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Using Air Conditioning Load Response for Spinning Reserve

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Energy and Transportation Science Division

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Contents

Abstract

This report assesses the use of air conditioning load for providing spinning reserve and discusses load forecasting challenges, temperature effect, and the effect of the load drop on customer homes. Air conditioning load is well suited for the spinning reserve service because it often increases during heavy load periods and can be curtailed for short periods with little impact to the customer. The report also provides an appendix describing the ambient temperature effect on air conditioning load.

Executive Summary

Air conditioning load grows so much as a function of temperature that it presents a prediction challenge. Air conditioning both drives the reliability need and provides the reliability solution. In addition, it comprises as much as 70% of net load on hot days. Higher SEER air conditioners use more power on hot days, but they are also more effective than the older units, and will run less to satisfy the thermostat setting. The composition of air conditioners in the general population is changing due to efficiency standards. New units must have a SEER 13 or higher. The efficiency standards are met by various technical modifications and controls. The impact on energy consumption at peak ambient temperatures differs depending on specific modifications. An appendix is provided which examines some of the impacts of these differences using an ORNL hardware-based simulation model of air conditioner operation.

The exact effect on net load as a function of temperature remains to be established. However, as more and more automated metering is installed, it will be possible to refine forecasting methods to provide highly accurate forecasts for both load planning and prediction of available reserves. Continued research is needed to develop and refine models based on automated meter data and ambient temperature. Responsive air conditioning load will necessarily become a key component of load management in large aggregations of variable renewable resources, energy storage, and conventional generation. It is essential that it be accurately forecasted with a high confidence factor.

Introduction

Spinning reserve is a term used to describe electric generators that are connected to the transmission grid, operating at part load, and ready to provide additional power in the event of a contingency such as the loss of a large generator. In addition to using operating generators to provide spinning reserve, some system operators are using responsive load. The responsive load would quickly shut off in the event of a contingency and would serve to maintain the reliability of the transmission system. The purpose of this paper is to review the potential for responsive air conditioning load to provide spinning reserve, as well as the barriers and opportunities involved. This report also discusses the trend for modern air conditioners to present a heavier load at higher ambient temperatures.

Previous work has shown that about three times as much load drop can be obtained from residential air conditioning used in spinning reserve programs than from peak reduction programs (Kirby 2003). This is because all of the enrolled air conditioning load can be curtailed completely for the spinning reserve event, while individual loads must be cycled (or set points must be adjusted) for peak load reduction because of the long time duration. Spinning reserve should be the preferred use for air conditioning response, though spinning reserve response can be combined with peak load reduction.

Air conditioning reserves should also be the preferred reserves to deploy when response is needed. The immediate load curtailment is much faster than the ramping response that generators provide. Air conditioning loads incur essentially no costs when responding, as long as the response duration is reasonably short, while generators incur fuel and maintenance costs.

The power system always needs spinning reserves. The required amount of reserves depends on the size of the largest credible contingency. This might be the largest single power plant or the largest transmission interconnection. The Electric Reliability Council of Texas (ERCOT), for example, guards against the 2300-MW simultaneous loss of two nuclear units. Contingency reserve *value* varies significantly over time, however. This is because the cost of supplying the reserves is primarily an opportunity cost for the generator that is being held back. For example, a coal-fired generator with a $40/MWH production cost would have to charge $20/MW-hr to stand ready to respond to a spinning reserve call if the wholesale market price for electricity were $60/MWH. This is because the generator would be giving up $20/MW-hr in profit when it withheld capacity from the energy market in order to provide reserves. The generator could offer contingency reserves for free in the middle of the night when it was idling at minimum load. Contingency reserve prices are a function of energy prices and generator marginal production costs. While this discussion has been in terms of electricity markets, it is equally applicable in the vertically integrated utility environment. Contingency reserve prices provide an excellent proxy for power system stress.

Air conditioning loads are not available to supply spinning reserve 8760 hours a year, but their availability is highly correlated with system need and contingency reserve prices. In fact, energy and ancillary service prices are high largely because air conditioning load is high. Figure 8 shows hourly spinning reserve prices for three large ISOs for June of 2005.

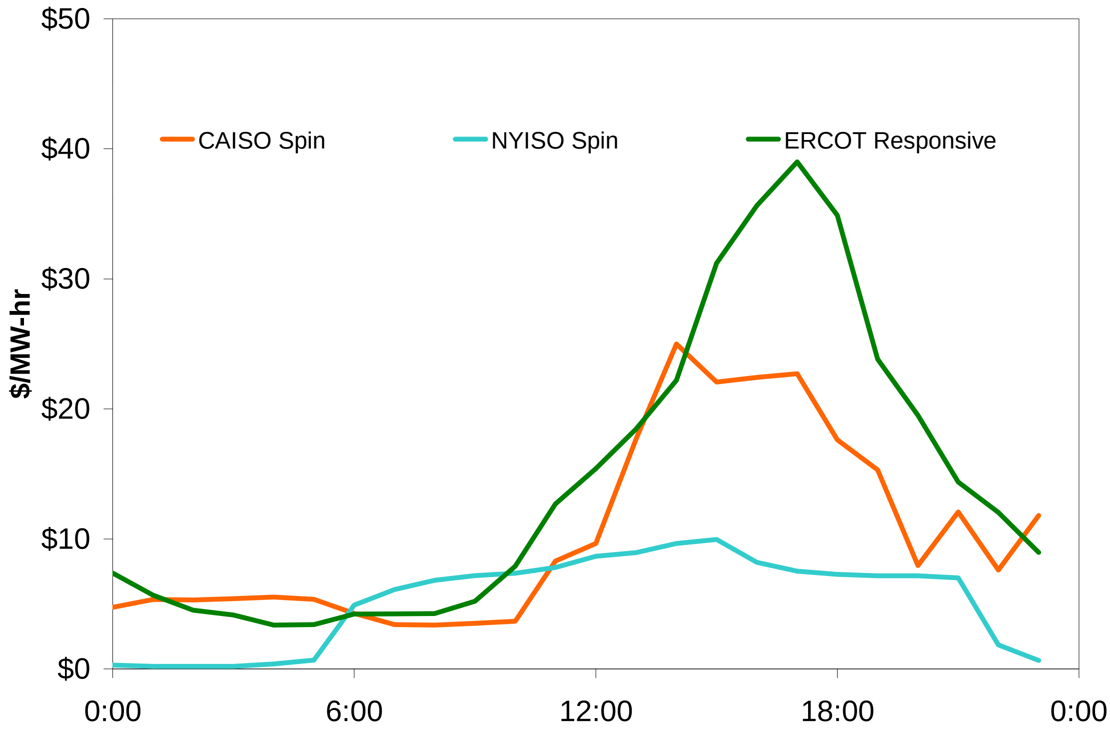

Figure 8. Spinning reserve prices, and power system need for alternatives to generation, are highest when air conditioning load is highest.

Air conditioning load is an attractive application for a spinning reserve program. (Eto 2007) Air conditioning can be interrupted for perhaps 30 minutes with little impact on the customer, and air conditioning itself is often the cause of problematic peak loads on extremely hot days.

Air conditioning load is also ideally suited to supply the reliability service of spinning reserve. Air conditioning load is typically at a maximum during times when the price of spinning reserve is at a maximum. The percentage of air conditioning load as a percentage of total load is growing rapidly. The use of air conditioning load for spinning reserve requires an accurate, high-confidence prediction of the actual responsive MW as a function of temperature, time, and day of week. The inherent response characteristics of air conditioning load and the reliability needs of the power system are well matched. If the reserve service program is structured properly, both the needs of the power system operator and the customer air conditioning can be met.

Because air conditioning load is so much a function of temperature, it presents an interesting prediction challenge. In this sense, air conditioning both drives the reliability need and provides the solution. A precise air conditioning load model is challenging to develop as air conditioning load is growing rapidly as a percentage of total load. Some estimates now place air conditioning load at 50% or more of total load on hot days. Interestingly, modern air conditioner load can grow significantly on days of high ambient temperature, compared with older air conditioners. An appendix A is provided which discusses and explains this effect.

I. Load Forecasting Challenges

Planning Demand Response

To make use of air conditioning as a spinning reserve reliability resource, power system operators need to know how many total MW are available to respond each hour for the current and following days. The speed of response and the response duration are important as well, but those are system design criteria which must be met rather than load characteristics that vary. (We will discuss response speed and duration in Sections V and VI.) To be useful to the system operator, near-term reserve forecasts must be 90% accurate with a 95% confidence level.

A study by Joe Eto and Mithra Moezzi "Analysis of PG&E's Residential End-Use Metered Data to Improve Electricity Demand Forecasts – Final Report" LBL-34431, Berkeley, CA, found that by using five years of end use metered central air conditioner data, a consistent set of new inputs for conventional load forecasting models could be developed, and the authors were able to compare various model results on an equal footing. Using this new consistent data set, the authors found that the "magnitude of potential implementation issues was small" between forecasting models. Thus, given the correct inputs, the conventional models do an accurate job of forecasting. "The data now available from recent end use metering projects holds the promise of reducing these uncertainties and thereby improving the planning process and outcomes… In addition, the testing criteria included the ability to forecast … daily peak demand and demand at 4 pm." The results of this report are quite encouraging, as a large number of smart meters are now being installed across the country. The availability of end use metered data is now becoming widespread.

These automated meters could be used to refine existing forecast methods based on temperature and the type of air conditioner. Ultimately, with wide spread automated meters, it is entirely reasonable to assume that highly accurate forecasts can be made and verified on a statistical sampling basis using the meter data. The authors believe that the system operator will have accurate near term load forecasts available in the future, as more and more end use metering is installed.

The system operator is accustomed to having reserves supplied by generators, and these reserve levels are highly reliable and accurate The key difference between cycling air conditioners simply to reduce peak demand vs. providing spinning reserve is that the spinning reserve response must be accurate, quick and of a short duration. System operators rely on specific, contracted levels of reserves. These reserve levels vary depending on the total load, and are a critical aspect of reliable system operation. Peak load reduction is provided by time of use tariffs for large scale load shifting and by special curtailment programs which are not precision methods but are more geared to reducing stress during system emergencies.

Load forecasting for demand response will probably fall into the categories of day-ahead planning, short-range load forecasting, and seasonal reliability assessment, just as conventional load forecasts do. The available spinning reserve from air conditioning load will be forecasted based on day-ahead planning.

Day-ahead planning is largely a function of weather forecasting and when performed using historical end use metered data, as found in the above study, is quite accurate. Today's load is adjusted based on tomorrow's forecast, and tried and proven corrections are made for holidays, shopping days, extended heat storms, etc.

Conventional short-range load forecasting generally only uses two factors: new customers and new uses of electricity. New customer additions are the result of new construction and population migration. For example, an effect seen recently is a migration into older urban areas that were once “decayed” but are now being refurbished because of their convenience to downtown work areas. New uses of electricity include new appliances, new whole-house air conditioning, and other improved devices that use more power (Willis and Dekker 2004, p. 911). Wide-screen TVs are an excellent example of appliances that sometimes consume surprising amounts of power, even when not in use.

Load forecasters develop regression curves that fit the historical annual peak load trend. Small area load growth typically undergoes transitions in behavior from “dormant“ to “growing” to “saturated.” The most recent six years of data are usually considered to give the best results (Willis and Dekker 2004, p. 928). However, short-range load forecasting must take into account the complications of higher peak loads that are due to a rapid increase in the number of home appliances, the growing energy consumption of these appliances, and especially air conditioning load.

Seasonal reliability assessments update load models from previous years using such factors as predicted weather, economics, diversity or timing of peak periods among internal zones, the period of years the model is based on, and sampling size. The purpose of seasonal reliability assessments is to estimate system reliability for the upcoming season and the probability that such measures as voltage reduction, reduction of operating reserve, and load shed will be needed.

Conventional load forecasters use extended template matching (ETM), which may require special care in the future. In ETM, pattern recognition is used to identify past trends which could be used as templates for future load projections (Willis and Dekker 2004, p. 954). To be effective, ETM requires a long period of load history. Past trends may be misleading, as air conditioning load may grow more rapidly and be more temperature-sensitive than in the past.

