results to best reflect the potential for savings in the California market, the representative cooling systems used in the simulations should be weighted by penetration rate in the California market. As is, the cooling systems are representative of products currently offered by major HVAC manufactures. It is best to consider the results in Figures 3.2.9a and 3.2.9b as bounding the actual savings.

Figure 3.2.9
Percentage Savings Achieved by SEER Upgrade
Min/Median/Max Systems, Min/Median/Max Building Prototypes





3.2.5 Cooling System Electric Demand

Peak cooling system electric demand was captured for each simulation. The relationship between system SEER and cooling demand is given in Figure 3.2.10 for Climate Zones 6 and 15 (coolest and hottest climates). DOE-2 simulated EER is equal to the nominal (ARI) cooling capacity of the system divided by the peak seasonal electric demand. (Cooling system peak electrical demand is found by multiplying the cooling system's nominal capacity by the DOE-2 simulated EER.) Results for Climate Zone 6 are shown as filled symbols; those for Climate Zone 15 as open symbols. It should be noted that the results are based on a sizing approach that is roughly equal to the use of an ASHRAE 1% cooling design temperature. System over sizing is addressed later.

Figure 3.2.10
DOE-Simulated EER vs. Rated SEER – CZ06 & CZ15
Single Family Residential Prototype, Climate Zones 6 (mild) and 15 (hot arid)
Min/Median/Max Building Characteristics, Min/Median/Max System Characteristics

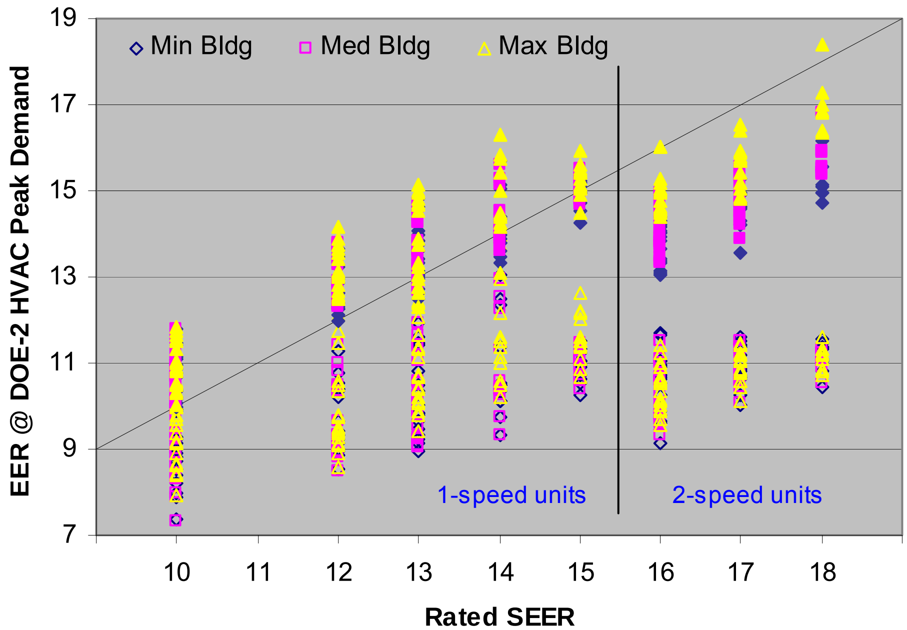
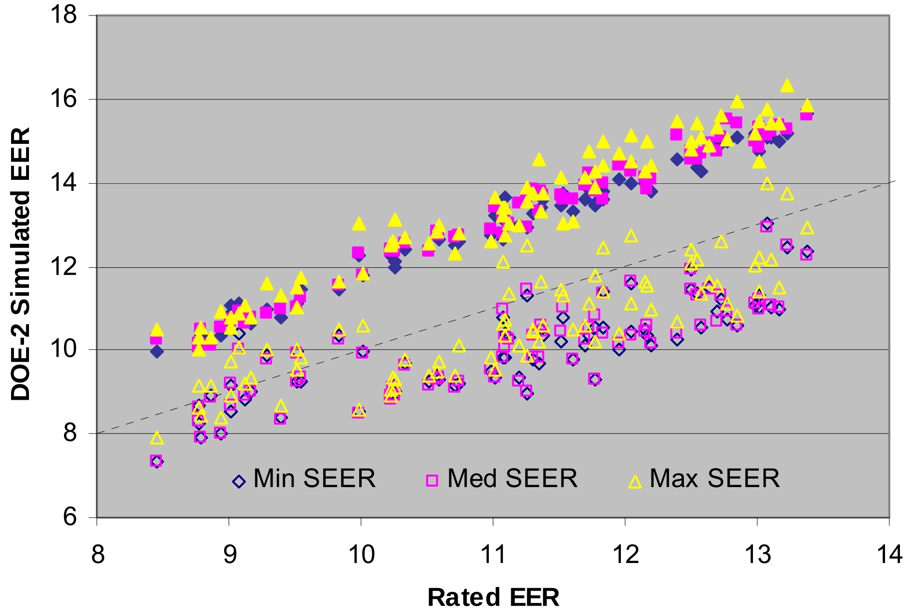


Figure 3.2.10 reinforces the common wisdom that SEER is a poor metric for predicting demand. Even when variations in weather and building characteristics are eliminated, simulations indicate that there are no guarantees that there will be any demand reduction when moving to a nest higher SEER level. Two-speed systems, as expected, impose cooling demands commiserate with their high-speed operation. This is typically similar to single-speed systems that are 2 SEER points lower than there two-speed counterparts.

Figure 3.2.11 shows the same results plotted against each system's rated EER, the standard metric for evaluating demand impacts. As with Figure 3.2.10, CZ06 results are shown as filled symbols and results for CZ15 are open symbols. While there is still a great deal of scatter, EER is a much better predictor of cooling system electric demand. Climate affects become obvious from the figure. Systems operating in cooler climates (CZ06) impose less electric demand than would be calculated using their rated EER. The same system used in a hotter climate zone (CZ15) produce cooling system electric demands that frequently exceed that which would be calculated based on their rated EER. Figure 3.2.11 includes two-speed systems, which become indistinguishable from their single-speed counterparts when rated EER is used as an indicator of peak HVAC system demand.

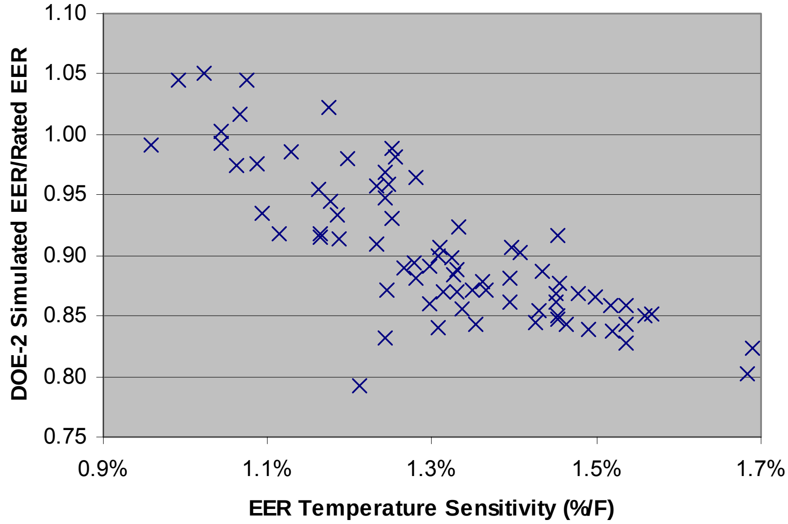
Figure 3.2.11
Operational EER vs. Rated EER – CZ06 & CZ15
Expanded Building and Expanded Equipment Prototypes



Scatter in DOE-2 simulated EER vs. the rated EER is more pronounced in the hotter climate zones (CZ 12 and CZ 15) than for the cooler (CZ03, CZ06, and CZ07). This appears to be caused by the outdoor conditions when the peak load occurs. In cooler climates, peak cooling loads occur at outdoor temperatures near the ARI 95ºF rating point. In hotter climates, the outdoor temperature is a good bit higher (115ºF to 120ºF for CZ15). Cooling systems differ in the way their cooling efficiency is affected by outdoor temperature. Systems that are more sensitive to increases in outdoor temperature will show a greater departure from their rated EER than those that are less sensitive. This is illustrated in Figure 3.2.12, which shows the impact of system temperature sensitivity on DOE-2 simulated EER for Climate Zone 15 simulations. The temperature sensitivity of the various systems can account for more than half of the scatter in the data shown in Figure 3.2.11. Figure 3.2.12 also implies that equipment-specific demand adjustments could be developed to better predict demand impacts from the rated EER‡. System temperature sensitivity can be determined from expanded ratings charts (preferred method) or EER_A and EER_B values determined during the SEER ratings process.

‡ Equipment-based adjustments were found to provide some improvement in demand estimates, as discussed in Section 4.4

Figure 3.2.12
Impact of Cooling System Temperature Sensitivity on Cooling Demand
(CZ15 Only)



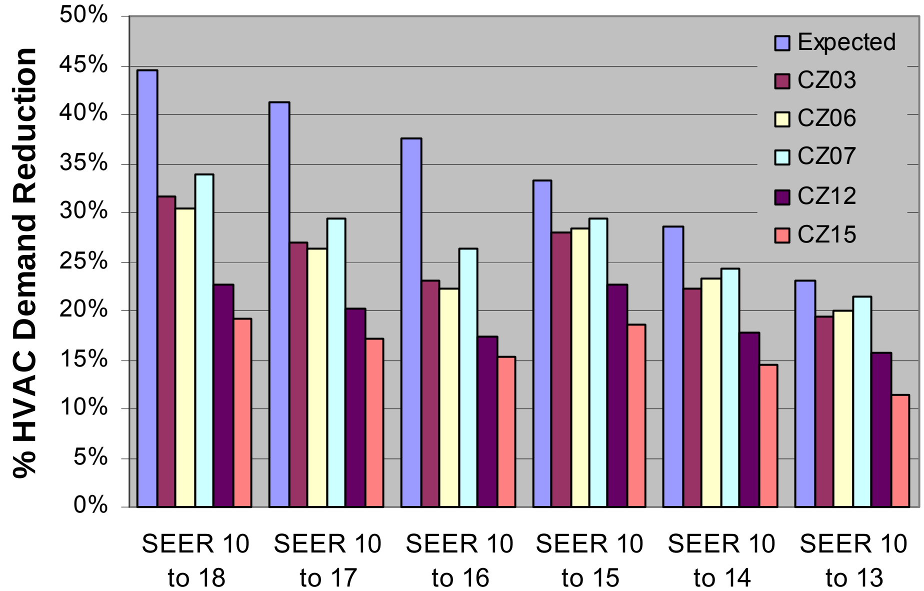
The overall demand benefits associated with moving to a higher SEER system are given in Table 3.2.5 for the median building prototype. The "Expected" demand reduction in the table is based on the SEER change.

One of the more notable finding is the minimum potential demand benefit of systems located in hotter climates (CZ12 and CZ15). If one were to randomly exhange one SEER-rated system for another, higher SEER level system, one could not be assured that demand would not increase unless one went up five SEER ratings points (from a SEER 10 to at least a SEER 15). EER is a better indicator of potential demand reduction, but can not guarantee demand savings because of differing system sensitivity to outdoor temperature (Figure 3.2.12).

Figures 3.2.14a and and b illustrate the variation in results across all climate zones. "Expected" values, shown in the left-most orange bar, are based on changes in the rated SEER. This is the demand reduction one would expect if changes in SEER level were a reliable indicator of changes in cooling system peak demand levels. Figure 3.2.14 also presents minimum, median, and maximum demand changes achieved (light blue, yellow, and green bars, respectively — read these bars against the LEFT axis). Figure 3.2.14a presents results considering upgrades from a vintage SEER 10 unit. In Figure 3.2.14b the upgrade cases are for an upgrade from a SEER 13 unit. The figures are based on median values over the 5 climate zones and for the building prototypes that produce minimum, median, and maximum simulated SEER values. The figures further illustrate problems with relying on SEER as an indicator of cooling system peak demands. Demand savings follow trends in expected savings for single-speed equipment (SEER 10 through 16), but not for two-speed equipment (SEER 16 through 18). For all SEER levels, relative changes in cooling system demand reduction fall far below that that indicated by changes in SEER.

Figure 3.2.13
Percentage Cooling HVAC Demand Reduction Achieved by SEER Upgrade
Results by Climate Zone
Min/Median/Max Systems, Min/Median/Max Building Prototypes

a: Upgrade from a Vintage SEER 10 System



b: Upgrade from a SEER 13 System

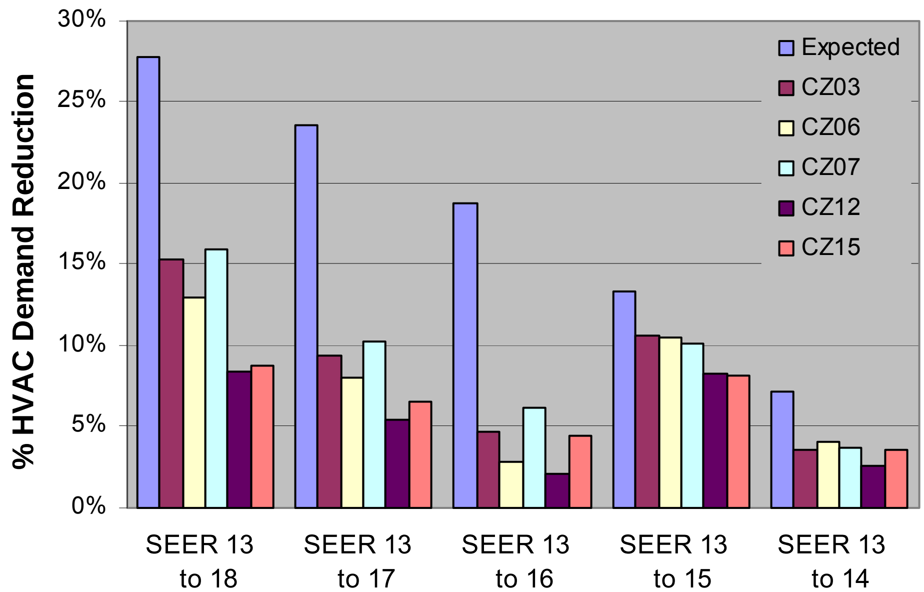


Table 3.2.4
Demand Reduction when Moving to a Higher SEER
Maximum, Median, and Minimum Building Type, All Systems

a: Climate Zone 03

	SEER Change	Percentage Decrease in Cooling System Peak HVAC Demand			
		Expected	Maximum	Median	Minimum
CZ03	*SEER 10 to 18*	44%	38%	32%	21%
	SEER 10 to 17	41%	34%	27%	15%
	SEER 10 to 16	38%	33%	23%	11%
	SEER 10 to 15	33%	35%	28%	19%
	SEER 10 to 14	29%	35%	22%	12%
	SEER 10 to 13	23%	31%	19%	6%
	SEER 10 to 12	17%	27%	16%	5%
	SEER 12 to 18	33%	25%	18%	6%
	SEER 12 to 17	29%	20%	13%	-2%
	SEER 12 to 16	25%	19%	8%	-7%
	SEER 12 to 15	20%	21%	14%	3%
	SEER 12 to 14	14%	21%	7%	-5%
	SEER 12 to 13	8%	16%	4%	-12%
	SEER 13 to 18	28%	23%	15%	1%
	SEER 13 to 17	24%	19%	9%	-7%
	SEER 13 to 16	19%	18%	5%	-12%
	SEER 13 to 15	13%	20%	11%	-1%
	SEER 13 to 14	7%	20%	4%	-10%
	SEER 14 to 18	22%	18%	12%	-5%
	SEER 14 to 17	18%	13%	6%	-13%
	SEER 14 to 16	13%	12%	1%	-19%
	SEER 14 to 15	7%	14%	7%	-8%
	SEER 15 to 18	17%	12%	5%	-5%
	SEER 15 to 17	12%	6%	-1%	-13%
	SEER 15 to 16	6%	5%	-7%	-19%
	SEER 16 to 18	11%	20%	11%	-3%
	SEER 16 to 17	6%	15%	5%	-11%
	SEER 17 to 18	6%	16%	7%	-4%

b: Climate Zone 06

CZ06

SEER Change	Percentage Decrease in Cooling System Peak HVAC Demand			
	Expected	Maximum	Median	Minimum
SEER 10 to 18	44%	41%	30%	21%
SEER 10 to 17	41%	36%	26%	15%
SEER 10 to 16	38%	33%	22%	12%
SEER 10 to 15	33%	35%	28%	19%
SEER 10 to 14	29%	36%	23%	11%
SEER 10 to 13	23%	32%	20%	6%
SEER 10 to 12	17%	27%	15%	4%
SEER 12 to 18	33%	27%	18%	7%
SEER 12 to 17	29%	21%	13%	1%
SEER 12 to 16	25%	18%	8%	-3%
SEER 12 to 15	20%	21%	15%	5%
SEER 12 to 14	14%	22%	9%	-4%
SEER 12 to 13	8%	17%	5%	-11%
SEER 13 to 18	28%	26%	13%	1%
SEER 13 to 17	24%	20%	8%	-7%
SEER 13 to 16	19%	17%	3%	-11%
SEER 13 to 15	13%	19%	11%	-2%
SEER 13 to 14	7%	20%	4%	-11%
SEER 14 to 18	22%	21%	9%	-5%
SEER 14 to 17	18%	14%	4%	-13%
SEER 14 to 16	13%	11%	-1%	-18%
SEER 14 to 15	7%	14%	7%	-8%
SEER 15 to 18	17%	14%	3%	-4%
SEER 15 to 17	12%	7%	-3%	-12%
SEER 15 to 16	6%	3%	-9%	-16%
SEER 16 to 18	11%	21%	10%	0%
SEER 16 to 17	6%	14%	5%	-8%
SEER 17 to 18	6%	17%	5%	-4%

c: Climate Zone 07

	SEER Change	Percentage Decrease in Cooling System Peak HVAC Demand			
		Expected	Maximum	Median	Minimum
CZ07	*SEER 10 to 18*	44%	40%	34%	23%
	SEER 10 to 17	41%	37%	29%	17%
	SEER 10 to 16	38%	37%	26%	15%
	SEER 10 to 15	33%	35%	29%	19%
	SEER 10 to 14	29%	36%	24%	14%
	SEER 10 to 13	23%	32%	21%	8%
	SEER 10 to 12	17%	28%	17%	4%
	SEER 12 to 18	33%	26%	21%	9%
	SEER 12 to 17	29%	22%	15%	2%
	SEER 12 to 16	25%	22%	11%	0%
	SEER 12 to 15	20%	20%	15%	5%
	SEER 12 to 14	14%	22%	9%	-2%
	SEER 12 to 13	8%	16%	5%	-9%
	SEER 13 to 18	28%	24%	16%	3%
	SEER 13 to 17	24%	19%	10%	-4%
	SEER 13 to 16	19%	19%	6%	-6%
	SEER 13 to 15	13%	17%	10%	-1%
	SEER 13 to 14	7%	19%	4%	-8%
	SEER 14 to 18	22%	18%	13%	-3%
	SEER 14 to 17	18%	13%	7%	-10%
	SEER 14 to 16	13%	13%	3%	-13%
	SEER 14 to 15	7%	11%	7%	-8%
	SEER 15 to 18	17%	13%	6%	0%
	SEER 15 to 17	12%	7%	0%	-8%
	SEER 15 to 16	6%	8%	-4%	-11%
	SEER 16 to 18	11%	17%	10%	-3%
	SEER 16 to 17	6%	12%	4%	-11%
	SEER 17 to 18	6%	15%	6%	-3%

d: Climate Zone 12

	SEER Change	Percentage Decrease in Cooling System Peak HVAC Demand			
		Expected	Maximum	Median	Minimum
CZ12	*SEER 10 to 18*	44%	36%	23%	10%
	SEER 10 to 17	41%	34%	20%	11%
	SEER 10 to 16	38%	32%	17%	3%
	SEER 10 to 15	33%	38%	23%	13%
	SEER 10 to 14	29%	35%	18%	7%
	SEER 10 to 13	23%	31%	16%	0%
	SEER 10 to 12	17%	29%	8%	-6%
	SEER 12 to 18	33%	26%	16%	-3%
	SEER 12 to 17	29%	23%	13%	-2%
	SEER 12 to 16	25%	22%	10%	-11%
	SEER 12 to 15	20%	28%	16%	1%
	SEER 12 to 14	14%	25%	10%	-7%
	SEER 12 to 13	8%	21%	8%	-15%
	SEER 13 to 18	28%	22%	8%	-7%
	SEER 13 to 17	24%	19%	5%	-6%
	SEER 13 to 16	19%	17%	2%	-16%
	SEER 13 to 15	13%	24%	8%	-3%
	SEER 13 to 14	7%	21%	3%	-11%
	SEER 14 to 18	22%	16%	6%	-13%
	SEER 14 to 17	18%	13%	3%	-13%
	SEER 14 to 16	13%	11%	-1%	-23%
	SEER 14 to 15	7%	18%	6%	-10%
	SEER 15 to 18	17%	10%	0%	-18%
	SEER 15 to 17	12%	7%	-3%	-17%
	SEER 15 to 16	6%	5%	-7%	-28%
	SEER 16 to 18	11%	20%	6%	-8%
	SEER 16 to 17	6%	17%	3%	-8%
	SEER 17 to 18	6%	13%	3%	-11%

e: Climate Zone 15

	SEER Change	Percentage Decrease in Cooling System Peak HVAC Demand			
		Expected	Maximum	Median	Minimum
CZ12	*SEER 10 to 18*	44%	36%	19%	1%
	SEER 10 to 17	41%	36%	17%	-4%
	SEER 10 to 16	38%	36%	15%	-12%
	SEER 10 to 15	33%	36%	19%	0%
	SEER 10 to 14	29%	43%	15%	-12%
	SEER 10 to 13	23%	38%	11%	-15%
	SEER 10 to 12	17%	36%	4%	-22%
	SEER 12 to 18	33%	26%	15%	-8%
	SEER 12 to 17	29%	26%	13%	-14%
	SEER 12 to 16	25%	26%	11%	-23%
	SEER 12 to 15	20%	26%	15%	-10%
	SEER 12 to 14	14%	35%	11%	-23%
	SEER 12 to 13	8%	29%	7%	-27%
	SEER 13 to 18	28%	22%	9%	-13%
	SEER 13 to 17	24%	22%	6%	-19%
	SEER 13 to 16	19%	22%	4%	-28%
	SEER 13 to 15	13%	22%	8%	-15%
	SEER 13 to 14	7%	31%	4%	-28%
	SEER 14 to 18	22%	19%	5%	-23%
	SEER 14 to 17	18%	19%	3%	-29%
	SEER 14 to 16	13%	19%	1%	-40%
	SEER 14 to 15	7%	19%	5%	-26%
	SEER 15 to 18	17%	10%	1%	-9%
	SEER 15 to 17	12%	10%	-2%	-14%
	SEER 15 to 16	6%	10%	-4%	-23%
	SEER 16 to 18	11%	19%	5%	-9%
	SEER 16 to 17	6%	19%	2%	-15%
	SEER 17 to 18	6%	13%	2%	-9%

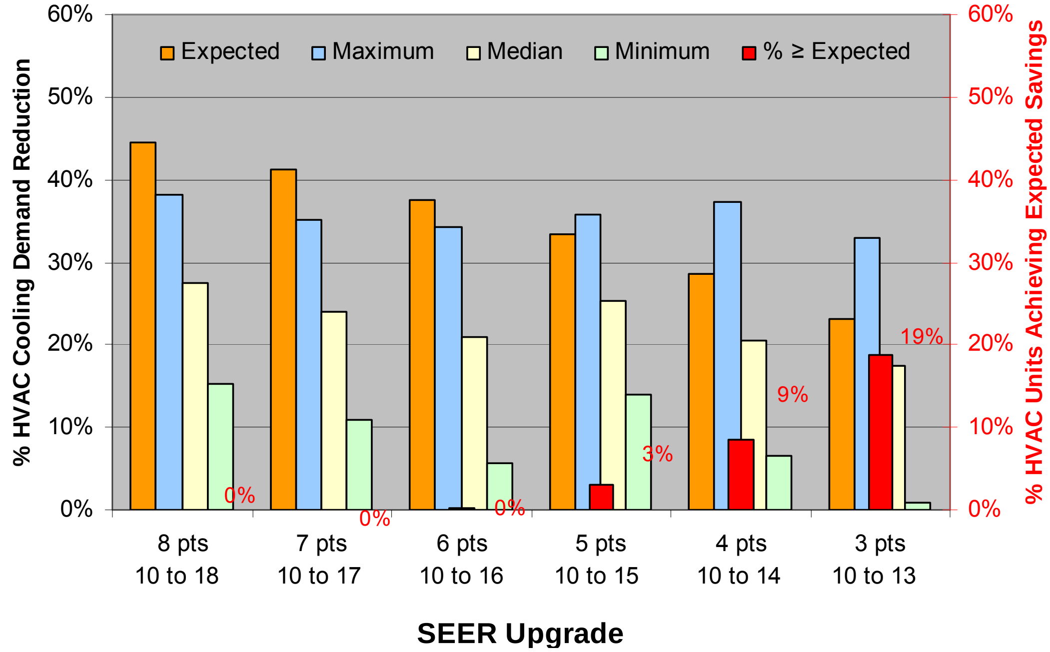
Figures 3.2.14a and b are repeated as Figures 3.2.14c and d, where the "Expected" demand

reductions are based on unit EER, rather than SEER. The EER value used to calculate "Expected" savings is the median value associated with each SEER level. These figures further illustrate the benefit of using rated EER as opposed to SEER when seeking information on cooling system demand impacts. Figures 3.2.14c and d show that DOE-2 simulated demand reductions closely match those based on changes in EER. Note that the actual demand reductions don't change from Figures 3.2.14a and b to Figures 3.2.14c and d, only how one defines the expected level of savings and how likely systems are to meet or exceed those expectations.

