CALIFORNIA
ENERGY
COMMISSION

INCREASED EFFICIENCY OF AIR CONDITIONERS AND HEAT PUMPS USING ADVANCED POWER ELECTRONICS

CONSULTANT REPORT

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Gray Davis, *Governor*

Legal Notice

Acknowledgements

ESI would like to thank the following individuals for their contributions to this project.

Michael Martin, California Energy Commission Contract Project Manager for most of the project, who provided the overall program direction with his vast experience and knowledge in air conditioner testing and certification.

Philip Spartz took over the project as Commission Contract Manager towards the end and came up to speed in a very short time. He managed the final phase of this project, providing emphasis on transitioning to the market place.

Jim Sprout, who started as a consultant and ended up as Vice President of Engineering at ESI, contributed to both to electronics technology and cost share.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for "Increased Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics," Contract Number: 500-98-021. The report is entitled **"**Increased efficiency of Air Conditioners and Heat Pumps Using Advanced Power Electronics." This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

This report describes work performed by Energy Savers International (ESI) between May 1999 and June 2001 on the project entitled "Increased Energy Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics." The California Energy Commission’s Public Interest Energy Research (PIER) program provided $411,614 in funding for this project. ESI‘s original cost share of $114,000 increased to $242,131 by project end in June 2001

Background

Assuming that the growing energy needs of the United States were met only through building additional power plants, an estimated 1300 new plants of 300 MW each would be needed by the year 2020. However, the severity of the energy problem can be considerably diminished by raising the energy efficiency of appliances and by managing their peak load demands. By increasing the efficiency standards currently coming into force for appliances, such as clothes washers, water heaters, and air-conditioners, it is estimated that the construction of 170 new 300 MW-power plants can be avoided.

Two issues commonly recognized by industry as barriers to the introduction of more efficient refrigerators and air conditioners are the prohibitive cost of devices that improve their efficiency and the increase in size that would prevent their installation in normal size homes.

ESI sought to develop an intelligent controller to increase the energy efficiency of refrigerators and air conditioners while solving these issues of cost and size. If the use of energy efficient devices reduces the energy consumption of electric motors in the residential sector by 20 percent, the savings would be nearly 1 Quad (10E15 Btu). More than 60 percent of this would come just from energy efficiency improvements in air conditioners and heat pumps using such devices as ESI's intelligent controller. To accomplish this ESI brought the benefits of low cost, high performance electronics to the development of an intelligent controller.

Project Objectives

The objectives as defined in the contract were to:

- Increase the efficiency of compressors used in typical residential refrigerators from 5.4 EER to 7.0 EER by the use of an innovative controller that converts single-phase electrical supply to three-phase power to run the compressor. This would be a 30 percent improvement in efficiency on a power rating of ~200 watts.
- Increase the efficiency of compressors used in typical residential and light commercial heat pumps by 30 percent using a similar controller on a power rating of ~4000 watts.
- While we set no specific economic objectives for the project, ESI identified early in the program that the high cost of efficiency improvement devices is a barrier to market acceptance and we developed our design to meet certain cost considerations. Specifically ESI established a goal of developing the intelligent controller with a selling price of $80 per ton for 100,000 units per year for units above one ton of cooling capacity, to the end user.

Project Outcomes

- For refrigerators, our modeling and analysis results showed that it was only possible to increase efficiency by about ten percent. Our models showed that the annual savings would be on the order of $4 to 5 a year. By comparison, the cost of the controller was too high to make this a practical solution. Based on these results, we made a mid-course correction in the research direction to drop refrigerators from further development and to replace them with development of controllers for residential and light commercial heat pumps.

- For A/Cs, our modeling and analysis results of a 3-ton air conditioner (A/C) showed that it was possible to increase efficiency by 30 percent. Our models showed that the annual savings would be on the order of $90 per year, based on U. S. Department of Energy (DOE) Climate Region 4 and an energy cost of $0.08 per kilowatt hour (kWh).

- For heat pumps, our modeling and analysis results showed that it was also possible to increase efficiency by 30 percent. Our models showed that the annual savings would be on the order of $180/yr. This is twice what we found we could get with A/Cs, because the unit can be used year-round.

- We verified that the compact size of the electronic controller made it possible to install it inside the existing cabinets of both heat pumps and A/Cs.

- We discovered that our controller has a low power factor. This was not unexpected, because this is typical of all rectifier input power circuits. It is possible to increase the power factor by installing a suitable filter, but we did not do that in this contract.

- Laboratory testing on a 2-ton heat pump verified that the electrical performance of the heat pump using the controller matched the expectations in the model. For example, when the controller reduced the speed of the compressor, the power requirements of the compressor dropped proportionately.

- Laboratory testing conducted on a three-ton A/C also verified that the electrical performance of the controller matched the expectations of the model.

- Independent laboratory testing was conducted in accordance with Air Conditioning and Refrigeration Institute ARI 210/240-94 on an unmodified 3-ton 3-phase A/C to establish the baseline efficiency. Our controller was installed and the efficiency tests were repeated. Results showed an improvement in efficiency of 19 percent, assuming a degradation coefficient of 0.25.

- Separate laboratory testing found that switching from single-phase to three-phase compressor motors resulted in an average increase in efficiency of four percent.

- We discovered that for heat pumps or A/Cs between one and five tons, we could sell the controller for an installed price of approximately $100/ton. For heat pumps and A/Cs 5 tons and above, we are able to meet our target of $80/ton.

- At 105°F, the controller did not improve the energy efficiency when operating at full load. However, the controller can operate the A/C at reduced speed with proportionately reduced peak electrical demand. For example, when operating at half speed, the power requirements dropped from 5.5 kW to 2.5 kW.

Conclusions

- Using the controller in heat pumps and A/Cs is very cost-effective, providing a return on investment of less than two and four years, respectively. In California, where the electricity rates are even higher than in our model, the return on investment will be even sooner.
- It is not necessary to increase the physical size of heat pump or A/C enclosures to accommodate the installation of our controller. This is important because other mechanical solutions that provide similar benefits may require significantly larger enclosures and comparably increased costs.
- Using this controller in refrigerator applications is not cost-effective.
- Installing a filter will improve the power factor and make the device more acceptable in widespread application.
- Although the independent laboratory tests compared the efficiency of 3-phase A/Cs, they did not account for the additional four percent improvement that we found could be obtained by switching from single-phase to 3-phase compressors.
- Combined with the 19 percent efficiency improvement (assuming a degradation coefficient of 0.25) observed on the 3-phase A/Cs, we project an overall improvement of 23 percent, which is more than 75 percent of our original target of 30 percent.
- Discussions with A/C and heat pump manufacturers revealed that it is unlikely that they will replace single-phase compressors with 3-phase compressors in the U.S. residential market. Given this inertia, it does not make sense to pursue our 3-phase controller for residential heat pumps or A/Cs at this time.

Benefits to California

In California, the successful commercialization of intelligent controller technology has the potential of providing a 20 percent savings (nearly 5,000 GWh per year) in the energy consumed by residential air conditioners and heat pumps. And because air conditioners are primarily responsible for the large peak demand in diurnal system load profiles, which can result in blackouts and brownouts, use of the controller could increase the reliability and quality of the power system while decreasing the number of future power plants needed in the State. In addition, controller commercialization could provide major benefits to California's economy through the generation of jobs and increased tax revenue while reducing the State's reliance on imported electricity.

Recommendations

- Test the performance of the intelligent controller with filtering designed to improve power quality.
- Test and analyze the controller's effect on the energy consumption of compressors and other equipment.
- Conduct a side-by-side comparison of two heat pumps, with and without the controller, both in the laboratory, and in the field for the period of one year. The purpose of this comparison is to get a better measure of the energy efficiency than is provided by the standard laboratory tests of SEER and will include a measurement of the degradation coefficient.
- Conduct field tests with a statistically useful number of units in small commercial applications in California. The purpose of these tests is to verify the energy efficiency, to determine the reliability and durability of the system and to assess its ability to reduce peak demand.

Abstract

This report, entitled “Increased Energy Efficiency of Air Conditioners and Heat Pumps using Advanced Power Electronics” summarizes research done in the Public Interest Energy Research (PIER) Program for the project Increased Energy Efficiency of Refrigerators and Air Conditioners Using Advanced Power Electronics under Contract #500-98-021.

In this project, Energy Savers International (ESI) generated several power electronics concepts, which were then evaluated, using modeling and analysis tools, at the circuit and system level. ESI selected a multi-phase, multi-speed controller concept as the best concept for improving the energy efficiency of air conditioners and heat pumps and used this concept to develop an intelligent controller using advanced power electronics hardware and software. ESI had an off-the shelf air conditioner tested, before and after installation of the ESI controller, by a reputable independent test laboratory (BR Laboratories) to obtain independent verification of their results. These tests followed Air Conditioning and Refrigerator Institute (ARI) 210/240-94 Standard guidelines to measure Seasonal Energy Efficiency Ratio (SEER). Using the equations and assumptions in that standard, SEER calculated from the test results showed a total improvement of 23 percent, assuming a degradation coefficient of 0.25. Because of linear extrapolations involved in calculating SEER in the ARI Standard, all benefits of three-phase operation were not accounted for. ESI recommends that the next step in validating the energy efficiency increase would be to field test air conditioners and heat pumps to verify the energy efficiency, to determine the reliability and durability of the system, and to assess its ability to reduce peak demand. Data generated through these field tests would be useful in developing a commercial product.

1.0 Introduction

1.1. Need for an Intelligent Controller Technology:

Assuming that the growing energy needs of the nation are met only through building additional power plants, an estimated 1300 new power plants of 300MW each will be needed by the year 2020. However, the severity of the energy problem can be considerably diminished by raising the energy efficiency of appliances and by managing their peak load demands. By increasing the efficiency standards currently coming into force for appliances such as clothes washers, water heaters, and air-conditioners, it is estimated that the construction of 170 new 300MW-power plants can be avoided.[1].

California's serious energy situation requires more near term solutions. The San Jose Mercury reported in its February 25, 2001 issue *"When millions of air conditioners click on this summer, California could be in even worse trouble. The forecast calls for widespread blackouts, unless the state finds a way to supply enough power."* Analysts have forecast a shortfall this summer of 5,000 megawatts while some predict it may be as much as 7,000 megawatts.[2]

Several research studies indicated that residential air conditioners, despite their relatively lower annual utilization rates, are primarily responsible for the large peak in diurnal system load profiles.[3] Modifying or altering the diurnal system load profile as a viable means of load shaving in commercial buildings has attracted the attention of many researchers in the past.[4,5,6]

Reddy, Norford and Kempton identified that the single-family residence is where peak-shaving schemes can be most effectively implemented. [4] Peak sharing schemes can be most effectively implemented in a single-family residence. While there are many ways to reduce peak loading, Reddy et al, indicate that increasing the efficiency of air conditioners leads to both peak load reduction and energy conservation. In addition, it saves residential customers real dollars by decreasing monthly electricity bills.

The energy savings potential of increased of air conditioner and heat pump efficiency in the residential sector is quite large

In California, there is a potential saving of nearly 5,000 GWh per year in electrical energy consumption by air conditioners, heat pumps, and blowers in the residential sector. In commercial sector there is a saving of about 6400 GWh. Information on total energy consumption came from California Energy Commission's reports.

Table 1 shows the electrical energy savings in the residential sector.

Table 1: Electrical Energy Savings in the Residential sector

	Year	
	2000	**2010**
Total electrical energy consumed in the residential sector in California in GWh (Ref. #8) (A)	77,633	92,416
Electrical energy consumed by air conditioners, heat pumps and blowers (C=27% % of A)	20,628	24,555
Potential energy savings in Cal. by ESI and similar controllers in GWh (C= 20% of B)**		4,911

**Electrical energy consumed by air conditioners, heat pumps, and blowers is 27 percent of total electrical consumption in the residential sector. Potential energy savings due to intelligent controllers is calculated to be 20 percent of electrical energy consumed by air conditioners, heat pumps, and blowers.

Table 2 shows the electrical energy savings in the commercial sector.

Table 2: Electrical Energy Savings in the Commercial Sector

	Year	
	2000	**2010**
Total electrical energy consumed in the commerciall sector in California in GWh (Ref. #8) (A)	99,259	118,802*
Electrical energy consumed by air conditioners, heat pumps and blowers (C=27% % of A)	26,799	32,076
Potential energy savings in Cal. by ESI and similar controllers in GWh (C= 20% of B)**		6,415

* California Energy Demand 20002-2012 Forecast

** Potential energy savings due to intelligent controllers is calculated to be 20 percent of electrical energy consumed by air conditioners, heat pumps, and blowers in the commercial sector also.

1.2. Project Objectives

ESI's overall goals were to develop economically viable, energy-efficient technologies in the residential and light commercial sector while launching a successful business in the energy-efficient appliance markets.

The objectives as defined in the contract were to:

- Increase the efficiency of compressors used in typical residential refrigerators from 5.4 EER to 7.0 EER by the use of an innovative controller that converts single-phase electrical supply to three-phase power to run the compressor. This would be a 30 percent improvement in efficiency on a power rating of ~200 watts.
- Increase the efficiency of compressors used in typical residential and light commercial heat pumps by 30 percent using a similar controller on a power rating of ~4000 watts.
- While we set no specific economic objectives for the project, ESI identified early in the program that the high cost of efficiency improvement devices is a barrier to market acceptance and we developed our design to meet certain cost considerations. Specifically ESI established a goal of developing the intelligent controller with a selling price of $80 per ton for 100,000 units per year for units above one ton of cooling capacity, to the end user.

1.3. Report Organization

This report summarizes the research work done in the PIER program to improve the efficiency of air conditioners and heat pumps using advanced power electronics. Section 2.0 – Project Approach provides an overview of concept generation, evaluation, and selection. It then describes the approach taken to realize the concept in hardware and software. Section 3.0 - Project Outcomes identifies and discusses the major results from this research program. Each objective and outcome meeting that objective is given. Section 4 – Conclusions and Recommendations presents final conclusions derived from the research conducted during this project along with recommendations on actions to take the technology to the next stage.

The report contains six appendices:

Appendix I	Modeling Analysis
Appendix II	Independent Testing Laboratory Final Report
Appendix III	ARI Standard 210/240-94: SEER Calculations and Link to ARI Website
Appendix IV	Improvements in Seasonal Energy Efficiency Ratio (SEER) by Intelligent Controller Technology
Appendix V	Residential Building Model Used for Peak Reduction Strategy Development
Appendix VI	Additional Result: Peak Loading Strategy

2.0 Project Approach

2.1. Theoretical Problem

Figure 1shows the distribution of ambient temperature in the cooling season, according to ARI 210/240-94 for region 4. More than 95 percent of the time, ambient temperature is less than 98°F. This means that the air conditioner operates at less than full load most of the time.

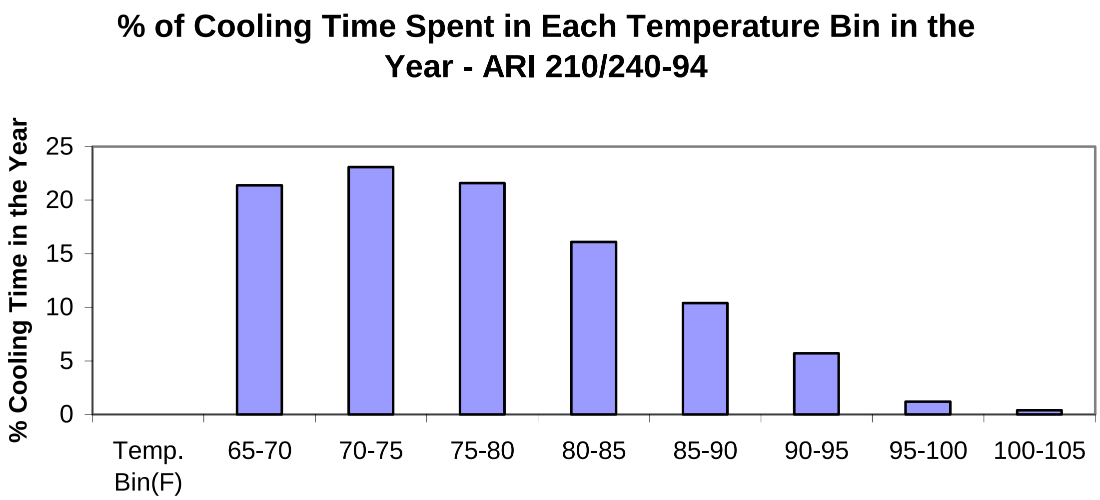

Figure 1: Distribution of Cooling Hours in the Year Used in ARI 210/240-94 Calculations (Region 4)

Figure 2 shows the fraction of full load at which the air conditioner operates resulting in electrical load mismatch.

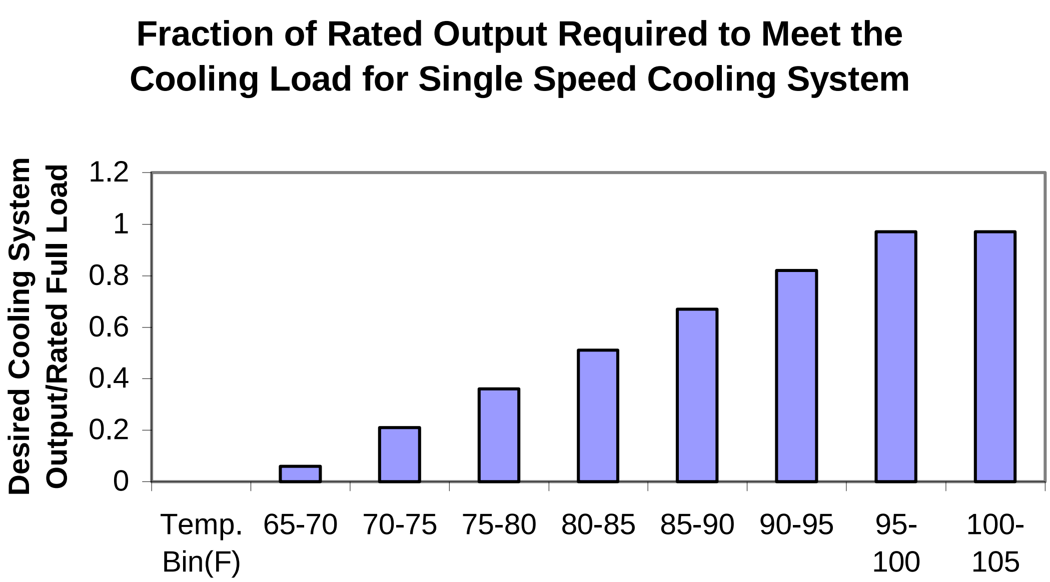

Figure 2: Air conditioner Operates at 1/2 Load or Less for Most of the Year

An important point to note from Figure 1and Figure 2 is that not only does the air conditioner operate most of the year at fractional load, but it operates at less than 50 percent load for significant amounts of time.