The authors suspect that underprediction of load is probably more likely than overprediction in the development of short-range forecasts and seasonal reliability assessments. From the point of view of air conditioning load used for spinning reserve, however, this is not a problem. Additional air conditioning load would mean additional available reserves. In planning for the next day's load, however, unless there is a major unforecasted change in temperature, planning methods have generally been found to be quite accurate, especially when end use metered data is available, as reported above. Because this data is becoming more common, we anticipate that day-ahead forecasts of available reserves from load will be quite accurate, especially when spread over a regional basis that averages out local temperature anomalies. This is discussed more in Section III.

As systems operate closer and closer to their margins, load forecasting is going to take on more importance, especially in terms of load control. It is already known to load forecasters that energy efficient appliances do save energy on an annual basis but can also increase the peak load. For example, “on-demand” water heaters have no storage tank and heat water with a large heating element that can consume five times the load of a conventional water heater. When many of these on-demand heaters are used during peak periods, they can make the peak load worse. Some types of variable-speed air conditioners can use more electricity during peak periods (Willis and Dekker 2004, p. 336). As we will discuss, a higher SEER (Seasonal Energy Efficiency Rating) can translate into a much higher load on extremely hot days.

II. Air Conditioning Temperature Effect and High SEER Ratings

The Increasing Value of Air Conditioner Load for Reliability Services

Air conditioner load is attractive for a reliability service because it grows on hot days, and it can normally be shut off for short periods without discomfort to the customer. Typically, air conditioners used in demand-response programs are curtail-able by the use of a contactor that interrupts the current flowing to the compressor. Compressor motors use 80 to 90% of the total electric power consumed by air conditioning (Bain 1995, p. 2-2).

As discussed below, higher ambient temperatures will result in higher refrigerant pressures, which increase the mechanical torque load of air conditioning compressors (Diaz 2002, p. 747). A higher load means that the compressor motor will draw more power.

Air conditioner efficiency has a surprising effect on load growth on hot days. Newer air conditioners have a much higher efficiency than those sold a few years ago. SEER is the most commonly used measure of the efficiency of consumer central air conditioning systems. (EER, or Energy Efficiency Rating, is the most commonly used measure of efficiency for *commercial* air conditioning systems.) EER measures steady-state efficiency, and SEER measures efficiency at selected operating points to provide an indication of a seasonal average. As of January 2006, an air conditioner must have a SEER of at least 13 to be sold in the United States. Higher efficiency models have SEERs of up to 23.

Newer, high-SEER air conditioners are more effective at air conditioning at an extremely high temperature range than older units. The older units tend to drop off in capacity (or unload) more at higher temperatures. This fact is probably only important to utilities that experience temperatures over 110°F. When compared with many of the older units, the new high efficiency air conditioners can draw significantly more power in extremely hot weather (115°F) than they use at 85°F. This is not to imply that the higher efficiency units use more total energy than the older 10-SEER units did at elevated ambient temperature, but rather that their peak electric load can be about the same or slightly higher than many of the 10-SEER units. This is further discussed and explained in Appendix A.

SEER for single-capacity residential units is calculated based on the equipment efficiency level at 82F ambient (and 80/67F indoor dry/web bulb conditions). For two-capacity and variable-speed equipment SEER is calculated using eight cooling season bin temperatures ranging from 67 to 102°F. Here, the fraction of total temperature bin hours is overwhelmingly focused on the lower temperature bins, so the efficiency is optimized for a temperature (and thus operating system pressure and torque) around 72 - 82°F (ARI 2006, p. 86) where the product of bin hours and building load (i.e., required cooling load) is at a maximum for most U.S. locations. The distribution of fractional hours within the temperature bins is shown in Table 1.

Table 1. Distribution of fractional hours within the temperature bins

Representative bin temperature	Fraction of total temperature hours
67	0.214
72	0.231
77	0.216
82	0.161
87	0.104
92	0.052
97	0.018
102	0.004

In the future, the problem of increasing load with temperature will become more pronounced as more of the new, high-SEER air conditioners are installed. DOE noted this in a technical support document on energy efficiency standards for air conditioners:

> "Many utilities and environmental advocates support the establishment of minimum efficiency standards based on EER at an outdoor temperature of 95°F, in lieu of SEER, which is based largely on an outdoor temperature of 82°F. They are concerned that an increase in SEER does not necessarily correspond to an increase in EER, and that a 95°F rating condition better represents the performance of an air conditioner on hot days when electricity demand is at its highest." (DOE 2002)

Recent test results have demonstrated the greater power increase of high efficiency air conditioners with higher ambient temperature than for lower-efficiency air conditioners. A reciprocating air conditioner with a rated EER of 10.6 has a 22% increase in power use with an ambient temperature change of 85 to 115°F. A scroll air conditioner with an EER of 11.3 has a 48% increase in power use for the same temperature change. This difference is caused by changing from a reciprocating compressor to a scroll compressor and using a modulating expansion valve (see Appendix A). A plot is provided in Figure 1 showing the increase in power over temperature for two units, of different SEER but similar capacity, of the ten residential units tested recently by Southern Cal Edison (SCE 2006). It can be seen that the electric load is lower for the 13 SEER unit at the moderate ambient but higher above 100°F. Although one should not draw conclusions from two units, this does suggest that further investigation of the situation may be warranted. An initial modeling investigation of this situation of higher load at higher ambients was conducted as described in Appendix A.

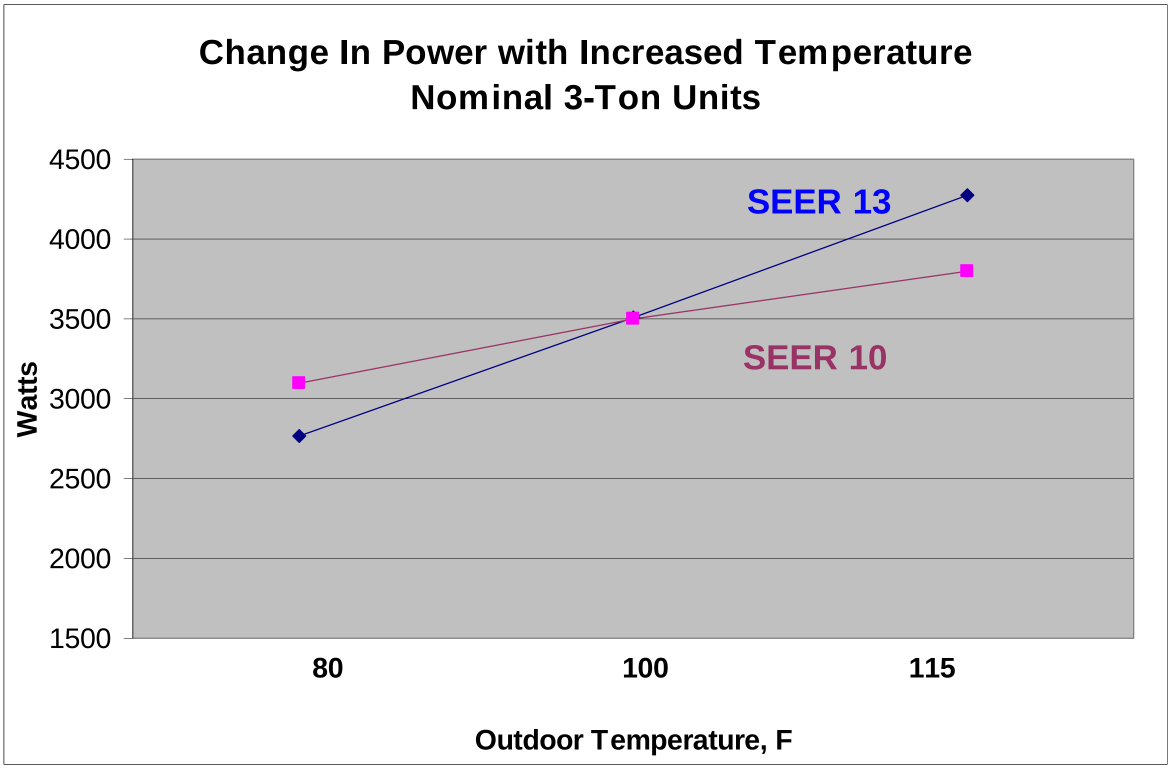

Figure 1. Increase in electric load with ambient temperature.

The increased slope of the power curve in Figure 1 for the 13 SEER unit is perhaps of as much or more concern as the relative end points of the available test data. When electrical load is composed of a larger percentage of high efficiency units, the load will grow more on an extremely hot day than historical load models would predict. As more high efficiency air conditioning is installed, we are concerned that existing utility load models may not reflect this large change in load with temperature and that unexpected load levels may occur on hot days. The lowest efficiency air conditioner that can be purchased since January 2006 is a SEER 13 and these generally use scroll compressors and R-410A refrigerant.

ORNL developed and maintains a Heat Pump Design Model (HPDM), which is a detailed mathematical model that can be configured to model air-to-air heat pumps and air conditioners.[1] The model confirms that the higher efficiency air conditioners can have a greater rate of power increase during extremely hot weather than the old air conditioners. There are at least three potential contributing factors to this result:

- The scroll compressors in most of the 13 SEER units maintain capacity better than the reciprocating compressors over high temperature conditions. The reciprocating compressors more commonly used in the 10 SEER units unload more with increasing ambient high temperatures.
- The new environmentally safe refrigerant, 410A, drops off faster in efficiency at high ambient temperatures compared with R22.

[1] An online version of the model can be accessed at http://www.ornl.gov/~wlj/hpdm/MarkVI.shtml.

- The new high efficiency models typically have an expansion valve which is automatically adjusted for temperature so that the refrigerant condenses properly. The old models usually had a fixed orifice expansion device which unloaded the system more at higher ambient temperatures.

A further discussion of the effects of these three factors on higher efficiency air conditioner operation trends with ambient is provided in Appendix A.

Very little testing on commercial air conditioners at high temperatures has been published, but Southern California Edison (SCE) has tested some air conditioners and in one case found that the change in power per degree Fahrenheit was 74% higher for a SEER-12 roof top air conditioner than for a SEER-10 model (Faramarzi 2004, p. 32).

Equipment sizing also has a significant bearing on the relative power use of older 10 SEER units vs newer 13 SEER models. It should noted that the steady-state power draw comparisons shown in Figure 1 and in the Appendix relate directly to increased aggregate peak power use only in cases where both AC units are running continuously at the peak ambient conditions. In cases where both units are oversized such that they are still cycling on and off at the extreme conditions (and thereby both still meeting the elevated cooling load), the lower SEER units with lower capacity at extreme ambients will be running longer to provide the same house cooling load requirement. In this case, the relative power draw will be governed by the inverse of the relative EER levels at the extreme ambient (assuming that the difference in cycling losses is small). This is because the inverse of EER is the power per unit capacity. For the same total delivered cooling (i.e., capacity * run time), the higher power draw rate of the 13 SEER scroll unit can be more than offset by the lower run time. Thus for an aggregated group of air conditioners cycling on and off at different times, the average hourly power draw for the 13 SEER scroll unit would be lower by the the inverse of the EER ratio at the elevated ambient.

If units of equal nominal capacity are sized closely to the application load at the design day ambient, and the peak condition is at a higher ambient where both units are running continuously, the relative power for such units will correspond to the steady-state power draws as shown above. If both units are sufficiently oversized so that each are cycling at the peak ambient condition, then the relative power use (over complete on/off cycles) will correspond closely to the inverse of the relative EER levels at the peak condition.

If the units are oversized to a lesser degree so that the 13 SEER scroll unit is cycling while the 10 SEER reciprocating unit is running continuously at the peak condition, the relative power use will fall somewhere in-between the above examples. On the other hand, if an oversized 10 SEER reciprocating unit is replaced with a closely sized 13 SEER scroll unit such that the 13 SEER unit is not quite meeting the AC load at the peak ambient, the reduction in power use is greater than the inverse in the EER ratio at the peak condition. (This is because the scroll unit is providing less cooling, rather than the same or more cooling as in the other cases.)

In general, if both the older unit and the higher SEER replacement unit run continuously at the peak condition (neither meeting the total peak cooling load), the comparisons of Table 1 would hold. The more oversized the older 10 SEER unit and the more rightsized the new 13 SEER unit, the more the benefits of the higher SEER unit will be realized in decreasing aggregate power demand.

