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DEVELOPMENT OF A DEMAND DEFROST CONTROLLER

Final Report

Prepared for

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ENERGY RESEARCH AND DEVELOPMENT AUTHORITY**

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MASTER

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ABSTRACT

The purpose of this project was to develop and commercialize a demand defrost controller that initiates defrosts of refrigeration systems only when required. The standard method of control is a time clock that usually defrosts too often, which wastes energy. The controller developed by this project uses an algorithm based on the temperature difference between the discharge and return of the display case air curtain along with several time settings to defrost only when needed.

This controller was field tested in a supermarket where it controlled defrost of the low-temperature display cases. According to test results the controller could reduce annual energy consumption by 20,000 and 62,000 kWh for hot gas and electric defrost, respectively.

The controller saves electric demand as well as energy, is adaptable to ambient air conditions, and provides valuable savings throughout the year. The savings are greatest for low-temperature systems that use the most energy.

A less tangible benefit of the demand controller is the improvement in food quality that results from fewer defrosts.

KEY WORDS: Defrost, refrigeration, control, supermarket.

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SUMMARY

Frost accumulates in refrigeration systems and must be removed for proper operation. Standard freezers use timers which are typically set to melt the frost that builds up on the most humid day of the year. This approach wastes energy on less humid days. The PKI demand defrost controller developed under this project employs an algorithm which uses the temperature difference between the discharge and return of a display case air curtain, along with several time settings, to perform defrosts only when needed. PKI received a patent on this "smart" control method on February 19, 1991 (U.S. Patent 4,993,233). In 1991 the U.S. Department of Energy awarded PKI one of 51 national awards for Energy Innovation for the demand defrost control device.

Other "smart" control methods have not been successfully introduced for three reasons: Freezer efficiency has not been a primary concern of food handlers or utilities, time clocks are very reliable and inexpensive, and other demand systems have proven unreliable, too complex, or too expensive. However, markets are changing. Utilities are being rewarded for saving energy and a scheduled ban on chlorofluorocarbons (CFCs) used in refrigeration will focus food purveyors' attention on efficiency. New refrigerants and insulation which do not contain CFC's are expected to require 20% more energy to achieve the same operating temperatures. PKI's controller has demonstrated a reliable way to detect frost and can be incorporated into new and existing refrigeration systems at low cost.

This project was a three-phase effort which tested five hardware versions of the controller in both the laboratory and in an operating supermarket on low and medium temperature rack refrigeration systems. In the supermarket the low temperature system consisted of three compressors with two satellite compressors refrigerating eight circuits of display case freezers and four circuits of walk-in freezers all with hot gas defrost. The medium-temperature system consisted of five compressors refrigerating ten circuits with a combination of hot gas and off-cycle defrost.

The field tests in the supermarket consisted of many months of approximately two-week periods of conventional time clock operation followed by two weeks of operation with demand defrost control. A data acquisition system installed by this project monitored refrigeration rack and case performance as well as electrical usage to enable comparison between the time clock and the demand defrost controller.

Commercial freezer cases can be defrosted either by recycling hot compressor gas through the evaporator coils or by using electric resistance heaters directly in the case. With each method, compressors must cool down the case after the defrost cycle. Reducing the number of defrosts, lowers the electrical energy consumption both to melt frost and recool the case. In a hot-gas defrost refrigeration system, PKI's defrost controller on a rack of eight low temperature freezer cases reduced the number of defrosts from 16 to 5.2 per day. Annualized this would generate a savings of 20,000 kWh. When electrical defrost is used, an additional 42,000 kWh in electric heater consumption would be saved for a total of 62,000 kWh. The total value of the savings per year for the freezer owner at 7.5¢/kWh would be \$1,500 for hot gas or \$4,650 for electric defrost operation.

Peak demand in compressor racks was also shown to be less when a deferred defrost algorithm was employed. The reduction ranged from 4 to 6 kW. Test results showed that energy savings with the algorithm measured 21,690 kWh and 80,049 kWh for hot gas and electric defrost, respectively.

PKI's control algorithm was used with a leading refrigeration equipment manufacturer's prototype controller in 1990 showing that it can be adapted to commercially available control hardware. Although energy savings were less than those seen when a test controller was employed, this reduced performance can be attributed to the version of the control algorithm used in the commercial prototype controller. PKI will work closely with licensees commercializing the product. Further development of a retrofit demand defrost controller will incorporate additional features appropriate to the refrigeration market consisting of supermarket, walk-in storage and Mom and Pop stores.

Section 1

BACKGROUND AND INTRODUCTION

The development of this demand defrost controller for commercial refrigeration systems has been a multiyear project sponsored by the New York State Energy Research and Development Authority (Energy Authority), Central Hudson Gas and Electric Co. (CHG&E), and Empire State Electric Energy Research Co. (ESEERCO). The purpose of the project was to demonstrate a cost-effective micro computer-based defrost controller which saved money by reducing energy consumption and minimizing electric power demand in large refrigeration systems. This goal was accomplished by Power Kinetics, Inc. and Foster-Miller, Inc. with the cooperation of Price Chopper, Inc., who provided a supermarket as a demonstration site for the field test of this system.

Refrigeration systems work by compressing a gas which then liquifies in the condenser releasing heat. The heat required to boil this liquid inside a low-pressure evaporator section is drawn from the space being cooled. Because the coils are cold, moisture in the air circulated through the coils precipitates and freezes. This frost accumulates and eventually clogs the air passages, preventing the system from keeping milk cold or food frozen.

The coils must be heated periodically to melt the ice. These defrost cycles are typically programmed by a clock set to defrost the system more often than would be required under the worst case frosting conditions. Heat is required to warm the evaporator and melt the ice, and then more energy is needed to cool everything down again. The process is energy intensive. The costs of performing defrost cycles too often are obvious, and many people have attempted to devise mechanisms to detect frost and initiate the melting process only when necessary. Many of these attempts have failed in commercial refrigeration systems.

The value of effective defrost controllers will be recognized by managers who are implementing energy conservation measures. In supermarkets these managers will already be using energy saving devices such as display cases with doors and possibly hot-gas defrosting in their refrigeration systems. To save near-term energy, defrost controllers must not only be incorporated in new systems but retrofit into existing ones. For this to happen users, manufacturers and installation contractors all have to benefit both financially and competitively by incorporating the product in stores.

SIGNIFICANCE OF DEFROST IN REFRIGERATION

Frost accumulates on the outside of evaporators in display cases and walk-in storage chests because they must operate well below freezing to keep the circulating air cold. If not removed, the frost builds up and prevents the evaporator from maintaining the desired temperature. In severe situations the ice insulates the evaporator preventing evaporation of the refrigerant, which damages the compressor if it enters it as a liquid.

There are four ways to melt frost from evaporators:

- Off-cycle. This method shuts the refrigeration off allowing the surrounding air to melt the frost. This technique is generally used when the expected frost build-up is small and the resulting temperature rise in the case will not damage the refrigerated product;
- Electric. Air is drawn through an electric heater and then through the evaporator which melts the frost. Although the defrost period can be short, electric power consumption can be significant, especially in large supermarkets where there are many refrigerated fixtures that must be defrosted;
- Air defrost. Certain display-case manufacturers offer an air defrost which redirects the case's warm air curtain flow through the evaporator, melting the frost; and
- Hot gas defrost. Hot gas discharged from the compressors is piped through the evaporator which melts the frost. Hot gas defrost is presently employed in systems with multiple parallel compressor racks. In these systems, multiple refrigeration circuits are operated in parallel which allows the heat rejected by the group to defrost an individual circuit. Hot-gas defrost is the quickest and least energy consuming type of defrost, but it is also the most mechanically complicated.

The most common form of defrost now used for commercial refrigeration is electric. Hot-gas defrost is used exclusively with multiple compressor racks and is normally found in newer supermarkets where more sophisticated refrigeration equipment has been installed.

Electric defrosts consume the greatest amount of power since electricity is used to directly melt the ice and then chilling is required to return the case to the desired operating temperature by removing the heat introduced into the fixture during defrost. Electric bills which reflect demand charges in addition to kilowatthours (kWh) show that this method is expensive. Due to large number of display cases that must be defrosted, defrosts are scheduled around-the-clock and do not avoid peak periods.

When hot-gas defrost is used, energy consumption is greatly reduced since no electric heaters are employed. The amount of heat added to the case for the defrost is also minimized since the heat is introduced from inside the frosted tubes, not into the air inside the case. A small amount of compressor power is required after the defrost to return the temperature of the evaporator to below freezing.

Energy consumption and power demand associated with defrost depend on the type of defrost employed. Display cases which use electric defrost are usually equipped with defrost heaters rated at 250 W/ft of display case. A typical supermarket containing 600 to 700 lineal feet of display cases uses from 150 to 175 kW of defrost heaters divided in perhaps twenty circuits. All display cases on a circuit are defrosted simultaneously. Due to the large number of circuits involved and because multiple defrosts are scheduled each day for each circuit, it is not unusual to have defrosts occurring concurrently for as many as two or three circuits, which results in an expected power demand for an electric defrost system of 17 to 26 kW. Defrosting each case circuit 30 minutes three times each day results in an annual power consumption of about 93,000 kWh.

In the case of hot-gas defrost, energy consumption for defrost is dramatically reduced because the heat needed to remove frost from the display case evaporator is supplied from other display case circuits through the refrigeration compressors. While no significant energy is consumed by the defrost, added compressor power is required immediately following the defrost to return the evaporator to the desired temperature.

The amount of power consumed for this recovery after defrost is variable. An estimate can be made based on the following assumptions:

- The total installed compressor power for a typical supermarket is approximately 130 hp that is evenly divided into three compressor racks;

- During the period of recovery from a defrost, an extra 3 to 5 hp of compressor power is needed to return the defrosted display case circuit to the desired operating temperature;
- The duration of the recovery period is approximately 30 minutes; and
- Three defrosts are required each day by each circuit.

With hot-gas defrost the number of circuits defrosting at one time is limited to one per compressor rack. Due to the large number of circuits involved it is not unusual to find one circuit defrosting in each rack concurrently. The power demand resulting from hot-gas defrost recovery would be 12 kW. The resulting annual power consumption would be approximately 13,700 kWh.

The most common method to control and schedule defrosts is a time clock which initiates and terminates defrosts on a schedule. The number of fixture defrosts controlled by the clock depends on the design of the refrigeration system. Single compressor condensing units generally use only one case circuit with each condensing unit, and, therefore, only one time clock. For multiple parallel compressor racks providing refrigeration to as many as 12 or 14 case circuits, a time clock is provided for each rack that schedules all defrosts for circuits associated with that rack. In some instances, a single time clock handles defrosts for all refrigerated fixtures. This arrangement is used when the site is equipped with a special control panel designed to execute all defrosts.

The number of defrosts scheduled for a particular case circuit is determined by recommendations from the case manufacturer based on operation at ambient conditions of 75°F dry bulb temperature and 55% RH, considered the highest allowable temperature and humidity for case operation. The actual number of defrosts recommended will vary according to case type and operating temperature. For example, multideck frozen food cases customarily operate with as many as four defrosts daily, while tub-type frozen food cases require two to three defrosts. Glass door cases often require as few as one or two defrosts daily. For medium-temperature cases, the number of defrosts can vary from as few as one per day for tub-type cases, to as many as three per day for multideck meat or dairy cases.

When the criteria have been established, the number of defrosts are scheduled on the defrost time clock and are executed daily throughout the year. The number does not change and does

not consider actual ambient conditions. Since the parameters anticipate temperature and humidity extremes that occur infrequently, many unnecessary defrosts happen because of the fixed operation of the time clock.

To eliminate unnecessary defrosts, attempts have been made to develop demand defrost systems that measure parameters which through use should establish when defrost is required. Based on these measurements, the defrost is initiated. Various types of demand defrost systems have been tried including:

- Frost sensors. Optically based sensors view the evaporator to detect frost buildup. When frost reached a preset thickness, the defrost is initiated. Several sensors of this type have been marketed with limited success primarily because the sensors triggered unnecessary defrosts and required intensive maintenance. Because sensors have to be located at the display-case evaporator, replacement of a failed sensor is very difficult, often requiring removal of refrigerated product from the case. For this reason, failed sensors have often been replaced with time clocks;
- Temperature sensors. A demand defrost controller was developed and introduced by Honeywell. The controller employed two temperature sensors located at the inlet and outlet of the display case evaporator. Defrost was initiated when the temperature difference between the two sensors reached a set point. This controller did not gain wide acceptance because it was prone to triggering defrosts unnecessarily. Like the frost sensors, the temperature sensors were located at the display case evaporator, making them difficult to service; and
- Pressure sensors. The change in air pressure through the evaporator as frost deposited on the surface could signal when defrost was required. The size of this pressure difference is very small, on the order of hundredths of inches of water column, which is difficult to measure accurately. The cost of accurate pressure sensors is prohibitively high which makes them unattractive for defrost control.

Modifications have also been made to defrost timers to allow them to modify time periods to some extent anticipating the actual defrost requirement of the display case. One such timer changes the time between defrosts based on the time required to complete the previous defrost. In this scheme, the defrost is terminated based on temperature measurement of the discharge air

curtain or refrigerant evaporator exit temperature, depending on the type of defrost used. The defrost is terminated when the measured temperature reaches a preset value. The time between defrosts is then adjusted according to the duration of the last defrost. The time between defrosts is increased when the defrost duration is shorter or is decreased if the duration is longer.

Another type of adaptive controller now marketed for defrost control interfaces with a standard time clock and varies the time between defrosts based on the ambient humidity in the store. The time between defrosts is increased as the store humidity decreases.

Most of the preceding types of controllers do not attempt to assess defrost requirements on a particular basis. Unnecessary defrosts may still occur. Also, none considers the effect of defrost on the electrical peak of the store. No attempt is made to avoid peak demand periods or provide interface with other energy management equipment so that defrosts can be scheduled to avoid adding to the total store demand.

