

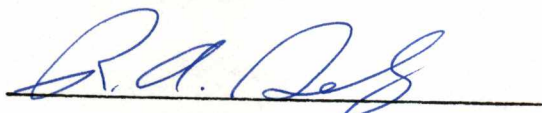
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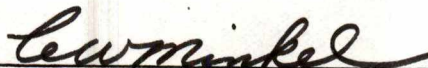


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November 1986



A MICROPROCESSOR-BASED
ENERGY MANAGEMENT SYSTEM AT THE
UNIVERSITY OF TENNESSEE SPACE INSTITUTE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

C. B. Alexander, III
December 1986

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Particular thanks are due to Karen Schwartz for her untiring efforts to type, edit and encourage the assembly of this thesis.

ABSTRACT

Because of rising energy costs and increasing energy use, a means of eliminating unnecessary energy consumption was needed at The University of Tennessee Space Institute. Such a means could not impair daily operations nor discomfort the occupants. Because of its centralized controls, the heating, ventilation and air conditioning system was selected as the primary target for these conservation measures. The heating and cooling system was separated into three categories: water circulating pumps, ventilation air handlers and front corridor air handlers. Each category was handled differently; however, all were scheduled for operation during occupancy rather than run continuously. Because of the overdesign of the air handlers, they were duty cycled to reduce their overall operation time. When moderate outside air temperatures prevailed, the heating and cooling could be terminated, using the outside air as the sole source of circulating air. During peak demand periods, the water circulating pumps were duty cycled to attempt to prevent an overrun of an established maximum demand limit and to reduce a high peak surcharge.

The energy management system employed the facilities of a VAX 11/780, a Cromemco Single Card Computer and peripheral devices including power demand and temperature sensors. Control of the heating and cooling system was

effected by means of relays wired to the contactors of the control panel. The employment of these control measures has the potential of greatly reducing the peak demand surcharges and total energy costs.

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INTRODUCTION

Because of the increasing costs of electrical energy and the increasing amount of electrical energy consumed by The University of Tennessee Space Institute (UTSI), the need for an energy management system (EMS) manifested itself. Over the past five years alone the cost per kilowatt-hour, after the first 500 kilowatt-hours, rose 25 percent, and cost per kilowatt for a 30 minute demand interval after the first 50 kilowatts rose 80 percent (see Figure 1).¹ At the same time, UTSI employed more machines and instruments to place a greater demand on electricity. Therefore, it became imperative to engage a system to minimize electrical energy use without impairing daily operations.

Within the past seven years, energy management systems have gained widespread application across the United States.² These systems take on many descriptions and sizes. At UTSI, the EMS is a computer-based control system which regulates the operation of the original facility's heating, ventilating and air conditioning (HVAC). The original facility includes A, B, C, D and E wings, as well as the auditorium and lobby. The EMS is limited to control of the

¹ Collection of utility bills to The University of Tennessee Space Institute from Duck River Electric Membership corporation dated from November 1979 to March 1984.

² Robert Ebisch, "Energy management systems: no longer a luxury," Building Design & Construction, June, 1981, p. 155.

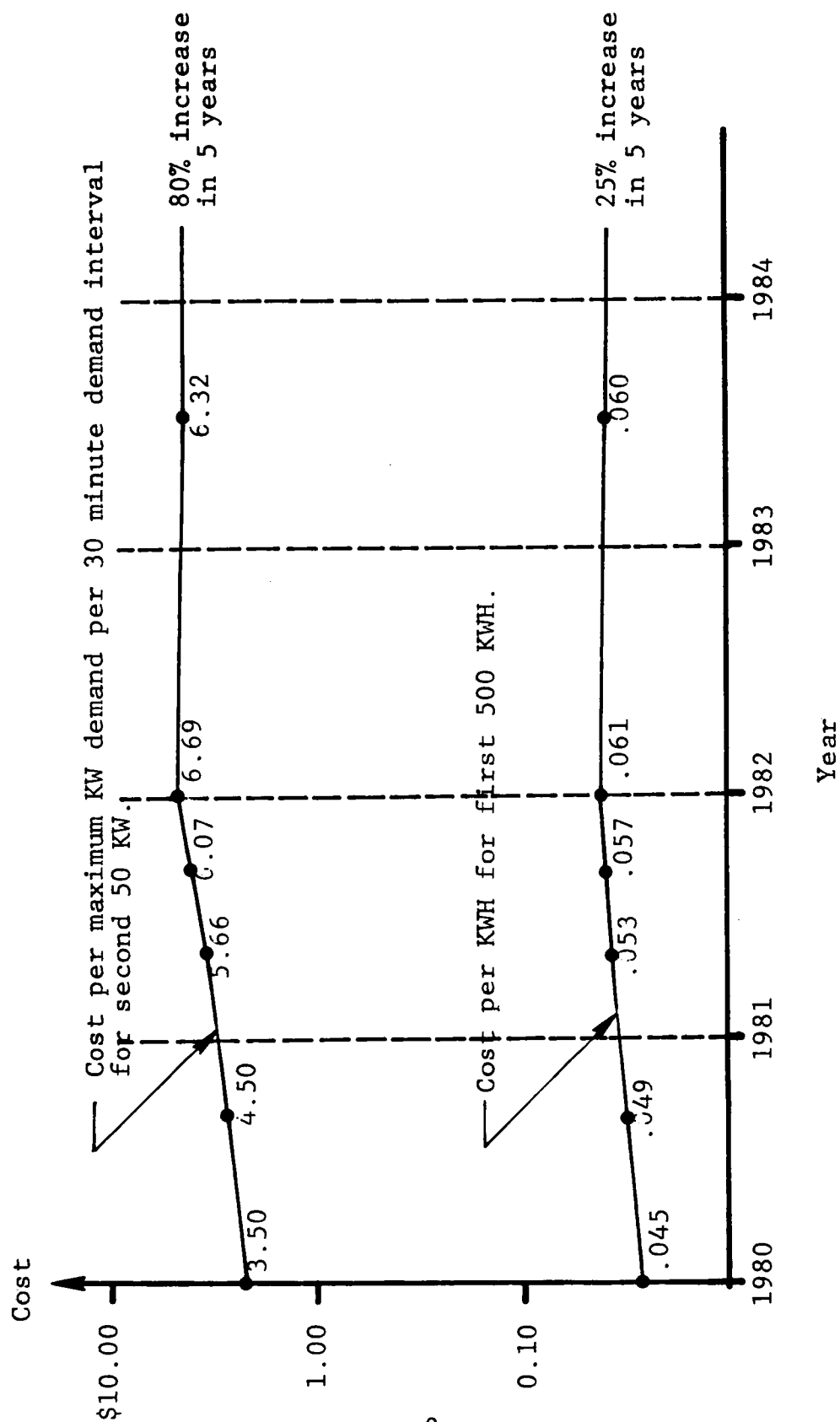


Figure 1. Rising costs for electrical energy.

HVAC operation for two reasons: (1) the centralized controls of the HVAC eliminate the costly wiring of a distributed control system and (2) regulation of other equipment requiring electrical energy may have impaired normal operations.

To understand the design rationale of an EMS, the composition of electrical energy costs must be understood. An energy consumer is billed monthly (see Figure 2). At UTSI there are two factors that greatly influence the amount of the bill: (1) the charge for total kilowatt-hours (KWH) consumed and (2) the surcharge for the kilowatts (KW) consumed within a 30 minute demand interval. The charge for total KWH is graduated, so as the number of KWH increases, the charge per KWH is reduced, however the more energy consumed the higher the total cost. In addition, the Duck River Electric Membership Corporation monitors the KW consumption at 30 minute intervals. Its customers are charged for the highest peak demand within these intervals, so that the greater the peak demand the greater the charge per KW.³ Therefore, the goals of the EMS were clearly defined: (1) to reduce the total KWH and (2) to limit the KW peak demand through the control of HVAC operation.

At UTSI, the heating and cooling system is basically a two-pipe, supply and return, system, circulating hot water in the winter and chilled water in the summer. Each wing of

³ Duck River Electric Membership Corporation bills.

ITEMIZED STATEMENT FOR ELECTRIC SERVICE			

FROM:	Duck River Electric Membership Corp. 1411 Madison Street Shelbyville, TN 37160		

SOLD TO:	UTSI Ofc of Phys Plant Tullahoma, TN 37388	Account # 9030490006	

29 Days Service from 06/15/81 to 07/14/81			

CONSUMPTION INFORMATION			

	KWH	KW	KVA
Present Reading	4482	0.74	0.75
- Prior Reading	4216		
Difference	266		
X Meter Constant	800	800	800
			X .85
Total	212,800	592.0	510.0

BILLING DETAILS			

KWH CHARGES			

Customer Charge			3.45
Energy charges	500 KWH @	.05676	28.38
	14,500 KWH @	.04896	709.92
	25,000 KWH @	.02730	682.50
	60,000 KWH @	.02520	1,512.00
	112,800 KWH @	.02420	2,729.76
Total Base Charges			5,666.01
Fuel Adjustment			
Total KWH Charges			5,666.01

KW CHARGES			

First	50.0 KW @	0.00	
Next	50.0 KW @	6.07	303.50
Next	492.0 KW @	6.22	3,060.24
Total KW Charges			3,363.74

KVA CHARGES			

First	50.0 KVA @	0.00	
Next	50.0 KVA @	6.07	303.50
Next	410.0 KVA @	6.22	2,550.20
Total KVA Charges			2,853.70

BILLING SUMMARY			

Electric Service			11,883.45
Other Credits			-2,853.70
TOTAL AMOUNT DUE			9,029.75

Figure 2. Typical monthly utility bill.

the facility is equipped with its own electric boiler and circulating pump to supply the wing with hot water. Chilled water is supplied from a central chiller located in the basement of the C wing. The wings' circulating pumps serve as secondary pumps for the chilled water. In either case, the water is circulated along the outer walls of each wing through fan-coil units (see Figure 3). Each fan-coil unit is equipped with a three-speed fan control and an adjustable thermostat. By adjusting the thermostat, occupants can control the temperature of their office space. The thermostat regulates the flow of water through the coil, so that when the desired room temperature has been reached, the thermostat causes the water to by-pass the coil. When the room temperature deviates from the desired room temperature, the thermostat forces the flow of water through the coil. The fan operation enhances the air circulation over the coil to improve the heat exchange between the room air and the circulated water. Without air circulation over the coil, there is little heat exchange. For the heating and cooling system to be effective, fan operation is imperative.

The front corridor and the rooms connecting to the front corridor are heated and cooled by means of electrical resistance coils and chilled water coils mounted within air handlers located off the corridor at the front of each wing. These air handlers distribute air through ducts to the corridor and adjacent rooms. The design temperature is

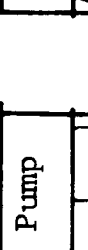
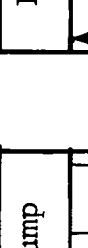
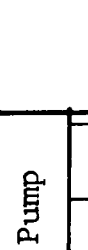
A Wing 	Auditorium	A Wing Front
B Wing 		B Wing Front
C Wing 		C Wing Front
D Wing 		D Wing Front
E Wing 		E Wing Front
Lobby		

Figure 3. Schematic of HVAC at UTSI.

preset and the system is adjusted by dampers located at each supply register. Air is recirculated through return grills located along the corridor.

The building's ventilation system consists of air handlers located at the rear of each wing. These air handlers draw air from the outside through vents located on the sides of the building. The air is either heated by electrical resistance coils or cooled by chilled water coils located within the duct work of the ventilation system. The air is distributed throughout the wing through ducts located along the wing's central hall to the office spaces and classrooms in that wing. There are no return air ducts to the ventilation air handlers, however, air is exhausted out of the restrooms causing the ventilation to flow from the wing to the corridors where the restrooms are located.