The capacity of an air conditioner increases as the ambient temperature decreases because of its inherent thermal properties (Figure 3). But building load decreases with the decreasing ambient temperature. The difference between the capacity of the air conditioner and the cooling load of the building increases as the ambient temperature decreases resulting in huge difference between capacity and cooling load during most of the cooling period in the year. This results in thermal capacity mismatch.

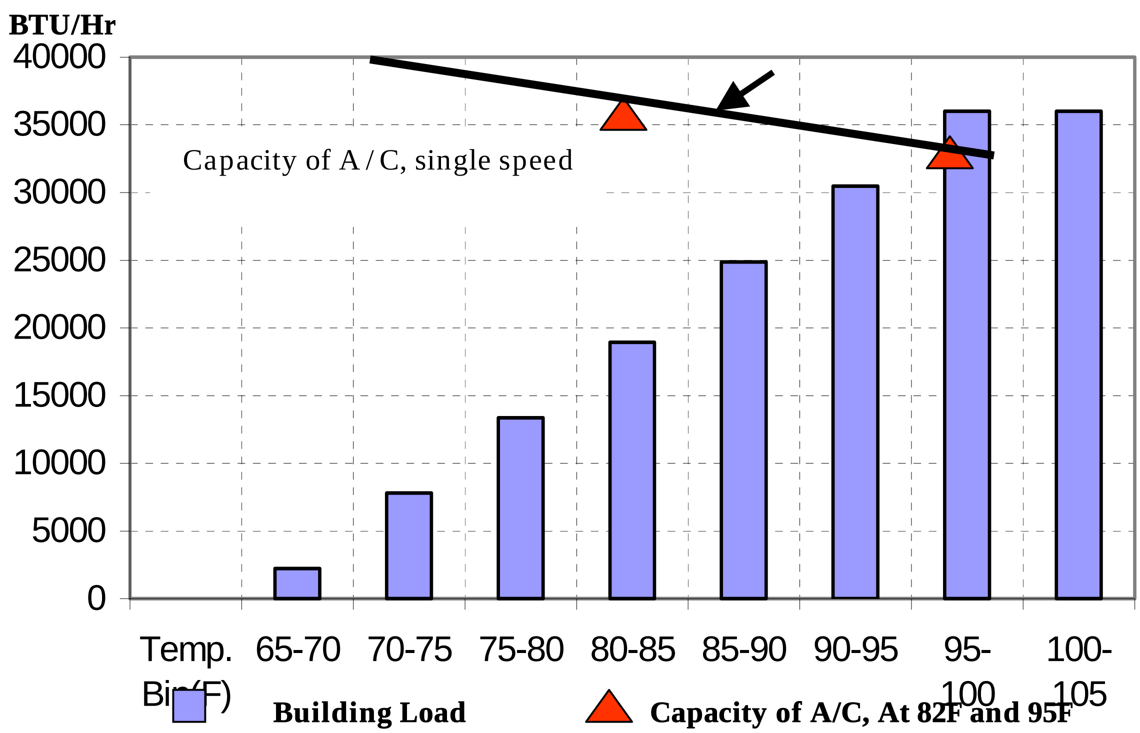

Figure 3: Data Points (Red Triangles) from BRL Test Measurements on 3-Ton Air Conditioner

Note: In current technology, an air conditioner runs at a single speed. Capacity increases and the load decreases as the ambient temperature decreases, causing huge difference between capacity and cooling load at most operating temperatures. Data points (red triangles) are from BRL test measurements on a three-ton air conditioner [10].

These two mismatches--electrical load mismatch and thermal capacity mismatch--result in significantly decreased energy efficiency in typical air conditioners, heat pumps and refrigerators, providing the rationale for this research project.

2.2. ESI’s Strategy and Concepts

In current technology, single-phase permanent split capacitor (PSC) motors drive air conditioners and heat pumps in residential applications. These PSC motors have two serious drawbacks.

- Although PSC motors can be designed for high efficiency, it is only at one load condition and one speed. Efficiency drops rapidly as the load on the motor decreases. Since the motor in an air conditioner primarily works at fractional load, this negates any improved efficiency.
- PSC motors are unsuitable for running at different speeds because of the detuning of the capacitor used to optimize its performance.

ESI's strategy was to use three phase motors instead of single-phase PSC motors. Three phase motors have the characteristics needed to increase energy efficiency because, unlike PSC motors, they maintain high efficiency even at fractional loads. And energy efficiency increases if the compressor is run at multiple speeds to match the load. Running the compressor at three speeds provides even higher energy efficiency as well as the added benefit of peak demand reduction.

Program managers at the California Energy Commission and ESI structured a program to achieve the project objective of developing an intelligent controller that would increase energy efficiency by 30 percent. In this program, 13 technical tasks and three reporting tasks were defined with deliverables for each important technical task.

Controller development progressed in four phases:

- Controller design
- Circuit board fabrication
- Component (circuit boards and motors)
- Equipment testing
  - Modifying a 2-ton heat pump and testing it with the controller.
  - Testing of off-the-shelf air conditioners before modifying with the ESI controller
  - Modifying an off-the-shelf air conditioner with the ESI controller and then testing

In Task 2.1 - Concept Generation and Evaluation, we generated several power electronics concepts that were then simulated on circuit simulation tools, such as SABRE and ISPICE, at ESI.

We chose two concepts for further evaluation:

- Three-phase induction motor driving a compressor and operating at single speed
- Three-phase induction motor driving a compressor and operating at multiple speeds

Power electronics for these two options differed greatly in circuit topology.

Ed Vineyard, ESI's consultant in this project for system studies, modeled, and analyzed the concepts. He used the validated models available for public use from the Oakridge National Laboratory to simulate and evaluate the performance of the candidate concepts.

To determine the cooling and heating efficiencies of the air conditioner / heat pump using concepts mentioned above, it was first necessary to calculate the energy efficiency ratio (EER) at the rating temperatures as specified in the Air-Conditioning and Refrigeration Institute (ARI) Standard 210 / 240-94. Once the EER had been determined, we used the National Institute of Science and Technology (NIST) Seasonal Energy Efficiency Ratio (SEER) and Heating Seasonal Performance Factor (HSPF) models to determine the SEER for air conditioners and HSPF for heat pumps. The SEER model requires the capacity and energy consumption at 82°F and 95°F. To make temperature consistent, SEER is calculated using bin weather data. Region 4, which is used as the national average for calculating HSPFs, was selected for this study. Appendix I gives details of Vineyard’s modeling and analysis studies.

The results of his system analysis decided the choice of hardware and software developed in this program. He concluded that a controller driving a three-phase air conditioner or heat pump at varying speeds could increase energy efficiency by 30 to 40 percent.

Vineyard also conducted similar studies refrigerators and concluded that the value of energy saved by an ESI controller in a refrigerator is only $4 per year. Since our estimate that in quantities of 100,000 per year, the manufacturing cost per controller would be about $20, we concluded that it was not a practical, cost effective solution to increase the energy efficiency of refrigerators with our controllers.

Vineyard's analysis also showed that heat pumps possibly present the best near term markets for ESI's controllers because heat pumps operate all year round and can save more than $180 per year.

To use our limited resources profitably, we requested the California Energy Commission to change the work statement to replace refrigerators with air conditioners at the first Critical Project Review. The request was granted and the work statement revised.

With the choice of the operating mode determined from system studies, work in this project progressed to the design and fabrication of an intelligent controller.

ESI designed the controller with two major functional blocks:

- A power stage handling power switching functions
- A controller stage that had all the intelligence functions, including the gating signals required in the power stage.

To accomplish all the processing functions, we selected a new signal-processing chip from a major chip manufacturer that had large processing capabilities and potential for low cost. Unfortunately there were persistent electrical noise problems that could not be resolved. In addition, the power stage was blowing up. This extended the schedule and drained the budget.

Taking a fresh approach that included changes in personnel and hardware design, the major functions were separated into two boards:

- The power stage to handle switching of the power transistors
- An intelligent controller board to perform control functions.

TB Woods, a manufacturer and a supplier of power boards to OEM customers, provided prototype power boards that met our requirements. Integrated power board technology is making rapid progress in cost reduction, a number of large manufacturers produce highly integrated power stages. Using the design approach of separating the power and control functions allowed ESI to make use of this rapid progress in power boards without having to make significant changes in the controller itself. The TB Woods power board controls speed, senses outside temperature, and performs the algorithms needed to control the air conditioner. ESI designed, fabricated, and tested the controller board in-house.

Figure 4 shows schematics of the current technology and of the new technology developed during this program. In current technology, a Permanent Split Capacitor (PSC) motor is driven by a single-phase supply at a single frequency (line frequency of 60 Hz). In ESI's technology, the controller runs a three-phase motor at multiple speeds, drawing power from single phase 60 Hz line supply available in residences or a three-phase supply, if available. We designed the controller with the necessary interfaces to provide inputs to the controller.

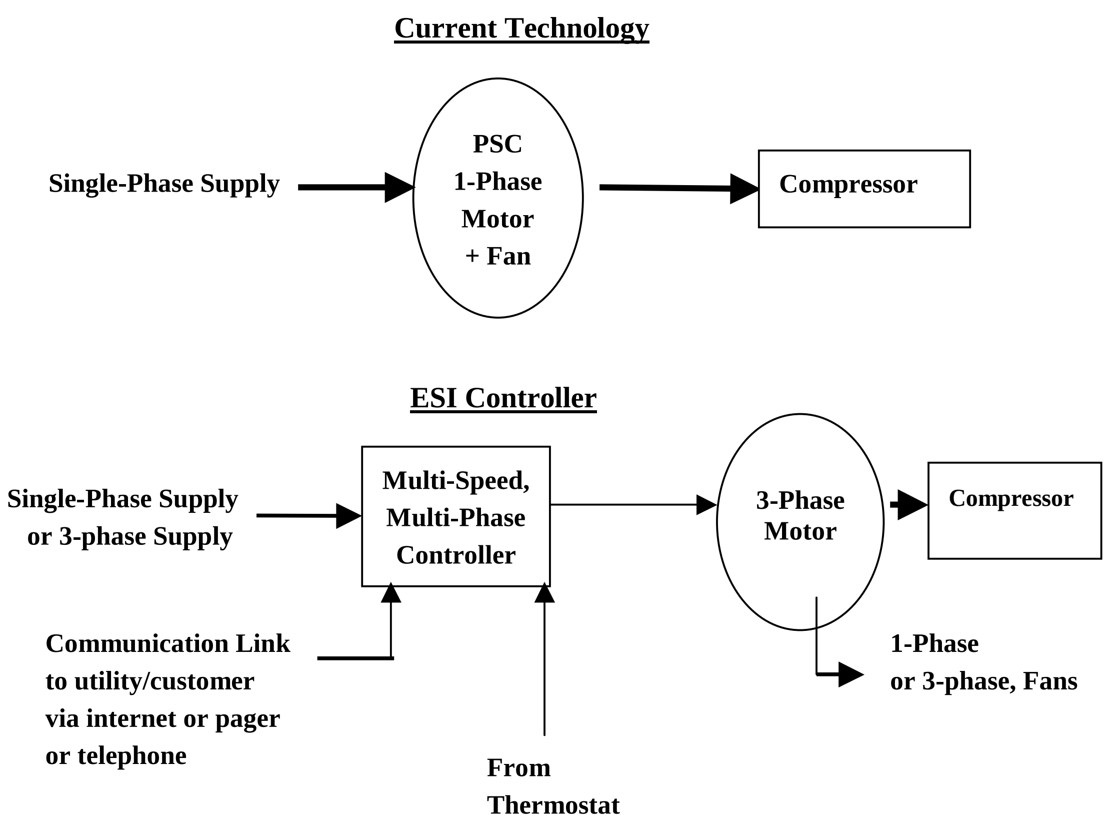

Figure 4: Comparison of Air-Conditioning/Heat Pump Controller Strategies: Current technology vs intelligent controller technology

ESI studied both new and retrofit residential and commercial applications.

Laboratory tests were conducted by ESI with the control and power boards were also installed in a two-ton off-the-shelf heat pump and on a three-ton A/C.

The control and power boards were installed on a three-ton off-the-shelf air conditioner, which underwent independent laboratory testing at BR Labs both before and after controller installation to determine the magnitude of the energy efficiency improvement. At this time, the Commission Contract Manager requested that we test the air conditioner at 105°F outdoor temperature in order to determine how well the controller would address the high temperature conditions and peak load issues found during California summers.

3.0 PROJECT OUTCOMES

ESI verified that the compact size of the electronic controller made it possible to install it inside the existing cabinets of both heat pumps and A/Cs.

ESI purchased an off-the–shelf three-ton air conditioner and a two-ton heat pump from a local distributor, which were then modified by installing intelligent controllers. Preliminary in house testing was conducted on the units' logic circuits and interfaces. These tests proved that ESI's controllers could be easily integrated with existing electrical controls in off-the-shelf equipment.

Table 3 provides the specifications fro the two-ton heat pump.

Table 3: 2-Ton Heat Pump Specifications

Make		Friedrich
Model Number		YL24J35A-1
Power		200/230 volts, 60 Hz, 1-Phase
Cooling	**BTU/hr**	23,800/24,000
	EER	9.0/9.0
	Amps	12.0/13.0
Heating	**BTU/hr**	22,000/23,000
	Amps	10.4/11.5

Figure 5 shows the heat pump fitted with the ESI controller (see circled area denoted by arrow).

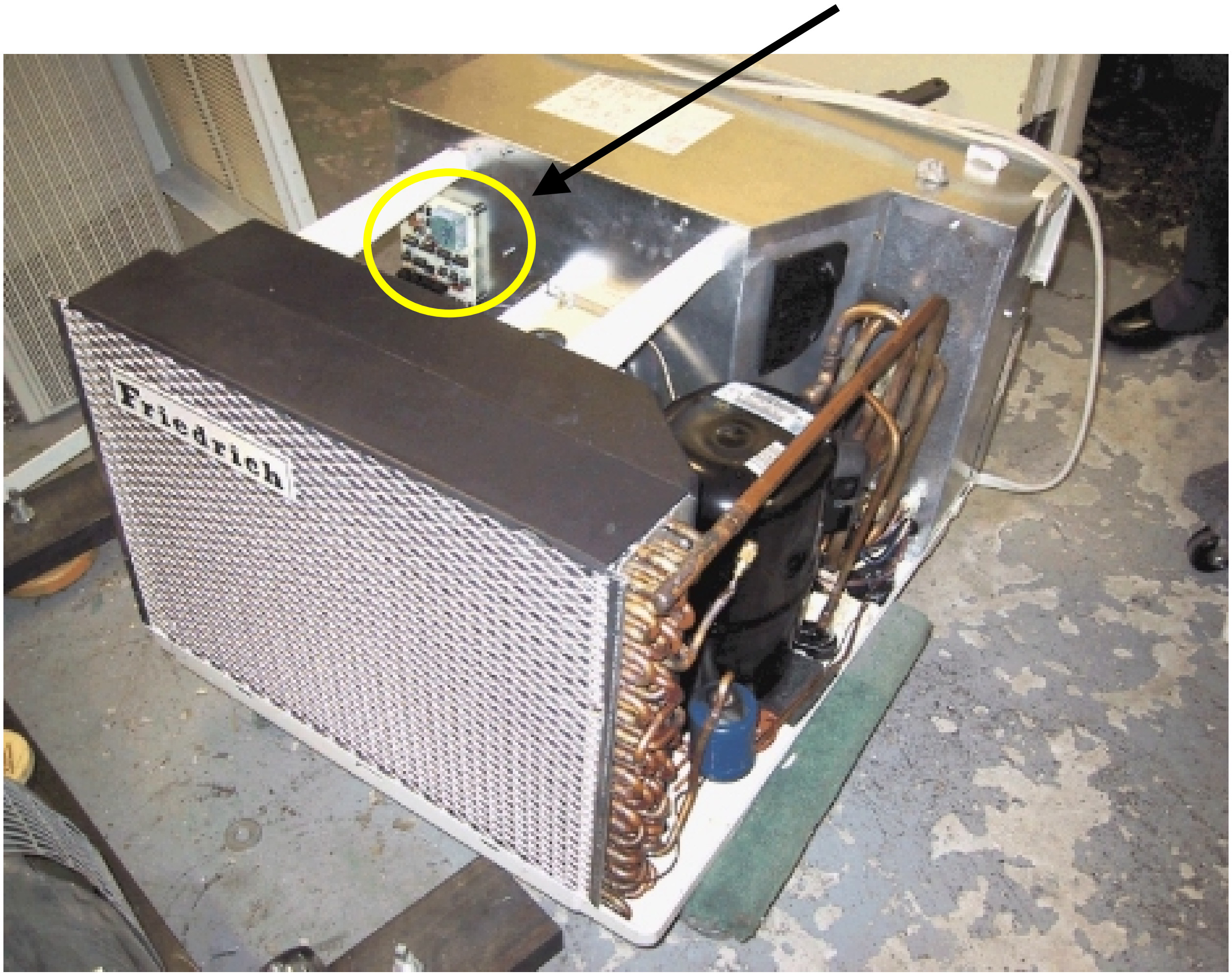

Figure 5: Two Ton Heat Pump Fitted with the ESI Controller

The Dayton Electric Manufacturing Company (Niles, Illinois 60714) manufactured the air conditioner. Table 4 provides the specifications for the unit.

