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The Effects of Variable Frequency Driven Evaporator Motors in Refrigerated Warehousing Blast Freezer Applications

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INTERIM/FINAL PROJECT REPORT

THE EFFECTS OF VARIABLE FREQUENCY DRIVEN EVAPORATOR MOTORS IN REFRIGERATED WAREHOUSING BLAST FREEZER APPLICATIONS

Prepared for: California Energy Commission

Prepared by: United States Cold Storage, Incorporated

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PREFACE

The California Energy Commission 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 conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Buildings End-Use Energy Efficiency
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- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

The Effects of Variable Frequency Driven Evaporator Motors in Refrigerated Warehousing Blast Freezer Applications is the final report for the Blast Freezer Fan Modulation Technology for Energy Efficient Refrigerated Warehouses project subcontract number MR‐07‐05A, conducted by the California Institute for Energy Efficiency. The information from this project contributes to PIER's Industrial/Agricultural/Water End-Use Energy Efficiency Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

ABSTRACT

The project objective was to implement evaporator fan speed modulation through the use of variable frequency drives and a new computerized control algorithm specifically designed for blast freezer control. An expected 55% to 65% reduction in blast freezer fan horsepower was expected resulting in an overall savings of approximately 35% to 45% in blast freezer combined fan and compressor electrical savings. The report discusses project approach to identify, select and install the variable frequency drive equipment, computer hardware and instrumentation, control software, and the development of a test apparatus to accurately measure product temperatures at various locations within the pallet of a blast freezer. The baseline and comparative blast freezing trials evaluated the relative product cooling performance of various fan speeds during different phases of product freezing in a blast freezing process. Cooling efficacy during the tests was measured by recording core product temperature at 12 different locations in a pallet layer of ground beef.

Different combinations of fan speeds were compared to the baseline cooling performance. The fan constant speed set point used for the baseline was 100%. Tests were conducted based on 40 hour total blast cycle run times. The fan speed modulation tests were conducted by reducing the fan speeds at predetermined time intervals. The fan speed modifications achieve 71% fan energy savings and a combined fan and compressor energy savings of 39% for a 40 hour blast test. Shortening the blast cycle time to achieve a -10° F final product core temperature would result in fan energy savings of 77% and an overall refrigeration energy savings of 48%.

The immediate benefit to California as a result of the project has been an average reduction of 1,621 kWh per blast freezing test trial or the equivalent energy to power 1,600 homes in California. The study results will strengthen efforts to promote the continued development of variable speed modulation technology to increase energy efficiency standards of batch style blast freezing cells typically found in the public refrigerated warehousing industry.

Keywords: Variable frequency drives (VFD), blast freezing, refrigerated warehousing, fan speed modulation, fan energy savings, industrial refrigeration system.

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EXECUTIVE SUMMARY

Introduction

This project outlined the development of the methodology to utilize variable frequency drives and upgraded computerized refrigeration control methods to modulate the blast freezing fan speed with product temperature. The product testing and installation of the variable frequency drives (VFD), instrumentation, control software and hardware for the Energy Commission research project was conducted at the United States Cold Storage (USCS) facility in Fresno, CA. The new methodology was expected to reduce the energy consumption by 35 percent.

Air Blast Freezing is a process by which a product's heat is removed in a relatively short period of time. The required freezing time is a function of the product's weight, shape, water content, and packaging. Typical blast freezing operations require product core temperatures to reach a specified temperature within 24 to 48 hours. Virtually all of the public refrigerated warehouses in California us air-coil evaporators for space refrigeration and air blast freezing.

The type of blast freezer used at the USCS Fresno, CA facility is the batch air blast freezing cell which is more common in the public refrigerated warehousing industry. The batch blast freezer is more flexible and is used when a variety of products need to be frozen, often at the same time, on individual pallets. Batch blast freezers provide a lower initial capital cost, tend to be similar in design and operation, and typically are less efficient on a kWh per 100 pounds of product (CWT) basis.

The refrigeration system must remove the fan heat load together with the product heat load. For products requiring several hours to reach the desired core temperature, the fan heat load eventually exceeds the heat released from the product and, therefore, requires continuous operation of the fan and ancillary refrigeration equipment.

Through the use of variable frequency drives, evaporator fan speed will modulate as the product core temperature lowers. As fan speed slows, electricity consumption by the fans will be reduced and the heat generated by the fan motors will decrease resulting in electricity savings. Fan Affinity Laws dictate a cubic relationship between fan horsepower requirement and fan. This results in the potential for a cubic reduction of input power (i.e. electricity).

Project Objectives

The project objective was to implement evaporator fan speed modulation through the use of variable frequency drives and a new computerized control algorithm specifically designed for blast freezer control. An expected 55% to 65% reduction in blast freezer fan horsepower was expected resulting in an overall savings of approximately 35% to 45% in blast freezer combined fan and compressor electrical savings. Using power consumption based upon 5,000 hour per year the electrical savings potential is 8 MW to 16 MW of electricity. 1 MW of electricity can power approximately 1,000 California homes. The savings associated with this project has a tremendous potential equivalent to the electricity needed to power 8,000-16,000 California homes.

The specific technical objectives for the project were to:

- Develop a complete mechanical and electrical scope of work for the design and installation of VFD's, instrumentation and control software development

- Identify, procure and install electrical and mechanical hardware, and develop control and monitoring software.

- Demonstrate the successful commission and start up of the electrical and mechanical hardware system and control and monitoring software by operating the blast freezer and controlling the fan speed profile based upon hours of run-time.

- Develop a methodology to use variable frequency drives and new computerized refrigeration control algorithms to modulate blast freezing fan speed with product temperature.
- Conduct baseline blast trials to establish fan speed schedules and develop measurement and verification protocols for comparative trials using the results of baseline trials.

- Perform comparative trials with blasts cells equipped with variable and fixed speed drives and collect performance and power consumption monitoring data

- Analyze the results of the comparative measurement and verification trials and compare the performance and energy consumption of the variable speed operation with fixed speed operation of similar loads.

- Verify that a 55% to 65% blast freezer fan horsepower reduction and an overall electrical savings of 35% to 45% were achieved.

Project Approach

The first project task was to identify, select and install the variable frequency drive equipment, computer hardware and instrumentation, control software, and development of a test apparatus to accurately measure product temperatures at various locations within the pallet of a blast freezer. The electrical and mechanical scope of work was broken down into two main categories; M&M Refrigeration supplied hardware, software, and an overview of Cascade Energy Engineering's services that were rendered during the testing process.

The second component of this task was to demonstrate the successful commission and start up of the electrical and mechanical hardware, system control and monitoring software by starting the blast freezer and controlling the fan speed using the fan speed profile based upon hours of run time. The commissioning and start up review of the installed electrical and mechanical scope of work was broken down into two main categories; M&M Refrigeration Electrical and Mechanical System Commissioning and M&M Refrigeration Software Commissioning and Verification.

Test Methodology Overview

A test methodology was developed in order to gain an understanding of the affect of modulating blast freezer evaporator fan speed on blast freezer performance. This consisted of measuring product temperature versus time in several blast freezing cycles. The goal of the first phase of testing was to determine baseline performance with the evaporator fans operating at a constant speed. Once a baseline performance was established, subsequent testing would be performed utilizing variable fan speeds.

The general theory for blast freezer fan speed modulation was that at the onset of a blast freezing cycle, cooling of the product is primarily a function of convective heat transfer. A decrease in air velocity around the product creates a proportional decrease in heat transfer. As the outer shell of the product approaches freezer air temperature, it is theorized that cooling of the product becomes much more influenced by conductive heat transfer and less influenced by convective heat transfer. Here, a decrease in air velocity around the product creates a smaller decrease in heat transfer relative to the early stages of the blast freezing cycle.

Project Outcomes

The baseline and comparative blast freezing trials evaluated the relative product cooling performance of various fan speeds during different phases of product freezing in a blast freezing process. Cooling efficacy during the tests was measured by recording core product temperature at 12 different locations in a pallet layer of ground beef. Different combinations of fan speeds were compared to the baseline cooling performance. The fan constant speed set point used for the baseline is 100%. Four blast cycle test runs were performed at this speed. For the fan speed reduction tests, fan speed was reduced after a predetermined time delay. The temperature profiles from the product core temperature readings were then compared between the tests to determine their relative product cooling performance.

Blast Freezing Test Summary

A summary of the tests conducted is presented in Table 1 below. The typical baseline blast cycle runtime for Fresno was 40 hours. All tests conducted were based on a 40 hour total blast cycle run time. The fan speed modulation tests were conducted by reducing the fan speed after a predetermined time interval. For example, in the 92/50% fan modulation test, the fans were run at 92% speed for the first 22 hours of the blast cycle, and then run at 50% speed for the remaining 20 hours of the blast cycle. Similarly, the 92/70/50% fan modulation tests were run at 92% fan speed for the first two hours, 70% speed for the next 20 hours and 50% for the remaining 18 hours.

Table 1: Summary of Test Trials

Test Summary	Number of Test Runs	Hours at Initial Speed	Hours at Second Speed	Hours at Third Speed
100% Baseline	*4*	*40*	*-*	*-*
92% Modulation	*4*	*40*	*-*	*-*
92/50% Modulation	*3*	*22*	*18*	*-*

92/70/50% Modulation	*3*	*2*	*20*	*18*
92/50/30% Modulation	*3*	*2*	*10*	*28*

Analysis of Results

The project demonstrated the successful implementation of evaporator fan speed modulation using computerized control. The fan modulation tests clearly documented the opportunity for reduction in fan speed without decreased cooling performance. The most effective fan speed control algorithm performed in the ground beef testing was a combination of 92%, 70% and 50% fan speeds. The fans were set to 92% speed for the first two hours, 70% speed for the next 20 hours, and 50% speed for the remaining 18 hours of the 40 hour total blast cycle. This approach shows significant energy savings over the baseline case. A second finding regarding additional energy savings potential associated with shortening blast cycle run time is presented in the next section.

Energy Savings Summary

The actual savings achieved during the tests varied slightly based on the variables discussed above, including incoming product temperature, blast cycle defrost frequency and overall blast cycle run time. A summary of the energy savings from the three 92/70/50% runs is shown in Tables 2 and 3 below.

Table 2: 40 Hour Blast Savings Summary

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	*55%*	*35%*
Actual Savings	*72%*	*39%*

Table 3: Energy Savings per Blast Cycle

Typical Energy Savings Per Blast Cycle		
Fan Energy Savings (kWh)	Compressor Energy Savings (kWh)	Total Energy Savings (kWh)
1,150	471	1,621

The energy savings for reduced blast cell durations were calculated in a similar manner, with additional savings for the reduced fan speed run time and reduced product cooling load as seen in the Table 4 and Table 5 summaries below. Estimates for product cooling load reduction were based on averages observed during the tests. These estimates make assumptions to standardize the product cooling load reduction between blast tests. Actual product cooling load savings would vary based on annual product types and volumes.

Table 4: Reduced Blast Duration Savings Summary

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	*55%*	*35%*
Actual Savings	*77%*	*48%*

Table 5: Energy Savings with Reduced Blast Duration

Typical Energy Savings Per Blast Cycle		
Fan Energy Savings (kWh)	Compressor Energy Savings (kWh)	Total Energy Savings (kWh)
1,297	764	1,998

Conclusions

I. Fan Modulation

The testing clearly showed the potential for fan speed reduction without compromising cooling performance. There were two separate thresholds for fan speed reduction depending on the stage of cooling. In the freezing stage of cooling, 70% was the minimum observed fan speed without compromising cooling performance. In the post freezing stage of cooling, 50% was the minimum observed fan speed without compromising cooling performance. The fan energy savings and total energy savings as a result of the optimal fan speed configuration yielded the following results:

- 72% fan energy savings or 1,150 kWh per blast session
- 39% total energy savings or 1,621 kWh per blast session

II. Reduced Blast Cycle Run Time

An additional result of the testing was the observation that the current final product core temperature is lower than it needs to be. Product is currently being pulled down as low as -50 F in the measured test product. It is expected that a -10° F final product core temperature would be satisfactory to account for all product positions that may experience less heat transfer during the blast freezing process. At the test product position within the blast cell, this temperature could be achieved with an average blast time of 25 hours, 15 hours less than the current blast cycle time. Shortening the blast cycle time would result in fan energy savings and refrigeration energy savings from the reduced fan and product load. The fan energy savings and total energy savings as a result of the optimal fan speed configuration to achieve a -10° F final product core temperature yielded the following results:

- 77% fan energy savings or 1,297 kWh per blast session
- 48% total energy savings or 1,998 kWh per blast session

Recommendations

In order to achieve the maximum energy savings possible, consideration must be given to actual facility operating constraints, including blast cycle loading protocol, schedules, and variations in blast cycle product types and volumes. Due to the diversity of use of the blast freezers, it may be worth exploring a fan modulation control algorithm that is based on actual operating conditions rather than simple time delays. The time delays chosen for this study were based on the worst case scenarios observed in order to ensure that the fan speed was not prematurely lowered before freezing was achieved. A method of feedback control would optimize energy savings and cooling performance. If the average time that it takes before the fan speed is reduced could be lowered to 17 hours, then the energy savings would increase to the numbers shown in Table 6 and Table 7 below.

Table 6: 40 Hour Blast Cycle Energy Comparison for Alternate Control Strategies

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	55%	35%
Time Delay Control	72%	39%
Feedback Control	75%	41%

Table 7: Reduced Blast Cycle Energy Comparison for Alternate Control Strategies

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	55%	35%
Time Delay Control	77%	41%
Feedback Control	80%	50%

Benefit to California

The immediate benefit to California as a result of the project has been an average reduction of 1,621 kWh per blast trial as a product from the implementation of evaporator fan speed modulation through the use of variable frequency drives for blast freezer temperature control. Using power consumption statistics based upon 5,000 hour per year (125 blast freezing runs), the actual electrical savings potential would be equal to 202 MW of electricity. 1 MW of electricity can power approximately 1,000 California homes. The savings associated with this project has a tremendous potential equivalent to the electricity needed to power 202,000 California homes, which was greater than originally anticipated.

The study results will prove useful for the California Energy Commission in their efforts to promote the continued development of variable speed modulation technology to increase energy efficiency standards of batch style blast freezing cells typically found in the public refrigerated warehousing industry.

CHAPTER 1: INTRODUCTION

Overview

This project outlined the development of the methodology to utilize variable frequency drives and upgraded computerized refrigeration control methods to modulate the blast freezing fan speed with product temperature. The product testing and installation of the variable frequency drives (VFD), instrumentation, control software and hardware for the Energy Commission research project was conducted at the United States Cold Storage (USCS) facility in Fresno, CA. The new methodology was expected to reduce the energy consumption by 35 percent.

Air Blast Freezing is a process by which a product's heat is removed in a relatively short period of time. The required freezing time is a function of the product's weight, shape, water content, and packaging. Typical blast freezing operations require product core temperatures to reach a specified temperature within 24 to 48 hours. Virtually all of the public refrigerated warehouses in California us air-coil evaporators for space refrigeration and air blast freezing.

Evaporators are cooling coils that provide the "cold air" in a refrigerated warehouse. Each evaporator typically utilizes several small fan motors, ranging in size from 1/3 horsepower upwards to 15 horsepower or larger, that promote heat transfer between the refrigerant and the air. Since these motors operate in a cold environment, they are often sized to operate well into their service factor. These motors not only use electricity, but also generate heat that must be removed from the space. Although the individual motors are small by industrial standards, in composite to the refrigeration system, they are large consumers of electricity and excellent candidates for energy efficiency. During the blast freezing process, evaporator fans operate at full speed during a specified period of time (typically 24 to 48 hours). Although the product core temperature is reduced during this period, evaporator fans continue to operate at full speed until turned off.

Through the use of variable frequency drives, evaporator fan speed will modulate as the product core temperature lowers. As fan speed slows, electricity consumption by the fans will be reduced and the heat generated by the fan motors will decrease resulting in electricity savings. Fan Affinity Laws dictate a cubic relationship between fan horsepower requirement and fan. This results in the potential for a cubic reduction of input power (i.e. electricity).

Technology Background

There are two types of air blast freezing utilized by public refrigerated warehouses; continuous blast freezers and batch blast freezers.

In the continuous blast freezer the product is carried through on trays or a conveyor; this method is most suited to mass production of standard packs with similar freezing characteristics typically performed by a spiral type blast freezer design. When trays are used they typically remain stationary except when a fresh tray is pushed into the end of the tunnel, thus moving the others along to release a finished one at the other end. This type of continuous blast freezer is called a vertical retention time blast freezer and offers flexibility in freezing times of products that have different freezing characteristics.

The second type of blast freezer is the batch air blast freezing cell which is more common in the public refrigerated warehousing industry. The batch blast freezer is more flexible and is used when a variety of products need to be frozen, often at the same time, on individual pallets.

Batch blast freezers provide a lower initial capital cost, tend to be similar in design and operation, and typically are less efficient on a kWh per 100 pounds of product (CWT) basis.

Air has a low heat capacity, and still air is a poor conductor of heat so that a fairly high air velocity is necessary. The air velocity across the product and the air temperature determine the rate of heat transfer from the surface of the product to the air. However, high air speeds require powerful fans, which generate heat that must also be removed.

The time it takes to cool or freeze a product to the desired temperature depends also on the weight, shape, water content, packaging and method of freezing. Once the product surface or packaging is frozen, the surface acts as insulation and slows down the heat transfer from the warmer core to the colder surface. At the end of the blast freezing cycle, the product surface temperature has to be lower than the desired product core temperature. In batch type blast freezers, the product heat load usually drops rapidly in the beginning of the freezing process then levels off.

The refrigeration system must remove the fan heat load together with the product heat load. For products requiring several hours to reach the desired core temperature, the fan heat load eventually exceeds the heat released from the product and, therefore, requires continuous operation of the fan and ancillary refrigeration equipment.

The project utilized variable frequency drives and upgraded computerized refrigeration controls to modulate fan speed. Research and blast freezing test trials established a time-based fan speed schedule for 50 pound boxes of ground beef. Alternate fan speed schedules can be generated for various types of products. Products may include poultry, meat, fish and produce.

The user will be able to set each blast cell to run for a programmable period of time based upon a pre-determined fan speed schedule. Each blast cell can either be started manually or set to start at a programmed time of day in order to take advantage of off-peak electricity costs.

The blast freezer control will support a custom feature that will stage blast cells start times using a programmable delay. This feature will help avoid multiple blast cells from starting simultaneously and creating a kilowatt (kW) demand spike.

Project Objectives

The project objective was to implement evaporator fan speed modulation through the use of variable frequency drives and a new computerized control algorithm specifically designed for blast freezer control. An expected 55% to 65% reduction in blast freezer fan horsepower was expected resulting in an overall savings of approximately 35% to 45% in blast freezer combined fan and compressor electrical savings. Using power consumption based upon 5,000 hour per year the electrical savings potential is 8 MW to 16 MW of electricity. 1 MW of electricity can power approximately 1,000 California homes. The savings associated with this project has a tremendous potential equivalent to the electricity needed to power 8,000-16,000 California homes.

The specific technical objectives for the project were to:

- Develop a complete mechanical and electrical scope of work for the design and installation of VFD's, instrumentation and control software development
- Identify, procure and install electrical and mechanical hardware, and develop control and monitoring software.

- Demonstrate the successful commission and start up of the electrical and mechanical hardware system and control and monitoring software by operating the blast freezer and controlling the fan speed profile based upon hours of run-time.

- Develop a methodology to use variable frequency drives and new computerized refrigeration control algorithms to modulate blast freezing fan speed with product temperature.

- Conduct baseline blast trials to establish fan speed schedules and develop measurement and verification protocols for comparative trials using the results of baseline trials.

- Perform comparative trials with blasts cells equipped with variable and fixed speed drives and collect performance and power consumption monitoring data

- Analyze the results of the comparative measurement and verification trials and compare the performance and energy consumption of the variable speed operation with fixed speed operation of similar loads.

- Verify that a 55% to 65% blast freezer fan horsepower reduction and an overall electrical savings of 35% to 45% were achieved.

Report Organization

This report presents the findings and recommendations that have resulted from investigating the feasibility of utilizing variable speed drives to modulate fan speed for blast freezer control. The report is organized as follows:

Chapter 1.0 Introduction

Chapter 2.0 Project Approach

Chapter 3.0 Project Outcomes

Chapter 4.0 Analysis of Results

Chapter 5.0 Conclusions

Chapter 6.0 Recommendations

Chapter 7.0 Public Benefits to California

Four appendices contain a summary of the USCS Blast Freezing Test Procedure (Appendix A), Fan Modulation Analysis (Appendix B), Refrigeration System Analysis (Appendix C), and Alternate Control Algorithms (Appendix D)

Attachment I contains the individual blast tests results.

CHAPTER 2: PROJECT APPROACH

USCS Fresno, CA Testing Facility

The Fresno facility is equipped with five blast freezer cells. Each cell has the capacity to hold forty-eight standard forklift pallet loads of product at a given time. Each cell is equipped with one door that accesses four levels of racking that can hold two rows of six pallets, as shown in Figure 1.

Each cell is equipped with one CO_2 refrigerant evaporator coil equipped with four (4) 15 hp evaporator fan motors controlled by a variable frequency drive (VFD). The coils are located above the cells and circulate air in a clockwise direction throughout the cell. Each blast cell typically operates between -45°F to -55°F. The cells are currently operated with the fans set at a constant 92% of full speed.

A two-stage Cascade CO_2/Ammonia refrigeration system serves the facility. The system consists of two (2) CO_2 booster compressor suction groups and one ammonia high stage compressor suction group. One (1) CO_2 booster suction is dedicated to the five blast cells. The suction pressure is controlled to maintain 84 psig (equivalent to a -58 °F saturated CO_2 temperature).

An array of product is handled in the blast freezers including beef, poultry, and fruit. Meat product is typically contained in cardboard boxes and fruit product is typically contained in 5 gallon buckets or 55 gallon drums. Note that black slip sheets, commonly known as "spacers", have been placed between each layer of boxes. The slip sheets are have an egg crate style design that provide spacing between the boxes to accommodate air flow and increase heat transfer rate in the blast freezer. Some pallet loads are equipped with slip sheets, others are not. In Figure 1 for example, the two pallets on the right side of the cell have slip sheets while the two pallets on the left do not.

Figure 1: Front View of a Blast Cell

Electrical and Mechanical Scope of Work

The first project task was to identify, select and install the variable frequency drive equipment, computer hardware and instrumentation, control software, and development of a test apparatus to accurately measure product temperatures at various locations within the pallet of a blast freezer. The electrical and mechanical scope of work was broken down into two main categories; M&M Refrigeration supplied hardware, software, and an overview of Cascade Energy Engineering's services that were rendered during the testing process.