In addition to the above, the auditorium and lobby areas are equipped with their own air handlers. These areas are normally neither heated nor cooled except on special occasions. The auditorium is equipped with its own electric boiler and the lobby air is heated by electrical resistance coils. Each air handler is cooled by the centrally supplied chilled water.

Controls for the circulating pumps and air handlers are centrally located within the Mechanical Room in the C wing basement. The boiler and chiller control temperatures are preset and maintained by the building maintenance personnel.

The EMS resides with software loaded on a Z80A-based microprocessor and VAX 11/780 (VAX). The microprocessor is linked to the VAX by a shielded cable pair and assigned a specific port number by the VAX for communications. Generally, software is programmed to perform the following functions:

1. monitor and record electrical power consumption;
2. monitor and record outside air temperatures;
3. schedule normal HVAC operations;
4. control unscheduled HVAC operations;
5. vary the duty cycle of ventilators and front air handlers;
6. modify HVAC operation during periods of moderate outside air temperature;
7. vary the duty cycle of wing circulation pumps during periods of excessive power demand.

To monitor electrical power consumption and outside air temperature, the microprocessor was connected to a pulse counter and a digital thermometer. Time was kept by the internal clock of the VAX. Control commands are outputted to relays which link the microprocessor to the HVAC controls.

The EMS is located in the Mechanical Room in the basement of C wing. The power demand pulse counter resides at the utility substation located behind the building. The digital thermometer's outside air temperature sensor was mounted above C wing (see Figure 3).

In the following chapters, the strategy to accomplish the stated goals will be outlined and an explanation of the software of the microprocessor and the VAX 11/780 will be discussed. Chapters describing the system hardware and an analysis of the effectiveness of the EMS will conclude the thesis. Operating procedures are included in the Appendix.

CHAPTER I

THEORY OF OPERATION

The primary purpose of the EMS is to reduce electrical power consumption and limit peak demands by controlling the operation of the HVAC system without impairing the comfort and productivity of the occupants.⁴ Secondly, the EMS provides a means of controlling unscheduled HVAC operations. By monitoring outside air temperature, the EMS can determine moderate climate conditions and modify HVAC operation accordingly. During the winter, outside air temperature monitoring serves as a safeguard against pipe freeze-ups by initiating limited HVAC operation when the outside temperature drops below the established lower temperature limit. The EMS also meters and records electrical energy demand and outside air temperature to provide data by which EMS performance can be judged.

Energy Conservation Strategy

A survey conducted by the Department of Energy outlines techniques to reduce energy consumption.⁵ Those applicable to the EMS at UTSI are described below.

⁴ Department of Defense, Controlling Energy Consumption In Single Buildings (Port Hueneme, California: Naval Civil Engineering Laboratories, 1982), p. 3.

⁵ Department of Defense, p. 5.

Scheduled Start/Stop

The EMS limits the operation of the building's HVAC to hours of occupancy. Starting HVAC units sequentially early enough, beginning at 0400 for example, so that by 0800 proper temperature and ventilation have been reached prevents excessive power demand. In addition, sequential stopping of HVAC heating/cooling units allows the building to take advantage of lingering temperatures. Ventilators are stopped promptly at the end of normal occupancy. On weekends, HVAC operation is restricted minimizing energy consumption. Figure 4 graphically demonstrates scheduling.

Optimum Start/Stop

Optimum start/stop is a mechanism used to modify HVAC operation depending on outside air temperature.⁶ It takes advantage of moderate outside temperatures by stopping boiler and front air handler operation when the temperature rises above the established winter upper temperature limit. During the summer months, secondary chiller water pumps are halted when the outside air temperature drops below the summer lower temperature limit. Ventilation air handlers are continuously operated in either situation, drawing moderate temperature air into the building. This results in considerable savings during the spring and fall.

⁶ Department of Defense, p. 6.

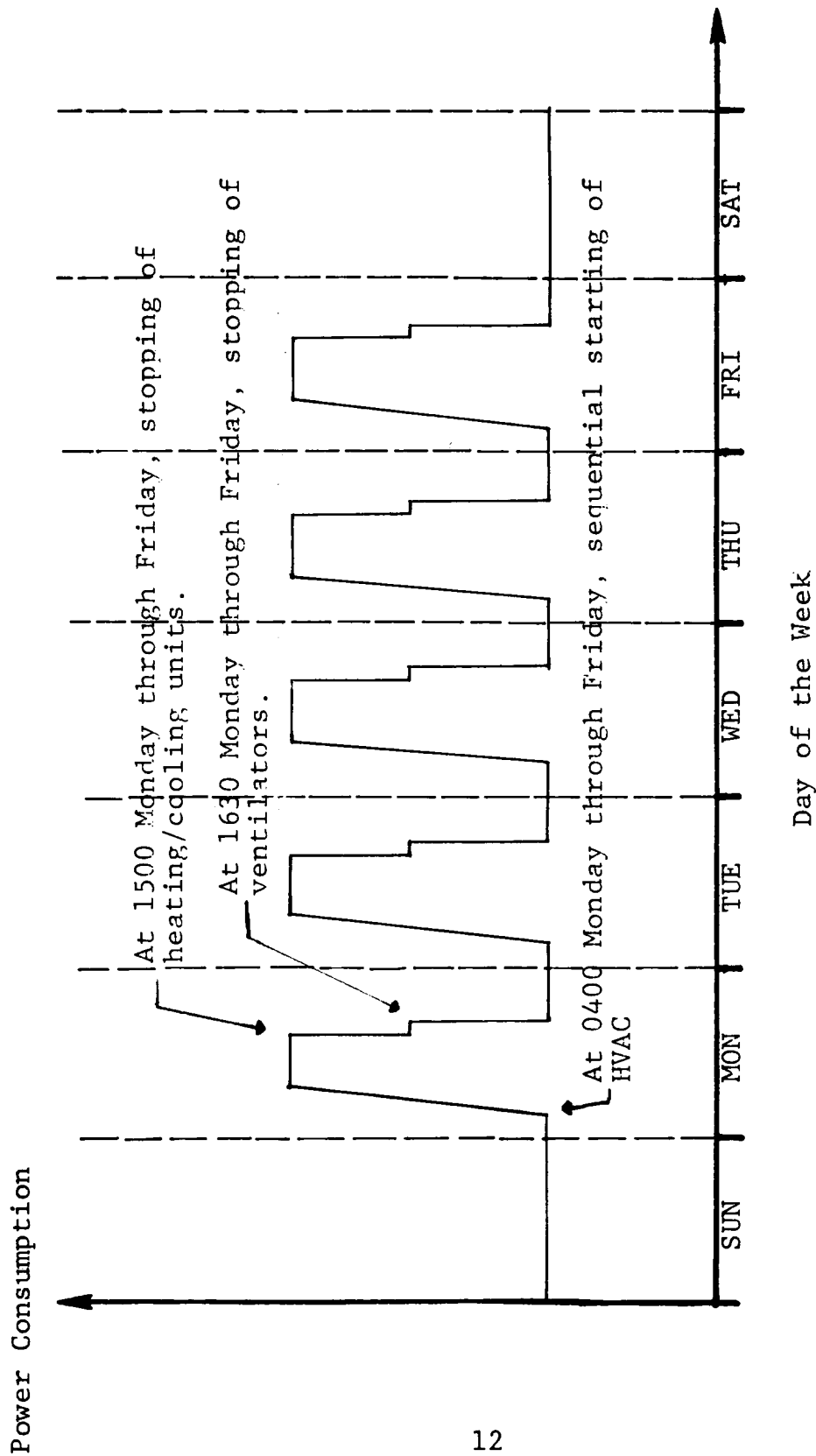


Figure 4. Weekly scheduling of HVAC operation.

Duty Cycling

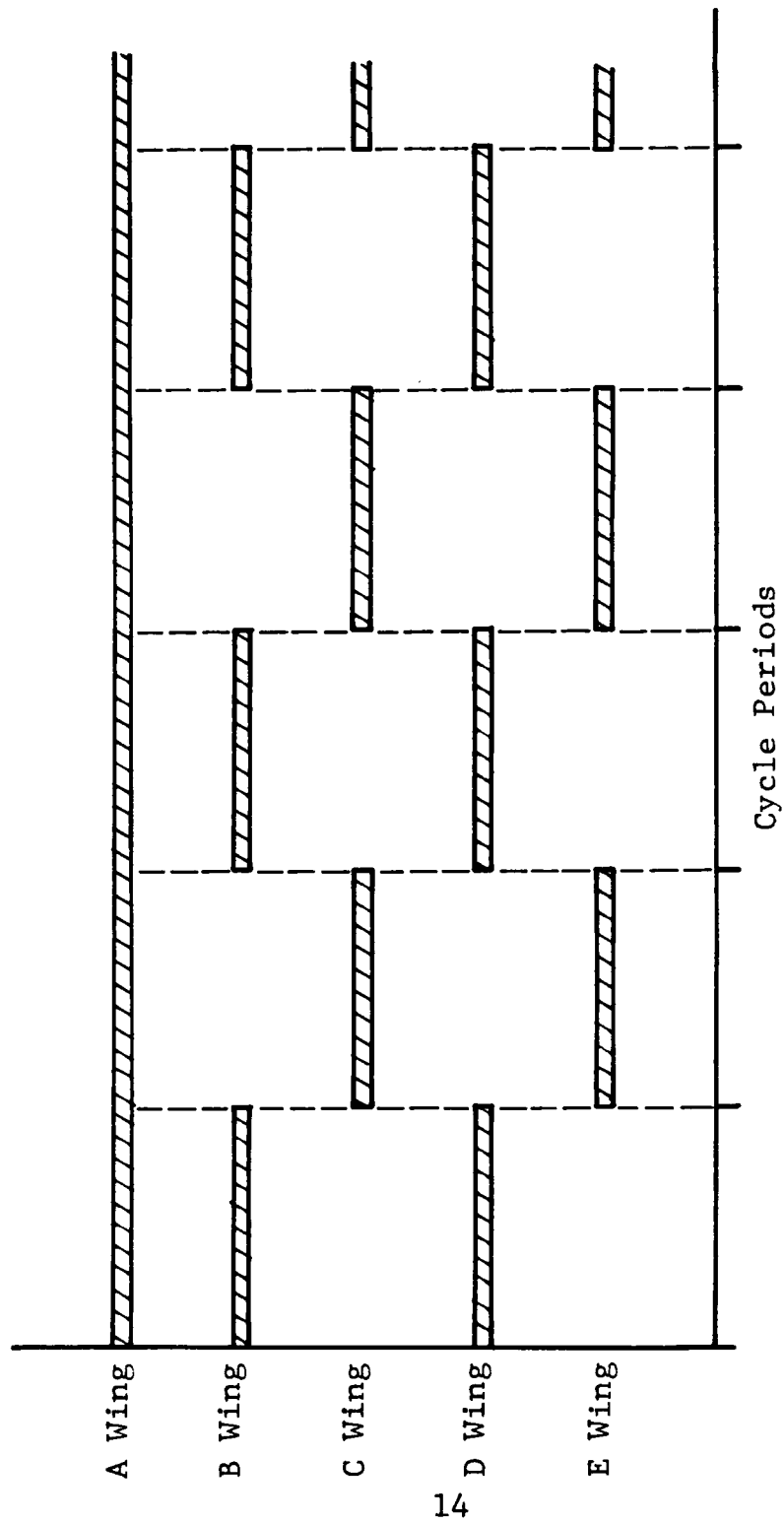
Duty Cycling is the periodic halting of operation of a specific HVAC unit to reduce its overall operation time. Since a wing's ventilation air handler provides 2000 cubic feet per minute (cfm) of fresh air to the wing when only 1000 cfm is required, the air handled may be duty cycled 50% of the time and still meet design requirements.⁷ Similarly, the air handlers located at the front of each wing are duty cycled 50% of the time since they provide 3600 cfm to the corridor and adjacent rooms when only 1800 cfm are required.⁸ Therefore, by periodically stopping an HVAC unit's operation, power consumption is reduced while HVAC requirements are maintained. In order to distribute the effects of duty cycling, alternate building wing's ventilators are cycled off while the others run and vice versa. This case is also true when duty cycling the front corridor air handlers. This strategy is aimed at minimizing the overall impact of the cycled-off units. This process is illustrated in Figure 5.