Table 4: 3-Ton Air Conditioner Specifications

Stock Number	3Ujo2 (outdoor use)
Model Number	mlka-a036ck 006
Serial Number	5661F260018613
Manufacturing Date	06/00
Power Supply	208/230 volts, 3-phase, 60Hz
Operating Volt Range	187-253 volts
Compressor	208/230 volts, 3-phase, 13 amps
Outdoor Fan	208/230 volts, 1-phase, 2 amps, 1/3 hp (0.249 KW)
Indoor blower	208/230 volts, 1-phase, 4 amps, ½ hp (0.373 KW)

Figure 6 shows the ESI controller (see circled area denoted by arrow) installed in a three-ton air conditioner. There was no increase in footprint because the controller easily fit inside the electrical cabinet.

Figure 6: Three-Ton Air Conditioner Fitted with the ESI Controller

Laboratory testing on a two-ton heat pump verified that the electrical performance of the heat pump using the controller matched the expectations in the model. For example, when the controller reduced the speed of the compressor, the power requirements of the compressor dropped proportionately.

- Laboratory testing conducted on a three-ton A/C also verified that the electrical performance of the controller matched the expectations of the model.
- We discovered that our controller has a low power factor. This was not unexpected, because this is typical of all rectifier input power circuits.
- Independent laboratory testing was conducted in accordance with ARI 210/240-94 on an unmodified 3-ton 3-phase A/C to establish the baseline efficiency. Our controller was installed and the efficiency tests were repeated. Results showed an improvement in efficiency of 19 percent. This number is less than what the modeling predicted.

ESI chose BR Laboratories Inc. (BR Labs or BRL), Huntington Beach, California to conduct efficiency tests under the guidance of the California Energy Commission Project Manager. BR Lab is a test laboratory performing testing and evaluation of home appliances for government agencies and the air conditioning industry. They conducted tests before and after installation of the ESI controller on an off-the-shelf three-ton air conditioner bought from a local vendor. Appendix II contains the test laboratory report with the testing method used and resulting data.

These tests followed ARI Standard 210/240-94 (Appendix III), which is widely accepted and commonly used by air conditioning industry for calculation of the Seasonal Energy Efficiency Ratio (SEER). SEER is the ratio of total cooling provided [Btu] in one year to the total electrical energy supplied [kWh]. Improvement in SEER indicates energy saved.

Table 5 shows the results of these tests. Rows containing 60 Hz data show the performance of the unit without the controller. The table shows how the performance of the unit varies with changes in frequency. At 82° / 65° outdoor conditions, EER increases from 9.8 to 10.6 as the frequency drops from 60 to 35 Hz. Capacity and power requirements (watts) drop proportional to the frequency. Since the capacity of the unit is based on design temperatures of 95°F, using our controller will enable the air conditioner to match the load with a significant savings in energy and power when the outdoor temperatures are moderate.

Table 5: Test Results at 82°/65° and 95°/75°

Outdoor Condition, 82°/65°						
Db Temp. (°F)	Frequency (Hz)	Capacity (Btu/h)	Power (Watts)	EER (Btu/Wh)	Btus (%)	W (%)
82	60	35142	3600	9.8		
82	50	28027	2940	9.5	80	82
82	40	23336	2240	10.4	66	62
82	35	21173	2000	10.6	60	56
Outdoor Condition, 95°/75°						
Db Temp. (°F)	**Frequency (Hz)**	**Capacity (Btu/h)**	**Power (Watts)**	**EER (Btu/Wh)**	**Btus (%)**	**W (%)**
95	60	33133	4190	7.9		
95	50	25911	3380	7.7	78	81
95	40	20477	2610	7.9	62	62
95	35	16970	2280	7.4	51	54

At 95°F / 75°F outdoor conditions, there appears to be no benefit from using the controller. Even though EER is the same at 60 and 40 Hz, the capacity is reduced and the unit is unable to meet the load.

Figure 7 uses test lab data to graphically show the relationship between ambient temperature and EER. The EER is plotted at 9.8 and 10.6 for 82°/65° outdoor conditions and 7.9 and 7.4 for 95°/75° outdoor conditions. Using the ARI method, ESI plotted the high-speed and low-speed EER lines.

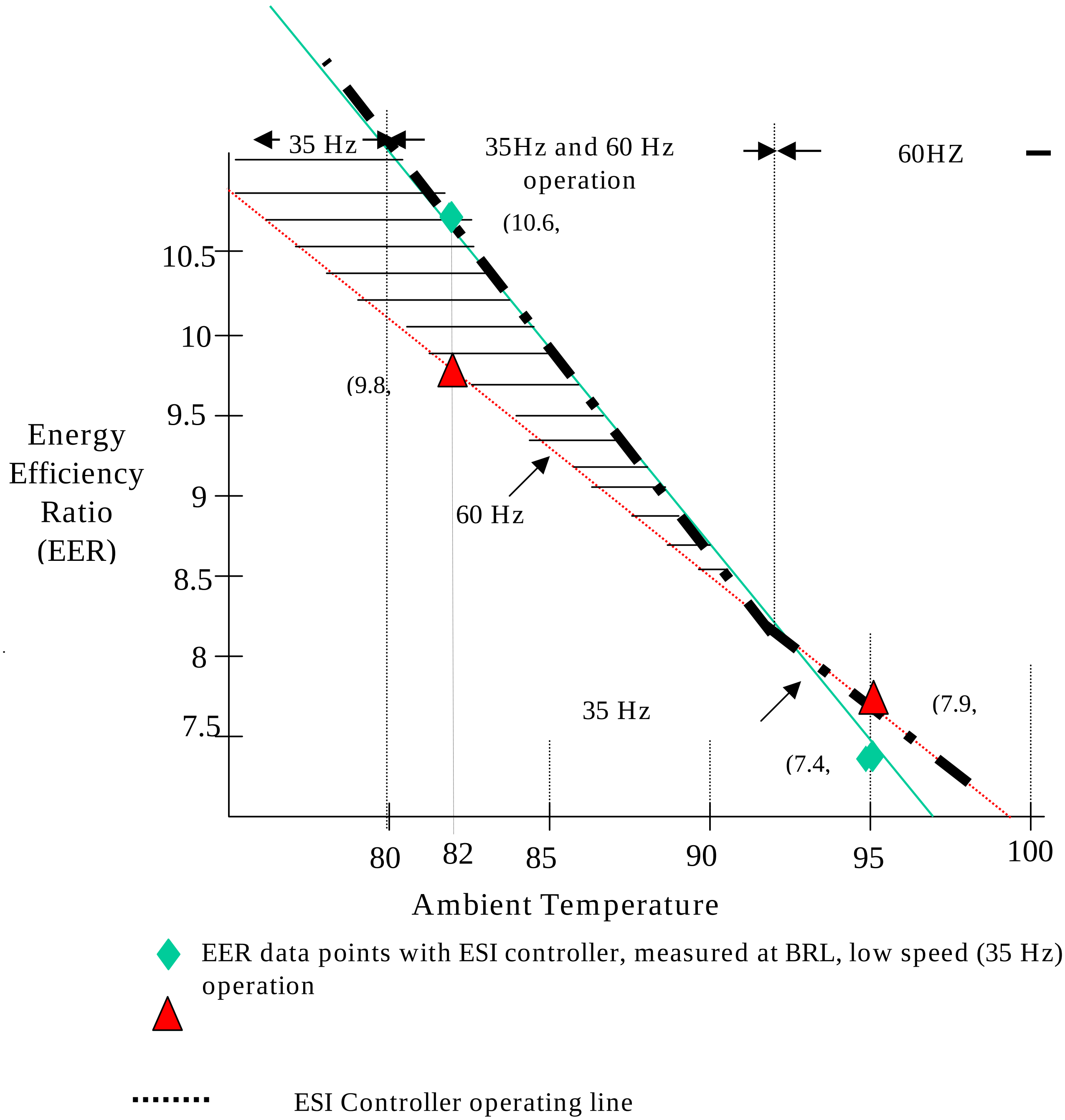

Figure 7: Relationship between Ambient Temperature and EER

The figure illustrates how the controller operates under outdoor conditions. The bold line shows how the controller matches itself to the load by changing frequency. At conditions below 82°/65°, the controller will be at 35 Hz, but at conditions between 82°/65° and 95°/75°, the controller selects the speed that best matches the load. At conditions above 95°/75°, the controller will be bypassed and the unit will operate at 60 Hz. The energy savings obtained occur between the bold line and the line for high-speed operation. The savings are due to two factors: an improvement in the EER and the continuous operation of the air conditioner as the controller allows it to better match the load, thus minimizing on/off cycling and its attendant losses.

The ARI method (see Appendix IV for more details) calculates SEER based on, EER and cycling losses, and includes a factor to account for on-off cycling losses called the degradation coefficient, $\mathbf{C_D}$. Table 6 shows the results of these calculations for degradation coefficients due to cycling losses of 0.25 and 0.07. The ARI method permits using a degradation coefficient of 0.25 when cycling losses for the specific unit are not measured, which was not done. The manufacturer quotes 0.07 for the degradation coefficient.

Table 6: SEER of 3-Ton Air Conditioner Driven by ESI Controller

	SEER – Two Speed 35 Hz and 60 Hz	SEER – Single Speed 60 Hz	Improvement due to Speed Conversion
C_D = 0.25	10.2	8.5	19%
C_D = 0.07	10.5	9.4	12%

At 105°F outdoor conditions, the controller did not improve in energy efficiency when operating at full load. However, the controller can operate the A/C at reduced speed with proportionately reduced peak electrical demand. For example, when operating at half speed, the power requirements dropped from 4.5 kW to 2.5 kW.

Table 7 shows the results of the tests we conducted at 105°/75°. Compared to operation at 95°/75°, capacity and EER are greatly reduced. Power consumption without the controller (60 Hz operation) is the highest, as in Table 6. With the intelligent, controller, power is reduced proportional to capacity. However, in all cases, the unit is unable to meet the cooling load in the building.

Table 7: Test Results at 105°/75°

Outdoor Condition, 105°/75°						
Db Temp. (°F)	Frequency (Hz)	Capacity (Btu/h)	Power (Watts)	EER (Btu/Wh)	Btus (%)	W (%)
105	60	30987	4580	6.8		
105	50	23786	3770	6.3	77	82
105	40	17549	2880	6.1	57	63
105	35	16794	2540	6.6	54	55

4.0 Conclusions and Recommendations

4.1. Conclusions

- It is not necessary to increase the physical size of heat pump or A / C enclosures to accommodate the installation of our controller. This is important because other mechanical solutions that provide similar benefits may require significantly larger enclosures and comparably increased costs.

- Using the controller in heat pumps and A / Cs is very cost-effective, providing a return on investment of less than 2 and 4 years, respectively. In California, where the electricity rates are even higher than in our model, the return on investment will be even quicker.

ESI designed and built an intelligent controller to drive three-phase motors at different speeds and to operate from a single-phase or three-phase energy supply. The controller used innovative and proprietary electronic circuits with the latest processor and power chips for signal and power processing. Successfully tested at ESI's laboratory, the controller demonstrated its efficiency and its capability to drive three-phase compressor motors from either a single-phase or three-phase power supply. Design of the controller was strongly influenced by economic considerations that would allow ESI to achieve its goal of $80 / ton of air conditioning in quantities of 100,000 / year.

ESI studied the production processes and estimated the cost of manufacturing in large quantities. ESI plans to use the same manufacturing processes as those already in use in manufacturing boards for the computer and communication industry. Because similar boards are manufactured in very large volume in many parts of the world, resulting in very low cost, ESI controller will also be low cost, benefiting from the already established manufacturing lines. A study of cost of materials and manufacturing showed that controllers for A / Cs from 1-5 tons, the end user cost can be about $100 per ton. For sizes from 5 to 30 tons, the end user cost of the controller can be about $80 per ton.

Based on these costs, a three-ton A/C or heat pump would need a controller that would cost $300. Table 8 shows the savings and payback using the controller with an A/C. These savings are based on the SEERs calculated from the EER data taken during our laboratory tests.

Table 8: Improvement in SEER Due to Speed Conversion and Phase Conversion.

	C_D = 0.25	C_D =0.07
SEER Two Speed	10.2	10.5
SEER Single Speed	8.5	9.4
Improvement Due to Speed Conversion	19%	12%
Improvement due to Phase Conversion	4%	4%
Total Efficiency Improvement	23%	16%

Since we did not measure the performance of a heat pump, we can only estimate the savings. Using the assumption that a heat pump runs about twice as many hours as an A/C, the savings would be twice as much and the payback half as long. The savings and payback for units greater than five tons would be about 20 percent larger due to the lower costs per ton for the controller (Table 9).

Table 9: Intelligent Controller Payback Calculations

QUANTITY [UNITS]	AIR CONDITIONERS				HEAT PUMPS			
	NATIONAL AVG. DESIGN HOURS [h/yr]:		CALIFORNIA AVG. DESIGN HOURS [h/yr]:		NATIONAL AVG. DESIGN HOURS [h/yr]:		CALIFORNIA AVG. DESIGN HOURS [h/yr]:	
	1000		1800		2000		3600	
	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller	standard unit	unit w/ ESI controller
Design Capacity,C [Btu/h]	36000	36000	36000	36000	36000	36000	36000	36000
SEER [Btu/(Wh)]	8.5	10.2	8.5	10.2	8.5	10.2	8.5	10.2
C/SEER [W]	4235	3529	4235	3529	4235	3529	4235	3529
(C/SEER)* Des.Hrs [Wh/yr]	4.24E+06	3.53E+06	7.62E+06	6.35E+06	8.47E+06	7.06E+06	1.52E+07	1.27E+07
Electric Cost [$/(kWh)]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Ann. Operation Cost [$/yr]	423.5	352.9	762.4	635.3	847.1	705.9	1524.7	1270.6
Delta [$/yr]	-	70.6	-	127.1	-	141.2	-	254.1
Payback [yr]	**-**	**3.4**	**-**	**1.9**	**-**	**1.7**	**-**	**0.9**

Cooling cost = Design Cap./SEER) * Design hours * Electric Cost * 1/1000

where Design Capacity = 36000 Btu/hr; Electric Cost = 0.10 $/kWh and Controller Cost = $240

Payback period = Controller Cost / Difference in Operation Cost (Delta)

NOTE: For heat pumps, the payback calculation is the same as for cooling only, but the period is half of that for A/C, because the controller saves energy in both heating and cooling modes

Installing a filter will improve the power factor and make the device more acceptable in widespread application. It is possible to increase the power factor by installing a suitable filter, but we did not do that in this contract. The addition of a passive filter is quite straight forward, but it will increase the cost by about ten percent and the weight by about 20 percent. An active controller will add only very small amount to weight, but is more expensive. The power quality issue becomes important for the utility as the penetration of motor controllers, not only in HVAC applications but in all power electronic motor controller applications, becomes significant. ESI will design and implement these filters as the utilities in domestic and international markets demand.

Although the independent laboratory tests compared the efficiency of 3-phase A/Cs, they did not account for the additional four percent improvement that we found could be obtained by switching from single-phase to three-phase compressors (Appendix IV). Combined with the 19 percent efficiency improvement observed on the three-phase A/Cs, we project an overall improvement of 23 percent, which is more than 75 percent of our original target of 30 percent.

4.2. Benefits to California

Successful commercialization of this technology will benefit California by significantly reducing electrical consumption and enhancing the value of electricity to end-users. It will also help decrease the peak demand, providing short term benefits by preventing rolling blackouts and decreasing the number of future power plants needed in the State.

4.2.1. Energy Savings

In California, the potential exists to save nearly 5,000 GWh per year in electrical energy consumption by air conditioners and heat pumps in the residential sector through the use of intelligent controller technology. Total electrical energy consumed in the residential sector (Table 10) came from the California Energy Commission's report "California Energy Demand 2000", supplied by the Commission Project Manager. ESI's intelligent controller technology has the potential to save 20 percent of the total electric energy consumed by air conditioners and heat pumps in California.

Table 10: Potential Annual Energy Savings (Assuming 20% Savings due to ESI Controller)

	Year	
	2000	2010
Total electrical energy consumed in the residential sector in California in GWh **(A)**	77,633	92,416
Potential savings by ESI and similar controllers in GWh **(D= 20% of C)**		4,911

4.2.2. Environmental Benefits:

Table 11 shows the projected annual air emissions reductions resulting from 20 percent reduction in energy consumption of air conditioners and heat pumps resulting from the application of technologies such as the ESI intelligent controller in the Year 2010 (calculated for 5000 gWh per year).

Table 11: Projected Annual Air Emissions Reductions

	United States Thousands of Pounds/Year			California Thousands of Pounds/Year		
Duration	CO_2	NOx	SO_2	CO_2	NOx	SO_2
Per year	104,000	374	677	12,500	44.2	81.2

4.2.3. Improving the Reliability and Quality of Generation

ESI's controller has a feature important to power system reliability. As described earlier, the controller can run peak reduction programs with an existing, low cost thermostat. It is well known that despite their relatively lower appliance annual utilization rates, air conditioners are primarily responsible for the large peak in diurnal system load profiles, which results in blackouts and brownouts. ESI controller offers a technical solution. To implement it in the field, teaming with the utilities and energy service providers is needed. It also requires a tariff structure that encourages peak power demand reduction by the customer.

4.2.4. Impact on State and Local Economies

State and local economies will benefit from the successful commercialization of the controllers. Based on U.S. market projections and the potential international market, sales of controllers could bring revenue of more than $100 million in the fifth year of business. This would represent less than five percent of the world market for an item that would be proprietary to ESI.