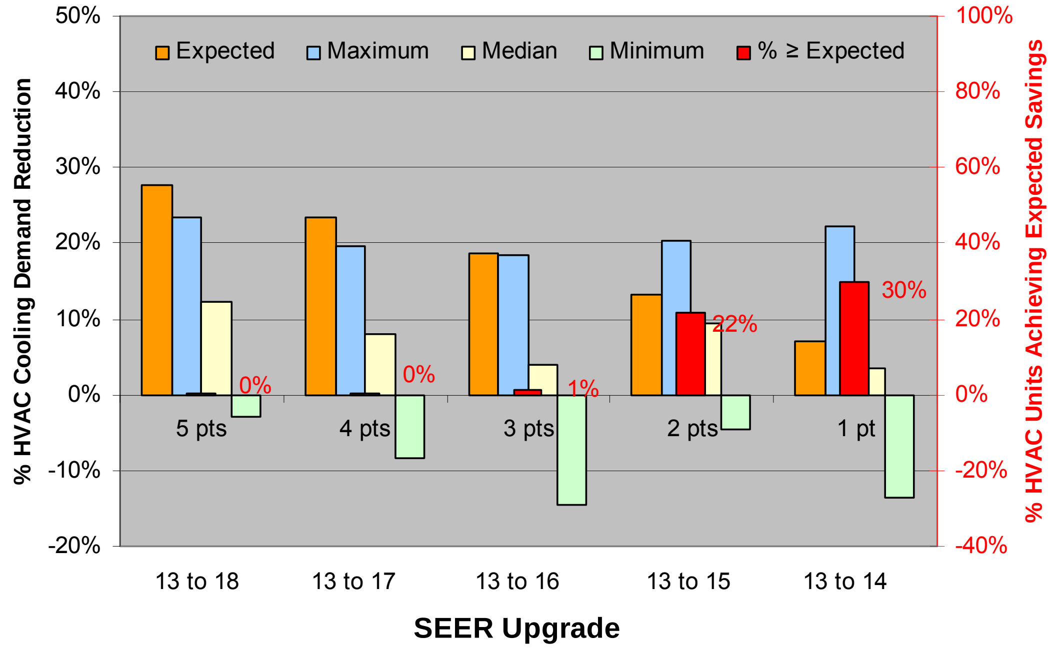
Figure 3.2.14

Percentage Cooling HVAC Demand Reduction Achieved by SEER Upgrade
Min/Median/Max Systems, Min/Median/Max Building Prototypes

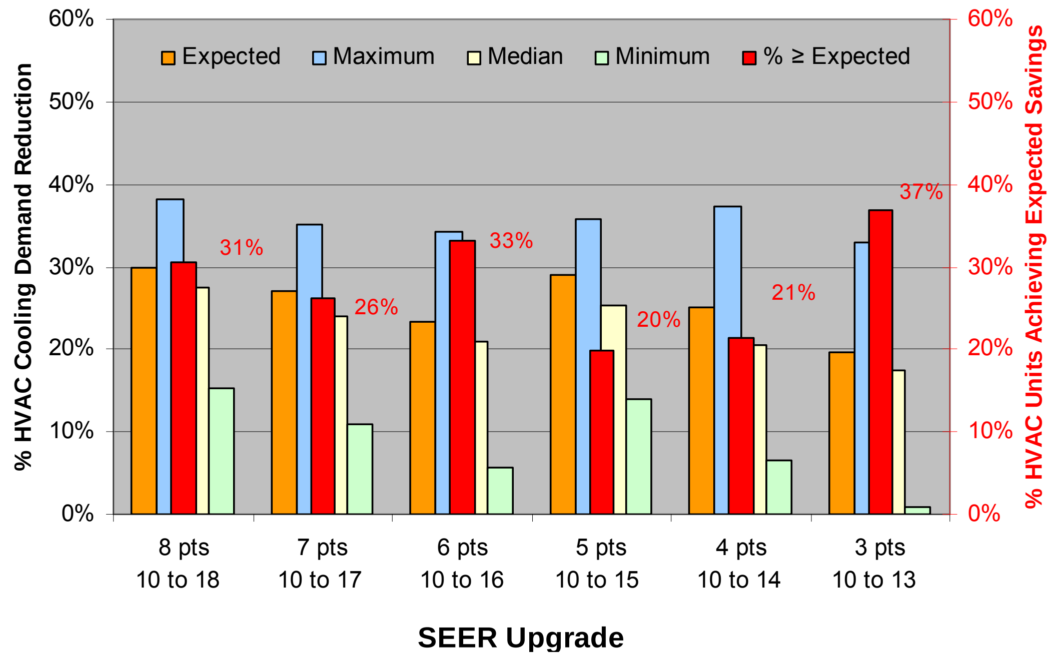
a: Upgrade from a Vintage SEER 10 Unit

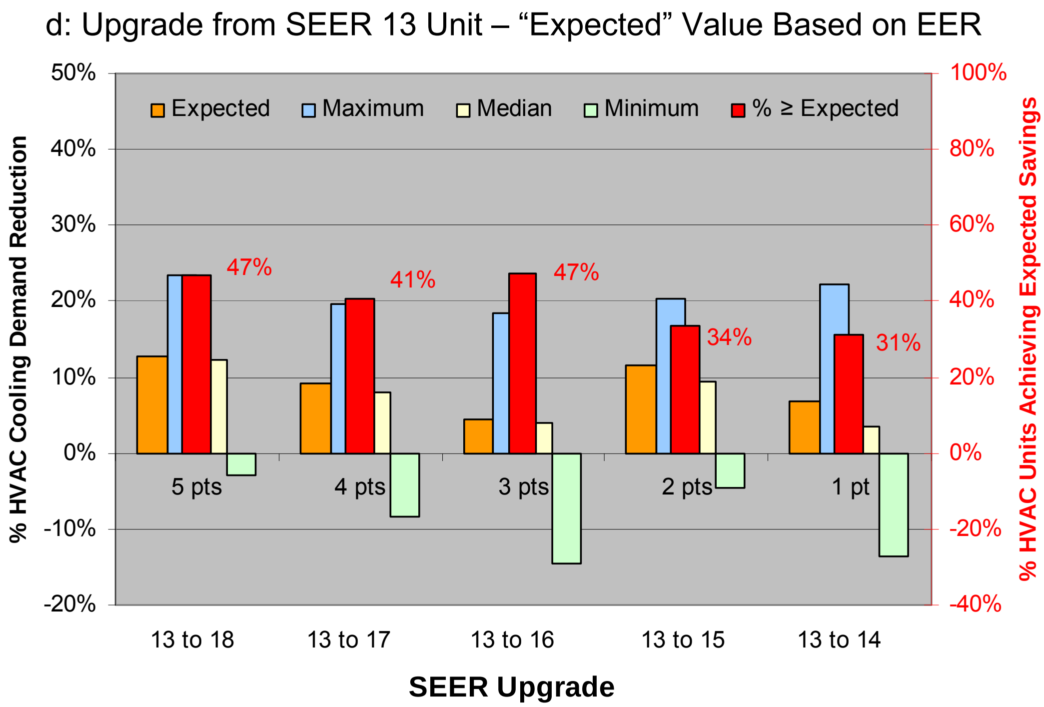


b: Upgrade from a SEER 13 Unit



c: Upgrade from a Vintage SEER 10 Unit – "Expected" Value Based on EER





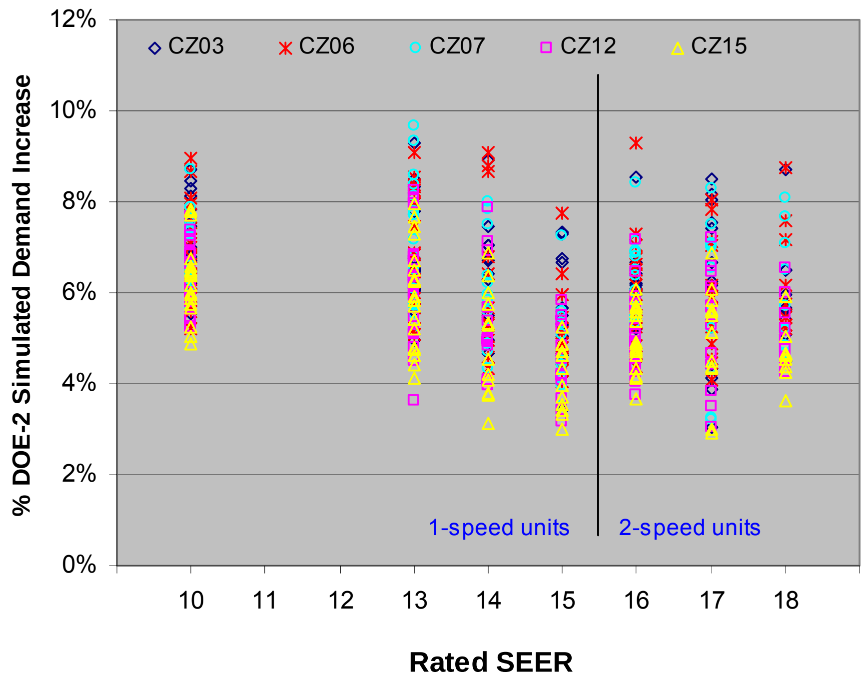
3.2.6 Fan Energy

Simulation results presented to this point are based on estimates of rated indoor fan power. Fan power values can be difficult to obtain for residential split systems. Manufacturers rarely publish fan power data and normally do not monitor fans power separately in system ratings tests. If the system in question is rated as a cooling coil and compressor combination, then one can assume a fan power of 365 W/1,000 cfm. Heat pumps or air conditioners with fan coils are rated at specific external static pressures, so rated fan power is seldom known. At times it can be deduced from expanded ratings charts as some manufactures provide gross cooling capacity and compressor power in their charts. If so, then fan power can be estimated from the ARI cooling capacity (which is net of fan power) and the ARI total system power (which includes fan power). At other times fan power can be estimated by comparing expanded ratings data for a system rated with a cooling coil to a system rated with a fan coil that uses the same cooling coil. If neither is available, then using 365 W/1,000 cfm should provide a reasonable estimate for most systems. The exception is fan coils that use variable-speed blowers. Variable speed blowers use more efficient fans and fan motors. A reasonable estimate of the fan power for these systems is 256 W/1,000 cfm (70% of standard systems).

Several site studies have shown that the 365 W/1,000 cfm and external static pressures used in the ratings process are not realistic field values (Appendix D). External static pressures and fan energy values in residential systems are a good deal higher. A more realistic fan power value is 510 W/1,000 cfm. External static pressures are on the order of 0.55 in w.g. and are independent of unit capacity (the ARI ratings process assumes external pressure depends on unit capacity). A fan power multiplier of 1.4 was applied to the rated fan energy for each system to account for these differences. The 1.4 multiplier is the ratio of the standard 365 W/1,000 cfm to the field-measured average of 510 W/1,000 cfm. A multiplier is used to account for the effects of the additional static pressure, while maintaining differences in fan power values from system to system (some systems are rated at more than 365 W/1,000 cfm, some less).

Additional simulations were made for the median building prototype with the extended range of cooling systems assuming the higher fan power. Simulation results are shown in Figure 3.2.15 as the percentage decrease in SEER caused by the higher fan energy. Referring to Figure 3.2.15, the reduction in SEER is on the order of the impact of higher indoor fan power on rated EER – 5% to +9% for vintage systems (SEER 10) and -3% to +10% for newer equipment (SEER 13 and higher). There is a general trend towards a reduction in indoor fan energy impact for more efficient systems, even though the variation in impact increases. The overall reduction is related to the use of more efficient fans and over-sized air handlers to improve efficiency in the higher efficient units. This is especially the case for 2-speed equipment where variable speed units with ECM motors are common. Scatter increases for some of the high efficiency units because some retain less efficient indoor fan systems while still improving overall efficiency. This produces a unit where indoor fan energy becomes a higher fraction of the total, and, thus, has a higher impact on seasonal efficiency when increased.

Figure 3.2.15
Impact of Higher Fan Energy on DOE-2 Simulated SEER



Note: Results for Climate Zones 03, 06, and 07 are nearly the same. Figure 3.2.11 shows the average effect for these three climate zones for clarity.

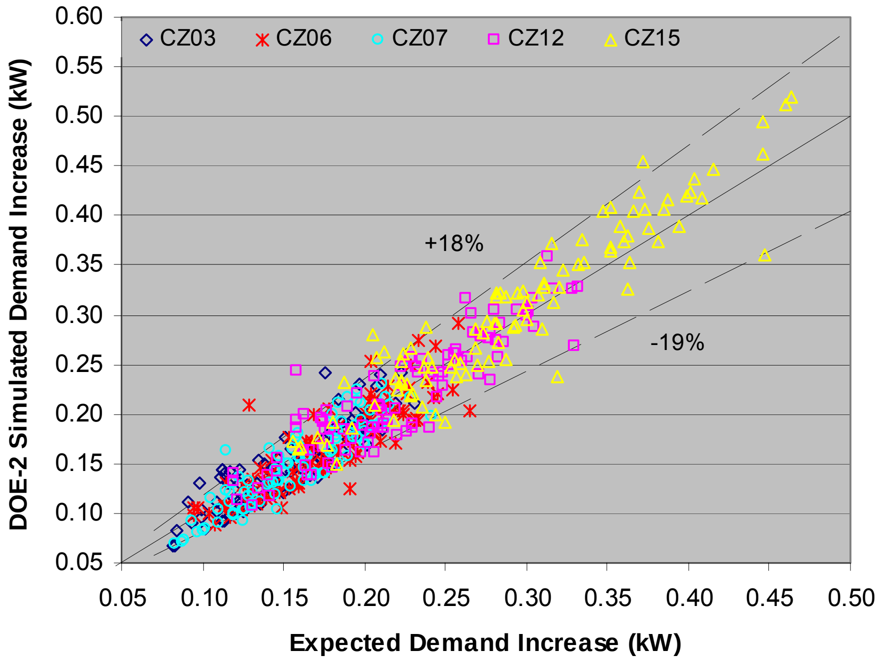
As one would expect, higher fan power increases the cooling system peak demand. Figure 3.2.16 compares the increase in demand from simulation results to the expected increase in demand. The expected increase in demand is given by:

$$\text{Expected Demand Increase} = \Delta\text{Fan kW} * (1 + \text{EIR}) \tag{3.3}$$

Where ΔFan kW is the increase in fan power and EIR is the energy input ratio of the condensing unit. The EIR is defined as the cooling system condenser unit power divided by the gross cooling output in like units (Btu/Btu or Watts/Watts). The (1 + EIR) multiplier accounts for the decrease in net cooling capacity caused by the larger fan. As the figure illustrates, the calculated demand impact caused by the larger fan follows the expected demand increase. Agreement is typically within ±19%. However, since fan power is typically only 10-15% of the total (fan + compressor) cooling system peak demand for single-speed units, and less for two-speed units, Equation 3.3 provides demand impact values that are typically within 2% to 3% of the total system demand.

Figure 3.2.16

Impact of Higher Fan Energy on Cooling System Electric Demand



3.2.7 System Sizing

Simulation results presented to this point are based on an assumed sizing rule that matches the SEER ratings procedure. As described in Section 2.2, each system is sized at approximately an ASHRAE 1% design condition for the assumed ratings cooling load profile. However, cooling systems are frequently oversized. A practice that is not uncommon would be to increase the design load to the nearest nominal capacity (say 32,000 Btu/hr to 36,000 Btu/hr, or 3 tons) and then install a system with the next larger capacity (a 3 ½ ton system instead of the 3 ton system). Thus a 32,000 Btu/hr cooling load would be met by a system with a cooling capacity of 42,000 Btu/hr. To capture this sizing approach, the original 90% sizing multiplier was replaced with a 125% sizing multiplier. Thus, systems were sized to 125% of the peak annual cooling coil load, or a capacity increase of approximately 40%.

Simulations were run with the higher sizing multiplier for the median residential building prototype using the expanded database of cooling systems. Impacts of cooling system over sizing on DOE-2 simulated SEER are shown in Figure 3.2.17. The figure shows the percentage change in SEER in comparison to the same system with the standard sizing applied to the same building prototype.

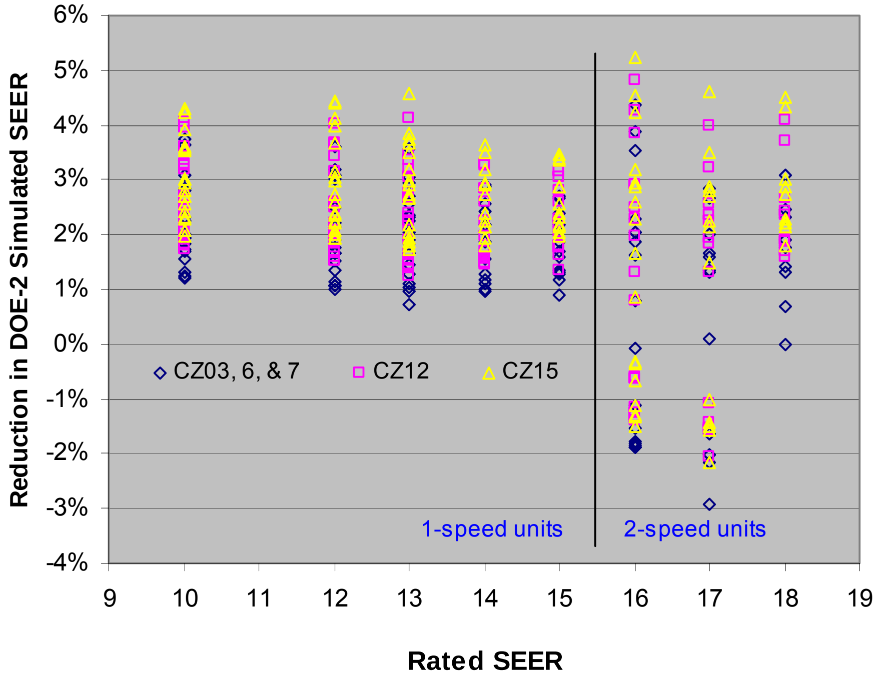
Results differ for single and two-speed equipment. While there is a good deal of scatter in the figure, overall impact is limited. For single-speed equipment, typical SEER impact is a 1 to 5% reduction in seasonal cooling efficiency, which is quite modest considering the system sizing was increased by nearly 40% (from 10% undersized to 25% oversized). For two-speed equipment, system over sizing can lead to as high as a 5% reduction in seasonal energy efficiency and as much as a 3% increase in some cases (negative values on in Figure 3.2.17). Over sizing two-speed equipment allows additional low-speed operation. For some unit, the higher low-speed operating efficiency overcomes low-speed cycling losses to provide an overall reduction in annual cooling energy consumption.

There is a modest climate zone relationship associated with over-sizing. Hotter climates (CZ12 and CZ15) show slightly greater SEER reduction than the cooler climates (CZ03, CZ06, and CZ07). This appears to be caused by slight differences in the total number of hours under-cooled between the hotter climates as compared to the cooler climates for the standard sizing method. That is, the original 90% sizing rule tended to produce a slightly higher fraction of hours under-cooled for the hotter climates that for the cooler climates because of differing weather patterns.

While seasonal cooling energy efficiency is affected by over-sizing, energy benefits associated with moving to a higher SEER are essentially unchanged from the values provided in Table 3.2.3.