Hopefully, annual load model benchmarking and updating will be capable of monitoring the trend of replacing older air conditioners with high-SEER units. Load modelers should be aware of the growing load impact of high-SEER air conditioning as a function of temperature.[2]

Estimates of the percentage of total load that is from AC motors have varied widely and are ranging upwards. It had been common practice to model motor load in the Western Electricity Coordinating Council's (WECC's) territory as 20% of total bus load, using historical references (Chinn 2006, p. 2). However, SCE modeling shows total motor load to be 27% based on adjusting load percentage until the voltage plot of a simulation matched an actual 2004 motor stall event (Chinn 2006, p. 4). Of the motor load, it is generally believed that the majority of the motor load is from air conditioning. Growing urban heat islands are causing increased air conditioning load factor, and on hot days it may be much more than 27%. Even in 1993, air conditioning load was analyzed as being as much as 50% of the summer load in some areas (IEEE 1993, Diaz 2002, p. 1). Anecdotal evidence of circuits in the "Inland Empire" (the region inland from Los Angeles and Orange County) indicates that the percentage may now be as high as 70% on hot days. If the available air conditioning load can be precisely and reliably predicted, this large load block represents an ideal target for exploiting spinning reserve from responsive load.

III. Spatial Resolution and Forecasting Load as a Function of Temperature

Locational Forecasting

A common complaint among utility load forecasters is that temperature data does not have adequate spatial resolution (Willis and Dekker, p. 1023), which is a key requirement for accurate forecasting of air conditioning load in specific small geographic areas. (In California, on the other hand, electric load forecasting has a long tradition of some 16 climate zones within the state.) Without spatial resolution, utilities will probably not be able to make accurate predictions for small geographic areas. For example, summer cold fronts coming in over the San Francisco Bay area sometimes have a sharply defined edge so that it's cool and foggy on the west side of the front, but hot on the east side, prompting customers to run their air conditioners. It is often difficult to predict exactly how far the front will move in. Also, historical utility load forecasting

[2] A note on margin to voltage collapse: Although this report is not intended to cover voltage collapse, we would like to include one paragraph on this concern as it relates to the other findings in the report on increased load level during high temperatures. As discussed, load modelers say that 27 to 50% of the total load is air conditioning on a hot day. Total air conditioning load is typically dominated by the load of the compressor motor. Let us use 27% as the percentage of total load that is comprised of compressor motors. As discussed above, both the SEER 10 and the SEER 13 equipment increase in load on a hot day, but the SEER 13 increases 29% more than the SEER 10 (one reference gives a 74% increase, but we will use 29%). So if we increase the 27% portion of load by 29%, the total load grows unexpectedly by a factor of 1.078 on a 115°F day. Is this a reliability concern? When power system planning engineers perform studies to ensure that the system stays stable on hot, high load days, one of the concerns they study is voltage collapse. They determine what the margin is to voltage collapse with certain levels of power flowing in the system. They typically like to have a 5% buffer over the predicted load level. If the load is a little higher than the prediction, perhaps 4%, they will still have adequate margin to voltage collapse. The rule is that the system must be able to withstand a single contingency such as a loss of generator or loss of transmission line and remain stable. This is known as the n–1 (or n minus one) criterion. At some future date, when half of the air conditioning load is high efficiency, the load prediction models may be low by about 7%, or much more, on very hot days. This unplanned change in load level may encroach on the voltage stability margins. If the margin is "eaten up" by an unexpected load increase, then a single contingency may result in system collapse.

data is usually made up of only a few temperature data points spaced miles apart. Temperature data is often available at each substation, but this resolution is typically not used in forecasting.

Conventional methods are probably inadequate for highly accurate locational (circuit-by-circuit) forecasting to predict these locational differences. However, is accurate locational forecasting needed for reliability reserves? High-resolution forecasting would be needed if we were trying to support individual distribution circuits, but reliability services are intended to support the balancing area, not individual circuits. Larger-area forecasts can be quite accurate and spatial differences can be averaged. Available reserves averaged over a balancing area can still be accurately predicted, and this is the parameter that needs to be accurately predicted if load is to supply a service such as spinning reserve.

Forecasting errors for load and contingency reserve availability are obviously correlated: the higher the load the greater the amount of available reserve. This has a fortunate consequence when using air conditioning load for spinning reserve. If the load forecast is wrong and underestimates the actual load, the system operator must find additional generation to serve that load. Fortunately, the forecast would also underestimate the amount of spinning reserve air conditioning can supply, freeing up some generation to serve the same load. Conversely, if the forecast overestimates the amount of spinning reserve that is available from air conditioning, it necessarily also overestimates the amount of air conditioning load, and so generation that was scheduled to supply the load is potentially available to supply reserves. Load and reserve forecasting errors at least partially cancel each other out.

IV. Use of Building Air Conditioning Models to Predict Load

The system operator typically only cares about the aggregate amount of response that is available. Aggregation helps increase forecast accuracy considerably when subcomponent errors are uncorrelated. Large building models may sometimes be useful for planners though, or in determining what the quantity of the available spinning reserve service may be.

If a highly accurate prediction of air conditioning load in a specific large building such as a hotel or office building is needed, a building air conditioning model could be useful. In this section, we will provide an example of such a model. Building designs obviously vary in their ability to maximize energy efficiency, but in this example, we will use some typical parameters for new construction.

A precise forecast will require a model of how the building air conditioning equipment responds to temperature. The model must calculate cooling capacity and electric load as a function of outside and conditioned space temperatures. The electric load per unit of delivered capacity gives an indication of the energy use to provide a unit of cooling capacity. As an example, the ORNL Mark VI HPDM was used to generate a plot of power per unit delivered capacity versus indoor and outdoor temperatures (Figure 2). Refrigerant R-410A was chosen because that is the replacement for the older R-22, and a scroll compressor is used instead of a reciprocating compressor to be representative of the higher SEER units. Indoor relative humidity was kept constant at 52% as should be maintained in a well designed installation. This plot shows the increasing amounts of energy required to provide a given amount of cooling with higher ambient temperatures and lower indoor temperatures. In a formal system study, either separate models would be required for each type of equipment or a composite model is required that reflects the mix of equipment in use.

To obtain total energy use, the air conditioning equipment model(s) must be coupled with models of the buildings they are used in. The customer's thermostat setting will affect not only the electric load per unit delivered capacity at a given outdoor ambient, but will also increase the required capacity, and thus run time and total energy consumption. This is because a lower customer set point will increase the cooling load requirements on the house due to the larger temperature difference between indoor and outside and thus result in more heat flow into the residence. Different building types also have different thermal time constants.

The equipment and building models will have to be combined with models of customer use. Customer use typically changes between weekdays and weekends and as a heat wave continues for multiple days. Customer response to energy price signals and appeals to conserve must also be incorporated.

Once the load response characteristics are known, an accurate weather forecast is required. Temperature is usually the dominant variable of interest but humidity, cloud cover, and wind are also important. Matching the spatial resolution of the weather forecast to the geographic distribution of the load is important as well.

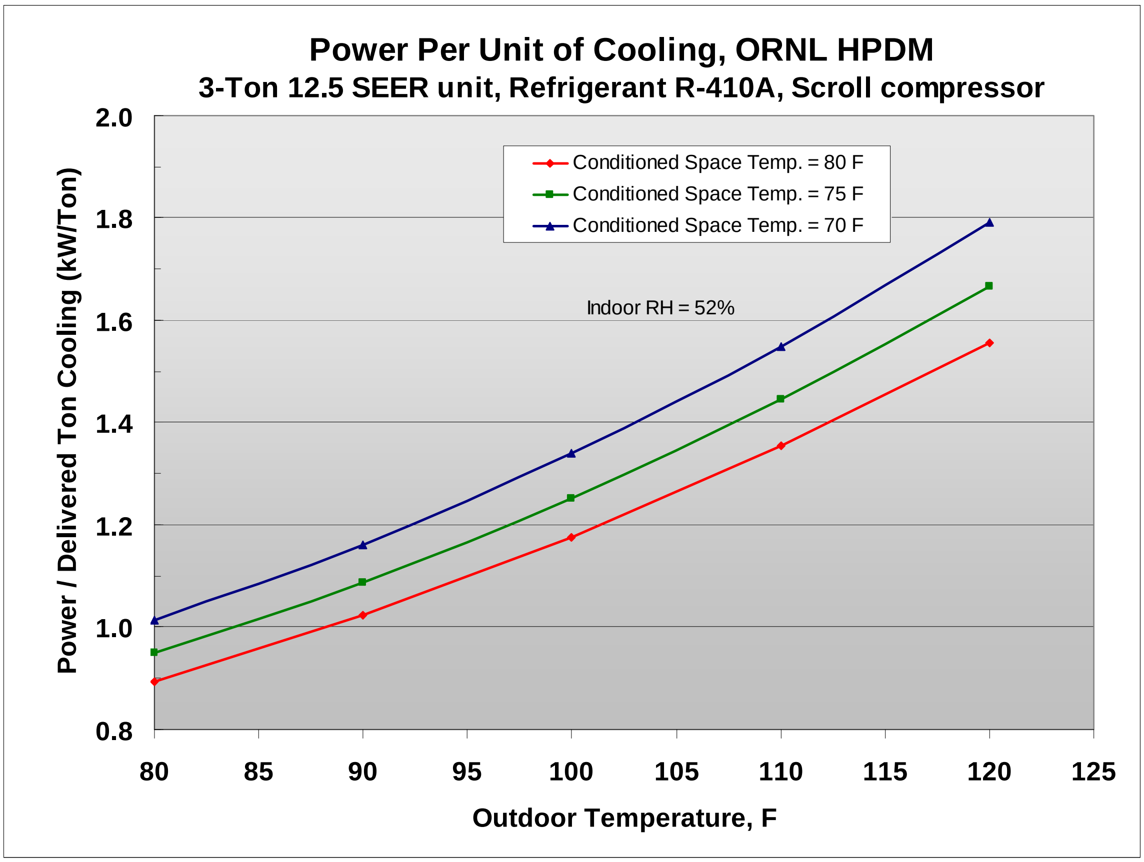

Figure 2. Electric load per unit of delivered cooling varies with both the outside air temperature and the customer's indoor temperature preference.

V. Speed and Duration of Spinning Reserve Response

Spinning reserves are deployed in two distinct ways to respond to the sudden loss of generation or transmission line, depending on the size of the contingency. Large contingencies require fast, automatic responses, and small contingencies are handled by dispatches from the system operator. Spinning reserves must locally detect and autonomously respond to contingencies that are large enough to depress power system frequency. Response must be rapid because there is essentially no energy storage within the power system, and generation and load must be continuously balanced. Spinning reserves respond autonomously to drops in power system frequency. Since power system frequency is available everywhere within an interconnection and since it reflects the instantaneous balance between generation and load, there is no need for communications. The spinning reserve resource simply monitors system frequency and responds if the frequency drops.

Proportional response can be obtained from a large aggregation of responsive loads by staggering the frequency response set points and creating a droop curve. Response to frequency deviations can be provided within cycles rather than within the ten minutes required by large generators to ramp up their output.

Spinning reserve specifications vary slightly from region to region, but the reason for having them and their basic characteristics are the same everywhere. Contingency reserves (spinning and non-spinning) respond to the sudden unexpected failure of a generator or transmission line.

Contingency reserves also respond to system operator commands. This is the more typical deployment method for most contingency events in large interconnections because the loss of a single generator typically does not move system frequency enough to call for response. Instead, system operators detect the generator failure as a sudden change in the interchange with their neighbors. Rules established by the North American Electric Reliability Corporation (NERC) Disturbance Control Standard require each balancing area to restore the generation/load balance within 15 minutes. To accomplish this they require individual reserve providers to fully respond within 10 minutes of system operator directives. Air conditioning load is an ideal spinning reserve candidate since frequency can be detected locally for immediate response, and within seconds communications can get a deployment signal from the system operator (or a frequency relay located at the substation) to the load. See "Load Response Fundamentally Matches Power System Reliability Requirements" B.J. Kirby, IEEE Power Engineering Society General Meeting, 2007.

The dispatch of air conditioners is done centrally with the system operator deciding when to activate. A different control scheme would be needed to be employed to respond based on frequency. Unlike generation response, which requires time for the generator to ramp up its output, air conditioning can immediately provide full response. The frequency deviation response must occur rapidly — seconds count. Load responds to frequency deviations much faster than generation because each load senses the frequency itself and gives full response essentially instantaneously, whereas generators take ten minutes to ramp up to full response. When the response is to a system operator's command, then there is no difference between 10 seconds and 30 seconds; 10 minutes is technically fast enough, though the load response is still much faster than generation and is better suited for system operation. Generators typically take the full 10 minutes to provide the full response. If generators could respond faster they would instead increase the amount of MW that they can bid into the market. Response speed is discussed in detail in Section VI.