Demand Limiting

Demand limiting provides the means to reduce peak demands. The EMS reads power demand once per minute. When

⁷ William J. McGuiness and Benjamin Stein, Mechanical and Electric Equipment for Buildings, Sixth Edition (New York: John Wiley and Sons, Inc., 1971), p. 208.

⁸ McGuiness, p. 208.



Note: Solid bars indicate cycle-on period.

Figure 5. Duty cycling of Front Air Handlers.

it determines that the power demand will exceed the established limits, it initiates controls that will reduce it. Two thresholds have been established to control excess demand. These were based on percentages of an established power demand. The lower threshold is established which is expressed as a percentage of the maximum power demand limit. The second threshold can be determined as half the difference between the lower threshold and the maximum power demand limit. When the power demand exceeds the lower threshold, the EMS duty cycles the wings' secondary circulating pumps off periodically one at a time. However, if the demand continues to rise and exceeds the upper threshold, the duty cycle is increased, so that two circulating pumps are cycled off periodically. If the demand continues to rise and exceeds the established maximum, then the maximum is replaced by this new power demand figure (see Figure 6). This new figure then serves as the maximum allowable demand limit. The maximum power demand limit should be reset each month based on historical data.

Controlling Unscheduled HVAC Operations

Aside from the energy conserving measures used by the EMS, a means of controlling unscheduled HVAC operations is provided. This feature allows a control operator to program HVAC operations to run immediately or to schedule their operation at some future time and date. For

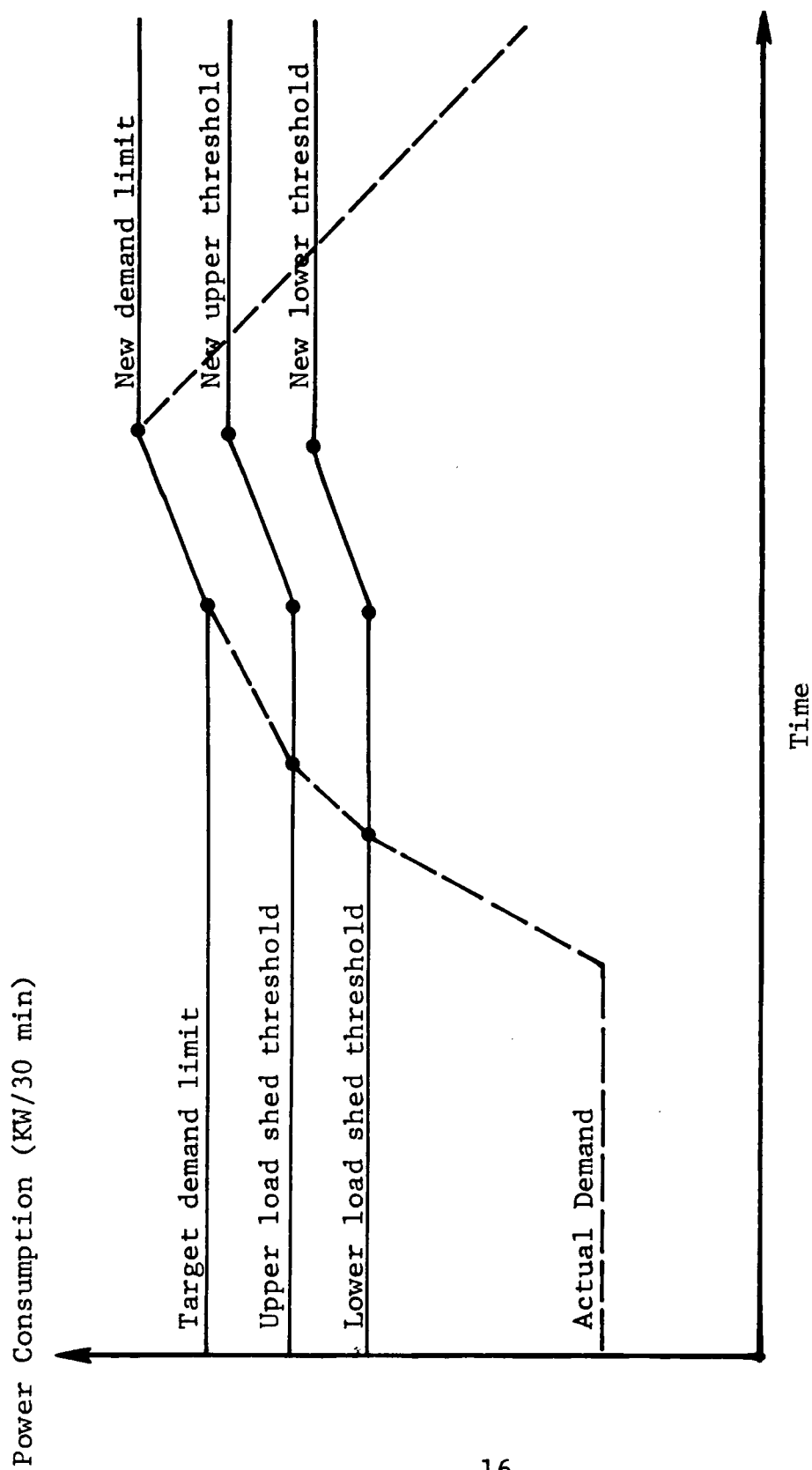


Figure 6. Demand limiting illustrated.

infrequently occupied areas, such as the auditorium and lobby, this allows the control operator to schedule the HVAC operation and avoid operation during unoccupied periods. More specifically, this feature allows the control operator to activate or deactivate any of the 16 control points in the HVAC system or schedule their operation at any future time and date. More specific operating instructions are provided in the Appendix.

Power Demand Records

Recorded for EMS performance analysis are the periodic readings of power demand. This data is stored on the VAX 11/780 to generate a graph. An example of this graph is shown in Figure 7.

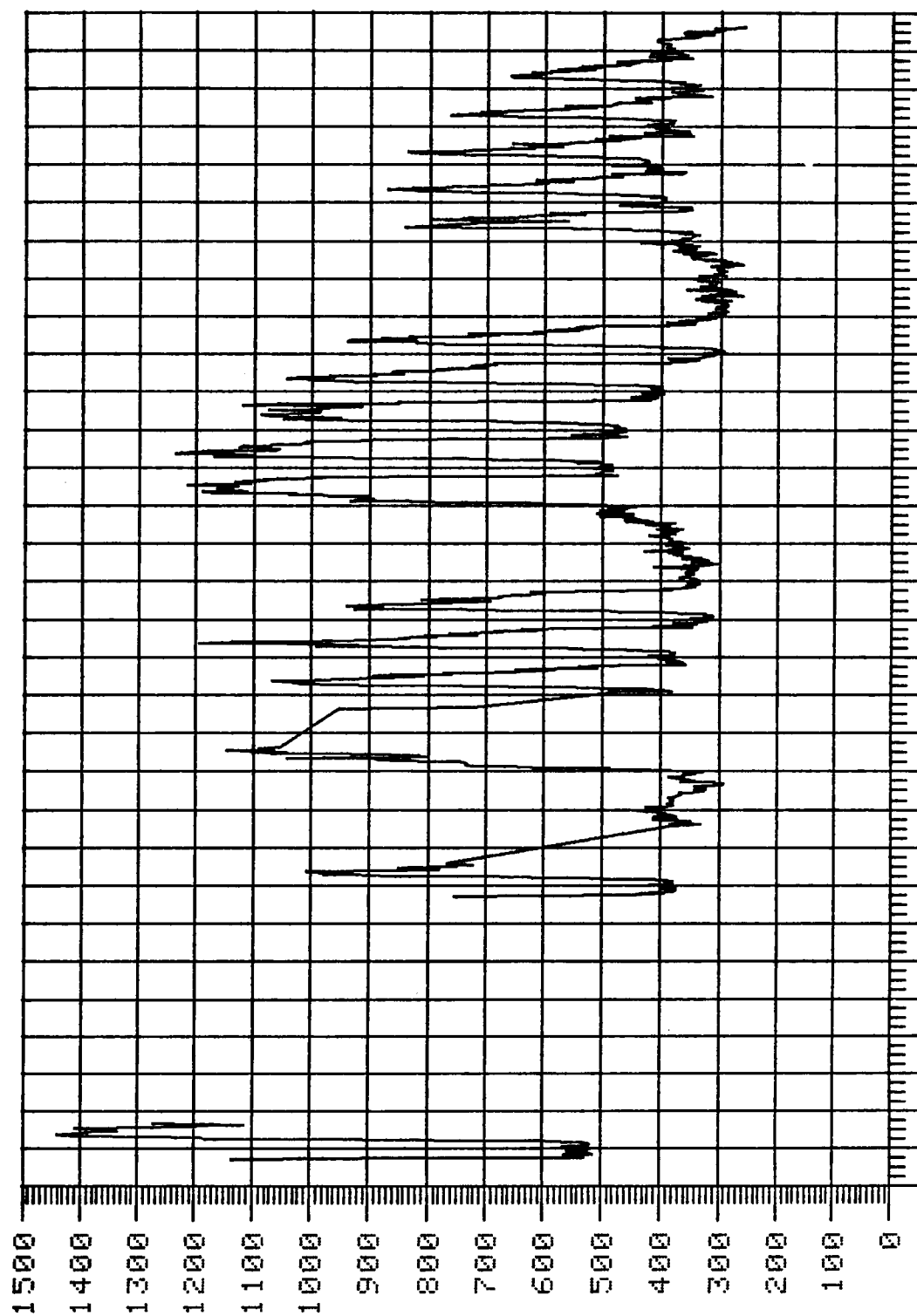


Figure 7. Power demand graph.

CHAPTER II

EMS SOFTWARE

The software for the EMS resides on both the VAX 11/780 (VAX) and the Cromemco Single Card Computer (SCC). The VAX programs provide operator control and scheduling ability, while the micro program retrieves power demand and temperature data, executes energy conserving and power limiting routines and sends data to the VAX for storage. These relationships between VAX resident and micro resident programs are more clearly defined in Figure 8.

VAX Resident Programs

Programs residing on the VAX are written in Digital Equipment Corporation (DEC) Command Language or Pascal. Each will be discussed below.