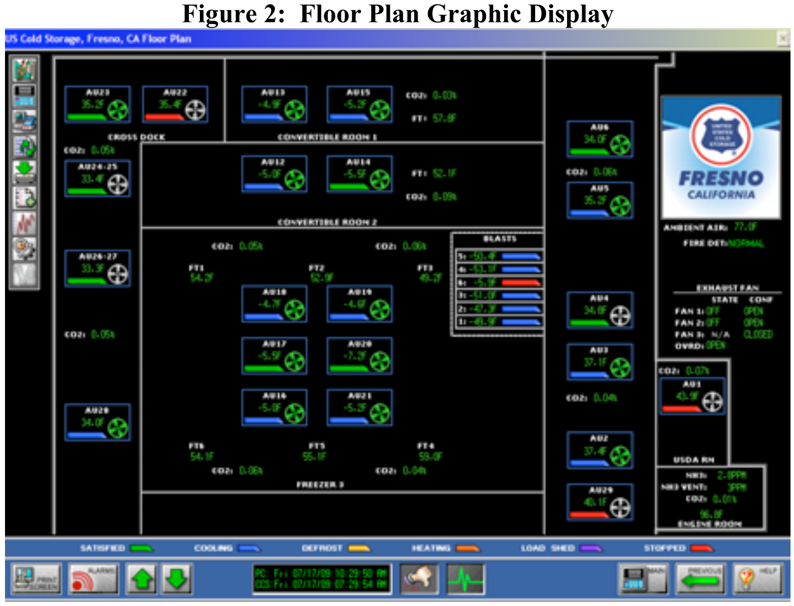
The second component of this task was to demonstrate the successful commission and start up of the electrical and mechanical hardware, system control and monitoring software by starting the blast freezer and controlling the fan speed using the fan speed profile based upon hours of run time. The commissioning and start up review of the installed electrical and mechanical scope of work was broken down into two main categories; M&M Refrigeration Electrical and Mechanical System Commissioning and M&M Refrigeration Software Commissioning and Verification. These scopes of work will be discussed in detail in the subsequent sections.

M&M Refrigeration Electrical & Mechanical System Commissioning

Variable Frequency Drives and Equipment

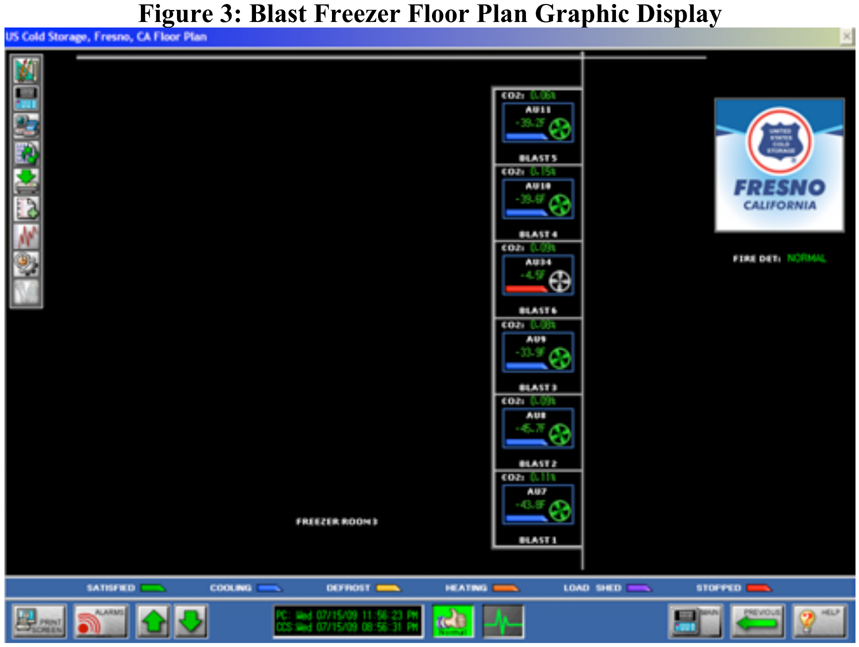
The installed Benshaw Variable Frequency Drives are rated for a 40 HP variable torque load to handle the four (4) fans per blast cell evaporator. All VFD's were equipped with Line Reactors before the VFD and Output Reactors after the VFD. All fan motors were equipped with fan overloads. The motor control center were installed with contactors for the four (4) stages of electric defrost heaters, fan bypass, VFD isolation, as well as start and run relays. Figure 2 below is a screen shot of the M&M PC Monitor™ control program which indicates the status of blast cell fans from a combination of visual graphics and analog instrumentation data.

Figure 2: Floor Plan Graphic Display



From this main floor plan graphic display screen, the user can click on portion of the area identified as "Blasts" and it will direct the user to a more detailed floor plan of only the blast freezer area as seen in Figure 3 below. The evaporator status is indicated by the color; blue indicating cooling mode, red indicating stop mode, and yellow indicating pump out or defrost modes. Additional detail such as the fan status can be viewed here.

Figure 3: Blast Freezer Floor Plan Graphic Display

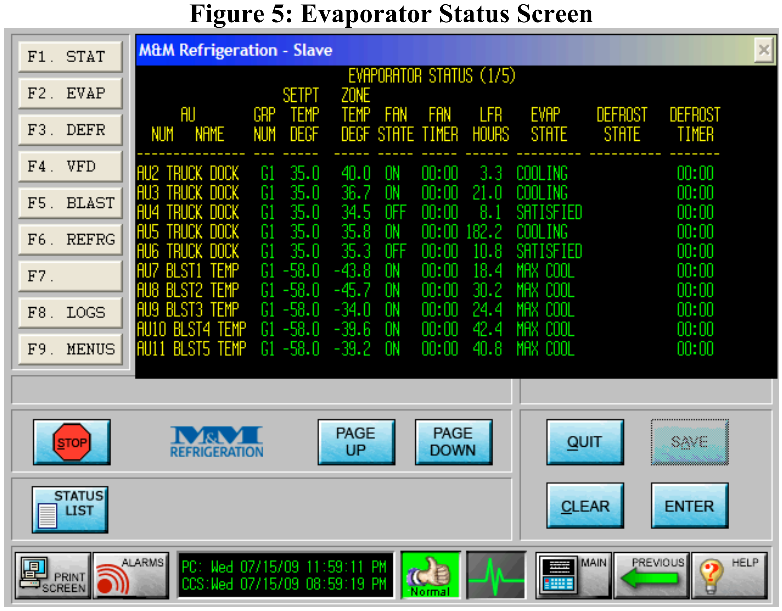


From the detailed blast freezer floor plan screen, the user can click on any blast evaporator and it will direct the user graphic version of the evaporator status as seen in Figure 4 below. The green illuminated and rotating fan display graphic indicates that all fans are running for that corresponding evaporator. The “MAX COOL” and “STOP” terms directly above the graphic display indicate the current status of the evaporator. Also displayed are the installed supply and return air temperatures, product probe temperatures, and VFD fan speeds for each air unit.

Figure 4: Blast Freezer Floor Plan

The user can view the same evaporator status information in a text only format by either clicking on any of the blast air units or by access from the master panel and evaporator status as seen in Figure 5 below. Additional information such as group, zone, and temperature set points, fan and defrost timers, and defrost state can be viewed here.

Figure 5: Evaporator Status Screen



Through the use of the M&M PC Monitor™ control program and visual confirmation, the Benshaw variable frequency drives, associated hardware, and control wiring for the blast cells evaporators have been successfully installed and demonstrated. The next section will detail the installation of the M&M hardware and instrumentation that provided the successful graphics display and operation of the blast freezer evaporators. It will also detail the installation of the customized blast freezer control options and system logging functions.

Computer Hardware and Instrumentation

In the Electrical and Mechanical Scope of Work report, it was identified that M&M Refrigeration was to supply and install all temperature probes and discrete input/output relays for the Fresno blast cell evaporators AU7-AU11 as identified in the tables below. In addition, screen shots of the Fresno M&M PC Monitor™ program will show the successfully installed input/output (I/O) components and their locations within the control system.

The installed analog fan outputs to the M&M for the blast freezer fans are shown in the slave panel diagnostics function shown in Figure 6 below. The screen indicates the value of the fan speed and the corresponding hexadecimal output value from the measurement device. In the example below, all five blast freezers are operating in a manual mode at 92 percent VFD fan speed.

Table 8: Specified Slave Panel Analog Outputs

SLAVE PANEL - ANALOG OUTPUTS					
OUTPUT TYPE	OFFSET	CHAN	NAME	RANGE	CONTROL DESCRIPTION
4-20 mA	0	1	AU7 BLAST 1 FAN	0-100 PCT	PID - Increase above - Profile
4-20 mA	1	2	AU8 BLAST 2 FAN	0-100 PCT	PID - Increase above - Profile
4-20 mA	2	3	AU9 BLAST 3 FAN	0-100 PCT	PID - Increase above - Profile
4-20 mA	3	4	AU10 BLAST 4 FAN	0-100 PCT	PID - Increase above - Profile
4-20 mA	4	5	AU11 BLAST 5 FAN	0-100 PCT	PID - Increase above - Profile

Figure 6: Installed Slave Panel Analog Outputs

The installed analog inputs to the M&M control system are located on the main board and expansion board 1 in order to accommodate all inputs needed for the blast freezer equipment and existing equipment identified in Figure 7 and Figure 8 below. In particular, the screen shot of Figure 6 indicates the degrees Fahrenheit value of the return air and product probe temperatures and their corresponding hexadecimal output values.

Table 9: Specified Slave Panel Analog Outputs - Main Board

SLAVE PANEL ANALOG INPUTS - Main Board						
ANALOG INPUTS	OFFSET	CHAN	NAME	RANGE	UNITS	SENSOR TYPE
RM TEMP	6	7	AU7 BLAST 1 RET TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	7	8	AU8 BLAST 2 RET TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	8	9	AU9 BLAST 3 RET TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	9	10	AU10 BLAST 4 RET TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	10	11	AU11 BLAST 5 RET TEMP	-58:122	DEGF	4 - 20 mA
PROD TEMP	11	12	BLAST 1 PROD PROBE	-58:122	DEGF	4 - 20 mA
PROD TEMP	12	13	BLAST 2 PROD PROBE	-58:122	DEGF	4 - 20 mA
PROD TEMP	13	14	BLAST 3 PROD PROBE	-58:122	DEGF	4 - 20 mA
PROD TEMP	14	15	BLAST 4 PROD PROBE	-58:122	DEGF	4 - 20 mA
PROD TEMP	15	16	BLAST 5 PROD PROBE	-58:122	DEGF	4 - 20 mA

Figure 7: Installed Slave Panel Main Board Analog Inputs

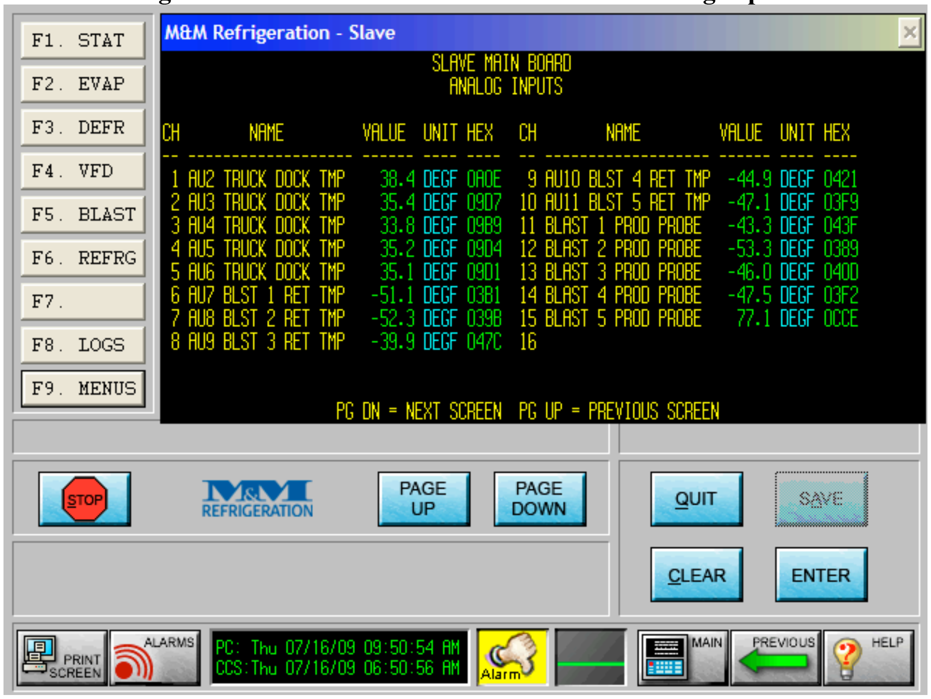


Figure 8 displays the installed analog inputs of expansion board 1 of the M&M slave panel. Expansion board 1 contains the analog outputs for the blast freezer supply temperatures displayed in degrees Fahrenheit in addition to the corresponding hexadecimal sensor output values.

Table 10: Specified Slave Panel Analog Inputs - Expansion Board 1

SLAVE PANEL ANALOG INPUTS - Expansion Board 1						
ANALOG INPUTS	OFFSET	CHAN	NAME	RANGE	UNITS	SENSOR TYPE
RM TEMP	NA	8	AU7 BLAST 1 SUP TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	NA	9	AU8 BLAST 2 SUP TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	NA	10	AU9 BLAST 3 SUP TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	NA	11	AU10 BLAST 4 SUP TEMP	-58:122	DEGF	4 - 20 mA
RM TEMP	NA	12	AU11 BLAST 5 SUP TEMP	-58:122	DEGF	4 - 20 mA

Figure 8: Installed Slave Panel Expansion Board 1 Analog Inputs

The installed discrete I/O inputs for the VFD faults are shown in slave panel I/O racks 1B and 2B shown in Figure 9 and Figure 10. The screens indicate the state of the fan as either ON or OFF and state of the VFD fault as either NORM or FAIL. Within this screen, the contactor positions are also identified as IN or OUT for the corresponding fan and VFD contacts.

Table 11: Specified Slave Panel Discrete I/O Inputs Racks 1 A/B

SLAVE PANEL - Discrete I/O Racks 1 A/B							
TYPE	HOA	OFFST	CHAN	DESCRIPTION	OFF STATE	ON STATE	NOTES
INPUT	X	23	24	AU7 VFD FAULT	ALARM	NORM	1,2
INPUT	X	29	30	AU8 VFD FAULT	ALARM	NORM	1,2

Notes:

1 – Normally closed contact with no power or level

2 – Failure when open

Figure 9: Installed Slave Panel Discrete I/O Rack 1B

The installed discrete I/O inputs for the VFD faults are continued in slave panel I/O rack 2B shown in Figure 10. This screen displays the continuation of the I/O inputs to identify the state of the fans and VFD's for the corresponding evaporators in addition to the added fan overloads.

Table 12: Specified Slave Panel Discrete I/O Racks 2 A/B

SLAVE PANEL - Discrete I/O Racks 2 A/B							
TYPE	HOA	OFFST	CHAN	DESCRIPTION	OFF STATE	ON STATE	NOTES
INPUT	X	37	6	AU9 VFD FAULT	ALARM	NORM	1,2
INPUT	X	43	12	AU10 VFD FAULT	ALARM	NORM	1,2
INPUT	X	49	18	AU11 VFD FAULT	ALARM	NORM	1,2

Notes:

1 – Normally closed contact with no power or level

2 – Failure when open

Figure 10: Installed Slave Panel Discrete I/O Rack 2B

M&M Refrigeration Software Commissioning and Verification

The M&M Refrigeration, Inc. PC Monitor ™ control program maintains the Fresno blast freezer VFD fan controls through the utilization of product probes, fan speed profiles, custom recipe acquisition functions, and system logging functions.

After modifications to the M&M PC Monitor™ control program, the refrigeration system operator is now able to enter a schedule for fan speed based on product probe temperature (Acquisition Mode), a predetermined recipe function (Recipe Mode), or Time Mode at a manual fan speed. A detailed description of the blast freezer operating modes, functions and capabilities will be addressed.

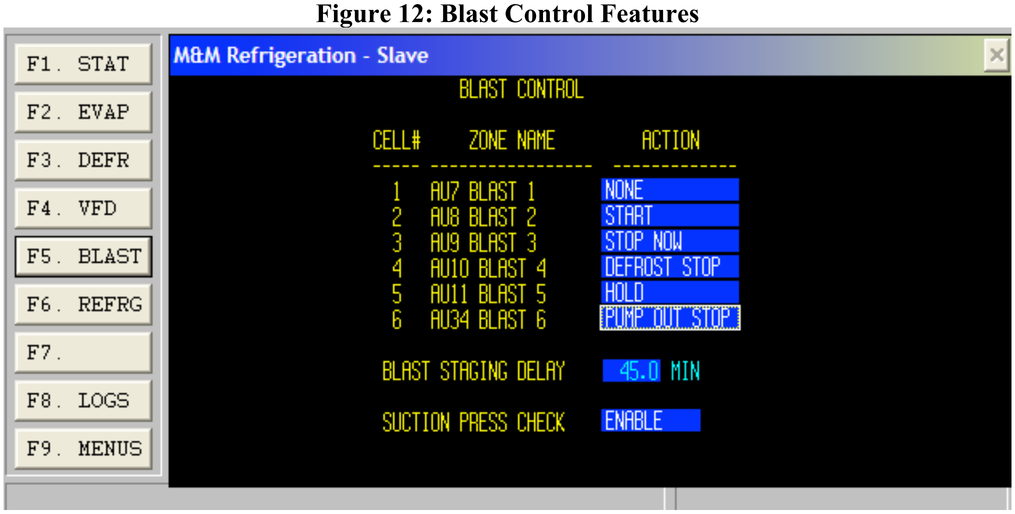
There are four main options to select in the main blast freezer program; Blast Control, Blast Setup, Fan Speed Profile and Recipe Setup as seen in Figure 11 below. Each option will be explored in detail in the upcoming sections.

Figure 11: Blast Freezer Control Screen

Blast Freezer Control

The blast control feature allows the user to force a blast cell to Start, Stop, Defrost Stop, Hold, Hold Defrost and Pump Out Stop an evaporator when desired. Figure 12 below shows a screen shot of the new blast staging delay feature which reduces the Demand kW load by allowing the cells to initiate sequentially at a predetermined time interval, currently set for 45 minute delays between blast cell starts.

Figure 12: Blast Control Features



Blast Setup

The next section of the blast control is the Blast Setup feature. This feature contains the new termination mode, timed termination speed, type of start, timed fan speed, and probe sensor options for the user to select. See Figure 13 and Figure 14 below for the installed new features.

- Termination Mode – This feature allows the user to perform blast freezing from three different methods; by using a pre-determined duration of time at a given fan speed, data acquisition from a product temperature probe, or one of ten possible Recipe functions. These functions will be explored later in the Fan Speed and Recipe functions of the blast control.

Figure 13: Termination Mode Acquisition

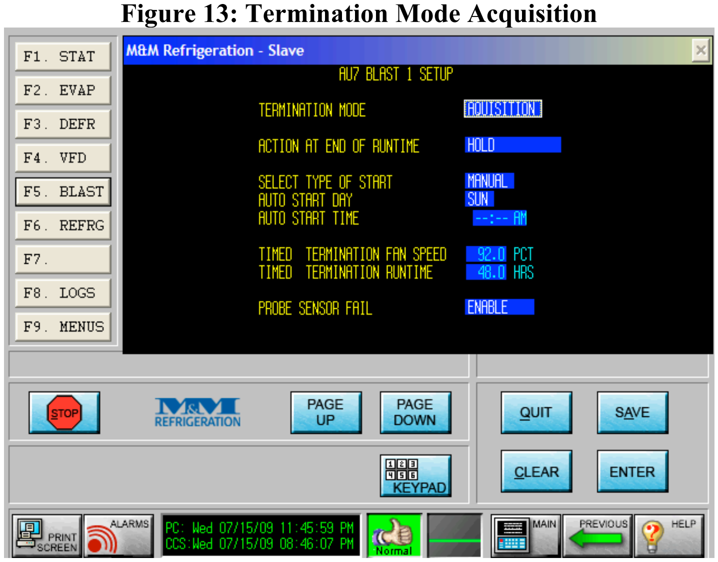
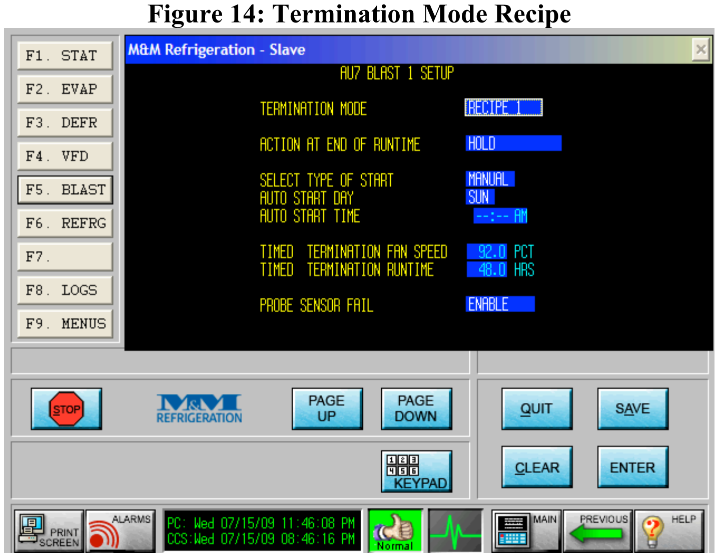


Figure 14: Termination Mode Recipe



- Select Type of Start – The feature allows a user to manually or automatically start the blast freezer. When in auto mode, the blast cell can be set to initiate by time of day. Automatic mode will also enable the use of the blast staging delay feature.

- Timed Termination Fan Speed – The feature allows the user to define the percent fan speed at the end of a blast freezing process.

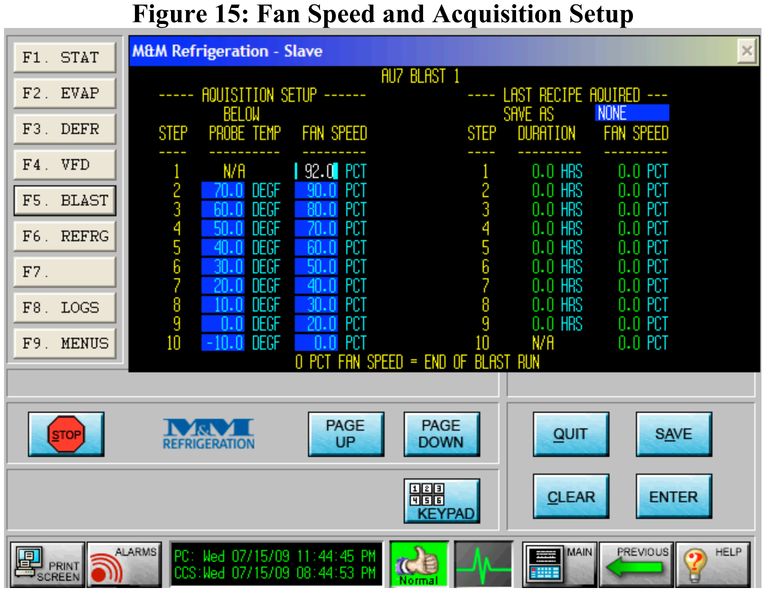
- Probe Sensor Fail – This feature will send an alert to the control system if there is a product probe sensor failure while operating in the Acquisition mode.

  Up to 10 steps will be supported to allow the fan speed to be reduced as specific temperatures are reached. Each blast cell will have an independent schedule. In acquisition mode the product probe will be used to monitor specific temperature step levels and reduce fan speed accordingly. At the end of the blast cycle the operator will be given the option to save the times it took to reach each temperature level to one of 10 recipe slots. These stored recipes can then be used in the future to perform a stepped fan schedule based on time (Recipe Mode) versus using the product probe once a baseline has been established for the product.

Fan Speed Profile

The fan speed profile option allows the user to indicate ten pre-determined fan speed percentages corresponding to product probe temperature during the blast freezing process as seen in Figure 15 below. During the blast freezing process, the fan speeds and temperature durations of each step are recorded and can be saved as a recipe function.