Figure 3.2.17

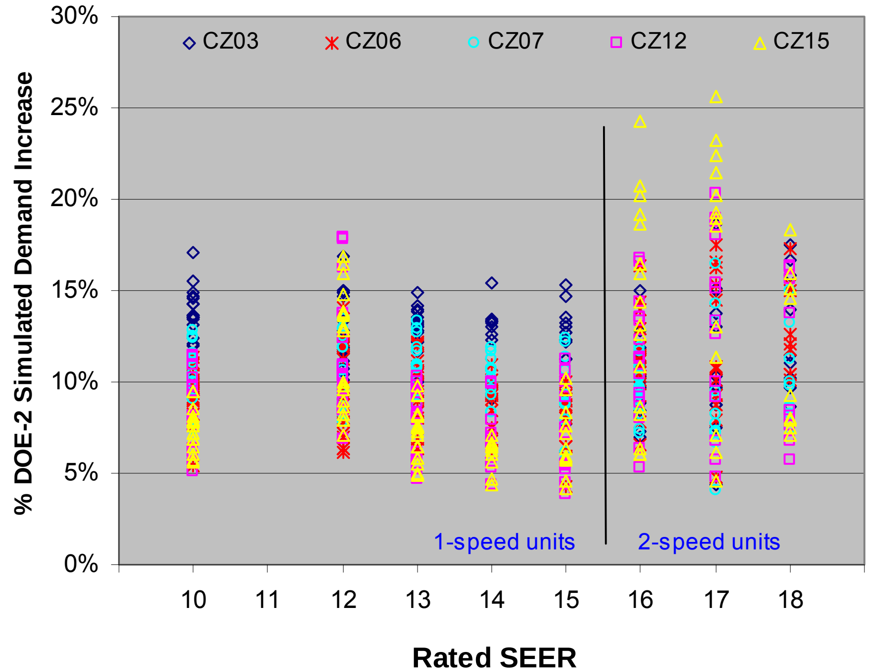
Impact of System Over Sizing on SEER



Simulations results predict that over sizing will have a significant impact on demand. With a change from a 90% sizing rule to the 125% sizing rule, one would expect an increase in peak demand as high as 16% to 18%. Increase demand estimates includes the additional condenser unit energy from 90% to 100% of the coil load plus all of the increase in fan power. Minimum demand increase would be 4% to 5%, based on the increase in fan power with no change in condenser unit power. Simulation results, shown in Figure 3.2.18 produce results with a similar range of demand impacts for single-speed units (3% to 17%) and a somewhat greater range for two-speed units (3% to 25%).

Figure 3.2.16

Impact of System Over Sizing on Simulated HVAC Cooling System Demand



The fact that not all simulations showed demand changes at the expected maximum range has to do with the 90% sizing procedure used in the simulations. The standard sizing procedure used in all analyses begins with an initial DOE-2 simulation to determine the cooling peak coil load for the given building prototype. Cooling system performance maps are then used in conjunction with climate zone-specific design outdoor dry-bulb and mean coincident wet-bulb conditions to determine the required ARI cooling capacity to meet the coil load at peak conditions. The outdoor and indoor conditions that produce peak cooling coil loads differ slightly from design conditions. This leads to small differences among the various systems in the cooling capacity used as the 90% design value since each cooling system differs in its sensitivity to outdoor dry-bulb and coil entering air wet-bulb temperatures. If nominal design conditions are very close to those that occur when the seasonal cooling peak occurs, then the system will be sized very close to the desired 90% level. If design conditions are not close, then systems can vary as to how close they are to the actual 90% design condition, depending on how sensitive they are to the outdoor dry-bulb or indoor wet-bulb. These small differences produce variations in the amount of under sizing among the various cooling systems. While this affect has no significant impact on simulated SEER (a sizing increase of 40% produced only a 1% to 5% impact on SEER), it is enough to account for the scatter shown in Figure 3.2.18.

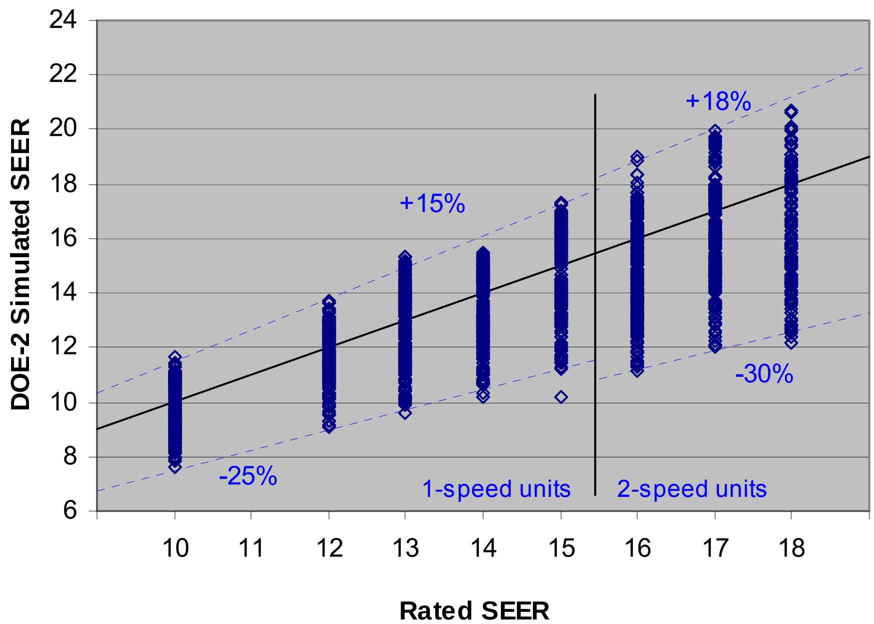
This is particularly notable for some two-speed units who exhibit greater demand changes. The cooling capacity of some of these units happen to be more sensitive to changes in outdoor temperature than either like-SEER two-speed units or single-speed units. This lead to a greater increase in peak cooling load than systems whose cooling capacity was less sensitive to outdoor temperature. Higher cooling capacities produced higher demand impacts.

4.0 SEER IMPROVEMENT MODELS

Section 3.1 illustrated that SEER is not well represented by a single ratings value, but is dependent on building characteristics, climate conditions, and cooling system performance differences not included in their SEER rating. While differing building characteristics can have a tremendous impact on annual energy use, they were found to have no more than a ±5% effect on SEER. The interaction of weather patterns, building characteristics, building use and operation, and mechanical system control that produce the changes in SEER are at a level of complexity that are beyond simple quantification. One should expect a ±7% uncertainty in SEER associated with variation in building operation and characteristics. Fortunately, this uncertainty in SEER is not a big factor when selecting between systems of differing SEER. That is, for a given house design, operational or design features that would tend to drive one cooling system to a significantly higher or lower SEER will tend to drive all systems in the same direction. Improving SEER estimates is reduced to accounting for climate conditions and cooling system performance differences.

The SEER multipliers given in Table 3.2.1 offer a means of providing climate and SEER-specific corrections to improve SEER estimates. The multipliers developed in Section 3 were expanded to include all climate zones through additional DOE-2 simulations. All 119 mechanical systems were simulated against the prototypical single-family residential DOE-2 model for all California climate zones. SEER values calculated in this process are compared to their rated values in Figure 4.1.1. Simulations results were used to expand Table 3.2.1 to include all climate zones.

Figure 4.1.1
DOE-2 Simulated vs. Rated SEER – All Climate Zones
Median* Building Characteristics, All Mechanical Systems
All Climate Zones Except CZ01



**This figure differs from 3.2.5 in that it includes only median building characteristics.*

4.1 Improved SEER – Climate Zone Multipliers

Climate and SEER specific multipliers are presented in Table 4.1.1. This is an expansion of Table 3.2.1 to include all climate zones. Multipliers that are SEER-specific can be applied to systems not in the table through interpolation. Using the average climate zone multiplier ignores general differences among systems as their efficiency increases. SEER-specific multipliers include those differences in a climate specific manner.

A comparison of Doe-2 simulated SEER and climate zone adjusted SEER using the multiplier in Table 4.1.1 is shown in Figure 4.1.2. The SEER multipliers reduce the error in SEER estimate from +31% to –25% to ±8% for single-speed units. The improvement in 2-speed units is from +15% to –31% to ±10%. They do this by accounting for overall climate affects (effective mid-load outdoor and coil entering wet-bulb temperatures) and the climate-specific sensitivities of each system (differing multipliers for each SEER level). Climate zones with multipliers greater than 1.0 are associated with cooler climates, those less than 1.0 with hotter climates.

Figure 4.1.2
DOE-2 Simulated vs. CZ Corrected SEER – All Climate Zones
Median Building Characteristics, All Mechanical Systems

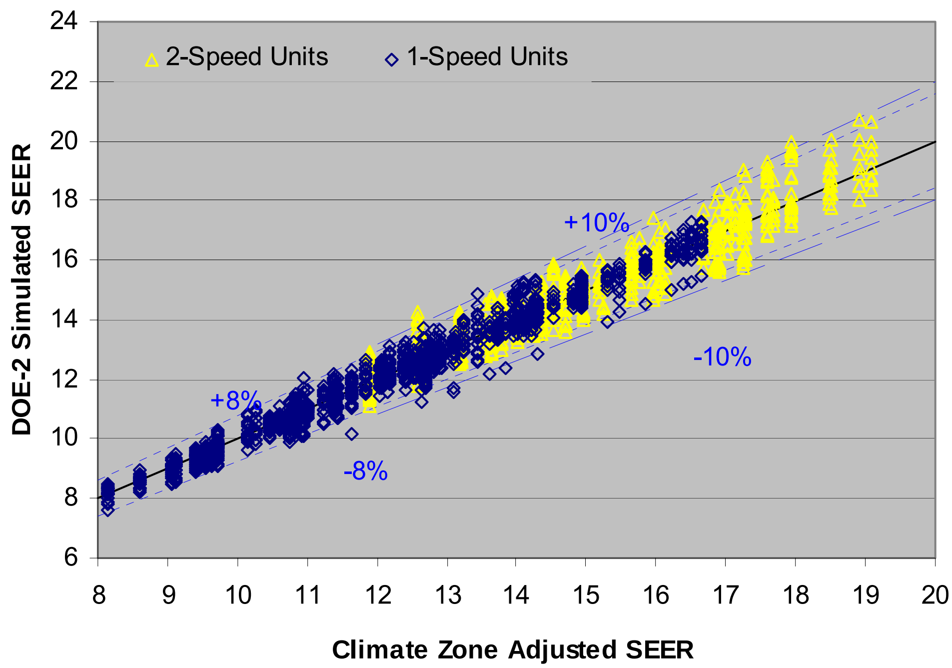


Table 4.1.1
Climate Zone SEER Multipliers*

	Single-Speed SEER Rating						Two-Speed SEER Rating				All Units
	10	12	13	14	15	All	16	17	18	All	
CZ01	1.20	1.16	1.19	1.16	1.23	1.19	0.98	1.11	1.08	1.11	1.10
CZ02	0.96	0.95	0.94	0.92	0.94	0.94	0.83	0.90	0.92	0.87	0.90
CZ03	1.08	1.06	1.08	1.07	1.09	1.08	0.95	1.06	1.03	1.03	1.04
CZ04	1.06	1.04	1.06	1.04	1.06	1.05	0.93	1.00	1.00	0.98	1.00
CZ05	1.08	1.07	1.08	1.07	1.10	1.08	0.96	1.08	1.06	1.05	1.06
CZ06	1.10	1.07	1.10	1.07	1.11	1.09	0.97	1.08	1.06	1.06	1.07
CZ07	1.08	1.06	1.07	1.06	1.08	1.07	0.95	1.05	1.04	1.03	1.04
CZ08	1.08	1.06	1.02	1.00	1.02	1.02	0.90	0.98	0.98	0.95	0.97
CZ09	0.97	0.97	0.95	0.94	0.95	0.96	0.85	0.92	0.94	0.88	0.91
CZ10	0.94	0.94	0.91	0.90	0.91	0.92	0.81	0.86	0.88	0.83	0.86
CZ11	0.91	0.90	0.87	0.86	0.87	0.88	0.78	0.82	0.84	0.80	0.82
CZ12	0.95	0.95	0.93	0.91	0.92	0.93	0.82	0.88	0.90	0.84	0.87
CZ13	0.91	0.91	0.88	0.87	0.87	0.88	0.79	0.83	0.84	0.80	0.82
CZ14	0.86	0.85	0.84	0.81	0.84	0.85	0.75	0.79	0.80	0.75	0.78
CZ15	0.81	0.81	0.78	0.77	0.78	0.79	0.72	0.74	0.74	0.70	0.73
CZ16	1.05	1.03	1.03	1.02	1.03	1.03	0.84	0.91	0.95	0.89	0.91

Note: Climate zone and SEER specific multipliers used in all presentation graphics and summary findings. Values noted as "All" are for the reader's interest only.

The 2005 Title 24 Alternative Calculation Method (ACM) provides means to adjust a units nominal SEER rating that is climate zone dependent. The method uses the unit's rated SEER and EER (or a default EER = 10 if the rated value is not available) in its calculations. The ACM calculation was applied to the building cooling loads from the DOE-2 calculations used to produce the results presented in Figure 4.1.2 (median building characteristics and all mechanical systems). Results of this analysis are presented in Figures 4.1.3a for single-speed equipment and 4.1.3b for two-speed equipment. The ACM adjusted SEER (x-axis) is plotted against the DOE-2 simulated SEER (y-axis). Also include in the figure are the DOE-2 simulated SEER plotted against rated SEER (green squares) and the uncertainty bands associated with using climate zone corrections as shown in Figure 4.1.2 (±8% for single-speed equipment and ±10% for two-speed equipment).

Figure 4.1.3a 2005 Title 24 ACM Calculated SEER, Single-Speed Systems Only
Single Family Residential Prototype, All California Climate Zones
Median Building Characteristics, and Min/Median/Max System Characteristics

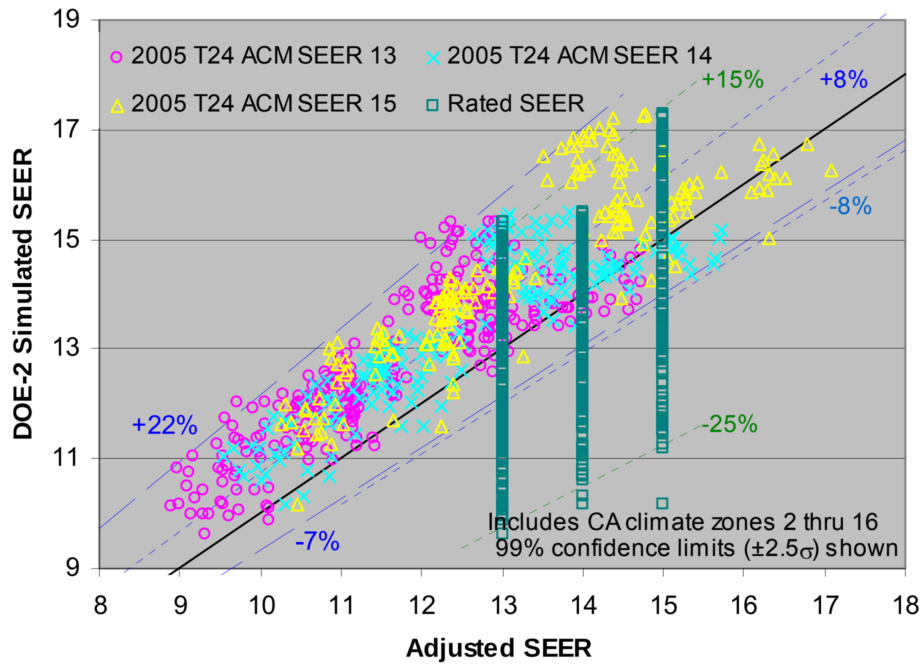
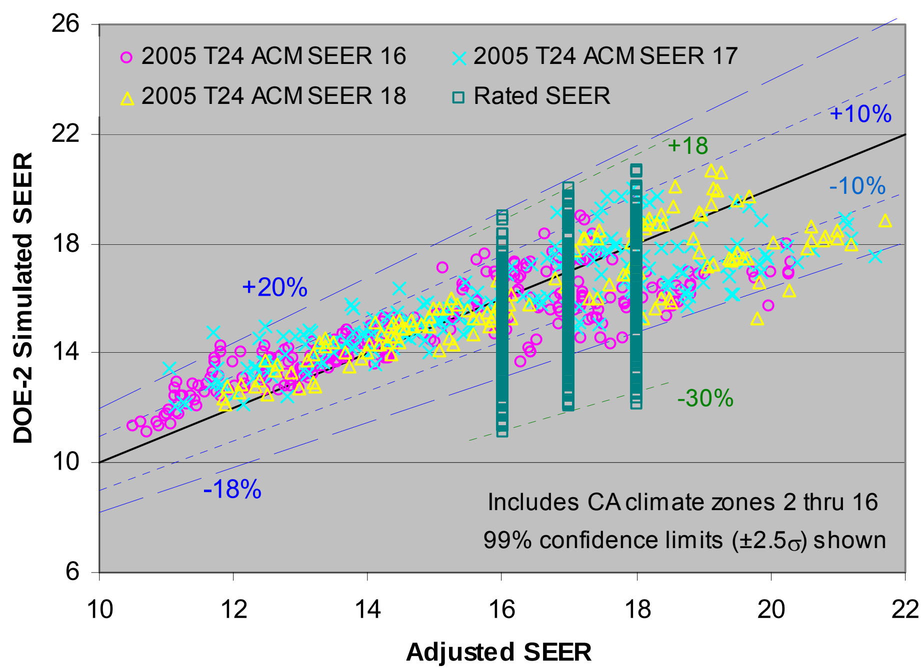


Figure 4.1.3b 2005 Title 24 ACM Calculated SEER, Two-Speed Systems Only
Single Family Residential Prototype, All California Climate Zones
Median Building Characteristics, and Min/Median/Max System Characteristics



Results from this analysis indicate the following:

- The 2005 Title 24 ACM calculation method does a better job of predicting seasonal cooling efficiency than would be obtained by using the nominal SEER rating. The scatter in results in comparison the DOE-2 simulated SEER is +22% to –7% for single-speed units and +20% to –18% for two-speed units. This compares to +15% to –25% for single-speed units and +18% to –39% for two-speed units when using rated SEER (see Figure 4.1.1). This represents a 30% improvement in SEER estimate.

- It is not as good as the climate zone multipliers developed in this effort, whose uncertainties are ±8% for single-speed equipment and ±10% for two-speed equipment. However, the 2005 Title 24 ACM calculation procedure has the benefit that, for a given SEER rating, it rewards higher EER units and penalizes low EER units by producing correspondingly higher and lower adjusted SEER values respectively. This effort separates the two issues by providing separate energy and demand adjustments.

- The 2005 Title 24 ACM calculation method produces a negative SEER bias (the ACM-calculated SEER is less than that obtained from DOE-2 simulations). This bias is ~8% for single-speed equipment and ~2% for two-speed equipment. This bias would overstate the benefits of non-HVAC system upgrades (i.e., more efficient windows, higher insulation levels, reduced infiltration, etc.) in an ACM evaluation process.

4.2 Improved SEER – Detailed Single-Speed Equipment Model

The climate and SEER-specific multipliers provide a tremendous improvement in SEER estimates. However, differences in equipment performance still lead to an estimate error around ±8% at a 95% confidence level. A nominal 13 SEER system could provide a corrected seasonal efficiency as low as 12.0 or as high as 14.0. This is obviously a potential problem for regulators who seek to use SEER as energy standard.

The uncertainty in the SEER estimate appears to be associated with subtle differences in equipment performance that are not addressed in the SEER ratings process. Many of these have been discussed in the previous section. The importance of among equipment differences varies from climate zone to climate zone. For example, differences in the systems’ efficiency to changes in outdoor temperature are most important in the hotter climates zones. In cooler climates, the dominant factor is often related to how sensitive a system is to the humidity of the air entering the cooling coil. At other times, differences in cycling efficiency come into play.

Detailed, equipment-based models for single-speed systems were developed to account for these factors as a means to reduce the uncertainty in the SEER estimate. Two-speed systems are not included as their operational characteristics and SEER ratings procedures differ significantly from their single-speed counterparts, introducing a level of complexity that could not be resolved in this effort. The general form of the single-speed, detailed model is as follows:

$$SEER_{mult} = C_0 + C_1*C_D + C_2*DB_{mult} + C_3*S_{WB} + C_4*SHR \tag{4.1}$$

where:

$SEER_{mult}$ is the SEER multiplier used to adjust rated SEER (like those in Table 4.1.4),

C_D is the cooling system's degradation coefficient as determined in cycling tests,

DB_{mult} is a dry-bulb multiplier used to adjust for differing outdoor conditions and the system's sensitivity to changing outdoor temperature,

S_{WB} is the sensitivity of the system's efficiency to changing coil entering wet-bulb,

SHR is the system's sensible heat ratio, or ratio of sensible cooling capacity to total at ARI design conditions, and

C_0, C_1, C_2, C_3, and C_4 are equation constants.

The independent variable, DB_{mult}, is a combination of two terms, and is calculated as:

$$DB_{mult} = S_{DB} * (82 - MLT) \tag{4.2}$$

Where:

S_{DB} is the sensitivity of the system's normalized (EER/Rated EER) efficiency to changing outdoor dry-bulb temperature and

MLT is the climate zone-specific mid-load temperature as given in Table 4.1.2.

The form of Equation 4.2 illustrates that DB_{mult}, is a measure of how much a given system is affected by outdoor conditions that differ from the assumed 82 F rated condition.

Determining the various independent variables requires access to manufacturer's ratings and expanded ratings charts. Expanded ratings charts provide sufficient data to estimate S_{DB} and S_{WB} and calculate SHR at ARI design conditions. The California Energy Commission maintains a database of rated systems that includes their degradation coefficients obtained during the SEER ratings process. Values of the degradation coefficient can be estimated for systems not in the database using the equation for SEER, expanded ratings charts, and the rated SEER, or:

$$C_D = 2*(1 - SEER/EER_{82}) \tag{4.3}$$

Where EER_{82} is the energy efficiency ratio of the system at 82 F outdoor temperature and 80 F dry-bulb, 67 F wet-bulb conditions entering the cooling coil. This can be obtained from manufacturer's expanded ratings charts.

The equation coefficients and climate zone-specific mid-load temperature are given in Table 4.1.2. A comparison of Figures 4.1.1 and 4.1.2 illustrate the improvement in SEER estimate obtained by using either the climate zone or detailed multipliers.