ON/OFF

Two DEC Command Language (DCL) programs ON and OFF provide routine scheduling for the EMS. Each program submits the other to the SYS\$FAST QUEUE for execution at the appropriate times. ON determines the day-of-the-week using a previously established DCL routine. On Saturdays and Sundays, it will resubmit itself to the SYS\$FAST QUEUE to execute on the following day; otherwise, it will call the control program CONTROL and give commands to activate specific HVAC units. ON then waits 30 minutes before

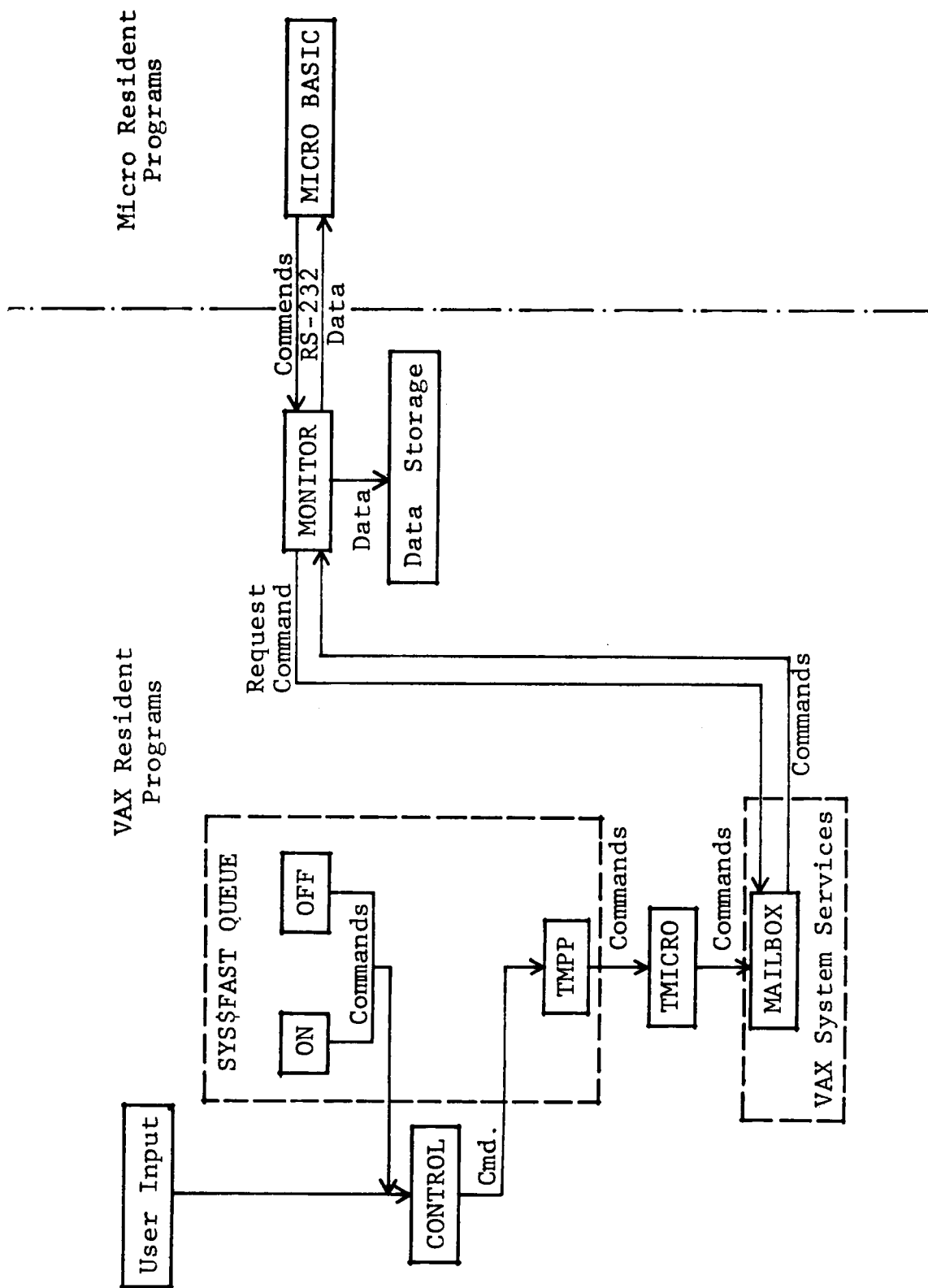


Figure 8. Software relationships.

calling CONTROL again to give more commands to activate other HVAC units. This continues until all the HVAC units are activated. Altogether, it takes four hours to activate the HVAC system. ON terminates after submitting OFF to the SYS\$FAST QUEUE to execute at 1630 hours the same day. OFF immediately deactivates the ventilators, then waits an hour and 30 minutes before halting all other HVAC units. It then submits ON to the SYS\$FAST QUEUE to execute at 0400 hours the following day and provides the regular scheduling of the EMS.

CONTROL

This DCL program enables the EMS to control specific HVAC units and change parameters of the micro resident program. CONTROL generates a temporary DCL command program TMPP and submits it to the SYS\$FAST QUEUE for execution at the designated time, but first deletes all previously submitted TMPP's to override normal HVAC control. CONTROL prompts the control operator for command input.

Type of Command:

In response to an inappropriate command the following message is displayed.

Type of Command: XX(CR)

Error in type of command input, please try again.
If you need assistance, type ?

Type of Command:

Typing "?" displays a command menu.

Type of Command: ?(CR)

Type O to control HVAC units.
Type S to change SEASONAL CONDITION.
Type D to change MAXIMUM DEMAND LIMIT.
Type P to change THRESHOLD for LOAD SHED ROUTINES.
Type F to change OFF-TIME of FRONT AIR HANDLERS.
Type V to change OFF-TIME of VENTILATORS.
Type U to change WINTER UPPER TEMPERATURE LIMIT.
Type L to change WINTER LOWER TEMPERATURE LIMIT.
Type K to change SUMMER LOWER TEMPERATURE LIMIT.

Type of Command:

CONTROL responds to command input by prompting for subsequent command input as will be discussed later. Afterwards, the operator schedules the command input by responding to the "time" prompt.

At what time is this to be done?

Again, typing "?" displays a help menu.

At what time is this to be done? ?(CR)

Enter a future time of the form 12-JAN-1983:24:13:59
or
Enter TODAY if you want it done now.

At what time is this to be done?

CONTROL generates a new TMPP scheduled to be run at the designated time. TMPP calls TMICRO and passes along its commands.

TMICRO

This short Pascal program passes the generated command on to a Monitor via the VAX MAILBOX system facility, then terminates.

MONITOR

This continuously running Pascal program establishes the communications link between the VAX and the micro. It

sends the commands and EMS parameter changes passed to it by TMICRO onto the micro for processing. And, in addition, it receives from the micro the data from the power demand meter and the temperature sensors and stores it in MICR01 data file.

During the Setup procedure, MONITOR uses the VAX system service \$ASSIGN and \$CREMBX to assign channels for communications with the micro and create the MAILBOX into which TMICRO passes its commands and EMS parameter changes. Next, the Recv_Char_Port procedure uses the VAX system service \$QIO to wait for characters received from the micro to ensure communications are established. More specifically, it waits to receive a ">" prompt from the micro indicating that the micro is ready to receive communications from the VAX. To generate such a response from the micro, the VAX sends the micro a series of spaces and carriage returns using the VAX system service \$QIOW until a ">" prompt is received. Recv_Char_Port stores received characters in a buffer. When the ">" prompt is received from the micro, Time Out, one of \$QIO parameters, is redefined and the Recv_EF flag is set, thus allowing the program to continue. Next, the Enable_Wrattn procedure sets an asynchronous trap, so that when MONITOR receives commands through the mailbox created earlier, the program will return to execute the asynchronous trap procedure Ast_Mail_Recv. This procedure awakes MONITOR from hibernation using the VAX system service \$WAKE.

Altogether, three different asynchronous traps (AST) awake MONITOR from a hibernation state. In other words, when a particular event occurs as defined by the AST, MONITOR executes a procedure defined by that particular AST. Two of the three AST's are defined above, Recv_Char_Port and Enable_Wrattn. Enable_1_Min_Ast is the third and serves as a one minute timer. This AST utilizes the VAX system services \$BINTM and \$SETMR to perform this function. Its AST procedure sets the Send_Line_Flag true and awakes MONITOR.

Waking MONITOR enables a number of functions and procedures to execute. First the function Line_Buf takes the characters stored in the buffer by Recv_Char_Port and calls the procedure Write_Err which writes them in a data file M.OUT, clearing the buffer. Then the procedure Process_Mail checks the mailbox for mail using the VAX system service \$GETCHN. If mail has been sent, Process_Mail equates the mail to the Mail_Recv_Line which serves as a buffer and checks the first character of the Mail_Recv_Line to decide how to process it. If a "C" is observed, it closes the data file MICRO1.OUT into which the data from the micro is stored and opens a new data file. If an "E" is observed, it sets the Exit_Command flag true causing the program to stop. Otherwise, it sends the mail to the micro for processing equating Mail_Recv_Line to Send_Line_2.

To send data to the micro, Process_Mail calls the Send_Line_Port procedure. This procedure first clears the receive buffer using the Line_Buf and Write_Err procedures and sends Send_Line_2 one character at a time through the serial port directly connected to the micro. Send_Line_Port uses \$QIOW and waits for the character to be acknowledged by the micro before sending the next character. Put_Buf records these acknowledged characters as the micro echoes them back to the VAX. Send_Line_Port then compares the sent characters with the echoed characters using the function Compare_Send_Recv. If they do not equate, both the sent line and the echoed line are recorded in M.OUT, noting the time and date of this occurrence.

The AST procedure Ast_Setimr, enabled at __::59.99 each minute by Enable_1_Min_Ast, sets the Send_Line_Flag true, enabling the procedure One_Min_Update. This procedure writes data received from the micro to a data storage file MICRO1.OUT. One_Min_Update prompts the micro to send the data by sending Send_Line_1 to the micro. Having received this prompt, the micro responds with power demand and temperature data. One_Min_Update converts the ASCII characters received from the micro to their numerical equivalent. These numbers, representing hexadecimal values, are again converted to their decimal equivalent. These figures are stored in MICRO1.OUT along with the time and data of their record. Also, One_Min_Update updates the

process name using the VAX system service \$SETPRN. The process name contains the updated information concerning power demand. MONITOR is put into a hibernation state by the VAX system service \$HIBER until awakened by one of the AST's. A flow chart of MONITOR is found in Figure 9.

Micro Resident Programs

The EMS employs a Cromemco Single Card Computer (SCC). Besides the EMS control program, resident on the Micro are the MCB-216 Monitor program, 3K Control Basic interpreter, and 1 kilobyte of RAM. Additionally, the micro is equipped with two 2716 Eraseable Programmable Read Only Memory chips (ERROM's). These chips are capable of storing up to 2 kilobytes of programmed memory. These chips are not volatile and are erased only by exposure to ultra violet light. The EMS program resides on two such chips. Figure 10 illustrates the memory map of the micro.

The SCC MCB-216 features an automatic program running facility (AUTORUN) which allows the EMS to be automatically booted by RESET. This is important for system reliability. The AUTORUN routine sets the baud rate of the micro to 300 providing sufficient time delay for communications between the VAX and the micro and preventing character overwrites. A bank of 16 relays are cleared by the AUTORUN routine under an OUT(port number of relay)=%00 command to the parallel input/output (PIO) ports to which the relays are connected.