Figure 15: Fan Speed and Acquisition Setup

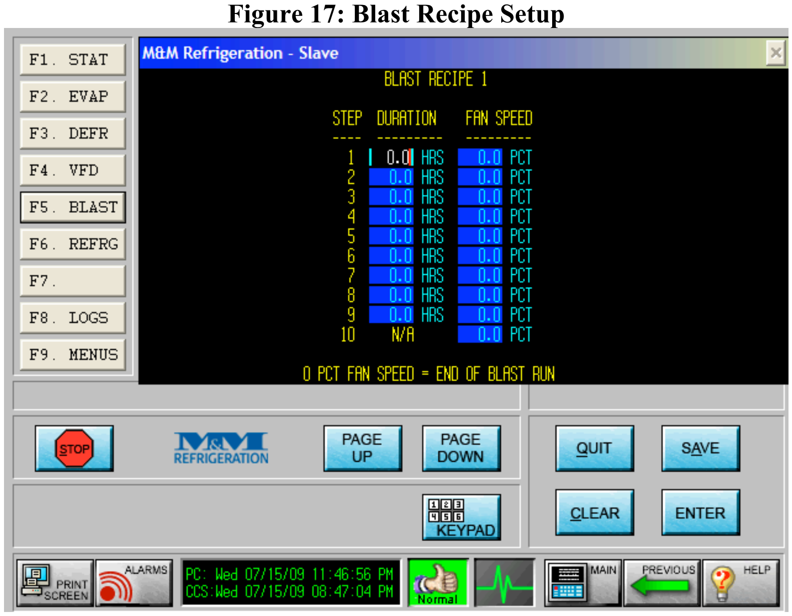


Recipe Setup

The recipe function allows a user to initiate a blast cell utilizing one of ten possible recipes functions as shown in Figure 16 and Figure 17 below. The recipes can be programmed to accept up to ten pre-determined fan speed percentages and corresponding durations for each step during the blast freezing process.

Figure 16: Recipe Number

Figure 17: Blast Recipe Setup



Variable-Speed Fan Setup

The blast cells support a product temperature probe and custom VFD fan control. The VFD fan setup screen contains the Proportional-Integral-Derivative (PID) controller parameters which dictate the operation of the VFD. The definitions for each PID parameter are identified below:

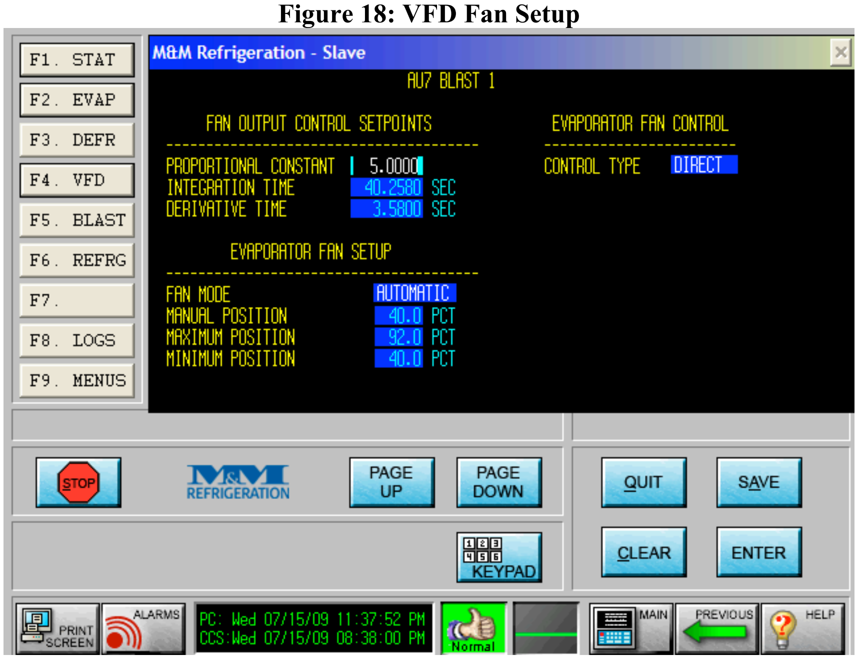
Table 13: PID Controller Parameters

TERM	DEFINITION	RANGE

PROPORTIONAL CONSTANT	Adjusts the fan speed based on how far the control parameter currently is from the control set point. A higher P term causes greater speed changes when far from the set point.	1 : 1000
INTEGRATION TIME	Adjusts the fan speed based on how rapidly the control parameter should approach the set point. A higher term causes a slower approach to set point when the control parameter is not changing.	1 : 1000
DERIVATIVE TIME	Adjusts the fan speed based on the past value of the control parameter. A large D term may cause large fluctuations in fan speed. Car must be taken to keep D as low as possible.	1 : 1000
FAN MODE	The control for the variable speed fans. Automatic lets the control system select the proper speed	1 : 1000

The VFD fan setup screen allowed the M&M programmers to setup the proportional constants, integration time, and derivative times for the VFD's installed on the blast freezer evaporator fans as seen in Figure 18 below. This feature also allows the fans to be put into an automatic, manual, or tuning mode. When operated manually, the fans will operate at a maximum user defined speed, which is currently set at 40 percent. In automatic mode, the minimum fan operation speed will remain at the user defined 40 percent fan speed with a maximum speed limited to 92 percent for increased energy efficiency.

Figure 18: VFD Fan Setup

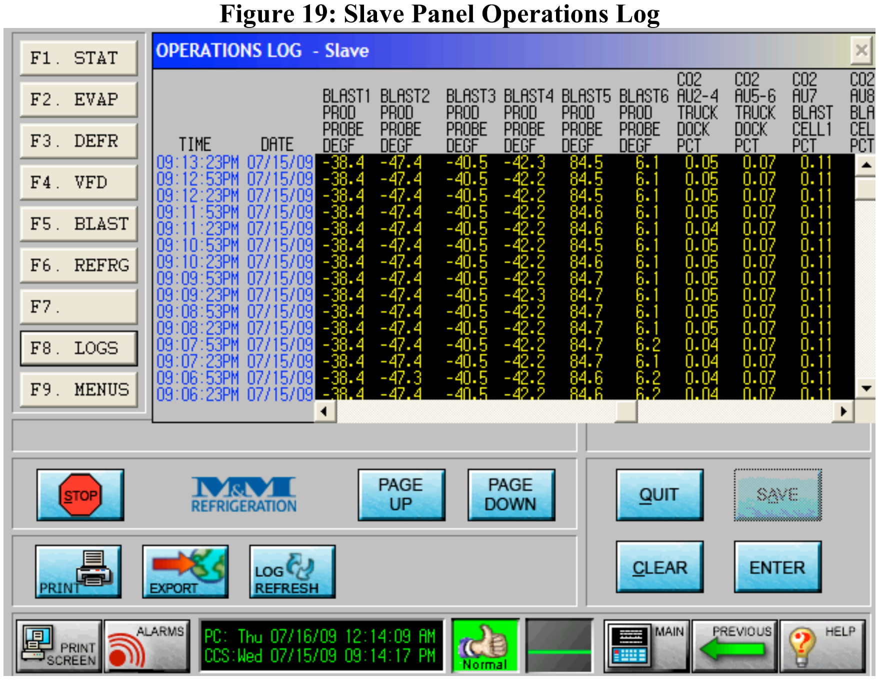


System Logging Functions

The M&M Refrigeration PC Monitor™ logging functions were modified to record the VFD fan speeds, return air temperatures, supply air temperatures, and product probe temperatures, as well as compressor energy utilization during the operation of the blast cells. The following logging functions have been modified from the standard PC Monitor™ program:

- Operations Log – The Operations Log of the slave panel displays the analog inputs/outputs of the product probe, return, and supply temperatures for the last hour at 30-second intervals. A screen shot of the slave panel operations log can be seen in Figure 19 below. Analog inputs/outputs, the system state variables and alarm information such VFD faults are displayed here.

Figure 19: Slave Panel Operations Log



- Alarm Log – The Alarm Log records the last 100 system alarms, such as VFD faults and temperature alarms. Alarms previously logged are then replaced by more recent alarms detected. VFD's are installed with fault signals for each variable speed fan. An alarm is be generated when the VFD fault signal is de-energized. These alarms will also appear on the operations and system logs.

- KW Log – The KW Log is an optional log used to record the periodic totals for Demand KW, Peak Demand, and Daily, Weekly, and Yearly usage. Compressor motor amps, Present KW, and Demand KW will be recorded every 30-seconds for operations logs and every 15-minuites for system logs. Power consumption data loggers for the blast freezer motors will be logged remotely by Cascade Energy Engineering in order to be able to easily move the data loggers on alternating blast cells.

Figure 20 below shows a real-time status of a CO2 reciprocating compressor (RC2) used for the blast freezer suction group. Figure 21 displays the 30-second RC2 operations log data containing the motor amps, present kW and demand kW from the operating compressor.

Figure 20: RC2 Reciprocating Compressor Status Screen

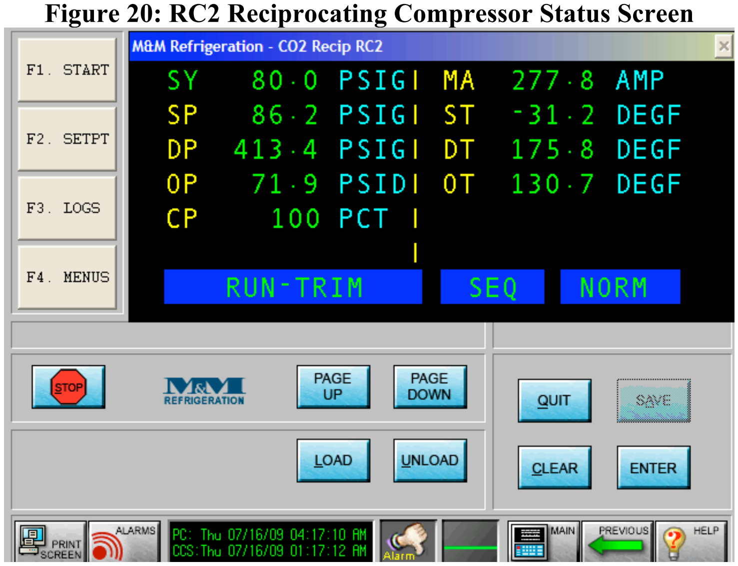
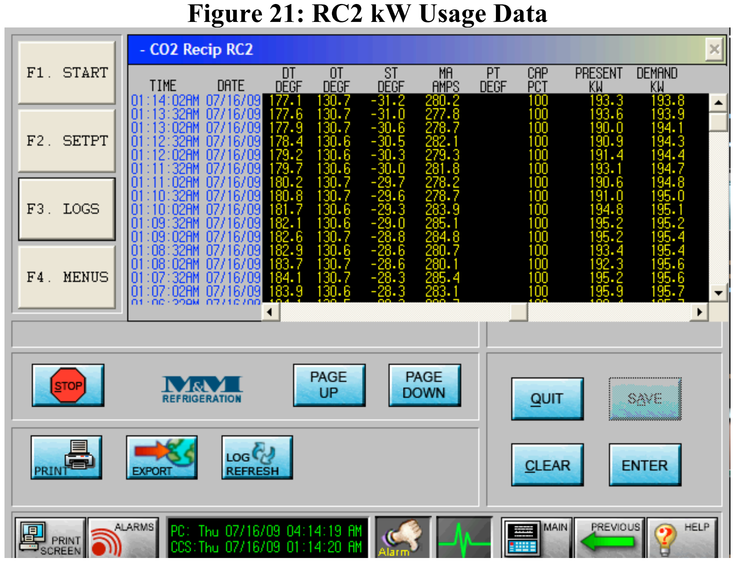
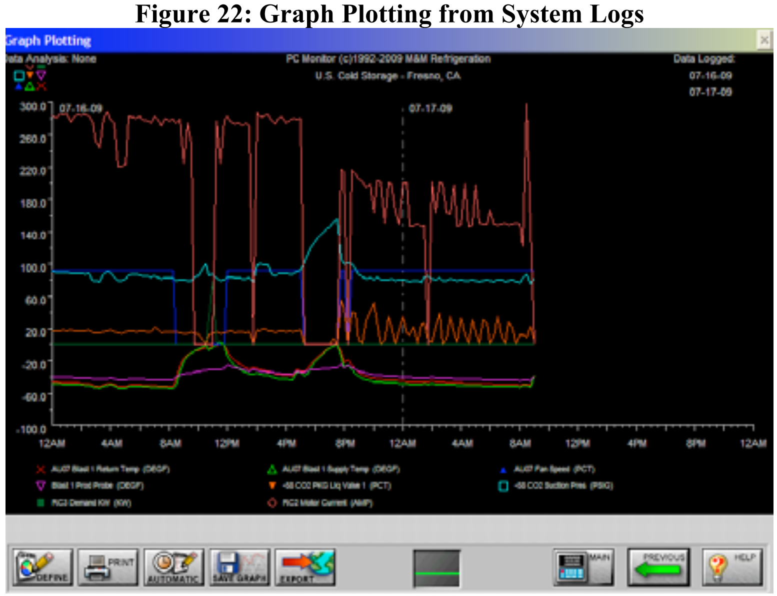


Figure 21: RC2 kW Usage Data



- System Log – The System Log tracks and accumulates all system data such as analog inputs/output, discrete I/O functions, alarms and some status information. The Reports or Graph Plotting functions allow USCS and Cascade Energy Engineering to compare historical and current trend data of blast freezing parameters such as return air temperatures, supply air temperatures, product probe temperatures, compressor KW, suction pressures, motor amps, liquid valve percentages and fan speeds similar to those identified in Figure 22 below.

Figure 22: Graph Plotting from System Logs



M&M Refrigeration also provided technical support during the start up and commissioning of the system as well as during the testing process. The selected equipment detailed drawings and specifications are included in Attachments section of the document.

Cascade Energy Engineering Services

Cascade Energy Engineering provided engineering consulting services associated with the Blast Freezer Variable Frequency Drive research project. The following components of the research project were performed by Cascade Energy Engineering:

- Assist in the development of blast freezer evaporator control strategies and any other factors associated with optimizing blast freezer efficiency.

- Assist in the development of the technical strategy for conducting the blast freezer field trials. This would include identifying the key variables to monitor during field trials to analyze performance.

- Assist in the development of a test apparatus and the procurement of supplemental data acquisition equipment for product test trials.

- Provide analysis of the data obtained during the field trials to the standard contractually agreed upon between USCS and the Energy Commission.

Test Methodology Overview

A test methodology was developed in order to gain an understanding of the affect of modulating blast freezer evaporator fan speed on blast freezer performance. This consisted of measuring product temperature versus time in several blast freezing cycles. The goal of the first phase of testing was to determine baseline performance with the evaporator fans operating at a constant speed. Once a baseline performance was established, subsequent testing would be performed utilizing variable fan speeds.

The general theory for blast freezer fan speed modulation was that at the onset of a blast freezing cycle, cooling of the product is primarily a function of convective heat transfer. A decrease in air velocity around the product creates a proportional decrease in heat transfer. As the outer shell of the product approaches freezer air temperature, it is theorized that cooling of the product becomes much more influenced by conductive heat transfer and less influenced by convective heat transfer. Here, a decrease in air velocity around the product creates a smaller decrease in heat transfer relative to the early stages of the blast freezing cycle.

Test Product

Ground beef product was the only product utilized for the baseline and modulation tests. An example of a pallet load of ground beef boxes is shown in Figure 23. Each box is 24″ L x 16″ W x 8″ H and contains 50 lbs of ground beef. Ground beef was selected for testing because it is consistent, homogenous product for measurement. The facility also handles a large volume of ground beef so issues with product availability for testing were minimized.

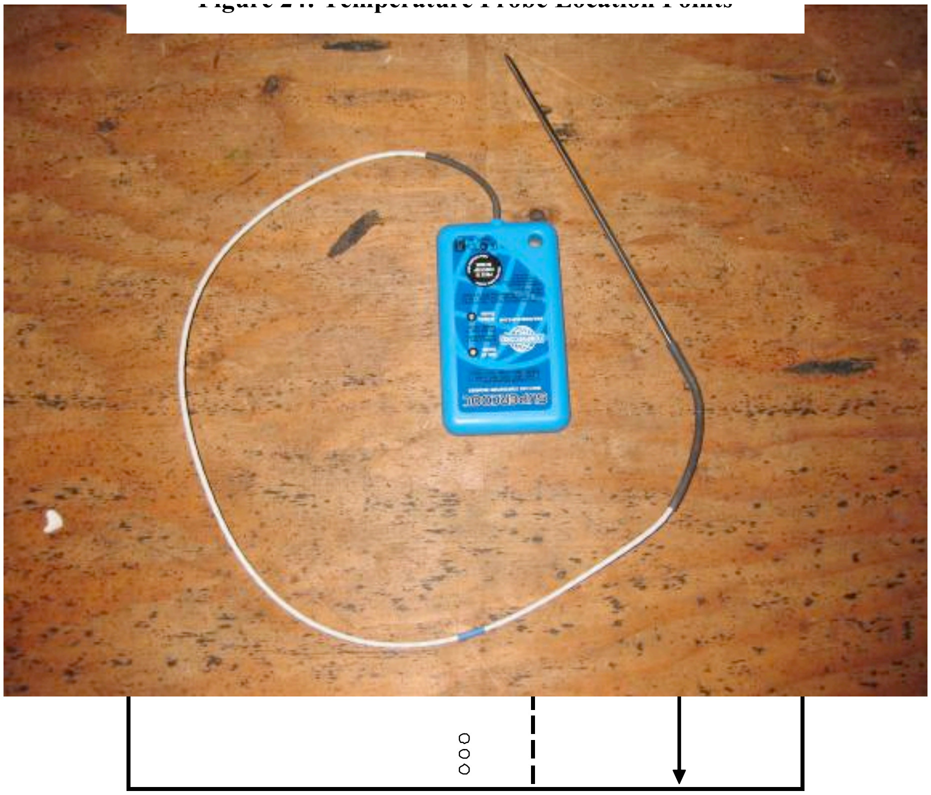
Figure 23: Pallet of Ground Beef Product

Baseline Testing

Baseline testing was performed for a minimum of eight blast freezer load cycles. Evaporator fan speeds were be maintained at a constant 100 percent fan speed for the first four baseline tests and 92 percent for the other four baseline blast freezing trials.

Product temperature was measured at twelve fixed locations along on a layer of ground beef boxes. The temperature measurements were located along the two centerline axes of the layer of boxes, shown in 24. Twelve TempRecord brand Supercool data loggers were utilized to measure product temperature. A sample logger is shown in 25. Each logger is equipped with a 10″ food grade temperature probe. The temperature probes have a range of -112 °F to +230 °F and are accurate within +/- 0.35 °F. The units are equipped with 8K memory and can be set to a sample rate range from 2 seconds to 36 hours. The TempRecord data loggers are capable of operating at the blast freezer temperature without any external heating. This was a critical feature of the loggers.

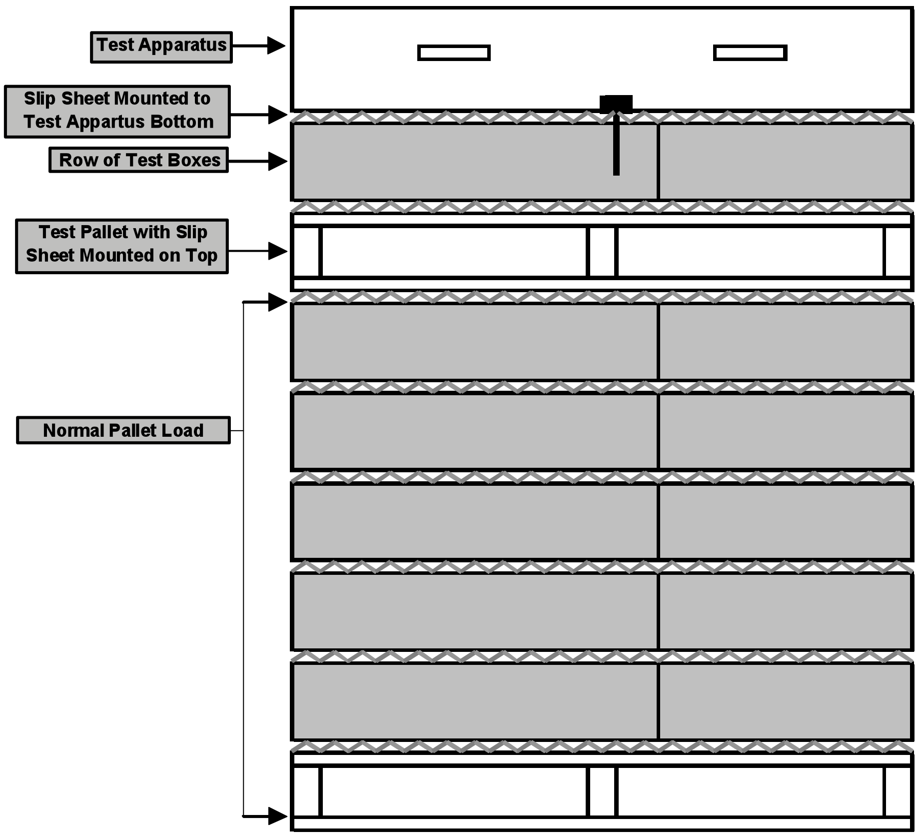
Figure 25: TempRecord Supercool Product Temperature Data Logger



A test apparatus had been constructed to control temperature probe measurement location and house the TempRecord data loggers during testing. The apparatus is approximately the size of a pallet, 48″ W x 48″ L. The top and bottom are constructed out of ½″ plywood and the walls with 2″ x 4″ lumber.

The test apparatus was placed on top of a pallet load of product. The base of the apparatus has twelve 1/4″ holes drilled in it to for temperature probes to be inserted in the pattern shown in 24. The temperature probes puncture the product cardboard box and penetrate through to the middle of each product. Along each axes, three probes are tightly spaced near the edge of the pallet load at approximately 1″ spacing. The interior probes were spaced out at approximately 5″ spacing. The tight spacing at the edge of the pallet load was intended to closely monitor edge temperature to determine the role in shell temperature versus heat transfer rate. Figure 26 shows how the test apparatus was placed on a pallet to simulate a row of product.

Figure 26: Test Apparatus Product Testing Configuration



A close-up photo of the apparatus where the TempRecord data loggers and temperature probes are housed along with the probe insertion holes is shown in Figure 27. A side view of the test apparatus on a pallet of test product is shown in Figure 28. After the apparatus is loaded on to the product and the temperature probes are inserted, the access door is closed. This allows a slip sheet to be placed and additional product boxes to be loaded on top of the apparatus for ease of access. A template for arranging the boxes underneath the apparatus was drawn on top of the apparatus to ensure product temperature probes would be in the same arrangement for each test. Figure 29 shows the pallet of boxed beef with the test apparatus being loaded into a blast cell for testing. See Appendix I, "USCS Blast Freezing Test Procedure", for the complete facility guide to the test product loading instructions, temperature probe calibration and placement, and data extraction procedures.