Adjusted SEER values are compared to those calculated by DOE-2 in Figure 4.1.2. Adjusted SEER values include those based on the multipliers in Table 4.1.1 (Climate Zone SEER Multipliers) and those using the detailed model as defined by Equation 4.1 (Detailed). The detailed model reduced the expected error in the adjusted SEER to within ±7%. The ability to reproduce DOE-2 simulated SEER via climate multipliers or the detailed model is dependent on the climate zone. Both SEER multiplier methods reproduce calculated results better for hotter climates (CZ02, and CZ10 – CZ15). Thus, SEER is more predictable for climate zones with the higher cooling loads. Standard errors expected from the SEER adjustments are given in Tables 4.1.3a and 4.1.3b by climate zone. Table 4.1.3a provides values for the climate-zone multipliers (provided in Table 4.1.1), while Table 4.1.3b is for the detailed model.

Table 4.1.2
Detailed Model Coefficients - Single-Speed Units Only

	C_0	C_1	C_2	C_3	C_4	MLT
CZ01	1.1735	0.2530	-1.1902	-0.2517	-0.2222	69.8
CZ02	0.9397	0.1739	3.3636	-0.2787	0.0635	81.4
CZ03	1.0114	0.1254	-0.6037	-0.2042	0.0228	74.0
CZ04	0.9394	0.1232	-0.0745	-0.2023	0.1592	76.9
CZ05	1.0189	0.1152	-0.7339	-0.2111	-0.0231	72.3
CZ06	0.9975	0.1182	-0.7147	-0.2031	0.0277	72.6
CZ07	0.9487	0.1277	-0.5787	-0.2239	0.1065	74.5
CZ08	0.9606	0.1221	0.2532	-0.2391	0.1201	77.7
CZ09	0.9322	0.0785	4.1892	-0.2639	0.1373	81.0
CZ10	0.9176	0.1300	-2.7777	-0.3145	0.1369	84.2
CZ11	0.9110	0.1625	-1.3463	-0.3754	0.0973	86.2
CZ12	0.9363	0.1126	-6.8001	-0.2414	0.1458	83.1
CZ13	0.9056	0.1199	-1.9377	-0.2695	0.1666	86.9
CZ14	0.8693	0.1395	-0.0830	-0.6099	0.0492	87.4
CZ15	0.8223	0.0877	-0.9946	-0.3843	0.1904	92.4
CZ16	1.1144	0.2442	-0.7408	-0.4543	-0.0964	80.2
All CZ'z	0.9414	0.1622	-1.2572	-0.3470	0.0495	Use above

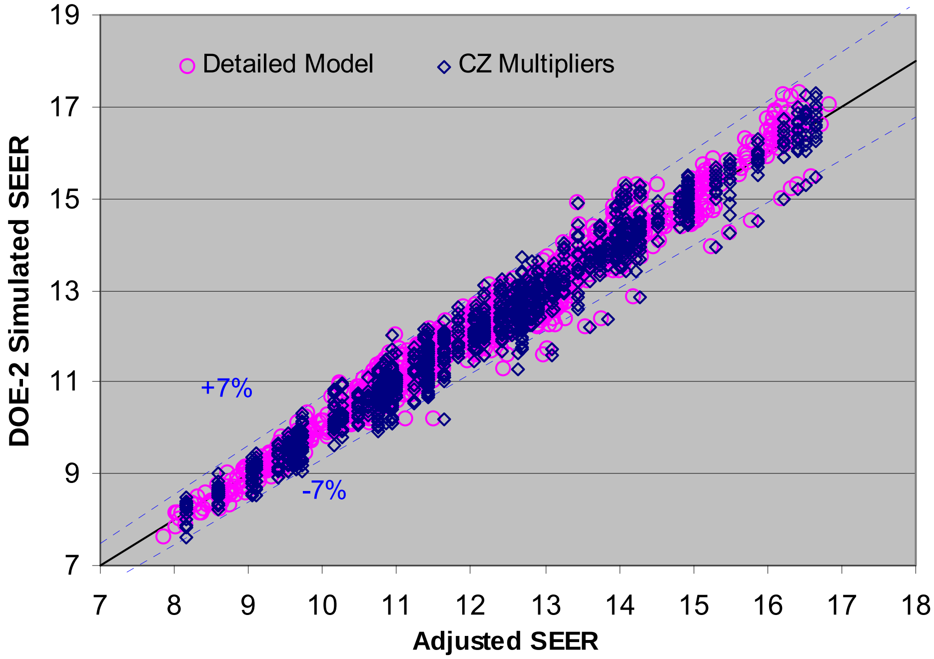
Table 4.1.3a
Standard Errors of Adjusted SEER Estimate – Climate Zone Multipliers

CZ01	CZ02	CZ03	CZ04	CZ05	CZ06	CZ07	CZ08
4.2%	2.6%	2.8%	2.2%	3.0%	2.8%	2.4%	3.3%
CZ09	CZ10	CZ11	CZ12	CZ13	CZ14	CZ15	CZ16
2.7%	3.0%	3.2%	3.0%	3.3%	3.7%	3.5%	3.4%

Table 4.1.3b
Standard Errors of Adjusted SEER Estimate – Detailed Multipliers

CZ01	CZ02	CZ03	CZ04	CZ05	CZ06	CZ07	CZ08
4.2%	2.3%	2.9%	2.2%	3.1%	2.9%	2.4%	2.4%
CZ09	CZ10	CZ11	CZ12	CZ13	CZ14	CZ15	CZ16
2.6%	2.6%	2.8%	2.6%	2.7%	3.3%	2.9%	3.0%

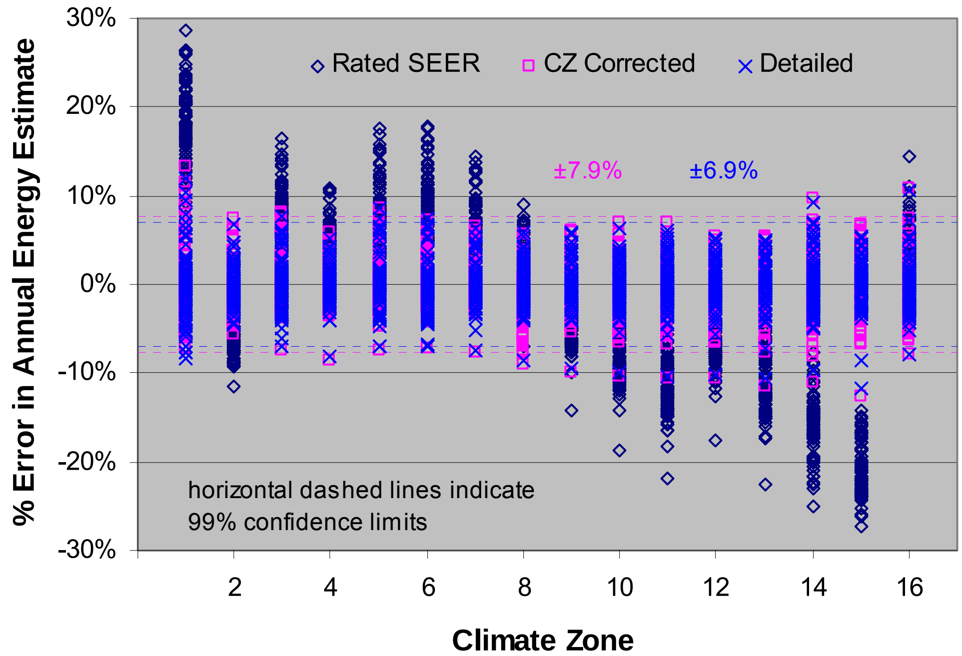
Figure 4.1.2
Adjusted SEER vs. Rated SEER – All Climate Zones
Single-Speed Systems



4.3 Benefit of Improved SEER

The benefits of adjusted SEER in predicting seasonal energy use are illustrated in Figure 4.1.3. This figure compares the error in seasonal energy estimates based on rated and climate zone-adjusted SEER and the detailed model. Both SEER modifiers have the ability to significantly improve estimates of seasonal energy use from known seasonal cooling loads. The additional effort required of the detailed model provides only a modest improvement in SEER estimate over the use of the climate zone multipliers provided in Table 4.1.1. (error is reduced from ±7.9% to ±6.9%). The figures also illustrate that neither SEER adjustment process can reproduce seasonal cooling efficiency with absolute certainty because of performance differences between systems that cannot be captured in a single ratings value.

Figure 4.1.3
Error in Seasonal Energy Use – Rated SEER vs. CZ-Adjusted SEER
Single-Speed Systems

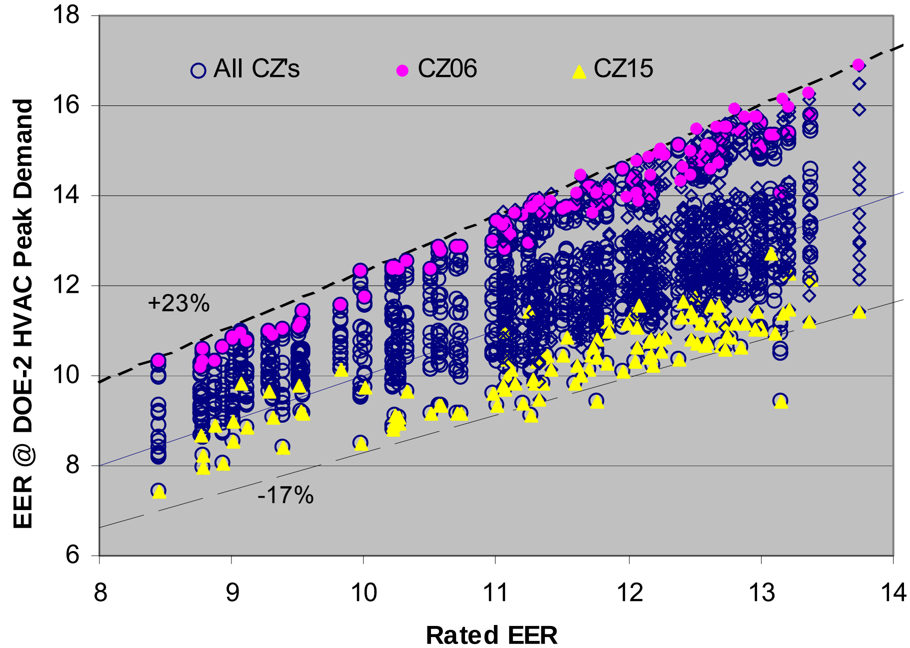


4.4 System Electric Demand

Section 3.2.5 showed that SEER is an inappropriate indicator of cooling system electrical demand – EER is a much better predictor even for two-speed equipment. It was also determined that demand impacts, for a given system, are climate zone specific. Simulations applied to all climate zones were used to determine appropriate climate zone multipliers applicable to cooling electric demand. These multipliers adjust a system's EER to peak weather conditions specific to each climate zone.

Simulation results are shown in Figure 4.1.4 where cooling system peaks are given as the simulated EER. The simulated EER is equal to the cooling system's design cooling capacity (ARI-rated conditions) divided by the peak HVAC electric demand determined from DOE-2 simulations. A systems electric demand is found by dividing its rated cooling capacity by the simulated EER. The figure illustrates both the relationships between rated EER and operational EER and its variation across climate zones.

Figure 4.1.4
EER at DOE-2 Peak HVAC Demand vs. Rated EER – All Climate Zones



Climate zone multipliers that adjust rated EER to operational values are given in Table 4.1.5. The multipliers provide estimates of cooling system demand via equation 4.4. The climate zone and SEER level EER multipliers (CZ EER_{Mult}) used in Equation 4.4 are given in Table 4.1.5. A comparison of the values in Table 4.1.1 and Table 4.1.5 shows consistent trends between SEER and EER multipliers. The multiplier is lower in hotter climates than cooler and lower for higher SEER systems that lower SEER systems. This general trend, when applied to demand, illustrates a case of diminishing return for demand reduction when moving to higher efficiency systems.

$$\text{Cool kW} = \text{Rated Cooling Capacity} / (\text{Rated EER} * \text{CZ } EER_{Mult}) \qquad (4.4)$$

A comparison of climate zone adjusted EER to that from DOE-2 simulations is provided in Figure 4.1.6. The climate zone multipliers provide an estimate of simulated EER to within ±8% at the 99% confidence interval. This includes both single and two-speed units.

Table 4.1.5
Residential EER Climate Zone Multipliers for All California Climate Zones
Single Family Residential Prototype, All California Climates
Median Building Characteristics, Median System Characteristics

	Single-Speed SEER Rating						Two-Speed SEER Rating				All Units
	10	12	13	14	15	All	16	17	18	All	
CZ01	1.24	1.30	1.30	1.26	1.32	1.29	1.35	1.34	1.41	1.37	1.32
CZ02	1.08	1.04	1.03	1.02	1.01	1.04	1.03	1.02	1.00	1.02	1.03
CZ03	1.16	1.17	1.16	1.15	1.15	1.16	1.16	1.15	1.16	1.16	1.16
CZ04	1.10	1.10	1.08	1.06	1.05	1.08	1.07	1.06	1.06	1.06	1.07
CZ05	1.18	1.19	1.18	1.16	1.17	1.18	1.19	1.19	1.19	1.19	1.18
CZ06	1.18	1.20	1.20	1.18	1.19	1.19	1.20	1.22	1.22	1.21	1.20
CZ07	1.15	1.18	1.17	1.16	1.15	1.16	1.21	1.20	1.21	1.21	1.18
CZ08	1.15	1.18	1.08	1.07	1.07	1.09	1.09	1.09	1.08	1.08	1.10
CZ09	1.06	1.07	1.01	1.01	0.99	1.03	1.00	1.00	0.99	1.00	1.02
CZ10	1.05	1.01	0.99	0.98	0.96	1.00	0.99	0.99	0.98	0.99	0.99
CZ11	1.03	0.98	0.96	0.94	0.93	0.97	0.96	0.96	0.94	0.95	0.96
CZ12	1.04	1.01	0.99	0.98	0.96	1.00	0.98	0.98	0.96	0.98	0.99
CZ13	1.03	0.99	0.97	0.96	0.94	0.97	0.95	0.95	0.93	0.94	0.96
CZ14	1.02	0.97	0.95	0.93	0.92	0.96	0.95	0.94	0.92	0.94	0.95
CZ15	0.97	0.89	0.88	0.86	0.85	0.89	0.88	0.88	0.87	0.88	0.89
CZ16	1.10	1.09	1.06	1.04	1.05	1.07	1.06	1.06	1.03	1.05	1.06

Note: Climate zone and SEER specific multipliers used in all presentation graphics and summary findings. Values noted as "All" are for the reader's interest only.

Detailed models like those used to improve the SEER estimate (Section 4.3) were examined for cooling system demand. While the exercise was informative, it could not provide significant improvement in HVAC demand estimates. The analysis did provide qualitative information on how cooling system features affect demand. The system features examined were a subset of those used in the SEER detailed model. They included the units' sensitivity to changes in outdoor dry bulb and coil entering wet-bulb temperatures, the units' design sensible heat ratio (sensible capacity divided by total capacity) and climate zone (as defined by the median mid-load temperature over all units within a climate zone). Observations obtained from the analysis are as follows:

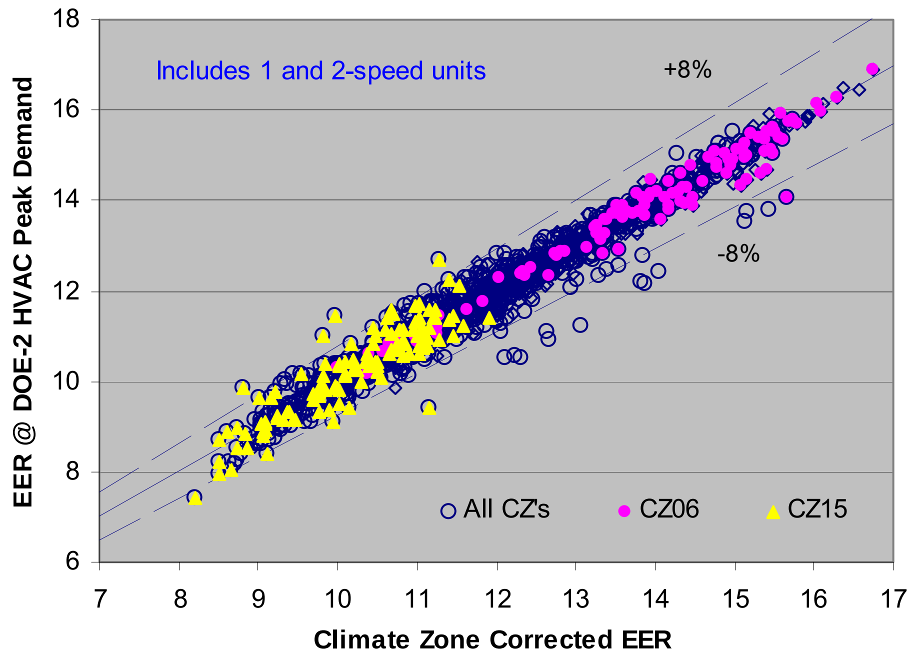
- Climate has the greatest impact on HVAC system demand, representing +16% to –20% impact on demand. This is consistent with the EER climate zone multipliers provided in Table 4.1.5.

- Units that are more sensitive to outdoor dry bulb and/or coil entering wet-bulb temperature have higher HVAC demand than those that are less sensitive. Each can impact demand from 2% to 3%. There is a correlation between the two in that cooling systems whose efficiency is more sensitive to outdoor dry bulb temperature also tend to be more sensitive to cooling coil entering wet-bulb temperature. One should expect the two effects to act together to impact cooling demand as much as 4% or 5%.

- Differences in sensible heat ratio from unit–to-unit should not have more than a ±1% impact on cooling system demand, with units with higher sensible heat ratios producing the slightly higher demands. Sensible heat ratios of the units examined in this study varied from 67% to 81%.

- Even when one accounts for all of these variables, one should expect HVAC peak demand values to vary an additional ±8% from unit-to-unit.

Figure 4.1.5
Climate Zone Adjusted EER vs Operational (Simulated) EER
Single Family Residential Prototype, All California Climates Median Building Characteristics, Median System Characteristics



4.5 Benefit of Improved EER

The benefit of adjusted EER in predicting peak HVAC cooling demand is illustrated in Figure 4.1.6. Cooling demand is represented by the units' EER when the demand occurs. The figure includes both single and two-speed equipment. The EER climate zone multipliers have the ability to significantly improve estimates of cooling system demand from known rated EER. The figures also illustrates that performance differences between systems limits the ability to predict demand to no better than ±8%.

Figure 4.1.6
Error in HVAC Peak Demand
As Predicted by Rated EER and CZ-Adjusted EER
Single and Two-Speed Systems

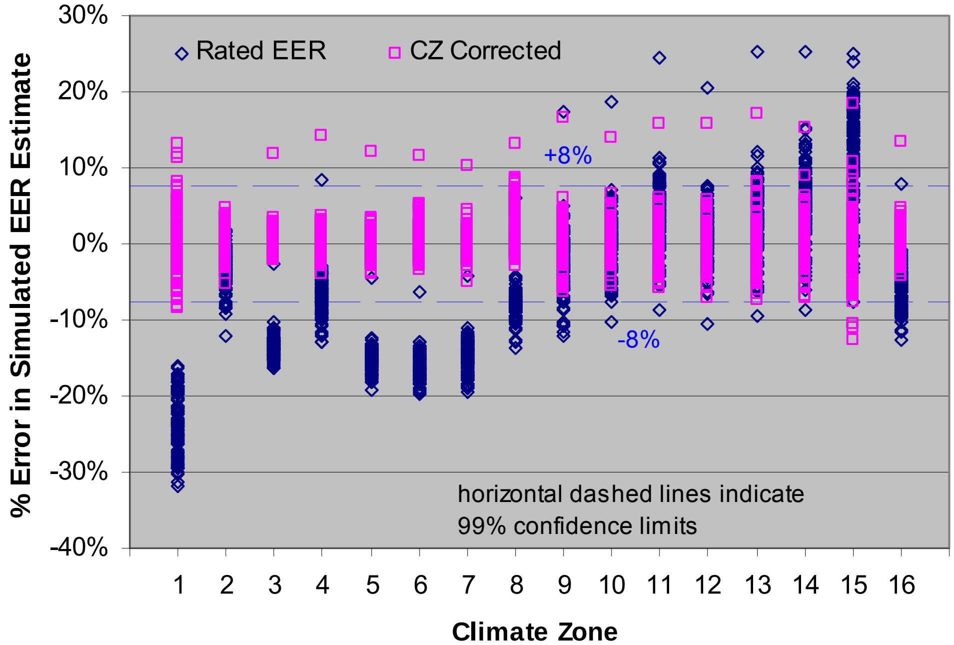


Figure illustrates error in EER at HVAC peak cooling demand. Positive values occur when demand in under-predicted, negative is when demand is over-predicted.

5.0 CONCLUSIONS

Results from residential DOE-2 simulations include the following:

- SEER rating alone is a poor predictor of expected cooling energy use. One should expect errors in estimates cooling energy between –22% and +30% for single-speed units and between –25% and +33% for two-speed units (negative values occur when rated SEER understates cooling system seasonal efficiency). Much of the error is associated with climate effects. Using SEER-specific multipliers given in Table ES-1 can minimize climate affects. An uncertainty of ±8% in seasonal cooling efficiency for single-speed equipment (±10% for two-speed equipment) cannot be eliminated even after the application of climate zone corrections. This uncertainty appears to be caused by small differences in how cooling systems respond to changes in outdoor and cooling coil entering conditions.

- SEER does not always rank systems as to their energy efficiency. One should expect that differences in the way cooling systems respond to outdoor and indoor conditions, along with cycling rates, will mean that SEER is reliable only to within 0.5 to 0.8 ratings points (5% of rated SEER). That is, a nominal SEER 13 system is as likely to produce seasonal cooling energy values equivalent to a SEER of 12.4 or 13.7. Because of this uncertainty, one could not be certain that purchasing the next higher SEER-rated system (SEER 14 instead of SEER 13, or SEER 15 instead of SEER 14, etc.) would provide seasonal energy savings.

- Residential building characteristics (insulation levels, glass type or amount, internal gains, thermostat settings, use of natural ventilation, etc.) have a relatively minor effect (±7%) on SEER. All these building characteristics can and do have a significant effect on annual cooling energy, but less so on seasonal cooling system efficiency. Their impact on savings in annual cooling energy resulting from replacing one SEER rated system with a higher SEER rated system is even less.

- SEER is poor predictor of cooling system electric demand in residential applications. Demand impacts can be predicted much more reliably when based on cooling systems' rated EER. One has to move to a SEER-14 rated system from a SEER-10 system to be assured of cooling system demand reductions. EER, when adjusted for climate effects via SEER-specific multipliers given in Table ES-2, can distinguish demand benefits to within ±8% of the climate-adjusted EER.