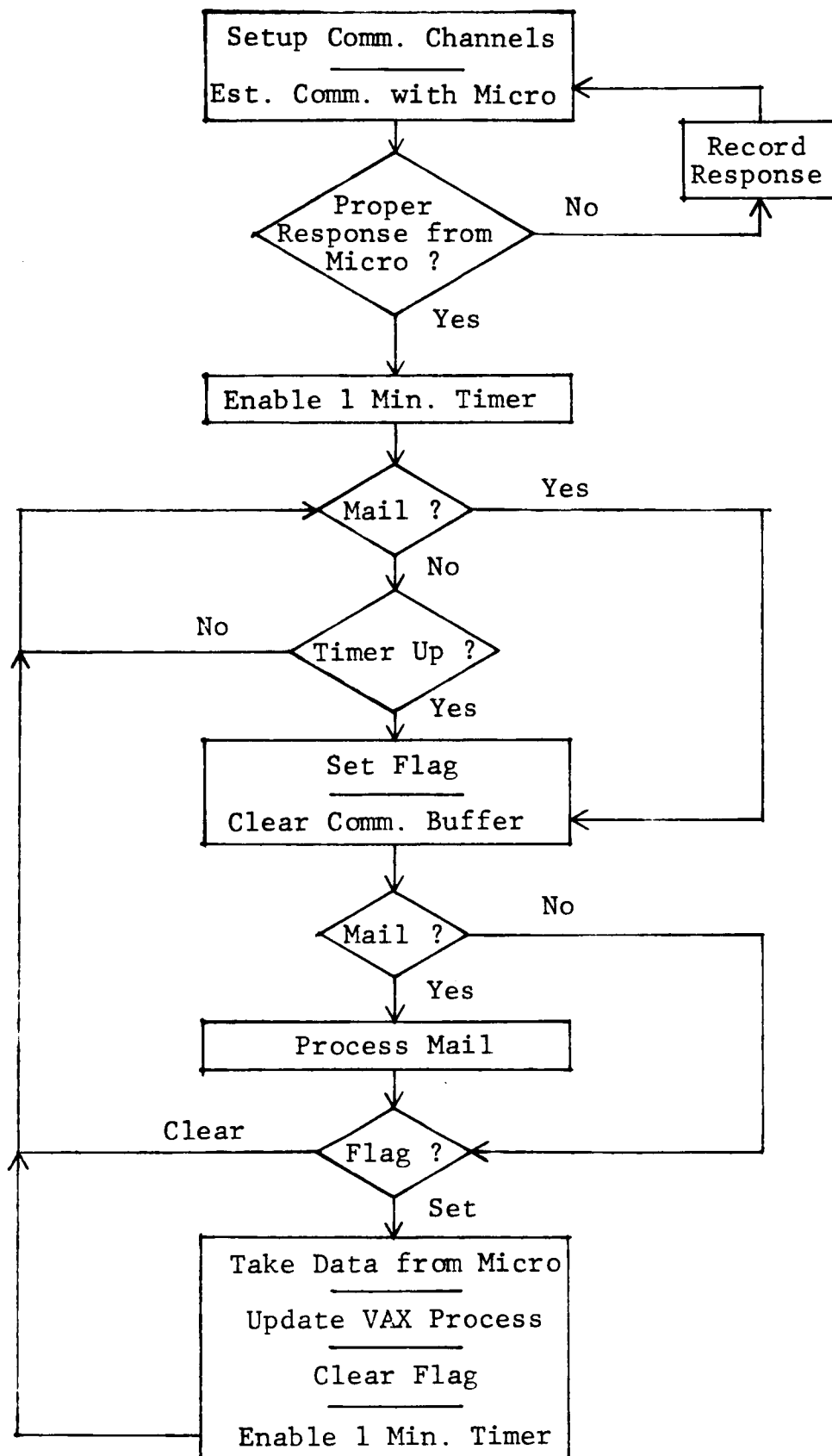


Figure 9. MONITOR flow chart.

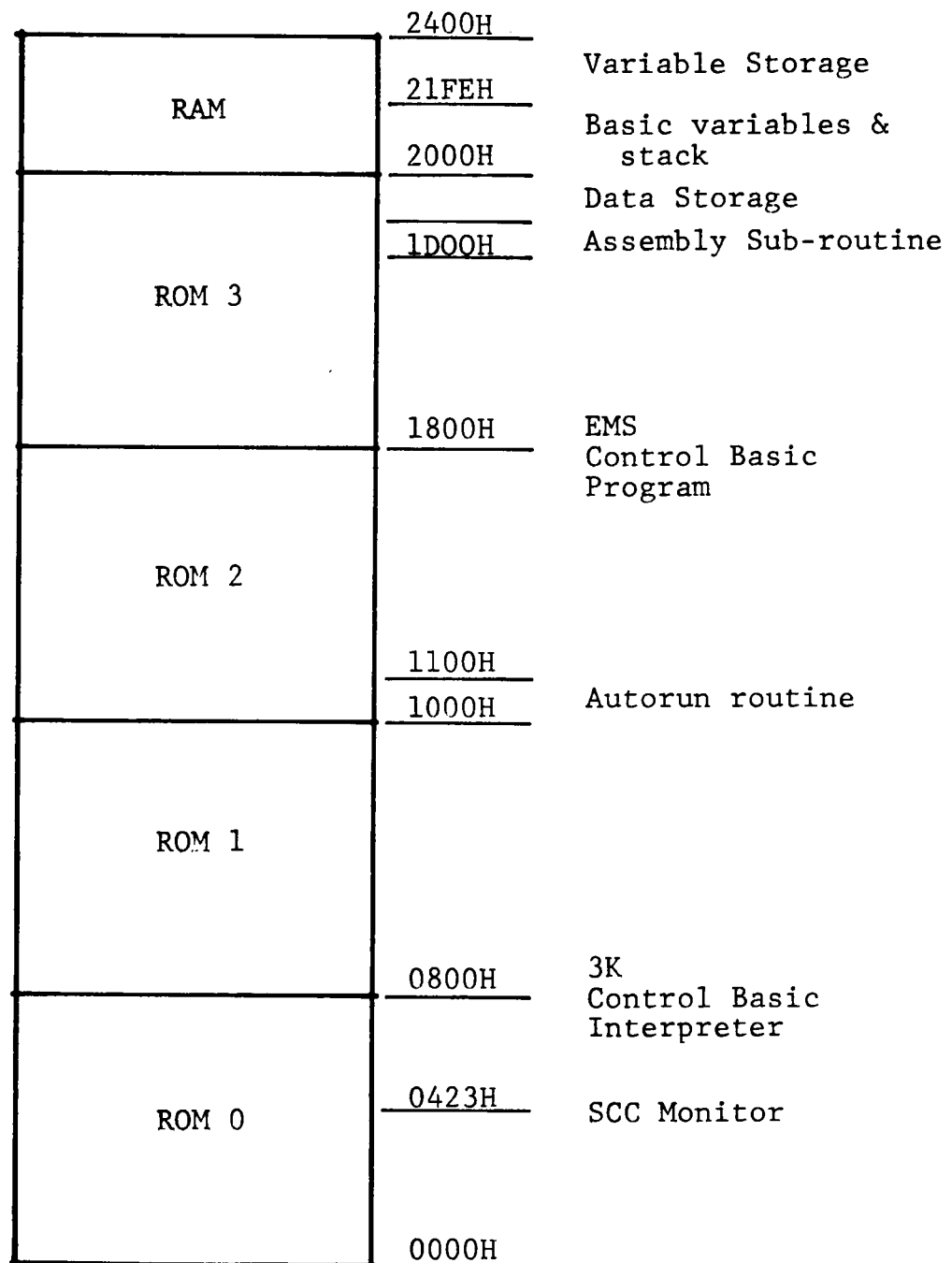


Figure 10. SCC memory map.

Finally, the AUTORUN routine calls the EMS program to execute.

The micro resident EMS program uses the Control Basic interpreter and calls Z80A assembler subroutines to perform its various functions. A flow chart of this program is illustrated in Figure 11. After initializing variables, the EMS program waits for input from the VAX. If space characters and a carriage return character are received, the micro program sends a ">", then continues to wait. If the micro receives a "P" character, the EMS program will jump to that portion of the program which reads power demand and temperature data and sends it to the VAX. In order to obtain the temperature data, the micro program must convert the Binary Coded Decimal (BCD) characters read from the digital thermometer to binary characters. It accomplishes this by calling a hand assembled Z80A subroutine. To obtain the power demand data, the micro program reads the PIO ports assigned to high and low bytes of a binary counter which records pulses from the power meter. The micro program then PRINT's this data to the VAX.

After checking the seasonal condition, the micro program compares the present temperature read with established temperature boundaries. In the winter, the lower boundary serves as a safeguard against pipe freeze-up during the evenings and weekends and activates the heating system when the temperature drops below this established limit.

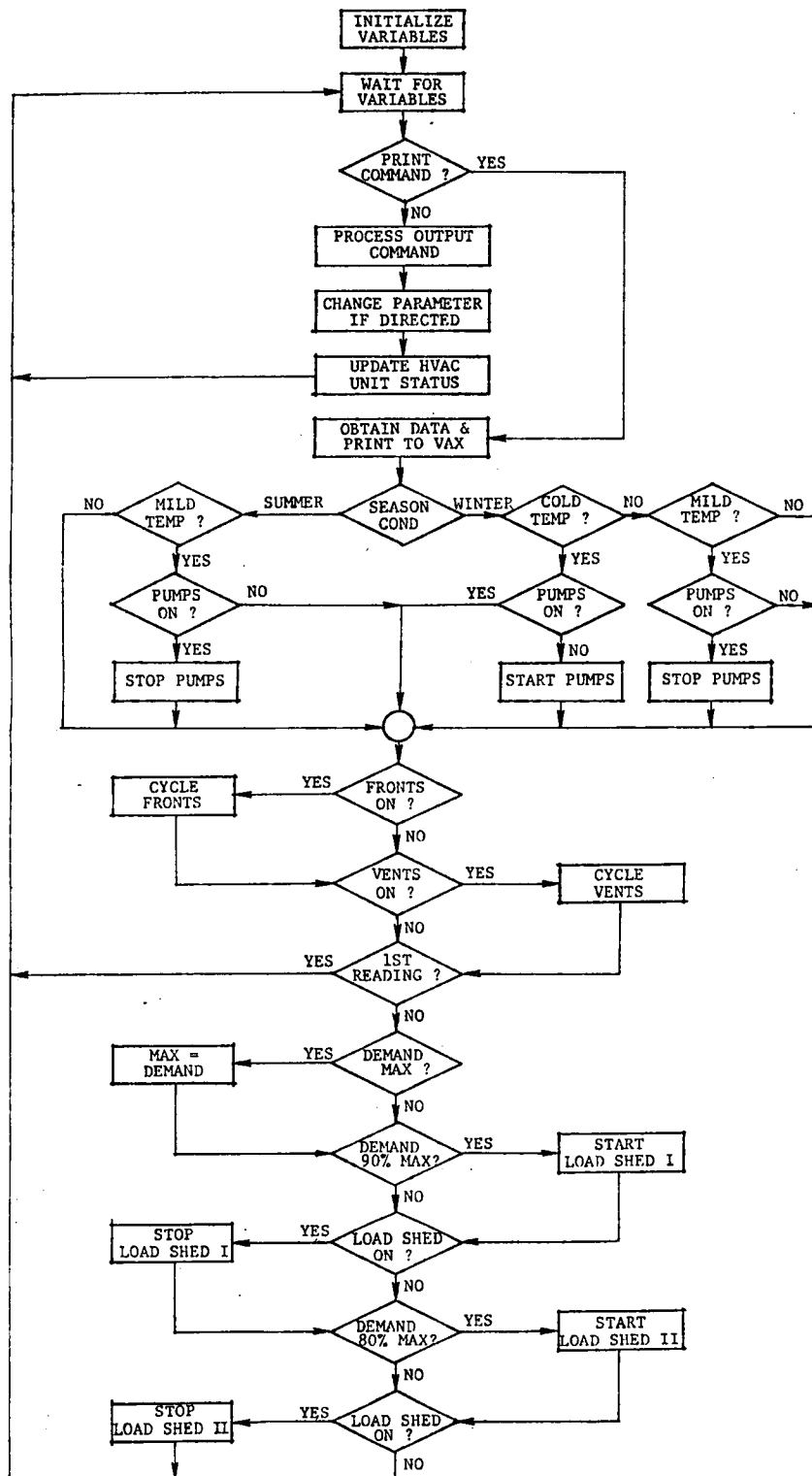


Figure 11. Micro-program flow chart.

The upper boundary eliminates the needless running of the heating system when the outside temperature is warm. During the summer, the lower temperature limit curtails the cooling system operation during cooler periods. The seasonal condition and temperature limits can be changed using the proper command input from CONTROL.

During the period of their operation, front air handlers and ventilators are cycled on and off. Their initial cycle period was established at 30 minutes, but this time can be changed by input from CONTROL. Both front air handlers and ventilators are treated as classes of HVAC units, and their cycle periods are treated separately.

Finally, the EMS compares the present power demand with the established maximum power demand limit (MAX). If the present power demand exceeds the MAX, it substitutes its value with that of the MAX. Load shed routines are activated when the power demand exceeds the established thresholds. These thresholds represent percentages of the MAX and can be changed by the control operator via CONTROL. Exceeding the threshold causes the EMS to cycle-off the wing circulating pumps. At the lower percentage level, one pump is deactivated for an established period of time. After this cycle period, a second pump is deactivated, while the first is restarted. At the higher percentage level, two pumps are cycled-off until demand drops below the higher threshold. After completing the above checks as illustrated

by Figure 11, the micro program waits for further input from the VAX.