Figure 27: Test Apparatus Photo 1

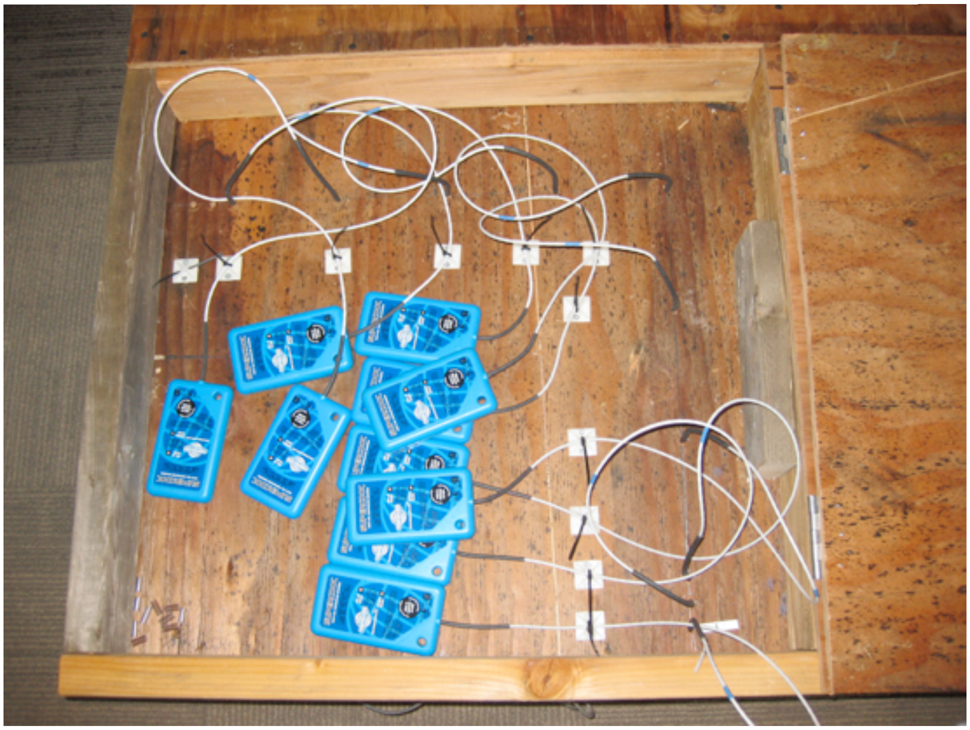


Figure 28: Test Apparatus Photo 2

Figure 29: Test Apparatus Photo 3

Baseline Testing and Analysis

In addition to the data obtained from the TempRecord loggers, testing personnel manually documented the following information for each blast test:

- Product loading date and time
- Product unloading date and time
- Tested blast cell pallet position
- Tested product stack height on pallet

The M&M control system was utilized to capture additional data for each test, including the following:

- Blast cell evaporator fan speed
- Blast cell evaporator leaving air temperature
- Blast cell evaporator return air temperature
- Blast cell evaporator liquid solenoid position
- CO_2 & NH_3 compressor suction pressures
- CO_2 & NH_3 compressor energy (KW)
- NH_3 screw compressor slide valve position
- CO_2 reciprocating compressor capacity

Modulation Testing

Once the baseline testing had been completed and the data analyzed, the second phase of testing was initiated. This consisted of performing similar tests with the evaporator fans operating at modulated (reduced) fan speeds. Fan speeds were adjusted based on a time-based schedule (e.g., first four hours at 92% speed, next four hours at 80% speed, etc).

Testing fan speed schedules were initially determined based on the results of the baseline tests. The hope was that during the baseline tests, a consistent pattern would be evident when product heat transfer rate began to diminish. At that point, it was theorized that fan speed could be reduced with limited negative effect on the heat transfer rate.

Several fan speed schedules were identified and tested. Definition of the schedules would be an iterative process based on the results of testing. Additional testing may be done for future blast tests if physical changes are made to the blast cells. This would consist of modifying the existing baffles within the cells to increase air flow velocity local to the product in an effort to increase heat transfer rate. This could be in conjunction with operating at other modulating fan speeds and product mixes as well.

Modulation Analysis

A minimum of three blast freezer load cycle tests per modified fan schedule were tested during the modulation phase with some additional tests performed as necessary in order to develop a thorough understanding of the modified fan speeds and its effect on heat transfer performance of the test product. The same data from the M&M control system was utilized to evaluate the fan modulation test results.

Energy Analysis

Energy analysis of baseline and modulation performance focused on energy use of the following components of the refrigeration system:

1. Blast cell evaporator fans
2. Blast cell booster suction CO2 reciprocating compressors
3. High stage suction ammonia compressors

Evaporator fan energy use in the baseline and modulation cases were calculated based on fan speed and run time. Evaporator fan speed data were obtained in each phase of testing from the M&M refrigeration control system. Fan power or fan energy use will not be directly measured during testing. Instead, a correlation between fan power and speed will be developed and utilized to convert measured fan speed to power. In general, a consistent relationship between fan power and speed exists so this approach was deemed to be appropriate.

This relationship has already been developed based on one-time fan power measurements at varying fan speeds. A three-phase power meter was used to measure total evaporator fan power in Blast Cell 7 at an array of fan speeds. The results are shown in Appendix II, Fan Modulation Analysis. A fan speed to power exponent of 2.85 was derived based on the data (3.00 theoretical). Note that by operating at 92% speed, as is current practice, fan power is reduced by 21% versus operating at full speed.

Reduction in fan energy use from operating at reduced speeds in the modulation case is ultimately a reduction in heat load placed on the refrigeration system. This reduction in refrigeration load ultimately reduces blast cell booster suction compressor, high stage suction compressor, condenser, and refrigerant circulation pump energy use. Affects on the refrigeration system condensers and refrigerant circulation pumps were not considered in this analysis because these savings are not significant enough to consider. Only the affect on the compressors were considered.

The energy savings at the compressor level were determined based on the observed part load performance of the blast cell booster and high stage suction compressors. For each set of compressors, a three-phase power meter will be utilize to measure compressor power at an array of slide valve positions while suction and discharge pressure is held at a relatively constant level (to negate any affect on power use from changes in suction or discharge pressure). A baseline analysis of the refrigeration system can be seen in Appendix III.

CHAPTER 3: PROJECT OUTCOMES

The baseline and comparative blast freezing trials evaluated the relative product cooling performance of various fan speeds during different phases of product freezing in a blast freezing process. Cooling efficacy during the tests was measured by recording core product temperature at 12 different locations in a pallet layer of ground beef. Different combinations of fan speeds were compared to the baseline cooling performance. The fan constant speed set point used for the baseline was 100%. Four blast cycle test runs were performed at this speed. For the fan speed reduction tests, fan speed was reduced after a predetermined time delay. The temperature profiles from the product core temperature readings were then compared between the tests to determine their relative product cooling performance.

Blast Freezing Test Summary

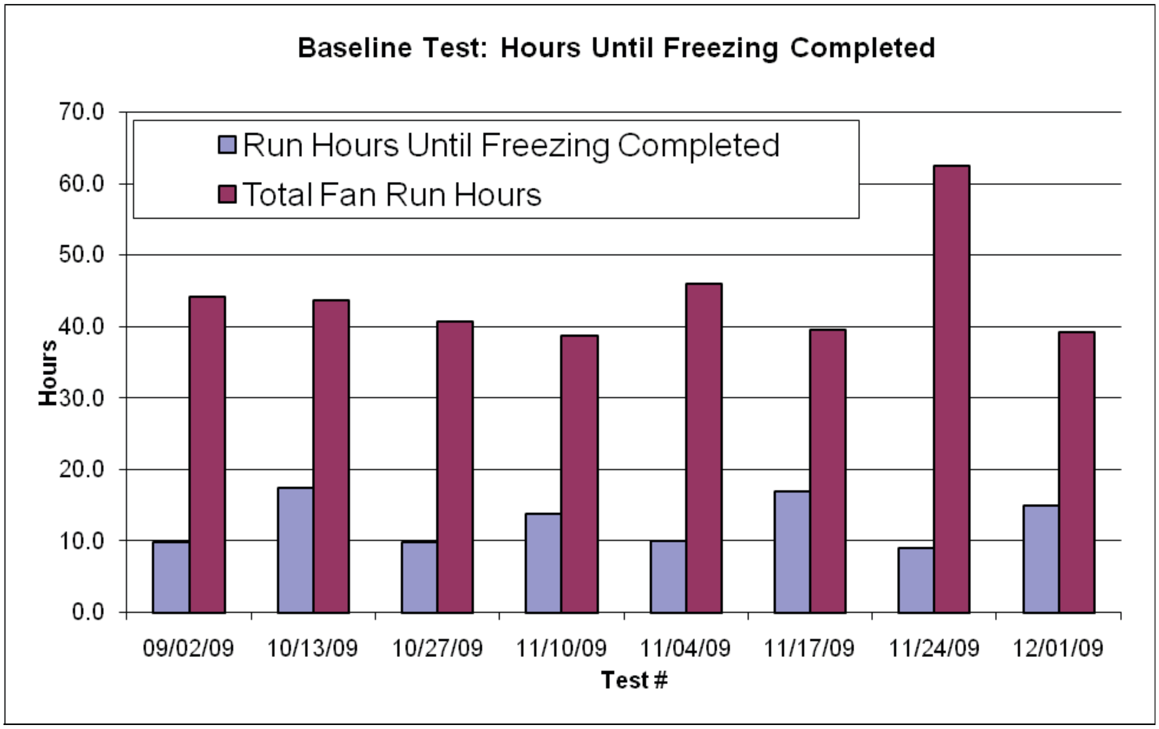
A summary of the tests conducted is presented below. The typical baseline blast cycle runtime for Fresno was 40 hours. All tests conducted were based on a 40 hour total blast cycle run time. The fan speed modulation tests were conducted by reducing the fan speed after a predetermined time interval. For example, in the 92/50% fan modulation test, the fans were run at 92% speed for the first 22 hours of the blast cycle, and then run at 50% speed for the remaining 20 hours of the blast cycle. Similarly, the 92/70/50% fan modulation tests were run at 92% fan speed for the first two hours, 70% speed for the next 20 hours and 50% for the remaining 18 hours.

Table 14: Summary of Test Trials

Test Summary	Number of Test Runs	Hours at Initial Speed	Hours at Second Speed	Hours at Third Speed
100% Baseline	*4*	*40*	*-*	*-*
92% Modulation	*4*	*40*	*-*	*-*
92/50% Modulation	*3*	*22*	*18*	*-*
92/70/50% Modulation	*3*	*2*	*20*	*18*
92/50/30% Modulation	*3*	*2*	*10*	*28*

The rationale for the fan speeds and time delays used in the fan modulation tests was based on observations from the baseline and 92% fan speed tests. Initial comparisons were made to evaluate the performance of 40 hour blast cell tests at 92% fan speed versus the 100% baseline fan speed.

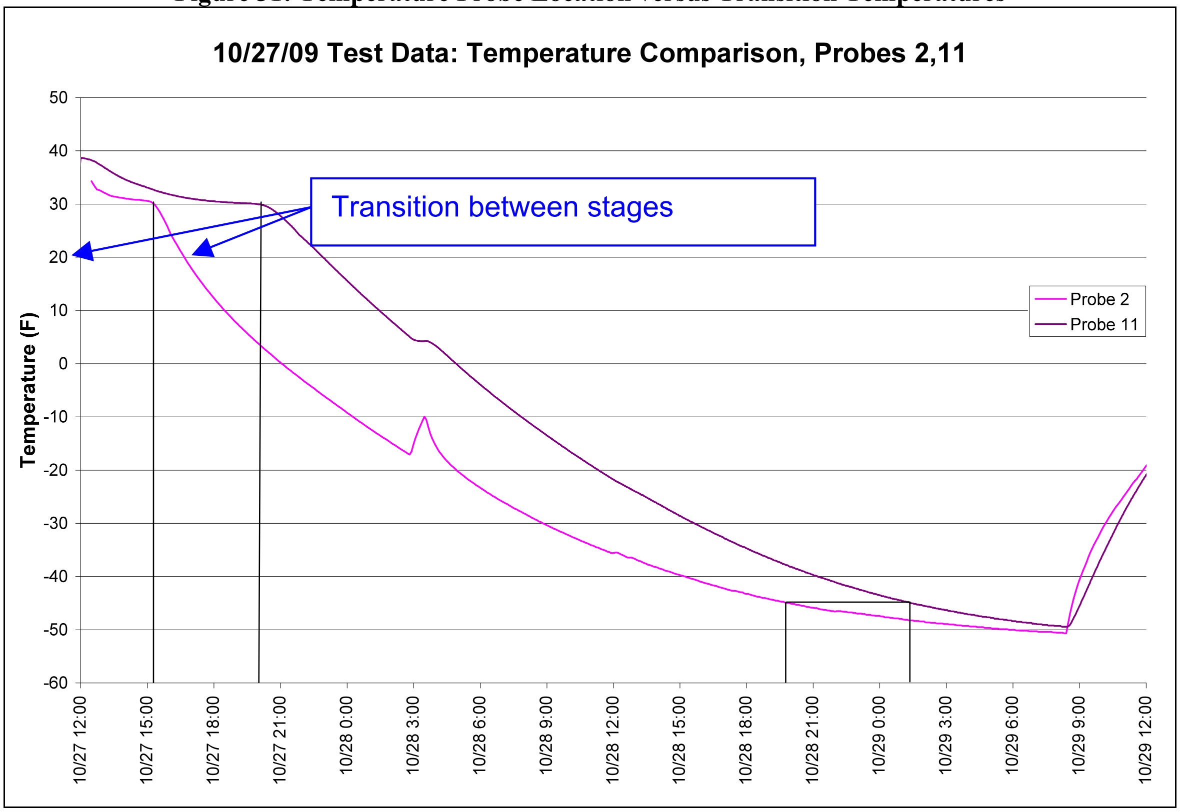
Figure 30: Comparison of 92% and 100% Fan Speeds



In Figure 30 above, the tests dated 11/04/09, 11/17/09, 11/24/09 and 12/01/09 were conducted at 100% fan speed. The remaining tests were conducted at 92% fan speed. The 11/24/09 test was not included in the analysis because it appeared to be an outlier. The 100% fan speed runs did not show significant heat transfer improvement over the 92% fan speed runs. This provided the basis for using an initial fan speed of 92% for the rest of the modulation tests.

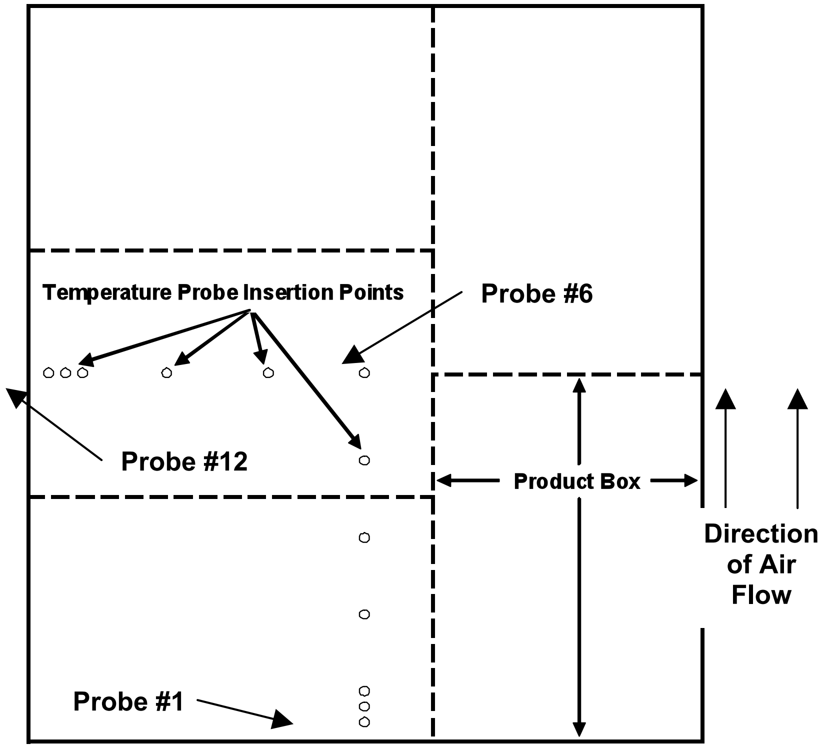
The blast cycle is discussed primarily in terms of three separate cooling stages. The first is the freezing stage, in which the product is cooled from initial temperature (anywhere from 31-45° F) down to freezing temperature (around 31° F). In the second stage freezing takes place at a nearly constant temperature. The third stage of cooling is labeled "post-freezing," in which the product is further cooled down to a minimum temperature. The point of transition between the stages is very clear and can be seen in the following Figure 31 below.

Figure 31: Temperature Probe Location versus Transition Temperatures



An explanation of the probe location numbering is demonstrated in the Figure 32 below. There are 12 probe insertion points numbered sequentially from 1 to 12, with number 6 located in the very middle of the pallet.

Figure 32: Plan View Temperature Probe Location Points



The most significant result from the baseline tests was the difference in cooling rates for probes 1-5 and 7-12. The difference is due to the fact that probes 1-5 are oriented on the side of the pallet that receives direct airflow from the evaporators. Probes 7-12 appear to get a significantly reduced airflow. The result is that probes 1-5 reach 30° F (frozen) much faster than probes 7-12. However, once freezing is achieved, both sets of probes cool at a very similar rate. For example, it typically takes probe 2 about five to ten hours longer than probe 11 to reach a completely frozen state, but after that it takes both probes a similar amount of time to reach -45° F. In the graph shown above, probe 2 completed freezing five hours faster than probe 11, but only reached -45° F five and a half hours faster. It was evident that the slopes of both curves are very similar once freezing is achieved. The implication is that exposing the product to more airflow increases the rate of freezing, but once freezing is achieved there is less effect on the rate of cooling. It is expected that the evaporator fan speed could be reduced dramatically in the post-freezing stage with little effect on the rate of cooling. The complicated target is determining the ideal time to reduce the fan speed. The following chart shows a comparison of the amount of time it took the baseline tests to achieve freezing. This judgment is based on the probe that achieved freezing last in each test (typically probe 6 because it is in the center of the pallet). The 11/24/09 test appears to be an outlier and was not included in the analysis. The longest time to reach freezing was 21.5 hours for the 11/17/09 test. For the fan modulation tests, it was expected that fan speed could be reduced after 22 hours and still have confidence that the product had reached the post-freezing stage. The 92/50% fan modulation test was set to run at 92% fan speed for the first 22 hours and then at 50% fan speed for the remainder of the test. This allows for comparison of cooling performance for reduced fan speed operation in the post freezing stage of the blast cycle.

According to the test data, there does not appear to be any consistent improvement at a fan speed of 100% versus 92%. This indicated that there was an opportunity to reduce fan speed further in the freezing stage of cooling. The 92/70/50% and 92/50/30% modulation tests were conducted to characterize the cooling performance for reduced fan speed operation in the freezing and post freezing stages of the blast cycle. Fans were only kept at 92% speed for the first 2 hours of the blast cycle to get the blast cell ambient air down to temperature. After the first 2 hours, fan speed was reduced.

CHAPTER 4: ANALYSIS OF RESULTS

I. Standard Blast Cycle Run Time

The project demonstrated the successful implementation of evaporator fan speed modulation using computerized control. The fan modulation tests clearly documented the opportunity for reduction in fan speed without decreased cooling performance. The most effective fan speed control algorithm performed in the ground beef testing was a combination of 92%, 70% and 50% fan speeds. The fans were set to 92% speed for the first two hours, 70% speed for the next 20 hours, and 50% speed for the remaining 18 hours of the 40 hour total blast cycle. This approach shows significant energy savings over the baseline case. A second finding regarding additional energy savings potential associated with shortening blast cycle run time is presented in the next section.

Standardized Energy Savings

Because there were variations in incoming product temperature, product type, blast cycle defrost frequency and overall blast cycle runtime, the overall energy savings results were compared on a standardized basis. The savings calculations were based on an average blast cycle time of 40 hours, with evaporator defrost time removed. Also, the compressor energy percentage savings were based on an averaged typical product cooling load. Thus, the compressor energy savings were claimed based only on reduction in fan motor heat load on the space due to reduced fan speed, and are not affected by any differences in product loading between tests. The following table and chart show a comparison of the project energy savings goals and actual savings achieved. Note that the fan energy savings exceed the project energy savings goal. Based on the information presented in Table 15, Table 16 and Figure 33 below, the combined fan and compressor energy savings surpassed the project energy savings goal.