CRITERIA FOR A DEMAND DEFROST CONTROLLER

No demand defrost control system has presently gained widespread implementation for several reasons:

- Demand defrost sensors are unreliable, causing unnecessary defrosts or failing and not triggering defrost when needed;
- The cost of maintaining demand defrost systems is excessive, often equalling or exceeding savings. The primary problem has been sensor failure. Since sensors are often located near the evaporator, replacement of failed sensors often involves the removal of refrigerated product from the display case, a practice avoided by most refrigeration repair mechanics. In such instances the common practice is to place the case circuit in question on a defrost time clock, rather than replace the failed sensor; and
- The first cost of a demand defrost controller is often significantly higher than a simple time clock controller. Since the energy savings potential of a demand defrost systems are somewhat limited, reasonable paybacks for such control systems are often difficult to achieve.

To develop a cost-effective demand defrost control system, it is important to address the above problems when designing the controller. To do this, certain criteria must be met and incorporated in the basic control algorithm, the controller design, and the hardware selection.

The first criteria for a defrost controller involves the performance and the ability of the controller to initiate defrost only when absolutely required. In order to do this it is important that the defrost controller evaluate the refrigeration performance of the display case in maintaining the correct operating temperature. The measurements used by the controller must represent requirements of the display case for refrigeration. The control algorithm must be able to interpret these measurements properly to avoid unnecessary defrosts. Allowances should also be made to initiate defrost if a problem such as a sensor failure occurs.

The second criteria that must be met is that the demand defrost controller must be as reliable and require as little maintenance as a time clock to minimize the cost of operation. Devices used must deliver repeatable and reliable measurements. It is also important that sensors be located at positions in the display case to facilitate servicing and replacement.

The third criteria of a demand defrost system is that the controller must be more cost effective than a simple time clock. Cost effectiveness includes maximizing energy and demand savings while minimizing first cost. First costs can be minimized by selecting proper hardware and using advanced manufacturing techniques. Other ways to increase cost effectiveness include combining the defrost with other control functions, such as case temperature control. The use of the demand defrost controller in conjunction with an energy management system (EMS) already installed at the store should also be examined, particularly when sensors and timers installed for the EMS could be shared by the defrost controller.

CHARACTERISTICS OF A DISPLAY CASE WITH FROST BUILD-UP

An important part of this project was characterizing the operation and performance of a display case as frost accumulated on the evaporator. Establishing this information was essential to plan the demand defrost control strategy. For this characterization a series of tests were conducted with a laboratory refrigeration system including a typical display case. The laboratory system used for these tests will be described later, along with detailed results from the tests.

Frost accumulating on the evaporator slowly reduced the output of the display case fans. Since less air passed through the evaporator, there was not enough cold air available to keep the display case at the desired temperature. This reduction in air flow decreased the refrigeration provided and led to the breakdown of the display case air curtain, both of which caused the return air temperature to rise. Therefore as frost accumulated on the evaporator, the discharge air temperature leaving the evaporator remained constant, while the temperature difference between the discharge and return air increased.

These same observations were made for several tests suggesting that the behavior of the discharge and return air temperatures for display cases was repeatable. From this information it was concluded that the measurement of the temperature difference between the discharge and return air could be used as an indicator of the defrost requirement for a display case.

PROJECT OVERVIEW

This report describes the work accomplished in the three phases of the project. It will begin with an overview of the work performed by Phase.

Phase I

Phase I developed a prototype demand defrost controller that was tested on a laboratory-scale refrigeration system. Sensors were added to the system to provide inputs for both the control of the system and its monitoring. Control algorithms were developed that proved effective in determining when a refrigeration circuit needed defrosting. The prototype controller initiated defrost both according to need and according to minimum and maximum time restraints. Phase I demonstrated the feasibility of a controller that merited field testing in a functional supermarket environment in Phase II.

At the end of Phase I, using the defrost controller to also provide temperature control for the refrigerated cases was discussed. Since in its operation the controller measures the discharge air temperature of the case, it establishes if the case is at the right temperature. To act as a thermostat, the controller would only have to compare the discharge temperature to the target temperature and turn the solenoid valve on or off providing refrigeration to the case. Since each case in a circuit has individual temperature controls, the number of temperature inputs and control outputs must be about five or six times greater than one which controls only defrost

cycles. To explore this possibility, the prototype controller was redesigned as a field test controller with the temperature control features.

Phase II

Phase II was designed as a field test of the controller under usual supermarket operating conditions. To optimize the test for the participants, the supermarket was to be:

- in New York State;
- in CHG&E operating region;
- near Troy for easy access by Power Kinetics, Inc. (PKI);
- under construction for ease of installation of control and monitoring equipment; and
- operating long enough so the refrigeration system was thoroughly tested, debugged, and fully operational.

Some of the desired specifications were somewhat contradictory and unlikely to be met. However, candidates were quickly narrowed down to a Price Chopper supermarket that was to be located in a store complex in Newburgh, New York.

The location was both in New York State and in CHG&E territory and only about two hours away from PKI in Troy. The refrigeration system was being installed at about the right time for concurrent installation of the demand defrost experiment; however, conditions at the time did not allow it. Cooperation from Price Chopper did however allow for the installation of the experiment about the time the store opened. The store was not used for the tests until it had been open a while to insure the refrigeration systems were operating.

The refrigeration system at Newburgh uses an electronic proportioning valve to control the temperature of each case. Since it does not have solenoid valves on the refrigeration branch lines to each case, the temperature control option for the field test defrost controller was not implemented.

At this site a defrost controller was installed on the low-temperature refrigeration system. Installing the field test controller was a cooperative effort. Price Chopper provided conduit access to refrigeration cases that were otherwise inaccessible. An electric contractor and a refrigeration contractor were required to install the sensor and control wiring throughout the store and the refrigeration rack-monitoring sensors in the machine room. Foster-Miller, Inc. (FMI) installed the sensors in the cases and all the data logging, recording and transmitting equipment, while PKI installed the controller. The installation went smoothly considering the complexity of the experiment, but it did not proceed without a hitch. The controller was used alternately with a standard time clock on a two-week basis to control the defrosts of the display cases.

Phase III

Phase III was designed to prepare the demand defrost controller for commercialization. Three new aspects were tested including:

- Peak demand reduction;
- Operation on medium temperature refrigeration; and
- Operation of a commercial prototype by Hussmann Corporation.

For peak demand reduction, demand-side management, the control algorithm was modified to prohibit defrosts from two selectable time periods each day. The periods of peak electric demand were identified, and during these times a request for defrosts was deferred in a queue until after the period lapsed. A scheme for prioritizing these queued defrosts is possible but was not tested. The demand-shifting algorithm worked as expected.

A second field test controller and associated instrumentation were installed at the test store on the medium temperature refrigeration system. The potential for energy savings was large due to the large number of open-type cases used for dairy, deli, and meat products, which typically use three to four defrosts per day. The energy savings per case were less for medium temperature cases due to the type of defrost systems used in some cases.

Hussmann Corporation, the largest commercial refrigeration equipment manufacturer in the world, participated in Phase III. Under a mutual agreement, Hussmann adapted one of their refrigeration controllers to implement the algorithms developed in this project. The Hussmann commercial prototype did not have the hardware interface to connect to a refrigeration system,

but communicated using a proprietary serial bus to an interface installed on the low-temperature refrigeration system in the test store. The commercial prototype was tested simultaneously with other tests in this project and performed the same way.

PATENTED TECHNOLOGY

During the course of this project, it became apparent that the technology was novel, effective and valuable. These qualities were both requirements for and reasons for patenting the technology. A patent application was developed, submitted and approved. On February 19, 1991, US Patent #4,993,233 entitled "Demand Defrost Controller for Refrigerated Display Cases" was issued. The patent covers the technologies described in this report.

Section 2

TECHNICAL DESCRIPTION

LOGIC FOR DEFROST CONTROL

Previous attempts to employ various measurements, such as frost thickness, temperature and air pressure for defrosting have had marginal success for the following reasons:

- Sensor failure, which can occur occasionally, results in either a failure to initiate defrost when needed or in triggering unnecessary defrosts;
- Sensor readings are misinterpreted by the controller, initiating unnecessary defrosts. In one instance, maintenance activity at the display case caused a sensor reading that mimicked one that signaled for defrosting.

Failure of the defrost control often leads to service calls or spoilage. Many problems incurred by previous demand defrost controls can be avoided by using simple controller logic:

- Interpret sensor readings to prevent false defrosts, and determine if sensors are functioning properly; and
- Provide backup, such as a time clock, to the sensors so that defrosts can be controlled in the event of sensor failure.

For these reasons, the following control logic elements were used in conjunction with the measured temperature difference between the discharge and return air to form the basis for the demand defrost control algorithm:

- The measured temperature difference must reach the control set point and remain above the set point for a pre-determined number of measurement cycles, so sudden changes in temperature readings caused by case activity do not trigger unnecessary defrosts;
- A minimum amount of time must pass since the last defrost of the display case before another defrost can be initiated as a backup so that unexpected operating

conditions or sensor failures will not initiate unnecessary defrosts. The minimum amount of time between defrosts for a particular display case is a set point for the controller and can be the same as that used by a standard time clock controller; and

- A maximum time interval is also employed so that if a display case has not defrosted within this time interval, a defrost is initiated regardless of sensor readings. This time interval guards against sensor failure which might prevent a defrost when required. The maximum time interval is also a set point for the controller.

DEFROST CONTROL ALGORITHM

The control algorithm that determines when defrost is required in a refrigerated display case uses temperature measurements taken at the outlet of the discharge air curtain and at the inlet of the air return. The temperature difference is calculated from these two measurements and compared to a set point. If the difference exceeds the set point, a defrost can be initiated if certain other criteria are met. The temperature difference must exceed the set point for a certain number of measurement cycles and a minimum amount of time must have elapsed since the last defrost of that particular display case before a defrost can be initiated. While measurement of the temperature difference is made, total elapsed time since the last defrost is also compared to a maximum time setting. If the elapsed time exceeds the maximum time setting, defrost can be initiated regardless of the value of the temperature difference.

In a hot-gas defrost system only one circuit can be defrosted at a time. The control algorithm allows for this by checking to see if any other circuits are in defrost before initiating a defrost cycle. If there is another circuit in defrost, the new defrost request is placed in a queue and waits until the existing defrost is terminated.

The algorithm is begun by the measurement of the discharge and return air temperatures of the display case. A temperature difference (return - discharge) is then calculated and compared to a set point for that display case. If the difference is greater than the set point, a counter is incremented. The counter is then compared to a count set point. If the count does not exceed the count set point, the control program returns to the start, the temperature measurements are repeated and the difference is again compared to the set point. This process continues until

either the count set point is exceeded or the temperature difference falls below the difference set point. In the latter instance the count is reinitialized to zero and the temperature measurement process is repeated. If the count set point is exceeded, defrost is initiated if the elapsed time since the last defrost of the display case is greater than a preset minimum value. If the elapsed time since the last defrost has not reached the minimum value, the control program returns to start. After comparisons are made with the difference and count set points, and if either of these comparisons routes the control program back to start, the elapsed time since the last defrost is compared to a maximum time between defrost value. If the elapsed time exceeds the maximum time, defrost is initiated.

After a defrost has been initiated, the control program then determines when to return to normal operation. The control program first measures the discharge air temperature and compares the temperature against a set point. If the temperature exceeds the set point, the defrost can be terminated. If the temperature set point is not exceeded, elapsed time of the defrost is checked and compared to a maximum duration. When the elapsed time exceeds the duration, defrost is terminated. The control program continues to check the discharge air temperature and the elapsed time until one of the termination criteria is met. At that time the defrost is switched back to normal operation.

Initial Algorithm Development

The initial testing employed the laboratory test controller to develop and evaluate the defrost control algorithm. After initial debugging and refinement of the control test program, the laboratory test controller was set to control defrosts for both the display case and walk-in chest available with the laboratory refrigeration system. For the display case testing, the case temperature was controlled by the EPR valve which maintained the suction pressure at the case at approximately 12 psi (evaporator temperature of -25°F).

The defrost controller was tested at several temperature difference set points. Observations were made of the case evaporator for frost build-up and time was noted between defrosts. At difference settings greater than 13°F, the defrosts were triggered primarily by the maximum time setting. It was found that the measured temperature difference would not increase above this value at a rate quick enough to avoid excessive frost build-up on the evaporator. At a difference set point of 13°F or less, the measured temperature difference was found to be a reasonable indicator of the frost level on the evaporator and properly triggered the defrost. The effect of the defrost control algorithm on the display case is shown in Figures 2-1 and 2-2.

Figure 2-1 shows the measured temperatures of the display case air curtain discharge and return, during a test of approximately 23 hours. The test was begun by defrosting the case so that the evaporator was free of frost. Over a period of approximately 16 hours, the air-temperature difference between the return and the discharge set point was reached. At that time a defrost was initiated. The measured temperature difference for this test is shown in Figure 2-2. The static air pressure at the outlet of the display case and inlet of the evaporator was also measured. During the control test the value of the pressure measurement rose steadily after the initial defrost until the signal saturated. When the temperature-initiated defrost occurred, the static air pressure reading returned to that measured when the evaporator was free of frost. This increase in static air pressure showed that the frost was building on the surface of the evaporator, reducing the air flow and that defrosting was appropriate.

For commercial applications, the algorithm has to keep track of all the variables for each circuit including:

- Discharge air temperature;
- Return air temperature;
- Temperature difference set point;
- Minimum time between defrosts;
- Maximum time between defrosts;
- Actual time since last defrost;
- Time interval for temperature difference to trigger defrost; and
- Length of time for defrost cycle.

Control Strategy

Laboratory testing showed that the measurement of the display case air curtain temperature at the discharge and return was accurate, reliable, and repeatable. It was found that the difference between these two temperatures increased as frost accumulated on the case evaporator. A maximum value of this difference was used as a set point of the defrost controller. When the temperature difference exceeded this set point, the defrost of the display case was initiated.

The temperature difference measurement was also used in conjunction with controller logic to avoid unnecessary defrosts due to sensor failure, or other abnormal case operation. Before the defrost was initiated, the time since the last defrost of the case was checked and, if a preset

minimum time setting was not exceeded, the defrost was delayed. This control feature prevented premature defrosts since adequate time had not elapsed for frost to accumulate.

A second time interval was also employed that represented the maximum time that the display case could operate without defrost. If the temperature difference did not reach the set point before passing this maximum time interval, the display case was defrosted regardless of the temperature values. This second time-setting feature was included as a control safety to ensure that the display case was defrosted to avoid operating problems.

The laboratory testing of a prototype showed that the chosen algorithm could perform demand defrost control, reducing the number of defrosts incurred, while maintaining the display case at proper operating conditions.