- The current 2005 Title-24 ACM calculation method provides a 30% improvement is estimating seasonal cooling system efficiency over rated SEER (ACM-calculated SEER based on the units' rated EER as opposed to the default EER of 10). The ACM method tends to understate seasonal cooling system efficiency by ~8% for single-speed equipment and ~2% for two-speed equipment. Understating cooling system efficiency overstates the benefits associated with non-HVAC system building upgrades (higher insulation levels, reduced infiltration, better windows, etc.).

6.0 REFERENCES

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APPENDICES

The following information is provided here as supporting detail and reference:

APPENDIX A Differences between the SEER Ratings Process and DOE-2 Calculations

APPENDIX B Cooling System Selection Procedure

APPENDIX C Generating Part-Load Curves for DOE-2

APPENDIX D Review of Residential Fan System Operation and Duct Losses

APPENDIX E Details of Single Family Building Prototype

APPENDIX A: THE SEER RATINGS PROCESS AND DOE-2 CALCULATIONS

The process whereby NIST conditions are matched by changes in the DOE2 models is given in Table A.1.

Table A.1.
Comparison of NIST & DOE-2 Calculation Approaches

	Cooling System Performance Assumptions	
Calculation Assumptions	NIST	DOE-2 Program
Calculation Method	Single point from simplified bin analysis	Hour-by-hour simulation.
Imposed Load Shape	Fixed	Closely matching load profiles with mid-load temperatures of 82.5º F and 84.5º F. See Figure 1.
Cooling System Capacity	Fixed	Cooling total capacity adjustment curve (COOL-CAP-FT) changed to a fixed value of 1.0.
Cooling System Efficiency	Fixed value for at an outdoor temperature of 82º F and 67º F entering air wet- bulb. Original work using temperature dependency for actual systems produced SEER within 10% of single point value.	2nd order variation with outdoor dry-bulb only via COOL-EIR-FT. Wet-bulb dependency eliminated by creating curve-fit coefficients at a fixed 67º F entering air wet-bulb.
Part-load performance	Assumes 50% cycling rate based on a fixed total cooling capacity	Varies with actual coil load and total capacity.
Cooling System sensible-to-total ratio & Coil Load sensible-to-total ratio	Not addressed. Ratings and load based on total net capacity with no consideration of sensible and latent components	System sensible heat ratio set to 1.0. Effect of coil entering conditions on the cooling coil by-pass factor removed. Sensible capacity adjustment curve set to the total (COOL-CAP-FT = COOL-SH-FT)
Cooling Coil Entering Conditions	Fixed at 80 F DB, 67 F WB	Fixed at 80 F DB, 67 F WB by setting capacity, efficiency, and by-pass performance curves to fixed ARI entering air conditions.

The load profiles generated in DOE-2 simulations are compared to that used by NIST in

Figure A.1. They DOE-2 profiles are for the two possible building orientations – north/south and east/west. The east/west orientation produces a slightly higher mid-load temperature of 84.5º F as compared to the 82.5º F mid-load temperature for the north/south orientation. Both profiles are similar to the NIST profile, with the 82.5º F mid-load temperature profile providing the closer match. These profiles are representative of either a single story house with a single cooling system or a two story house with a single cooling system. Simulation results based on two story houses with a cooling system per floor were not used. The bottom floor load profile differed too much from NIST assumptions to be useful.

Figure A.1.
NIST and DOE-2 Generated Cooling Load Profiles

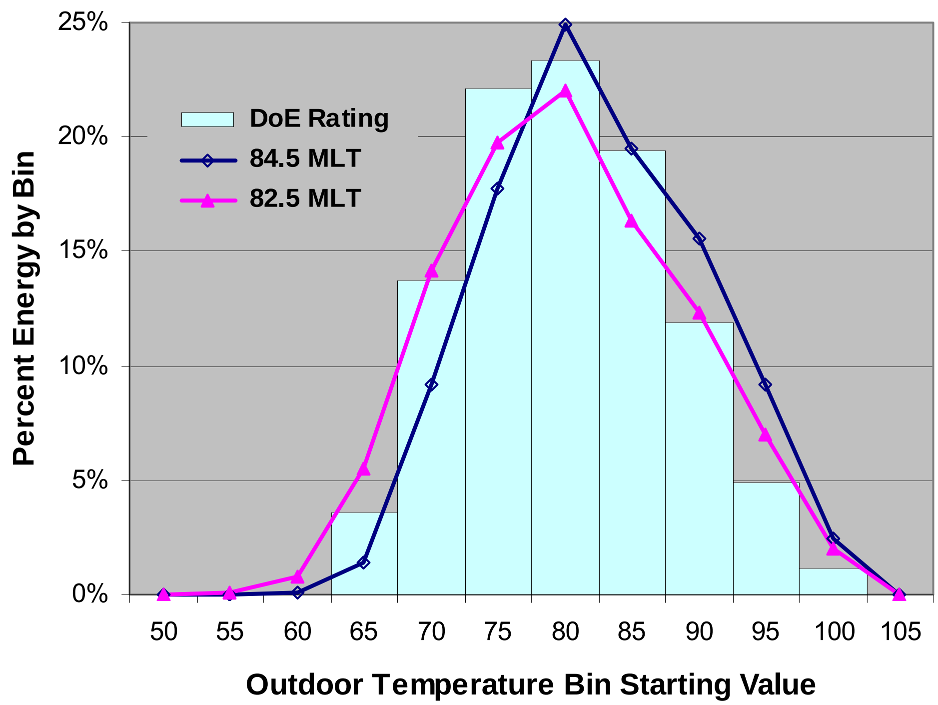


Figure A.2 provides a comparison of predicted SEER ratings using full DOE-2 performance curves versus those adjusted to match NIST assumptions. The points noted as “Full Model” use performance curves based on manufacturer’s published data and expanded ratings tables. Those noted as the “Simple Model” have had their “Full Model” performance curves adjusted to match conditions noted in Table A.1. Performance curves in the “Simple Model” are no longer dependent on cooling coil entering air conditions and produce performance values that would occur at cooling coil entering conditions of 80º F dry-bulb and 67º F wet-bulb. The curves also force the sensible cooling capacity to equal the total since the NIST ratings procedure does not differentiate between the two.

The agreement between the SEER generated by the “Simple Model” and rated values for single speed (SEER 10, 12 and 14) systems is quite good. The scatter in the results is within ±5% of the rated SEER. This is within the variation Kelly and Parken reported in the development of the

SEER ratings procedure when they applied the full bin method to real systems and compared results to the single point analysis. The scatter is associated with slight differences in the performance characteristics of the various systems (more so than differences in the load profiles). Some scatter in predicted SEER is to be expected as a result of even minor differences in cooling equipment performance characteristics, load sequencing, and cycling losses. On hindsight, it seems unrealistic that a single seasonal efficiency prediction should be expected given the detail to which the DOE2 program looks at the cooling system's response to building loads. A more reasonable view might be that DOE2-predicted SEER values are equivalent if within 5% of each other.

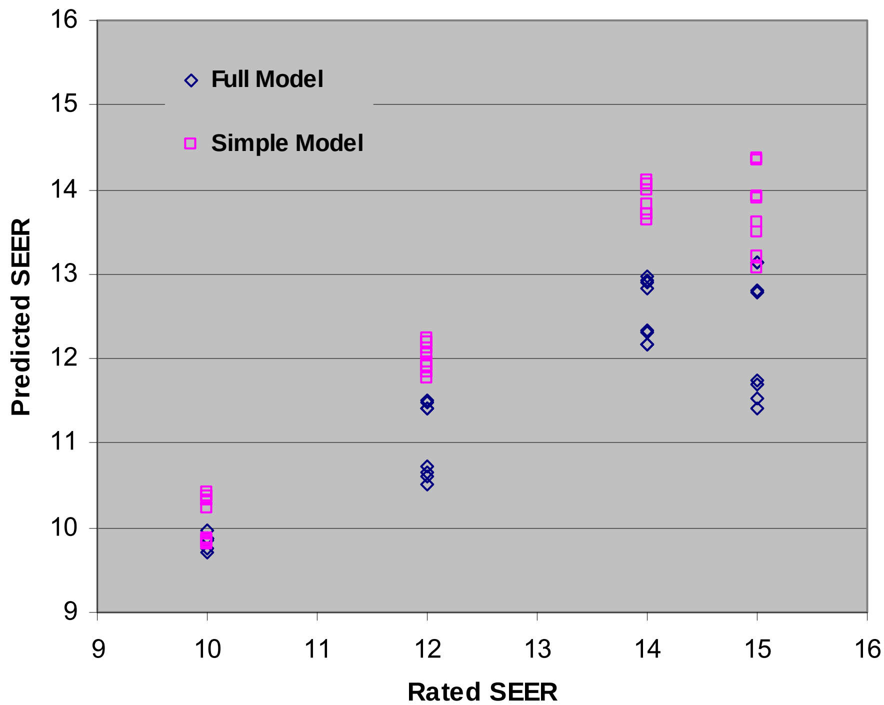
While SEER agreement using the "Simple Model" is good for single-speed systems, it is not so for two-speed systems. The "Simple Model" applied to two-speed systems did result in much better agreement than "Full Model" simulations. Differences improved from a range of 12% to 25% to a range of 4% to 13%. The rating of the two-speed systems are much more load shape dependent than the single speed systems. As such, greater differences between the rated and DOE2-predicted SEER values are to be expected. It is not clear at this point if there is an inherent problem in the NIST rating approach for two-speed systems or if the residential load models haven't adequately reproduced the necessary load sequencing to replicate the rated SEER.

Predicted SEER values for two-speed systems based on the "Simple Model" are more sensitive to changes in the mid-load temperature and system performance characteristics than single speed systems. Differences in mid-load temperature accounts for approximately 4% of the scatter in the points; differences between the performance characteristics of the two systems accounts for 6% of the scatter. Scatter for the single speed systems (about 5%) is almost entirely a result of differences in the different system performance characteristics.

A comparison of DOE2 predicted SEER between "Simple" and "Full" model simulations indicate that the lack of agreement between rated and DOE2-predicted SEER values for the "Full Model" are a result of more realistic cooling coil entering conditions rather than any problem with the DOE2 simulation process. The difference between predicted SEER of the full and simple models provides a measure of the impact of coil entering wet-bulb temperature on SEER (for at least climate zone 12.) The mid-load wet-bulb of the air entering the coil for simulations whose results are shown in Figure A.2 is 58º F ±1º F. The lower average entering air wet-bulb will lead to a loss of cooling efficiency in comparison to the 67º F rated conditions. A review of the EIR dependency on wet-bulb for the systems used in the simulations suggests efficiency reductions of 7%, 12% and 15% for the 10, 12, and 14 SEER systems respectively. The difference between the simple and full model predicted SEER values are 2%, 8%, and 9%, preserving the overall trend of increasing efficiency loss from lower to higher SEER-rated systems.

The magnitude of the efficiency loss is affected by factors that are also impacted by the lower entering air wet-bulb temperature. These include higher sensible fraction and lower total cooling capacity. The higher sensible fraction means that more of the condenser unit energy is used to control space temperature, rather than remove moisture. Since runtime is determined by the sensible capacity of the system, the higher the sensible fraction, the lower the system runtime for a given condenser unit energy input. The lower wet-bulb also causes a reduction in cooling capacity, which is why the EIR increases as the entering air wet-bulb decreases. But the reduced capacity means the system runs longer, leading to lower cycling losses. So, while the lower capacity increases the EIR, the increased runtime reduces the overall effect. Thus, both higher sensible fraction and reduced cycling losses work together to reduce the impact of the higher EIR on overall efficiency.

Figure A.2.
Comparison of DOE2–Predicted SEER, Full and Simple Models



From this it seems unlikely that the difference between the mid-load entering air wet-bulb and the NIST 67º F rating point will produce a SEER correction based on manufacturer's expanded ratings data alone. However, there may be some appropriate multipliers that can be applied to account for this effect, perhaps on a climate zone basis, or climate zone plus expanded rating data. A determination of possible correction factors will require a comparison of "Simple" and "Full" models in other climate zones.

APPENDIX B: COOLING SYSTEM SELECTION PROCEDURE

There are approximately 7,000 different cooling systems listed in the CEC air conditioner and heat pump database. The Hiller database contains details on nearly 1,000 systems. It would be an overwhelming effort to simulate even the systems in the Hiller database, let alone the full CEC database. As such, a rational means is required to select a subset of available systems for analysis. The approach taken was to use a number of metrics to identify specific cooling systems. Selected systems would be representative of other systems with the same or similar metrics. The metrics used include the following:

- Nominal SEER
- System arrangement – split system or packaged
- System type – air conditioner or heat pump
- Cycling performance – degradation coefficient (C_D) as determined in DOE SEER test procedures
- EER/SEER ratio – System's EER_{ARI}/SEER
- System's sensitivity of EER to outdoor temperature as indicated by the linear slope of its normalized EER curve, or $EER\_f(T_{osa})/EER_{ARI}$ = constant + $slope_{EER}$ * outside air temperature. $Slope_{EER}$ is the EER temperature sensitivity metric.
- System's sensitivity of capacity to outdoor temperature - linear slope of its normalized capacity curve, or $Cap\_f(T_{osa})/CAP_{ARI}$ = constant + $slope_{CAP}$ * outside air temperature. $Slope_{CAP}$ is the capacity temperature sensitivity metric.

The best way to show how these metrics can be used to select cooling systems is to begin with the definition of SEER for single speed system, or

$$SEER \equiv EER_{82F}(1\text{-}0.5{*}C_D).$$

Thus, systems that only differ by their C_D value will have different EER's at ARI conditions. This is illustrated in Figure B.1, which shows how C_D reflects performance differences among similar nominal 10 SEER systems.

Notice that differing values of C_D cause a vertical shift in the system's EER curve. Higher values of C_D shift the EER curve upward; lower values shift the curve downward. This is because the EER_{82F} (large markers in the figure) must increase as C_D increases to maintain the same SEER. The values of C_D shown in Figure B.1 represent the range of values appropriate for SEER 10 air conditioners. As such, one should expect to see a range of EER_{ARI} (small marker in the figure) from as low as 8.7 to as high as 9.9 just to account for the full range of C_D.

The sensitivity of a system to outside air temperature also impacts its efficiency at differing conditions. This is illustrated in Figure B.2, where all systems are assumed to have the same value of C_D, and thus EER_{82F}, but differing sensitivity to outdoor temperature. The range of EER slope provided in the figure is typical of SEER 10 air conditioners. In this case, different values of EER_{ARI} result from the system's temperature sensitivity even though all have the same C_D.

Figure B.1.
Effect of C_D on System Performance – SEER 10 Systems

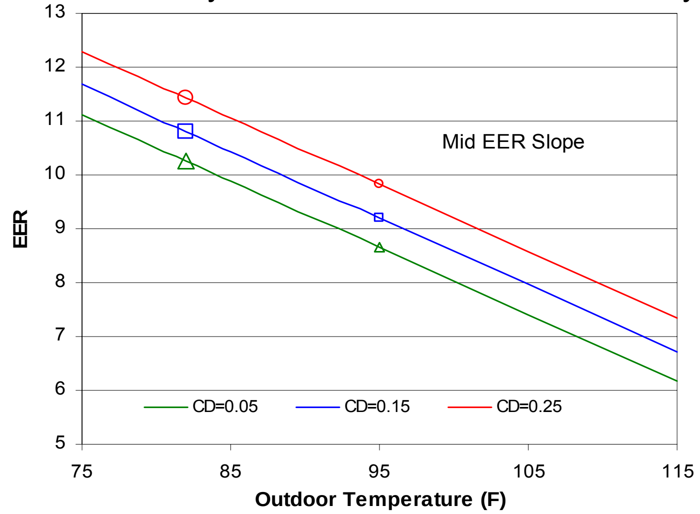
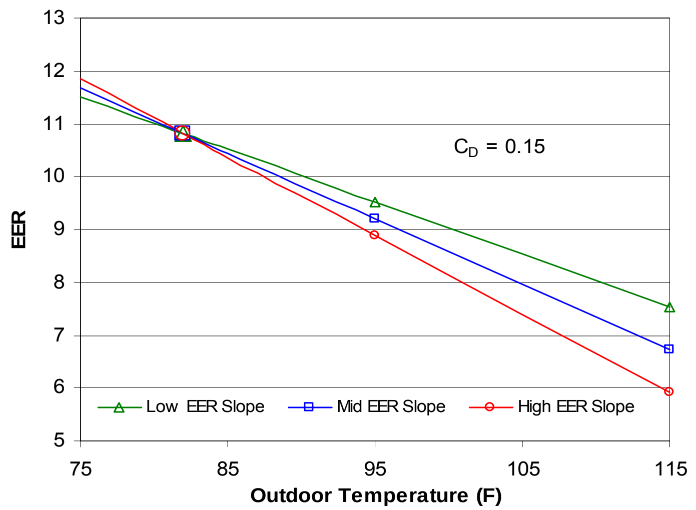
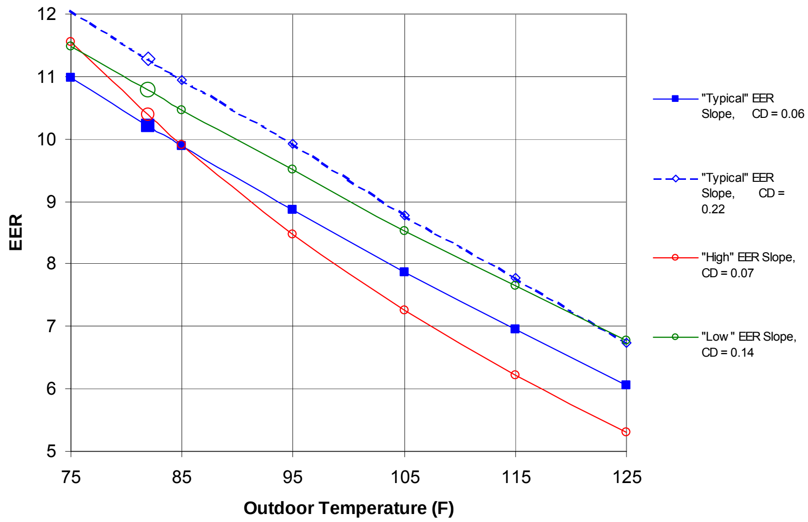


Figure B.2
Effect of $Slope_{EER}$ on System Performance – SEER 10 Systems



The significance of these particular metrics is that they define EER performance boundaries for a particular class of cooling systems. A cooling system class is defined by a system's nominal SEER rating, whether it is an air conditioner or a heat pump, and whether it is a split or packaged system. An example of the EER performance boundary for SEER 10 air conditioners is shown in Figure B.3. The EER curves are for actual systems from the Hiller database of single-speed, split system air conditioners with a nominal 10 SEER. They span the range of EERs expected for this type of cooling system. Different systems (higher efficiency systems, or heat pumps, or packaged systems for example) would have different EER boundaries.

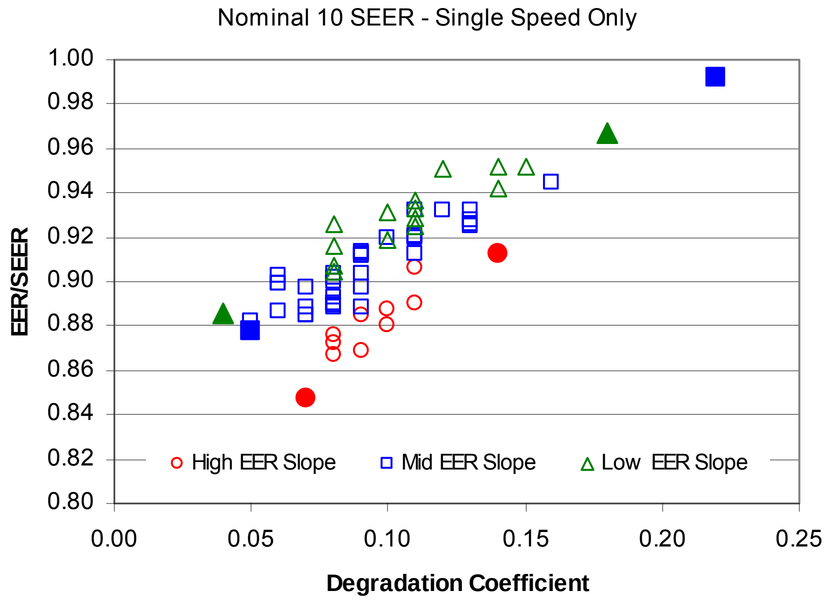
Figure B.3
Comparison of EER Data for SEER 10 Split-System Air Conditioners



The Hiller database provides additional information on the relationships between values of C_D and $Slope_{EER}$, Typically, systems with high values of $Slope_{EER}$ tend to have lower values of C_D. Systems with lower values of $Slope_{EER}$ tend to have higher values of C_D. Systems with mid-values of $Slope_{EER}$ can exhibit the full range of C_D values. The range of expected values of both C_D and $Slope_{EER}$ changes when going from low SEER systems to high SEER systems and differs between air conditioners and heat pumps, split and packaged systems. The Hiller database provides the expected range of conditions for each cooling system class as systems were selected by Hiller to represent performance extremes. In particular, for a particular cooling system class, it provides high and low values of C_D for high, low, and mid values of $Slope_{EER}$.

The selection process is illustrated in Figure B.4. (The actual selection would be based on a sorting and ranking process rather than graphics). The figure is a plot of the EER_{ARI}/SEER ratio for all SEER 10, single-speed, split system air conditioners in the database. System capacity ranges from 1.5 to 5.0 tons. The EER_{ARI}/SEER ratio is plotted against the system's C_D. Color-coding identifies systems with high, mid, and low values of $Slope_{EER}$. The figure shows the relationships between the various selection metrics and limits on their values. The selection process would pick systems shown as filled symbols in the figure. Three others, representing median values of C_D would also be selected. If necessary, additional systems would be selected that have the highest and lowest EER_{ARI}/SEER ratio. This approach spans the expected performance range of all SEER 10 split system air conditioners. Systems selected by this approach would have $8.5 < EER_{ARI} < 9.9$.

Figure B.4
Example of System Selection Procedure



It is worth noting that a system's rated cooling capacity is not part of the selection process. This is because no trend has been found that suggests that capacity should be considered. There are some occasions when, within a given product line, larger capacity systems have somewhat different selection metrics than smaller capacity systems. However, differences within a product line are small in comparison to other product lines from the same manufacture or different manufacturers' products. More often than not, there is no discernable difference for systems within a product line, or there is no discernable trend (e.g. a 3.5-ton system looks like a 2-ton system while a 6-ton system looks like a 1.5-ton system, etc.)