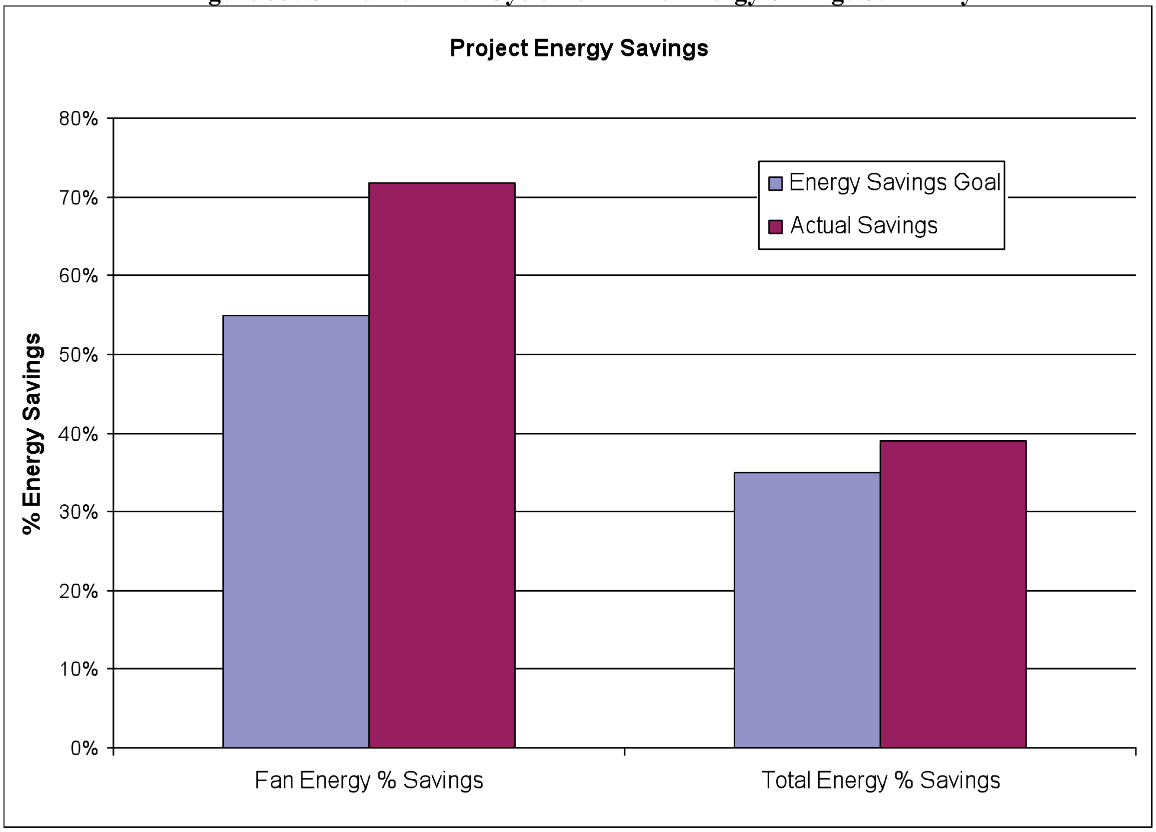
Table 15: Standard Blast Cycle Run Time Energy Savings Summary

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	*55%*	*35%*
Actual Savings	*72%*	*39%*

Table 16: Energy Savings per Blast Cycle

Typical Energy Savings Per Blast Cycle		
Fan Energy Savings (kWh)	Compressor Energy Savings (kWh)	Total Energy Savings (kWh)
1,150	471	1,621

Figure 33: Standard Blast Cycle Run Time Energy Savings Summary



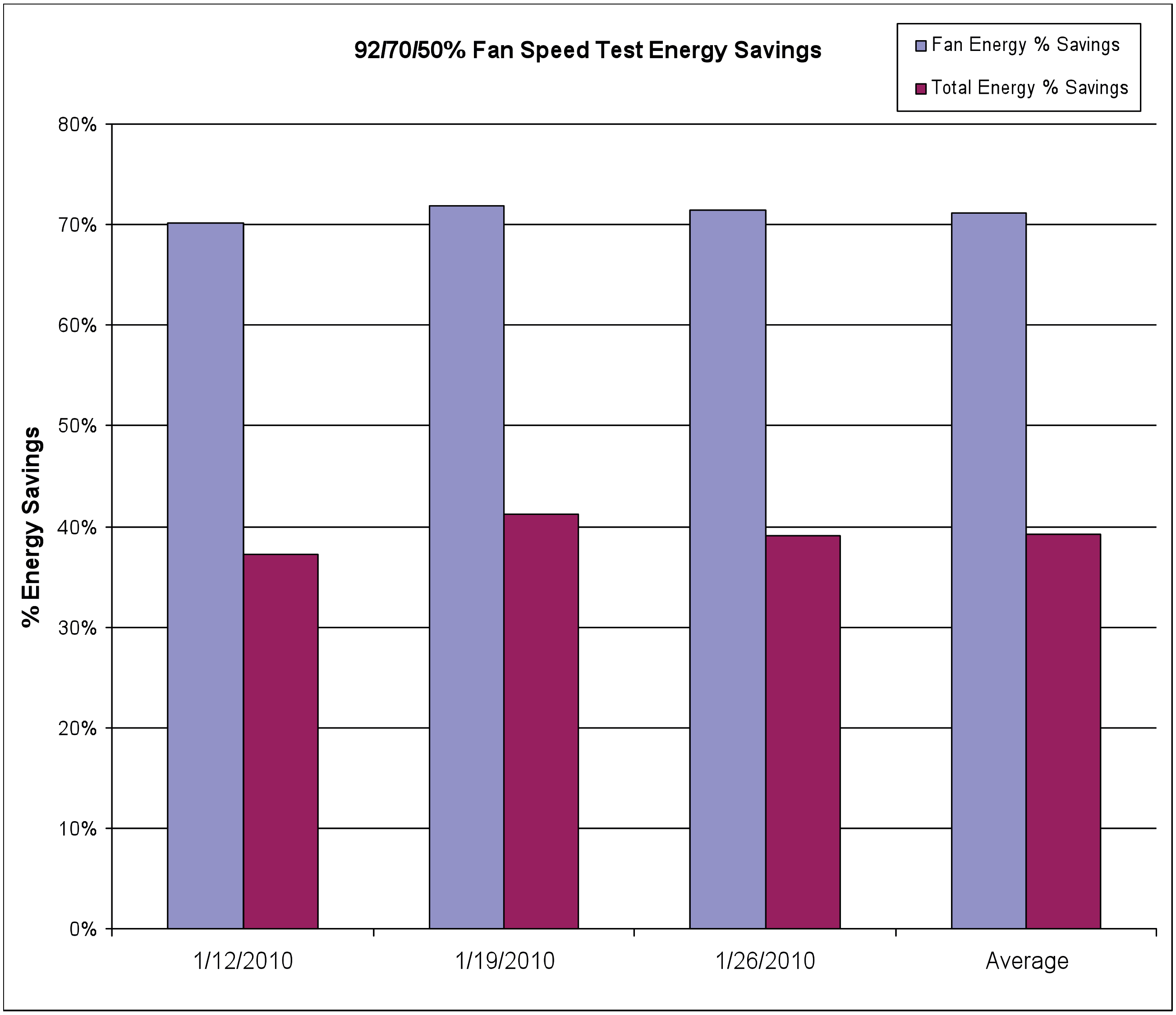
Actual Test Result Energy Savings

The actual savings achieved during the tests varied slightly based on the variables discussed above, including incoming product temperature, blast cycle defrost frequency and overall blast cycle run time. A summary of the energy savings from the three 92/70/50% runs is shown in the Table 9 and Figure 34 below.

Table 17: Energy Savings Test Summary

Test Date	Fan Energy % Savings	Total Energy % Savings
1/12/2010	70%	37%
1/19/2010	72%	41%
1/26/2010	71%	39%
Average	**71%**	**39%**

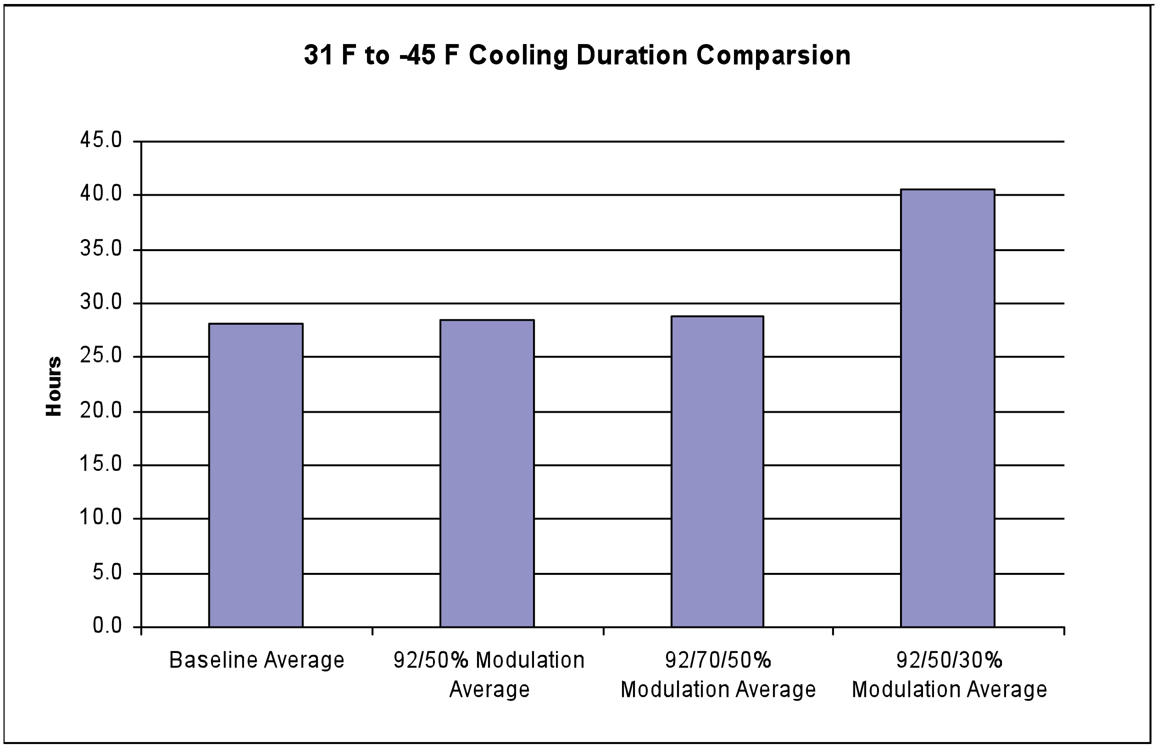
Figure 34: Energy Savings Test Summary



Basis for Comparison

Because of varying incoming product temperatures, product runs were compared on the basis of cooling performance between freezing temperature (around 31° F) and -45° F final product temperature. These temperatures were chosen as the most representative of common temperatures for all tests. Because some tests received product just above freezing temperature, 31° F was chosen as the most reasonable initial temperature. Product final temperature varied between -45° F and -50° F, so -45° F was chosen as the most reasonable final temperature. Each test run was compared on the basis of how long it took to reduce the product temperature from 31° F to -45° F. Because evaporator defrost cycles were sometimes necessary during tests, the time that the evaporator was in defrost was removed from the overall comparison time. This basis for comparison allowed for objective analysis between fan modulation test runs. A summary of the average time it took for each set of fan trial runs to pull the product temperature down from 31° F to -45° F is shown in Figure 35 below. Note that there is no notable increase in product pull-down time except for the set of test runs where the fan speed was reduced to 30%. For the other tests, it was observed that the fan speed could be reduced with no reduction in cooling performance.

Figure 35: Cooling Duration Comparison



Refrigeration Load Profile

In addition, there was variation between blast cycle product loads in terms of the types and amounts of products included each blast test. For the purpose of examining the relative portion of refrigeration energy saved, a typical product refrigeration load profile was assumed. This product refrigeration load profile was generated by examining the hourly evaporator load throughout several baseline tests, and averaging the results. An example evaporator load profile is shown in Figure 36 below. Interesting to note is that for the 92% fan speed setting, the fan motor load on the refrigeration system was approximately 9 TR (tons of refrigeration). At the end of the blast cycle the total refrigeration load gets down to around 20 TR. As seen in Figure 37, at this point of the blast freezing process, the fan load makes up almost half of the total refrigeration load.

Figure 36: Estimated Total Refrigeration Load

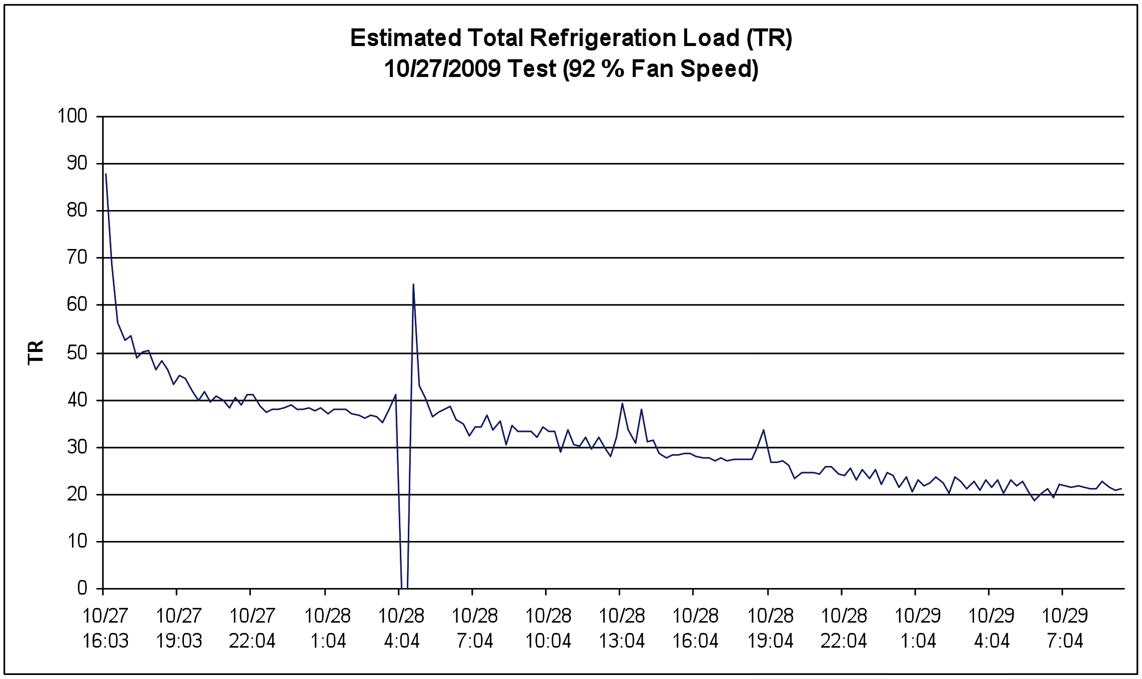
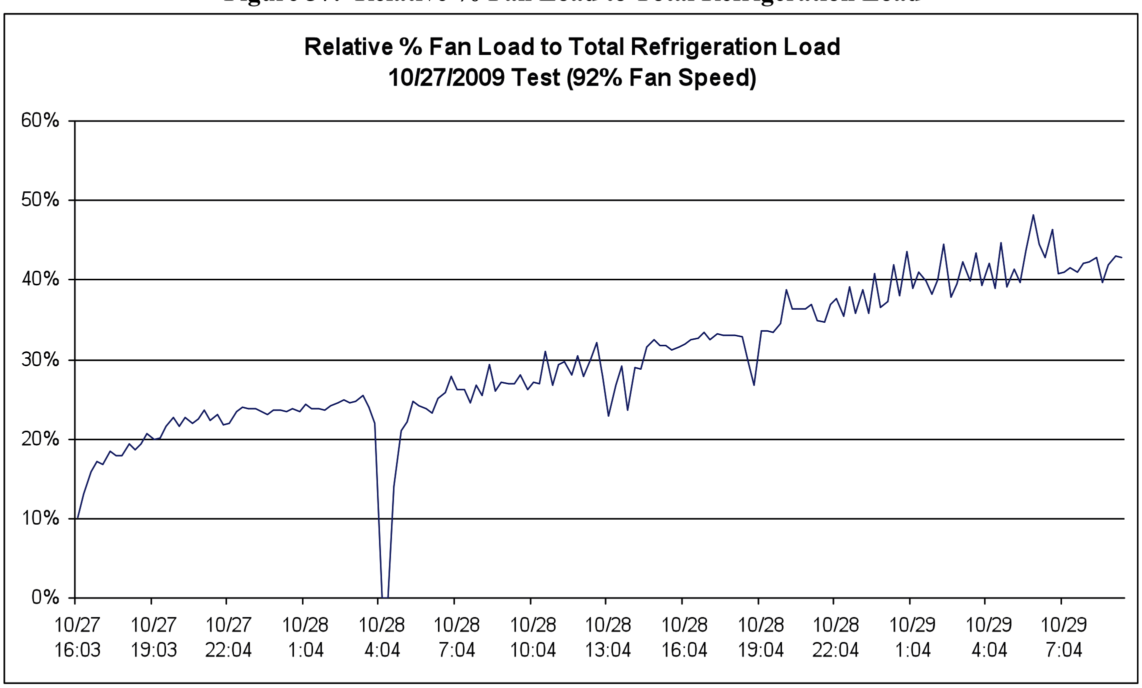


Figure 37: Relative % Fan Load to Total Refrigeration Load



II. Reduced Blast Cycle Run Time

An additional outcome of the project was identifying the opportunity to shorten blast cycle times. Based on the examination of product temperatures achieved during the current blast cycle process, it was observed that the product final temperature is much lower than necessary.

USCS believes that a product final temperature of -10° F would be acceptable for their operation. As a result, there is also an opportunity to reduce blast cycle run time and achieve additional energy savings. Not only will less product refrigeration energy be required, the fan runtime will be reduced, as well as the associated fan refrigeration load. Based on testing results, it is expected that blast cycle run time can be reduced from 40 hours to 25 hours. The proposed fan control algorithm for reduced blast cycle run time is shown in Table 10 below. It is based on reducing the hours for the final stage of cooling for the regular length blast cycle algorithm.

Table 18: Reduced Blast Cycle Run Tim Control Algorithm

	Hours at 92%	Hours at 70%	Hours at 50%
92/70/50% Algorithm	2	20	3

Energy Savings

The energy savings were calculated in a similar manner, with additional savings for the reduced fan speed run time and reduced product cooling load as seen in the Table 11 and Figure 37 summaries below. Estimates for product cooling load reduction were based on averages observed during the tests. These estimates make assumptions to standardize the product cooling load reduction between blast tests. Actual product cooling load savings would vary based on annual product types and volumes.

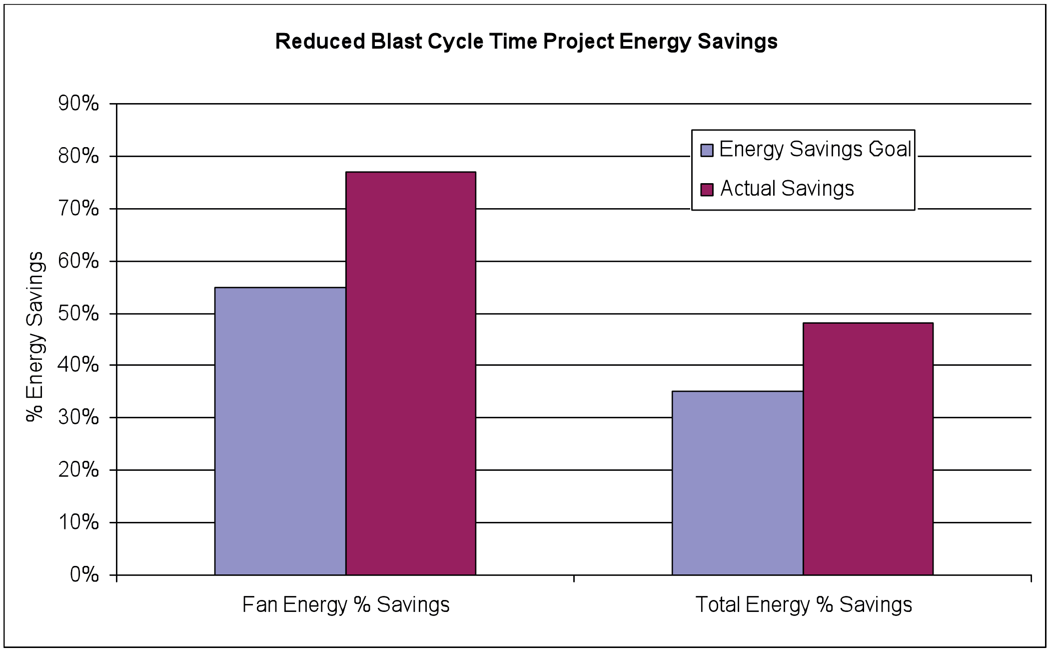
Table 19: Reduced Blast Cycle Run Time Energy Savings Summary

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	55%	35%
Actual Savings	77%	48%

Table 20: Energy Savings per Blast Cycle

Typical Energy Savings Per Blast Cycle		
Fan Energy Savings (kWh)	Compressor Energy Savings (kWh)	Total Energy Savings (kWh)
1,297	764	1,998

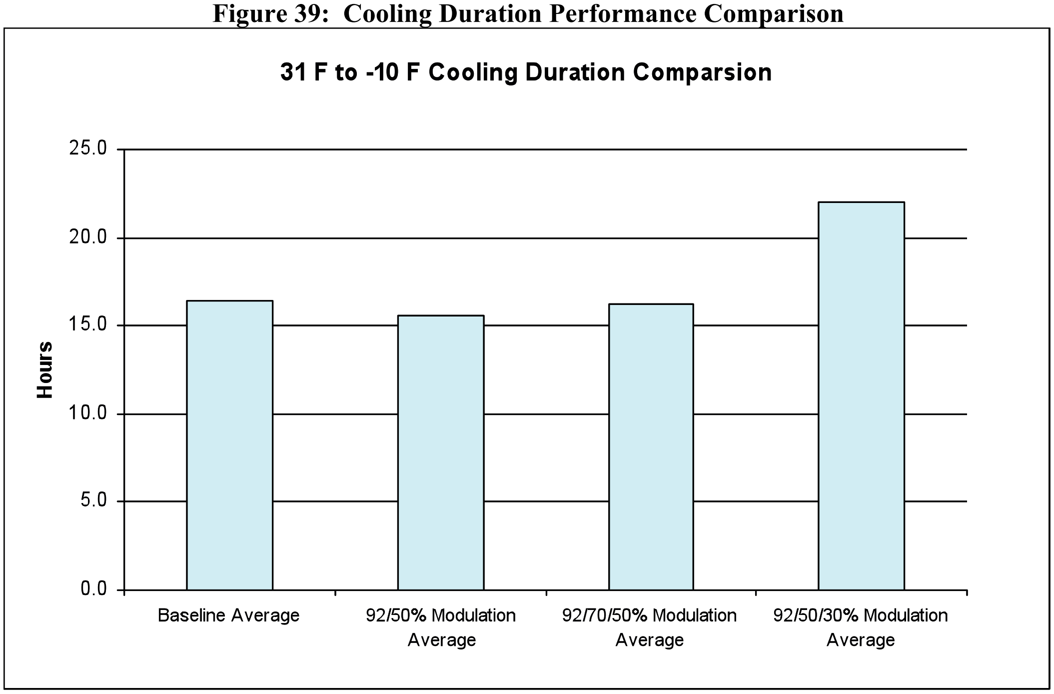
Figure 38: Reduced Blast Cycle Run Time Energy Savings Summary



Basis for Comparison

The cooling performance of different fan speeds was compared in a similar fashion, except using -10° F as the product target final temperature instead of -45° F. Note that the 92/70/50% test runs have comparable cooling performance as the baseline, but the 92/50/30% test runs have reduced cooling performance as seen in Figure 39 below.

Figure 39: Cooling Duration Performance Comparison



CHAPTER 5: CONCLUSIONS

I. Fan Modulation

The testing clearly showed the potential for fan speed reduction without compromising cooling performance. There were two separate thresholds for fan speed reduction depending on the stage of cooling. In the freezing stage of cooling, 70% was the minimum observed fan speed without compromising cooling performance. In the post freezing stage of cooling, 50% was the minimum observed fan speed without compromising cooling performance. The fan energy savings and total energy savings as a result of the optimal fan speed configuration yielded the following results:

- 72% fan energy savings or 1,150 kWh per blast session
- 39% total energy savings or 1,621 kWh per blast session

II. Reduced Blast Cycle Run Time

An additional result of the testing was the observation that the current final product core temperature is lower than it needs to be. Product is currently being pulled down as low as -50 F in the measured test product. It is expected that a -10° F final product core temperature would be satisfactory to account for all product positions that may experience less heat transfer during the blast freezing process. At the test product position within the blast cell, this temperature could be achieved with an average blast time of 25 hours, 15 hours less than the current blast cycle time. Shortening the blast cycle time would result in fan energy savings and refrigeration energy savings from the reduced fan and product load. The fan energy savings and total energy savings as a result of the optimal fan speed configuration to achieve a -10° F final product core temperature yielded the following results:

- 77% fan energy savings or 1,297 kWh per blast session
- 48% total energy savings or 1,998 kWh per blast session

CHAPTER 6: RECOMMENDATIONS

In order to achieve the maximum energy savings possible, consideration must be given to actual facility operating constraints, including blast cycle loading protocol, schedules, and variations in blast cycle product types and volumes. Now that the test apparatus is readily available, ongoing testing should be performed to confirm the results of this study are applicable to the variety of operating conditions. In addition, due to the diversity of use of the blast freezers, it may be worth exploring a fan modulation control algorithm that is based on actual operating conditions rather than simple time delays. The time delays chosen for this study were based on the worst case scenarios observed in order to ensure that the fan speed was not prematurely lowered before freezing was achieved. However, it should be noted that the average time it took for a test to reach freezing was only 16.6 hours, much less than the 22 hours that it took the longest baseline test. A method of feedback control would optimize energy savings and cooling performance. If the average time that it takes before the fan speed is reduced could be lowered to 17 hours, then the energy savings would increase to the numbers shown in Table 12 and Table 13 below.

Table 21: 40 Hour Blast Cycle Energy Comparison for Different Control Strategies

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	*55%*	*35%*
Time Delay Control	*72%*	*39%*
Feedback Control	*75%*	*41%*

Table 22: Reduced Blast Cycle Energy Comparison for Different Control Strategies

	Fan Energy % Savings	Total Energy % Savings
Energy Savings Goal	*55%*	*35%*
Time Delay Control	*77%*	*41%*
Feedback Control	*80%*	*50%*

The difficulty is determining an accurate way to control fan speed. The ideal candidate for a control parameter is product core temperature, but unfortunately it does not appear to be practical to measure product temperature for every blast cycle. The other options include controlling fan speed based on ambient air temperature or evaporator return air temperature. The available evidence from the testing shows that both of these parameters are just as likely to be subject to variations between blast cycles, and therefore may not provide superior performance over time delay control. A more detailed discussion of the alternate control algorithms explored is contained in Appendix III. The complexities of setting up a more sophisticated control algorithm should be weighed against the value of the additional potential energy savings, and further testing should be performed if merited.