The prototype testing also discovered a better way to determine when the temperature difference set point was exceeded. Instead of counting a number of measurement cycles, the algorithm calculated a running average. The time period for the average needed to be long enough to avoid spurious temperature transients which did not affect system operation. The running average taken over a 10-minute period was successful in determining when the set point temperature difference was exceeded. The laboratory prototype controller did not include the routines necessary for control in a real supermarket environment. These additional routines include:

- Set the clock time;
- Set the wait time for temperature initiation;
- Correct the variables (previous list); and
- Display current data.

Figure 2-1. Display Case Temperature Profiles.

Figure 2-2. Temperature Difference Profile.

TEMPERATURE CONTROL

Temperature control of the display cases was a fairly easy feature to add to the defrost controller for cases with thermostat and solenoid valve control. The advantage of adding temperature control was that the thermostat could be deleted during case manufacture. For a display case that already had defrost control, it was a simple matter to add a solenoid-type temperature control. Since the sensor for measuring the temperature of the discharge air was already included, only one more digital output line is needed to actuate the solenoid valve through a solid state relay.

This simple solution does not apply to many new refrigeration display cases which use an electronic variable flow-control valve instead of a thermostat and solenoid valve. It also does not address situations with multiple cases on one defrost circuit. This is not a problem for the microcomputer and the control algorithms, but requires that additional sensors and a solenoid control output be provided for each case which increases the installation time and materials, and more important, multiplies the complexity of the wiring severalfold.

HARDWARE DEVELOPMENT

In Phase I, the general design of specific sensors, actuators, control hardware and software were brought together. The overall project involved several levels of controller hardware development including:

- laboratory development system;
- prototype controller;
- field test controller;
- medium temperature controller; and
- commercial prototype.

Laboratory Controller

The laboratory development system consisted of a desk top, general purpose computer with a standard keyboard and screen connected using plug-in cards to sensors and actuators. The addition of floppy-disk-based software turned the system into a defrost controller that was used to develop working algorithms for defrost control as previously described.

Thermocouple temperature sensors were used in the laboratory development system because they are reliable, accurate and appropriate. However, thermocouples require an expensive and complex interface which is inappropriate in a finished commercial product. Additionally, thermocouples put out small voltage signals that are susceptible to noise over the long wires that connect the sensors in the refrigeration cases with the controller located in the equipment room in supermarket systems. The prototype controller used sensors that emitted current signals that are less subject to noise.

The laboratory system used digital control of an optically-isolated, solid-state relay for output. The relay operated the hot-gas defrost valves on the display case circuit of the refrigeration test setup.

The personal computer chosen for the laboratory controller included:

- 256 Kbytes of RAM;
- digital input and output; and
- optically isolated relays.

The control software used routines provided with the analog card to measure and scan sensors and operate the digital inputs and outputs. Routines were added to convert and display the measurements in engineering units and provide control logic. The basic control procedure consisted of measuring the temperatures at the display case and comparing the measured values to set points. Where necessary, the clock within the computer was used to determine time and time intervals. When defrost was to be initiated or terminated, the computer sent the appropriate digital signal through the interface board to the isolated relays.

Prototype Controller

To provide flexibility in accommodating a wide variety of supermarket environments and to match the inherent 8-bit structure of microcomputers, the prototype was modular, with controls for refrigeration circuits in groups of eight. Eight circuits require eight actuators for initiating defrost and sixteen temperature inputs to establish the eight temperature differences. In this case, the actuators were digital outputs through solid state relays.

Additional requirements were:

- a clock;
- battery backup for power failure;
- Operator interface;
 - display screen
 - simple keypad.

The CPU chip for the controller was chosen to use a computer language similar to the laboratory development system. Sufficient RAM and EPROM were added to cover the variables and algorithm details necessary to turn a small micro-processor system into a defrost controller.

Field Test Controller

Tests of the laboratory development system and the prototype controller showed that both the defrost controller and case temperature control worked in the laboratory. Based on these results and preliminary information about a supermarket available as a field-test site, a field-test controller was designed and built. The main difference between the two controllers is the inclusion of temperature control in the field test controller, which multiplied the number of input and output lines to the controller by a factor of three. As the controllers are otherwise very similar, the field-test controller hardware will be discussed.

The field-test controller is a complete computer on a 7" x 10" printed circuit board that has been specifically designed as a demand defrost controller. The computer has all the requisite components: a central processing unit (CPU), an operator interface, memory, system and real-time clocks, power supplies with battery back-up, digital I/O to the refrigeration system, and analog temperature-measuring inputs from the display cases. The operator interface is a key pad and 2 line x 40 character LCD display mounted on the front case of the controller. The other components not on the printed circuit board are the power supplies and back-up battery, which are mounted in the controller box in a separate section behind the printed circuit board.

The CPU is a 8052 connected by address and data bus lines to all the components on the board. The major components constitute the memory, both random access memory and ultra-violet erasable, programmable, read-only memory, as well as the real-time clock, LCD display, and analog to digital converters which connect to the real world.

The digital I/O is provided by two 8255 chips, each of which provides three 8-line ports, for a total of 48 digital I/O's. Some of these I/O lines go to a 4 x 5 scanned matrix keypad through which operators can provide input to the system. The LCD display mounted on the front panel shows operators the system status and other information. The system clock in the 8052 is an 11 MHz crystal which provides the basic clock rate for all operations.

As a defrost controller, the system needs to know time of day which is provided by a 6242 real-time clock chip. It has its own 32 kHz crystal and connections to both the address and data buses. This chip has a separate lithium battery so the clock will continue to operate even if the board is removed from the controller. The main battery back-up located behind the board has sufficient power for three days in the event of an extended power failure. The latter is a gel cell lead acid battery which can power the whole system including the clock chip.

The programs which controlled the defrost controller required 8K of program firmware, and reside in the EPROM (32K). An 8K RAM was used. Both memory devices were addressed by the multiplexed address and data bus system of the 8052 CPU.

Temperature measurement was provided by AD592 temperature chips which provide a current proportional to absolute temperature. The current was scaled by on-board resistors and operational amplifiers before being fed into the analog to digital converter. The A to D converter was an 8-channel, 8-bit device and each channel was multiplexed to eight additional inputs providing 64 different channels of analog input. This temperature measuring system provided the controller with the capability of measuring 32 circuits for temperature control as well as demand defrost control. In the test supermarket, the 48 digital I/O ports from the 8255 chips were not fully used as the temperature control feature was not used, and only 12 circuits of demand defrost were controlled. A 13th output line was used to signal the data acquisition system when a defrost was initiated by temperature set point as opposed to time out. This line was not required in the demand defrost controller though it was important for data acquisition and analysis.

The hardware described could be used for a wide variety of general purpose computing and control applications. The firmware turns this controller into a demand defrost control system.

Medium Temperature Controller

A second field test controller identical to the first was manufactured and connected to the medium temperature refrigeration system at the field test supermarket to test both demand defrost control on medium temperature cases and electric demand reduction routines. The controller hardware and software are identical to that described in the field test controller section. The parameters for control of the individual circuits of the medium-temperature system are, of course, different than parameters for the field test controller connected to the low temperature circuits in the store. The controller design is flexible enough to handle these types of refrigeration defrost systems.

Commercial Prototype Controller

Hussmann Corporation was interested in testing this demand defrost control system and agreed to make a commercial prototype controller combining their hardware and our software algorithms to try out our control concepts with their equipment. Originally they planned to run this test on a general purpose controller they already used in their product line. After several months it became apparent that they would like to use a different controller that they were developing which was more applicable to defrost control. Both these controllers are connected to the hardware of their refrigeration systems by a proprietary serial protocol link. This serial link isolates the hardware input/output from the CPU-controlled decisions.

PKI agreed to make the hardware front end and back end with the serial protocol link so the test site equipment could be connected to the Hussmann prototype controller. Although both Hussmann controllers used a 8051 chip which is similar to the 8052 chip used in the field test controllers, the serial port protocol was not the same for the two chips. This necessitated replacing the front and back end of the field test controller with a desktop computer connected with a parallel bus to the freezer control rack and connected through an analog interface to the temperature sensors in the store. A serial interface was developed with the correct protocol so the Hussmann controller could be given temperature information to allow it to make control decisions. The control decisions were relayed to the desktop computer which then turned on and off the defrost control through a parallel bus.

The Hussmann controller was found to be susceptible to noise and brown-outs that frequently occurred on its 110 volt AC line. To avoid problems an uninterruptable power supply and power conditioner was included. The hardware for the commercial prototype and the data

acquisition for these tests consisted of seven microcomputers. In a final implementation, of course, only one microprocessor-based computer would be required for each refrigeration system that is controlled for demand defrost and electric demand reduction.

TESTING FACILITIES

The demand defrost controller was tested at two locations. In Phase I, the laboratory and prototype controllers were tested at an existing FMI facility. In Phases II and III, the field test, medium temperature and commercial prototype controllers were tested on the low temperature and medium temperature refrigeration racks at the Price Chopper supermarket in Newburgh, NY. The field testing in the test store provided an excellent, real-world environment for determining the operational characteristics of the demand defrost controller.

Laboratory Refrigeration Test Facility

The demand defrost algorithm was first tested using a laboratory refrigeration system available at FMI that consisted of three compressors that produced refrigeration for a set of up to four parallel independent loads. The compressors were mounted in a rack-type arrangement and were piped between common suction and discharge manifolds.

Along with the main refrigerant piping, the rack held all necessary electrical components and control valves for operation of the refrigeration system. The rack was equipped to provide hot-gas defrost to several of the test circuits. An air-cooled condenser mounted on the roof of the building was used for rejecting heat.

A refrigeration load model was used for the defrost tests. The load was divided into four circuits:

- one walk-in chest;
- one display case; and
- two brine chillers.

The display case and the walk-in chest were run normally; i.e., the magnitude of the refrigeration load for these fixtures was controlled by the operating temperature of the fixture evaporator and ambient conditions. The display case and the walk-in chest were equipped with plumbing to allow defrost periods using hot gas. The brine chillers were piped in closed-loop

arrangements; cooling was provided to brine consisting of ethylene-glycol and water. The temperature of the brine was controlled by heating with steam in a heat exchanger. The brine loops provided a baseload for the refrigeration system and insured that adequate hot gas was available to defrost the display case and walk-in chest. No defrost was required for the brine chiller loops. Testing the demand defrost control algorithm was done primarily with the display case, a frozen food multideck unit associated with the refrigeration test facility. For the defrost tests the case was maintained at an operating temperature of approximately 0°F. At this operating temperature the required refrigeration load varied from 10,000 to 16,000 Btu/h, depending on ambient conditions.

Instrumentation was also added to the case for the defrost tests. Temperature measurements were added to the air curtain at the discharge outlet and the return inlet at three locations, left and right sides and center. Temperature measurements were also installed in the product area in three locations. To measure the air-side pressure change at the evaporator, a differential pressure transducer was installed across the evaporator. It was found that the pressure differential rose as the evaporator clogged with frost. The evaporator fan outlet static pressure tended to rise as the resistance to airflow increased. A dew point transducer was installed in the product area of the case to measure changes in the case humidity during operation. This particular measurement was not very successful, because the operating temperature and humidity of the case were not within the range of the instrument.

Test Store Description

The field test of the demand defrost controller was done at a Price Chopper Supermarket in Newburgh, NY, which is located approximately 60 miles north of New York City. The Price Chopper is a recently renovated superstore containing 60,000 ft² of sales area that is open 24 hours/day.

The supermarket contained 37 display-case systems and walk-in coolers that required refrigeration. The compressor arrangement consisted of three racks of parallel compressors. In parallel compressor systems, a rack of several compressors provides refrigeration to a large number of refrigerated cases through common suction and discharge manifolds. Each compressor rack services a group of cases with similar temperature requirements. Table 2-1 lists the system number, the size and type of display case or cooler, the design load, and the suction temperature for each of the cases on the high-temperature rack. The total load on the

high-temperature rack is 450,000 Btu/h at a suction temperature of 20°F. Table 2-2 lists the R-22 compressors used to meet the load on the high temperature rack. Table 2-3 lists the systems on the medium-temperature rack. This rack contains two satellite compressors in which the compressor suction is connected to a single refrigerated case circuit, while the discharge is manifolded with all other compressors on the rack. This arrangement allows the saturated suction temperature for that case circuit to run lower than the rest of the rack. The total load on the main part of the medium temperature rack is 225,000 Btu/h at a suction temperature of 10°F. Table 2-4 lists the R-22 medium temperature compressors used on the main rack and satellites A and B. The EER for the main rack is 9.21, while the EER for the satellites, which are run at a lower suction temperature, is 7.81.