If the micro program receives a change of parameter instruction, it will change the value of the parameters depending on the command received. If an OUT command is received which activates or deactivates a specific HVAC unit, the status of that unit is altered.

Because communications between the VAX and the micro were found not to be 100 percent reliable, the micro-processor is equipped with an automatic reset switch. When activated, the switch enables a two minute timer. If the port connected to the binary counter to which impulses from the power meter are sent is not read before the timer times out, a reset signal is sent to the SCC rebooting the EMS program. The VAX occasionally sends control characters which the SCC does not understand putting it into a state of confusion. The fact that the binary counter was not read indicates a disorder in the EMS program since the VAX sends a command to read it once per minute. The reading of the counter or the sending of the reset signal resets the timer. Thus, this communication problem is minimized.

CHAPTER III

HARDWARE

The hardware of the EMS includes: (1) a DEC VAX 11/780; (2) a Cromemco Single Card Computer and peripheral devices including two Cromemco 4 Parallel Input/Output (4PIO) boards and a thermometer interface board; (3) a binary counter connected to the power meter; (4) an Analog Devices 6 Channel Scanning Digital Thermometer with one Analog Devices Temperature Transducer and (5) a bank of 17 transistor driven, two-pole relay switches connected to the HVAC control board. The logical relation between this hardware is illustrated in Figure 12.

VAX

The VAX provides the EMS with HVAC scheduling ability and operator control of unscheduled HVAC operation and EMS parameter adjustment. Also the VAX stores accumulated temperature and power demand data. Communications between the VAX and the micro are established by means of a shielded cable pair directly connecting the two. The software on the VAX can be accessed through any of its terminals.

The EMS Control Center

The EMS Control Center is located in a metal cabinet in the Mechanical Room located in the C wing basement. Located

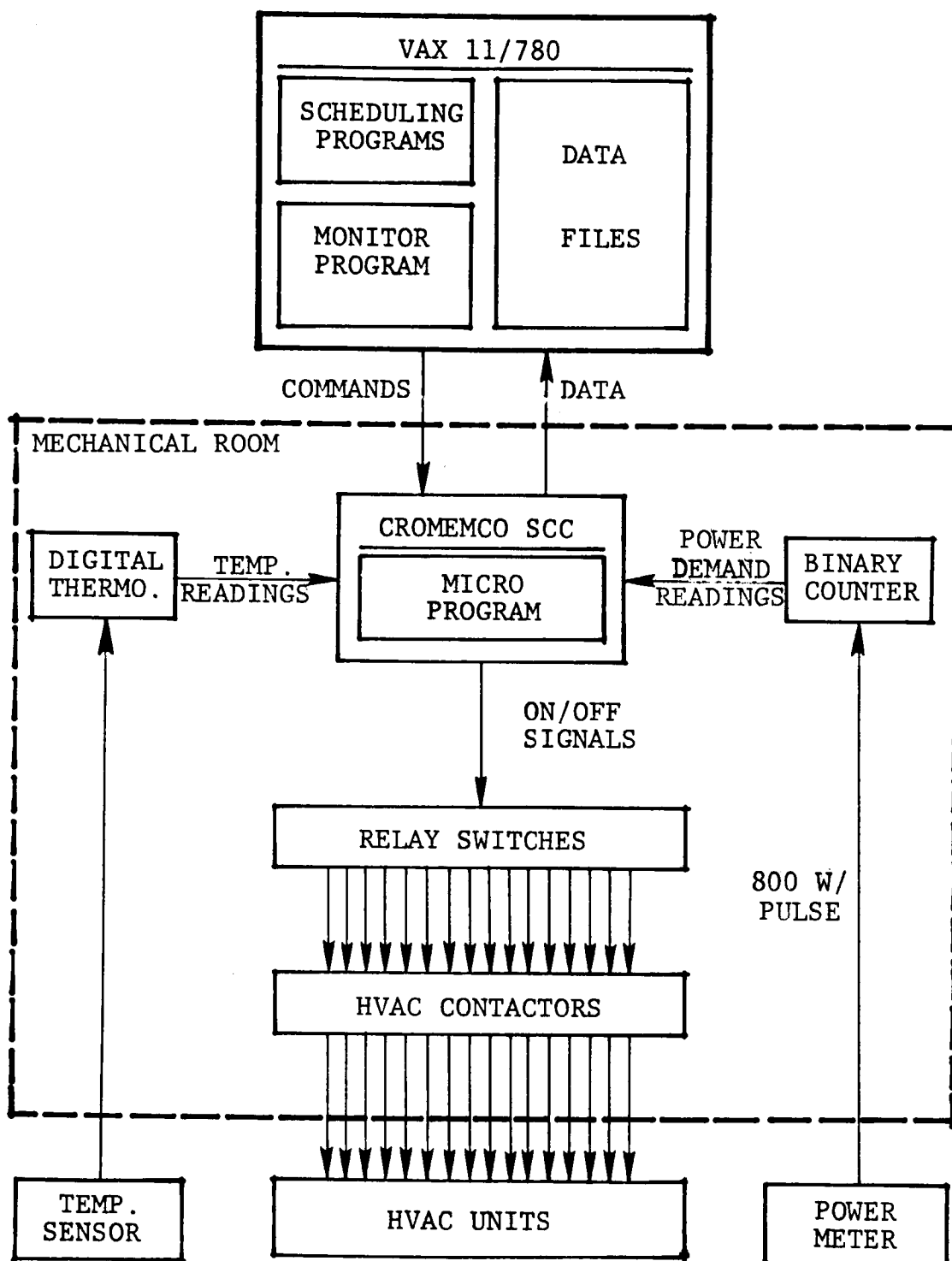


Figure 12. Logical relations between hardware.

in this cabinet are: (1) an S100 twelve card, cardcage with SCC, two 4PIO boards and thermometer interface board; (2) digital thermometer; (3) binary counter connected to power meter; (4) digital thermometer connected to one thermal transducer; and (5) 34 relay switches mounted on five circuit boards. Figure 13 shows the cabinet and its contents.

SCC

The Cromemco Single Card Computer with a MCB-216 interpreter is a Z80A microprocessor with one serial and three parallel input/output ports. The SCC uses the serial port to communicate with the VAX. Mounted in the S100 Bus cardcage, the SCC is capable of addressing 256 different parallel input/output (I/O) ports. This facility allows the communication with the 4PIO boards and thermometer interface board. The MCB-216 interpreter, resident on the SCC, consists of a monitor program and a 3K Control Basic interpreter. The micro resident program is written in this Control Basic. The SCC can handle two 2716 EPROM's with 2 Kilobytes of ROM each. The micro program resides on these two EPROM's. The SCC is also equipped with 1 Kilobyte of RAM for storage of variables and arrays and common memory area.

The SCC is equipped with automatic program running ability (AUTORUN) so that with a RESET the SCC will reboot itself.

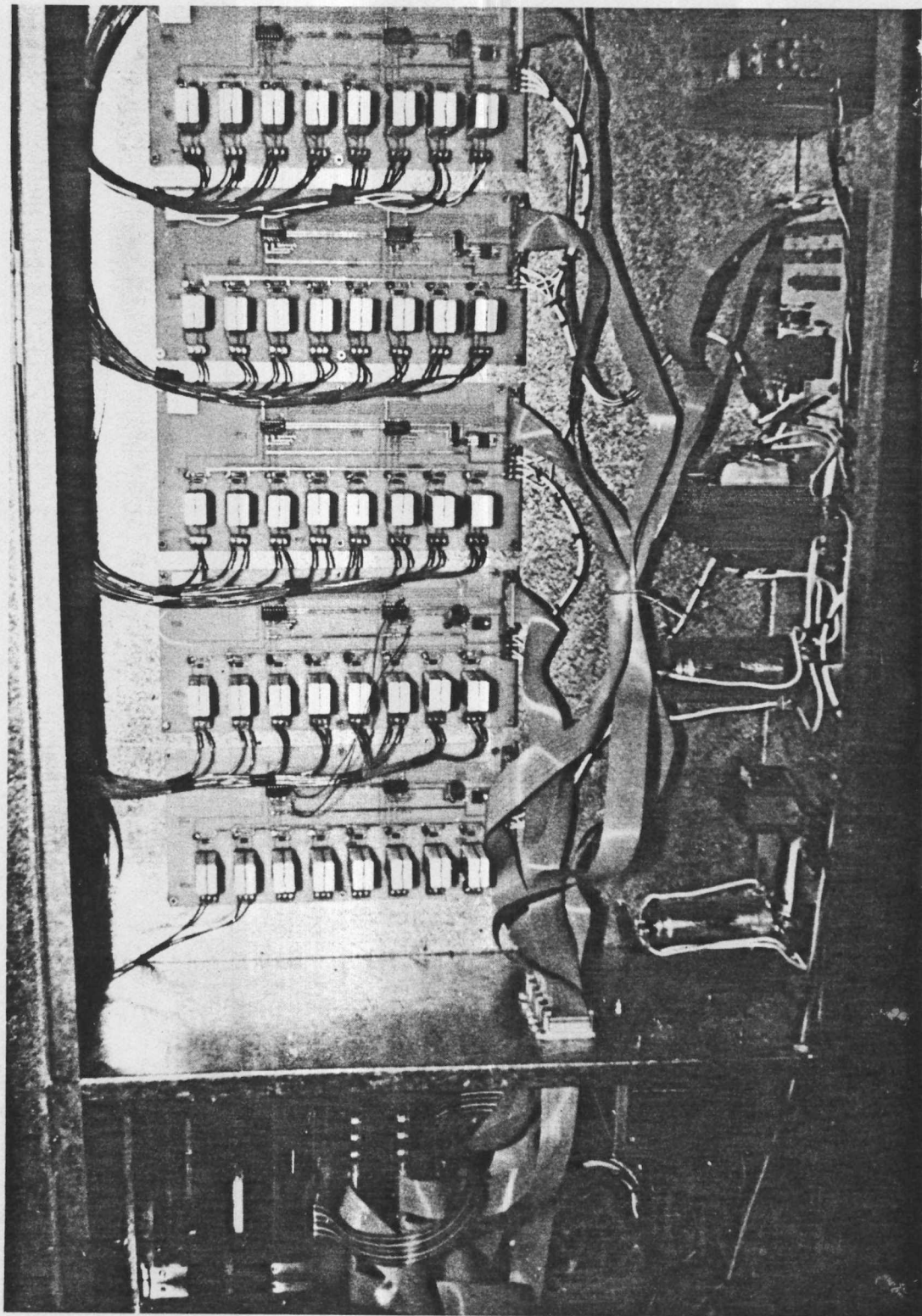


Figure 13. Photo of EMS control center.

PIO Board

The two Cromemco 4 Parallel Input/Output boards mounted in the S100 Bus provide the connection between the SCC and the four banks of relay switches and the high and low byte of the power meter counter. Each 4PIO board is equipped with four 25D connections. From these connectors ribbon cables are run to each of the four banks of relay switches and the two connectors on the power meter counter. The ribbon cable transmits control signals and data between the SCC and the relays and power meter counter.

Thermometer Interface Board

The thermometer interface board was designed and built to accommodate the Analog Devices 6 Channel Scanning Digital Thermometer. The board was designed around the S100 Bus system. This digital thermometer is capable of scanning up to 6 channels connected to 6 Analog Devices Thermal Transducers and transmits these readings to the thermometer interface board after converting them from analog to BCD signals. The thermometer interface board latches these readings and transmits readings to the SCC depending on the channel number requested. Since, at this time, only one thermal transducer is connected to Channel 1, the thermometer interface only transmits its readings, however, Channel 1 must be specified when data is requested. A schematic diagram of the thermometer interface board is provided in Appendix E.

EMS Peripheral Devices

Power Meter Counter

The power meter counter was designed and built to record pulses transmitted by a meter pulse initiator installed by the Duck River Electric Membership Corporation at the UTSI utility substation. Each pulse represents 800 Watts of power usage. These pulses are counted and the count is stored in high and low byte data latches. The SCC reads these latches by transmitting read signals to the parallel I/O ports to which these latches are connected.