Table 12 shows the five-year sales forecasts for air conditioners and heat pumps in the United States (thousands of units) residential market.

Table 12: Five-Year Sales Forecasts for Residential Markets

	2001	2002	2003	2004	2005
Air-Conditioners, Unitary	6,252	6,485	6,755	7,018	7,874
Heat Pumps	1,550	1,609	1,668	1,739	1,908

(From Appliance Magazine's annual forecast – January 2000)

Sales at these projected levels could have the following impacts on the California economy:

Jobs – Approximately 25 percent of the cost of ESI's products will be made in California, which represents approximately $100 million in products manufactured. Therefore, an average $25 million will be spent on labor in California every year to meet ESI's production. If the average job costs $50,000 (including benefits), 500 direct jobs would be created as a result of the proposed work. Using a four to one multiplier to compute the number of indirect jobs (standard for manufacturing jobs), results in the creation of 2,000 indirect jobs for the California economy, a total of 2,500 new jobs created.

Income Taxes – If $25 million of ESI's revenues are paid to employees who are paying the 10 percent income tax in California, $2.5 million a year will be generated in State income tax just for direct jobs. There are four times as many indirect jobs as direct jobs. There are therefore additional tax revenues that will accrue to the State due to these indirect jobs.

Sales Tax Revenue – If ESI sells $100 million a year of goods and they are taxed at eight percent, $8 million will be generated each year in sales tax revenues.

Percentage of Sales: One and a half percent of sales of controllers developed in this PIER project goes to the state treasury, according to the contract between ESI and the State, until three times the contract money (three times $411, 464) has been paid back.

Reduction in Energy Imports – As ESI's products penetrate the California market, the demand for electricity for air conditioners and heat pumps will be reduced. This will in turn reduce the demand for electricity imported into the state and also the need for fossil fuel for generation plants in the state.

4.3. Recommendations

- Test the performance of the intelligent controller with filtering designed to improve power quality.
- Test and analyze the controller's effect on the energy consumption of compressors and other equipment.
- Conduct a side-by-side comparison of two heat pumps, with and without the controller, both in the laboratory, and in the field for the period of one year. The purpose of this comparison is to get a better measure of the energy efficiency than is provided by the standard laboratory tests of SEER and will include a measurement of the degradation coefficient.
- Conduct field tests with a statistically useful number of units in small commercial applications in California. The purpose of these tests is to verify the energy efficiency, to determine the reliability and durability of the system and to assess its ability to reduce peak demand.

5.0 Commercialization Potential

ESI's controller can be integrated in air conditioners and heat pumps – one controller in each appliance. Since ESI's total market size (in number of units) is the same as that of the two appliances, controller market size can be estimated from the size of the market for air conditioners and heat pumps. The following data points apply to the market for controllers:

- About six million new air conditioners and heat pumps were sold in U.S. in 2000 (Appliance Magazine, Jan.2001) and at least about five times that in the international market.
- The value of shipments of HVAC equipment reported in 1996 Annual Survey of Manufacturers is slightly more than $28 billion; air conditioners accounting for $4.6 billion (SIC 35852).
- Appliance Magazine, a trade journal serving this industry forecasts that by the year 2005 the shipment of air-conditioners could reach 7,874,000 units and heat pumps 1,908,000 units. (Table 12).
- As every new air conditioner and heat pump can be fitted with the ESI controller, the total market for controllers is the same as for new air conditioning units (Table 12).

5.1. Pre-commercialization Efforts:

ESI prepared a business plan with the help of Silicon Valley Small Business Development Center in San Jose. It also developed a marketing plan. ESI is actively pursuing implementation of these plans with the goal of building a business based on intelligent controller technology.

The next logical step in bringing this technology to market is to launch a field test program to generate data for final product development and its marketing. ESI will fabricate 100 circuit boards for the controller using the services of contract manufacturers in the valley.

Although market potential is large, barriers to market penetration are also large. In the specific case of ESI, its success depends on obtaining the capital needed to enter the business and produce in the volume required to meet the low-price targets.

6.0 Glossary

A/C	Air Conditioning, Air Conditioner
ACEEE	American Council for an Energy-Efficient Economy
ARI	Air Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BR Labs	BR Laboratories
Btu	British thermal unit
C_D	Degradation Coefficient (**C_D**) is a measure of the efficiency loss due to the cycling of the unit (air-conditioner).
Commission	California Energy Commission
DOE	U.S. Department of Energy
EER	Energy Efficiency Ratio (EER) is the ratio calculated by dividing the cooling capacity of the air conditioner in Btu / hr by the power input in watts at any given set of rating conditions, expressed in units of Btu / Wh
ESI	Energy Savers International
GWh	Gigawatt hour
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, Ventilation and Air Conditioning
Hz	Hertz
kWh	Kilowatt hour
NIST	National Institute of Science and Technology
OEM	Original Equipment Manufacturer
ORNL	Oakridge National Laboratory
PG&E	Pacific Gas & Electric
PSC	Permanent Split Capacitor
Quad	One quadrillion (10^{15}) British thermal units (Btus). An amount of energy equal to 170 million barrels of oil. Total U.S. consumption of all forms of energy is about 83 quads in an average year. (1990 Figures)
SEER	Seasonal Energy Efficiency Ratio (SEER) is the total cooling output of a central air conditioner in Btu during its normal usage period for cooling divided by the total electrical energy input in watt-hours during the same period (It includes the effect of degradation coefficient, expressed in units of Btu / Wh.
SOW	Statement of Work
TOU	Time-of-Use (a.k.a. “Time-Dependent Valuation”)

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Appendix I

Modeling Analysis

MODELING ANALYSIS OF THE EFFICIENCY GAINS FOR POWER ELECTRONICS VERSUS 3-PHASE MOTORS FOR A HEAT PUMP IN THE HEATING AND COOLING MODES

ABSTRACT

The steady-state operation of a heat pump was modeled in the heating and cooling modes to determine the efficiency improvement when the conventional single-speed compressor motor is replaced with one employing power electronics (PE) technology. A comparison is also made to a heat pump with a 3-phase motor. The main difference between the PE motor and a 3-phase motor is that PE enables the compressor to be operated at several speed ratios (including overspeeding) while the 3-phase motor can only be operated at a 1:2 speed ratio. The results indicate that the seasonal energy efficiency ratio (SEER), a measure of the cooling efficiency, can be increased from 10.52 to 16.51 Btu/Wh by using the PE motor, a 56.9% improvement. The SEER improvement for the 3-phase motor is 36.9% (10.52 versus 14.40 Btu/Wh). The improvement in the heating season performance factor (HSPF) for the PE motor is 26.3% (7.368 versus 9.309). The HSPF for the 3-phase motor shows an improvement of 15.1% (7.368 versus 8.477). The higher energy savings for the PE motor results from its ability to operate at a lower turndown ratio than the 3-phase motor for a heat pump in the cooling mode and by overspeeding at low ambient temperatures in the heating mode. Using a national average energy cost of \$0.0842/kWh, the annual savings using the PE motor is \$205.00/year (\$90.00 for cooling and \$115.00 for heating). The annual energy savings using a 3-phase motor are \$139.00/year (\$67.00 for cooling and \$72.00 for heating).

MODELING ANALYSIS

In order to determine the cooling and heating efficiencies of the heat pump using PE and 3-phase technology, it was first necessary to calculate the energy efficiency ratio (EER) at the rating conditions as specified in the Air-Conditioning and Refrigeration Institute (ARI) Standard (ARI 1998). Once EERs were determined, the SEER and HSPF were determined using the National Institute of Science and Technology (NIST) SEER and HSPF models. The SEER model requires the capacity and energy consumption at 82°F and 95°F to calculate a SEER using bin weather data (Kelly et al 1978). A second SEER calculation is also determined using a degradation coefficient and the capacity and energy consumption data at 82°F. This second calculation is used for the Department of Energy (DOE) Standard and is the one selected for calculating the energy costs for this study. Both calculated SEERs are within 1% agreement. The HSPF model requires the capacity and energy consumption at 47°F, 35°F, and 17°F along with a degradation coefficient and the minimum design heating requirement (Parken et al 1980). Calculations can be performed based on bin data from 6 DOE regions. Region 4, which is used as the national average for calculating HSPFs, was selected for this study.

EFFICIENCY IMPROVEMENTS

Two of the main contributors to improved EER resulting from changing the compressor speed, improved motor efficiency and heat exchanger unloading effects, were determined for this study. The motor efficiency improvements were determined by estimating the fractional design torque from data (Figures 1 and 2) generated in a previous study by Rice (Rice 1988) and then calculating the motor efficiency improvements from motor efficiency curves for the 3-phase and PE motors (Figures 3 and 4). Heat exchanger unloading effects on EER, shown in Figure 5, were estimated from a second study by Rice that investigated the efficiency gains from capacity modulation (Rice 1988).

The efficiency improvement multipliers for the motor and heat exchangers are shown in Tables 1 through 4. Tables 1 and 2 contain the cooling multipliers along with improvements to EER and SEER at the ARI Standard rating conditions for a range of operating speeds. Tables 3 and 4 contain similar information for the heating conditions.

The cooling results (Tables 1 and 2) show that by replacing the motor with no changes to the speed ratio yields minor improvements in the SEER; a 2.8% increase (10.52 to 10.81) for the 3-phase motor and a 0.7% improvement (10.52 to 10.60) using the PE motor. However, when the compressor speed is reduced at the 82°F rating point temperature for the 3-phase motor in a ratio of 1:2 and the power electronics motor is reduced by 1:4, the efficiency gains are quite impressive. The SEER for the PE motor increases to 16.51 (56.9% increase) and to 14.40 for the 3-phase motor, a 36.9% increase.

The heating results (Tables 3 and 4) indicate that replacing the motor improves the HSPF by 2.7% with the 3-phase motor and by 1.0% with the PE motor. When optimal speed changes (1:2 at 47 °F, 1:2 at 35 °F, and 2:1 at 17 °F) for the three rating points are selected for the PE motor, the HSPF increases to 9.309, a 26.3% improvement. Additional speed permutations, such as reducing the speed at the 47 °F rating point by ratios of 1:3 and 1:4, were investigated, but the resulting increases in HSPF were lower due to the building load exceeding the capacity of the heat pump at such low turndown ratios. This resulted in the use of backup resistance heat; thus reducing the HSPF. The HSPF for the 3-phase motor increased from 7.368 to 8.477 (15.1% increase) when the speed was reduced by a 1:2 ratio at the 47 °F and 35 °F rating temperatures. There was no overspeeding at the 17 °F temperature since 3-phase motors can only reduce the speed in half.

ENERGY COST SAVINGS

Cost savings were determined for the motor improvements using a national average energy cost of $0.0842/kwh. This value is used by ARI in determining operating costs for heat pumps and air conditioners (ARI 1998). U.S. national average cooling energy costs are determined from the following equation:

Cooling Cost = (Design Capacity/SEER) x (Design Hours x Electricity Cost) x K **(1)**

where Design Hours = 1000 and K = 1/1000 (factor for converting kilowatts to watts) (Kelly 1978).

U. S. national average heating energy costs are determined using equation 2, which follows:

Heating Costs = (Design Capacity/HSPF) x (Design Hours x Electricity Cost) x K x C (2)

where Design Hours = 2080, K = 1/1000 and C = 0.77 (experience factor for improving the agreement between calculated and measured building loads) (Parken 1980).

Cooling and heating costs for different areas of the U. S. are shown in Tables 5 and 6. The cooling costs are formulated for different areas of the U.S. based on the number of cooling hours (Figure 6). Heating costs are calculated for six regions of the country shown in Figure 7, based on the number of heating hours. These figures, along with cooling and heating cost factors from the ARI Directory (ARI 1998), were used to generate the cooling and heating energy costs in Tables 5 and 6.

The results in Table 5 show that the maximum cooling energy cost savings (U.S average) for the PE motor is $90.00 ($249.00 – 159.00). The maximum savings for the 3-phase motor is $67.00 ($249.00 – 182.00). The maximum heating energy cost savings, shown in Table 6, for the PE motor are $115.00 ($549.00 – 434.00) and $72.00 ($549.00 – 477.00) for the 3-phase motor. The total annual U.S. average energy savings is $205.00 for the PE motor and $139.00 for the 3-phase motor. Additional savings for specific areas of the country can be determined from the tables and Figures 6 and 7.

CONCLUSIONS

The SEER improved from 10.52 to 16.61, a 56.9% improvement for the PE motor and from 10.52 to 14.40 for the 3-phase motor, a 36.9% improvement. The improvement in HSPF was 26.3% (7.368 versus 9.309) for the PE motor and 15.1% (7.368 versus 8.477) for the 3-phase motor. The increases in SEER were mainly attributed to improvements resulting from heat exchanger unloading. For heating, the improved efficiencies resulted from heat exchanger unloading and, for the PE motor, overspeeding the compressor at low ambient temperatures. Annual energy savings for the PE motor were $205.00, a 25.7% decrease. For the 3-phase motor, the annual energy savings were $139.00, a 17.4% decrease.

The optimal speed ratios for the PE motor in a heat pump application are 1:2 at 82 °F, 47 °F, and 35 °F; 1:1 at 95 °F; and 2:1 at 17 °F. For the 3-phase motor, optimal speed ratios are 1:2 at 82 °F, 47 °F, and 35 °F; and 1:1 at 95 °F and 17 °F.

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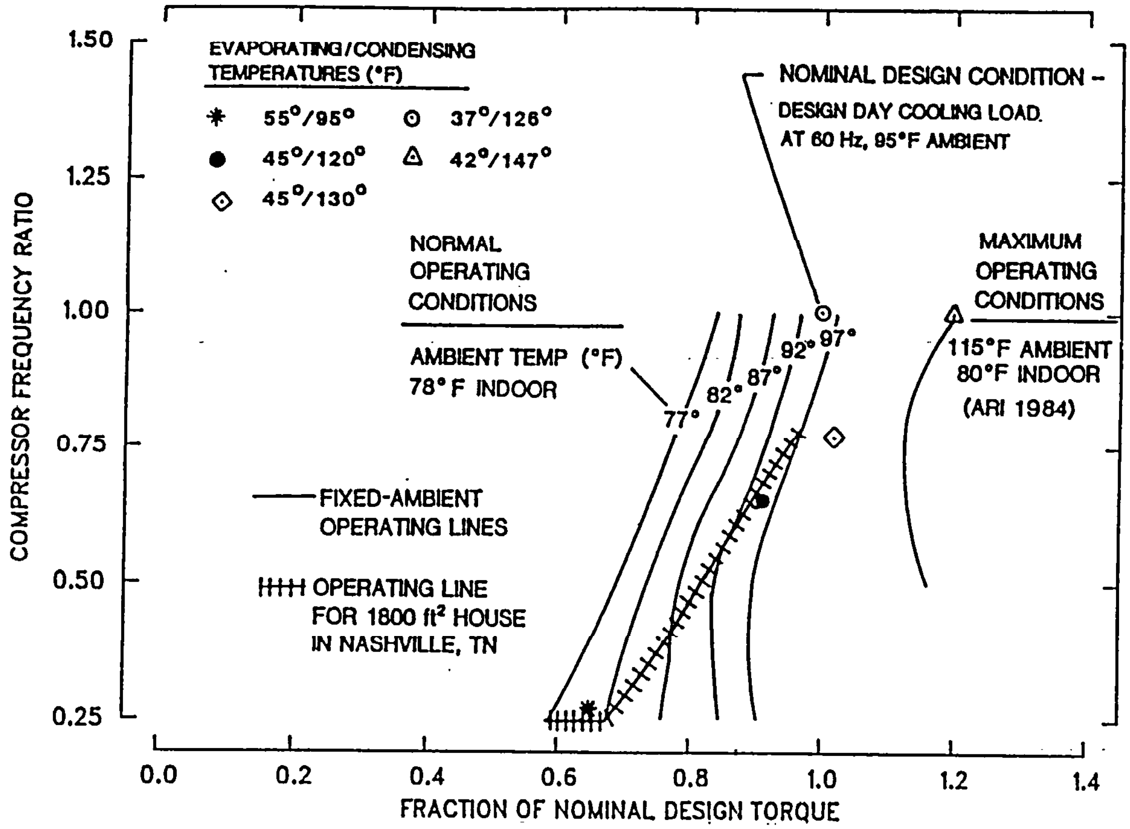