Table 2-1
High-Temperature Rack Refrigerated Cases

No.	Size	Type	Btu/h	Suction Temperature
1-1	48	DIDCM dairy	69,600	20
1-2	24	FGV serv meat	7,560	20
1-3	28	DIDCM beverage	40,000	20
1-4	60	48 ft FVH / 12 ft FVWE	56,100	30
1-5	72	60 ft FVW / 12 ft FVWE	66,900	20
1-6	40	12 ft DMED / 20 ft FGVB	12,600	20
1-7	10 x 12 x 9	Baker's cooler	9,564	20
1-8	10 x 16 x 9	Deli cooler	9,622	20
1-9	18 x 23 x 9	Dairy cooler	20,641	20
1-10	25	Meat preparation	42,500	35
1-11	20 x 40	Custom cut and fish	56,000	35
1-12	8 x 14	Serv meat cooler	10,060	20
1-13	8 x 14 x 9	Fish cooler	7,811	20
1-14	18 x 24	Product preparation	21,600	35
1-15	12 x 42 x 9	Product cooler	19,211	25
Total			449,769	

Table 2-2
High-Temperature Rack Compressors

	hp	Capacity(Btu/h)	EER
1	15	123,900	
2	15	123,900	
3	15	123,900	
4	15	123,900	
	60	495,600	9.76

Table 2-3
Medium-Temperature Rack Refrigerated Cases

No.	Size	Type	Btu/h	Temperature
2-16	28	DDCM DELI	46,200	15
2-17	48	DDCM dairy	69,600	20
2-18	12	DDCH cheese	18,600	15
2-19	36	24 ft FVH / 12 ft FVWE	34,500	20
2-20	12	DMG sausage	5,100	15
2-21	24	DMG cheese	10,200	15
2-22	8	Pizza case	3,800	15
2-23	25 x 34 x 9	Meat cooler	<u>37,446</u>	<u>20</u>
Total			225,446	
2-24	28	DHMG meat	<u>42,700</u>	<u>10</u>
2-25	28	DHMG meat	<u>42,700</u>	<u>10</u>

Table 2-4
Medium-Temperature Rack Compressors

	hp	Capacity(Btu/h)	EER
1	10	83,350	
2	10	83,350	
3	<u>10</u>	<u>83,350</u>	
	30	250,050	<u>9.21</u>
Sat. A	7.5	49,299	7.81
Sat. B	7.5	49,299	7.81

The low-temperature systems are listed in Table 2-5. Systems 3-26 and 3-27 are multideck frozen food display cases. System 3-26 is 16 ft. long with a design load of 23,800 Btu/h at -25°F suction temperature. System 3-27 is 24 ft. long with a load of 35,800 Btu/h at -25°F. Systems 3-28, 3-29, 3-30, and 3-31 are reach-in door cases for frozen food. Each of these systems is 36 ft. long and has a design load of 23,400 Btu/h at a suction temperature of -20°F. Systems 3-32 through 3-35 are walk-in cooler units of various sizes and design loads. The suction temperature for the walk-in units is -25°F. Systems 3-36 and 3-37 are tub-type display cases for frozen food. Each has a designated satellite compressor to meet the 30,400 Btu/h design load at the -35°F suction temperature. Table 2-6 lists the R-502 compressors installed on the low-temperature rack. The main part of the rack uses three compressors, two 22 hp units and one 27 hp unit. A total refrigeration capacity of 245,000 Btu/h may be produced at an EER of 5.19. Each of the satellites relies on a 10 hp compressor operating at an EER of 4.80.

Table 2-5
Low-Temperature Rack Refrigerated Cases

No.	Size	Type	Btu/h	Temperature
3-26	16	DGF FF	23,800	-25
3-27	24	DGF FF	35,800	-25
3-28	36	DSEF FF	23,400	-20
3-29	36	DSEF FF	23,400	-20
3-30	36	DSEF FF	23,400	-20
3-31	36	DSEF FF 10,200	23,400	-20
3-32	10 x 12 x 9	Bakery freezer	10,471	-25
3-33	6 x 8 x 9	Deli freezer	6,399	-25
3-34	18 x 29 x 9	Food freezer	25,110	-25
3-35	10 x 18 x 9	Ice cream freezer	<u>13,351</u>	<u>-25</u>
		Total	<u>208,531</u>	-25
3-36	36	FZJ FF w/1 - end	<u>30,400</u>	-35
3-37	36	FZJ IC w/1 - end	<u>30,400</u>	-35

Table 2-6
Low-Temperature Rack Compressors

	hp	Capacity(Btu/h)	EER
1	22	75,892	
2	22	75,892	
3	27	93,140	
	71	244,924	5.19
Sat. A	10	33,949	4.80
Sat. B	10	33,949	4.80

The low-temperature display cases at the test store used hot-gas defrost. In many installations, electric defrost would be used instead. To estimate savings from using the demand defrost controller, electric defrost heaters normally specified for these cases were identified from the manufacturer's literature. The heater size along with the number and duration of each defrost were used to calculate the energy that would be consumed if electric defrost were used.

Table 2-7 gives the defrost heaters specified for the low-temperature cases.

Table 2-7
Heater Sizes Specified for Electric Defrost of
The Low-Temperature Display Cases

System No.	Case Type	Size (ft)	Heater Size (kW)
3-26	Multideck	16	10.8
3-27	Multideck	24	16.2
3-28	Door	36	11.4
3-29	Door	36	11.4
3-30	Door	36	11.4
3-31	Door	36	11.4
3-36	Tub	36	12.9
3-37	Tub	36	12.9

For the medium-temperature cases, either hot gas or off-cycle defrost was used. For the cases using hot gas, electric heaters were also specified and used to estimate electric defrost energy consumption. Table 2-8 lists the electric defrost heaters for the medium-temperature display cases.

Table 2-8
Heater Sizes Specified for Electric Defrost of
The Medium-Temperature Display Cases

System No.	Case Type	Size (ft)	Defrost* Type	Heater Size (kW)
2-16	Multideck	28	Hot gas	5.0
2-17	Multideck	48	Off-cycle	--
2-18	Tub	12	Off-cycle	--
2-19	Produce	36	Off-cycle	--
2-20	Tub	12	Hot gas	2.2
2-21	Tub	24	Off-cycle	--
2-22	Multideck	8	Off-cycle	--
2-24	Multideck	28	Hot gas	5.0
2-25	Multideck	28	Hot gas	5.0

* Defrost type now employed at test site

Data Acquisition

To determine the performance of the controllers and compare the results to the operation under control of the time clock, an independent data acquisition system was installed at the test site for both the low and medium-temperature refrigeration systems. Table 2-9 lists the field measurements required to quantify the performance of the controllers. The operating (discharge and return) air temperatures and a digital signal indicating the occurrence of defrost for each of the refrigerated cases were recorded. The temperature measurements allow the case performance over time to be determined and provide a check on the controller algorithm. The defrost digital signal indicates the frequency, the length, and the time of defrost for each case. This measurement allowed the number of defrosts occurring while the controller is operating to be compared to the number of defrosts while under time clock control.

Table 2-9
Field Measurements

- Display cases and walk-ins
 - Operating temperatures
 - Defrost occurrence
- Refrigeration load and power
 - State points and flow
 - Energy and demand
- Store power consumption
 - Energy and demand
- Ambient conditions (inside and outside)
 - Dry bulb
 - Dew point

The next item in Table 2-9 is the refrigeration load and power. The refrigeration load on the rack was determined by measuring the refrigerant state points and flow rate. Measurement of the refrigeration load was performed on the low-temperature system only. A flowmeter could not be installed on the medium-temperature refrigeration rack due to the piping arrangement used with this rack.

The state point measurements consisted of compressor suction and discharge temperature and pressure and the refrigerant liquid temperature exiting the condenser. The system performance as a function of refrigeration load was evaluated to determine if differences between controller operation and time-clock operation were related to load fluctuations. The energy and power consumption of the low-temperature compressor rack and condenser were measured to determine the effect of the controller operation on power draw. Likewise, total store power and demand were measured. Lastly, ambient conditions such as outside dry-bulb and dew-point temperatures and inside dry-bulb and dew-point temperatures were measured to correlate test results with ambient effects.

The monitoring instruments listed in Table 2-10 for low-temperature refrigeration and Table 2-11 for medium-temperature refrigeration provided the required field measurements.

Table 2-10
Monitoring Instrumentation
Low-Temperature Refrigeration

- Temperature measurements (29)
 - 10 discharge air
 - 10 return air
 - 2 ambient dry bulb (inside and outside)
 - 2 ambient dew point (inside and outside)
 - 3 refrigerant suction (low and very low temperatures)
 - 1 refrigerant liquid
 - 1 refrigerant discharge
- Pressure measurements (4)
 - 3 refrigerant suction
 - 1 refrigerant discharge
- Flow measurements (1)
 - 1 refrigerant
- Power measurements (5)
 - 1 total store
 - 1 total rack
 - 2 very low temperature compressors
 - 1 condenser
- Digitals (14)
 - 12 circuit defrost in/out
 - 1 controller on/off
 - 1 defrost initiation time/temperature

Table 2-11
Monitoring Instrumentation
Medium-Temperature Refrigeration

- Temperature measurements (27)
 - 10 discharge air
 - 10 return air
 - Inside ambient dry bulb
 - Inside ambient dew point
 - 3 refrigerant suction (main rack and 2 satellites)
 - 1 refrigerant liquid
 - 1 refrigerant discharge
- Pressure measurements (4)
 - 3 refrigerant suction (main rack and 2 satellites)
 - 1 refrigerant discharge
- Power measurements (4)
 - 1 total rack
 - 2 satellite compressors
 - 1 condenser
- Digitals (12)
 - 10 circuit defrost in/out
 - 1 controller on/off
 - 1 defrost initiation time/temperature

The data were averaged over a 15 minute period by the site data loggers, stored locally, and collected daily by telephone. Table 2-12 lists some of the features of this unit. In conjunction with the data logger, a floppy disk storage system was used to store the data, which had a 1.2 Megabyte capacity. A 2,400 baud modem with error checking completed the test side system. At FMI, a personal computer was equipped with a 2400 baud error correction modem as well. A data-collection routine was written to automatically dial the field test site every day at midnight and transfer the data from the site data storage to a hard disk on the PC at the FMI office. When the data was transferred, the site data disk was erased and the system was placed back into the data collection and storage mode. The communications line was then disconnected and a data reduction routine was run by the PC on the collected data. When the reduction routine was completed, the raw and reduced data were stored on floppy disk. Figure 2-3 schematically illustrates the field test data collection setup.

Table 2-12
Data Acquisition System

Features of the Data Logger:

- Rugged, industrial environment construction
- 64 channel CPU
- Three separate 12 MHz microprocessors
 - One dedicated to channel scanning
 - One dedicated to computation
 - One dedicated to serial line control
- 20 pre-programmed math functions
- Real-time clock with battery backup
- Intelligent serial line (RS-232 port)
 - Allows communications, w/o channel scan interruption
- 30 channel/second scan rate
- Front panel display control
 - Continuous channel scan
 - Freeze channel scan
- Data output
 - Time initiated (every 15 minutes)
 - Command initiated (through serial line)

Figure 2-3
Field Test Data Collection

Data Reduction

Data reduction routines were written to process the raw data taken from the test site. The files created by the data reduction routines could then be loaded into Lotus spreadsheets for graphing. Table 2-13 and 2-14 list the channels monitored by the data acquisition system. The digital filtering capabilities of the data loggers were used to calculate a 15-minute running average on most channels. The real-time math capabilities calculated a more precise 15-minute average for the remainder of the channels.

Table 2-13
Display Case Temperature And Defrost Controller
Monitoring Channel List
Low-Temperature Refrigeration

Channel No.	Measurement	Units
1	Outside dry-bulb temperature	Deg F
2	Outside dew-point temperature	Deg F
3	Inside dry-bulb temperature	Deg F
4	Inside dew-point temperature	Deg F
5	Discharge-air temperature - multideck No. 3-1	Deg F
6	Return-air temperature - multideck No. 3-1	Deg F
7	Discharge-air temperature - multideck No. 3-2	Deg F
8	Return-air temperature - multideck No. 3-2	Deg F
9	Discharge-air temperature - door type No. 3-3	Deg F
10	Return-air temperature - door type No. 3-3	Deg F
11	Discharge-air temperature - door type No. 3-4	Deg F
12	Return-air temperature - door type No. 3-4	Deg F
13	Discharge-air temperature - door type No. 3-5	Deg F
14	Return-air temperature - door type No. 3-5	Deg F
15	Discharge-air temperature - door type No. 3-6	Deg F
16	Return-air temperature - door type No. 3-6	Deg F
17	Discharge-air temperature - door type No. 3-11	Deg F
18	Return-air temperature - door type No. 3-11	Deg F
19	Discharge-air temperature - tub type No. 3-12	Deg F
20	Return-air temperature - tub type No. 3-12	Deg F
21	Discharge-air temperature - walk-in No. 3-9	Deg F
22	Return-air temperature - walk-in No. 3-9	Deg F
23	Discharge-air temperature - walk-in No. 3-10	Deg F
24	Return-air temperature - walk-in No. 3-10	Deg F
25	LT refrigerant suction temperature	Deg F
26	Sat. No. 1 refrigerant suction temperature	Deg F
27	Sat. No. 2 refrigerant suction temperature	Deg F
28	* Discharge refrigerant temperature	Deg F
29	Liquid refrigerant temperature	Deg F
30	LT refrigerant suction pressure	psig
31	Sat. No. 1 refrigerant suction pressure	psig
32	Sat. No. 2 refrigerant suction pressure	psig
33	* Discharge refrigerant pressure	psig
34	* Refrigerant flow rate	CFM
35	* Total store power	kW
36	* Total rack power	kW
37	* Satellite compressor No. 1 power	kW
38	* Satellite compressor No. 2 power	kW
39	Condenser power	kW
40	Defrost digital - multideck No. 3-1	--
41	Defrost digital - multideck No. 3-2	--
42	Defrost digital - multideck No. 3-3	--
43	Defrost digital - multideck No. 3-4	--
44	Defrost digital - multideck No. 3-5	--

Table 2-13 (continued)
Display Case Temperature And Defrost Controller
Monitoring Channel List
Low-Temperature Refrigeration

<u>Channel No.</u>	<u>Measurement</u>	<u>Units</u>
45	Defrost digital - multideck No. 3-6	--
46	Defrost initiation digital	--
47	Defrost digital - walk-in No. 3-8	--
48	Defrost digital - walk-in No. 3-9	--
49	Defrost digital - walk-in No. 3-10	--
50	Defrost digital - walk-in No. 3-11	--
51	Defrost digital - walk-in No. 3-12	--
52	Controller digital	--
53	* Math counter	kW
54	* Math - average store power	kW
55	* Math - average rack power	kW
56	* Math - average compressor No. 1 power	kW
57	* Math - compressor No. 2 power	kW
58	* Defrost digital - walk-in No. 3-7	--
59	* Math - average refrigerant discharge pressure	psig
60	* Math - average refrigerant flow	lb/h

* All channels except these use digital filtering to obtain 15-minute averages

Table 2-14
Display Case Temperature And Defrost Controller
Monitoring Instrument List
Medium-Temperature Refrigeration