This selection approach will be used when performing final statistical analyses over the full range of available systems. The CEC air conditioner database contains C_D values for all listed systems. In addition, the database provides EER at 95 F and at 82 F, which can be used to estimate the $Slope_{EER}$ metric. The database will be used to provide statistical profiles for C_D, $Slope_{EER}$, and correlate limits on their values (e.g. appropriate range and distribution of values of C_D for each selected value of $Slope_{EER}$, etc.).

The definition of HVAC system characteristics for Phase 1 includes both the selection of the SEER-rated cooling system and a definition of air distribution system. The method of selecting the SEER-rated cooling systems was identified in "HVAC Selection Process – Interim Report", issued December 2002. Single-speed air-conditioners and heat pumps were selected based on their rated degradation coefficient and their EER sensitivity to ambient temperature. As indicated in the interim report, variations in these two metrics define the full range of EER values for systems with a given SEER.

Once selected, a system performance database was developed which includes all the nominal values and performance curves required to define the systems' operational characteristics for a DOE-2 simulation. The database holds curve fit coefficients that define off-design characteristics for the DOE-2 simulations. Nominal values and off-design curve-fit coefficients held in the system performance database are described in Table 1. The database currently holds performance data on twelve systems. They include SEER 10, 12, & 14 rated split system heat pumps and air conditioners, SEER 10 and 12 packaged heat pumps and air conditioners, and two two-speed air conditioners. The single speed systems selected had median values of EER sensitivity to ambient temperature and degradation coefficient. The database will be expanded to include systems with high and low EER sensitivity and high and low degradation coefficient. The implementation of phase two will see the addition of SEER 11 and SEER 13 systems to the database.

The only variable that defines the size of the cooling system is its rated cooling capacity. All other performance variables given in Table B.1 are defined in terms of the cooling capacity. While the cooling capacity of each system is included in the equipment database, it typically is not the capacity used in DOE-2 simulations. A sizing criterion replicates the overall methodology of the SEER ratings process. The SEER ratings assume a building load based on the cooling system capacity. The building load is defined as:

$$BL(T_j) = \frac{5j - 3}{95 - 65} * \frac{Q_{ss}(95\ F)}{1.1} \qquad (B.1)$$

where:

$BL(T_j)$ is the building load at outdoor temperature T_j,

j is the temperature bin number from 1 to 8,

$Q_{ss}(95\ F)$ is the system's cooling capacity at 95 F ambient temperature and

the constant 1.1 represents 10% excess capacity at the 95 F ratings condition.

The peak load on the cooling system in the SEER ratings process occurs at the maximum bin temperature, or when j = 8. Using equation 1, the system's cooling capacity can be related to the peak cooling load by setting j to 8, or:

$$BL_{max} = 1.23 * \frac{Q_{ss}(95\ F)}{1.1} \qquad (B.2)$$

Rearranging,

$$Q_{ss}(95\ F) = BL_{max} * \frac{1.1}{1.23} \qquad (B.3)$$

or the capacity of the cooling system equals ~90% of the peak coil load.

This is the sizing criterion used in all simulations. This requires two simulations for each building prototype examined. The first determines the peak cooling coil load to determine the required cooling capacity. The second determines the seasonal performance of the system base on the cooling capacity as determined by the first run. This sizing approach is possible since it has been determined that cooling capacity is not a factor in the selection of the various cooling systems (see above). Finally, sizing issues will be reviewed in when the sensitivity of SEER to over and under-sizing is addressed.

Table B.1.
DOE-2 Equipment Performance Data Base

Field #	Description	Systems	Curve Fit Dependent Variable	Curve Fit Independent Variables
1	Evaporator Config.	Splt/Pkg	n/a	n/a
2	System Type	AC/HP	n/a	n/a
3	Nominal SEER	None	n/a	n/a
4	EER Slope	H, M, L	n/a	n/a
5	Degradation Coeff.	H, M, L	n/a	n/a
6	Mfg. & Model #	n/a	n/a	n/a
7	Gross Cooling Cap	Btu/hr	n/a	n/a
8	Sen. Heat Ratio	none	n/a	n/a
9	EIR	none	n/a	n/a
10	Rated Air Flow	cfm/Btu/hr	n/a	n/a
11	Fan Energy	W/cfm	n/a	n/a
12	Coil By-Pass Factor	none	n/a	n/a
13	Crankcase Energy	W/Total W	n/a	n/a
13	Crankcase Off Temp	F	n/a	n/a
14-19	Curve Fit Coefficients	none	Total Capacity	EA WB, Amb DB
20-25	Curve Fit Coefficients	none	Sensible Capacity	EA WB, Amb DB
26-31	Curve Fit Coefficients	none	EIR	EA WB, Amb DB
32-37	Curve Fit Coefficients	none	Coil By-Pass	EA WB, EA DB
38-49*	Curve Fit Coefficients	none	EIR	Part-load Ratio
50	Number Cooling Stages	1, 2	n/a	n/a
51	Low-Speed Cap Ratio	none	n/a	n/a
52	Low-Speed cfm Ratio	none	n/a	n/a

* Up to three curves are defined for each system to account for ductwork transients described below.

Additional information defines the air distribution system. This includes ductwork parameters such as R-value, area, leakage rate, and transient response time, along with fan energy requirements. Values for the various residential building prototypes are provided in Table B.2. Notes on the data sources and/or assumptions used in the table follow. Information on non-residential prototypes is given in Table B.3.

Table B.2.
Distribution System Definition – Residential Prototypes

		Residential Prototype		
Variable	Range	1 Story SF	2 Story SF	Multi-Fam.
Cooling Sources	n/a	A/C & HP	A/C & HP	A/C & HP
System Type	n/a	Split	Split	Split
System Capacity (% Peak Coil Load)	Low	90%	90%	90%
	Median	*110%*	*110%*	*110%*
	High	*150%*	*150%*	*150%*
System Fan	Rated	*From System*	*From System*	*From System*
Energy (Watts)[1]	High	*1.4 Mult*	*1.4 Mult*	*1.4 Mult*
Fan Operation	n/a	Intermittent	Intermittent	Intermittent
Fan Location	A/C	Blow-Thru	Blow-Thru	Blow-Thru
	HP	Draw-Thru	Draw-Thru	Draw-Thru
Supply Duct Area in Attic[2]	n/a	27% FA	18% FA	18% FA
Return Duct Area in Attic[2]	n/a	5% FA	10% FA	10% FA
Duct work R-Value[2]	n/a	4.9	4.9	4.9
Ductwork Time Delay[3]	Temp CZ's	12 sec	12 sec	12 sec
	Mod CZ's	21 sec	21 sec	21 sec
	Hot CZ's	29 Sec	29 Sec	29 Sec
Supply Leakage to Outside[4]	A/C Low	*3%*	*3%*	*3%*
	A/C Median	7%	7%	7%
	A/C High	*14%*	*14%*	*14%*
Supply Leakage to Outside[4]	HP Low	*2%*	*2%*	*2%*
	HP Median	4%	4%	4%
	HP High	*9%*	*9%*	*9 %*
Return Leakage to Outside[4]	A/C Low	*1%*	*1%*	*1%*
	A/C Median	3%	3%	3%
	A/C High	*7%*	*7%*	*7%*
Return Leakage to Outside[4]	HP Low	*3%*	*3%*	*3%*
	HP Median	7%	7%	7%
	HP High	*14%*	*14%*	*14%*

Notes:

1. *Data from Florida Solar Energy Center and PG&E residential survey reports. See Appendix D.*
2. *From California Non-Residential ACM manual, Appendix F. Ductwork R-value includes exterior and interior film resistance with nominal R-4.2 duct insulation.*
3. *Ductwork time delays based on CFD analysis presented in "EER-SEER Cooling System Cyclic*

Performance" forwarded December 2002. Time delays are based on expected attic temperatures related to the three climate zone categories listed in the table. Temperate climate zones (Temp CZ's) are CZ-03 through CZ-08, plus CZ-16. Moderate climate zones (Mod CZ's) are CZ-02, CZ-09, CZ-10, CZ-12, and CZ-13. Hot climate zones (Hot CZ's) are CZ-11, CZ-14, and CZ-15. Time delays assume lightweight ductwork including fiberboard and spiral flex duct. Time delays in the table add to the cooling systems' response times as incorporated in their degradation coefficients. Their effects are accounted for in DOE-2 simulations via EIR_f(PLR) performance curves. This is why there are up to 12 fields used define the EIR_f(PLR) curves in Table 1as they represent coefficients for three possible curves. Each curve includes the effects of the three ductwork time delays. Simulations will pick the appropriate curve for the climate zone used.

4. *Data from Florida Solar Energy Center and PG&E residential survey reports. See Appendix D. The PG&E RNC report suggest a higher duct leakage rate for multi-family in comparison to single-family construction. The report suggests that the additional leakage may be associated with the use of wall cavities for ductwork. It is assumed that leakage from wall cavities (typically return chases) is predominantly from the conditioned space and that overall leakage to the outside is similar to single-family construction. Low leakage values assume a duct-sealing program has been implemented.*

Phase I of the project is divided into phase 1a and 1b. Phase 1a uses typical system characteristics over the full range of residential and non-residential building prototype variation. Phase 1b examines the full range of system characteristics for "typical" building prototypes. Only median values of the system characteristics given in Tables B.2 and B.3 are used in Phase 1a, with the exception of system sizing. Here, the low value of system sizing is used as it matches SEER ratings procedures. Note that duct transients apply to the specific climate zone against which the simulation models are executed. As such, there are no low, median, and high values of duct transients – only temperate, moderate, and hot climate zones. Values used in Phase 1a in the table are presented in a standard font – those added in Phase 1b are shown in italics.

Once the go-ahead is given to execute Phase 1a, results will be generated by running all building prototype models against the typical mechanical systems. This will allow a statistical selection of building prototype variables that reflects median building characteristics. Once approved, Phase 1b will simulate low and high system variables (shown in italics in the tables) against "typical" building prototypes.

Table B.3.
Distribution System Definition – Non-Residential Prototypes

Variable	Range	Non-Residential Prototype Retail	Office	School.
Cooling Sources	n/a	A/C & HP	A/C & HP	A/C & HP
System Type	n/a	Split & Pkgd	Split & Pkgd	Split & Pkgd
Packaged Systems – System External Static (in wg)	Low	*0.5*	*0.5*	*0.5*
	Median	0.75	0.75	0.75
	High	*1.0*	*1.0*	*1.0*
Split Systems – System Fan Energy (Watts)[1]	Rated	*From System*	*From System*	*From System*
	High	*1.4 Mult*	*1.4 Mult*	*1.4 Mult*
Fan Operation	n/a	Continuous	Continuous	Continuous
Fan Location	A/C	Blow-Thru	Blow-Thru	Blow-Thru
	All other	Draw-Thru	Draw-Thru	Draw-Thru
Ductwork Location	n/a	Rtrn Plenum	Rtrn Plenum	Rtrn Plenum
Supply Duct Area[2]	n/a	13% FA	13% FA	13% FA
Supply Duct R-Value	n/a	2.8	2.8	2.8
Supply Duct Leakage[3]	n/a	2%	2%	2%
Ductwork Transients[4]	n/a	0	0	0

Notes:

1. *Split systems can not support full range of external static pressures assumed for packaged systems.*
2. *Assumes half the duct surface area of residential system. Assumption based on a doubling of the flow per diffuser in commercial applications in comparison to residential. The larger flow results in half the number of branch ducts and reduced branch duct area per cfm delivered because of the large branch duct diameter (a 6" diameter duct supplies half the flow of an 8" diameter duct, but has only 1/4 less perimeter). The number of trunk ducts is also reduced because of the higher air-volume per branch duct.*
3. *Assumes Class C duct seal with a 0.5" wg static pressure differential across the supply duct. Ductwork leakage is assumed to be from the supply to a return plenum rather than to the outside.*

There are no ductwork transients with continuous fan operation. Thermal delays that occur when the compressor starts are assumed to be recovered when the compressor turns off.

APPENDIX C: GENERATING PART-LOAD CURVES FOR DOE-2

I. Generating Thermostat-Based Part-Load Curves for Use in DOE-2 Simulations

The cyclic performance of the air conditioning system is calculated from the equivalent delay time (Z_D) method. This is a thermostat-based approached developed by Honeywell and presented by Rice, et al (C.11). The equivalent delay time is defined such that difference between an air conditioner's capacity at start up and its steady state capacity is equal to an on-time delay, or

$$q_{cyc} = (t_{on} - Z_D)\, Q_{ss}, \tag{1}$$

where

q_{cyc} = cooling output at start-up.

Q_{ss} = steady-state cooling capacity

t_{on} = the runtime in a cooling cycle, and

Z_D = the equivalent delay time.

The equivalent delay time is a close approximation of the first order air-conditioning system response model given in Henderson and Rengarajan (C.4). They define the cooling output over a cooling cycle as

$$q_{cyc} = [t_{on} - \tau(1 - \exp(-t_{on}/\tau))]\, Q_{ss}, \tag{2}$$

where

τ = time constant of the air-conditioning system, and all other terms are as previously defined.

A comparison of Equations 1 and 2 show that

$$Z_D = \tau[1 - \exp(-t_{on}/\tau)]. \tag{3}$$

The difference between Z_D and the time constant used by Henderson and Rengarajan can be determined by substituting reasonable values for the time constant and runtime in Equation 3. For a standard DOE cyclical test as mandated by ARI Standard 210 (C.1), the system's runtime is 6 minutes, or 360 seconds. From Henderson, et al (6), the largest time constant expected from the DOE cyclical test is 76 seconds, as this corresponds to a degradation coefficient of 0.25. Systems with lower degradation coefficients will have lower time constants. Using these values with equation 3 gives $Z_D = 0.992\tau$. Henderson, et. al. (C.6) suggest that the six minute system run times used in the DOE cyclical test are less than typically observed in the field. In addition, the 76 second system time constant (corresponding to a $C_D = 0.25$) is the highest value used in any cooling system SEER rating. A more typical value is based on a $C_D = 0.1$ is 29 seconds. Both factors will reduce differences between the equivalent time delay (Z_D) and the system time constant (τ). Thus, for typical cycling rates over the range of expected values of air-conditioning system time constants, the two approaches can be viewed as equivalent. Subsequent derivations based on the equivalent time delay approach will use the system time constant (τ) in lieu of the equivalent time delay (Z_D).

Using Equation 1, the cooling load factor (CLF), as defined in ARI Standard 210 (C.1), can be written as:

$$CLF = (t_{on} - Z_D)/(t_{on} + t_{off}) \tag{4}$$

where:

t_{off} = the off-time in a cooling cycle, and all other terms are as previously defined.

Defining the fractional on-time (f_{on}) as the on-time divided by the total cycle time, and the total number of cycles in an hour as N, Equation 4 can be re-written as:

$$CLF = f_{on} - N\,\tau/3600, \tag{5}$$

where:

N = the cycling rate of the air conditioner defined as $1/(t_{on} + t_{off})$ in cycles/hour.

The cycling rate is calculated from the thermostat characteristic equation given by (4, 5, 10, and 11)

$$N = 4N_{max}\, f_{on}\,(1 - f_{on}) \tag{6}$$

where:

N_{max} = the thermostat maximum cycling rate in cycles/hour.

From Equations 5 and 6, the fractional on-time of the air conditioning system can be calculated from the cooling load factor, the thermostat maximum cycling rate, and the cooling system's time constant, or:

$$f_{on} = \frac{-(1-X)+\sqrt{(1-X)^2 + 4X\,CLF}}{2X} \tag{7}$$

where:

$X = 4\,N_{max}\,\tau/3600.$

The part-load factor can then be determined from the fractional on-time by assuming that the power consumption of the system is achieved immediately, or

$$PLF = \frac{CLF}{f_{on} + (1 - f_{on})P_{off}} \tag{8}$$

where:

PLF = the ratio of the part-load EER to the steady state EER, and

P_{off} = percentage of off-cycle power consumption to that at full load. P_{off} would include any controls power consumption or, more likely, crankcase heat as controls power consumption is typically negligible.

Henderson, et al (C.6) show that the EIR_*f*(PLR) relationship used by the DOE-2 is equivalent to

$$\text{EIR\_}f(\text{PLR}) = \text{PLR}/\text{PLF}. \tag{9}$$

The cooling load factor used in the development of a SEER rating, as defined by Kelly and Parken (C.7), is the same as the part-load factor as used in the DOE-2 program. Equating the two (CLF = PLR) allows a combination of Equations 9 and 10, giving 10a.

$$\text{EIR\_}f(\text{PLR}) = f_{on} + (1- f_{on})\, P_{off}\,, \tag{10a}$$

In 10a, the fractional on-time of the system (f_{on}) is calculated via Equation 7. From Equation 7, f_{on} is a function of CLF, τ, and N_{max}. Thus, for a given PLR (PLR = CLF), the impact of cycling on a cooling system's EIR is a function of the system time constant (τ) and maximum thermostat cycling rate (N_{max}). DOE-2 used the EIR_*f*(PLR) curve to simulate the cycling losses of a compressor when the fan operates continuously. The program uses a cycling loss curve [C-LOSS_*f*(PLR)] when the fan cycles with the compressor. The two curves are related to each other as the EIR curve equals the PLR divided by the C-LOSS curve, or:

$$\text{C-LOSS\_f(PLR)} = \text{PLR}/[\, f_{on} + (1- f_{on})\, P_{off}] \tag{10b}$$

II. Determining the Cooling System Time Constant from C_D

The definition of the degradation coefficient (C.7) is

$$C_D = (1 - \text{PLF})/(1 - \text{CLF}) \tag{11}$$

This can be cast in terms of the system's time constant by substituting Equation 8 into Equation 11. For essentially all air conditioner and most heat pumps, P_{off} can be assumed to be zero. This is appropriate since crankcase heat is typically the only significant off-cycle power consumption, and is invariably listed as an "option" and not part of the "standard test system" when cyclical tests are performed. Finally, f_{on} for the ARI Standard 210 cycling test is 0.2. With these observations,

$$C_D = (1 - 5\ \text{CLF})/(1 - \text{CLF}) \tag{12}$$

Using Equation 5 to relate CLF to the system time constant,

$$\tau = 288\ C_D/(1 - 0.2\ C_D), \tag{13}$$

where τ is the time constant of the cooling system in seconds. This equation is important in that time constant can be assumed to be a physical characteristic of the cooling system. Time constants corresponding to various values of CD are given in Table C.1.

Table C.1

Response Time for Various Values of C_D

C_D	τ (sec)
0.25	76
0.20	60
0.15	45
0.10	29
0.05	15

There is some concern that the ARI cyclical test may skew the determination of the degradation coefficient, and thus the estimate of its time constant. In particular are issues associated with the use of isolation dampers in conjunction with highly insulated duct sections before and after the cooling coil. The effect of these features is to isolate the cooling coil from its environment during the off-cycle.

The literature is unclear as to the magnitude of this effect. Nguen et al (C.9) suggested that the use of dampers could result in significant differences in the calculation of the degradation coefficient. Their comparison, however, was based on two different systems with the same EER_A rating (EER at 95 F outdoor temperature; 80 F dry-bulb and 67 F wet-bulb return air temperature). There is no indication as to how much of the difference in the degradation coefficient is a result of physical differences between the two systems (type of refrigerant control device, refrigerant charge, system response to changing ambient conditions, etc.) as opposed to the measurement process.

Lamb and Tree (C.8) examined the potential errors associated with the use of dampers in cyclical test measurements. Their analysis looked at the transient thermal effects associated with the mass of the cooling coil and surrounding ductwork (5 feet ahead and behind the coil). The magnitude of the largest error calculated was within 3% of the "ideal" measurement associated with a zero-mass coil. While they felt that use of dampers could affect the response time of the system for some types of flow control devices, dampers would have minimal impact on response times resulting from the mass of coil and test ductwork.

Goldschmidt, et al (C.3) looked at the field performance of a heat pump in the heating and cooling mode and an air conditioner with the goal of determining seasonal degradation coefficients. They found that the transient response of both systems was essentially constant over the full test range of ambient and indoor conditions. They also found that the time constant of the heat pump in the heating mode differed from that measured in the cooling mode. The difference suggested to the authors that the transient response was related to refrigerant dynamics as the mass of the indoor coil, by itself, could not explain the differences in the heating and cooling response times, nor the magnitude of the response time observed. Goldschmidt used transient temperature responses in the cooling mode to calculate degradation coefficients based on Standard 210 cycling rates. Their estimates of C_D are presented in Table C.2, along with those that would have been calculated by Equation 13. There is good agreement between the two calculation methods.

Table C.2
Comparison of Measured and Calculated Values of C_D

	Measured Time Constant τ (sec)	C_D	
		From Measurements	From Equation 13
Heat pump – cooling	19.2	.066	.066
Air conditioner	28.2	.095	.096

Parken, et al (C.10) took seasonal test data on three heat pumps in the cooling mode. The data provided measured values of the systems' part load factors (PLF) over a range of cooling load factors (CLF). The seasonal data allowed relationships to be developed between fractional on-times and system cycling rates. They also performed standard cyclical tests to determine the degradation coefficient of one of the systems (System 3). Their results provide the following observations:

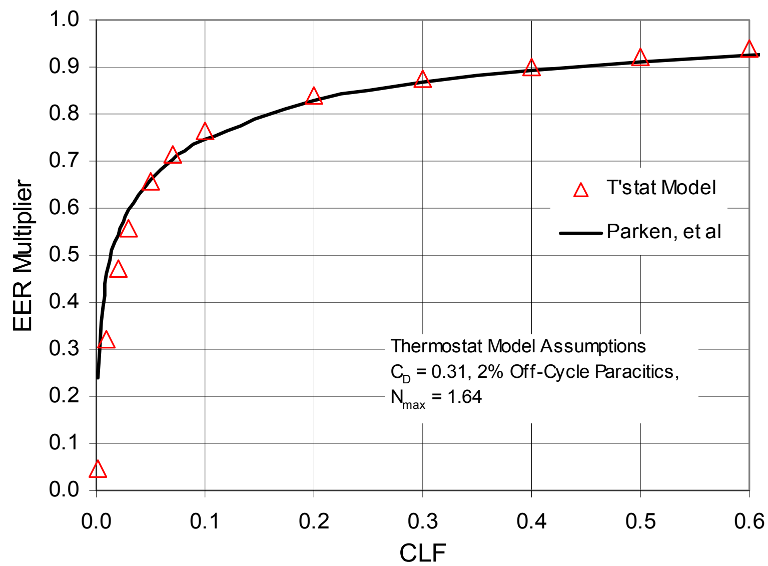
1. There was good agreement between the ideal thermostat model as provided in Equation 6 and observed cycling rates. The maximum cycling rate (N_{max}) for System 3 was calculated as 1.64 cycles per hour. Maximum cycling rates for the other two systems were 2.0 and 2.28 cycles per hour.
2. All three systems had a part-load factor that went to zero as the cooling load factor approached zero. This occurs when there are non-zero off-cycle power requirements – typically crankcase heat. Crankcase heaters would have been included in these systems as they were heat pumps located in a cold climate. It is unlikely that temperature controls to de-activate the crankcase in the cooling season would have been used at the time of the test (1980 cooling season).
3. The bench test of System 3 produced a degradation coefficient of 0.31 at the prescribed ARI maximum cycling rate of 3.125 cycles per hour. The measured degradation coefficient includes the off-cycle power consumption of the crankcase heater. The expected time constant of the system is less than that which would be predicted by Equation 13, as this equation assumes no off-cycle power consumption. Assuming 2% off-cycle parasitic losses, the time constant of System 3 as calculated via Equation 8 is 72.5 seconds.
4. They provided curve fits of measured PLF versus CLF for the three systems. Correcting for the delay in condensation formation on the cooling coil, PLF is related to CLF ($0.0 \le CLF \le 0.7$) for System 3 by

$$PLF_{System\ 3} = 1 - \exp(-3.0855\ CLF^{\,0.35}) \qquad (14)$$

Figure C.1 compares the measured performance of System 3 in the Parken et al test to that predicted by thermostat Equations 7 and 8. The thermostat equations use the measured degradation coefficient (C_D = 0.31), the measured maximum cycling rate (N_{max} = 1.64), and assumed off-cycle parasitic losses of 2% over a range of cooling load factors. As the figure shows, agreement is quite good.