Figure 1 - Compressor Torque versus Frequency Ratio - Cooling Mode

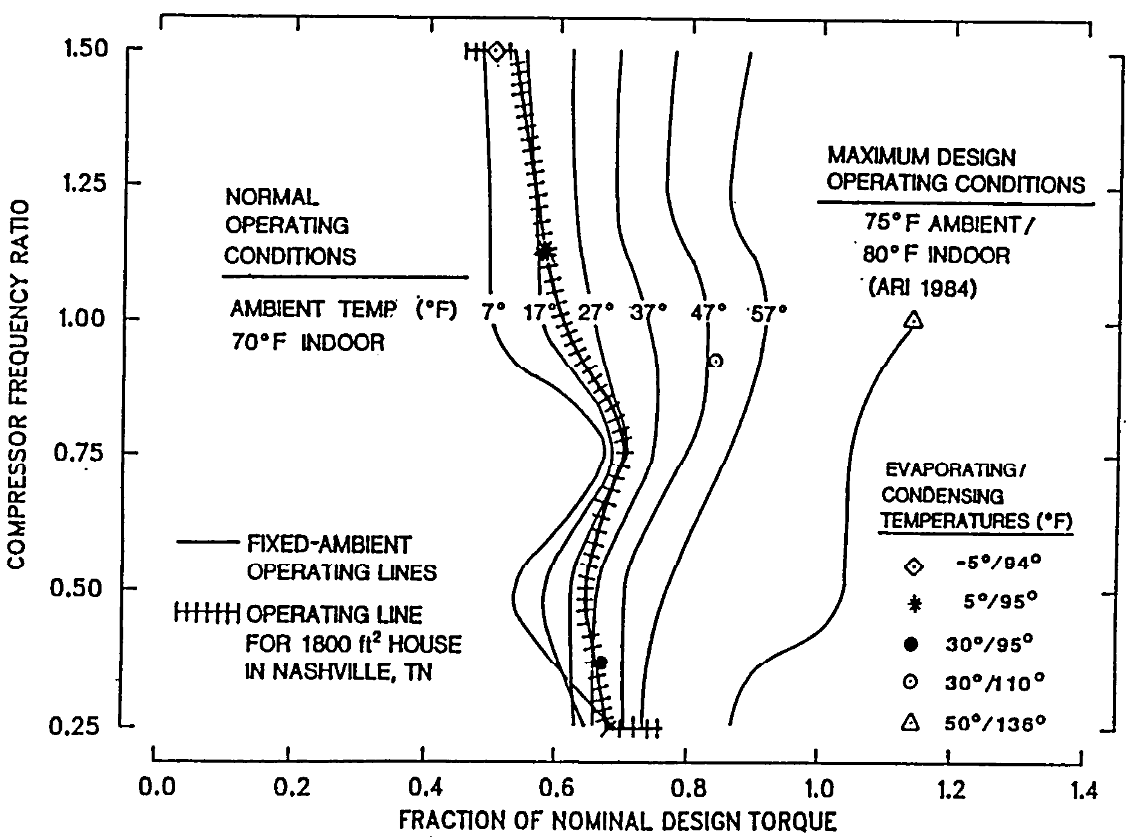

Figure 2 - Compressor Torque versus Frequency Ratio - Heating Mode

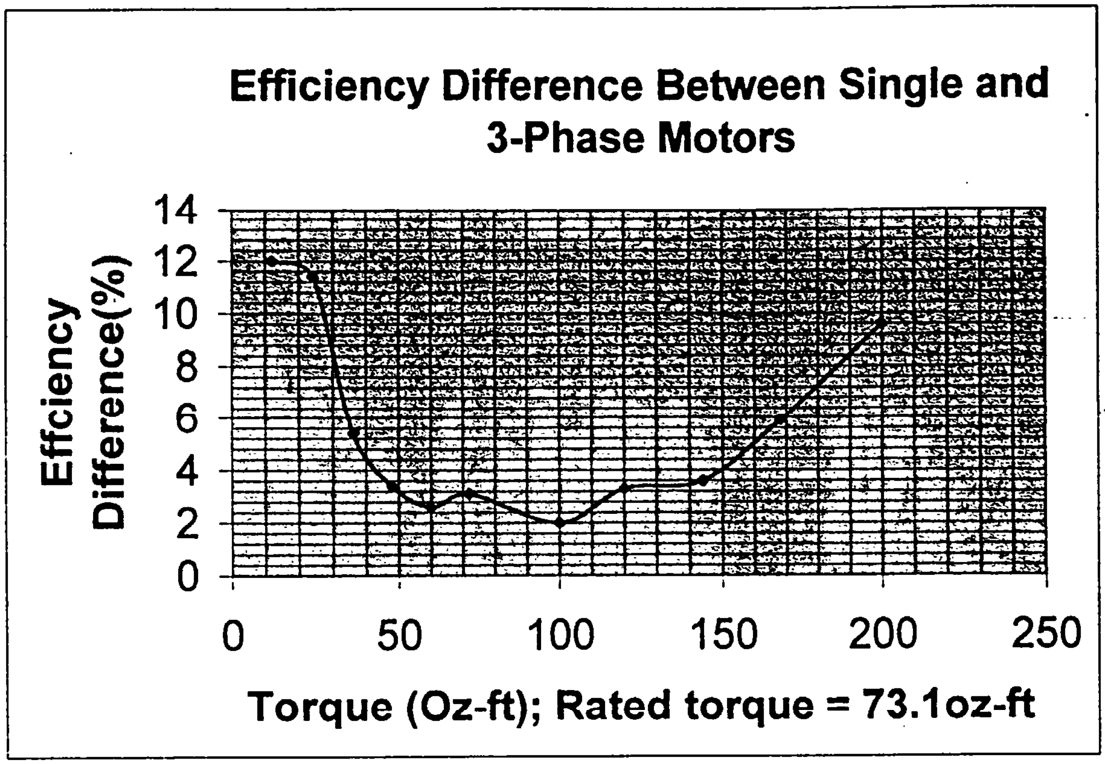

Figure 3 - Torque versus Efficiency Difference - 3-Phase Motor

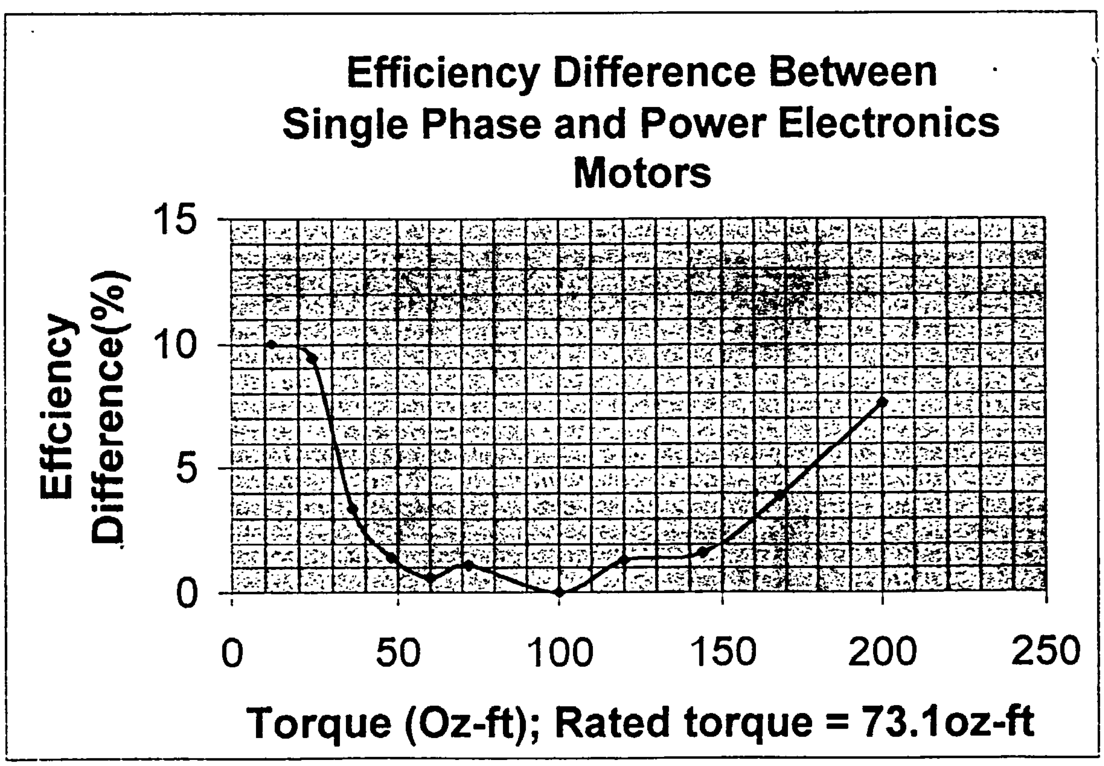

Figure 4 - Torque versus Efficiency Difference - Power Electronics Motor

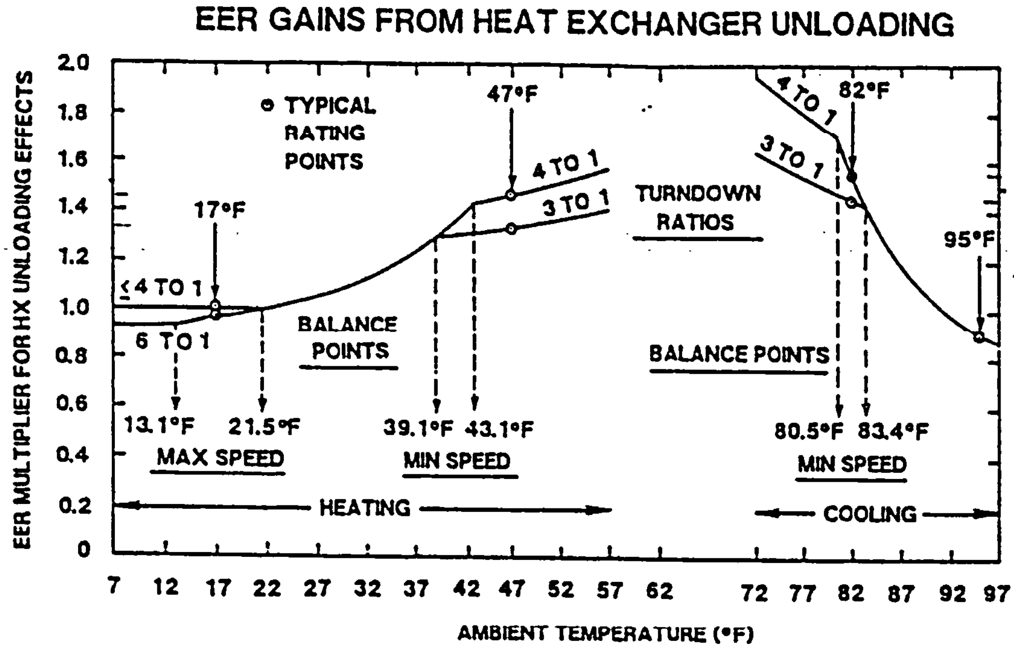

Figure 5 - EER Multipliers for Heat Exchanger Unloading Effects

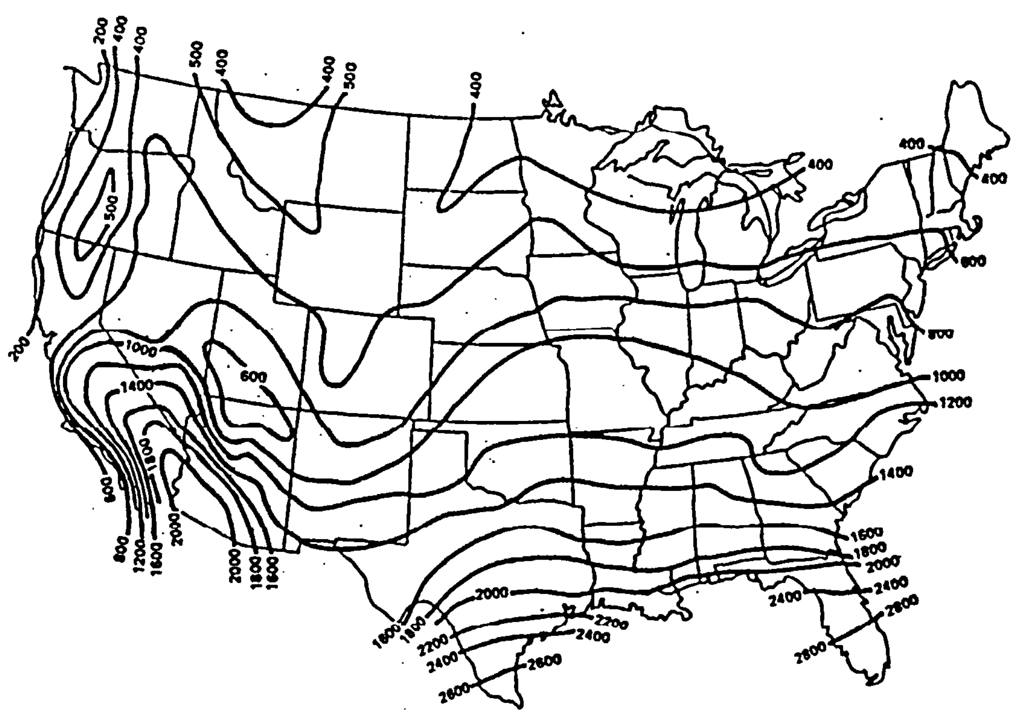

Figure 6 - Summer Cooling Load Hours

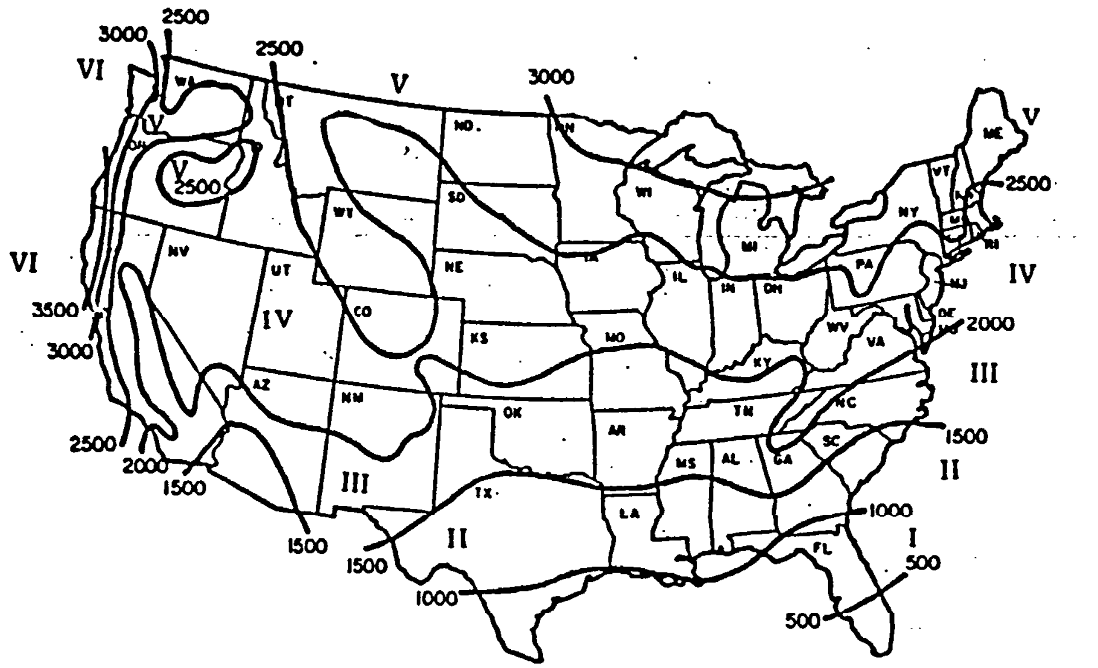

Figure 7 - Winter Heating Load Hours

Table 1 – Efficiency Improvement Multipliers for Power Electronics Motors - Cooling

	82°F				95°F		
Speed Ratio 82/95	Motor	Heat Exchanger	Total	EER	Motor	EER	SEER
Base	1.000	1.000	1.000	12.02	1.000	10.25	10.52
1:1/1:1	1.008	1.000	1.008	12.11	1.000	10.25	10.60
1:2/1:1	1.010	1.330	1.343	16.15	1.000	10.25	14.14
1:3/1:1	1.012	1.440	1.458	17.52	1.000	10.25	15.32
1:4/1:1	1.013	1.550	1.571	18.88	1.000	10.25	16.51

Table 2 – Efficiency Improvement Multipliers for 3-Phase Motors - Cooling

	82°F				95°F		
Speed Ratio 82/95	Motor	Heat Exchanger	Total	EER	Motor	EER	SEER
Base	1.000	1.000	1.000	12.02	1.000	10.25	10.52
1:1/1:1	1.028	1.000	1.028	12.35	1.000	10.25	10.81
1:2/1:1	1.030	1.330	1.370	16.46	1.000	10.25	14.40

Table 3 - Efficiency Improvement Multipliers for Power Electronics Motors - Heating

	47°F				35°F				17°F				
Speed Ratio 47/35/17	Motor	Heat Exchanger	Total	EER	Motor	Heat Exchanger	Total	EER	Motor	Heat Exchanger	Total	EER	HSPF
Base 1-Phase	1.000	1.000	1.000	3.24	1.000	1.000	1.000	2.81	1.000	1.000	1.000	2.14	7.368
1:1/1:1/1:1 PE	1.006	1.000	1.006	3.26	1.011	1.000	1.011	2.84	1.023	1.000	1.023	2.19	7.444
1:2/1:2/2:1 PE	1.011	1.200	1.214	3.93	1.011	1.200	1.213	3.41	1.026	0.910	0.934	2.00	9.309

Table 4 – Efficiency Improvement Multipliers for 3-Phase Motors - Heating

	47°F				35°F				17°F				
Speed Ratio 47/35/17	Motor	Heat Exchanger	Total	EER	Motor	Heat Exchanger	Total	EER	Motor	Heat Exchanger	Total	EER	HSPF
Base 1-Phase	1.000	1.000	1.000	3.24	1.000	1.000	1.000	2.81	1.000	1.000	1.000	2.14	7.368
1:1/1:1/1:1 3-Phase	1.026	1.000	1.026	3.33	1.031	1.000	1.031	2.90	1.043	1.000	1.043	2.23	7.568
1:2/1:2/1:1 3-Phase	1.032	1.200	1.238	4.01	1.031	1.200	1.237	3.48	1.043	1.000	1.043	2.23	8.477

Table 5 – Cooling Costs (Dollars) for Power Electronics and 3-Phase Motors

	MOTOR TYPE / SEER						
COOLING HOURS	Base Single-Phase 10.52	3-Phase 10.81	PE 10.60	3-Phase 14.41	PE 14.14	PE 15.32	PE 16.51
U.S. Avg.	249	242	247	182	185	171	159
400	100	97	99	73	74	68	64
800	199	194	198	146	148	137	127
1200	299	290	296	218	222	205	191
1600	398	387	395	291	296	274	254
2000	498	484	494	364	370	342	318
2400	598	581	593	437	444	410	382
2800	697	678	692	510	518	479	445

Table 6 – Heating Costs (Dollars) for Power Electronics and 3-Phase Motors

	MOTOR TYPE / HSPF				
REGION	Base Single-Phase 7.368	3-Phase 7.568	PE 7.444	3-Phase 8.477	PE 9.313
U. S. Avg.	549	534	543	477	434
1	111	108	110	96	88
2	232	226	230	202	184
3	365	355	352	317	289
4	528	514	522	459	418
5	751	731	743	653	594
6	675	657	668	587	534

Appendix II

Independent Testing Laboratory Final Report

Introduction

To evaluate the performance of the intelligent controller developed in this program, ESI subcontracted the testing task to BR Laboratories (BRL) of Huntington Beach, CA. BRL is reputed as an independent test lab and supports California Energy Commission, Department of Energy and other government agencies in testing and evaluating efficiency of home appliances. The following test procedure was followed:

1. The tests were conducted strictly according to ARI 210/240-94 for single speed and two speed compressors.
2. A new, off-the-shelf air conditioner (A/C) was purchased and tested in its normal operation mode. The A/C was run at single speed and tested at the two test points specified by ARI210/240-94. They are:

    a. 82^0F DB, 65^0F WB

    b. 95^0F DB, 75^0F WB

3. Then the same a/c was modified by installing ESI controller and run at two speeds corresponding to 35Hz and 60Hz to get data at the following points:

    Low speed: corresponding to 35Hz

    a. 82^0F DB, 65^0F WB

    b. 95^0F DB, 75^0F WB

    High speed: corresponding to normal operation of 60 HZ

    a. 82^0F DB, 65^0F WB

    b. 95^0F DB, 75^0F WB

However, we tested the controller at many other test conditions in order to get knowledge of the behavior of the controller at different ambient temperatures.