Channel No.	Measurement	Units
1	Inside dry-bulb temperature	Deg F
2	Inside dew-point temperature	Deg F
3	Discharge-air temperature - case No. 2-1	Deg F
4	Return-air temperature - case No. 2-1	Deg F
5	Discharge-air temperature - case No. 2-2	Deg F
6	Return-air temperature - case No. 2-2	Deg F
7	Discharge-air temperature - case No. 2-3	Deg F
8	Return-air temperature - case No. 2-3	Deg F
9	Discharge-air temperature - case No. 2-4	Deg F
10	Return-air temperature - case No. 2-4	Deg F
11	Discharge-air temperature - case No. 2-5	Deg F
12	Return-air temperature - case No. 2-5	Deg F
13	Discharge-air temperature - case No. 2-6	Deg F
14	Return-air temperature - case No. 2-6	Deg F
15	Discharge-air temperature - case No. 2-7	Deg F
16	Return-air temperature - case No. 2-7	Deg F
17	Discharge-air temperature - walk-in No. 2-8	Deg F
18	Return-air temperature - walk-in No. 2-8	Deg F
19	Discharge-air temperature - case No. 2-9	Deg F
20	Return-air temperature - case No. 2-9	Deg F
21	Discharge-air temperature - case No. 2-10	Deg F
22	Return-air temperature - case No. 2-10	Deg F
23	MT refrigerant suction temperature	Deg F
24	Sat No. 1 refrigerant suction temperature	Deg F
25	Sat No. 2 refrigerant suction temperature	Deg F
26	Discharge-refrigerant temperature	Deg F
27	Liquid refrigerant temperature	Deg F
28	MT refrigerant suction pressure	psig
29	Sat No. 1 refrigerant suction pressure	psig
30	Sat No. 2 refrigerant suction pressure	psig
31	Discharge-refrigerant pressure	psig
32	Refrigerant flow rate	CFM
33	Total store power	kW
34	Total rack power	kW
35	Satellite compressor No. 1 power	kW
36	Satellite compressor No. 2 power	kW
37	Condenser power	--
41	Defrost digital No. 2-16	--
42	Defrost digital No. 2-17	--
43	Defrost digital No. 2-18	--
44	Defrost digital No. 2-19	--
45	Defrost digital No. 2-20	--

Table 2-14 (continued)
Display Case Temperature And Defrost Controller
Monitoring Instrument List
Medium-Temperature Refrigeration

Channel No.	Measurement	Units
46	Defrost digital No. 2-21	--
47	Defrost digital No. 2-22	--
48	Defrost digital No. 2-23	--
49	Defrost digital No. 2-24	--
50	Defrost digital No. 2-25	--
51	Controller digital	
63	Discharge-air temperature No. 2-16	Deg F
64	Return-air temperature No. 2-16	Deg F
65	Discharge-air temperature No. 2-17	Deg F
66	Return-air temperature No. 2-17	Deg F
67	Discharge-air temperature No. 2-18	Deg F
68	Return-air temperature No. 2-18	Deg F
69	Discharge-air temperature No. 2-19	Deg F
70	Return-air temperature No. 2-19	Deg F
71	Discharge-air temperature No. 2-20	Deg F
72	Return-air temperature No. 2-20	Deg F
73	Discharge-air temperature No. 2-21	Deg F
74	Return-air temperature No. 2-21	Deg F
75	Discharge-air temperature No. 2-22	Deg F
76	Return-air temperature No. 2-22	Deg F
77	Discharge-air temperature No. 2-23	Deg F
78	Return-air temperature No. 2-23	Deg F
79	Discharge-air temperature No. 2-24	Deg F
80	Return-air temperature No. 2-24	Deg F
81	Discharge-air temperature No. 2-25	Deg F
82	Return-air temperature No. 2-25	Deg F
83	MT refrigerant suction temperature	Deg F
84	Sat. No. 1 refrigerant-suction temperature	Deg F
85	Sat. No. 2 refrigerant-suction temperature	Deg F
86	Discharge-refrigerant temperature	Deg F
87	Liquid-refrigerant temperature	Deg F
88	MT refrigerant-suction pressure	psig
89	Sat. No. 1 refrigerant-suction pressure	psig
90	Sat. No. 2 refrigerant-suction pressure	psig
91	Discharge-refrigerant pressure	psig
92	Refrigerant flow rate	CFM
93	Total store power	kW
94	Total rack power	kW
95	Satellite compressor No. 1 power	kW
96	Satellite compressor No. 2 power	kW
97	Condenser power	kW
98	Time, temperature digital	

In addition to the Lotus files, daily summary sheets were also generated by the data reduction routines. Figure 2-4 shows an example of the daily summary sheet. Average ambient and store dry-bulb and dew-point temperatures are shown at the top of the sheet along with the calculated average relative humidity for each. The next group of values is listed for each of the systems on the low-temperature refrigeration rack. The first column lists the system number and type. Systems 1 and 2 are multideck display cases. System 3 through 6 are reach-in door-type display cases. Systems 7 through 10 are walk-in coolers and systems 11 and 12 are tub-type display cases. The next column gives the controller set point for the return minus discharge air temperature. When this value has been exceeded for a given length of time, the controller initiates a defrost on that system. Notice that the set points on the walk-in coolers are zero. The controller algorithm was developed for display cases, not walk-in coolers which behave somewhat differently. As a result, no attempt was made to provide on-demand defrost of the walk-in coolers. Instead, when the controller is operating, the walk-in coolers are defrosted on time limits.

The next column in the summary sheet gives the daily average discharge air temperature for each system excluding values recorded during a defrost. Notice that the walk-in systems 7 and 8 read zero in all temperature columns. Since the defrosts of the walk-in coolers were initiated on time limits, there was no need to collect temperature data on all these units. Temperature data were collected on two of the walk-in units, systems 9 and 10, for future reference. The defrosts were recorded digitally on all walk-in units. The next column lists the average return air temperature for the day. To repeat, the values recorded during a defrost are not included in the average. The average differences between the return and the discharge air temperatures are listed in the next column. The daily maximum delta may be found in the following column. This value may be compared to the set-point delta to determine if a defrost should have been initiated due to temperature limits. Notice that the walk-in systems 7 and 8 read zero and list the total number of defrosts in the day for each system broken down into those initiated due to time or temperature limits. The last column in this group lists the estimated electric defrost kWh which represents the amount of energy which would have been consumed over the day due to case defrosting had this store been equipped with electric defrost rather than hot gas.

Figure 2-4
Defrost Controller Data Summary
Price Chopper - Newburgh, NY
Daily Averages for: 6/4/89
Defrost Control Status: Test

Ambient dry bulb:	72.9°F	Store dry bulb:	70.8°F
Ambient dew point:	51.4°F	Store dew point:	54.6°F
Ambient RH:	46.8%	Store RH:	56.6%

System No.	Type	Set Point Delta	Average Dis (°F)	Average Ret (°F)	Average Del (°F)	Maximum Del (°F)	No. Defrost Time - Temp		Est. Elec. Def kWh
1	M	40	-4.0	29.7	33.8	40.4	1	2	33
2	M	30	0.1	22.0	21.9	32.7	1	2	48
3	D	15	2.8	9.7	6.8	11.6	0	0	0
4	D	15	5.1	11.7	6.6	11.0	0	0	0
5	D	15	5.2	8.0	2.8	10.2	0	0	0
6	D	15	-5.6	3.1	8.7	11.4	0	0	0
7	W	00	0.0	0.0	0.0	0.0	2	0	0
8	W	00	0.0	0.0	0.0	0.0	2	0	0
9	W	00	-2.0	-0.5	1.5	3.6	2	0	0
10	W	00	4.1	1.9	-2.2	0.3	3	0	0
11	T	15	-11.4	0.1	11.5	14.8	0	0	0
12	T	18	-18.6	-2.3	16.2	20.9	0	1	15

Power	kWh/Day	Store Peak kW	Rack Peak kW
Total store	11,745.5	550.3	543.0
Low temperature rack	1,028.7	45.5	47.7
Sat. No. 1 (system No.12)	143.1	6.5	6.5
Sat No. 2 (system No. 11)	106.0	6.2	5.9
Low temperature condenser	176.4	7.4	7.1

Loads	Btu/h
Low temperature rack	251,620
Ice cream system No. 12	51,029
Frozen OJ system No. 11	26,599

Miscellaneous	Temperature	Pressure (Psig)	Flow (lb/h)
Low temperature rack suction	36.3	12.1	6,462
Sat. No. 1 suction	42.6	-0.5	
Sat. No. 2 suction	58.4	5.7	
Low temperature rack discharge	200.1	189.2	
Low temperature liquid	86.9		

The next group is the power and energy consumption for the total store, the entire low-temperature rack, satellite compressor No. 1 (which services system 12), satellite compressor No. 2 (which services system 11), and the low-temperature rack condenser. The first column lists the kWh per day for each item. The second column lists the kilowatt value for each item at the time of the peak-store value. The third column lists the kilowatt value for each item at the time of the peak for the compressor rack.

The following group of numbers is the calculated daily average refrigeration loads. The first value is for the low-temperature refrigeration rack not including systems 11 and 12. The next value is for system 12, the ice cream tub case. The following value is for system 11, the frozen orange juice tub case.

The last group of numbers of the daily summary sheet are average temperatures, pressures and flow rates from the low-temperature compressor rack.

In addition to the daily summary sheet, the data reduction routines can generate a test summary sheet that is identical to the daily sheet but with average and total values for the entire test period. The tests were usually run in two-week intervals switching between the time clock and the controller.

Section 3

TEST RESULTS

The project included testing the demand defrost controller in its various hardware configurations. In Phase I, the laboratory development system and prototype controllers were used to determine the basic operation of the control algorithms. In Phases II and III, hardware and software implementations were tested in an operating supermarket. This section describes the results of these tests.

PHASE I: OBSERVATIONS OF DISPLAY CASE OPERATION

The initial tests performed at the laboratory test facility examined the operating characteristics of the display case to determine the appropriate criteria for demand defrost control. For these tests, the display case evaporator temperature was controlled at a constant value of -15°F using the case EPR. The display case was allowed to operate at this evaporator temperature for an extended period of time, on the order of several days. During this operation, measurements were gathered at five-minute intervals to establish the parameters of case operation.

Visual observation of the display case evaporator and measurements taken during operation developed a description of the frost buildup. The display case evaporator air-side pressure drop, and the temperature of the discharge and return air were of particular interest. The usual profiles for these three measurements are shown in Figures 3-1 and 3-2. The temperature profiles for the display case are shown in Figure 3-1. The air static pressure measured at the outlet of the display case fans and inlet of the evaporator is shown in Figure 3-2. The profiles shown began at the end of a defrost with a frost-free evaporator and ended approximately 38 hours later.

The temperature values recorded for the test display case are shown in Figure 3-1 which gives the discharge and return air temperatures along with the temperature measured in the product area. After the defrost there was a large temperature difference between the discharge and return air temperatures, due to the increased rate of refrigeration needed to lower the temperature of the display case to the desired level. After lowering the case temperature, the temperature difference between discharge and return air decreased to approximately 10°F to 12°F . As frost accumulated on the evaporator, the value of the discharge air temperature remained fairly constant while the value of the return air temperature tended to increase as the amount of frost on the evaporator increased.

Figure 3-1. Display Case Temperature Profiles.

Figure 3-2. Air-Side Static Pressure.

The corresponding evaporator air pressure measurement taken at the test display case is shown in Figure 3-2. The air static pressure difference at the inlet of the evaporator and the outlet of the display case fans is shown in this figure. This rising fan discharge pressure indicated a decrease in air flow. Because the rise in air pressure measured at the test display case often exceeded the measurement range of the sensor, there was a saturated signal output from the sensor during the frost buildup. This saturated level is shown in Figure 3-2 as flat portions of the plot. During these time periods, the air pressure actually increased although the plot shows the pressure value remaining constant. As can be seen from the plot shown in Figure 3-2, the pressure of the outlet of the display case fan rose as the case operated over time which indicated that the air flow through the evaporator decreased due to frost accumulation.

As frost accumulated in the evaporator, it tended to increase the resistance to air flow which reduced the flow of the display case fans. Since less air was passed through the evaporator, less refrigeration was provided to the display case. The discharge-air temperature was still made cold enough but the reduction in air flow reduced the amount of heat removal capacity of the unit. The decrease in refrigeration provided, and the breakdown of the display case air curtain both caused by the reduction in air flow, accounted for the rise in the return air temperature.

Defrosting the evaporator after prolonged operation removed the frost from the evaporator, decreased the fan outlet static pressure, and changed the temperature values back to those shown at the beginning of the profile in Figure 3-1. Figures 3-3 and 3-4 respectively, show the effect of defrost on the case temperatures and fan outlet static pressure. Defrost is indicated in Figure 3-3 by the peak. After the defrost, the difference between these two temperatures is initially large, decreasing as the case returned to the desired operating conditions. The effect of defrost on the outlet static pressure of the fan is shown in Figure 3-4. During defrost, the pressure dropped as the frost was removed and air flow through the evaporator increased. The static pressure then rose as frost accumulated on the evaporator.

These same observations were made for several tests which suggested that the behavior of the discharge and return air temperatures for a display case was repeatable. From this information it was concluded that the measurement of the temperature difference between the discharge and return air could be used as an indicator that the display case needed to be defrosted.

Figure 3-3. Display Case Temperature Profiles.

Figure 3-4. Air-Side Static Pressure.

Similar tests were conducted on walk-in chests. It was found, however, that the operating characteristics of the walk-in chest were significantly different than those observed in the display case. In general, it was found that the temperature difference across the walk-in chest evaporator decreased as the frost accumulated on the surface of the evaporator. The difference in performance between the case and the walk-in can be attributed to the fact that the evaporator of the display case is enclosed so that no air can by-pass it. In the walk-in, the fans were mounted in a way that when the evaporator was blocked with frost, air passed around the evaporator rather than through it. Since air flow through the fans remained the same, the reduction in refrigeration as the frost accumulated caused the air temperature difference across the evaporator to decrease.

Because the walk-in observations were significantly different from those for the display case, it was decided that a different control algorithm was needed for walk-in chests and that more information was needed before it could be developed for display case defrost, based on measured temperature differences between the return and discharge of case air curtain.

Combined Temperature and Defrost Control

Testing was undertaken to develop a combined case temperature and defrost control algorithm to provide simultaneous control of both the display case discharge air curtain temperature and to determine when defrost of the case was required. The algorithm tested was also capable of controlling multiple display case circuits for both temperature and defrost.

The algorithm used the same control hardware and sensors for both case temperature and defrost control. The temperature of the discharge of the air curtain was used for temperature control and was combined with those taken at the case return for establishing the defrost criteria.

Testing used both a display case and walk-in chest. The display case was equipped with discharge and return-air temperature sensors and both temperature and defrost were controlled based on readings taken from these sensors. For the testing, the set point used for the display case for temperature control was 0°F. For defrost, the temperature difference set point was 14°F with minimum and maximum times between defrost of 4 and 30 hours, respectively.