Digital Thermometer and Thermal Transducers

The Analog Devices 6 Channel Scanning Digital Thermometer converts the analog signals from the Analog Devices Thermal Transducer mounted on top of the C wing roof to digital signals in Binary Coded Decimal (BCD). This digital thermometer is capable of scanning 6 different transducers or addressing any one particular transducer by an OUT command from the SCC signifying which transducer is to be read.

Relay Switches

A bank of 34 single pole, single throw relay switches corresponding to the on and off positions of 17 HVAC units are mounted on 5 boards. Because the HVAC units 15 and 17 function similarly, these two units were wired together to prevent having to wire up an entire new bank of relays.

These relay switches are directly tied into the electrical contactors on the HVAC control board. Sending a pulse to the "on" relay switch temporarily closes the circuit on the electrical contactor which causes the contactor to close and activates the unit. Sending a pulse to the "off" relay switch releases the contactor, deactivating the unit.

Automatic Reset Switch

Located on the power meter counter is an automatic reset switch which can be deactivated by means of a simple toggle switch. This device is comprised of a two minute counter which is reset by a read instruction to the data latches located on the counter. Since the counter is read once a minute, the timer never times out and is reset under normal operation. However, if the counter is not read, a reset signal is transmitted to the SCC upon time out via the S100 Bus, rebooting the micro program.

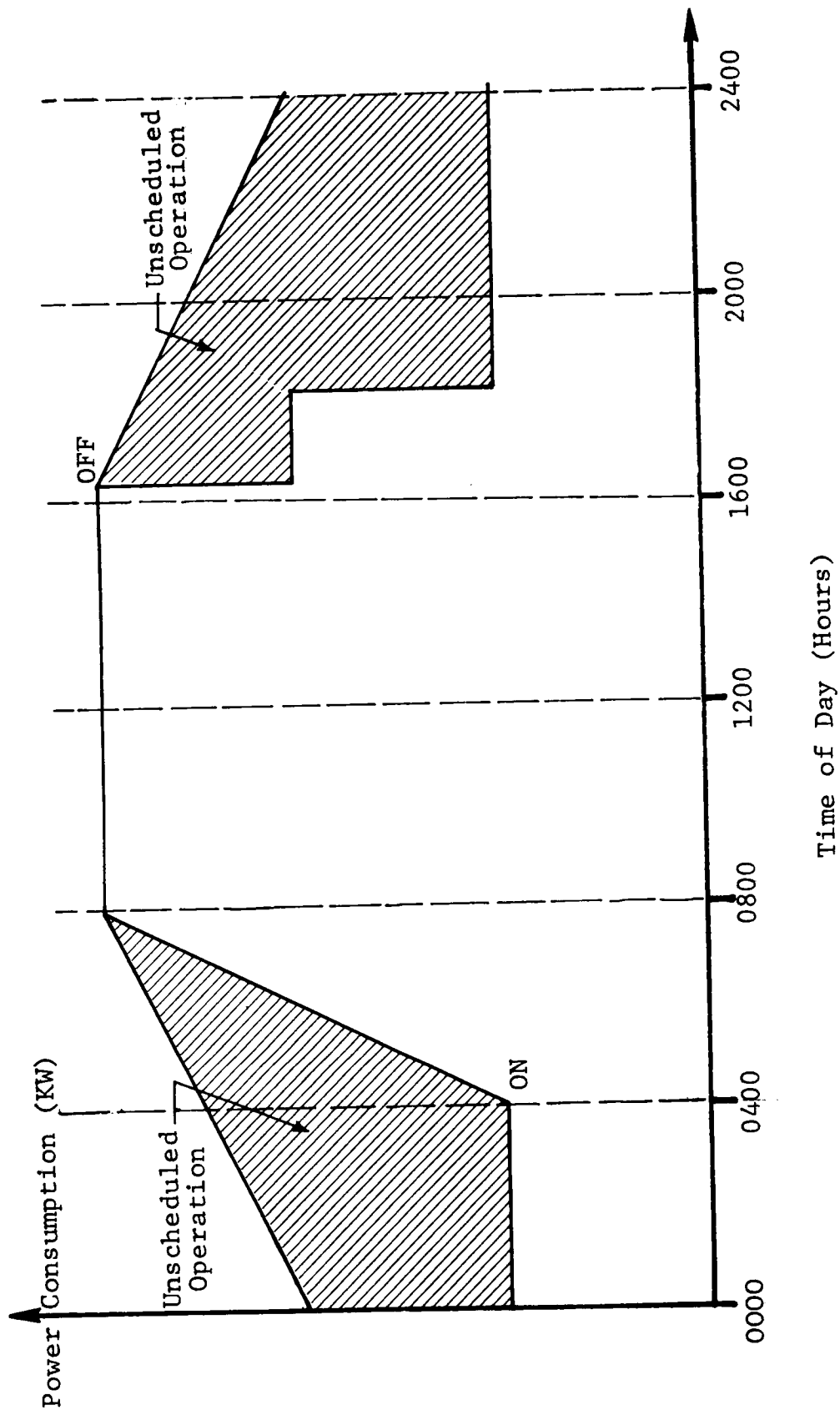
CHAPTER IV

ANALYSIS

The true measure of the success of the EMS is how much energy has been conserved by its use. Energy costs are not necessarily a good measure since rates steadily climb, producing an increase in cost even though high energy usage may have been avoided and high peak demands may have been averted. For the sake of this analysis, therefore, comparisons will be made on the basis of KWH and KW. Energy savings can be shown in four ways as a result of employing the EMS, scheduling, optimizing HVAC operation, duty cycling ventilators and front air handlers and load shedding during peak demand periods. Each will be discussed below.

Scheduling

The most obvious savings comes from scheduling HVAC operation by deactivating it during unoccupancy. However, as mentioned before, if activation of the HVAC is not handled carefully, an extremely high peak demand can result during start-up which offsets any KWH savings because of the high KW demand surcharge. This problem was averted by a gradual activation of the HVAC components. The shaded areas in Figure 14 indicate the potential KWH savings as a result of scheduling HVAC operations. Through software control, scheduling can be changed depending on varying occupancy periods.



Note: Shaded area represents potential savings in KWH.

Figure 14. Potential savings due to scheduling.

Optimizing

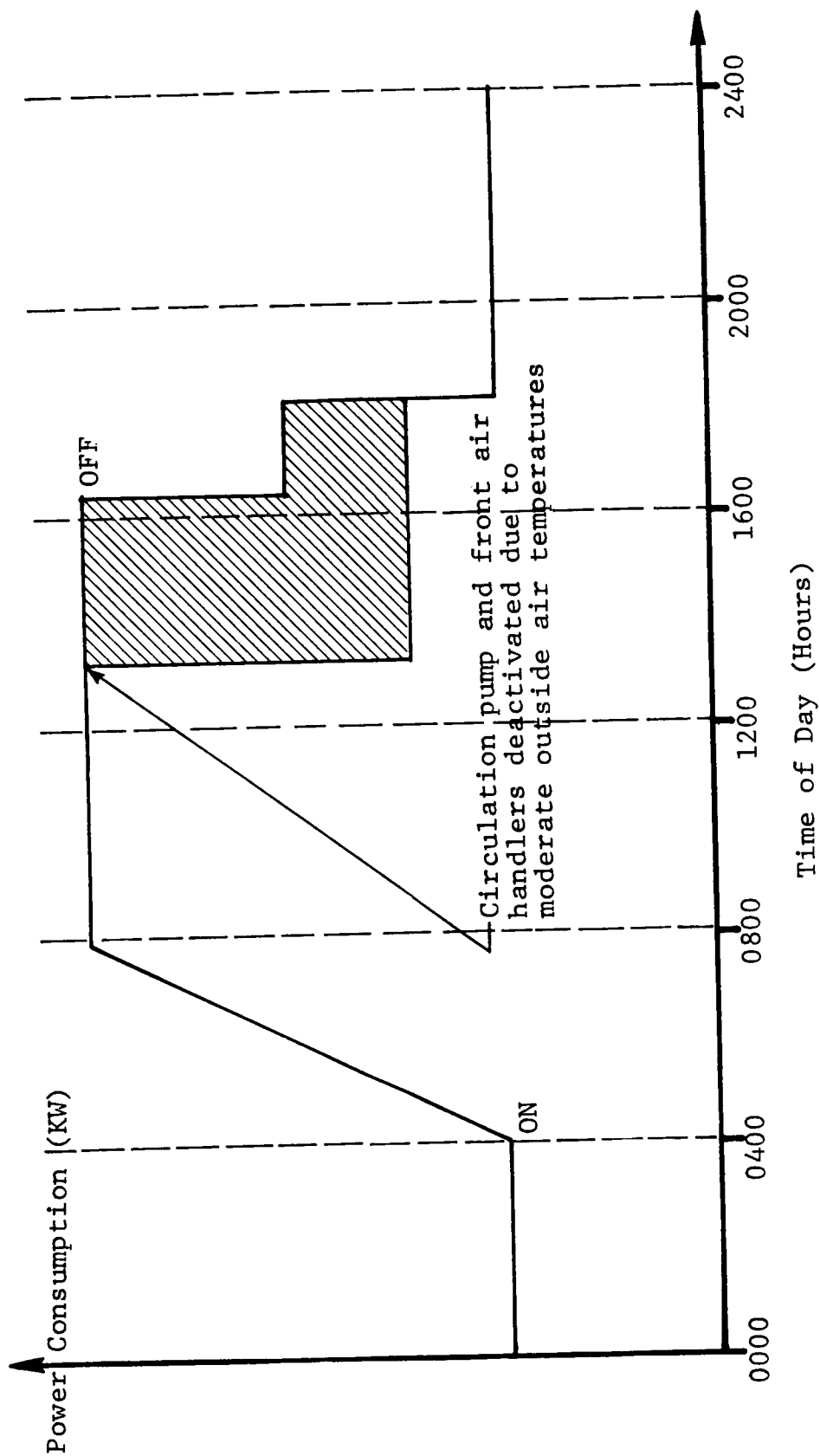
Savings from optimizing HVAC operation result when the outside air temperature is moderate enough so that heating or cooling can be terminated, halting the wing circulating pumps and front air handlers. The ventilators continue to run providing the building with moderate outside air, as the sole source of distributed air. This potential savings is illustrated by Figure 15. These seasonal temperature limits at which this optimizing function occurs can be adjusted via software to suit occupant comfort.

Duty Cycling

As both the ventilators and front air handlers were overdesigned (see Chapter II), their duty cycle will have minimum effect on occupant comfort. However, their off-time can be adjusted via software to better suit occupant comfort. The potential savings as a result of their duty cycle is illustrated in Figure 16.