The design of the ESI controller has a unique feature, which minimizes the cost, which makes the technology practical and may lead to marketable products. This feature allows operation of the a/c at full speed or at low (nearly half) speed, but the power rating of the controller is only half the rated power. For example, a 3-ton a/c tested in this program draws 4.1 kW at full speed and 2.1 kW at low speed. But the rating of ESI controller is only 2.1kW.

Even though the required rating of the controller is only 2.1kW, we operated the a/c at different ambient temperatures as high as 105^0 F and frequencies of 75Hz. These are, of course, not practical solutions because the power rating needed is 5.6kW at 105F, which makes the cost of the controller very high and hence impractical. We have included in this test report all the test data obtained. The results confirmed our initial assumptions about rating of controllers and their operating frequencies in order to make them low cost and thus offer a viable solution to the energy problem.

BR LABORATORIES, INC.
P.O. Box 1249
Huntington Beach, CA 92647
(714) 891-0206
(714) 893-0818 FAX

REPORT NO.: 0105-07
TOTAL PAGES: 18
(Including Title Page, Table of Contents and Appendix)

FINAL TEST REPORT ON ENERGY EFFICIENCY TESTING OF AN AIR CONDITIONER DRIVEN BY ESI'S INTELLIGENT CONTROLLER

AIR CONDITIONER MODEL NO.: MLKA-4036CK006
BRAND: DAYTON
SERIAL NO.: 5661F2600181613
ESI'S INTELLIGENT CONTROLLER, MODEL NO.: 3T2S2
SERIAL NO.: P3

MAY 14, 2001

TEST PROCEDURE : ARI 210/240-94 and ANSI/ASHRAE 37-88

PREPARED FOR : ENERGY SAVERS INTERNATIONAL, INC.
897 Independence Avenue, Suite 2-E
Mountain View, CA 94043

CONTACT: Jay Jayadev, Ph.D, President
PHONE: (408) 257-6465
FAX: (650) 964-3252

PREPARED BY : BR LABORATORIES, INC.
P.O. Box 1249
15161 Triton Lane
Huntington Beach, CA 92647

PHONE: (714) 891-0206
FAX: (714) 893-0818

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FAX: (714) 893-0818

TABLE OF CONTENTS

I. INTRODUCTION

Under the Public Interest Energy Research (PIER) Program of California Energy Commission (CEC), Energy Savers International (ESI) is developing an intelligent Controller to drive air conditioners and heat pumps. The controller using innovative power electronics under development at ESI will improve the energy efficiency of air conditioners and heat pumps in residential and light commercial applications. Fabrication and component testing of power electronics is completed at ESI facility in Mountain View, CA. This assures product quality control.

BR Laboratories was subcontracted by ESI to test the energy efficiency performance of ESI's Intelligent Controller on a commercially available 3 ton air conditioner.

II. OBJECTIVE

To test a commercially available 3 ton air conditioner driven without and with ESI's Intelligent Controller to the test procedures outlined in Standards ARI 210/240-94, Unitary Air-Conditioning and Air-Source Heat Pump Equipment; and ANSI/ASHRAE 37-88, Methods of Testing for Rating Unitary Air-Conditioning and Heat Pump Equipment.

III. EQUIPMENT TESTED

1. Air Conditioner

MANUFACTURED FOR DAYTON ELECTRIC MFG. CO.
NILES, ILLINOIS 60714 USA
MADE IN USA

STOCK NO.		3UJO2 OUTDOOR USE
MODEL NO.	:	MLKA-A036CK 006
SERIAL NO.	:	5661F260018613
OPTION CODE	:	
MFG DATE	:	06/00
POWER SUPPLY	:	208-230 VOLTS 3 PH 60 HZ
OPERATING VOLT RANGE		187-253
COMPRESSOR	:	208-230 VOLTS 3 PH 13 RLA 88 RLA
OUTDOOR FAN	:	209-230 VOLTS 1 PH 2 FLA 1/3 (.249) HP (KW)
INDOOR BLOWER	:	208-230 VOLTS 1 PH 4 FLA ½ (.373) PH (KW)
DESIGN PRESSURE	:	300 PSIG (2068 KPA) HIGH SIDE 150 PSIG (1034 KPA) LOW SIDE
FACTORY CHARGE	:	EACH 72 OZ; R22

For additional information see Appendix.

2. ESI's Intelligent Controller

Model No.: 3T2S2
Serial No.: P3

EQUIPMENT WAS TESTED AS 1. AND AS 1 + 2.

The 3 ton air-conditioner was purchased from local GRAINER's retail outlet and Intelligent Controller was fabricated at ESI. ESI provided the 3 ton air conditioner and intelligent controller to BR Laboratories.

IV. APPROACH

- ARI Standard 210/240-94 establishes for unitary air conditioning equipment the requirements of testing, rating and operating conditions. The standard is intended for the guidelines of the industry, including manufacturers, engineers, installers, contractors, and users.

  This standard applies to unitary air conditioners with a capacity less than 135,000 Btu/h. The air conditioner to be tested in this program meets the rating and functional requirements defined in ARI Standard 210/240-94. Efficiency ratios are defined in this standard as follows:

  Energy Efficiency Ratio (EER):
  EER is the ratio calculated by dividing the cooling capacity of the air conditioner in Btu/hr by the power input in watts at any given set of rating conditions expressed as Btu/h/W.

  Seasonal Energy Efficiency Ratio (SEER):
  SEER means the total cooling output of a central air conditioner in Btu, during its normal usage period for cooling divided by the total electrical energy input in watt-hours during the same period (It includes the effect of degradation coefficient).

  Degradation Coefficient (Cd):
  The Cd is a measure of the efficiency loss due to the cycling of the unit (air-conditioner).

- The air conditioner was tested at the following outdoor conditioners:

Dry Bulb Temperature, °F	Wet Bulb Temperature, °F
82 ± 2	65 ± 1
95 ± 2	75 ± 1
105 ± 2	75 ± 1

  Indoor air condition was maintained at 80°F ± 2°F dry bulb and 67°F ± 1°F wet bulb temperatures.

IV. APPROACH (CONT'D)

- The air conditioner was modified and tested in conjunction with ESI Intelligent Controller for the following outdoor conditions:

Dry Bulb Temperature, °F	Wet Bulb Temperature, °F
82 ± 2	65 ± 1
95 ± 2	75 ± 1
105 ± 2	75 ± 1

Indoor air condition was maintained at 80°F ± 2°F dry bulb and 67°F ± 1°F wet bulb temperatures.

- DAYTON 3 ton air conditioner is certified to the California Energy Commission with the following ratings:
(RHEEM Year-Round, Single-Package Air Conditioner, Air Cooled Model MLKA-A036C)

BRAND	MODEL	Voltage	Phase	Btu/h Cooling	w Input	Btu/wh EER	Btu/wh SEER
DAYTON	MLKA-A036C	230	3	36,000	3,829	9.4	10.2
DAYTON	MLKA-A036C	208	3	36,000	3,829	9.4	10.2
(60 HZ)							

- DAYTON MLKA-A036C air conditioner without and with ESI Intelligent Controller was tested with electric supply of 208 V, 3 PH, 60 HZ and other frequencies like 35HZ, 40 HZ and 50 HZ.

V. TEST RESULTS

1. 3 Ton Air Conditioner:

The air conditioner as received with indoor condition of 80°F dry bulb (DB) and 67°F wet bulb (WB) temperatures had the following performance results:

Electric	Outdoor Condition	Btu/h Cooling	w Input	Btu/wh EER	Btu/wh SEER*
208 V, 3 PH, 60 HZ	82°F DB 65°F WB	35,142	3,600	9.8	9.5
	95°F DB 75°F WB	33,133	4,190	7.9	—
	105°F DB 75°F WB	30,987	4,580	6.8	—

* SEER = 0.965 EER, based on Cd = 0.07 and single speed (see page A3 in Appendix)

2. 3 Ton Air Conditioner + ESI's Intelligent Controller

The air conditioner modified and tested in conjunction with ESI Intelligent controller, with indoor condition of 80°F dry bulb (DB) and 67°F wet bulb (WB) temperatures had the following performance results:

Electric	Outdoor Condition	Btu/h Cooling	w Input	Btu/wh EER
208 V, 3 PH, 50 HZ	82°F DB 65°F WB	28,027	2,940	9.5
208 V, 3 PH, 40 HZ	82°F DB 65°F WB	23,336	2,240	10.4
208 V, 3 PH, 35 HZ	82°F DB 65°F WB	21,173	2,000	10.6

V. TEST RESULTS (CONT'D)

3. 3 Ton Air Conditioner + ESI's Intelligent Controller with outdoor conditions of 95°F DB, 75°F WB; and 105°F DB, 75°F WB

The air conditioner modified and tested in conjunction with ESI Intelligent Controller, with indoor condition of 80°F dry bulb (DB) and 67°F wet bulb (WB) temperatures had the following performance results:

Condition	Outdoor Condition	Btu/h Cooling	w Input	Btu/wh EER
208 V, 3 PH, 50 HZ	95°F DB 75°F WB	25,911	3,380	7.7
208 V, 3 PH, 40 HZ	95°F DB 75°F WB	20,477	2,610	7.9
208 V, 3 PH, 35 HZ	95°F DB 75°F WB	16,970	2,280	7.4
208 V, 3 PH, 50 HZ	105°F DB 75°F WB	23,786	3,770	6.3
208 V, 3 PH, 40 HZ	105°F DB 75°F WB	17,549	2,880	6.1
208 V, 3 PH, 35 HZ	105°F DB 75°F WB	16,794	2,540	6.6

VI. CONCLUSION

a) Based on the test results given below, it is concluded that ESI Intelligent Controller improved the EER of 3 ton air conditioner at 35 HZ and 40 HZ while providing relatively lower cooling capacity with an outdoor condition of 82°F DB and 65°F WB.

Air Conditioner as received	:	208 V, 3 PH, 60 HZ
Air Conditioner equipped with ESI Intelligent Controller (A/C + IC)	:	208 V, 3 PH, 35 HZ 40 HZ 50 HZ

Model (S/N)	Rating Condition	HZ Frequency	Btu/h Cooling	w Input	Btu/wh EER
MLKA-4036CK006 (5661F260018613)	Indoor: 80°F DB, 67°F WB; Outdoor: 82°F DB, 65°F WB	60	35,142	3,600	9.8
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 82°F DB, 65°F WB	50	28,027	2,940	9.5
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 82°F DB, 65°F WB	40	23,336	2,240	10.4
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 82°F DB, 65°F WB	35	21,173	2,000	10.6

VI. CONCLUSION (CONT'D)

b) The EER performance of 3 ton air conditioner without and with ESI Intelligent Controller was approximately the same with outdoor condition of 95°F DB and 75°F WB temperatures and IC operating at 40 HZ.

Air Conditioner as received	:	208 V, 3 PH, 60 HZ
Air Conditioner equipped with ESI Intelligent Controller (A/C + IC)	:	208 V, 3 PH, 35 HZ 40 HZ 50 HZ

Model (S/N)	Rating Condition	HZ Frequency	Btu/h Cooling	w Input	Btu/wh EER
MLKA-4036CK006 (5661F260018613)	Indoor: 80°F DB, 67°F WB; Outdoor: 95°F DB, 75°F WB	60	33,133	4,190	7.9
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 95°F DB, 75°F WB	50	25,911	3,380	7.7
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 95°F DB, 75°F WB	40	20,477	2,610	7.9
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 95°F DB, 75°F WB	35	16,970	2,280	7.4

VI. CONCLUSION (CONT'D)

c) The ESI Intelligent Controller did not improve the EER performance of 3 ton air conditioner when tested to an outdoor condition of 105°F DB and 75°F WB temperatures.

Air Conditioner as received	:	208 V, 3 PH, 60 HZ
Air Conditioner equipped with ESI Intelligent Controller (A/C + IC)	:	208 V, 3 PH, 35 HZ 40 HZ 50 HZ

Model (S/N)	Rating Condition	HZ Frequency	Btu/h Cooling	w Input	Btu/wh EER
MLKA-4036CK006 (5661F260018613)	Indoor: 80°F DB, 67°F WB; Outdoor: 105°F DB, 75°F WB	60	30,987	4,580	6.8
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 105°F DB, 75°F WB	50	23,786	3,770	6.3
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 105°F DB, 75°F WB	40	17,549	2,880	6.1
MLKA-4036CK006 (5661F260018613) (A/C + IC)	Indoor: 80°F DB, 67°F WB; Outdoor: 105°F DB, 75°F WB	35	16,794	2,540	6.6

VI. CONCLUSION (CONT'D)

- The ESI Intelligent Controller with the capability of improving air conditioner efficiency may have a potential application to other size smaller or larger than the tested 3 ton air-conditioner. The most effective application will be retrofitting the existing air conditioner equipment, in which case the energy savings will be substantial with an outdoor conditions of 82°F DB and 67°F WB temperatures.

The tested 3 ton air conditioner and ESI Intelligent Controller are shown in photos provided in the APPENDIX.

Respectfully Submitted,

Bodh R. Subherwal. 5/18/01

Bodh R. Subherwal, P.E.
President

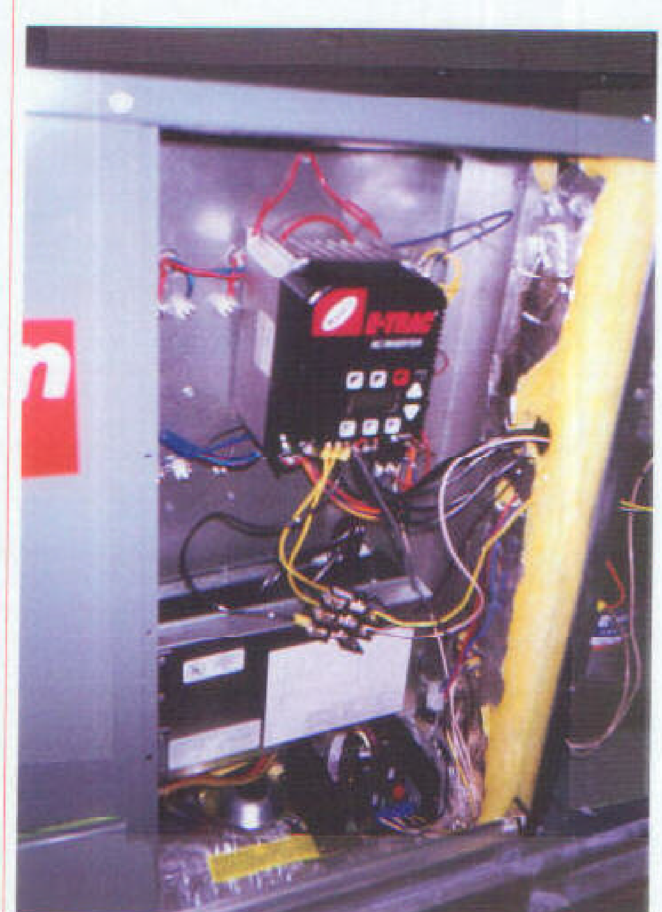
Date

APPENDIX

- PHOTOS
- CALCULATION EXAMPLES
- APPLIANCE DATA
- INSTRUMENTATION/EQUIPMENT

3 TON AIR CONDITIONER
'DAYTON' BRAND
MODEL : MLKA-4036CK006
S/N : 5661F260018613

UNDER TEST



MODEL : 3T2S2
S/N : P3
ESI INTELLIGENT CONTROLLER
ADAPTED TO 3 TON AIR CONDITIONER "DAYTON"
(MFR: RHEEM)

CALCULATION EXAMPLES

AIR CONDITIONER AS RECEIVED

INDOOR CONDITION	:	80 °F DB, 67 °F WB
OUTDOOR CONDITION	:	82 °F DB, 65 °F WB

Q_{mi}	=	768 CFM
ha_1	=	30.0 Btu/lb. of dry air
ha_2	=	20.0 Btu/lb. of dry air
V	=	13.02 ft^3/lb
W	=	0.0071 lb. moisture/lb. of dry air
q_{tci}	=	$\frac{(60)(768)(30.0 - 20.0)}{(13.02)(1 + 0.0071)}$
	=	35,142 Btu (Total Cooling)
Electrical Input	=	3,600 wh (208 V, 3 PH, 60 HZ)
EER	=	$\frac{35,142}{3,600}$
	=	9.76 $\simeq$ 9.8 Btu/wh
Cd, Degradation Coefficient	=	0.07, single speed
SEER	=	PLF (0.5) EER
PLF (0.5)	=	(1 – 0.5 x 0.07) = 0.965
SEER	=	(0.965) (9.8)
	$\simeq$	9.5 Btu/wh