The walk-in chest was equipped with a discharge-air temperature sensor that was used only for temperature control. Defrost for the walk-in was controlled on a time basis with the test defrost controller as the time clock. The temperature set point for the walk-in chest was 10°F. The

time between defrosts was set at six hours so the walk-in would be defrosted four times daily. The discharge-air temperature remained at about 2°F during the test, which was slightly higher than the set point. The discrepancy was probably caused by a calibration difference between the control sensor and the monitoring thermocouples. The temperature stayed at a fairly constant level, however, indicating that the case temperature algorithm functioned properly.

During the test, the display case was defrosted four times. The value of the temperature difference between the return and discharge air had risen to close to the set point for the defrost controller before each defrost, indicating that the defrost control was performing as desired. The air-static pressure measurement indicates that the static air pressure had risen before each defrost and then dropped afterward, showing that frost had accumulated on the evaporator prior to each defrost.

Ambient dry-bulb and dew-point temperatures were recorded during the test. The dew point recorded can be considered high for display case operation (50 to 56°F) and that accounted for the large number of defrosts.

The walk-in temperature was maintained (except for time periods before and during defrosts) at approximately 12°F, which was slightly higher than the desired set point. The temperature rise before defrost was probably due to the loss of refrigeration capacity by the evaporator due to frost blockage.

Medium-Temperature Testing

Testing was performed with the display case operating at medium-temperature conditions. For this test, the case evaporator was controlled by the EPR valve and held at a value of 20°F. The set points for the defrost controller were 5°F for the temperature difference; minimum time between defrosts three hours; and maximum time between defrost 96 hours.

The results of the five days of tests are similar to the low-temperature tests. The case was initially defrosted to start the test with a clean evaporator. Defrost was later initiated by the controller after approximately two days. The corresponding temperature difference started at a value of 4°F and rose to a value of about 5.5°F before the defrost. The static air pressure rose after the initial defrost until the signal saturated. After the second defrost, the pressure again dropped, indicating that frost had built up on the surface of the evaporator and had been removed by the defrost.

PHASE II: TEST RESULTS

When the instrumentation and controller were installed at the field-test store, a test plan was formulated. The test plan addressed monitoring the display cases, establishing the correct set points for the defrost controller, and establishing the energy savings achieved by using the defrost controller. The method to establish these savings was to alternate control of the defrosts between the demand controller and standard defrost time clock to compare the system operating measurements and energy consumption with both methods of defrost control.

The set points that had to be established through initial monitoring of the display cases were:

- The temperature difference at which defrost was initiated;
- The minimum elapsed time between defrosts which prevented a defrost from being initiated until this amount of time had elapsed; and
- The maximum elapsed time between defrost, which was the largest allowable time interval before the controller triggered a defrost, regardless of the measured temperature difference.

When these set points were established, the demand controller and defrost time clock were alternately operated and tested.

The schedule followed for this alternate operation is shown in Table 3-1. Each test was assigned a test number which included a letter suffix of either "T", for test operation under the demand controller, or "N", for normal operation under the time clock. The type of defrost controller used for each test, either "Demand" or "Clock," is also indicated. The actual dates for each test are also shown. The desired length for each test was 14 days. The actual test lengths varied from 5 to 19 days due primarily to availability of personnel to perform the changeover between the two controllers. Problems developed with the demand controller during test number 5T, which necessitated returning the defrost control to the time clock while repairs and changes were made. This operating change accounted for the shortened length of test number 5T to 5 days and the increased length of test number 6N to 19 days.

The variable test lengths required that the test results be normalized so that each test could be compared to others. All test results were, therefore, formulated and presented in terms of the values seen over each test and on a per day basis.

Test Set Points

The initial observations of the operation of the display cases were used to determine the four set points for the demand controller, which were the maximum temperature difference between the discharge and return air that initiated defrost, the minimum and maximum times between defrosts, and the duration of defrost.

Table 3-1 Defrost Test Schedule			
Test Number	Control	Dates	# of Days
1T	Demand	12/08 - 12/21/88	14
3T	Demand	01/12 - 01/22/89	11
5T	Demand	02/02 - 02/06/89	5
7T	Demand	03/02 - 03/12/89	11
9T	Demand	03/29 - 04/10/89	13
11T	Demand	04/27 - 05/05/89	9
13T	Demand	05/24 - 06/05/89	13
15T	Demand	07/07 - 07/25/89	19
17T	Demand	08/15 - 09/04/89	21
DEMAND CONTROLLER AVERAGE			
2N	Clock	12/23 - 01/10/89	19
4N	Clock	01/24 - 01/31/89	8
6N	Clock	02/08 - 02/27/89	19
8N	Clock	03/15 - 03/27/89	13
10N	Clock	04/12 - 04/20/89	9
12N	Clock	05/09 - 05/22/89	14
14N	Clock	06/07 - 07/05/89	29
16N	Clock	07/28 - 08/13/89	17

The discharge and return air temperatures for each display-case circuit were used to determine the temperature difference set point. Examining the resulting temperature difference between these temperatures suggested appropriate parameters. The general procedure was to observe the trend of these temperatures after a defrost period. The rate of change of these temperatures and the resulting temperature differences with time were noted.

The temperature difference set points chosen for each of the eight display-case circuits are given in Table 3-2. The system number refers to the case identity used in the test store. The multideck display case circuits, numbers 3-26 and 3-27, were given temperature difference set points of 40 and 30°F, respectively. The variation in set points was due to a higher rate of temperature change observed in the display case in circuit number 3-26. The temperature set points for the door display cases, circuit numbers 3-28 through 3-31, were 15°F, while the tub-case circuit numbers 3-26 and 3-27 were 15 and 18°F, respectively.

Table 3-2
Demand Defrost Controller Set Points

System Number	Case Type	Temp. Difference Set Point (°F)	Min. Time (hr)	Max. Time (hr)	Def. Length (min)
3-26	Multideck	40	8	12	26
3-27	Multideck	30	8	20	26
3-28	Door	15	24	168	26
3-29	Door	15	24	168	26
3-30	Door	15	24	168	26
3-31	Door	15	24	168	26
3-36	Tub	15	24	168	26
3-37	Tub	18	24	168	26

The minimum elapsed time setting for each of the display case circuits is also given in Table 3-2. These settings were chosen based on the recommended time clock settings of the case manufacturer. The multideck cases had a minimum time setting of eight hours, while the door and tub cases had minimum settings of 24 hours.

The maximum time setting for each case circuit is also shown in Table 3-2 and represents the maximum duration allowed before a defrost was initiated regardless of the air temperature difference. The multideck cases had maximum time settings of 12 and 20 hours. The shorter time setting for circuit number 3-26 was chosen due to the tendency of this case to show a faster rate of temperature difference change between the discharge and return air, indicating a higher rate of frost accumulation. The door and tub cases were given maximum time settings of 168 hours (seven days) which were close to the longest duration used by the experimental controller. One defrost per week, whether or not it is required, may be an appropriate operating procedure.

The defrost time length, which is also shown in Table 3-2, was chosen based on the display case manufacturer's recommendation. A defrost duration of 26 minutes was used for all case types.

Test Results - Number of Defrosts and Energy Consumption

The results of the controller and defrost time clock tests are summarized in Table 3-3, which shows the total number of defrosts and number of defrosts per day for each test. The energy consumption for the low temperature compressors is also given in terms of kWh/day. The three loads shown correspond to the three main low temperature compressors which operate in parallel, and to two satellite compressors which have separate suction returns. The designations given in Table 3-3, low temp, sat 1, and sat 2, stand for the low temperature, satellite 1, and satellite 2 compressors, respectively. The total average daily energy consumption for these compressors is also shown.

The preceding results are given for both the demand-control and time-clock tests. Overall averages are given for each test group. The overall results show that the use of the demand defrost controller dramatically reduced the number of defrosts incurred by the low temperature refrigeration system. *During the controller tests, the number of defrosts initiated averaged 5.2 per day, while during the time clock tests, the average number of defrosts rose to 16 per day.*

The average energy consumption recorded during the controller test was lower for the low temperature and both satellite compressors than that measured for the time clock tests. The average compressor energy consumption measured for the controller tests was 1,152.1 kWh/day, compared to 1,206.9 kWh/day for the time-clock tests. The energy compressor savings achieved by the controller were 54.9 kWh/day, or 4.5%.

Estimated Performance with Electric Defrost

The preceding measurements were taken for a refrigeration system using hot-gas defrost. In many instances, electric defrost would be used. An estimate of the energy savings that would have been achieved by the defrost controller if electric defrost was employed was, therefore, made.

Test No.	Control	Dates	No. of Days	No. of Def.	Defrosts per Day	Lt Comp kWh/Day	Sat 1 Comp kWh/Day	Sat 2 Comp kWh/Day	Total Comp kWh/Day
1T	Demand	12/08 - 12/21/88	14	59	4.2	824.9	107.9	74.6	1007.4
3T	Demand	01/12 - 01/22/89	11	43	3.9	853.8	115.6	79.5	1048.9
5T	Demand	02/02 - 02/06/89	5	15	3.0	863.9	109.8	60.9	1034.6
7T	Demand	03/02 - 03/12/89	11	44	4.0	829.3	112.9	79.2	1021.4
9T	Demand	03/29 - 04/10/89	13	58	4.5	874.0	122.3	92.4	1088.7
11T	Demand	04/27 - 05/05/89	9	44	4.9	928.8	127.3	97.4	1153.5
13T	Demand	05/24 - 06/05/89	13	84	6.5	1017.3	141.6	115.6	1274.5
15T	Demand	07/07 - 07/25/89	19	118	6.2	1016.7	142.4	118.0	1277.1
17T	Demand	08/15 - 09/04/89	21	139	6.6	6.2	138.3	114.1	1248.6
Demand Controller Average					5.2	927.3	127.2	97.5	1152.1
2N	Clock	12/23 - 01/10/89	19	304	16	928.6	121.0	92.8	1142.4
4N	Clock	01/24 - 01/31/89	8	128	16	951.2	119.8	79.7	1150.7
6N	Clock	02/08 - 02/27/89	19	306	16	907.1	110.5	89.6	1107.2
8N	Clock	03/15 - 03/27/89	13	209	16	968.5	120.5	100.5	1189.4
10N	Clock	04/12 - 04/20/89	9	144	16	958.4	124.0	88.5	1170.9
12N	Clock	05/09 - 05/22/89	14	224	16	1014.5	134.7	108.2	1257.4
14N	Clock	06/07 - 07/05/89	29	442	15	1010.7	144.6	124.8	1280.1
16N	Clock	07/28 - 08/13/89	17	272	16	1020.1	140.8	122.2	1283.1
Time Clock Average					16	973.1	129.0	104.8	1206.9
Demand Controller kWh/Day Savings						45.8	1.8	7.3	54.9
Demand Controller Percent Savings						4.7	1.4	7.0	4.5

Table 3-3.
Summary of Test Results
Number of Defrosts and Compressor Energy Consumption

Table 3-4
Estimate of the Savings Achieved with Electric Defrost

Test No.	Control	Dates	No. of Days	No. of Defrosts	Defrosts Per Day	Total Def kWh	Defrost (kWh/d)
1T	Demand	12/08 - 12/21/88	14	59	4.2	724	51.7
3T	Demand	01/12 - 01/22/89	11	43	3.9	538	48.9
5T	Demand	02/02 - 02/06/89	5	15	3.0	194	38.8
7T	Demand	03/02 - 03/12/89	11	44	4.0	526	47.8
9T	Demand	03/29 - 04/10/89	13	58	4.5	726	58.6
11T	Demand	04/27 - 05/05/89	9	44	4.9	572	63.6
13T	Demand	05/24 - 06/05/89	13	84	6.5	1123	86.4
15T	Demand	07/07 - 07/25/89	19	118	6.2	1596	84.0
17T	Demand	08/15 - 09/04/89	21	139	6.6	1821	86.7
Demand Controller Average					<u>5.2</u>		<u>67.7</u>
2N	Clock	12/23 - 01/10/89	19	304	16	3477	183
4N	Clock	01/24 - 01/31/89	8	128	16	1464	183
6N	Clock	02/08 - 02/27/89	19	306	16	3507	183
8N	Clock	03/15 - 03/27/89	13	209	16	2390	183
10N	Clock	04/12 - 04/20/89	9	144	16	1647	183
12N	Clock	05/09 - 05/22/89	14	224	16	2562	183
14N	Clock	06/07 - 07/05/89	29	442	15	5070	175
16N	Clock	07/28 - 08/13/89	17	272	16	3111	183
Time Clock Average					<u>16</u>		<u>183</u>
Demand Controller kWh/day Savings							115.3
Demand Controller Percent Savings							63.0

To implement electric defrost, each of the display cases would have been equipped with an electric heater. The rating of these heaters was taken from the display case manufacturer's literature. The energy consumption for electric defrost was made based on the size of the electric heaters given in Table 2-7, the expected duration of each defrost, and the number of defrosts indicated for each test. The results of these calculations are shown in Table 3-4. For each test conducted, an estimate of the energy consumption for electric defrost is given. For the controller tests, the daily energy consumption for electric defrost was estimated at 67.7 kWh. For the time clock tests, the daily consumption was estimated at 183 kWh. Using these assumptions the demand defrost controller would save 115.3 kWh/day, or 63.0%.

Projected Annual Savings

From the field test results and the estimates of electric defrost energy consumption, the savings achieved by the defrost controller were 54.9 and 115.3 kWh/day on compressor and electric heater energy, respectively.

These daily savings can be used to project annual savings. The annual energy savings which could be achieved by the use of the defrost controller are 20,030 kWh in compressor consumption and 42,085 kWh in electric heater consumption.

The value of the above savings depends on the prevailing electric rates. *As an example, at an electric rate of \$0.075/kWh, the savings achieved per year by the controller would be \$1,502 for hot-gas defrost operation, and \$4,658 for electric defrost operation.*

Variations in Controller Performance

The performance of the demand defrost controller varied significantly during the test period due to changes in ambient conditions that produced a varying amount of moisture collected by the display case evaporators that changed the number of defrosts required, and varying operating conditions for the compressor system, seen primarily in the condensing temperature which influenced compressor energy consumption.