CHAPTER 7: PUBLIC BENEFITS TO CALIFORNIA

The immediate benefit to California as a result of the project has been an average reduction of 1,621 kWh per blast trial as a product from the implementation of evaporator fan speed modulation through the use of variable frequency drives for blast freezer temperature control. Using power consumption statistics based upon 5,000 hour per year (125 blast freezing runs), the actual electrical savings potential would be equal to 202 MW of electricity. 1 MW of electricity can power approximately 1,000 California homes. The savings associated with this project has a tremendous potential equivalent to the electricity needed to power 202,000 California homes, which was greater than originally anticipated.

The study results will prove useful for the California Energy Commission in their efforts to promote the continued development of variable speed modulation technology to increase energy efficiency standards of batch style blast freezing cells typically found in the public refrigerated warehousing industry.

References

Stoecker, Wilbert F. Industrial Refrigeration Handbook. McGraw-Hill, New York, 1998.

APPENDIX A – USCS BLAST FREEZING TEST PROCEDURES

SUMMARY

This document summarizes the procedures for performing blast freezer tests of ground beef product at the USCS Fresno facility.

EQUIPMENT NECESSARY FOR TESTING

The following equipment will be necessary for conducting the test:

1. **TempRecord Data Loggers:** Twelve separate data loggers each equipped with a 10" temperature probe that is food grade safe.
2. **TempRecord Reader Interface:** Hardware interface to the TempRecord data loggers. The reader interface allows the user to program the data loggers and download data from the loggers with a laptop computer.
3. **Laptop Computer with TempRecord Software**: Computer equipped with TempRecord software that will be utilized with the TempRecord Reader Interface to program the data loggers and download data from the loggers.
4. **Test Apparatus:** Wood box that has been created to provide specific insertion points for the temperature probes. The Test Apparatus houses the TempRecord data loggers. The Test Apparatus has the same footprint as a pallet and is designed to sit on a stacked row of ground beef boxes. The Test Apparatus can have product stacked on top of it if desired.
5. **Test Pallet:** Pallet with a slip sheet mounted to the top of it. The Test Pallet is utilized to stack the one row of ground beef product that will be tested. The Test Pallet is necessary because after testing is completed the temperature probes will be frozen in to the product. The operator will utilized the Test Pallet to remove the tested ground beef boxes and Test Apparatus so that the ground beef can thaw to the point that the temperature probes can be removed.
6. **Blast Freezer Log Sheet:** Log sheet for testing where the blast cell that testing occurs in, testing start date and time, and testing end date and time are manually recorded.

STEPS TO COMPLETE PRIOR TO TESTING

The following steps will need to be completed before conducting tests. The steps only need to be done prior to the first tests. They will not be required for subsequent tests.

1.0 Install TempRecord Software

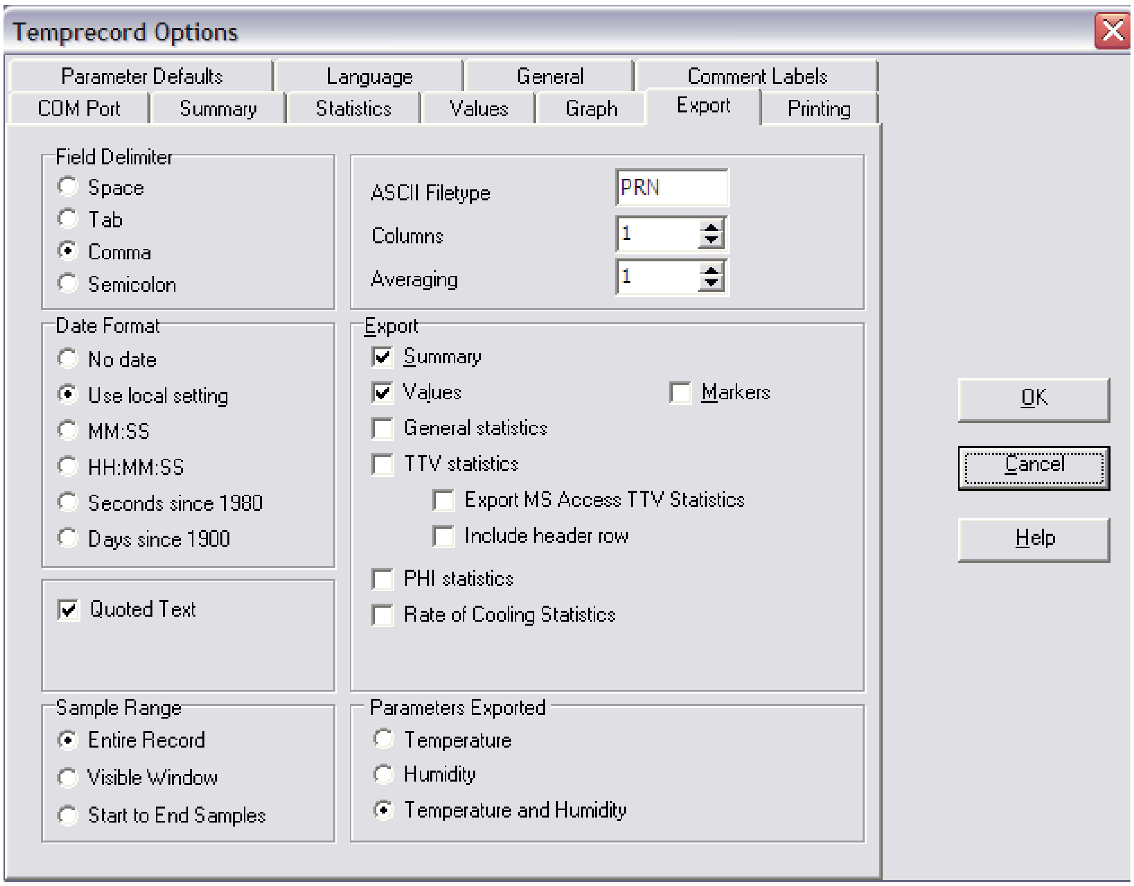
These are instructions for installing the TempRecord software on a laptop computer:

1.1 Insert software CD
1.2 Open file software.html
1.3 Select TempRecord for Windows 32 bit
1.4 Insert TempRecord Logger (blue device) into TempRecord Reader Interface (grey device)
1.5 Plug in TempRecord Reader Interface USB port into computer
1.6 A Found New Hardware Wizard should pop up. Select ok for this installation.

2.0 Set TempRecord Software Parameters

These steps are to set up the general parameters for how the TempRecord loggers track and output data. This process only needs to be performed once.

2.1 Open TempRecord software
2.2 Go to **Options => General**
2.3 Click on the **Export** tab and select the same options as shown below:



2.4 Click on the **General** tab
2.5 Under **Units** select **Fahrenheit**

3.0 Complete Assembly of Test Apparatus

There are a few final assembly instructions for the Test Apparatus:

3.1 The Test Apparatus was shipped with 11 TempRecord data loggers. USCS Fresno has the 12th logger. Place the 12th logger in the Test Apparatus and use a zip tie to mount the temperature probe wire to the Test Appartus, similar to the other wires.

3.2 A plastic bag was included with the Test Apparatus. Within the bag are printed labels for the 12th logger and temperature probe. Place a label on the 12th logger and the temperature probe.

3.3 The bag also includes for handles. Mount the handles to the external wall of the Test Apparatus to aid in carrying.

3.4 The bottom of the Test Apparatus should be equipped with some method to provide approximately 1" of clearance above the ground beef boxes. This will allow air flow along the top surface of the box. A slip sheet is generally utilized in between rows of boxes to create this clearance. A slip sheet can be mounted to the bottom of the Test Apparatus. If so, drill holes through the temperature probe insertion points through the slip sheet so the temperature probes can readily pass through the slip sheet. As an alternate to a slip sheet, "feet" could be mounted on the bottom of the Test Apparatus. The feet would elevate the Test Apparatus above the boxes 1" and would be spaced such that they would provide minimal blocking of air flow. **The advantage of mounting feet on the bottom of the Test Apparatus is that it would allow a forklift to be able to pick up the Test Apparatus.**

4.0 Construct Test Pallet

Assemble the Test Pallet that the row of ground beef product to be tested will sit on.

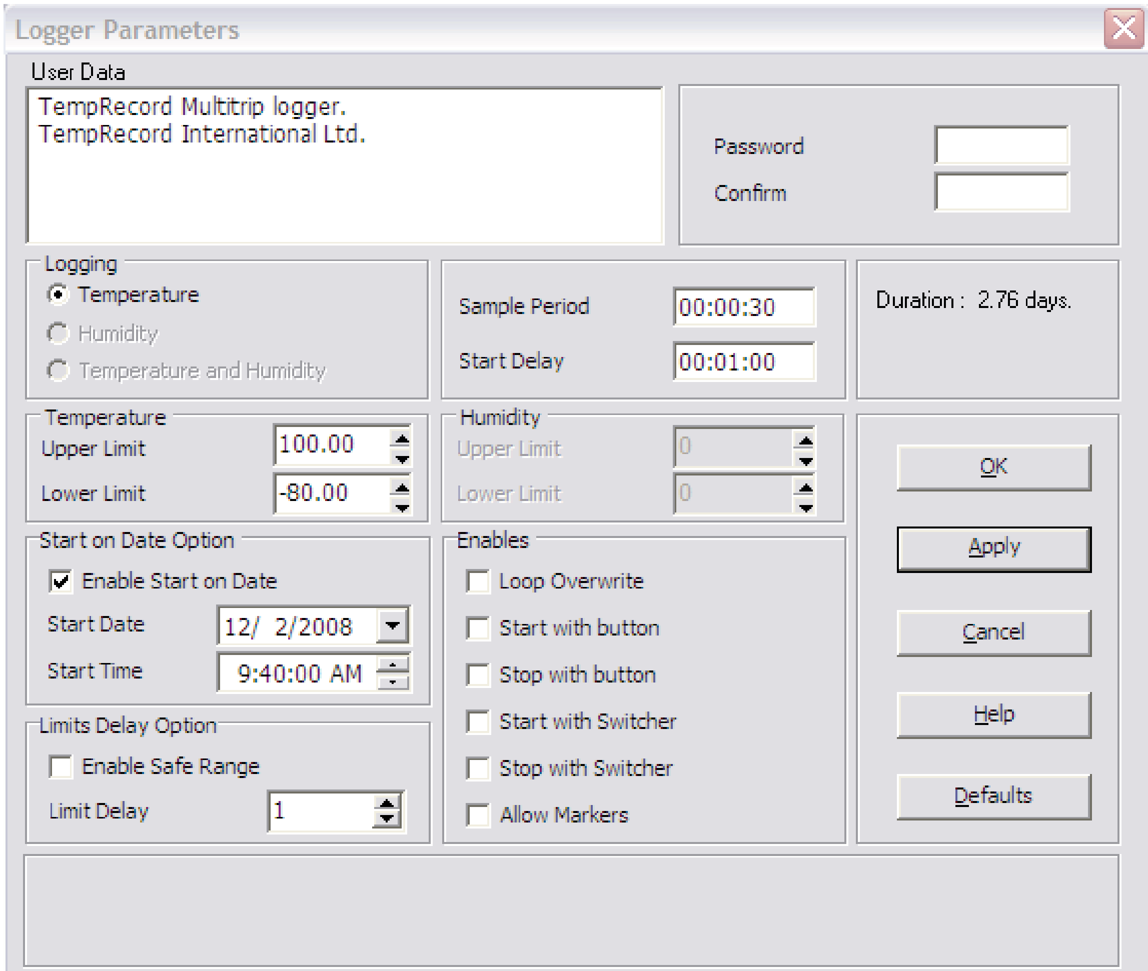
4.1 Mount a slip sheet on the top of a pallet.

BLAST FREEZE TEST INSTRUCTIONS

The following procedure lists the steps necessary to complete one blast freeze test. This process will need to be followed for each test run.

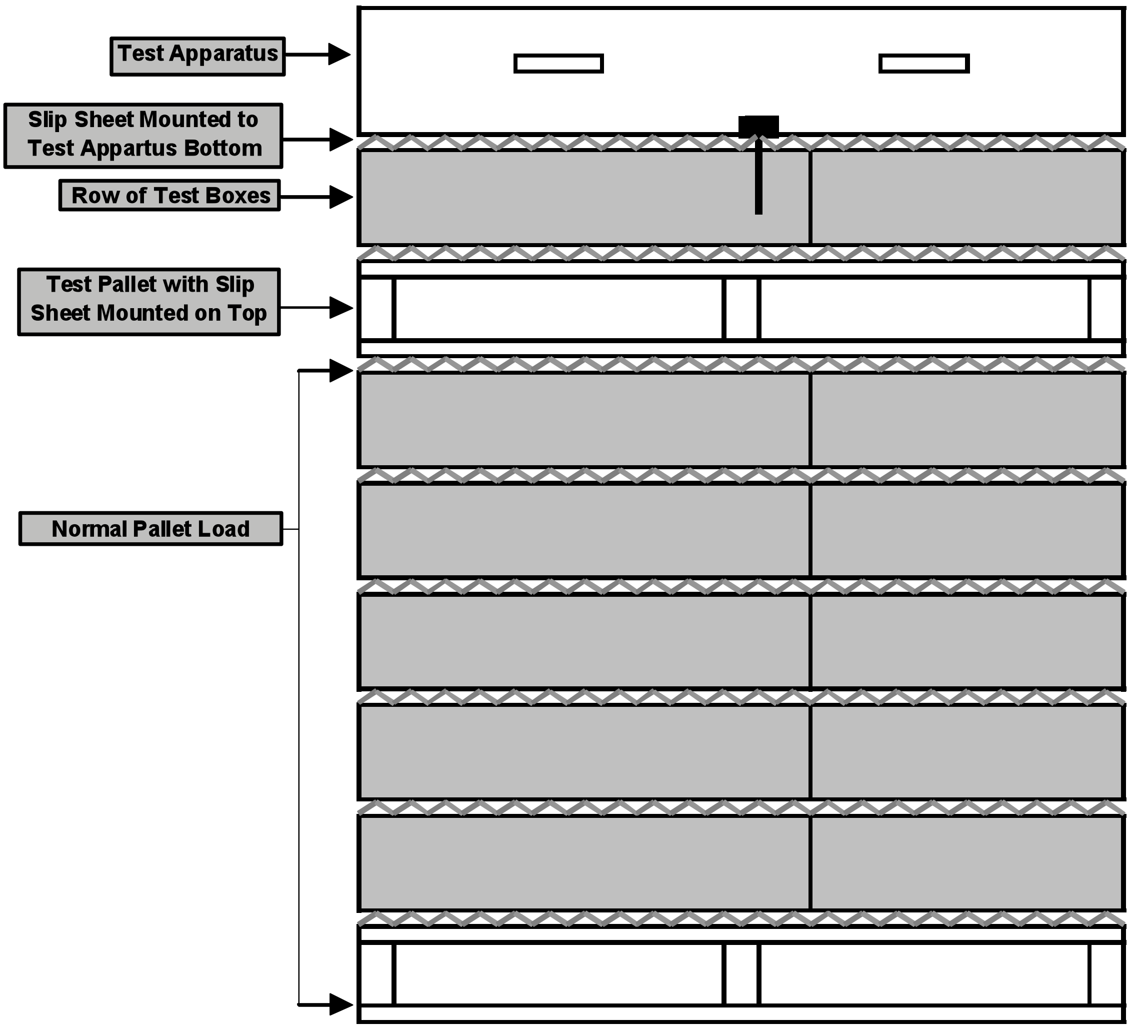
1.0 Program TempRecord Data Loggers

1.1 Open TempRecord software
1.2 Insert TempRecord Logger #1 (blue device) into TempRecord Reader Interface (grey device)
1.3 Plug in TempRecord Reader Interface USB port into computer
1.4 Select **Program => Stop Logger**, select **Yes** under "Do you wish to stop the TempRecord logger?"
1.5 Select **Program => Re-Use Logger**, select **Yes** under "Do you wish to re-use TempRecord logger?" and select **No** under "The data from this logger has not yet been read. Do you with to read the data and save it before re-using the logger?" (Note that after each test run the data will be downloaded and saved from the TempRecord loggers so it is okay to not save the data again a this point.)
1.6 Select **Program => Parameters**
1.7 Under **Temperature**, set the **Upper Limit** to **100** and **Lower Limit** to **-80** (see below)
1.8 Under **Start on Date Option**, check **Enable Start on Date** and set the date and time to when you want logging to begin (see below)
1.9 Set the **Sample Period** to **00:00:30** (30 seconds) (see below)
1.10 Select **Apply**
1.11 Select **OK**
1.12 Repeat the above steps for Logger #2 through Logger #12. **Ensure that the same Start Date, Start Time, and Sample Period are programmed for each logger.**


Logger Parameters
User Data
TempRecord Multitrip logger.
TempRecord International Ltd.
Password
Confirm
Logging
Temperature
Humidity
Temperature and Humidity
Sample Period
00:00:30
Start Delay
00:01:00
Duration : 2.76 days.
Temperature
Upper Limit
100.00
Lower Limit
-80.00
Humidity
Upper Limit
0
Lower Limit
0
OK
Apply
Cancel
Help
Defaults
Start on Date Option
Enable Start on Date
Start Date
12/ 2/2008
Start Time
9:40:00 AM
Enables
Loop Overwrite
Start with button
Stop with button
Start with Switcher
Stop with Switcher
Allow Markers
Limits Delay Option
Enable Safe Range
Limit Delay
1

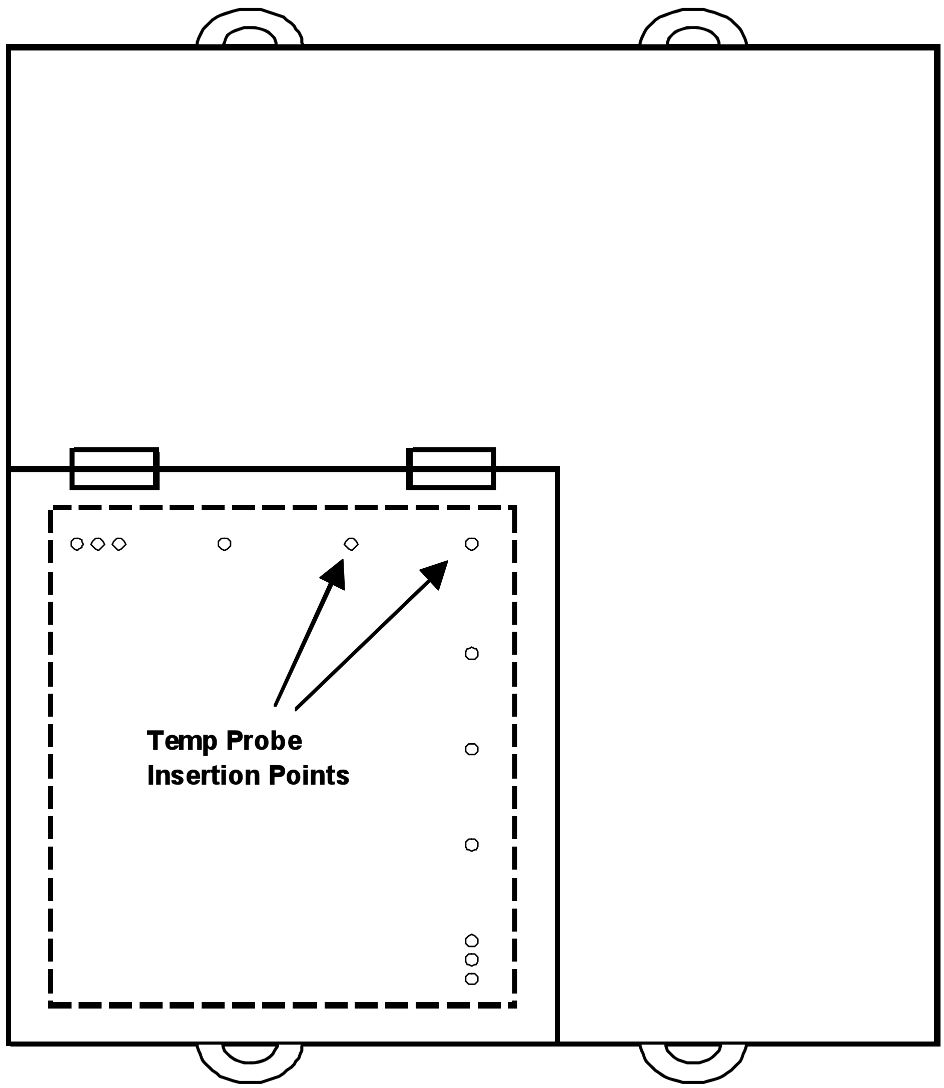
2.0 Loading Test Apparatus

2.1 Testing will only be performed on 16" x 24" ground beef boxes that are stacked with 5 boxes per row. For the first phase of testing, the test apparatus will measure the top row of beef boxes on the pallet. A sketch of how a pallet load would be assembled for testing is shown below:



2.2 Load one row of boxes on the Test Pallet to be tested.
2.3 Place the Test Apparatus on the top row of ground beef boxes to be tested. **<u>It is critical that the test box is oriented correctly on the ground beef boxes.</u>** See the drawing on top of the Test Apparatus that shows the correct orientation of ground beef boxes below.
2.4 Open the hinged door of the Test Apparatus.
2.5 Sterilize the 12 temperature probes in the Test Apparatus.

2.6 Insert the 12 temperature probes through the drilled holes in the test box into the beef. Each temperature probe is labeled 1 through 12 and corresponds to the labeled holes 1 through 12. A top view of the Test Apparatus is shown below:



2.7 Close the hinged door of the Test Apparatus.

2.8 Document the date, time of the start, and blast cell for test on the "Blast Freezer Test Log Sheet".

2.9 Load test pallet load into the Blast Cell. Do not use any Blast Cells that are equipped with additional booster fans. **The pallet is to be loaded on the second row of racking from the bottom, on the right hand side of the cell in the front row.**

3.0 Unloading the Test Apparatus

3.1 Remove the Test Pallet with the row of test boxes and Test Apparatus and place on the dock to thaw.
3.2 Document date and time of the end of the blast cycle "Blast Freezer Test Log Sheet".
3.3 Remove the temperature probes once the beef has thawed enough to allow removal.
3.4 Clean and sterilize temperature probes.
3.5 Remove beef boxes and move test box to shop.