Response duration is a bit more complicated. Spinning and non-spinning reserves are normally relieved by replacement reserves or increases in energy-supplying generators within 30 minutes. This is desirable because it restores the reserves and prepares the power system for another event. NERC rules require reserves to be restored within 105 minutes and WECC rules require reserves to be restored within 75 minutes (Figure 3).

The first response after the spinning reserve and non spinning reserve are provided is, surprisingly, the market response. Real-time markets operate in as little as 5 minutes now, with 10 and 15 minutes being common. All of the independent system operators (ISOs) either operate fast real-time energy markets or will soon. The complexity comes with the distinction between when reserves "should," "must," and usually are restored. To be sure, the spinning reserve must be capable of sustaining response for 105 minutes. Some regions require the reserves to be capable of sustaining response for 2 hours to add a bit more margin. While air conditioning response can easily be extended for 120 minutes or longer, most customers would not offer to regularly provide this response.

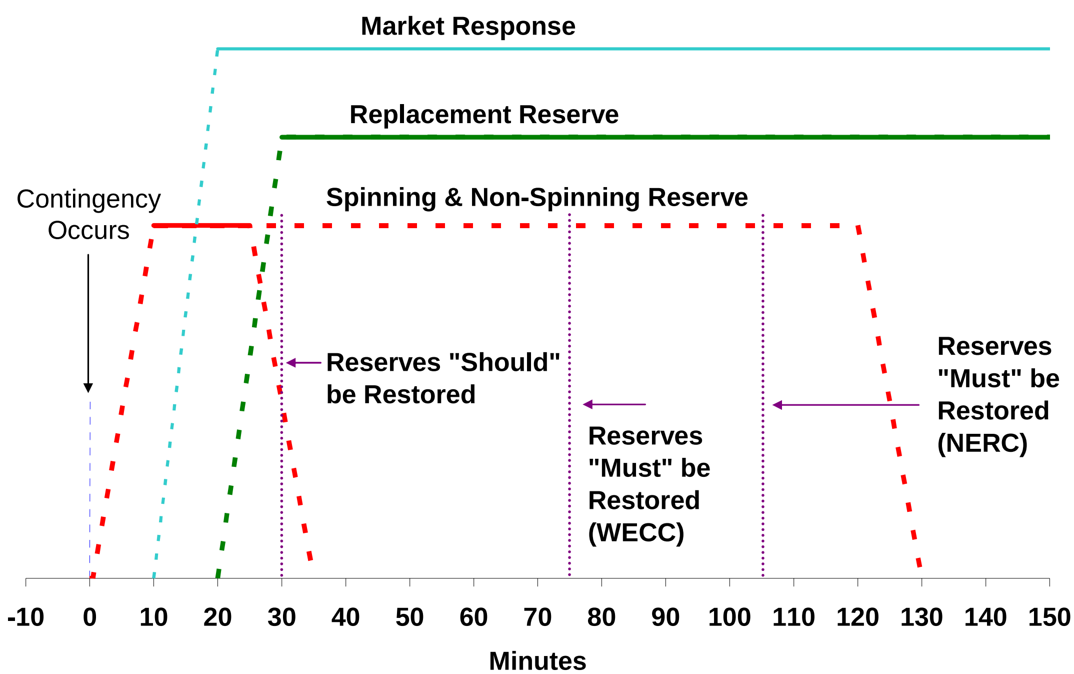

Figure 3. Spinning reserve responds immediately to a contingency but is quickly replaced by market response or replacement reserve.

Actual use of contingency reserves is *much* more limited. System operators want to restore reserves rapidly to increase power system reliability by preparing the system to withstand the next event. Figure 4 shows that actual reserve deployments by three major ISOs average about 10 minutes. A response of 30 minutes or longer is only very rarely needed. Actual use of spinning reserve matches air conditioning response capability and customer tolerance very well. An exclusive focus on very long deployments that rarely occur distorts and likely eliminates the opportunity. It is also possible that many of the longer deployments could be replaced with non-spinning reserve, replacement reserves, or market response. The customer contract could indicate something to the effect that the average deployment will be 10 minutes or less, but the operator has the authority to interrupt air conditioning for 2 hours in the event of emergency conditions. When the air conditioning load is restored, the switches would come back on at random times over a period of perhaps one minute. This is a standard feature of existing curtailment technology.

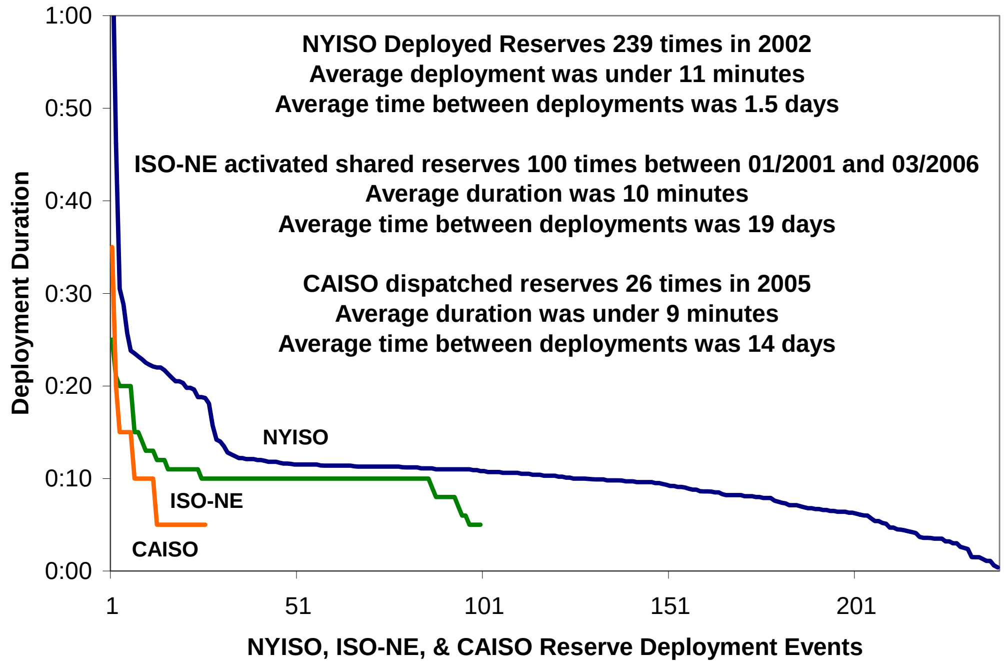

Figure 4. While ISOs differ in their use of spinning reserves they all average about 10 minutes for deployment duration and only very rarely require response longer than 30 minutes.

Spinning reserves must also automatically respond to dispatch signals from the power system operator for events which are not large enough to significantly move system frequency and which the system operator detects through imbalances and SCADA. In both cases, NERC and regional reliability council standards (BAL-002) require the resources to begin responding immediately and to be fully responsive within 10 minutes, as shown by the dotted red line in Figure 3. The system operator has 15 minutes to restore the generation and load balance.

These two distinct response modes ideally match responsive load capabilities. Power system frequency is available wherever there is voltage. Responsive loads, even highly distributed responsive loads like residential air conditioners, can easily detect power system frequency and instantly respond. Proportional response can be obtained from a large aggregation of responsive loads by staggering the frequency response set points and creating a droop curve. Response can be provided within cycles rather than within the 10 minutes required by large generators to ramp up their output.

Responses to system operator dispatch commands must also be automated, although they do not have to be completed in seconds. Communications to large numbers of distributed responsive loads may be slower than communications to large generators — tens of seconds rather than seconds. Overall response will still be much faster with responsive load than with generation, however, because distributed loads respond immediately when they receive the command while generators take 10 minutes to ramp up their output.

VI. Effect of 20-, 40-, and 60-minute Load Drop on Customers

AC Shutoff and the Thermal Time Constant of a Home

This section provides a brief discussion of an analysis to estimate the temperature rise in a home during a curtailment. A lumped-parameter analysis of heat loss or gain in a home provides insight into its thermal time constant. Understanding the thermal time constant allows easier comprehension and parameterization of thermal drift that would be expected if the space conditioning system were turned off for a specified period of time.

Treating the analysis with lumped parameters means that all the important heat transfer quantities are averaged and the average values are used in a simplified calculation of temperature response to turning off heating or cooling. This simplification also allows the average thermal time constant to be calculated, which also simplifies presentation of temperature response results. Inversely, the lumped parameter approach is a time-constant approach.

The thermal response time constant equation can be expressed as

$$T = T_\infty + (T_i - T_\infty)\, e^{-(t/tc)}$$

where
- T = the new indoor temperature after time t
- T_i = the initial indoor temperature when heating or cooling shut off,
- T_∞ = a fixed outdoor temperature boundary condition,
- tc = the thermal time constant of the home, and
- t = the elapsed time.

For the case of cooling, the time constant equals the effective overall thermal capacitance of the home divided by the effective overall heat gain rate of the home [e.g., (Btu/F) / (Btu/hr-F)]. The thermal capacitance results from the thermal mass, and the heat gain rate depends on thermal conductance and leakage, solar gain, and indoor loads. The time constant can change with time if factors such as indoor loads, outdoor wind speed (increasing infiltration), increased solar heat input, or changes in solar transmittance vary (e.g., extended cooking might heat things up).

In this exponential time constant equation, after three time constants, response is most of the way from initial conditions to the boundary condition, and about 60% of the difference is reached after about one time constant has elapsed. Typical home thermal time constants were analyzed and found to be in the range of 10 hours. Thus, it appears that we can characterize the range of potential temperature response behaviors of homes fairly well by examining time constants of 5, 10, and 15 hours. For scenarios of shutting off air conditioners, the most critical case will be homes with low time constants, so the 5-hour case is possibly of most interest for this scenario.

Some homes may have an upstairs with a 5-hour time constant and a downstairs with a 10-hour time constant, due to the upstairs receiving more heat input.

The graph in Figure 7 shows temperature rise for a nominal 5-hour home at 110°F outside temperature. If the initial temperature is 70°F, after one hour the home is at 77°F, and if starting at 75°F, after one hour the home is at 81°F. One could assume a straight line over the first hour to estimate values at 20- and 40-minute intervals. Thus after 30 minutes, our sample homes would have a rise of three or four degrees.

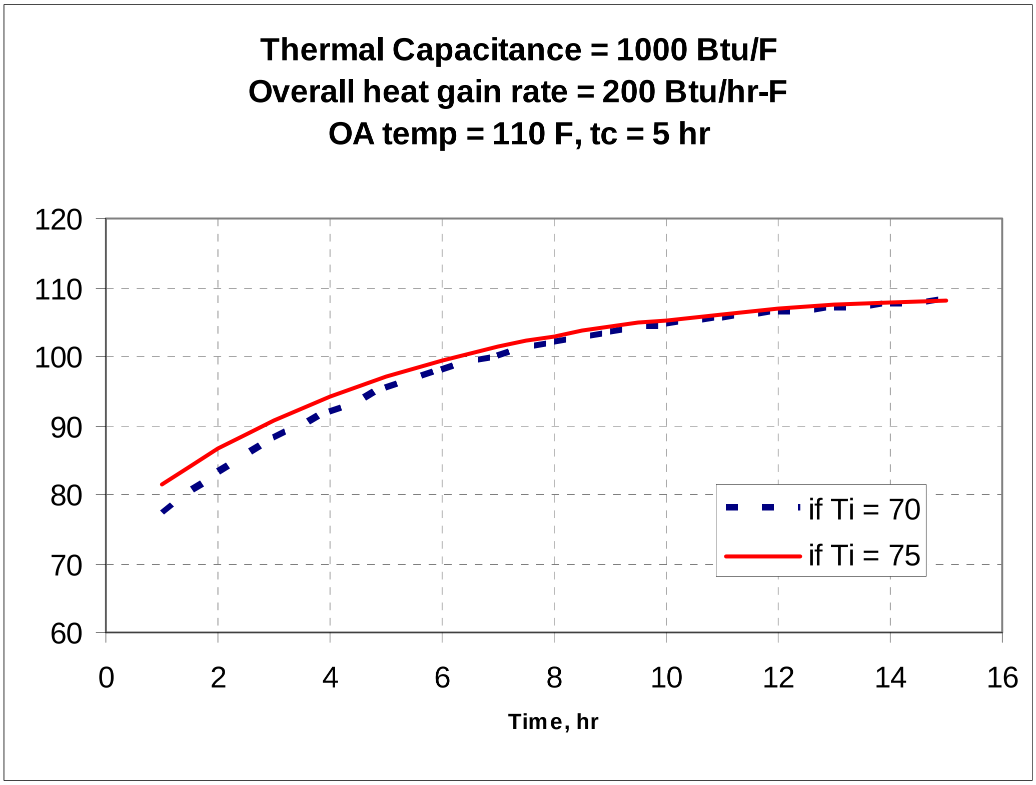

Figure 7. Temperature rise for a nominal 5-hour home at 110°F outside temperature.