The ambient testing conditions are shown in Figures 3-5 and 3-6 which are graphs of average daily outside dry-bulb (Figure 3-5) and dew-point (Figure 3-6) temperatures measured at the test site. The figures show that both dry-bulb and dew-point temperatures increased during the test as expected for the period of December to August. No ambient temperature data were collected during March (test number 8N) due to problems measuring those temperatures by the DAS during this time.

The impact of changing ambient conditions on the number of defrosts required by the display cases is shown in Figure 3-7. The number of defrosts initiated by the time clock predictably remained constant at 16 per day for all clock tests. The number of defrosts initiated by the controller changed significantly from December to August. The lowest number of defrosts initiated per day was 3.0 in February, while the highest number was 6.6, recorded in August.

This change in the number of daily defrosts was expected and appropriate considering the increase in ambient humidity.

The change in ambient conditions also affected the operation of the system compressors due to the change in condensing temperature and pressure as shown in Figure 3-8. The increase in outside dry-bulb temperature caused the condensing temperature and pressure to increase, which resulted in higher compressor energy consumption.

The impact of changes in the number of defrosts and the condensing pressure on compressor energy consumption is shown in Figure 3-9. Consumption was less during operation of the demand defrost controller than during time clock operation for all months tested. The difference in compressor energy consumption between the two modes of operation decreased as the average ambient dry-bulb temperature increased, which was expected as the number of defrosts per day initiated by the controller approached the time defrosts.

The estimated average daily energy consumption for electric defrost during the test is shown in Figure 3-10. These estimates were based on the method outlined previously. The energy consumption for electric defrost remained constant for the time clock operation because the number of defrosts remained constant. The electric energy consumption during controller operation was low during the winter months with the lowest value being 38.8 kWh/day in February. It rose during the summer months, the highest value being 86.7 kWh/day in August. The increase in electric energy consumption during controller operation followed the increased number of defrosts.

The impact of ambient conditions on electricity savings achieved by the controller is shown in Figure 3-11, which gives the average daily savings achieved for each month of testing. The savings for both compressor operation (hot-gas defrost) and compressors and electric heaters (electric defrost) are presented. The savings recorded from December 1988 through May 1989 were significantly greater than those in June and July 1989. This decrease in savings occurred as the number of defrosts initiated by the controller approached the number of timed defrosts.

PHASE III: DEFERRED DEFROST ALGORITHM, DSM

The purpose of the deferred defrost algorithm within the defrost controller is to provide a means to limit the number of defrosts that could occur during periods of peak power demand

for the supermarket, DSM. With a demand defrost controller, defrost is unscheduled, depending on the criteria for defrost. It is possible that one or more defrosts could be initiated during a peak power demand period, which would cause an increase in the billable demand of the store. The size of this increase depends on the type of defrost. For hot gas defrost, the power increase would be from 1 to 5 kW, as a result of the added compressor power needed to return the display case to temperature after a defrost. For electric defrost, an increase of as much as 10 kW is possible. In utility service territories where demand billing rates are high, these increases in demand could negate much of the energy savings produced by the use of the demand defrost controller.

Another benefit from the use of the deferred defrost algorithm is that supermarket operators prefer not to defrost display cases during high-shopping periods. The higher case temperature and fog that forms during defrost makes products less attractive. Defrost time clocks are often arranged so that more defrosting occurs during off hours. Use of the deferred defrost algorithm could help alleviate this problem when a demand defrost controller is used.

The existing test controller was provided with a control algorithm giving it the capability of disabling defrosts during a predetermined time period. Display cases indicating the need for defrost were placed in a queue and were later defrosted when the time period expired. For the initial testing, the time period blocked off from defrost was 8 a.m. to 8 p.m.

Initial test results suggested several changes to the algorithm. The time period when defrosts were allowed was too long, extending into the peak 8 a.m. to midnight period. Shortening the time for defrost did create one significant problem, which was that the multideck display cases often required several defrosts per day. Delaying these defrosts could cause operational problems compared to the door and tub cases which defrost, at most, once per day and can be scheduled for defrost at any time. A possible solution is to provide a second time band for critical cases, such as the multidecks. This second band would allow defrost during a longer time period for critical cases or walk-ins. A possible second band is from 10 p.m. to 10 a.m., which adds four hours to the allowable defrost period for critical cases. It was found that walk-in chests should have a higher priority than display cases, since they require frequent defrosts. The defrost of the walk-in chests should be given first placement in the queue at any time, regardless of the order that the defrosts were requested.

Figure 3-5. Average Daily Outside Dry-Bulb Temperature.

Figure 3-6. Average Daily Outside Dew-Point Temperature.

Figure 3-7. Average Number of Defrosts Initiated Daily.

Figure 3-8. Average Daily Condensing Pressure.

Figure 3-9. Average Daily Compressor Energy Consumption.

Figure 3-10. Estimated Electric Defrost Energy.

Figure 3-11. Daily Energy Savings During Testing.

Time Period from Sept. 8 through Sept. 17, 1990
Figure 3-12. Store Power Profile for the Defrost Test Site.

Initial testing also showed that defrosting within the allowable time period must be stretched out for the longest possible time. If defrosts are initiated as soon as possible, all defrosts scheduled occur during the early portion of the allowable time period. This can result in many of the display cases and walk-ins being at high temperature and requiring a long and sustained pulldown. It is possible that this condition could cause a larger power demand by the refrigeration compressors. Defrosting should be scheduled to one circuit every 60 to 90 minutes, which will allow the refrigeration system to return to operating temperature without requiring excess power.

Store power demand was examined in detail during the initial testing to determine the best time periods to initiate defrost. Figure 3-12 shows the power profile for the store from September 8 through September 17, 1990. The pattern was fairly consistent for all days in this time period. The store power tended to be at two distinct levels each day. The higher level occurred from 9 a.m. to approximately 11 p.m. At night, between the hours of 11 p.m. to approximately 8 a.m., the power level of the store dropped by about 60 to 80 kW. This low power period was targeted as the time used primarily for defrosts.

Figure 3-13. Relation Between Peak Power Demand and Average Daily Outdoor Dry Bulb Temperature.

An analysis of store power demand was also carried out using data collected during previous tests. The store peak demand was compared to the average daily outside dry-bulb temperature. There was a strong relationship between these two quantities as shown in Figure 3-13. The store peak demand rose as the outside temperature increased. A curve fit of the data, also shown in Figure 3-13, suggested that the relation was second order and that the power level tends to flatten at ambient temperatures less than 40°F. This relation between power demand and ambient temperature suggests that HVAC, particularly air conditioning, has a strong impact on store peak demand. The rise in power associated with the operation of the refrigeration also contributes to this phenomenon.

Table 3-5 gives the results of the tests performed with the defrost controller modified for the deferred defrost algorithm. The test data were collected using the same procedure used previously. The low-temperature refrigeration system was operated alternately with the defrost controller and the standard time clock. Each test was conducted for approximately a two-week period.

The defrost controller significantly reduced the number of defrosts incurred for the low-temperature display cases, 4.1 per day with the controller versus 16 per day with the time clock. A comparison of compressor energy consumption shows that the use of the demand

Test No.	Control	Dates	No. of Days	No. of Def	Total Def kWh	Def kWh per Day	Lt Comp kWh/Day	Sat 1 Comp kWh/Day	Sat 2 Comp kWh/Day	Total Comp kWh/Day
1 LT	Demand	09/06 - 09/17/90	15	50	691	46.1	723.1	104.8	109.7	937.6
3 LT	Demand	10/11 - 10/17/90	7	37	517	73.9	747.5	103.8	104.3	955.6
5 LT	Demand	10/25 - 11/06/90	7	31	421	60.1	764.3	94.2	98.9	957.4
7 LT	Demand	12/01 - 12/19/90	14	63	838	59.9	745.4	90.1	93.5	929.0
11 LT	Demand	02/01 - 02/13/91	13	48	592	45.5	661.3	76.9	76.1	814.3
Demand Controller Average				4.1		54.6	722.5	93.2	95.8	911.6
1 LNA	Clock	08/21 - 09/04/90	14	262	3104	221.7	765.3	121.6	128.4	1015.3
2 LN	Clock	09/19 - 10/03/90	15	264	3132	298.8	711.7	105.3	109.3	926.3
4 LN	Clock	10/19 - 10/23/90	5	81	1074	214.8	786.9	102.2	108.0	997.1
6 LN	Clock	11/08 - 11/14/90	7	126	1491	213.0	746.9	95.7	100.1	942.7
8 LN	Clock	12/21 - 01/02/91	13	234	2769	213.0	896.4	91.0	89.3	1076.7
10 LNA	Clock	01/11 - 01/21/91	11	194	2307	209.7	742.6	93.5	90.8	926.9
10 LNB	Clock	01/22 - 01/30/91	7	133	1568	224.0	695.4	81.6	83.6	860.6
Time Clock Average				18.0		214.5	767.3	100.6	103.1	971.0
Demand Controller kWh/Day Savings						159.9	44.7	7.4	7.3	59.4
Demand Controller Percent Savings						74.5	5.8	7.4	7.0	6.1
Project Annual Savings				kWh	\$	\$	\$			
					(\$.050/kWh)	(\$.075/kWh)	(\$.100/kWh)			
Hot Gas defrost				21,690.0	1084.5	1626.7	2169.0			
Electric defrost				80,049.4	4002.5	6003.7	8004.9			

Table 3-5.
Results for Demand Defrost Controller Tests
Low Temperature Refrigeration with Deferred Defrost Algorithm

defrost controller reduced compressor energy by 59.4 kWh/day, which represents a savings of 6.1%. Estimated savings if electric defrost were employed were 159.9 kWh/day, or 74.5% of the electric defrost consumption. An annual projection of savings based on these results suggests that 21,690 kWh would be saved if hot gas defrost was used and 80,049 kWh would be saved with electric defrost. At \$0.075/kWh, this corresponds to an annual savings of \$1,626 and \$6,003 respectively.

An analysis of the data was then undertaken to determine the demand savings achieved by the defrost controller with the deferred defrost algorithm. The relationship between the electric demand of the low temperature compressors and the average daily outdoor ambient dry bulb temperature was established. Two demand values were considered: the peak demand of the rack and the power demand of the rack coincident with the peak demand of the store. The relation between demand and ambient temperature was considered separately for the controller and time clock test results.

Figure 3-14 compares the coincident demands of the compressor rack for demand defrost and time clock operation. The comparison shows a store peak demand savings when the defrost control is used. The value of these savings decreases as the average daily ambient temperature increases. No savings were seen at a daily ambient temperature of 70°F. Savings were greatest at a temperature of 30°F at a value of 2.4 kW. Figure 3-15 shows the difference in rack peak demand between controller and time clock operation. Savings over the entire ambient temperature range vary from 5.6 kW at 30°F to 3.6 kW at 70°F.

Credit can also be taken for added demand savings if electric defrost were employed rather than hot-gas defrost. Table 2-7 lists the heater sizes that would be employed with these cases and suggests that the savings would range from 10.8 to 16.2 kW, depending on which case type was defrosted.

Figure 3-14. Deferred Defrost Algorithm, Store Peak.

Figure 3-15. Deferred Defrost Algorithm, Rack Peak.

MEDIUM-TEMPERATURE REFRIGERATION DEFROST CONTROL

A test defrost controller was also installed on the medium-temperature refrigeration system. The test controller was employed to defrost all display cases associated with this system. Alternate testing between the controller and a standard time clock was performed in a similar fashion as was done with the low-temperature refrigeration. Test durations were approximately two weeks.

The test results for the medium temperature refrigeration are shown in Table 3-6. The table is arranged in the same manner as the results for the low-temperature refrigeration. The defrost controller significantly reduced the number of defrosts required. The average number of defrosts occurring daily with the controller was 11.6, while 25.6 defrosts occurred daily with the time clock operation. The impact of this reduction was not as great as with low-temperature refrigeration. The reduction in compressor energy consumption was 6.6 kWh/day, or 1.7% of total compressor energy consumption. An estimate of savings for electric defrost operation was also made based on the defrost heaters listed for the medium-temperature display cases in Table 2-8. The use of the demand defrost controller would produce a savings of 11.2 kWh/day, or 53.8% of the total electric consumption for electric defrost.

The projected annual savings for demand defrost control with medium-temperature refrigeration are 2,412 kWh for combined hot-gas and off-cycle defrost, and 6,502 kWh for electric and off-cycle defrost. These savings are considerably less than those for low-temperature refrigeration operation, despite the fact that the demand controller reduced the number of defrosts incurred by approximately 54%. The results suggest that the fact that off-cycle defrost is employed for many of the display cases influences the amount of energy consumed by defrosts. It is likely that the amount of added compressor energy needed to return the display case to temperature is less when off-cycle defrost is employed. Off-cycle defrost is not used when the off-time would be too long resulting in an unacceptable rise in the stored product temperature, which occurs in the refrigeration of fresh meats and frozen foods when either hot-gas or electric defrost is used. The savings for electric defrost is diminished by the number of display cases using off-cycle defrost.