4.0 Download TempRecord Data Loggers

4.1 Open TempRecord software
4.2 Insert a TempRecord Logger (blue device) into TempRecord Reader Interface (grey device)
4.3 Plug in TempRecord Reader Interface USB port into computer
4.4 Select **File => Read Logger**
4.5 Once the download is complete, select **File => Save File**
4.6 Create a folder to save each of the 12 logger download files in. The folder should be named according to the following convention based on the test start data: "YYYY-MM-DD Blast Freeze Test". For example, for a test that begins on August 9h, 2009, the following folder name would be created: 2009-08-09 Blast Freeze Test
4.7 Save the .TR file for the logger in this folder. Use the following file naming convention: "YYYY-MM-DD Logger XX.TR". For Logger #3, the file name would be: 2009-08-09 Logger 03.TR
4.8 Click **Save**
4.9 Repeat this process for each of the twelve loggers

5.0 Download M&M Control System Data, Scan Blast Freezer Log Sheet, and Email Data

5.1 On the M&M control system, create two reports, "Blast Freezer Report" and "-58 CO2 Sequencer Report". Each report should be for the entire duration of the blast cycle that was tested. Create each report with a 5 minute interval. Save both reports under the same folder that the 12 data logger downloads for the test are stored in.
5.2 Create an electronic copy of "Blast Freezer Test Log Sheet" and store in the same folder
5.3 Email the 12 data logger download files, two M&M control system reports, and a copy of the "Blast Freezer Test Log Sheet to josh.bachman@cascadeenergy.com

APPENDIX B – FAN MODULATION ANALYSIS

Fan Speed to Power Relationship

Evaporator fan energy use in the baseline and modulation cases is calculated based on recorded fan speed and run time. Fan power was not directly measured during testing. Instead, a correlation between fan power and speed was used to convert recorded fan speed to power. In general, a consistent relationship between fan power and speed exists so this approach is felt to be appropriate.

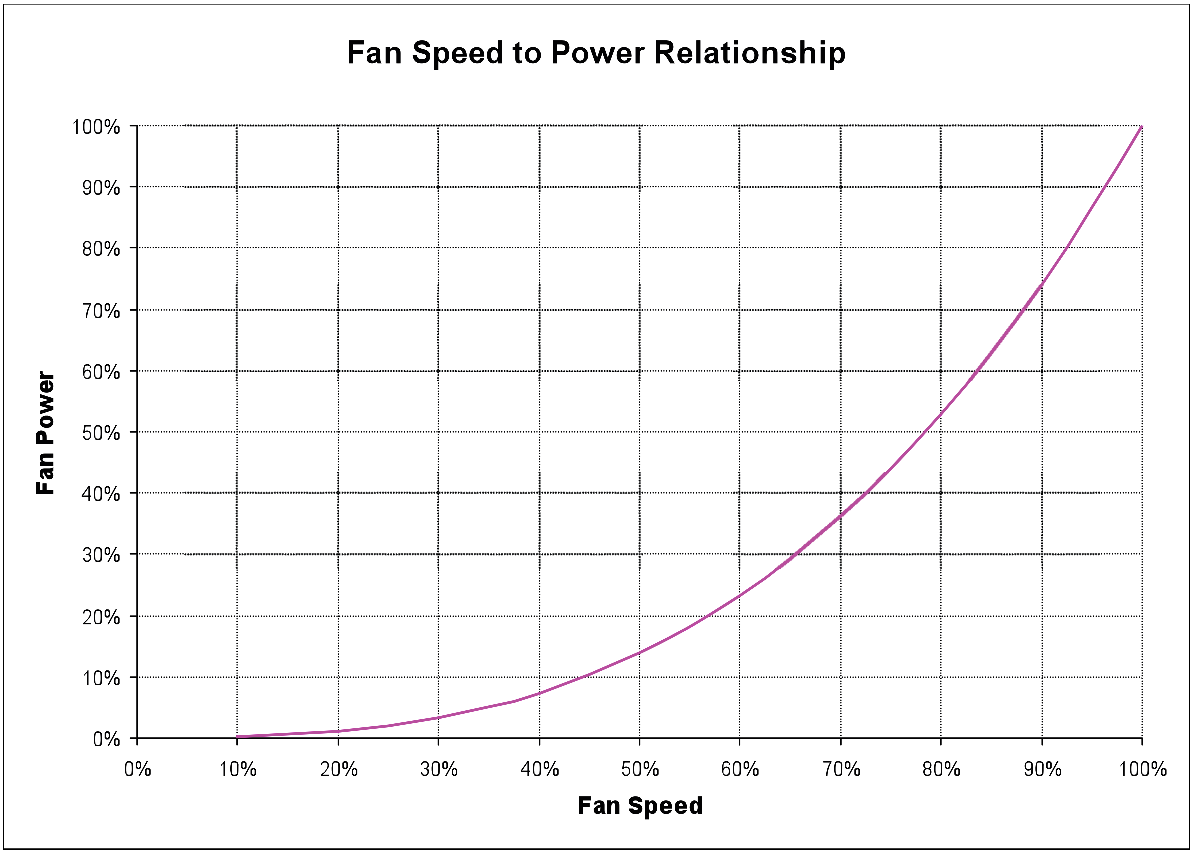
The correlation was derived from actual power readings taken on site. A three-phase power meter was used to measure total evaporator fan power in Blast Cell 7 at an array of fan speeds. The results are shown in the table below. A fan speed to power exponent of 2.85 was derived based on the data (3.00 theoretical).

Percent Fan Speed	Measured Power (kW)
50%	5.6
60%	9.4
70%	14.3
80%	21.1
92%	31.7
100%	40.1

The resulting fan speed and power relationship used in the analysis is as follows:

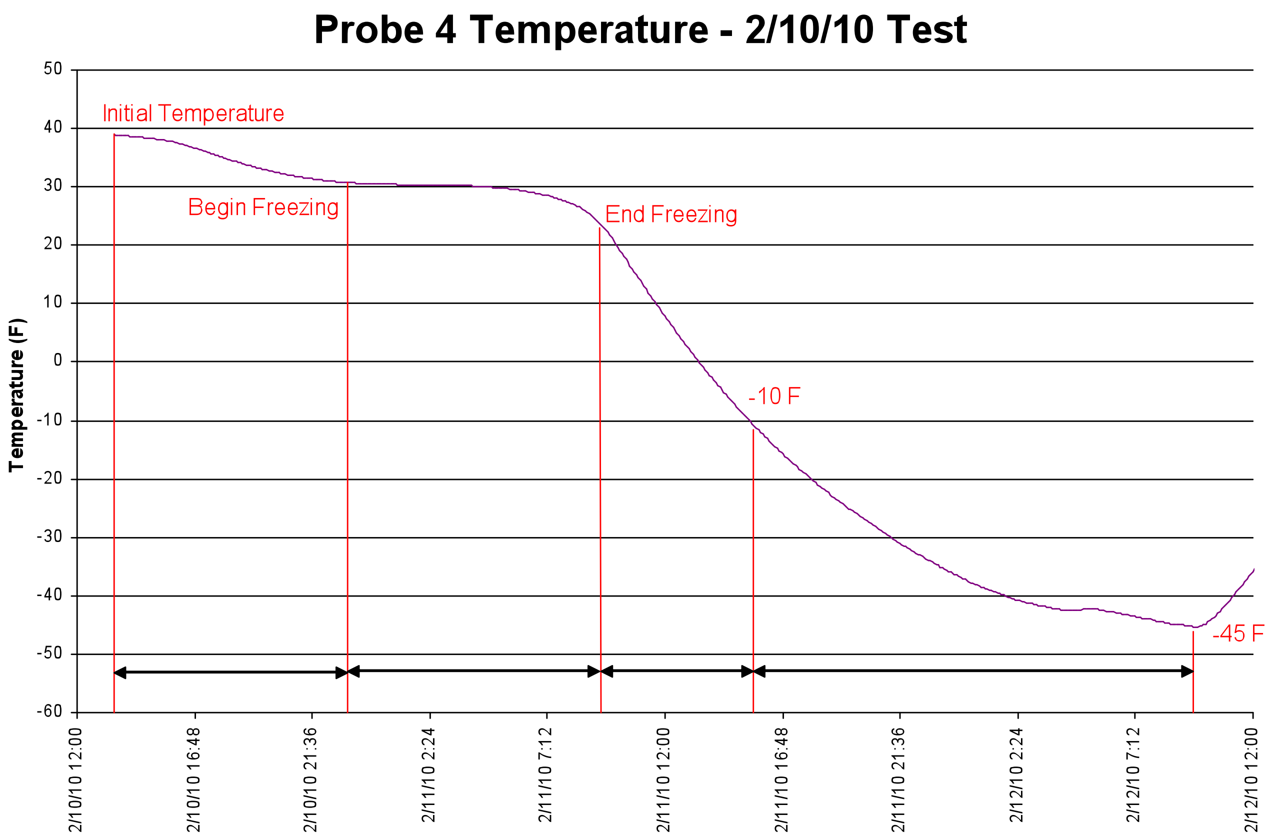
Fan Power = (Fan Speed)^2.85

A graphical representation of this relationship is shown in the chart below.



The Effect of Fan Speed on Product Cooling Rate

The performance of each test was characterized in terms of the amount of time it took for the product to reach a certain temperature. Several different final temperatures were used for the basis of comparison of different stages of cooling. An explanation of the different stages of cooling used in the analysis can be seen in the figure below.



The "initial temperature" is the temperature the product is at when the blast cycle is started. As there is significant variation between product entry temperatures from 31° to 45° F, the tests are only compared for the hours after they achieve 31° F. The "begin freezing" and "end freezing" temperature is around 31° F and 30° F, depending on the consistency of the product. Although there is slight variation of freezing temperature between tests, the main freezing zone is evident by the zone of constant temperature. There also appears to be a shoulder zone at the end of the freezing stage before the beginning of a more rapid rate of temperature change. This is most likely due to final freezing crystallization of a small portion of the product. For the sake of analysis, the freezing and shoulder hours are grouped together. Tests were compared for two different final temperatures, -45° F and -10° F. The current practice is to cool product to a final temperature of -45° F or lower, but it is expected that the final product target temperature could be increased to -10° F.

In all tests, the worst case temperature probe was used for the basis of comparison. In other words, the last temperature probe to reach each temperature threshold was used to characterize the whole test. This was typically probe 4, 5 or 6, as these probes were in the center of the pallet.

The following table summarizes the cooling performance of different fan speed settings observed during the testing. The result of each fan speed setting is the combined average of three tests. The first column reads the average number of hours it took for the test to cool the product from just above freezing to the start of steep slope. The second and third columns read the average number of hours it took for the test to cool the product from the start of steep slope to -10° F and -45° F respectively. Several cells are blanked out because they were not included in the testing runs.

Fan Speed Versus Cooling Performance Comparison

	Freezing Hours	Frozen to -10 F Hours	Frozen to -45 F Hours
Baseline	10.9	10.7	21.8
70% Fan Speed	10.7	12.3	
50% Fan Speed	14.3		22.5
30% Fan Speed		17.3	30.9

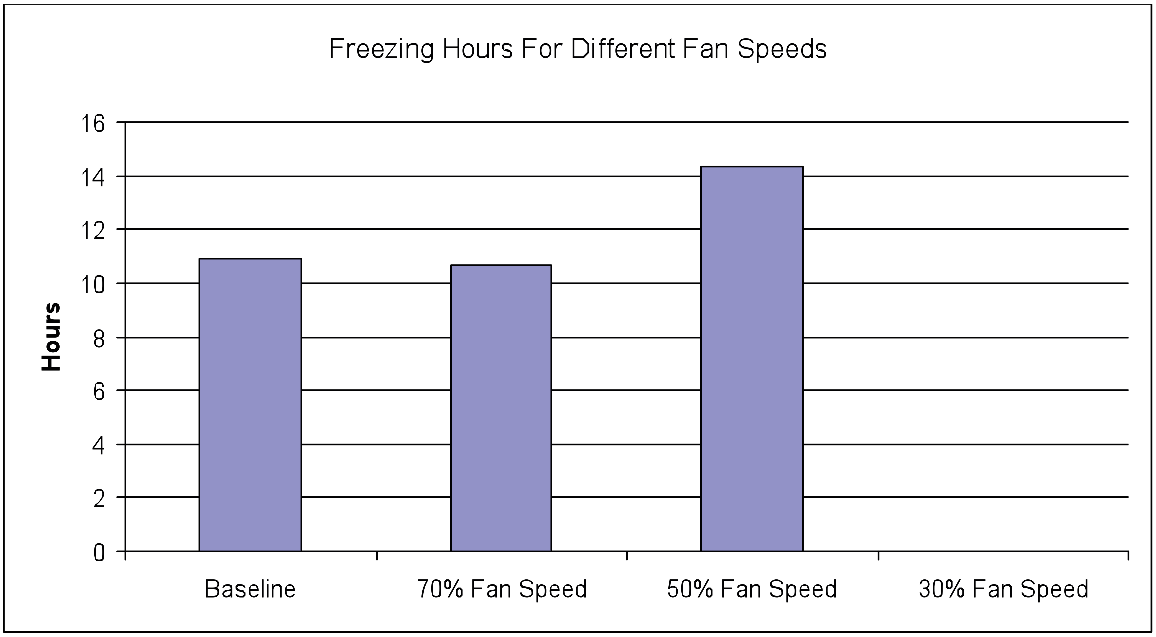
The same table is shown below, but expressed in terms of a percentage of time increase over the baseline. Note that during freezing, the 70% fan speed shows a negligible increase over the baseline, while the 50% fan speed shows a 31% increase over the baseline. This suggests that the fans can be reduced as low as 70% speed during the freezing stage with little loss in cooling performance. Also note that for both the post freezing stages, the 70% and 50% fan speeds show a small increase over the baseline, while the 30% fan speed shows a large increase. This suggests that the fans can be reduced as low as 50% speed during the post freezing stage with little loss in cooling performance. Thus, the final recommendation for fan speed settings is 70% during the freezing stage and 50% during the post freezing stage.

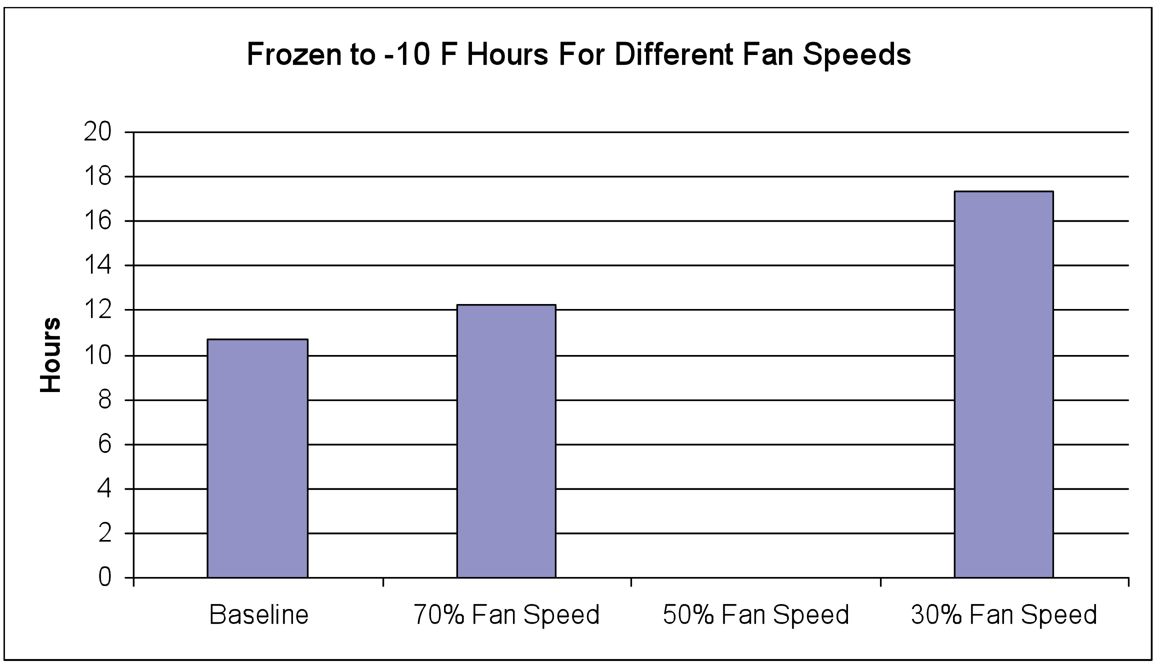
Fan Speed Versus Cooling Performance Comparison

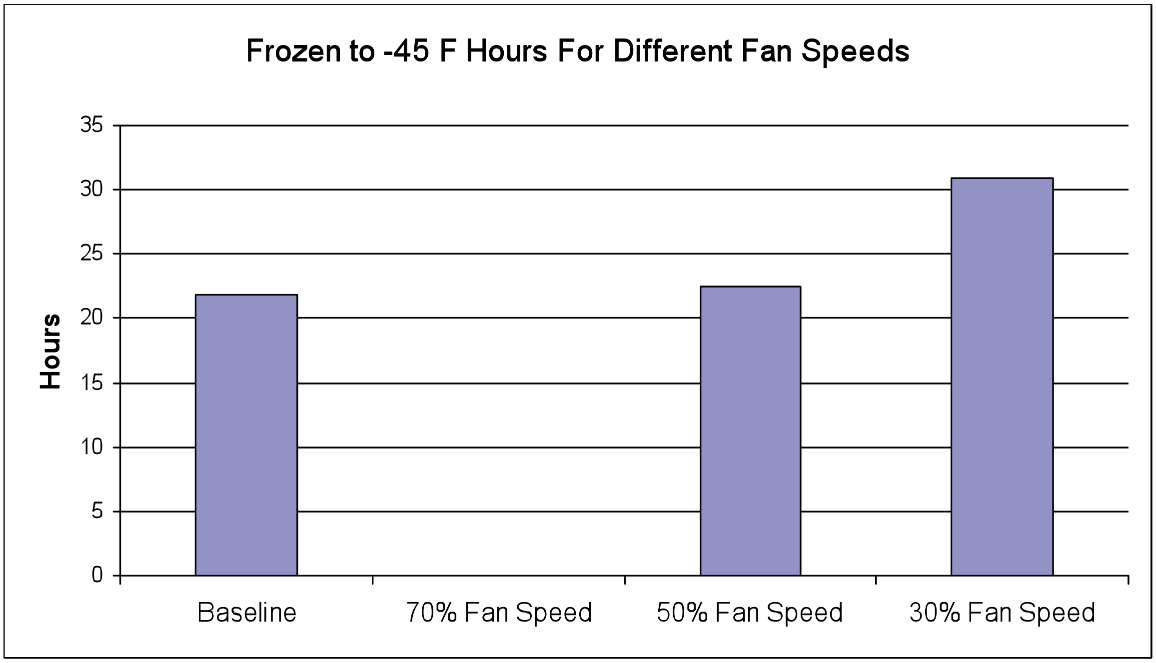
(Percentage increase over baseline)

	Freezing Hours	Frozen to -10 F Hours	Frozen to -45 F Hours
Baseline			
70% Fan Speed	98%	115%	0%
50% Fan Speed	131%	0%	103%
30% Fan Speed		162%	142%

A graphical interpretation of these results is shown in the next three figures.


Freezing Hours For Different Fan Speeds
Hours
16
14
12
10
8
6
4
2
0
Baseline
70% Fan Speed
50% Fan Speed
30% Fan Speed


Frozen to -10 F Hours For Different Fan Speeds
Hours
20
18
16
14
12
10
8
6
4
2
0
Baseline
70% Fan Speed
50% Fan Speed
30% Fan Speed



Frozen to -45 F Hours For Different Fan Speeds
Hours
35
30
25
20
15
10
5
0
Baseline
70% Fan Speed
50% Fan Speed
30% Fan Speed

APPENDIX C - Refrigeration System Analysis

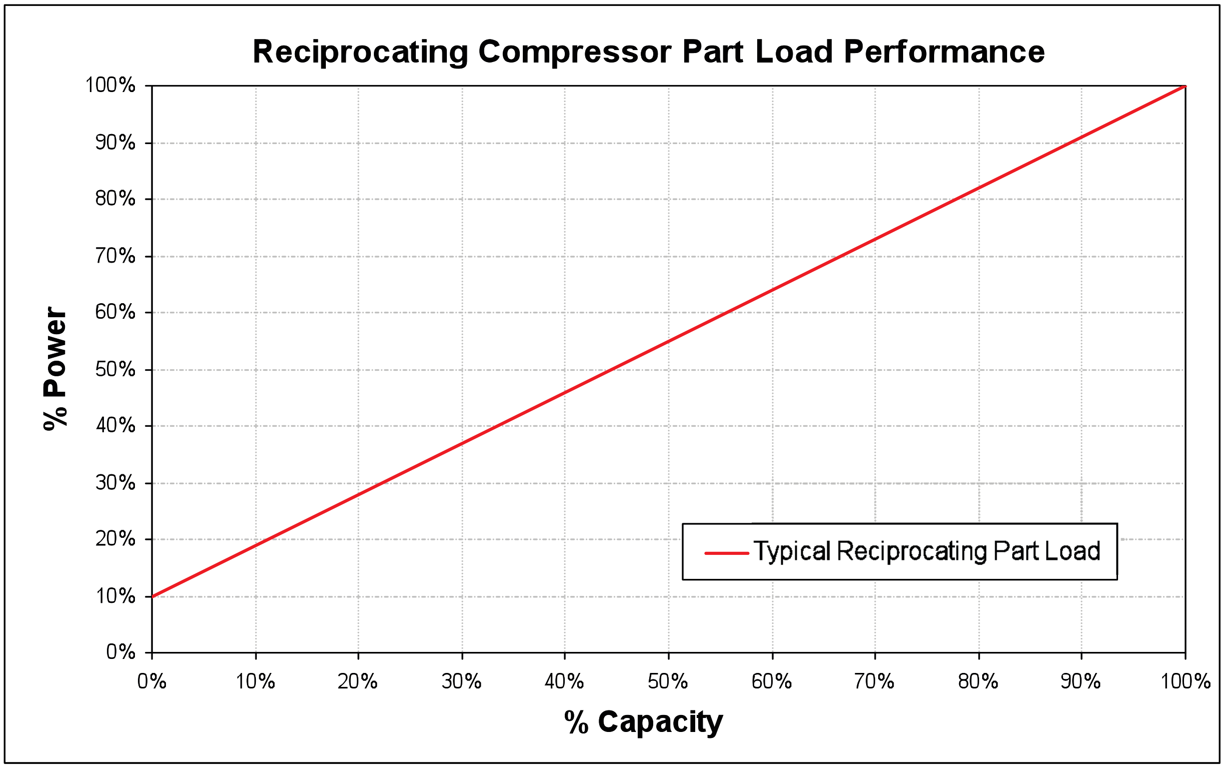
Refrigeration System Summary

In order to quantify the refrigeration system energy savings potential associated with fan speed reduction, the refrigeration system was analyzed. The refrigeration system is made up of a two stage ammonia and CO2 system. The low stage is CO2 with a -58° F design suction temperature and three reciprocating compressors. The high stage is ammonia with a +11° F design suction temperature and three economized screw compressors. The ammonia system is served by evaporative condensers. There is a heat exchanger between the CO2 and ammonia systems. A summary of the compressors is shown in the table below.