The agreement between the Parken et al data and the equivalent time delay thermostat model suggest that the model is sufficiently robust to account for differences in thermostat maximum cycling rates and off-cycle parasitic losses. Given that the thermostat model can be translated into a DOE-2 EIR-f(PLR) curve, the agreement between the Parken et al data and the thermostat curve also suggests that current methods used by the DOE-2 program are sufficiently robust to account for cycling losses over a broad range of part-load operation. The data used by Parken to generate the curve fit shown in Figure 1 include points with fractional on times as low as 5%. The cooling load factor (part-load ratio in DOE-2 parlance) is always less than the fractional on-time. As such, part-load curve used by DOE-2 based on the thermostat model should account for cycling losses down to very low space loads.

Figure C.1
Comparison of Parken et al Data to Equiv. Time Delay T'stat Model



III. Appliance Cycling Losses

While the cooling system's time constant may be fixed, this is not the case for a system's cyclical losses. As illustrated by Equation 7, cyclical losses also depend on the load on the system and the thermostat maximum cycling rate. The ARI cyclical loss test procedure prescribes a maximum thermostat cycling rate by fixing the number of cycles per hour and the fractional on-time per cycle. The test forces two cycles per hour (two cycles of 6 minutes on and 24 off in one hour) with a 20% on-time fraction. Using these values (N=2 and f_{on} = 0.2) in Equation 6 gives a maximum cycling rate (N_{max}) of 3.125 cycles per hour. Thus, Equation 13, which relates degradation coefficients to system time constants, is valid for cycling rates as prescribed by the ARI test procedure. Once system time constants are known, however, the literature (C.3) suggests that they are unaffected by thermostat operation. Cycling losses will vary with changes in the thermostat cycling rate, but in response to a fixed cooling system time constant.

Actual maximum cycling rates depend on many factors, including the thermostat operation, minimum run-time controls, and the temperature response of the room in which the thermostat is located (C.5, C.3). In the literature maximum cycling rates from as low as 1.5 to as high as 3 (C.6) are reported. Henderson et al (C.6) recommends a value of 2.5 as typical. Lower maximum cycling rates result in reduced cycling losses for a given cooling system load factor. Seasonal energy consumption should decrease as a result. Part load factors for a 50% cooling load factor are compared in Table 3 for assumed maximum cycling rates of 3.125 cycles per hour (ARI Standard 210 test requirements) and 2.5 cycles per hour.

Table C.3.

Cooling System Time Constants for Various Values of CD

		PLF at CLF = 0.5	
C_D	τ (sec)	N_{max} = 3.125	N_{max} = 2.5
0.25	76	0.885	0.906
0.20	60	0.907	0.924
0.15	45	0.929	0.942
0.10	29	0.952	0.961
0.05	15	0.975	0.980

Note that PLF values in Table C.3 for N_{max} = 3.125 can differ from those used in SEER calculation as Table C.3 values are based upon the equivalent time delay thermostat model. Table C.3 suggests that the use of realistic thermostat-based part-load performance at more typical maximum cycling rates should lead lower seasonal energy consumption than that predicted by the SEER rating.

There are some potential problems with the use of the thermostat cycling model with the DOE-2 simulation program. The DOE-2 program forces a cooling cycle for every hour in its simulation in which a cooling load exists. Actual systems operating at very low loads may cycle the system only once in several hours, depending on the thermostat's response to the space load. For an assumed maximum thermostat cycling rate of 2.5 cycles per hour (the typical value as reported by Henderson et al), a system's cycling rate would drop to 1 cycle per hour at a part-load ratio around 8.5% (based on Equations 6 through 8). It would occur at a slightly higher value for cooling systems with lower time constants (low C_D values) and a lower value for systems with higher time constants (high C_D values). The associated overstatement of cycling losses increases as the part-load ratio decreases. For reasonably sized cooling systems, overstatement of cycling losses at low part-load conditions should not be a concern as they accumulate only when cooling loads are minimal. It could become a problem for grossly oversized cooling system where DOE-2 would tend to over-predict cycling losses.

IV. Cooling System Cycling Losses

The equivalent time delay method appears to reasonably predict the part-load performance of the cooling system at the coil. This is the approach taken by the Standard 210 test methods, treating the cooling system as an appliance. Test data taken by Goldschmit et al (C.3) and Parken et al (C.10) used to compare the thermostat model to actual performance were obtained via temperature and humidity measurement near the cooling coil. As such, both treat the cooling system as an appliance and ignore distribution transients and losses. Coil loads are equated to space loads, both in the calculation of the cooling system efficiency and in estimates of the cooling load factor.

This is not the case in DOE-2 simulations. Space loads are calculated directly and are used to determine a cooling load factor (part-load ratio in DOE-2 parlance). All cycling losses associated with the response of the cooling system to the space load under part-load conditions is accounted for by the cooling system's EIR-f(PLR) curve. This curve must account for transients associated with both the cooling system and the air distribution system (associated ductwork). While the program can account for steady-state duct losses, there is no separate part-load curve that can account for transients in the ductwork independently of the cooling system.

The significance of distribution system transients and losses can be illustrated by examining the formula used to calculate SEER ratings for single speed equipment (C.1), or:

$$SEER = EER_B\,(1 - 0.5\,C_D) \tag{15}$$

A particular SEER rating can be obtained by designing for a relatively high value of EER_B with a high degradation coefficient, C_D. Conversely, one could design a system with a low degradation coefficient, requiring a lower EER_B. Steady state distribution losses would affect both design approaches equally as they would reduce the effective EER_B equally. This is may not be the case with distribution system transients.

The actual transient response of the cooling system, including ductwork transients, would be the sum of the system and the ductwork time constants. If delay times are on the same order of magnitude as the cooling system time constants, then systems with low time constants (low C_D values) are affected to a greater proportion than those with high time constants (high C_D values). This is illustrated in Table C.4, which compares cooling system and cooling system degradation coefficients with assumed ductwork time constants of 14 and 47 seconds. The lower time constant is for a system with a fiberboard and flex-duct supply-air system, the higher is for a system using insulated metal ductwork. A system degradation coefficient is determined by adding the ductwork time constant to the cooling system time constant. Equation 13 is then used to give a system degradation coefficient based on the increased time constant.

A comparison of system and system degradation coefficients in Table C.4 illustrates the non-uniform impact of duct transience on overall system performance.

Table C.4
Effect of Duct Transients on SEER

Cooling System		Cooling System C_D	
C_D	τ (sec)	14 sec Delay	47 sec Delay
0.25	76	0.29	0.39
0.20	60	0.24	0.35
0.15	45	0.20	0.30
0.10	29	0.14	0.25
0.05	15	0.10	0.20

A simplified ductwork analysis was used to verify the overall approach and ductwork delay times used to generate the values in Table 4. A CFD analysis was used to determine the transient response of a "typical" run of supply ductwork. The ductwork consists of 27 feet of 8" diameter duct supplying 200 cfm. The diameter of the duct provides a typical ratio of cross-sectional area to perimeter for applications using SEER-rated cooling equipment (less than 65,000 Btu/hr rated capacity).

The length of the ductwork was estimated from typical ductwork sizes as provided in Means Mechanical Cost Data. Means suggests an average weight for ductwork for split-system cooling systems of 102 pounds/ton of installed capacity. It was assumed that duct was mostly comprised of 26-gauge sheet metal as the Means table is for commercial installations (residential systems will likely use 30-guage ducts). This results in a duct surface area of 113 square feet. The simulated ductwork would deliver ½ ton of cooling for the assumed 200 cfm volumetric flow. Thus, the 8" diameter duct would need to be 27 feet long to generate 56.5 square feet of surface area.

The model further assumed that the duct was located in 80 F surroundings and was wrapped with foil-faced R-2.1 insulation. Simulations with fiberboard ductwork replaced the insulated metal ductwork with flex-duct. The properties of the flex-duct differed from the insulating wrap only in that it included a 1% by volume internal metal spiral support. Finally, the temperature of the air delivered to the ductwork was varied over time to match the assumed time constant of the cooling system. The temperature of conditioned air entering the ductwork was calculated as:

$$T(t) = T_{ret} + \Delta T_{ss} * [1 - \exp(t/\tau)] \quad (16)$$

where:

$T(t)$ = supply air temperature entering the duct at time = t,

T_{ret} = the return air temperature (80 F),

t = time,

ΔT_{ss} = stead-state temperature difference across the coil (20 F), and

τ = the cooling system time constant (values of 15, 45, and 76 seconds examined corresponding to C_D = 0.05, 0.15, and 0.25, respectively).

Results from the CFD analysis were used to determine an overall system (cooling system + ductwork) time constant. This was done by fitting the transient temperature response of air leaving the ductwork to Equation 16. The data fit provided a new value of τ that included both the cooling system and the ductwork. The difference between the system time constant and that of the cooling system was taken to be the ductwork time constant. Results of the CFD analysis are compared to a curve fit based on Equation 16 in Figure C.2 for one of the analyses. Simulations based on higher cooling system time constants provide a closer match between the curve fit and CFD results. Ductwork time constants are given in Table C.5 for systems using insulated metal and flex-duct distribution systems. Table C.4 was generated from the ductwork time constants presented in Table C.5. Figure C.2 also indicates that the response of a cooling system with its attached ductwork can be approximated by a system with a combined time constant. As such, the thermostat-based approach to creating DOE-2 part-load curves as embodied in Equations 2 through 9 remains valid.

Table C.5
Ductwork Time Constants

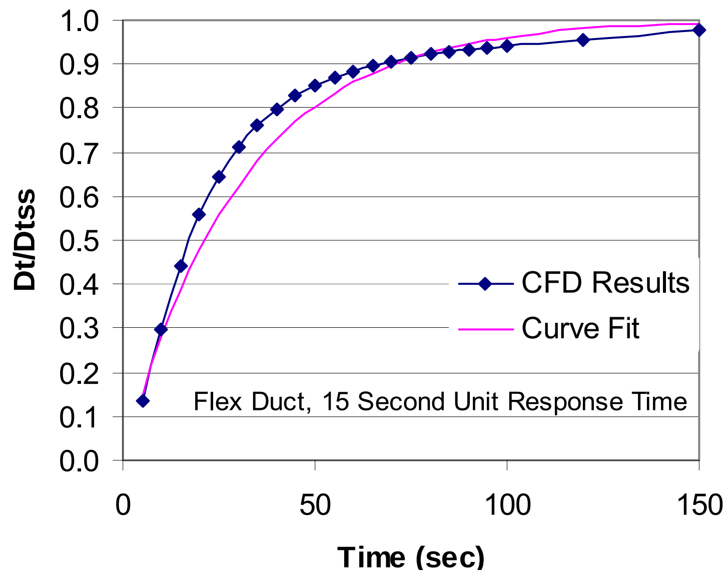
System Time Constant (sec)	Insulated Metal Ductwork	Fiber (Flex-duct) Ductwork
15 (C_D = 0.05)	16 sec	48 sec
45 (C_D = 0.15)	14 sec	47 sec
76 (C_D = 0.25)	14 sec	54 sec

It should be noted that "steady-state", as used in developing ductwork time constants, includes steady state ductwork heat gains. The steady-state temperature differential used in Figure C.2 is the difference between the return air temperature (assumed to be 80 F) and the average supply air temperature at the end of the ductwork. This is less than the assumed steady state temperature differential across the cooling coil.

There is concern about how effectively ARI cycling tests capture the cyclical response of split-system cooling systems whose indoor air handler and ductwork is located in an attic. It most likely does a poor job. An attic location will obviously increase the overall system transient response because of a warmer ductwork and air handler. A reasonable estimate based on an increased temperature differential would be to double ductwork time constants given above.

It is not clear how an attic location would affect refrigerant migration in the off-cycle. This is important, as refrigerant migration within the system appears to be the determining factor in the cooling system's transient response. Since attics tend to be warmer than the outdoors, systems that do not include a shut-off valve in the liquid line (bleed back TXV or orifice valve) should see a migration of refrigerant from the evaporator to the condenser. (This is the reverse of a non-attic application where the condenser coils are at a higher temperature than the evaporator.) Off-cycle migration of refrigerant to the condenser should reduce the response time of the system since a liquid seal at the expansion device would occur sooner. Conversely, attic locations typically require the compressor to pump refrigerant a longer distance and against gravity. This would seem to work against a quicker response time. No data have been found that looks at these issues and the effect of an attic location on response time remains unanswered.

Figure C.2
Comparisons of CFD Results and Time Constant Curve Fit



V. Summary

Results of our investigation into cooling system cycling issues include the following:

1. A thermostat model has been found that provides a means of determining cooling system time constants from published or estimated cooling system degradation coefficients.
2. Cooling system transient response, as embodied in their degradation coefficient, appears to be dominated by refrigerant migration issues in the off-cycle. This was noted by Goldschmidt et al and Lamb and Tree, and implied by Henderson et al. Analyses presented by Lamb and Tree showed that dampers used in the ARI cyclical test procedures should have no more than a 3% impact on test results, for a fixed system time constant. Reports to the contrary provide by Nguyen et al may not be reliable as the comparison of degradation coefficients measured with and without isolation dampers were apparently made on two different systems. While degradation coefficients obtained via ARI test procedures are probably made under more ideal settings than actual applications, our initial concerns that the use of isolation dampers may be "cooking the books" are probably overstated.
3. Time constants can be expanded to include ductwork transients through the addition of a ductwork time constant to that for the cooling system. CFD simulations of typical ductwork imply that a 14 second ductwork time constant would be appropriate for split-systems used in a residential application (fiberboard ductwork). A 47 second time constant should be used for commercial applications of split systems (insulated metal ductwork). Packaged systems may, or may not include significant distribution system transients, depending on whether or not the system includes connecting ductwork. Equations 4 through 9 can then be used to develop EIR-f(PLR) curves based on the total system time constant.
4. Overstatement of cycling losses at low part-load conditions by the DOE-2 program should not be a concern for reasonably sized systems. It could become a problem for grossly oversized cooling systems, in which case DOE-2 would tend to over-predict cycling losses.

Appendix C References

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APPENDIX D: REVIEW OF RESIDENTIAL FAN SYSTEM OPERATION AND DUCT LOSSES

D.1 Introduction

Two recent studies provide information on air handler and duct system leakage in new residential construction. Results from these studies are presented in the *Residential New Construction Study*[2] (RNCS) issued by Pacific Gas and Electric Company in September 2001 and *Field Testing and Computer Modeling to Characterize the Energy Impacts of Air Handler Leakage*[3] (FSEC) issued by the Florida Solar Energy Center in September 2002. The RNCS reports results of dust blaster tests from 72 newly constructed residences. The FSEC report is based on detailed examination of operating pressures, air handler leakages, and (for a subset of 20 homes) duct blaster tests for 69 cooling systems in Florida homes. Leakage rate estimates rely heavily on results from the FSEC report, as more system operational details are available. Summary information from the FSEC report compares favorably to that provided in the RNCS, allowing reasonable predictions of duct and air handler leakage rates for cooling system types built with typical California construction practices. Table D.1 compares the information available from the two databases.

Table D.1
RNCS and FSEC Duct Leakage Databases

	Database	
Data Description	RNCS	FSEC
Number of Systems	72	69
Duct Blaster Tests	72	20 Systems
Air Handler Leakage Tests	n/a	All Systems
Measured “in and out” Leakage	n/a	20 Systems
Operating Pressures	n/a	Four Points in Air Handler
Measured Air Flow Rates	n/a	All Systems
Rated Cooling Capacity	n/a	All Systems
Rated Heating Capacity	n/a	All Systems
System Model Numbers	n/a	All Systems
System Type (A/C, HP, Other)	n/a	All Systems
System Location	n/a	All Systems

There are differences in construction practices and system types observable from the two databases. The typical cooling system construction in California as provided by RNCS is overwhelmingly a split-system air conditioner with a central gas furnace (~ 99% of homes with cooling systems) with an air handler located in the attic (~79% of homes with cooling systems). Florida system are more likely to be heat pumps located in the garage or indoors (state-wide penetration estimates are not available). The FSEC database does include cooling systems with gas furnaces (13% of database) and systems located in the attic (33% of database), providing adequate information on systems typically found in California.

D.2 Results From FSEC Database

The FSEC database includes a wealth of information on operating pressures, system flows, air-handler and ductwork leakage rates, and leakage rates to the conditioned space and to outside. A summary of pertinent findings is included in Table D.2. The results presented in the table are value expected for air conditioners with gas furnaces. These were found to have slightly higher air handler leakage rates than heat pumps (~12 cfm at 25 Pa). As such, system leakage information in the table includes an adjustment to the observed leakage rates of heat pumps of 12 cfm at 25 Pa.

Table D.2
General Findings from FSEC Report and Database

	FSEC Database	
Data Description	Value	Notes
Air Handler Leakage @ 25 Pa	33 cfm	Gas furnace systems only
AHU @ Leakage Operating Pressure	100 cfm	Gas furnace systems only
Air Handle total ΔP (in wg)	0.93	No difference between HP and A/C
Raw Total External ΔP (in wg)	0.61	May include filter
Raw Total Internal ΔP (in wg)	0.32	May not include filter
Adj. Total External ΔP (in wg)	0.51	0.12" wg filter allowance
Adj. Total Internal ΔP (in wg)	0.42	0.12" wg filter allowance
Rated Cooling Capacity	38 kBtu/hr	Based on cond./coil combination
Nominal Cooling Capacity	39.6 kBtu/hr	Based on cond. nominal capacity
System total Flow	1,204 cfm	All Systems – Measure total flow
cfm/ton (rated capacity)	380	All Systems
cfm/ton (nominal capacity)	365	All Systems
Duct Blaster Leakage @ 25 Pa	196 cfm	HP systems adjusted for AHU leakage
Percent Leakage at 25 Pa	15.8%	% leakage based on 20 system subset
Leakage at Operating Pressures	264 cfm	HP systems adjusted for AHU leakage
20 System Subset Total Flow	1,241 cfm	Measured total flow
Percent Leakage at Operating Press	21.5%	% leakage based on 20 system subset

In addition, the presentation of operating pressures includes "raw" data, and "filter adjusted" data. The "raw" data are actual field measurements of pressures on the return side of the air handler. The database includes information on the location of filters. Filters were located in return grilles for approximately 2/3 of the systems; filters were located in the air handler for the remaining systems. The data set suggest that, on average, the return ductwork pressure drop was 0.12” greater for systems with filters in the return grilles than for systems with filters in the system. The “filter adjusted” data in the table increases the system’s internal static pressure by 0.12” w.g. and reduces the return external pressure by 0.12” w.g. for those systems with filters in the return grille. These resulting “filter adjusted” values provide a better basis for comparisons to ARI-rated cooling systems, which include filters in the air handler and specify total external pressure drops.

The cooling capacities provided in the table include rated and nominal values. Rated values are those associated with the particular condensing unit and indoor coil combination. The nominal capacity is that associated with the condensing unit model number. The rated capacity was typically less than the nominal (e.g. nominal 6 ton system had a rated capacity or 55 kBtu/hr); however reverse conditions were noted. These values are important since estimates of percentage leakage rates in the NRCS report were based on noted nominal capacities and assumed flow rates for the given nominal capacity (i.e. 400 cfm/ton of nominal capacity).

Approximately 26% of the total leakage is via the return system (portion of distribution system including the air handler that is under negative pressure) for air conditioners with gas furnaces. The supply and return leakage rates are approximately equal for heat pump cooling systems. The difference in the two types of systems is largely a result of the air handler configuration. Air conditioners with furnaces are blow through systems (blower is located immediately after filter section and before furnace and cooling coil). Approximately 2/3 of the air handler is under positive pressure, while the remainder is under negative pressure. Heat pumps are draw-through systems (blower is located after filter and coil) and essentially the entire air handler is under negative pressure. Because of this, heat pump systems have a greater fraction of the distribution system under negative pressure (and thus return system leakages) than do air conditioners.

The FSEC duct blaster tests also included measurements of “inside” and “outside” leakage rates. This was accomplished by adjusting the pressure within the residence to –25 Pa while the same pressure drop was imposed on the supply and return ductwork. This, essentially, equalized the pressure on both sides of all ductwork located within the residence so that the remaining leakage was to “outside”. Results of these test for various air handler locations is provided in Table D.3.

Table D.3
Duct Leakage to Outdoor

Portion of Leakage to Outdoors		
Air Handler Location	Return	Supply
Attic	81.4%	56.5%
Garage	67.6%	51.7%
Indoors	28.0%	52.6%

D.3 Comparison of FSEC and NRCS Findings

The NRCS reports an average leakage rate of 218 cfm for their 72 tests on single-family detached residences. This compares favorable with the 198 cfm (±36 cfm at 95% confidence interval) found in the FSEC study. However, percentage leakage rates differ. NRCS reports leakage rates of 13.5% of the total flow, while the value determined from the FSEC data was 15.8% (±2% at the 95% confidence level). The method in which the percentage leakage rates were determined differed in the two studies. The NRCS estimated the total system air flow rate assuming a system flow of 400 cfm per ton of nominal capacity. The FSEC study indicates that a better estimate of system flow is 365 cfm/ton of nominal capacity (380 cfm per ton of actual capacity). Adjusting the NRCS leakage percentage to account for the lower volumetric flow gives an adjusted leakage rate of 14.8% (=13.5% * 400/365). This is within the 2% confidence level associated with the 15.8% leakage rate found in the FSEC study. Given this, duct leakage results from the two tests are essentially equivalent.