Test No.	Control	Dates	No. of Days	No. of Def	Total Def kWh	Def kWh per Day	Mt Comp kWh/Day	Sat 1 Comp kWh/Day	Sat 2 Comp kWh/Day	Total Comp kWh/Day
7 MT	Demand	12/05 - 12/19/90	15	256	211.1	14.1	294.5	71.3	24.1	389.9
9 MT	Demand	01/04 - 01/09/91	6	92	75.9	12.6	322.8	71.3	27.0	421.1
13 MTA	Demand	02/01 - 02/07/91	7	89	73.4	10.5	282.6	64.3	24.1	371.0
13 MBA	Demand	02/08 - 02/13/91	6	82	67.6	11.3	271.1	61.7	23.7	356.5
15 MTA	Demand	02/22 - 03/07/91	14	119	98.1	7.0	276.1	71.3	30.3	377.7
15 MTB	Demand	03/08 - 03/26/91	17	140	115.5	6.8	267.2	66.1	28.3	361.6
17 MT	Demand	04/04 - 04/12/91	9	103	84.9	9.4	317.0	76.0	45.7	438.7
17 MTA	Demand	04/18 - 04/21/91	4	36	29.7	7.4	272.0	70.7	44.3	387.0
19 MT	Demand	05/08 - 05/13/91	6	59	48.7	8.1	310.0	80.2	51.3	441.5
21 MT	Demand	05/24 - 05/30/91	6	72	59.4	9.9	361.0	- 0 -	76.3	437.3
Demand Controller Average				11.6	0.0	9.6	292.6	65.4	34.4	392.4
6 MN	Clock	11/13 - 12/03/90	21	469	386.8	18.4	281.1	76.7	30.5	388.3
8 MN	Clock	12/21 - 01/02/91	13	377	310.9	23.9	319.7	76.7	27.2	423.9
10 MN	Clock	01/11 - 01/15/91	5	139	114.6	22.9	270.4	70.8	23.6	364.8
14 MN	Clock	02/15 - 02/20/91	6	156	128.6	21.4	260.4	70.5	26.8	357.7
16 MN	Clock	04/02 - 04/03/91	2	52	42.9	21.4	259.3	60.9	28.2	348.4
18 MN	Clock	04/23 - 05/06/91	11	286	235.9	21.4	294.6	79.9	27.2	401.7
20 MN	Clock	05/16 - 05/22/91	7	161	132.8	19.0	371.0	50.7	33.2	454.9
Time Clock Average				25.2		20.8	297.4	72.9	28.7	399.0
Demand Controller kWh/Day Savings						11.2	4.8	7.5	-5.7	6.6
Demand Controller Percent Savings						53.8	1.6	10.3	-19.8	1.7
Project Annual Savings					kWh	\$	\$	\$		
						(\$.050/kWh)	(\$.075/kWh)	(\$.100/kWh)		
Hot Gas & off-time defrost					2412.3	120.6	180.9	241.2		
Electric & off-time defrost					6501.8	325.1	487.6	656.2		

Table 3-6.
Results for Demand Defrost Controller Tests
Medium Temperature Refrigeration

COMMERCIAL PROTOTYPE CONTROLLER TESTING

A commercial prototype version of the defrost controller was also installed and tested at the field test site. The controller was provided by Hussmann Corporation and consisted of one of their general purpose controls used for control of compressor racks. The controller was reprogrammed to use the demand defrost algorithm and was integrated with a test controller on-site such that the test controller handled the input/output functions of measuring temperature and initiating and terminating defrosts. The commercial prototype controller interpreted the input measurements and used the control logic to determine when defrost was required. This arrangement was used because the Hussmann controller did not have adequate I/O capability for this application. Modifying the controller for more I/O would have required more work than was deemed warranted for an evaluation of the control algorithm. Integration of the controllers was seen as a reasonable compromise for test purposes.

The testing of the prototype controller was done in conjunction with the low- temperature refrigeration. The test procedure consisted of alternating between the prototype controller and the time clock on a two-week basis.

Table 3-7 shows the results of these tests. The prototype controller reduced the number of defrosts from 18.2 to 11.1 per day. The compressor energy savings due to this reduction were 19.0 kWh/day, or 1.8% of total compressor energy consumption. For electric defrost operation, the estimated savings were 74.3 kWh/day, which is 34.6% of electric defrost consumption. The annual projected savings were 6,944 kWh for hot-gas defrost and 34,054 kWh for electric defrost.

The savings obtained by the prototype controller were not as great as those with the test unit because the control settings used with the prototype controller were more conservative, particularly in terms of maximum time allowed between defrosts. Also, the prototype controller used a different approach to averaging the temperature values which caused the temperature difference to exceed the set point more frequently than the method used with the test controller.

The test results showed that the Hussmann controller could be adapted to the defrost algorithm, which was the goal of the tests. Further fine tuning and refinement of the Hussmann adaptation of the algorithm would increase electric energy savings.

Test No.	Control	Dates	No. of Days	No. of Def.	Def. Per Day	Total Def kWh	Def kWh per Day	Lt Comp kWh/Day	Sat. 1 Comp kWh/Day	Sat. 2 Comp kWh/Day	Total Comp kWh/Day
14 LT	Test	07/16 - 07/25/91	8	93	11.6	1130	141.3	955.6	116.1	120.8	1192.5
16 LT	Test	08/14 - 08/27/91	11	130	11.8	1590	144.5	912.0	108.7	115.2	1135.9
18 LT	Test	09/10 - 09/22/91	12	137	11.4	1681	140.1	893.6	96.1	103.2	1092.9
18 LTB	Test	09/25 - 09/29/91	5	44	8.8	769	153.8	813.9	87.9	95.1	996.9
20 LT	Test	10/17 - 11/05/91	13	138	10.6	1707	131.3	637.2	90.6	95.6	823.4
Demand Controller Average					11.1		140.3	831.7	99.9	105.9	1037.5
15 LN	Clock	07/30 - 08/11/91	10	180	18.0	2130	213.0	965.0	115.9	117.5	1198.4
17 LN	Clock	08/29 - 09/08/91	11	200	18.2	2370	215.5	931.6	107.0	115.0	1153.6
19 LN	Clock	10/01 - 10/15/91	14	253	18.1	2993	213.8	803.5	95.6	105.4	1004.5
21 LN	Clock	11/08 - 11/26/91	18	330	18.3	3882	215.7	767.9	90.4	100.6	958.9
Time Clock Average					18.2		214.6	848.5	100.0	108.0	1056.5
Demand Controller kWh/Day Savings							74.3	16.8	0.1	2.1	19.0
Demand Controller Percent Savings							34.6	2.0	0.1	2.0	1.8
Project Annual Savings			kWh		\$ (\$0.050/kWh)		\$ (\$0.075/kWh)		\$ (\$0.100/kWh)		
Hot Gas defrost			6944.1		347.2		520.8		694.4		
Electric defrost			34,054.8		1702.7		2554.1		3405.5		

Table 3-7.
Results for Demand Defrost Controller Tests
Hussmann Prototype Controller

Section 4

CONCLUSIONS

OVERVIEW

This project was initiated because defrosts scheduled by a time clock occur too frequently during most of the year and waste energy. A demand defrost control system was developed that compared to a time clock, saved energy and reduced demand, while maintaining better quality of refrigerated food.

A temperature difference technique using a running average of temperature data reliably determined the need for defrosts. To limit risk, the technique was incorporated into an algorithm that included a minimum time between defrosts as well as a maximum time between defrosts, which provided conventional boundaries for normal operation. A queuing technique was incorporated that allowed safe operation of the compressor racks with both defrost limiting and demand management during programmable, high electric demand periods of the day.

A feature of the demand defrost controller which is not readily quantifiable is the improvement of the quality of food products that are subjected to fewer defrost cycles, a benefit supermarket managers understand.

The project showed dollar paybacks on the order of a year using energy savings alone on low-temperature racks. The economics become complex when type of defrost, demand charges and time of day rates are included. The result of the project is a system that can provide significant economic benefits through use of the controller and significant electric energy and demand savings.

PHASE I

Phase I results showed the feasibility of the demand defrost control hardware and control scheme. That success led naturally to field testing the system in a real-world environment. The tests reported here show success in determining the need for defrost and scheduling defrost timing.

During Phase I a control algorithm was developed to determine frost blockage and to initiate defrosts for refrigerated display cases. The control algorithm initiates defrosts based on the temperature difference between the return and discharge of the air curtain used to cool the display case. The temperature difference increased as frost accumulated on the display case evaporator. By comparing the temperature difference to a predetermined set point, defrost for the display case could be initiated when the difference exceeded the set point value.

This basic concept had previously been tried by others and been found unsuccessful because the temperature difference was influenced by other aspects of case operation, such as stocking or cleaning. In those instances, the controller using temperature difference only could initiate unnecessary defrosts. To avoid this, certain logic was included within the control algorithm that consisted of:

- Multiple temperature difference measurements for defrost initiation. The temperature difference must be above the set point for multiple successive readings before defrost is initiated; and
- Minimum time between defrosts. A predetermined time interval between defrosts must be exceeded before a defrost can be initiated, regardless of the value of the temperature difference measurement.

To insure against such problems as sensor failure, and to reduce control and sensor maintenance, a maximum time between defrosts value is also used in the algorithm. If the time between defrosts exceeds this maximum value, defrost is initiated.

The preceding control algorithm was programmed into a test controller and tested in the laboratory with the following conclusions:

- The control algorithm initiated defrosts using measured temperature difference between the return and discharge of the display case air curtain;
- When defrosts were initiated, measurements of air static pressure at the case fan outlet indicated that the evaporator was clogged with frost, indicating that defrost was needed;

- The controller responded to changes in ambient humidity. The number of defrosts initiated increased during periods of high humidity compared to the number of defrosts performed during periods of low humidity; and
- The defrost controller was successfully used when the case air curtain temperature was controlled by the use of a thermostat and liquid line solenoid valve. The defrost controller properly initiated defrosts with no apparent conflict between the two controllers.

The preceding test results were achieved with the display case operating at frozen food temperatures. A series of tests were also conducted at a medium temperature with an evaporator temperature of 20°F. The controller operated properly, but defrosts were initiated using the programmed maximum time between defrosts. The slow rate of frost accumulation resulted in a small rise in temperature difference in the air curtain. The display case used was designed to operate as a frozen food case, which meant that for these tests, operation was at an off-design condition. It is felt that with an appropriate medium-temperature display case the design operating temperature difference would be much larger and the defrost controller would operate properly.

A second control algorithm was also tested that combined the defrost control with a simple case temperature control scheme in which the controller used the discharge air curtain temperature measurement as the basis to control the liquid line solenoid. This combined temperature and defrost controller was successfully tested, demonstrating an appropriate controller with multiple functions.

Finally, the preceding combined control algorithm was configured so that a single controller could implement temperature control and initiate defrosts in multiple display cases simultaneously. This algorithm was also successfully tested in the laboratory.

Attempts were made in the laboratory to quantify the possible demand and electric energy savings that could be achieved through using the demand defrost controller. These attempts were unsuccessful, primarily due to the nature of the laboratory test rig used for the tests. Meaningful measurements of this type can only be made during a field test of the controller at an operating supermarket.

Attempts were made to use the defrost control algorithm for the refrigerated walk-in chest in the laboratory. It was found, however, that the temperatures of the air curtain for the walk-in chest behaved differently than those observed for the display case, as frost accumulated on the evaporator. In general, the temperature difference for the walk-in evaporator became smaller as the evaporator clogged with frost, which is the opposite of the behavior observed for the display case. Further testing is required before an appropriate defrost control algorithm can be developed for walk-in chests.

PHASE II

The Phase II results of the defrost tests showed that significant electric energy savings could be achieved through using the demand defrost controller. For hot-gas defrost, the controller reduced compressor energy consumption associated with the recooling or pulldown of the display case temperatures after defrost. For electric defrost, much greater savings could be achieved because these devices consume more power.

The estimated annual savings calculated from the test results of one rack of eight controlled circuits were 20,030 and 62,115 kWh for hot gas and electric defrost, respectively. At an electric rate of \$0.075, the value of these annual savings is \$1,502 for hot gas defrost and \$4,658 for electric defrost. An initial controller-installed cost of \$3,004 to \$9,316 could, therefore, be justified, assuming a simple payback criterion of two years.

Through Phase II, the controller had been applied only to low-temperature refrigeration systems. Significantly more savings could be achieved using the controller on a store-wide basis. Medium-temperature display cases are open, multideck types, used to display meat and dairy products. The potential for frost buildup is large and electric and hot gas defrost are often applied. The requirement for testing the demand defrost controller with the medium temperature refrigeration at the test store was, therefore, appropriate.

The controller could also be expanded to act as an electric peak-shaving device. Defrosting during the peak period should definitely be avoided, particularly when electric defrost is employed. The simple demand defrost controller could trigger defrosts during periods of high demand. The control algorithm needed to include expected peak demand periods during which defrosts should not be initiated. The controller would then need to schedule these defrosts at off-peak. Initiation of defrosts during non-peak periods must also be controlled to avoid creating an electric demand peak. A queuing scheme would also be required that would limit

the rate at which defrosts are initiated and effectively spread the defrosts over a longer time period. Development and testing of this peak demand control algorithm led to Phase III.

PHASE III

The testing conducted during Phase III addressed three different aspects of the demand defrost control:

- Development of a deferred defrost algorithm to help reduce electric power demand;
- Testing the demand defrost control with medium temperature refrigeration; and
- Test and evaluation of a manufacturer's commercial prototype version of the demand defrost controller.

The deferred defrost algorithm prevented defrost from being initiated during potential peak demand periods. Calls for defrost were stored in a queue and were later scheduled during non-peak periods. Test results showed that coincident compressor demand savings ranged from 0 to 2.2 kW, depending on outside ambient temperature. For electric defrost, demand reduction would be from 11 to 165 kW for this particular site, depending on how many display cases were included. Peak demand of the compressor rack, was shown to be less when the deferred defrost algorithm was used. The reduction ranged from 4 to 6 kW. Test results also showed that energy savings were not decreased when the controller employed the deferred defrost algorithm. Annual savings were estimated at 21,690 kWh and 80,049 kWh for hot-gas and electric defrost, respectively. These savings were slightly greater than those recorded earlier in Phase II testing.

The use of the demand defrost controller with medium-temperature refrigeration produced a 54% reduction in the number of defrosts incurred. The electric energy savings were not as significant, however, as those seen with low-temperature refrigeration possibly because many of the medium-temperature display cases used off-cycle defrost, rather than hot gas or electric. The resulting compressor energy consumption for system pulldown was less in this situation. The size of the electric heaters associated with medium-temperature cases was smaller than heaters used with low-temperature cases, also reducing the potential energy savings. The test

results suggest that the use of demand defrost with medium-temperature refrigeration may not be cost-effective.

Testing the manufacturer's prototype controller showed that the control algorithm can be adapted to commercially available control hardware and that the resulting controller could reduce the number of defrosts. Energy savings were obtained by this controller, but these savings were less than when the test controller was used. This reduction in savings can be attributed to the version of the control algorithm used in the commercial prototype controller.

Possible further development for the controller is to incorporate other display case control features. The temperature measurements now used could be used as the basis of a refrigeration control in which refrigerant to the case would be turned on or off depending on air temperature. The temperature measurements could also be used in an algorithm to adjust the refrigeration suction pressure, which would allow the compressors to operate at a higher suction pressure when less refrigeration is required. The controller could also be adapted to control the case expansion valves based on air temperature and possibly evaporator outlet temperatures.

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