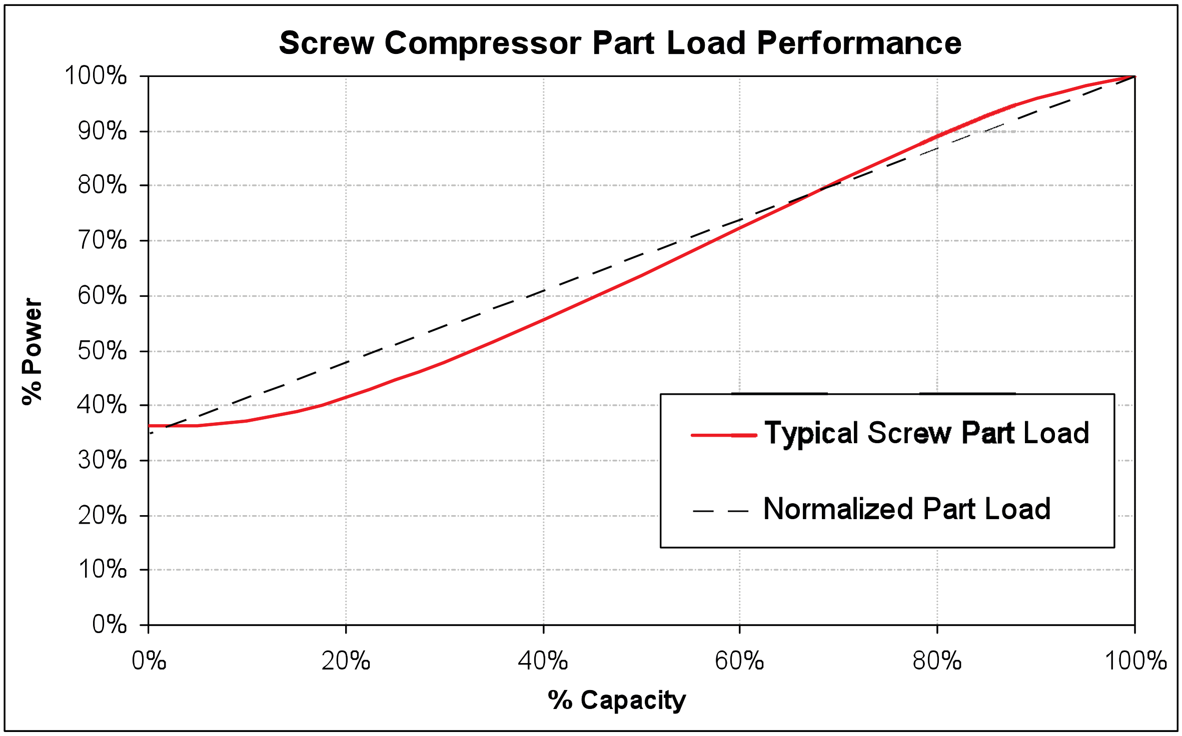
Compressor	System	Type	Rated Capacity (TR)	Rated Power (BHP)	Rated Suction (F)	Rated Discharge (F)
RC 1-3	CO2	Reciprocating	123	154	-58	+20
SC 1	Ammonia	Screw	258	286	+11	+90
SC 2-3	Ammonia	Screw	425	455	+11	+90

Refrigeration System Energy Savings

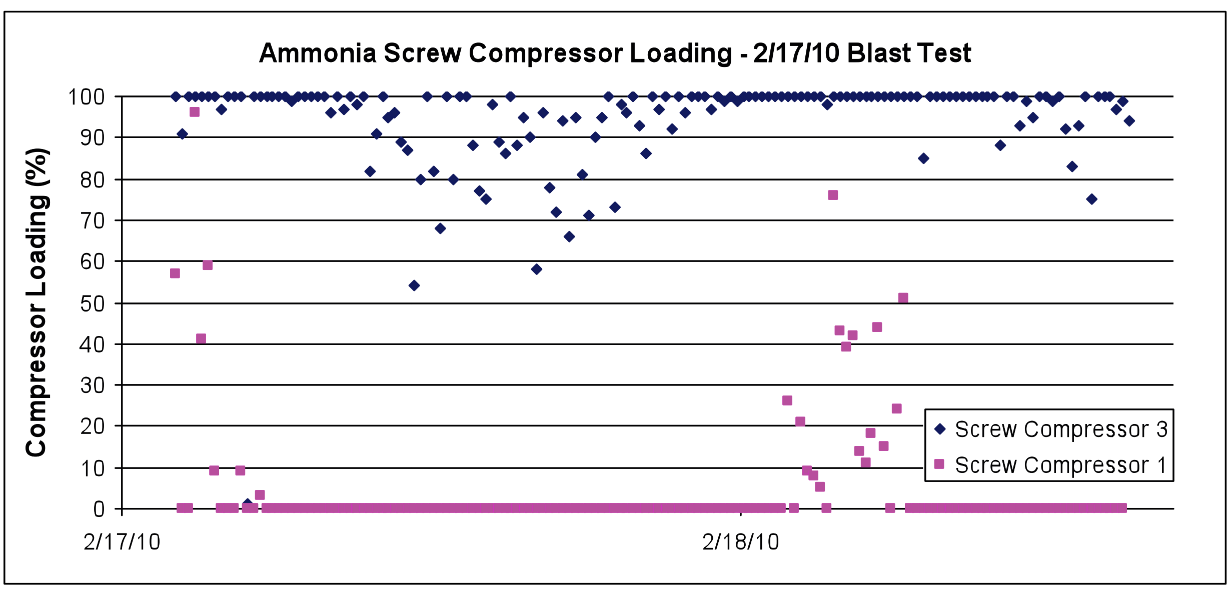
The facility operates many blast cells concurrently on the same refrigeration system. Since the refrigeration load from any one blast cell can't be separated from the others the refrigeration energy savings could not be directly measured during the tests. Instead, the refrigeration energy savings were calculated by subtracting the fan associated refrigeration load from the overall compressor load. All of the power that is input into the evaporator fan motors ends up as a load on the refrigeration system. As the fan speed is reduced, the input power and refrigeration load are reduced. The resulting energy savings are dependent on the compressor power reduction per unit of load reduction. The CO2 reciprocating compressors use cylinder unloading capacity control and have very good part load efficiency. As the load is reduced, the compressor power is also reduced in a linear fashion. Although actual performance data was not recorded for the site compressors, there is very consistent performance between compressors of this type and operating conditions. The relationship used in the analysis is based on the research presented in Wilbert Stoecker's *Industrial Refrigeration Handbook*, page 122. The research data was also compared to empirical data from other projects with similar compressors to ensure accuracy. The reciprocating compressor part load performance relationship used in the analysis is shown in the figure below.



The ammonia screw compressors use slide valve capacity control and have poor part load efficiency. At minimum load the compressors still use about 40% of full load power. The part load performance is not linear, but for the sake of the calculations a linear approximation was used. This was necessary to provide consistency between the tests, as the overall facility refrigeration load profile varies depending on the number of blast cells operating at any given time. Although actual performance data was not recorded for the site compressors, there is very consistent performance between compressors of this type and operating conditions. The relationship used in the analysis is based on the research presented in Wilbert Stoecker's *Industrial Refrigeration Handbook*, page 139. The research data was also compared to empirical data from other projects with similar compressors to ensure accuracy. The screw compressor part load performance relationship used in the analysis is shown in the figure below.



According to facility personnel, the ammonia system typically operates with one or two compressors loaded at a time. Either S2 or S3 is usually fully loaded, with S1 lightly loaded as the trim machine, depending on loads. An example screw compressor load profile during the 2/17/10 blast test is show below. During the test, SC 3 was loaded at 100% capacity for the majority of the time, with SC 1 lightly loaded between 0-50% capacity for only a few hours and off the remainder of the time.



The compressor power reduction was calculated according to the part load performance shown in the figures above. A reduction in load is expected to reduce the compressor power proportionally according to the slope of the linear part load relationship. For example, the reciprocating compressors are expected to reduce their power draw by 1.13 brake horse power (BHP) per ton of refrigeration (TR) in load reduction. The part load power summaries are shown in the tables below.

Typical Reciprocating Part Load Performance				
Capacity	**Power**	**TR**	**BHP**	**Slope (BHP/TR)**
100%	100%	123	154	1.13
0%	10%	0	15	

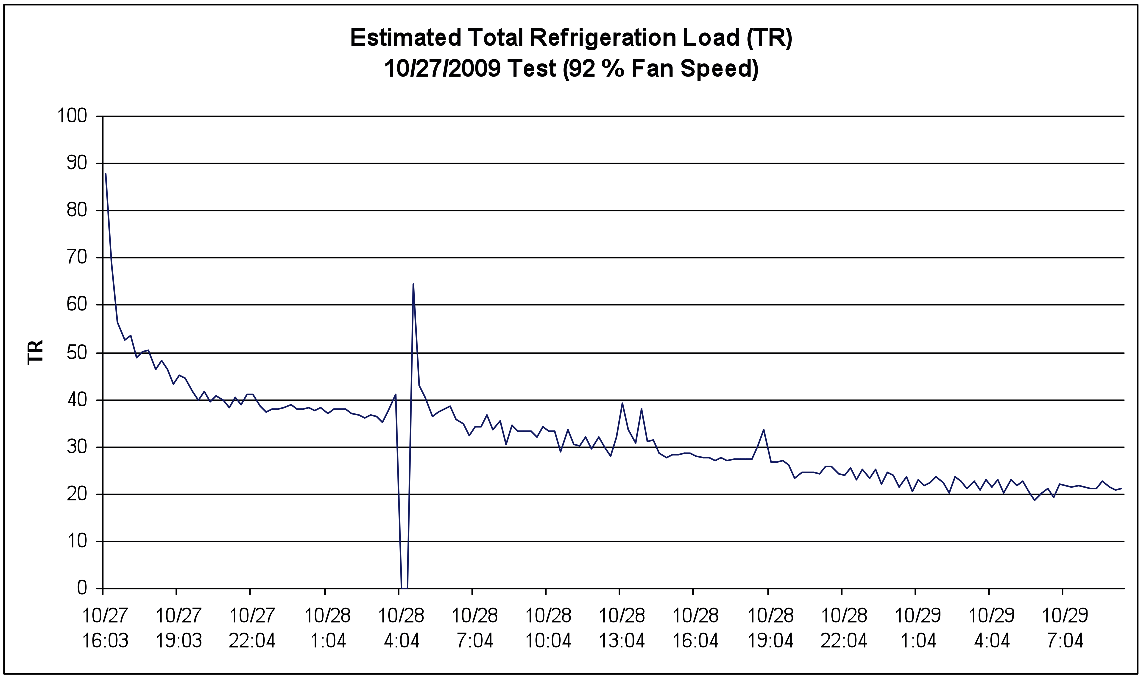
Normalized Screw Part Load Performance				
Capacity	**Power**	**TR**	**BHP**	**Slope (BHP/TR)**
100%	100%	425	455	0.70
0%	35%	0	159	

Accounting for compressor motor efficiency and converting to more convenient units provides the relationship in the table shown below. The first column shows compressor BHP power reduction per TR load reduction. The second column shows compressor motor kW power reduction per TR load reduction. The third column shows compressor motor kW power reduction per kW fan power reduction. In summary, the compressor power is expected to be reduced by 0.42 kW per each reduction in evaporator fan kW. For example, if the evaporator fan power is reduced by 10 kW, the compressor power is reduced by 4.2 kW.

Compressor	BHP/TR	kW/TR	Compressor kW /Fan kW
Recip	1.13	0.89	0.25
Screw	0.70	0.55	0.16
Total	**1.82**	**1.44**	**0.41**

Reduced Blast Cycle Run Time

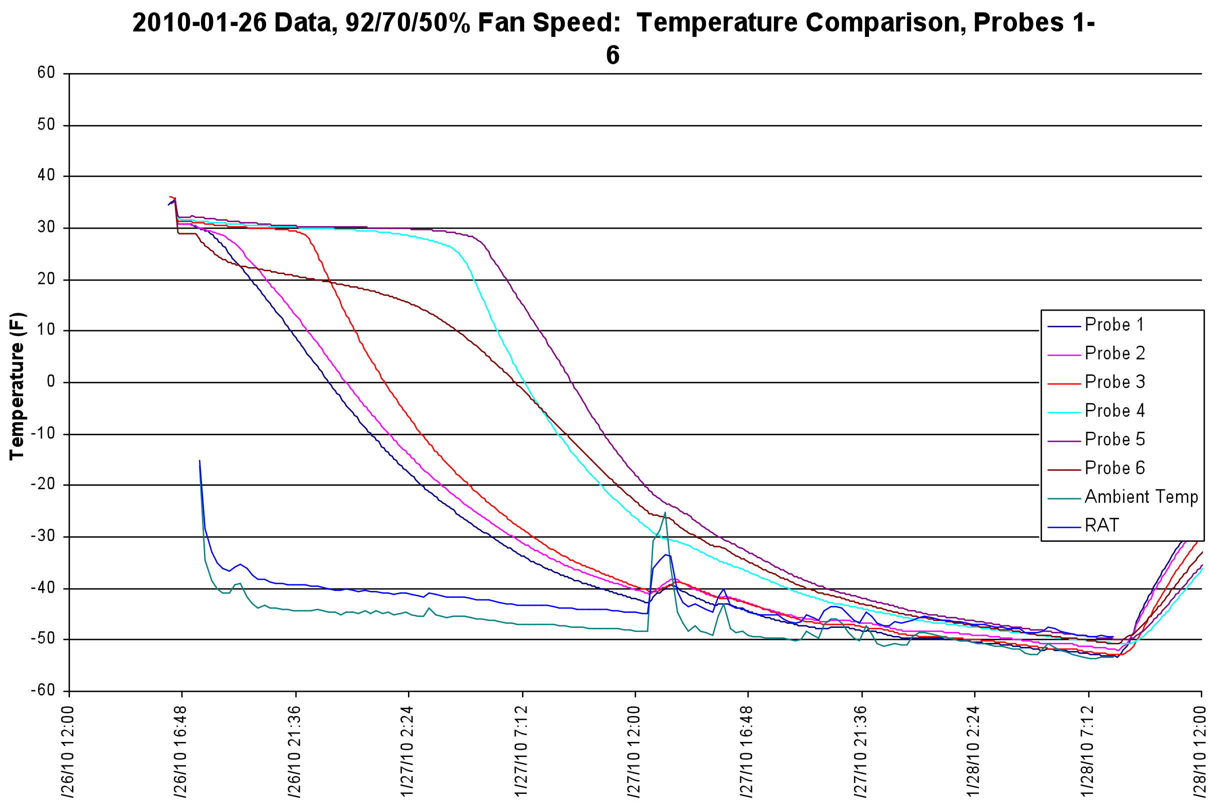
The refrigeration energy savings associated with reduced blast cycle run time are made up of both fan load and product load reduction. The fan load reduction is predictable, but the product load varies according to the amount and type of product in each blast. In order to compare the different blast tests objectively, a normalized refrigeration load was used. The normalized load was chosen based on observations from the testing. The hourly evaporator load from the baseline tests was calculated based on evaporator rated capacity and actual operating conditions. This showed that the average refrigeration load during the last stage of the blast cycle was 21 tons of refrigeration (TR) on average. With the evaporator fans set to 100% speed, the fans make up 11.4 TR of the total load. With the evaporator fans set to 92% speed, the fans make up 9 TR of the total load. The fan energy savings are calculated separately, so to determine the product load, the fan load is subtracted from the total load. Therefore, the product associated load is approximately 12 TR. An example of the evaporator load profile for the 10/27/2009 blast test is shown below.



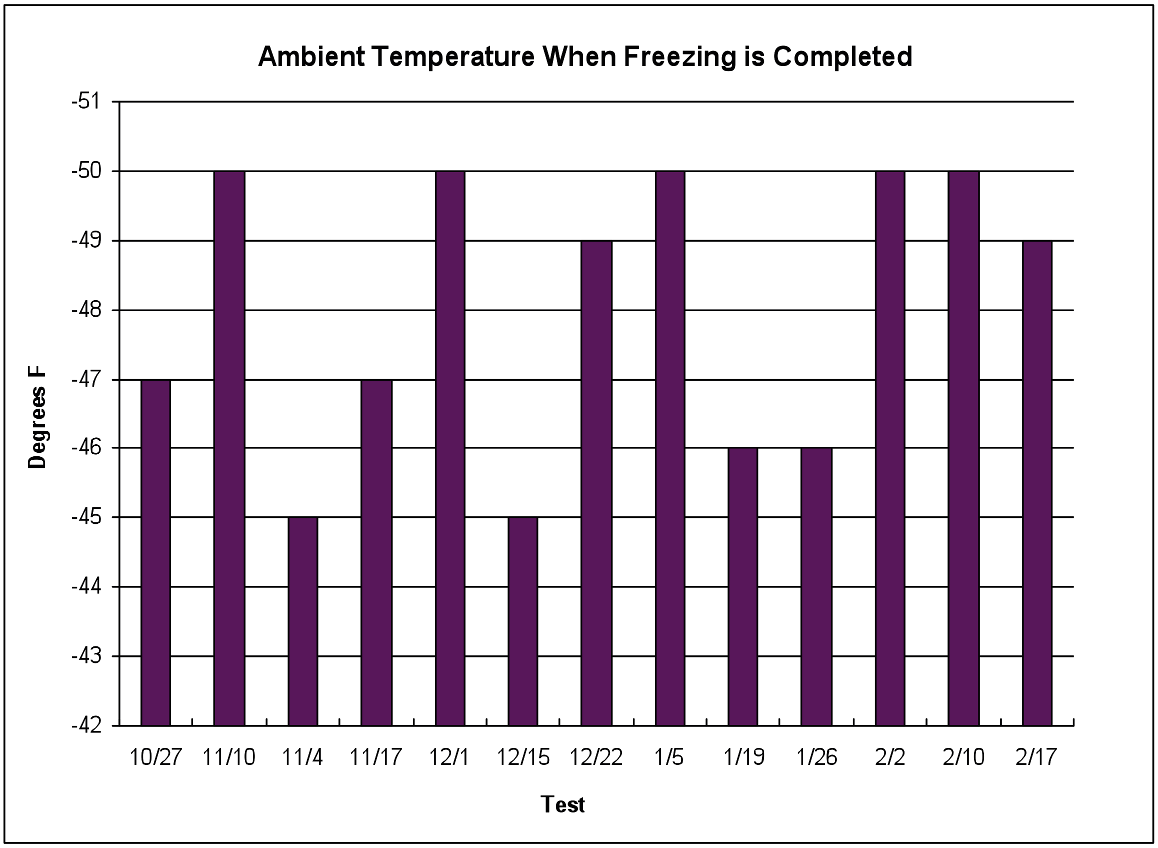
For the sake of calculating energy savings, a standard load reduction of 12 TR was assumed for the hours of reduced blast cycle time. For example, in the proposed case that the blast cycle time would be reduced from 40 hours to 25 hours, the refrigeration system load is expected be reduced by 12 TR over 15 hours. The resulting compressor energy savings are calculated according to the compressor power vs. load correlations determined in the previous section. Again, this calculation is normalized to an average refrigeration load seen in the baseline testing in order to objectively compare different test runs. The actual energy savings associated with reduced blast cycle run time would be based on annual product throughput and type.

APPENDIX D - Alternate Control Algorithms

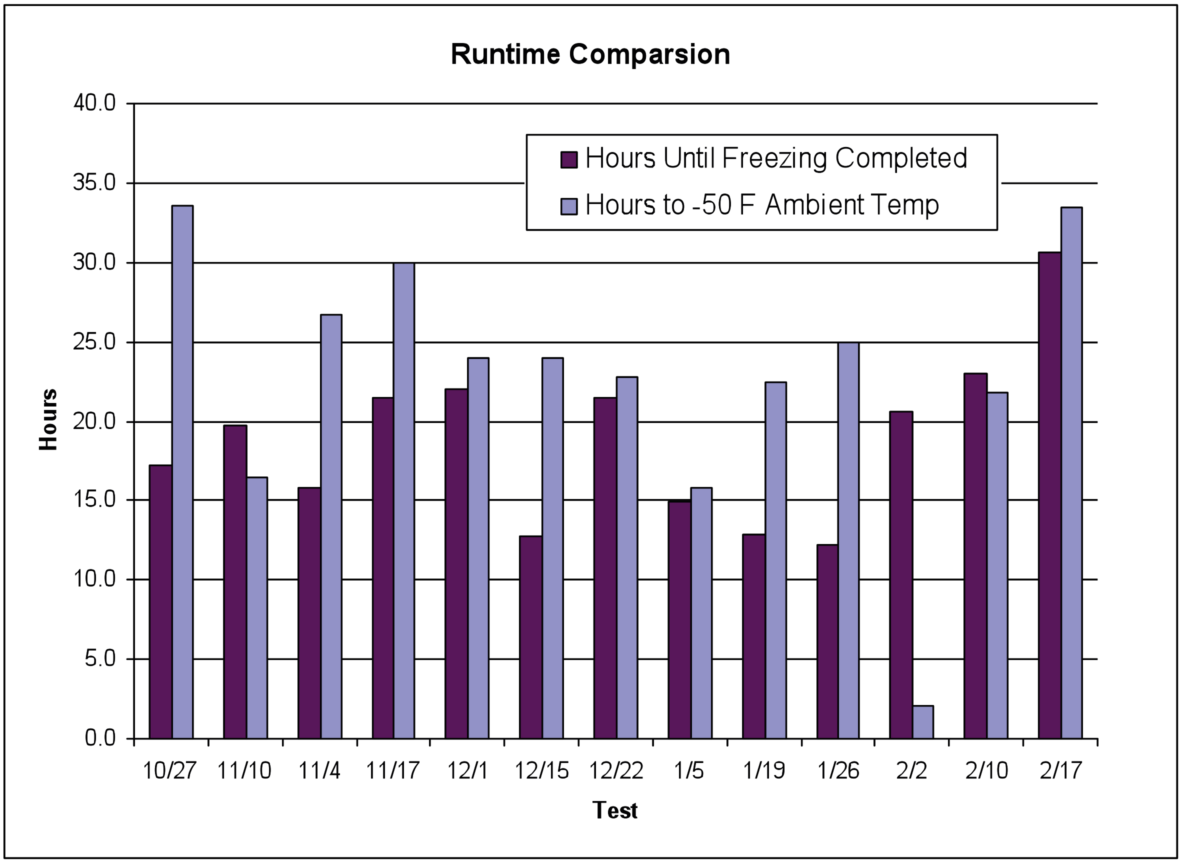
In order to optimize fan speed control algorithm performance, several options were considered in addition to the simple time delay strategy. These options attempt to use a feedback control mechanism to modulate fan speed based on another input variable. The input variables considered were blast cell ambient air temperature and evaporator return air temperature. These variables are already incorporated into the computer control system. An example of the temperature profiles from the 1/26/2010 test including ambient air temperature and return air temperature is shown below.



Note that the return air temperature and ambient temperature have a similar profile, but are offset by a few degrees. The proposed control strategy is to use one of these inputs to control the fan speed reduction. As can be seen in the above figure, the ambient air temperature gradually decreases as the blast cycle progresses. The concept is to correlate an ambient air temperature that corresponds to the point at which the product achieved the "post-freezing" stage of cooling. If there is a strong correlation then this would provide an effective control strategy to reduce fan speed at the correct time. Investigation of the available test data shows that there is not a strong correlation between a particular ambient air temperature and the stage of product cooling. It is likely that the ambient air temperature is affected by many of the same variables that cause inconsistencies between tests, including variations in product type and loading in a particular blast cycle. The chart below shows the ambient air temperature for each test at the time when the "post-freezing" stage of cooling is achieved. Note that the typical "worst case" ambient air temperature is -50° F. This would indicate that an appropriate ambient air temperature that fan speed could safely be reduced at is -50° F.



According to the test data, the amount of time it typically takes for the blast cell to reach -50° F ambient air temperature is 23 hours. Because the time delay control is set to reduce fan speed after 22 hours anyway, it is clear that this control strategy would not be effective. In addition, there were several tests in which the ambient air temperature reached -50° F before the "post-freezing" stage was achieved. In these cases, fan speed would have been reduced prematurely with an ambient air temperature control strategy. A comparison of test runtime until "post-freezing" and -50° F ambient air temperature are achieved is shown in the chart below.



Also explored was the concept of gradually decreasing fan speed either at a set rate or based on feedback control. For similar reasons this approach does not appear to be viable.

ATTACHMENT I – Test Data