VII. Conclusion

Air conditioning load is ideally suited to providing the service of spinning reserve because short duration curtailments are typically not a problem to the user. In addition, air conditioning load, itself, is actually the predominant load causing system stress. Periods of system stress occur at the same time as periods of maximum air conditioning load. Anecdotal information received as this report was being completed indicates that in desert areas of inland California, air conditioning load is now believed to be as much as 70% of the total load on hot days. The need for spinning reserve, expressed as the price, as shown above, is well correlated with the peak load. In addition, the large majority of interruptions would be short, less than a half hour, and would result in only a one- or three-degree change in temperature in the typical home.

Appendix A has been provided to explain the effect of air conditioner load change at higher ambient temperatures.

The authors are convinced that spinning reserve from air conditioning load is a practice that will be essential to reliable power system operation in the near future.

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APPENDIX A

A/C Power Trends with Increasing Ambient Temperatures

Authors: C.K. Rice and M. R. Ally, ORNL, 6/25/08

Introduction

The composition of A/C units in the general population is changing due to efficiency standards. New A/C units must have a SEER 13 or higher. The efficiency standards are met by implementing various technical modifications and controls. The impact on energy consumption at peak ambient temperatures differs depending on specific modifications. This appendix examines some of the impacts of these differences using an ORNL hardware-based simulation model of A/C operation.

1. Lab Tests of A/C Systems Done for California Utility

A 2006 report done for Southern California Edison (Bravo et al, 2006) looked at the power demand and other electrical operational characteristics of ten A/C units. These units ranged in SEER from 10 to 13 SEER and in capacity from 3 to 5 tons nominal cooling capacity. The lower SEER units from 10 to 12.5 SEER all used HCFC R-22 as the refrigerant while those with SEERs of 13, the current minimum efficiency level as of January 2006, used the ozone-safe HFC refrigerant R-410A. Another significant difference between units was in the type of compressor used. Both reciprocating and scroll compressors were used in the five SEER-10 units tested while scrolls were in each of the 12 SEER and higher units.

The absolute and relative trends in power demand of each of the ten units were determined under similar indoor dry-bulb conditions over a range of ambient temperatures from 80 to 110F applied to the outdoor coil of each unit. It should be noted that 80F is close to the average ambient temperature of 82F used in determining the SEER rating value. As such, the baseline condition reflects the average operating condition over the cooling season in most U.S. locations. Similarly a 100F condition represents the maximum ambient in most U.S cities with the exception of the Southwest and perhaps some central regions of California, where peak ambient temperature up to 115F or beyond may occur. In Figure A.1, the percent increase in power demand with ambient temperature is shown for each of the ten tested units, relative to the 80F baseline. The range of SEERs is shown on the x-axis along the ambient temperatures and refrigerant-type. The different families in the legend identify the compressor type and capacity levels. As all of the reciprocating units are the first three bars shown from the left, it can be seen immediately that their relative power demand at higher ambient temperature is much less than that for the remaining seven scroll units.

In Figure A.2, the power increases for different families of SEER, refrigerant, and compressor type are averaged for unit capacities ranging from 3 to 4 tons and shown again as a function of ambient. At the 115F condition, the average power demand increase for the reciprocating units is about 22% as compared to 53% for the 13 SEER scroll units of similar capacity ranges. Scroll units of 10 to 12 SEER with R-22 as the refrigerant have a lower increase to 46%, as compared to the 53% increase for the R-410A systems. A number of factors are involved in the higher power demand trends with ambient of the tested 13 SEER A/C units. A major contributor is the compressor type and its capacity and power efficiency performance trends. A significant secondary effect is from the cycle performance characteristics of the refrigerant. Additional potential factors are the SEER level and the refrigerant flow control type (TXV or short-tube orifice).

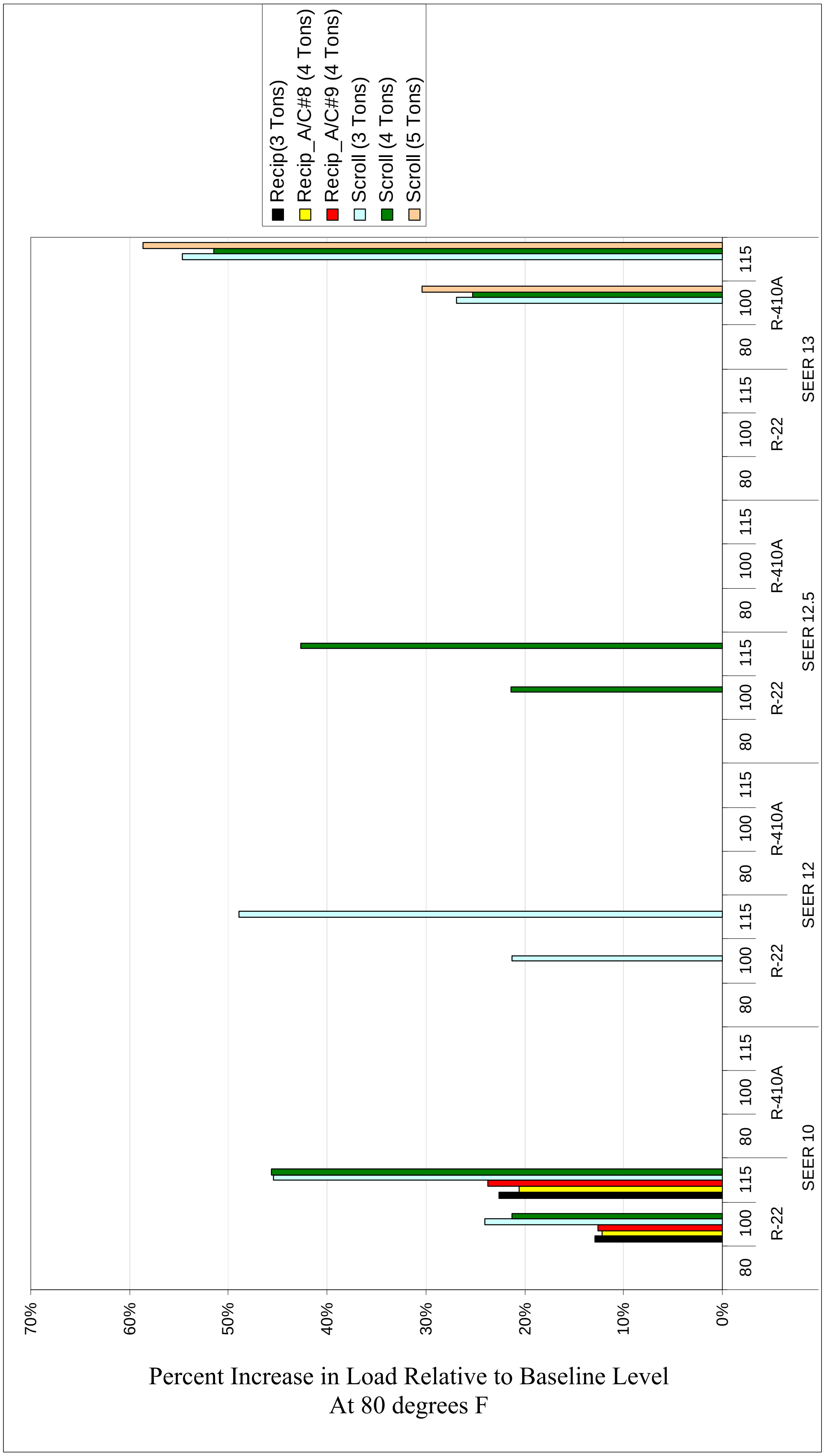

Figure A.1.

Measured Relative Load Increase with Ambient Temperature for a Range of 10 to 13 SEER A/C Designs of 3 to 5 Tons Capacity

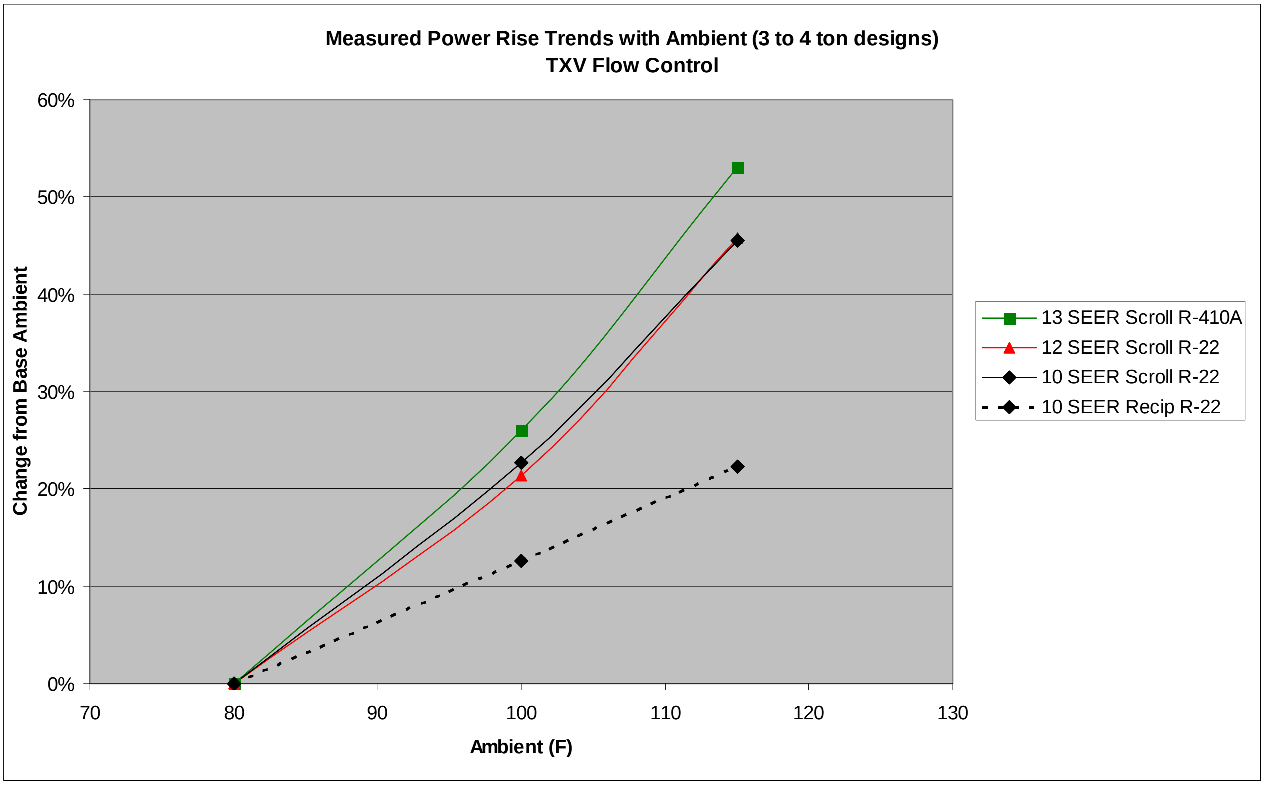

Figure A.2. Measured Average Relative Power Increase versus Ambient for a Range of 10 to 13 SEER A/C Designs of 3 to 4 Ton Capacity

2. Modeling of Similar A/C Systems at Elevated Ambient temperature

To investigate these effects quantitatively, we used the DOE/ORNL Heat Pump Model that has been developed and applied at ORNL over the last 30 years (Fischer et al, 1983; Rice et al, 1991, 1997, 2002). This is a hardware-based representation of the compressor, heat exchanger, and flow controls as applied to the vapor compression cycle in air-to-air A/Cs and heat pumps for space conditioning. (An online version of the model can be accessed at http://www.ornl.gov/~wlj/hpdm/MarkVI.shtml.) The simulation was used to model the predicted performance of nominal 3.5 ton design capacity units with the heat exchanger sizes selected to give approximately 10 and 13 SEER levels. This size was chosen to represent the average of the majority of sizes tests by SCE. We also selected combinations of compressor types, models, and refrigerants consistent with those tested.