APPLIANCE DATA

MANUFACTURED FOR DAYTON ELECTRIC MFG. CO.
NILES, ILLINIS 60714 USA

MADE IN THE USA

STOCK NO. 3UJO2
MODEL NO.: MLKA-A036CK 006
OPTION CODE:
POWER SUPPLY: 208-230 VOLTS 3 PH 60 HZ
COMPRESSOR: 208-230 VOLTS 3 PH 13 RLA 88 LRA
OUTDOOR FAN: 208-230 VOLTS 1 PH 2 FLA 1/3 (.249) HP (KW)
INDOOR BLOWER: 208-230 VOLTS 1 PH 4 FLA ½ (.373) HP (KW)
DESIGN PRESSURE: 300 PSIG (2068 KPA) HIGH SIDE 150 PSIG (1034 KPA) LOW SIDE
FACTORY CHARGE: EACH 72 (2.041) OZ (KG) R22

OUTDOOR USE
SERIAL NO.: 5661F260018613
MFG DATE: 06/00
OPERATING VOLT RANGE 187-253

SINGLE POWER SUPPLY FOR BOTH UNIT AND HEATER KIT
SCRATCH INK OFF SQUARE OF HEATER KIT INSTALLED

HEATER KIT MODEL NO. RXJJ	HEATER KW @ 208-240 V	HEATER KIT FLA	UNIT MIN. CKT. AMPACITY	MAX. FUSE OR CKT. BKR. SIZE (CKT. BKR. MUST BE HACR TYPE FOR USA)	
IF NO HEATER KIT INSALLED →			23 / 23	35 / 35	
A06C	4.2 / 5.6	11.7 / 13.5	23 / 23	35 / 35	X
A10C	7.2 / 9.6	20.0 / 23.1	31 / 34	35 / 35	
A11C	7.2 / 9.6	20.0 / 23.1	31 / 34	35 / 35	
A12C	8.4 / 11.2	23.4 / 27.0	35 / 39	40 / 40	
A15C	10.8 / 14.4	30.1 / 34.7	43 / 49	45 / 50	
A20C	14.4 / 19.2	40.1 / 46.2	56 / 63	60 / 70	
A21C	14.4 / 19.2	40.1 / 46.2	56 / 63	60 / 70	

SEPARATE POWER SUPPLY FOR BOTH UNIT AND HEATER KIT
SCRATCH INK OFF SQUARE OF HEATER KIT INSTALLED

CIRCUIT 1 HEATER KIT

HEATER KIT MODEL NO. RXJJ	HEATER KW @ 208-240 V	HEATER KIT FLA	HEATER KIT UNIT MIN. CKT. AMPACITY	MAX. FUSE OR CKT. BKR. SIZE (CKT. BKR. MUST BE HACR TYPE FOR USA)	
A06C	4.2 / 5.6	11.7 / 13.5	15 / 17	15 / 20	X
A10C	7.2 / 9.6	20.0 / 23.1	25 / 29	25 / 30	
A11C	7.2 / 9.6	20.0 / 23.1	25 / 29	25 / 30	
A12C	8.4 / 11.2	23.4 / 27.0	30 / 34	30 / 35	
A15C	10.8 / 14.4	30.1 / 34.7	38 / 44	40 / 45	
A20C	14.4 / 19.2	40.1 / 46.2	50 / 58	50 / 60	
A21C	14.4 / 19.2	40.1 / 46.2	50 / 58	50 / 60	

CIRCUIT 2
UNIT MIN. CKT. AMPACITY 23 / 23
UNIT MAX. FUSE OR CKT. BKR. SIZE 35 / 35
(CKT. BKR. MUST BE HACR TYPE FOR USA)

CLEARANCE TO COMBUSTAIBLE MATERIAL: 0 (0) IN. (M) FOR CABINET, DISCHARGE PLENUM & DISCHARGE DUCT.
DESIGN CERTIFIED FOR OUTDOOR INSTALLATION ONLY 92-23634-05-00

UL LISTED CENTRAL AIR CONDITIONER 7F62

UNITARY AIR-CONDITIONING EQUIPMENT
MANUFACTURER CERTIFIED TO ARI AS COMPLYING WITH
CERTIFICATION SECTIONS OF ARI STANDARD 210

CSA VERIFIED ENERGY PERFORMANCE EEV 91598 92-23435-01-00

INSTRUMENTATION/EQUIPMENT

WATT-HR METER
Manufacturer: ELECTRO INDUSTRIES, INC.
Model: WH –201 – DP
Serial No.: 863824

DATA LOGGER
Manufacturer: CAMPBELL SCIENTIFIC, INC.
Model: 21X MICROLOGGER
Serial No.: 1342

TEMPERATURE
Manufacturer: OMEGA ENGINEERING, INC.
Model: TYPE "J" THERMOCOUPLE WIRE

RELATIVE HUMIDITY
Manufacturer: CAMPBELL SCIENTIFIC, INC.
Model: 207 TEMPERATURE AND RH PROBE

DEW POINT TEMPERATURE
Manufacturer: GENERAL EASTERN
Model: SYSTEM 1200 POWER CONTROL MODULE
Serial No.: 15635
Model: 1211 OPTICAL DEW PT. SENSOR
Serial No.: 15636

EXTERNAL STATIC PRESSURE GAGE
Manufacturer: DWYER INSTRUMENTS, INC.
Model: MANOMETER 20-D (826 SP.GR. RED OIL)

AIR VELOCITY GAGE
Manufacturer: DWYER INSTRUMENTS, INC.
Model: No. 400 DURABLOK MANOMETER
WITH 18″ PITOT TUBE

AIR VELOCITY APPARATUS
SINGLE 8″ NOZZLE ASSEMBLY

Appendix III

ARI Standard 210/240-94:

SEER Calculations and Link to ARI Website

SEER Calculations - Equations from ARI Standard 210/240-94

SEER of Single Speed Compressor given in A 5.1.1, page 20
SEER = PLF (0.5) * EER (82F)
PLF(.5) = 1 - 0.5 * Cd
Where SEER = Seasonal Energy Efficiency Ratio; PLF = Part-Load Factor
Cd = Degradation Coefficient; EER = Energy Efficiency Ratio measured in 82/65 tests

From A 2.1
In lieu of conducting tests C and D, an assigned value of 0.25 may be used
for degradation coefficient, Cd.

SEER of Two - Speed Compressor given in A 5.1.3

A5.1.3

To evaluate steady state capacity Qss(Ti) and power input Ess (Ti) at temperature Ti for each compressor speed, k=1 (low speed) and k=2 (high speed), the results of tests at 82F and 95F shall be used in the following equations:

Qss^k(Ti)=Qss^k(95F) + ((Qss^k(82F)-Qss^k(95F))(33-5*j)/13
Qss^k(95F) = steady state capacity measured from test 95F DB/75F WB
Qss^k(82F) = steady state capacity measured from test 82F DB/65F WB

Ess^k(Ti)=Ess^k(95F) + ((Ess^k(82F)-Ess^k(95F))(33-5*j)/13
Ess^k(95F) = Electrical Power input measured from test 95F DB/75F WB
Ess^k(82F) = Electrical Power input measured from test 82F DB/65F WB

Building cooling load BL(Ti) shall be obtained from the following equation:
BL(Tj)= ((5j-3)/30)*(Qss^k=2*/(1.1)
where, Qss^k=2 (95F) = steady state capacity measured from 95F tests at the high compressor speed

A5.1.3.1

Units operating at low speed,(k=1), for which Qss(Ti) is greater than building cooling load, evaluate the following equations:
(X^k=1) = [BL(Tj)]/[Qss(k=1)at Tj] [1]
where (X^k=1) = Load Factor; [BL(Tj) = building cooling load from previous section;
[Qss(k=1)at Tj]= Steady state cooling capacity from A5.1.3

Q(Tj)/N = BL(Tj)*ni/N [2]
Q(Tj)/N = ratio of total cooling(Btu) in temperature bin j to the number of temperature bin hours;
ni/N = the fractional number of hours in temperature bin j from the accompanying table;

[E(Tj)/N] = X1*E1(Tj)*(1/PLF)* (nj/N) [3]
[E(Tj)/N] = ratio of energy usage (watt-hr) in temperature bin j to the nuber of temperature bin hours

PLF=1-Cd* (1 - X^k=1);
Cd= Degradation coefficint,

A5.1.3.2

When the unit alternates between high (k=2) and low (k=1) compressor speeds to satisfy the building lo at temperature Tj, evaluate the following equations:

X^k=1 = (Q^k=2 (Tj)- BL(Tj)) / [Q,2(Tj) - Q1(Tj)] [1]

X2 = 1-X1 [2]

Q(Tj)/N = [X1*Q1(Tj) + X2*Q2(Tj)] * (nj/N) [3]

E(Tj)/N = [X1*E1(Tj) + X2*E2(Tj)] * (nj/N) [4]

A5.1.3.4

When a unit operates continuously at high compressor speed (k=2) at an outdoor temperature T, evaluate the following equations:

Q(Tj)/N = Q2(Tj) * (ni/N)

E(Tj)/N = E2(Tj) * (ni/N)

A5.1.3.5

Calculate the SEER in Btu's/watt-hr using the values for the terms Q(Tj)/N and E(Tj)/N as determined at each temperature bin, using the equation:

SEER = [Sum Q(Tj)/N] / [SUM E(Tj)/N]

Distribution of fractional hours in temperature bins to be used for 2-speed compressors - page 27

A 6.1.2			
Bin#	T range	T representative	
1	65-69	67	0.214
2	70-74	72	0.231
3	75-79	77	0.216
4	80-84	82	0.161
5	85-89	87	0.104
6	89-94	92	0.052
7	95-99	97	0.018
8	100-104	102	0.004

Link to ARI Website

<http://www.ari.org/std/individual/210.240-94.pdf>

Appendix IV

Improvements in Seasonal Energy Efficiency Ratio (SEER) by Intelligent Controller Technology

Introduction

To quantify the improvements in Seasonal Energy Efficiency Ratio (SEER) of air conditioners by the intelligent controller developed in this program, an accurate and extensive test program was conducted on an off-the- shelf air conditioner and on the same air conditioner modified by installing ESI's controller. The tests followed the method described in ARI 210/240-94, which is widely accepted by the air conditioning industry. An independent test laboratory – BR Laboratories in Huntington Beach, California, conducted these tests. Data at appropriate test points and calculation method as specified in ARI 210/240-94 were used to calculate improvement in SEER. The improvement in SEER depends heavily on the assumption of degradation coefficient. This appendix describes in detail, the improvement in SEER to be expected using ESI's controller, based on the test data generated by BR Laboratories.

Background

To elucidate the strategy in developing the controller, it is important to point out the limitations of present air conditioner technology.

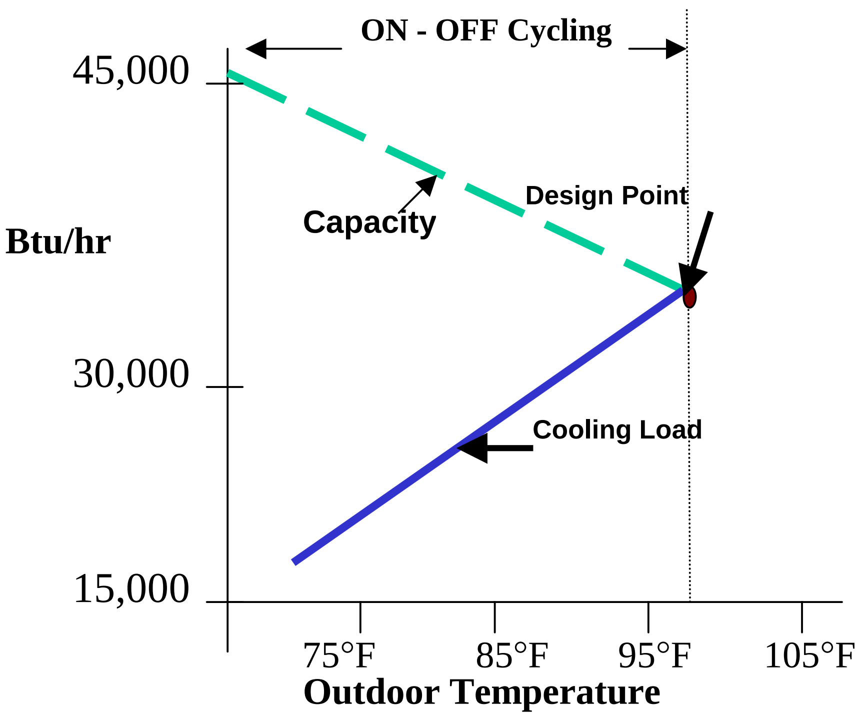


Figure A4- 1. Divergence of cooling load and air conditioner capacity increases as the ambient temperature decreases.

When the compressor is switched on, cooling capacity is zero even though it is using full energy. During this transient period, thermal efficiency is lower than at steady state. (Ref: R.W. Griffith, ASHRAE -LA-80-1, p 474, 1980)

The characteristics of current technology are:

- The A/C system is usually specified to satisfy the cooling load at 95°F.
- The capacity of the air conditioner increases and the cooling load decreases as the ambient temperature goes down (Figure A4- 1).

Therefore, at all temperatures below the design temperature of 98°F, the capacity of the air conditioner is greater than the load and the difference increases linearly as the ambient temperature decreases.

The current control strategy for reconciling the difference between capacity and cooling load is taken care of by cyclic operation of the A/C system by turning the system on and off as required by the thermostat. This on-off cycling continues until cooling supplied by the system approximates the cooling load of the building, leading to energy losses (called cycling losses).

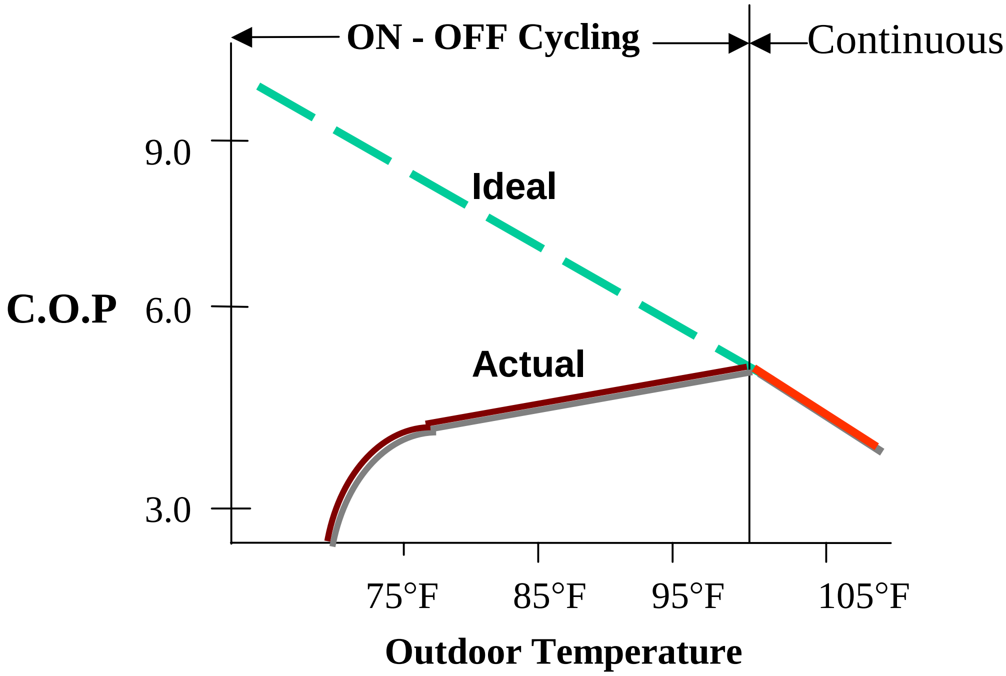


Figure A4- 2. Effect of Cycling Losses on EER

As shown in Figure A4-2, actual energy efficiency ratios (EERs) are much less than ideal because of cycling losses. This loss is accounted for in the ARI equations used to calculate Seasonal Energy Efficiency Ratio (SEER) by the degradation factor (C_D). The figure demonstrates that EER in a single speed operation is much smaller than the ideal (steady state) case where capacity matches the load.

The database supplied by California Energy Commission Program Manager to ESI showed C_D varying from .01 to 0.25 for the same SEER value of 11. Experiments to determine C_D were not conducted, as the functional operation of the controller does not affect the value of C_D, which is used for calculating the SEER of the air-conditioning unit. This also allowed limited resources available under the contract to be used to conduct the testing necessary to evaluate the controller.

If the transient losses are not measured by experiment, ARI 210/240-94 allows a C_D of 0.25. Because the C_D of the unmodified air conditioner was not measured this value was used.

Test data for the unmodified and modified units at various operating conditions were submitted to ESI and are presented in Appendix 2. This data was used to calculate SEER using the procedure specified in ARI 210/240-94 for 2-speed compressors.

According to the California Energy Commission's appliance database, the manufacturer of this equipment claims a C_D of .07.

Calculations of SEER for both of these values of C_D are given below.

Single-speed SEER Calculations:

For single speed, only the EER at 82°F was needed to calculate SEER using ARI Standard 210/240-94 equations. No other data was needed.

For the air conditioner purchased, BRL measured the EER before modification at 82/65 (a dry bulb temperature of 82°F and a wet bulb temperature of 65°F).