Table D.4
Duct Blaster Test Leakage Categories

Leakage Category	NCRS	FSEC
cfm ≤ 100	23.1%	20%
100 > cfm ≥ 300	55.9%	70%
300 > cfm ≥ 500	13.4%	10%
cfm ≥ 500	7.6%	0%

Leakage categories from the NRCS and FSEC reports are compared in Table D.4. The general trends in leakage categories are consistent between the two databases. The largest leakage category is between 100 and 300 cfm. There is insufficient data to determine whether or not differences in the leakage categories are statistically significant.

D.4 Application of Leakage Data to DOE-2 Simulations

Equation 1 can be used to estimate total duct leakage rates as a percentage of the total system supply volume. The equation adjusts measured leakage rates obtained by duct blaster tests to actual operating conditions within the system. Typical values for use in Equation D.1 are provided in Table D.5. The table provides data on typical, high, and low values for each of the equation variables. It also provides high and low values of the variable that, when used in combination, produce the expected high and low values of the total leakage percentage. That is, the low value of total leakage percentage is obtained by applying the combination values of low percentage leakage at 25 Pa and low total static pressure to Equation 1.

$$\%\ \text{Total Leakage} = \%\ \text{Leakage}_{25\ \text{Pa}} * 1.533 * \text{TSP} \qquad \text{(D.1)}$$

where:

$\%\ \text{Leakage}_{25\ \text{Pa}}$ = the leakage rated determined from duct blaster tests,

TSP = total static pressure across fan (in. w.g.)

1.533 = adjustment value from FSEC duct blaster data.

Table D.5
Values for Total Leakage Equations

Equation Variable	Range	Value
% Leakage $_{25\ Pa}$	Typical	15%
	Alone Low†	10%
	Alone High†	20%
TSP (in. w.g.)	Typical	0.93
	Alone Low†	0.67
	Alone High†	1.19
% Leakage $_{25\ Pa}$	Combination Low‡	12%
	Combination High‡	19%
TSP (in. w.g.)	Combination Low‡	0.75
	Combination High‡	1.15

† *High and low values are typical ±1.15*standard deviation to span 75% of maximum range.*

‡ *High and low values used in combination to produce expected "High" and "Low" values of % Total Leakage.*

The total leakage can be broken down into its various components – return or supply-side leakage and leakage to the outdoors. Return system gains from outdoor is given by Equation 2, or:

$$\% \text{ Return}_{out} = \% \text{ Total Leakage} * f_{return} * f_{ret,out} \qquad \text{(D.2)}$$

where:

$\%\ \text{Return}_{out}$ = leakage gains to the return system from the ambient surroundings (unconditioned spaces) as a percentage of total flow,

f_{return} = fraction of total leakage that is on the return side of the distribution system, and

$f_{ret,out}$ = fraction of leakage on the return system that are gains from the ambient surroundings (unconditioned spaces).

Similarly, Equation D.3 provides an estimate of supply system losses to the surroundings, or:

$$\% \text{ Supply}_{out} = \% \text{ Total Leakage} * f_{supply} * f_{sup,out} \qquad \text{(D.3)}$$

where:

$\%\ \text{Supply}_{out}$ = leakage from the supply system to the ambient surroundings (unconditioned spaces) as a percentage of total flow,

f_{return} = fraction of total leakage that is on the supply side of the distribution system, and

$f_{ret,out}$ = fraction of leakage from the supply system that is to the ambient surroundings (unconditioned spaces).

The leakage fractions depend on the type of cooling system (air conditioner or heat pump) and the location of the air handler. For air conditioners with gas furnaces, f_{return} = 0.26 and f_{supply} = 0.74. For heat pumps, f_{return} = f_{supply} = 0.5. Values for $f_{ret,out}$ and $f_{sup,out}$ are given in Table 3 for air handlers located in attics, garages, or inside the residence. The typical California cooling system is a split system air conditioner (99% of single-family residences with cooling systems) located in the attic (79% of residences). Thus, for a typical residence, the lost air leakage on the return and supply sides of air conditioner are given in D.4 and D.5.

$$\% \text{ Return}_{\text{out}} = 0.21 * \% \text{ Total Leakage} \qquad \text{(D.4)}$$

$$\% \text{ Supply}_{\text{out}} = 0.42 * \% \text{ Total Leakage} \qquad \text{(D.5)}$$

The total leakage percentage ranges from 14% to 33%, with a typical value of 21%, of the total system flow rate, as given by Equation 1 and Table 5.

D.5 Fan Power Data in DOE-2 Simulations

It is recognized that ARI test requirements yield unrealistically low fan power values. Studies[4] in California suggest that average fan energy is 510 Watts per 1,000 cfm of cooling system air flow. The ARI[1] default is 365 Watts per 1,000 cfm for rated condensing unit/cooling coil combinations (coil without an air handler). Tests of SEER-rated condensing unit/ air handler combinations require test to be made with external pressure drops ranging from 0.1" to 0.2" w.g., depending on the system's capacity. Pressure measurements from the FSEC test data suggest a median external pressure drop of 0.54" w.g. that is independent of system capacity.

The frequency distributions of total, internal, and external pressure drops from the FSEC database are shown in Figures D.1 through D.3. The internal and external pressure drops are best estimates based on filter adjustments. As discussed previously, approximately two-thirds of the systems tested had filters installed in return grilles as opposed to in the air handler. The best estimate of the average filter pressure drop from the database is 0.12" w.g. Internal static pressure drop was increased and external pressure drop was decreased by 0.12" w.g. for those systems with filters in the return grilles. This was done to produce internal and external pressure drops that represent air handler and ductwork configurations consistent with ARI test conditions. Total pressure drop is unaffected by the filter adjustment.

Figure D.1
Total Static Pressure Drop Across Fan – FSEC Database

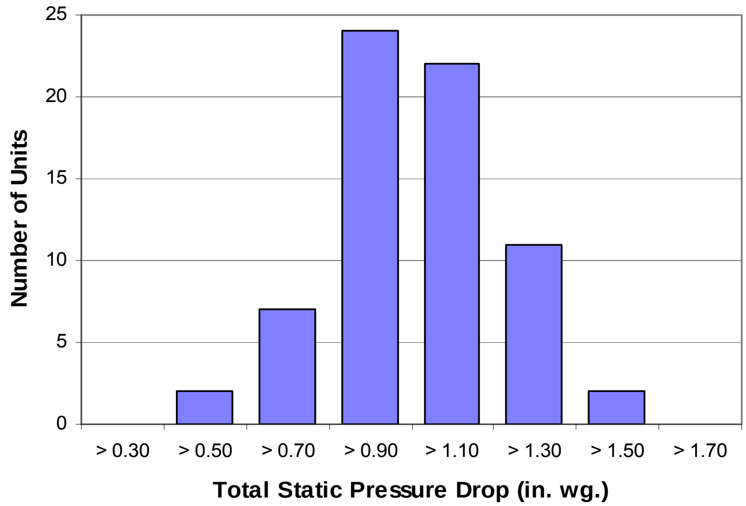


Figure D.2
External Static Pressure Drop Across Air Handler – FSEC Database

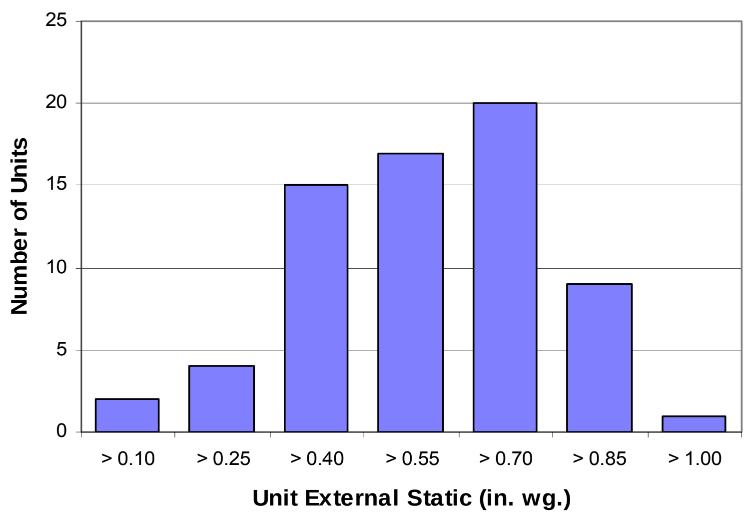
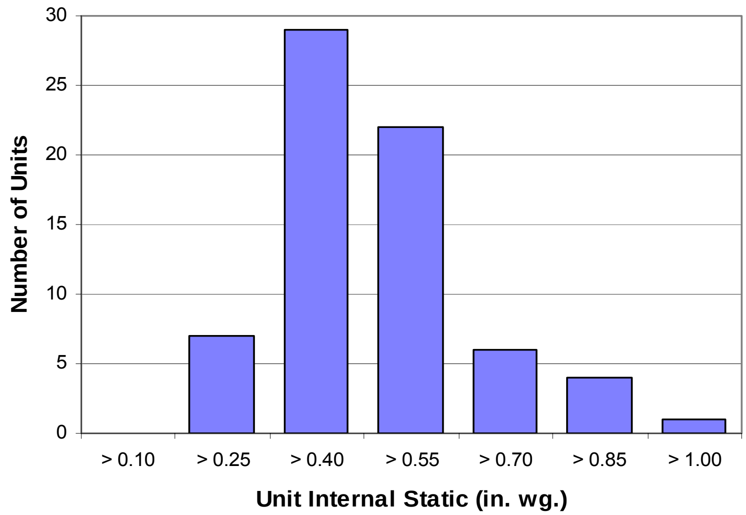


Figure D.3
Air Handler Internal Pressure Drop – FSEC Database



While the information on system pressure drop is informative, it does not provide a direct method for estimating fan power in residences. It is clear from the two reports that default assumptions used in ARI testing procedures are too low, but fan power measurements were not included in FSEC measurements. An approximate method for predicting fan power can be made by combining the average fan power of 510 Watts/1,000 cfm found in the study of California homes with the 0.93" w.g. average total static pressure noted in the FSEC study. An initial approach to estimate fan power could be to pro-rate it based on total static pressure. This would overstate changes in fan power as it ignores the effect of pressure differential on fan efficiency. A more realistic estimate of fan power would be:

$$\text{Fan Power} = 510 * (\text{TSP}/0.93)^{0.66} \tag{D.6}$$

where:

Fan Power = Supply fan power in Watts/1,000 cfm of supply volume and

TSP = Total static pressure drop across the fan in inches w. g..

This equation predicts fan power of 365 Watts/1,000 cfm (ARI default) for a total static pressure of 0.56" w. g.. The 0.56" w. g. is the median value of internal static pressure from the FSEC database plus 0.15" w. g. external pressure, the average value specified in ARI testing of air handlers. Using low and high values of total static pressure as given in Table 5 in conjunction with Equation 6, one would expect that 75% of residential systems would have fan power values between 410 and 600 Watts per 1,000 cfm of supply air.

Appendix D References

1. *ARI, 1984. ARI Standard 210/240-84, unitary air-conditioning and air-source heat pump equipment. Air-conditioning and Refrigeration Institute.*
2. *Gobris, M., 2001, "Residential New Construction Study", Pacific Gas & Electric Report.*
3. *Lombardi, M., 2002, "Field Testing and Computer Modeling to Characterize the Energy Impacts of Air Handler Leakage," FSEC-CR-1357-02*
4. *Wilcox, B., Nittler, Proctor, & Modera, 2000. California Energy Commission Assembly Bill 970 Building Energy Efficiency Standards, Contractor Report, 2001 Update – AB 970 Draft Residential Building Standards. Energy Commission Publication No. P 400-00-023/V3.*

APPENDIX E: DETAILS OF SINGLE-FAMILY BUILDING PROTOTYPES

Details of the single-family building prototype DOE-2 models are as follows:

		Single Family Building Characteristics								
Climate Region	Wth File	Total Floor Area			Number of Stories			Aspect Ratio		
		Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	1400	1575	3427	1	2	2	1.0	1.2	1.5
North Coast	CZ02	1400	2335	3427	1	2	2	1.0	1.2	1.5
North Coast	CZ03	1400	2485	3427	1	2	2	1.0	1.2	1.5
North Coast	CZ04	1400	2586	3427	1	2	2	1.0	1.2	1.5
North Coast	CZ05	1400	2164	3427	1	2	2	1.0	1.2	1.5
South Coast	CZ06	1400	2858	3427	1	2	2	1.0	1.2	1.5
South Coast	CZ07	1400	2503	3427	1	2	2	1.0	1.2	1.5
South Coast	CZ08	1400	2718	3427	1	2	2	1.0	1.2	1.5
South Inland	CZ09	1400	2890	3427	1	2	2	1.0	1.2	1.5
South Inland	CZ10	1400	2343	3427	1	2	2	1.0	1.2	1.5
Central Valley	CZ11	1400	1953	3427	1	1	2	1.0	1.2	1.5
Central Valley	CZ12	1400	2216	3427	1	2	2	1.0	1.2	1.5
Central Valley	CZ13	1400	1952	3427	1	1	2	1.0	1.2	1.5
Desert	CZ14	1400	1958	3427	1	1	2	1.0	1.2	1.5
Desert	CZ15	1400	2155	3427	1	1	2	1.0	1.2	1.5
Mountain	CZ16	1400	2358	3427	1	2	2	1.0	1.2	1.5
	Min:	Itron data, 10th percentile			Itron data, 10th percentile					
Sources:	Median:	Itron data, average by CZ			Itron data, average by CZ			Itron data, derived from wall areas		
	Max:	Itron data, 90th percentile			Itron data, 90th percentile					

Climate Region	Wth File	Occupancy*			Roof Type			Floor Type		
		Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	2	3	5	Attic	Attic	25% Cath	Slab	Crawl	Crawl
North Coast	CZ02	2	3	5	Attic	Attic	25% Cath	Slab	Crawl	Crawl
North Coast	CZ03	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
North Coast	CZ04	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
North Coast	CZ05	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
South Coast	CZ06	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
South Coast	CZ07	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
South Coast	CZ08	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
South Inland	CZ09	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
South Inland	CZ10	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Central Valley	CZ11	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Central Valley	CZ12	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Central Valley	CZ13	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Desert	CZ14	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Desert	CZ15	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
Mountain	CZ16	2	3	5	Attic	Attic	25% Cath	Slab	Slab	Crawl
	Min:	Itron data, 10th percentile			Itron data (97% framed attic)			Itron data		
Sources:	Median:	Itron data, median for all CZ			Itron data (97% framed attic)			Itron data, median by CZ		
	Max:	Itron data, 90th percentile			SCE + DEER2001 data			SCE + DEER2001 data		

* *see associated Occupancy level description*

		Single Family Building Characteristics								
Climate	Wth	Glass Area (Fraction)			Glass U-value			Glass SC		
Region	File	Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	0.13	0.16	0.22	0.37	0.61	0.99	0.48	0.64	0.91
North Coast	CZ02	0.13	0.19	0.22	0.37	0.57	0.99	0.48	0.61	0.91
North Coast	CZ03	0.13	0.18	0.22	0.37	0.59	0.99	0.48	0.63	0.91
North Coast	CZ04	0.13	0.18	0.22	0.37	0.58	0.99	0.48	0.63	0.91
North Coast	CZ05	0.13	0.21	0.22	0.37	0.58	0.99	0.48	0.62	0.91
South Coast	CZ06	0.13	0.17	0.22	0.37	0.59	0.99	0.48	0.63	0.91
South Coast	CZ07	0.13	0.15	0.22	0.37	0.59	0.99	0.48	0.63	0.91
South Coast	CZ08	0.13	0.18	0.22	0.37	0.60	0.99	0.48	0.63	0.91
South Inland	CZ09	0.13	0.18	0.22	0.37	0.60	0.99	0.48	0.64	0.91
South Inland	CZ10	0.13	0.17	0.22	0.37	0.59	0.99	0.48	0.63	0.91
Central Valley	CZ11	0.13	0.17	0.22	0.37	0.57	0.99	0.48	0.61	0.91
Central Valley	CZ12	0.13	0.17	0.22	0.37	0.59	0.99	0.48	0.63	0.91
Central Valley	CZ13	0.13	0.15	0.22	0.37	0.69	0.99	0.48	0.70	0.91
Desert	CZ14	0.13	0.20	0.22	0.37	0.59	0.99	0.48	0.63	0.91
Desert	CZ15	0.13	0.18	0.22	0.37	0.57	0.99	0.48	0.61	0.91
Mountain	CZ16	0.13	0.16	0.22	0.37	0.60	0.99	0.48	0.64	0.91
	Min:	Itron data, 10th percentile			Itron data, minimum value			all values based on		
Sources:	Median:	Itron data, average by CZ			Itron data, average by CZ			corresponding glass U-val		
	Max:	Itron data, 90th percentile			Itron data, maximum value					

Climate	Wth	Wall Cons Type			Roof Insulation			Crawlspace Insulation		
Region	File	Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	2x4,wd	2x6,st	2x6,ib	19	30	38	0	5	17
North Coast	CZ02	2x4,wd	2x6,st	2x6,ib	19	38	38	0	5	17
North Coast	CZ03	2x4,wd	2x6,st	2x6,ib	19	30	38	0	5	17
North Coast	CZ04	2x4,wd	2x6,st	2x6,ib	19	30	38	0	5	17
North Coast	CZ05	2x4,wd	2x4,st	2x6,ib	19	30	38	0	5	17
South Coast	CZ06	2x4,wd	2x4,st	2x6,ib	19	30	38	0	5	17
South Coast	CZ07	2x4,wd	2x4,st	2x6,ib	19	19	38	0	5	17
South Coast	CZ08	2x4,wd	2x4,st	2x6,ib	19	19	38	0	5	17
South Inland	CZ09	2x4,wd	2x4,st	2x6,ib	19	30	38	0	5	17
South Inland	CZ10	2x4,wd	2x4,st	2x6,ib	19	30	38	0	5	17
Central Valley	CZ11	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
Central Valley	CZ12	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
Central Valley	CZ13	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
Desert	CZ14	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
Desert	CZ15	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
Mountain	CZ16	2x4,wd	2x4,st	2x6,ib	19	38	38	0	5	17
	Min:	Itron data, minimum value			Itron data, minimum value			no insulation		
Sources:	Median:	Itron data, average by CZ			Itron data, average by CZ			R-5 crawlspace wall insulation		
	Max:	Itron data, maximum value			Itron data, maximum value			crwlspc ceiling insulation		

Min: 2x4 filled cav, wood siding
Med: filled cavity, stucco siding
Max: 2x6 filled cav, stucco w/ins board siding

		Single Family Building Characteristics								
Climate	Wth	Natural Ventilation			Cooling Thermostat SP			Cooling T-stat Setup		
Region	File	Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	none	5ach/72	10ach/75	74	76	78	80	82	85
North Coast	CZ02	none	5ach/72	10ach/75	74	76	78	80	82	85
North Coast	CZ03	none	5ach/72	10ach/75	74	76	78	80	82	85
North Coast	CZ04	none	5ach/72	10ach/75	74	76	78	80	82	85
North Coast	CZ05	none	5ach/72	10ach/75	74	76	78	80	82	85
South Coast	CZ06	none	5ach/72	10ach/75	74	76	78	80	82	85
South Coast	CZ07	none	5ach/72	10ach/75	74	76	78	80	82	85
South Coast	CZ08	none	5ach/72	10ach/75	74	76	78	80	82	85
South Inland	CZ09	none	5ach/72	10ach/75	74	76	78	80	82	85
South Inland	CZ10	none	5ach/72	10ach/75	74	76	78	80	82	85
Central Valley	CZ11	none	5ach/72	10ach/75	74	76	78	80	82	85
Central Valley	CZ12	none	5ach/72	10ach/75	74	76	78	80	82	85
Central Valley	CZ13	none	5ach/72	10ach/75	74	76	78	80	82	85
Desert	CZ14	none	5ach/72	10ach/75	74	76	78	80	82	85
Desert	CZ15	none	5ach/72	10ach/75	74	76	78	80	82	85
Mountain	CZ16	none	5ach/72	10ach/75	74	76	78	80	82	85
	Min:	no natural ventilation						constant t-stat schedule		
Sources:	Median:	5 ACH max, 72F max outdoor T						daytime t-stat setup to 80F		
	Max:	10 ACH max, 75F max outdoor T						daytime t-stat setup to 85F		

Occupancy Levels

Min: Two occupants, not home weekdays from 9a-5p,
- One Story: t-stat set up from 9a-5p weekdays
- Two Story: 1st floor, t-stat set up from 9a-5p weekdays
  2nd floor, t-stat set up from 9a-6p all days

Median: Three occupants, two not home weekdays from 9a-5p,
- One Story: no t-stat set up
- Two Story: 1st floor, no t-stat set up
  2nd floor, t-stat set up from 9a-6p all days

Max: Five occupants, two not home weekdays from 9a-5p,
- One Story: no t-stat set up
- Two Story: 2nd floor, no t-stat set up
  1st floor, no t-stat set up

Notes: One story house has a single A/C system
Two story house has dedicated A/C for the first and second floors

		Single Family Building Characteristics								
Climate	Wth	Slab F2			Duct Loss (fraction)			Duct R-Value		
Region	File	Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
North Coast	CZ02	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
North Coast	CZ03	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
North Coast	CZ04	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
North Coast	CZ05	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
South Coast	CZ06	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
South Coast	CZ07	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
South Coast	CZ08	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
South Inland	CZ09	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
South Inland	CZ10	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Central Valley	CZ11	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Central Valley	CZ12	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Central Valley	CZ13	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Desert	CZ14	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Desert	CZ15	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
Mountain	CZ16	0.60	0.77	1.10	6%	10%	20%	0	4.2	8.4
	Min:	carpeted slab, R-5 insulation								
Sources:	Median:	carpeted slab, no insulation								
	Max:	uncarpeted slab, no insulation								

Climate	Wth	Shading Level			Internal Gains			ACH		
Region	File	Min	Median	Max	Min	Median	Max	Min	Median	Max
North Coast	CZ01	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
North Coast	CZ02	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
North Coast	CZ03	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
North Coast	CZ04	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
North Coast	CZ05	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
South Coast	CZ06	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
South Coast	CZ07	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
South Coast	CZ08	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
South Inland	CZ09	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
South Inland	CZ10	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Central Valley	CZ11	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Central Valley	CZ12	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Central Valley	CZ13	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Desert	CZ14	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Desert	CZ15	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
Mountain	CZ16	low	medium	high	50%	T-24 std	135%	0.20	0.35	0.50
	Min:	soffits only			50% of T-24 standard					
Sources:	Median:	soffits + site shading			T-24 Residential standard					
	Max:	architectural + site shading			135% of T-24 standard*					

* approx equivalent to the proposed IECC/HERS std