Accordingly, at the 10 SEER level, we looked at scroll and reciprocating compressor options with R-22 as the refrigerant, For the 13 SEER designs, we initially modeled only scroll compressor cases with both R-410A and R-22 refrigerant. The compressors were modeled using performance maps of refrigerant mass flow and power as a function of refrigerant saturation suction and discharge temperatures. These were the standard 10-coefficient performance representations as specified in ARI Standard 540 (2006) as provided by the manufacturer. These maps were generated for fixed airflow conditions over the compressor of 95F. The maps for both the scroll and the reciprocating compressors were for models that were among the ten units tested by SCE.

For the refrigerant flow control, we assumed Thermostatic Expansion Valves (TXV's) with their performance characteristic modeled implicitly by holding the compressor inlet superheat constant and controlling the condenser exit subcooling to values that were reduced slightly with higher ambient temperature. The subcooling/ambient trends were based on test data taken up to extreme ambient temperature by NIST (Domanski and Payne, 2002) in an ARTI project for both R-22 and R-410A systems using identical heat exchangers. For R-22, a design subcooling of 7F was specified per the system manufacturer's recommendation, decreasing to 6.2F at 120F ambient based on NIST test data as reported in Rice 2005. The same design subcooling was used for R-410A, decreasing to 5.4F at 120F. (Both systems were charged to provide the same design subcooling at the capacity rating point.)

With the four systems suitably configured, the Mark VI Web version of the model (Rice et al 2002) was used to generate system performance results over a range of ambient temperature from 80 to 120F. The results of these simulations are shown in Figure A.3, where the power demand for the four cases relative to the 80F baseline values are plotted similarly to that in Figure 1. (It was assumed for comparison purposes that the tabulated power demand in the SCE tests was that measured for the total unit.) The only difference in the four cases in the two figures is the replacement of a 12 SEER R-22 case in Figure 1 with a 13 SEER R-22 case in Figure A.3. From a comparison of Figures A.2 and A.3, it can be seen that the predicted trends between the comparable cases are quite similar. The strong influence of compressor type on increased power demand is clearly reflected in the system modeling results. The effect of changing refrigerant from R-22 to R-410A is seen to be more significant than that of moving from a 10 to a 13 SEER system.

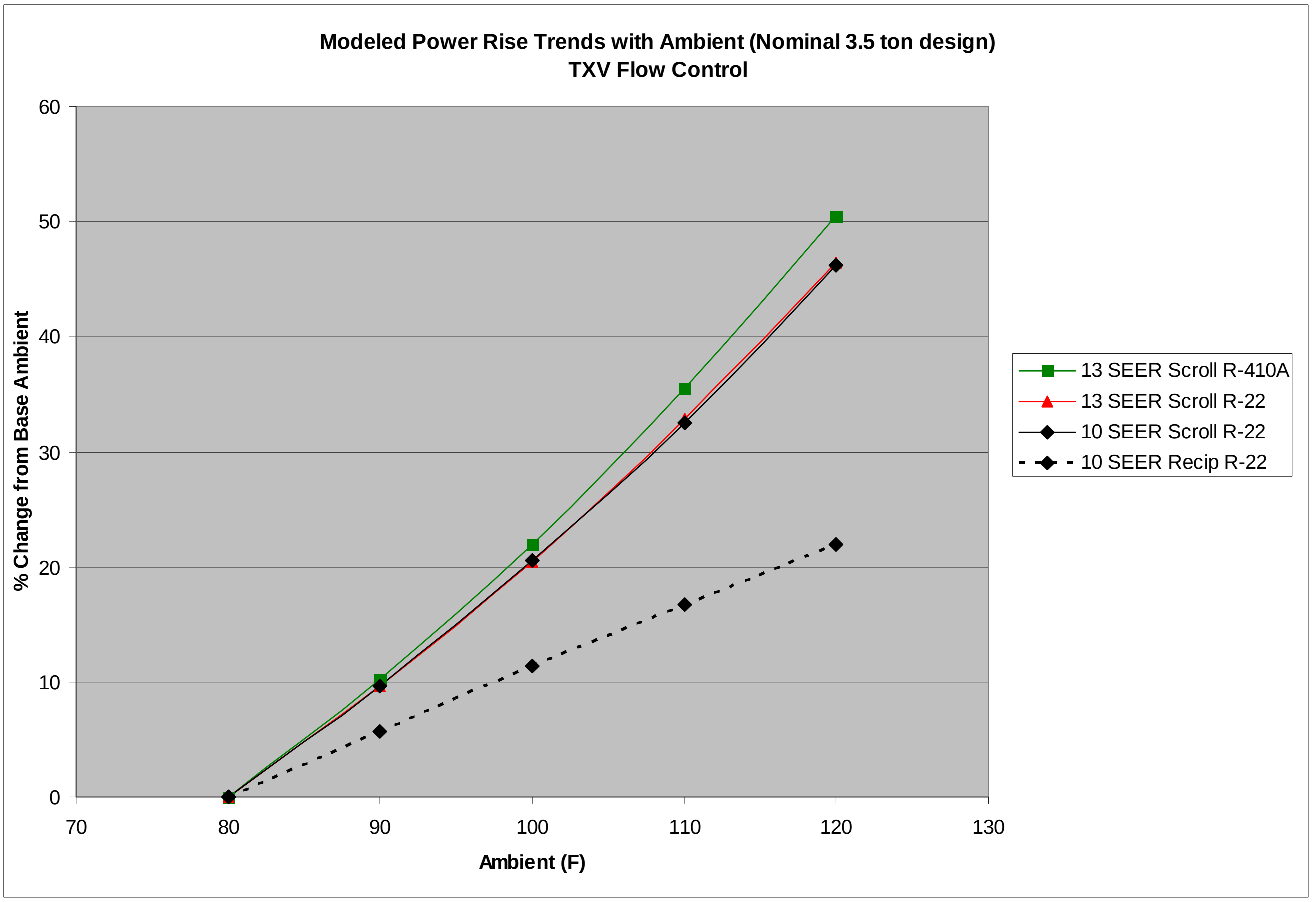

Figure A.3. Modeled Relative Power Increase with Ambient for a Range of 10 to 13 SEER A/C Designs

In absolute terms, the results from the model analysis are underestimating the power demand increase by about 10 percentage points at the highest ambient temperature for the scroll cases (note the different ambient end points of 115 vs 120F on the two plots). We expect that a good portion of this difference is due to the compressor operating with less heat transfer from the shell than was the case for the performance maps. At 115F ambient, the air temperature over the compressor shell would be over 130F if the compressor is located in the exiting airflow stream and is uninsulated. If the compressor is in an isolated enclosure, the equilibrium ambient would be expected to be higher than ambient along with limited airflow over the shell, so shell heat transfer would be further reduced. From our work with the extreme ambient data from the ARTI project (Rice 2005), power increases of 5% were found at 120F for a similar scroll compressor relative to the manufacturer's performance map along with reduced refrigerant mass flow (consistent with hotter suction gas entering the compressor and a less efficient motor at higher operating temperatures). A remaining possibility for part of the underestimate is that the scroll units may not have been fully broken in when the tests were run. This could cause the compressor power to also be higher than the maps due to the excess friction until the sliding surfaces of the scroll reach their worn-in level of smoothness and sealing.

For the reciprocating case, the model predicts the power rise at 115F to within a couple of percentage points. Without knowing more details of the systems tested including the location of the compressors, we cannot postulate further about why there is closer agreement for this case.

Next, we discuss causes for the two major reasons for the higher relative power demands with 13 SEER R-410A scroll compressor systems relative to R-22 reciprocating compressor designs.

3. Relative Cycle Performance of R-22 vs R-410A A/C Systems at Elevated Ambient temperature

It has been reported in the HVAC research community since the late 90s (e.g., Bullock, 1999, Wells et al, 1999) that the "theoretical cycle" efficiency of R-410A at elevated ambient temperature is poorer than that with R-22 due to the closer approach to the critical point of R-410A (of approx 161F as compared to 205F for R-220) at 130F and higher saturation temperatures. Even so, at lower condensing temperatures below 110F, system performance with R-410A is superior to that of R-22 due to improved system effects of higher heat transfer and lower pressure drop losses, and thus the selection of this HFC refrigerant to replace HCFC R-22 due to the non-zero ozone depletion potential of this chlorine containing, yet widely used, refrigerant.

The performance trends of R-410A relative to R-22 were evaluated in more detail by Domanski and Payne in laboratory tests in 2002 of newly released residential A/C equipment using scroll compressors and in related simulation analyses by Rice (2005).

The net effect is as shown in Figure A.4, with an increase in power of about 4%, decrease in capacity of 4%, and a net loss in EER of 7% at 115F ambient. This was for equipment with the same type of scroll compressor design and the same heat exchangers and TXV-type flow controls. These power increases are approximately reflected in the comparative performance of the modeled SEER 13 scroll systems shown in A.3 with R-410A versus R-22.

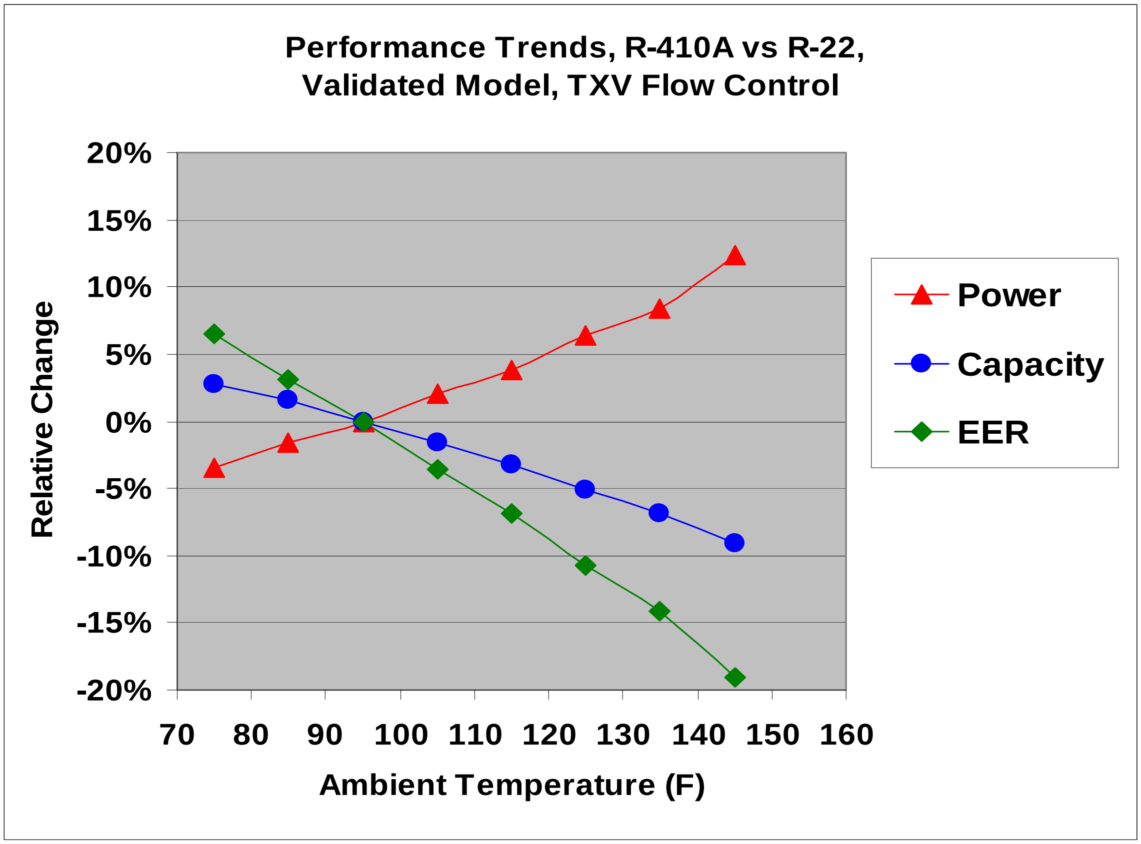

Figure A.4. Validated Performance Trends for R-410A versus R-22 in a Nominal SEER 13 Design (Rice 2005)

4. Relative Component Performance of Scroll Versus Reciprocating Compressors in A/C Applications at Elevated Ambient temperature

The compressor isentropic (power) and volumetric (flow) efficiency trends with ambient for scroll and reciprocating compressor play the major role in determining the peak power demand characteristics in A/C units.