EER (82/65) = 9.8 (page 5 of BR Lab Test Report report, also included as a Appendix II)

Calculating SEER from ARI 210/240-94 equations,

$$\text{SEER}_{\text{single speed}} = (1 - .5 * C_D) * \text{EER at } (82/65)$$

Table A4- 1. SEER of an As Received 3-ton Air Conditioner (BR Lab Data)

For C_D = .25,	SEER, single speed = 8.6
For C_D = .07,	SEER, single speed = 9.5

It can easily be seen how SEER is so dependent on the assumed C_D.

The SEER value listed by the manufacturer for this air conditioning unit is 10.2.

The EER listed in the California Energy Commission's database, as quoted in the BR Lab Test Report, was also less than what was measured at BR Labs.

EER from CEC database	EER measured at BR la
9.4	7.9

Speed Conversion: 2- speed Operation

An important benefit of three phase motors is their ability to operate at different frequencies with high efficiency while, more importantly, producing the desired torque demanded by the compressor at that frequency. This was well documented by conducting tests on single phase and three phase motors in the program.

Two Speed Calculations:

Page 20 of ARI 210/240-94 gives equations to calculate SEER for two-speed compressors. Four data points are needed for two-speed calculations:

Low speed	EER(82 / 65)	EER(95 / 75)
High speed	EER(82 / 65)	EER(95 / 75)

Table A4- 2. Measured Values by BRL at the Required Data Points (page 5 and 6 of BRL Report)

Low speed	EER(82/65)	EER(95/75)
(35Hz or 2100rpm)	10.6	7.4
High speed	EER(82/65)	EER(95/75)
(60Hz or 3600rpm)	9.8	7.8

The values shown in the table were used to calculate SEER using ARI 210 / 240-94 equations.

EER at low speed and 95°F is not an operating point.

As the controller only operates the air conditioner at low speed at temperatures below 82°F, it was necessary to linearly extrapolate for temperatures below this, as at least two points were needed for linear extrapolation in the ARI equations.

Between 82°F and 95°F, controller operates the air conditioner at a combination of high and low speed, with complete high-speed operations achieved at 95°F. This is the method assumed in the ARI equations.

Table A4- 3 shows the SEER from the above 2-speed equations for two assumed values of Cd with the percentage of improvement resulting from speed conversion.

Table A4- 3. SEER of 3-ton air conditioner driven at 2-speeds by ESI controller

	SEER – Two Speed	SEER – Single Speed	Improvement caused by Speed Conversion
	35Hz and 60Hz	60Hz	
0.25	10.2	8.5	19 %
0.07	10.5	9.4	12%

Phase Conversion: Single Phase vs. Three Phase Operation

In a meeting held at BR Labs to discuss the testing plans and procedures, it was decided to test an A/C with a 3-phase compressor before and after modification with ESI's intelligent controller. The replacement of a single-phase compressor with a 3-phase compressor would be a major change and it would be difficult to verify whether the air conditioner was optimized for the new compressor or not. As the test objective was to obtain verifiable test data on the controller, it was agreed that an air conditioner with a 3-phase compressor be purchased and tested. Therefore, the tests at BRL could only quantify the benefits of two-speed operation and not the benefit of changing from single phase to three phase.

The efficiency of 3-phase motors for the same amount of electrical and magnetic material is higher than single-phase motors. This fact has been known for more than a 100 years and can be found in many textbooks.

The efficiency of single phase and 3-phase compressor motors of the same 3 HP rating used in three-ton air conditioners was measured. The measured values on the motors used in the three-ton air conditioner were plotted in Figure A4- 3. Unfortunately, the 3-phase motor used in a three-ton unit had a smaller volume than a single-phase motor used in a similar three-ton unit by eight percent. If the volumes were the same, efficiency would be higher than what was measured. This delta in efficiency is not included in the figure.

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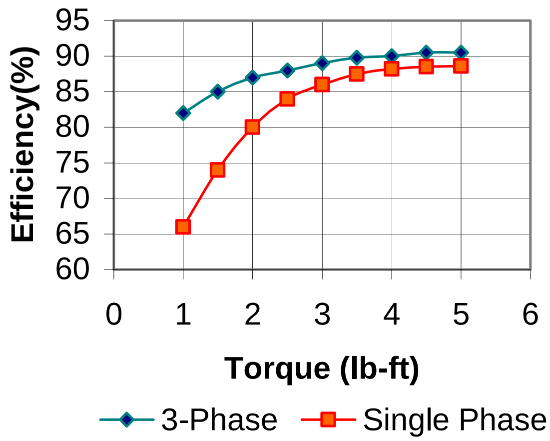

Full Load = 4.7 lb-ft

Figure A4- 3. Efficiency Curves for 3-phase and Single Phase Motors used in 3-ton Air Conditioners

The difference in efficiency is quite large, particularly at fractional loads (Figure A4- 3).

As pointed out before, the motor was rated to produce the full rating power of 3 HP at 97°F. But outdoor temperatures are 97°F or above for less than ten percent of the year, so the motor operates at partial load for most of the time. The difference in efficiency from measured values varies from three percent at full load (4.7 lb-ft) to ten percent at a quarter load (1.2 lb-ft).

Because the variation in the efficiency of a motor as a function of load cannot be input into the ARI equations to calculate SEER, the increase in efficiency has to be accounted as phase conversion (3-phase vs. single phase) by adding to the speed conversion (2-speed vs. single-speed) improvement derived from measured data.

Consequently, the A/C operates half the time at temperatures below 82°F. The load required of the air conditioner is less than half capacity for 6 months out of the year. The difference in motor efficiency in this region goes from five percent to ten percent. A conservative estimate in increased efficiency is 4 percent, this increase is due to electrical aspects. There is an additional benefit of heat exchanger unloading due to decreased losses, because of increased motor efficiency, but this was not included in the estimate.

The 3-phase plot of Figure A4-3 is a conservative estimate of expected motor efficiency because the 3-phase motor measured had an eight percent smaller volume than the single-phase motor. The efficiency of a 3- phase motor of the same size as that of the single phase motor would be even higher.

It is difficult to make a quantitative statement on annual energy savings based on these results for motors using SEER equations, because SEER assumes a linear relationship between load and electrical power input.

In summary, a four to five percent improvement in SEER because of phase conversion alone is a rather conservative estimate. As Table A4- 4 shows, SEER improvement is the sum of both speed and phase conversion.

Table A4- 4. Improvement in SEER

	SEER Two Speed	SEER Single Speed	Improvement Due to Speed Conversion	Improvement due to Phase Conversion	Improvement Total
C_D =0.25	10.2	8.5	19%	4%	23%
C_D =0.07	10.5	9.4	12%	4%	16%

References

Vienott, C. G., " Theory and Design of Small Induction Motors", Mc Graw Hill, 1959

Appendix V

Residential Building Model Used for Peak Reduction Strategy Development

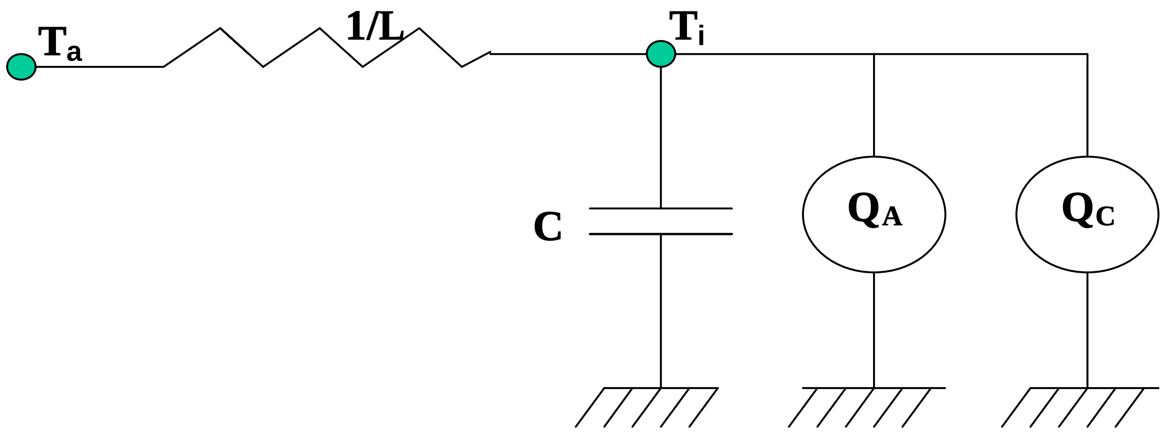

Figure A5-1: 1R1C Electric Analog Model for Thermal Performance of a Building

While there are several sophisticated models to analyze the thermal behavior of buildings, the simplest is the so-called 1R1C model [1].

It is an electrical analogue of the thermal model for a residence. The transient response is easily calculated using circuit analysis tools. Figure A5-1 illustrates the model. Indoor temperature rise depends on the thermal storage, heat inputs - both internal and external, heat loss and cooling provided by the air conditioner. The electrical circuit represents the differential equation for heat flow given by:

$$C \ dT_i(t)/dt = L \ [\ T_a(t) - T_i(t) \ ] + Q_A(t) - Q_C(t)$$

Where

C = building heat capacity

$T_i(t)$ = indoor air temperature

L = Steady state heat loss coefficient for the building

T_a = Ambient temperature

$T_i(t)$ = indoor temperature

$Q_A(t)$ = Internal and solar thermal heat inputs

$Q_C(t)$ = Cooling energy provided by the air conditioner

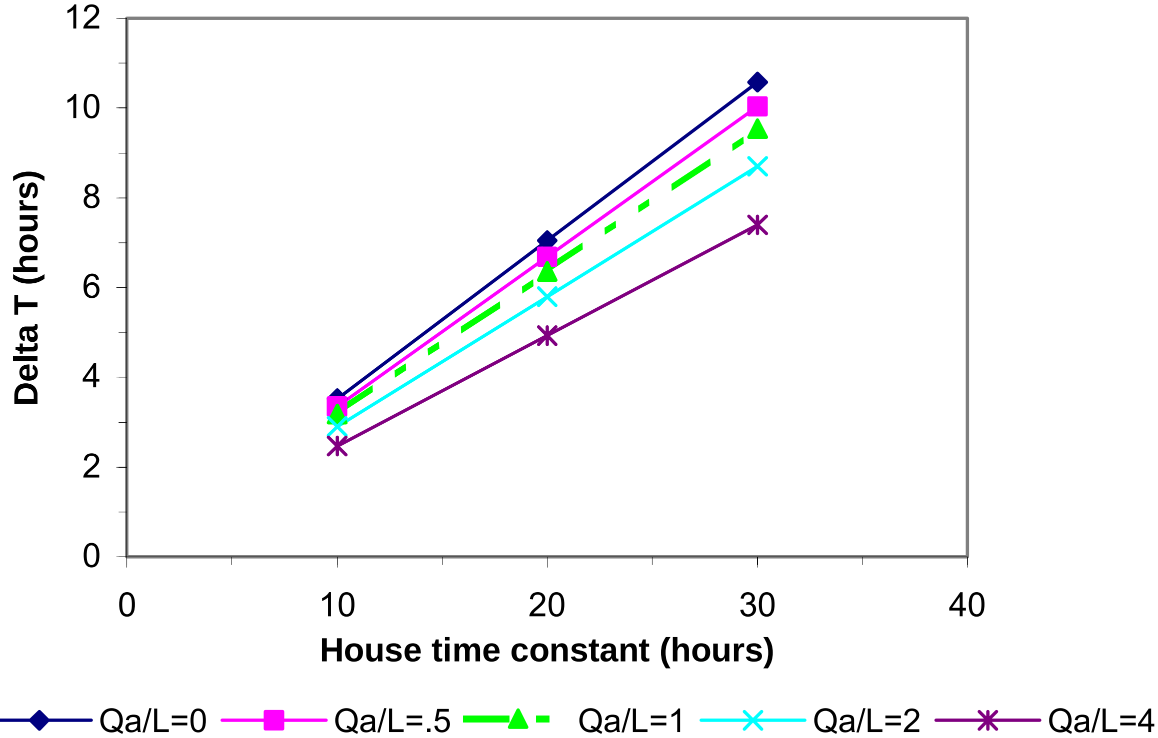

Figure A5-2: Time for temperature to rise from 72F to 78F when the indoor temperature is floating, given $T_{ambient}$ is 95°F.

This equation can be solved in closed form for the condition where *the air conditioner is switched off*. We can find the time required for rise in indoor temperature when the residence is thermally floating . The solution is given by:

$$\Delta t = -\tau \ln \{ 1 - \Delta Ti / [Ta - Ti,b + Q_A . (1/L)]\}$$

Where

Δt = time required for temperature to rise

ΔTi = specified rise in indoor temperature

Ta = ambient temperature

Ti,b = indoor temperature at the beginning of the floating period

τ = Residence time constant

These calculations are done to get a feel for the number of hours the residence can float without the air conditioner being ON. For example, for a time constant of 20 hours, Qa/L =2, it takes about four hours for indoor temperature to rise from 73°F to 77°F.

This analysis has led us to the conclusion that a typical residence can float from four to six hours without air conditioning if precooling is done because the LOW POWER mode can maintain the temperature limits if the residence thermal time constants are short.

References

A. Rabl, *in "Parameter Estimation in Buildings…,"* ASME Journal of Solar Energy Engineering, v.110, pp 52-62, 1988.

Appendix VI

Additional Result: Peak Loading Strategy

Solution to Peak Load Problem:

<u>Run the air conditioner using a control algorithm to reduce peak demand</u>

Several research studies have indicated that residential air conditioners, despite their relatively lower appliance annual utilization rates, are primarily responsible for the large peak in diurnal system load profiles. [1] Modifying or altering the shape of the diurnal system load profile as a viable means of load shaving in commercial buildings has attracted the attention of many researchers in the past.

This research demonstrated that the ESI controller developed in this project has the following capabilities:

1. Can easily be made to communicate with the utility/customer
2. Can run any predetermined control algorithm to run the air conditioner.

This study explored at a very top level the possibility of applying the controller for peak reduction, using ESI's internal resources and not Commission's funds.

Strategy for Peak Power Reduction

Given the hardware and software capability of the ESI controller, load management algorithms can be run to reduce peak demand.

An example of such a strategy involves running the air conditioner using the intelligence and real time clock capability of the controller and using the inherent thermal storage properties of the building itself. A Time-of-Use (TOU) meter in series with the controller records the power consumption as a function of time of day. In a simple tariff scheme as the one that Pacific Gas & Electric (PG&E) offers to residential customers, it is just recording energy consumption in the two time periods:

- During peak hours when the cost of electricity is four to five times higher than the off-peak.
- During off-peak hours for the rest of the day when the cost of electricity is relatively low.

Two operating conditions were defined:

Condition 1: A hot summer day when the utility system needs to shed the load during peak hours to keep the power system reliable and avoid rolling blackouts.

Condition 2: A normal summer day when there is not much concern for peak power demand reaching critical limits.

Condition 1: A hot summer day, when the utility system needs to shed the load during peak hours

The utility or customer sends a signal to the controller a few hours before the expected system peak. Such information is usually available to the system operator and the utilities. The information can arrive on any communication technology used by the utility: telephone, wireless, or Internet. Alternatively, with the information from local news or signals from the utility, the customer can implement the peak reduction strategy.

The controller can run peak reduction control algorithms triggered by a signal from utility or customer (Figure A6-1).

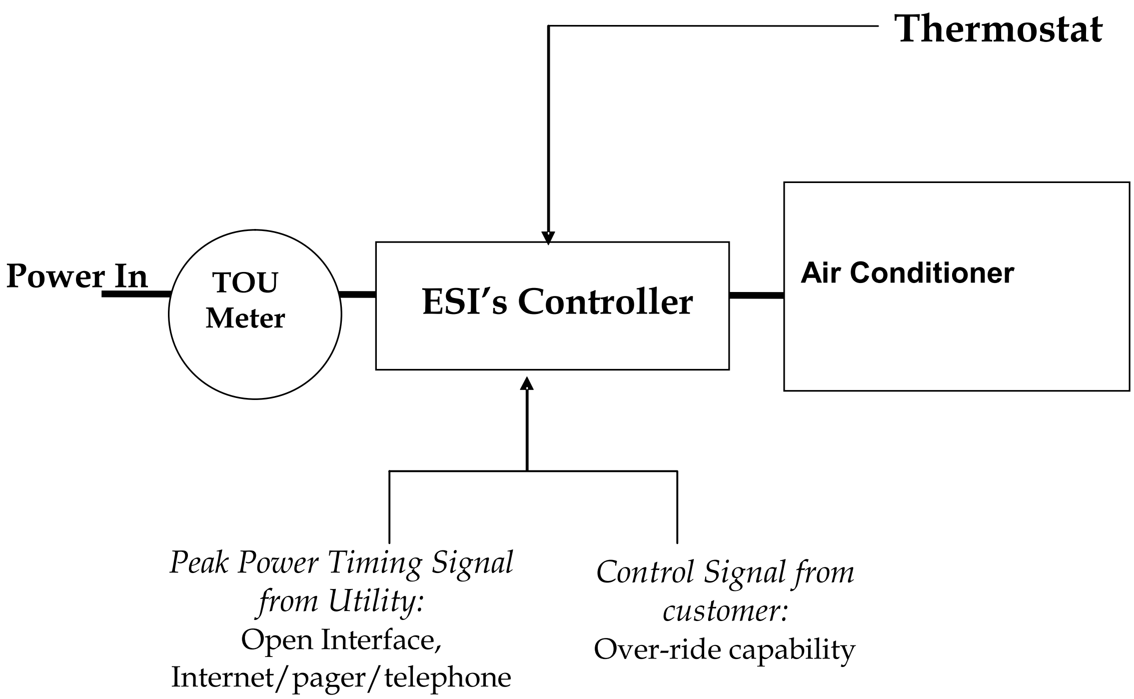

Figure A6-1: Peak Reduction Control Algorithms Triggered by a Signal from Utility or Customer

References

1. T.A. Reddy and D.E. Claridge, “Effect of Air Conditioner Oversizing and Control on Electric Peak Loads in a Residence”, Energy, Vol.16, p.1139-1152, 1993.