In Figure A.5, the volumetric efficiency values are shown for both scroll and reciprocating compressors for the four modeled systems as a function of ambient temperature. The reciprocating compressor has a relatively large clearance volume at the end of each stroke, the effect of which results in a residual pocket of hot gas that mixes with the suction gas on the next intake stroke. This reduces the amount of gas compressed from that theoretically possible and so the volumetric efficiency is somewhat lower than for a scroll design with very small residual volumes. At the higher discharge pressures with elevated ambient temperature, the discharge gas is hotter and this reheating effect is larger. Thus the volumetric efficiency of the reciprocating case falls off more at the higher ambient temperature than for the scroll, as seen in Figure A.5. The relative change in volumetric efficiency is shown in Figure A.6 where it is seen that the volumetric efficiency drops by almost 12% at 120F ambient as compared to less than 3% for the scrolls. As refrigerant flow is directly proportional to volumetric efficiency, and power is proportional to flow, this effect alone would give a 9% drop in power for the reciprocating case (and corresponding drop in capacity).

With a larger drop in capacity with ambient for the reciprocating case, the heat exchangers become more unloaded and so the resultant temperature differences from the air to the refrigerant become less, dropping the discharge pressures and raising the suction pressures. This unloading lowers the power requirements significantly in relation to the reduced pressure, especially for the 10 SEER system with the more heavily loaded (smaller) heat exchangers. The combination of the reduced flow rate and lower power per unit flow requirement for the more unloaded reciprocating system is the major contributor to the reduced electric load at higher ambient temperature.

The main negatives of the lower volumetric efficiency of the reciprocating compressor are in the larger physical size required to provide a certain design capacity and in reduced heating capacity at milder ambient temperatures. However, in the cooling mode, the additional unloading of the system from the reciprocating compressor pumping characteristics, which drops cooling capacity that the customer may need at these extreme ambient temperature (in a closely sized system), nevertheless provides an automatic yet passive means of reducing power demand under extreme conditions.

A further contributing effect to the increased power demand at high ambient temperature for the scroll compressor is in terms of the isentropic (or power) efficiency trends. These efficiencies are shown for the four modeled systems in Figure A.7. Here the R-22 scroll compressors are seen to have somewhat higher isentropic efficiencies than for the R-410A scroll and the R-22 reciprocating below 100F ambient, especially around the SEER rating point of 82F ambient. This is because scroll compressors are fixed volume ratio machines and so the design ratio is generally selected to correspond to the condition with the most operating hours and energy use. At other pressure ratio (and thus volume ratio) conditions, the efficiency of the scroll drops off from the optimum. This drop-off is generally somewhat less pronounced with reciprocating compressors and is more a function of the valve design.

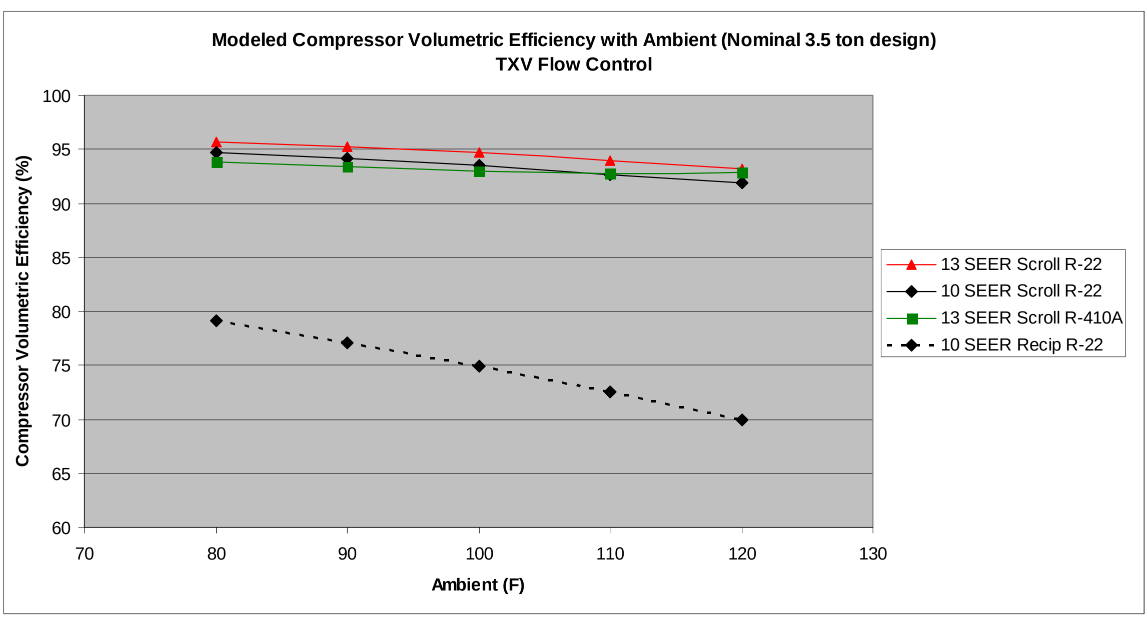

Figure A.5. Compressor Volumetric Efficiency Levels of Four Modeled A/C Designs versus Ambient

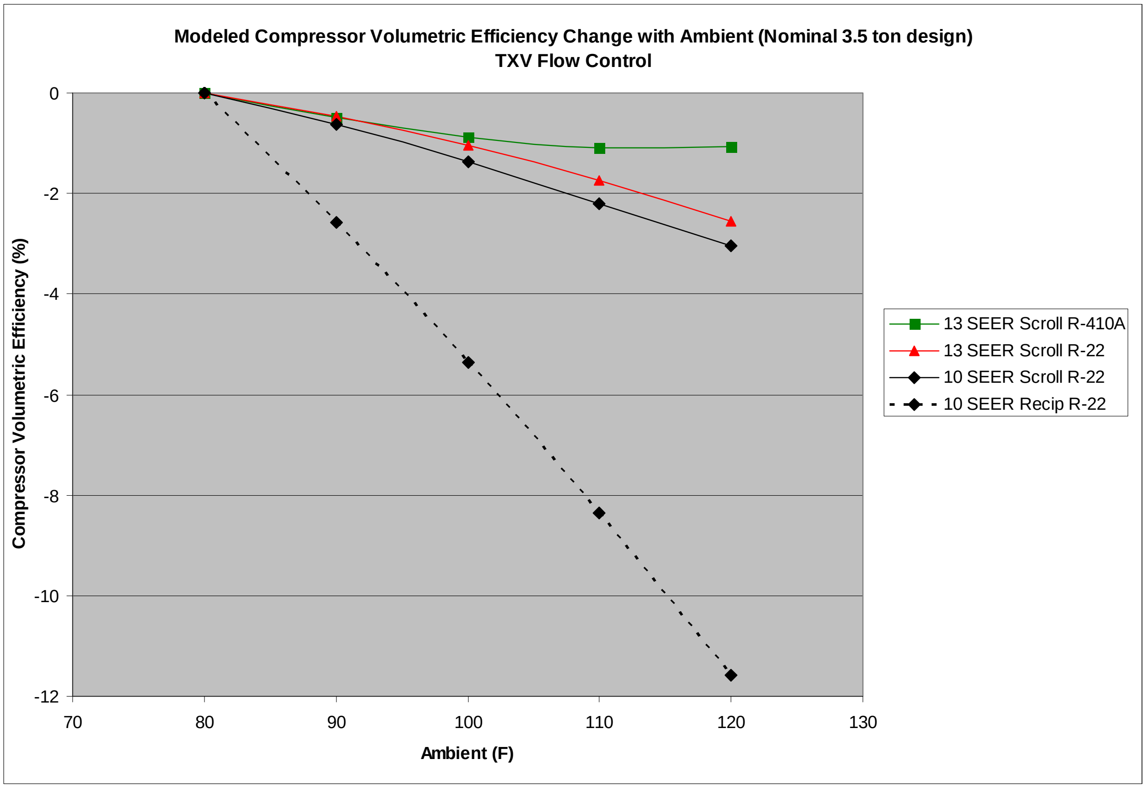

Figure A.6. Relative Compressor Volumetric Efficiency Change of Four Modeled A/C Designs versus Ambient

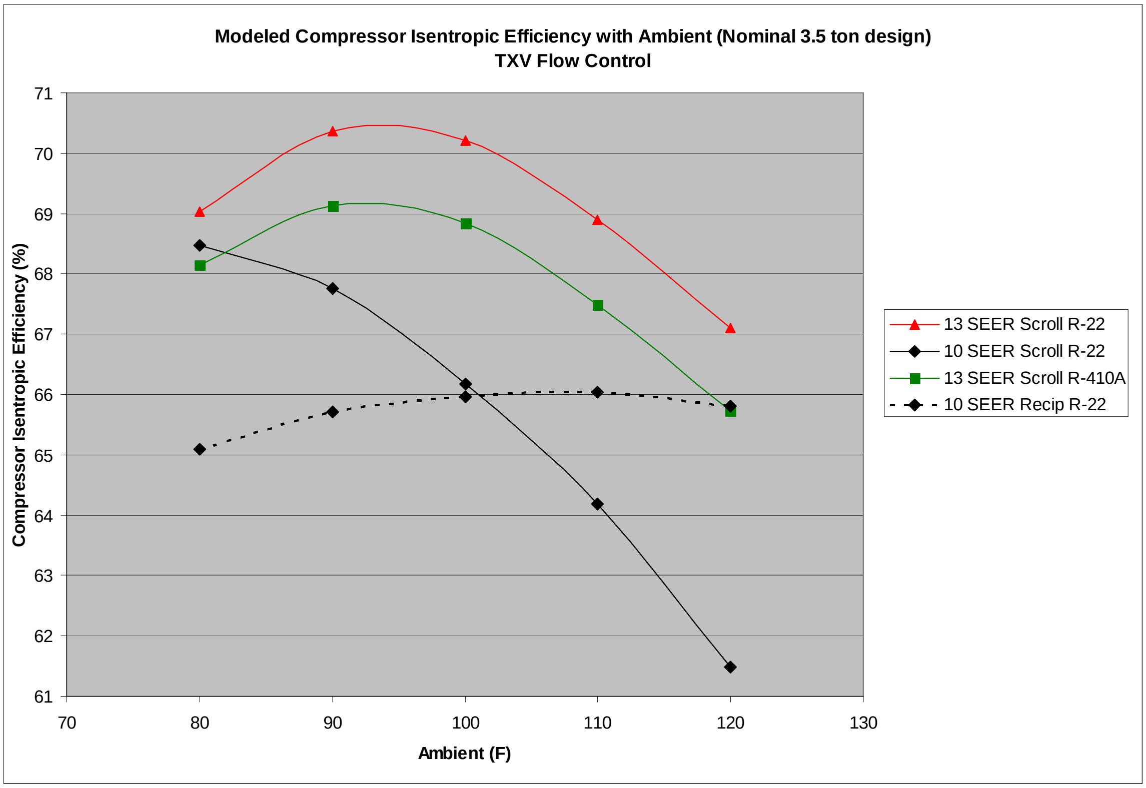

Figure A.7. Compressor Isentropic Efficiency Levels of Four Modeled A/C Designs versus Ambient

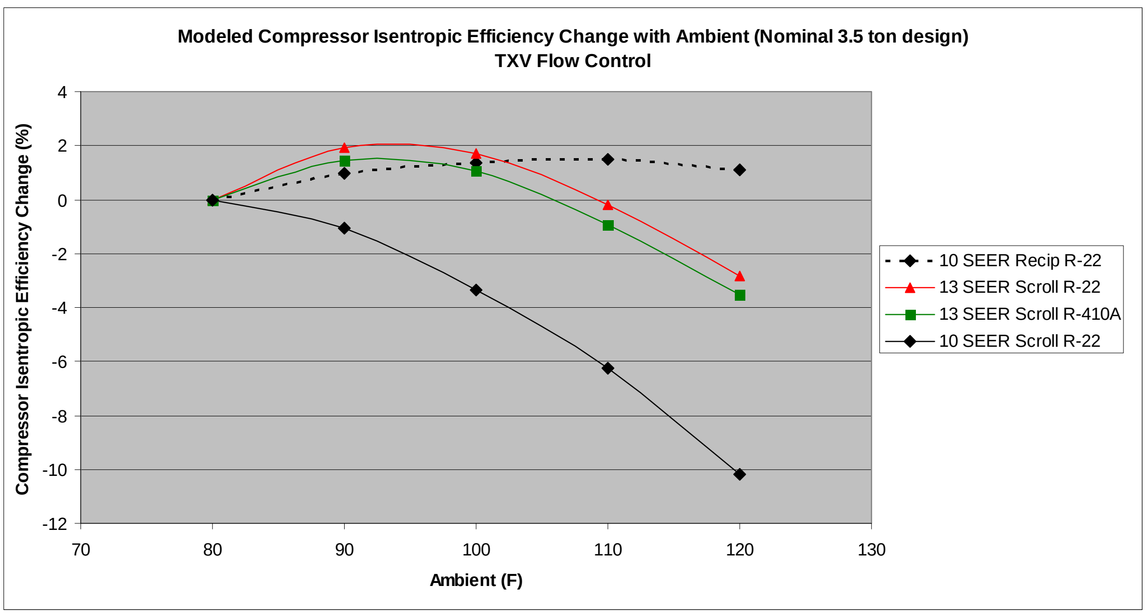

Figure A.8. Relative Compressor Isentropic Efficiency Change of Four Modeled A/C Designs versus Ambient

The relative amount of falloff in isentropic efficiency with increasing ambient temperature is shown in Figure A.8. Here, the reciprocating unit actually increases in power efficiency by almost 2% at 120F, relative to the 80F baseline. In contrast, the scroll units dropoff in power efficiency by almost 3 to 10% for a net power disadvantage of nearly 5 to 12%. As the total power use is the ideal power divided by the isentropic efficiency, the increases in power from the above stated decreases in efficiency are greater than 5 to 12%. This dropoff in power efficiency thus accentuates the increase in ideal power required of the scroll systems which maintain higher capacity and thereby pressure ratios at higher ambient temperature.

5. Potential Effect of Flow Control Type

One remaining secondary reason that can contribute in a smaller way to higher peak power demand in higher efficiency systems is the flow control type. The new high efficiency models typically have an expansion valve which is automatically adjusted with ambient conditions, so that the refrigerant subcooling and superheat levels are maintained nearly constant so that the condenser and evaporator operate at full capacity at higher ambient temperature. The SEER 10 models often have a fixed orifice expansion device which lost more system capacity at higher ambient temperature and thus unloaded the compressor and lowered electric load (but at a lower EER than a TXV system).

It was not clear from the SCE study if any of the 10 SEER systems used a fixed orifice (although the 10 SEER reciprocating model tested did have a fixed orifice as standard equipment. The effect of this switch to TXVs on increasing peak electric load is smaller than the refrigerant change to R-410A. An example of the effect is given by Rice (2005) in the ARTI extreme ambient report. The potential effect on increasing power demand in the examples is about 2 to 3% at 115F for R-22 and R-410A TXV systems, respectively, relative to fixed orifice designs.

6. Summary Analysis

Test data and analysis have been used to study the differences in power demand at elevated ambient temperature between selected 10 and 13 SEER systems. Compressor type has been demonstrated to be the major factor in these differences and is shown to be directly related to the capacity and power performance contrasts between scroll and reciprocating compressor. The new 13 SEER systems generally use scroll compressors because of their higher basic efficiencies at SEER conditions. Use of scroll compressors causes the power demand in these systems at elevated ambient temperature to rise higher than that for reciprocating systems relative to their respective levels at an 80F baseline near the SEER rating ambient. This is due in largest measure to the natural system capacity unloading of the reciprocating compressors at higher ambient temperature, with a larger dropoff in compressor power efficiency for the scrolls at elevated ambient temperature being a contributing factor.

Other secondary factors were noted to be 1) the switch from HCFC R-22 to the more ozone-friendly HFC R-410A in the new 13 SEER products and 2) the change from fixed orifice to TXV refrigerant flow control devices.

While the nominally higher SEER efficiencies of scroll compressors may allow manufacturers to meet the 13 SEER minimum efficiency levels with less heat exchanger surface (and thus smaller cabinets) and/or lower efficiency fans, the increase in power demand at elevated ambient temperature appears to be one unfortunate result of this design approach with current scrolls. An alternative design with a reasonably efficient R-410A reciprocating compressor could provide a system with power demand trends with ambient that are more desirable from a utility perspective, but may cost more due to larger heat exchanger and /or more efficient fan requirements. It would seem that if the cost/performance of high efficiency reciprocating compressors using R-410A are reasonably competitive with those for similar efficiency scrolls, a case could perhaps be made for utilities in hot/dry climates to consider providing customer incentives for purchasing a 13 SEER reciprocating design that had lower power demand at > 110F than current 13 SEER scroll systems of similar capacity. Giving rebates or other incentives for systems with higher EER levels at 115F, such as with the CEE Efficiency Tiers (CEE 2008) is one approach toward doing this, but does not fully capture the benefit to utilities of reciprocating compressor systems with EER levels comparable to scroll systems, but with reduced capacity at > 110F and thus lower electric load. In fact, with R-410A, the EER level at higher ambient temperature drops in large part because of a drop in delivered capacity, which also has an attendant drop in electric load.

From the above analysis of tested and modeled performance, it becomes apparent that the 30% higher SEER of the new systems with different compressor types, refrigerant, and possibly flow control does not result in a 30% higher EER at elevated ambient temperature and the attendant 23% lower electric load (1 – 10/13) as is realized at the 82F rating point. In the above analysis, the modeled 13 SEER R-410A scroll system had only a 2% higher EER at 120F as for the 10 SEER R-22 reciprocating unit. This, in combination with the lower capacity of the 10 SEER reciprocating system at 120F, resulted in only a predicted 1.5% system power decrease at 120F for the 13 SEER R-410A system, when all systems were normalized on the basis of per ton nominal capacity. (Normalizing the power values by the rated nominal capacity at 95F is important for consistent comparisons.) Based on the comparison between Figure A.3 to the available test data of Figure A.2, the actual power increase for the scroll system may have been 5% or more higher with a more fully calibrated model.

These results are summarized in Figure A.9 where the values of power per nominal ton of cooling capacity are shown for the four modeled systems discussed previously. From this it can be seen that the 13 SEER scroll R-410A system is just below the power per ton values of the 10 SEER reciprocating R-22 system, as noted above. With the 13 SEER scroll system using R-22, the power per ton values are seen to be further below that for the 10 SEER reciprocating system due to the higher compressor efficiency of the R-22 scrolls versus recips as shown in Figure A.7.

Note that we have also added an additional 13 SEER reciprocating R-22 system in Figure A.9 as the lowest curve, using the same compressor as for the 10 SEER reciprocating case. Comparison with this new case shows that the power per ton values for this system at 120F is reduced by almost 11% relative to a 13 SEER scroll R-22 system and is about 14% lower than the comparable scroll R-410A system. From this, one can estimate that comparable 13 SEER reciprocating versus scroll performance on a power per unit ton basis with both systems using R-410A could also be around 11% if the relative R-410A scroll versus reciprocating power efficiency values are similar to that for R-22. (A high efficiency R-410A reciprocating compressor by the same manufacturer was not available for use in this analysis.) All these scroll versus reciprocating power differences could be even greater by another 5% or more if the larger power increases with the scroll compressors in the SCE tests than modeled is confirmed with more tests with fully run-in scroll units. Note also that the electric load per ton at 115F for 13 SEER R-22 scroll is 19.3% below that for the 10 SEER R-22 scroll. This change with the same compressor and refrigerant is closer to the expected 23% power reduction based on the 30% higher SEER level.

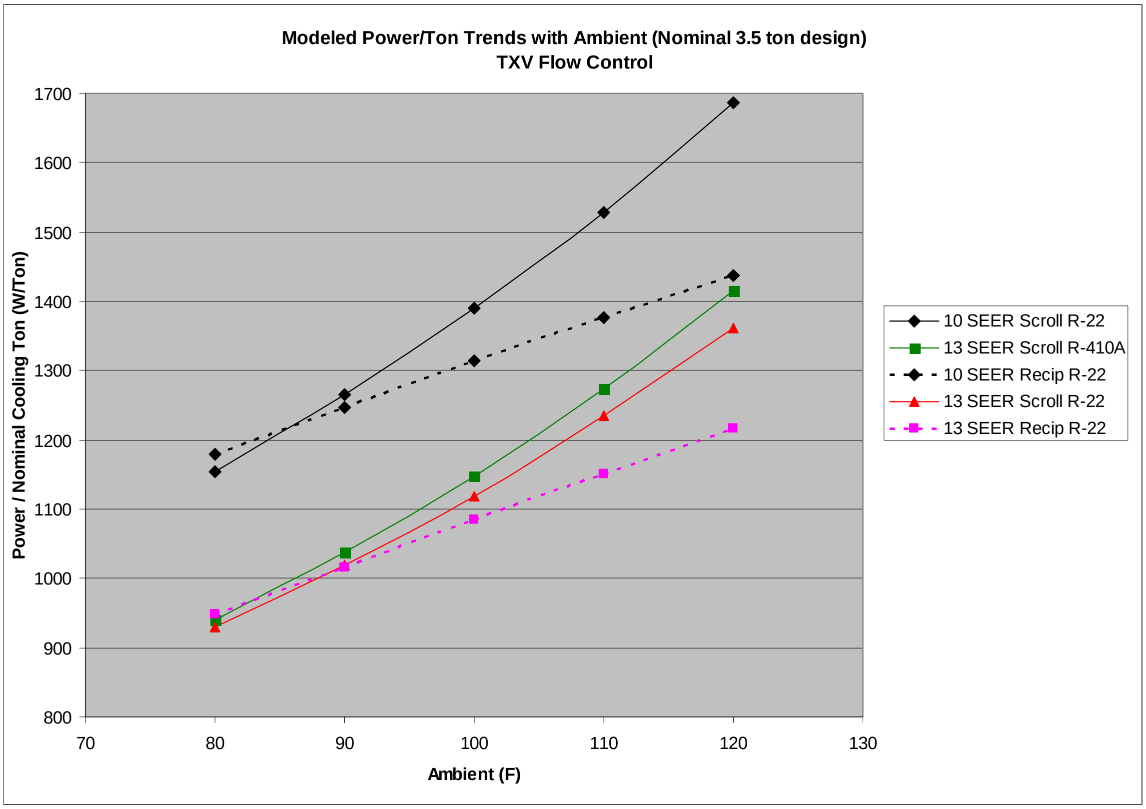

Figure A.9. Modeled Power Increase Per Ton of Rated Cooling Capacity versus Ambient for a Range of 10 to 13 SEER A/C Designs

Giving incentives to systems that have 10% lower power per nominal ton levels at 115F than currently seen with 13 SEER scroll systems would be one approach recommended for consideration. It should be noted that units are currently tested at 115F ambient (ARI Standard 210/240, 2003) just to see that they operate at this maximum operating condition. If manufacturers would provide the system electric load at this condition, this could be used along with the rated capacity to calculate the needed power per nominal ton values for such an incentive program.

In relating the above comparisons of steady-state power draw between units of different SEER and capacity characteristics to the aggregated peak power usage at elevated ambients, the assumptions regarding unit sizing should be considered.

For the comparisons shown above to relate directly to inferences regarding peak power draw, both units, as installed, must be running continuously at peak ambient conditions (such as 115F). If both units are oversized, such that they are still cycling on and off at peak conditions, or an oversized older unit is replaced with a more closely sized higher SEER unit, then the relative peak power use over complete on/off cycles will be proportional to or better than the inverse of the relative EER levels at the peak conditions. For such cases, the unloading capability of reciprocating compressors is negated by unit oversizing which results in the peak cooling load being met by longer run times and thus higher aggregated peak power draw..

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