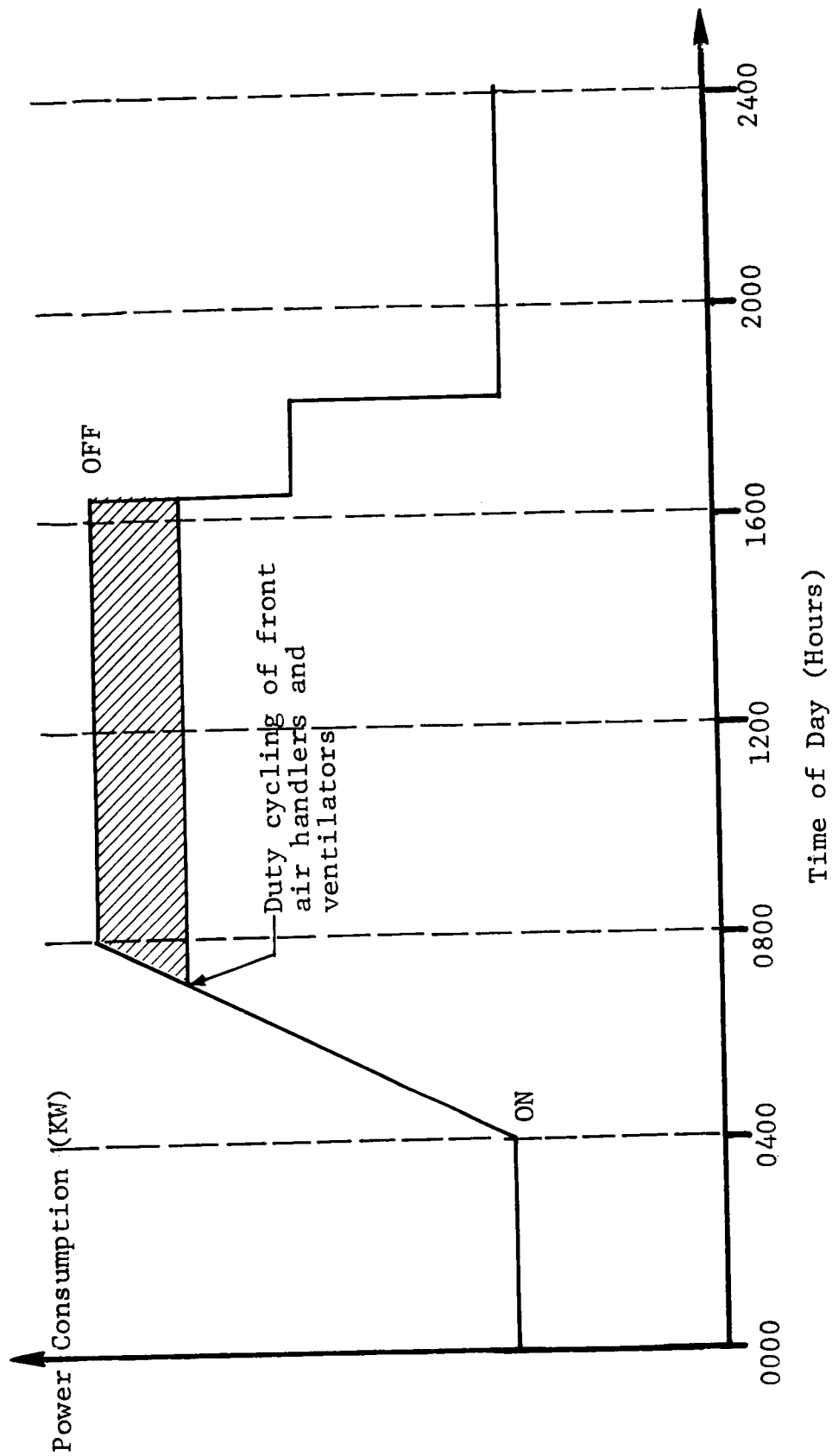
Demand Limiting

The savings resulting from demand limiting is caused by: (1) the cost reduction associated with the high peak surcharge and (2) energy savings resulting from duty cycling the circulating pumps. The maximum demand limit can be adjusted via software. Depending on recorded data, the



Note: Shaded area represents potential savings in KWH.

Figure 15. Potential savings due to start/stop optimizing (winter).



Note: Shaded area represents potential savings in KWH.

Figure 16. Potential savings due to duty cycling of front air handlers and ventilating fans.

maximum demand limit should be adjusted each month to achieve the greatest potential savings, since peak demands vary monthly. Limiting peak demands represents the greatest potential savings as the peak demand surcharge is considerable.

When the power demand exceeds the lower load shed threshold, the circulating pumps are duty cycled one at a time. If the power demand continues to rise and exceeds the upper load shed threshold, two of the circulating pumps are duty cycled. If these measures do not curtail the power demand from exceeding the established maximum demand limit, a new maximum is established by the rising power demand. However, in the process of limiting demand, a higher peak demand was averted. This newly established maximum remains until adjusted by software.

Reliability

Paramount to the success of the EMS is its reliability. Two approaches are used to prevent the failure of the EMS: (1) monitoring the EMS through the VAX resident program and (2) an automatic reset device to the SCC. As discussed above, the EMS process can be monitored from a VAX terminal. This will indicate to the operator the running of the EMS process. In addition, the SCC has an automatic reset. This facility reboots the SCC resident program, if it should fail for any apparent reason. The data lost during its

brief down time will not be significant to the success of the EMS.

Recommendations

During the course of this work, it was noted that if the maintenance of the building were improved, considerable energy savings would result. In particular:

(1) Inoperative thermostats in fan coil units should be replaced. These allow room occupants to control the room environment without deactivating fans. According to survey results, many occupants resort to turning on or off the fans to control room temperature. Sudden widespread activation of fans causes high peak demands.

(2) Windows should be caulked to prevent excessive infiltration of outside air.

(3) Other doors should be repaired and weather stripped for the same reason.

(4) The receptionist located in the A wing lobby needs to be better isolated from the lobby and supplied with a local heater and fan. The present unit is ineffective and costly. Isolating the receptionist would allow the deactivation of the larger unit, except on special occasions.

The EMS can be enhanced by including the following:

- (1) The control of lighting using scheduling algorithms.
- (2) Temperature sensors centrally located in each wing to account for local temperature variances. This would

allow temperature set-backs during unoccupancy to be scheduled.

An analysis should be made of the effectiveness of this system by comparing electricity useage for the previous year to the current in which the EMS is used. The average temperature per day could be used to compile the data for the two years. Likewise printed indicators as to which load shedding subroutine is being run could be used to determine the effectiveness of this approach.

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BIBLIOGRAPHY

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APPENDIX

APPENDIX

OPERATING PROCEDURES

The control operator can access the EMS from any terminal connected to the VAX. From the terminal, the control operator should be able to:

- 1) check proper functioning of the micro;
- 2) initiate and observe the VAX monitoring process
MONITOR;
- 3) initiate and check the recurrent scheduling
programs ON and OFF;
- 4) schedule specific HVAC operation, and
- 5) change the EMS parameters using CONTROL.

Check the Micro

MONITOR normally maintains control over the micro, so to communicate with the micro, MONITOR must first be halted. To do this, perform the following steps:

- (1) Type: SHOW SYSTEM [carriage return (CR)]
This will display all the currently running VAX programs.
- (2) Locate MONITOR by its distinctive process name M0000P0000I0000 (note that the zeros may be replaced by decimal numbers).
- (3) Note the 8-digit identification number immediately preceding the process name.

(4) Inserting noted identification number,

type: STOP PROC/ID=identification number(CR)

This should successfully halt MONITOR so that direct communication with the micro can be established. To establish communications, the control operator must run another VAX program, performing the following steps:

(1) Type: RUN MICRO(CR)

This will cause a prompt to be displayed on the terminal screen: INPUT PORT ID I.E. _TTE7:

(2) Type: _TXB4:(CR)

It is possible that _TXB4 may already be in use, however, it's probably only for a short time. Therefore, steps (1) and (2) must be repeated until the VAX displays the prompt:

You may now boot the HASPBOX processor. Type Control-Y to abort.

The control operator is now in direct communication with the micro.

The micro can be in one of three states:

- 1) properly running;
- 2) not running, but will respond to keyboard input, or
- 3) not running and will not respond to keyboard input.

To determine the present state of the micro,

type: P(CR)

If the micro responds with a 6-digit hexadecimal number, then the micro is running properly. If the micro responds in any other way, or does not respond, then it is not

running and the control operator should notify the VAX system personnel.

To terminate communications with the micro,
type: Control-Y(CR)

Initiate and Observe MONITOR

To initiate the MONITOR program, the control operator must perform the following steps:

(1) Type: M(CR)

This will display the message: "% RUN-S-PROC_10, identification of created process is ____". However, to ensure that the program is running successfully,

(2) Type: SHOW PROC/ID=identification number(CR)
using the identification number indicated in the message displayed following the "M" command. This should cause information concerning the program. If any other message is displayed, the control operator must repeat steps (1) and (2). If the program continues to fail, the VAX system personnel should be notified.

To observe MONITOR at work, monitoring the maximum power demand, the previous 30 minutes' power demand and the current power demand based on the past minutes' demand projected over a 30 minute demand period, the control operator must perform the following steps:

(1) Type: SHOW PROC/ID=identification number/CONT(CR)

This will cause information concerning the process to be

displayed which is updated every minute. The power demand will be displayed at the top of the screen in the format:

 ┌───→ M0000 P0000 I0000 ←──┐
maximum power demand ↑ current power demand
 previous power demand

- (2) To abort observing this process,
type: Control-Y

Initiate ON and OFF

To maintain the scheduling process of the EMS, ON and OFF programs must run alternately. ON runs at 0400 daily and checks to see if it is a workday. If so, ON will activate the HVAC, otherwise it will reschedule itself to run at 0400 the following day. After ON has run, it schedules OFF to run at 1630 the same day. OFF halts the HVAC. After OFF has run, it schedules ON to run at 0400 the following morning. Therefore, depending on the time day ON or OFF should run. Between the hours of 0200 and 1300, ON should be run, otherwise, run OFF.

To run ON or OFF the operator must

type: SUB/QUE=SYS\$FAST/AFTER=time ON or O_F(CR)

replacing "time" with

TODAY

if the program is to run immediately or

12-JAN-1983:12:00:00

inserting the appropriate time.

To see if ON or OFF have successfully been registered on the SYS\$FAST QUEUE

type: SHOW QUE/ALL SYS\$FAST(CR)

This will display a list of programs registered with their entry number preceding the program name and the time they are to run following. For example,

AFTER 9926 SYSTEM ON Pri=5 17-OCT-1983 15:20

To remove the program from the SYS\$FAST QUEUE

type: DEL/ENTRY=entry number SYS\$FAST QUEUE(CR)

inserting the entry number displayed as a result of the previous command.

Running either ON or OFF is sufficient to initiate the scheduling process of the EMS, since one schedules the other.

Schedule HVAC Operation and Change EMS Parameters

The control operator can schedule operation of specific HVAC units, such as the Lobby and Auditorium which are not normally run. Also, the parameters governing EMS operation can be changed by running the program CONTROL. To run this program

type: CONTROL(CR)

The "command" prompt will be presented.

Type of Command:

If the control operator is unfamiliar with the type of commands available, he should respond with a "?".

Type of Command:

Type O to control HVAC units.
Type S to change SEASONAL CONDITION.
Type D to change MAXIMUM DEMAND LIMIT.
Type G to change THRESHOLD for LOAD SHED ROUTINES.
Type P to change OFF-TIME of CIRCULATING PUMPS.
Type F to change OFF-TIME of FRONT AIR HANDLERS.
Type V to change OFF-TIME of VENTILATORS.
Type U to change WINTER UPPER TEMPERATURE LIMIT.
Type L to change WINTER LOWER TEMPERATURE LIMIT.
Type K to change SUMMER LOWER TEMPERATURE LIMIT.

Type of Command:

Using the command menu above, the operator responds with the appropriate one-letter command abbreviation. Subsequent "command" prompts will be presented as discussed below.

Control HVAC Units (O)

The control of specific HVAC units can be temporarily overridden by the operator with an "O" response to the "command" prompt, e.g.

Type of Command: O(CR)
Enter command and RETURN. Press RETURN again after last command:

A menu of commands can be obtained by typing "?".

Enter command and RETURN. Press RETURN again after last command: ?(CR)

AUD_ (Auditorium, 1 on or 0 off)
LOB_ (Lobby, 1 on or 0 off)
WP (A,B,C,D, or E Wing Circulating Pumps, 1 on or 0 off)
WF (A,B,C,D, or E Wing Fans, 1 on or 0 off)
WV (A,B,C,D, or D Wing Ventilators, D and E together, 1 on or 0 off)

Enter command and RETURN. Press RETURN again after last command:

The operator will be able to enter the proper command with the assistance of this menu. Commands consist of a three-letter abbreviation and "0" to turn off the HVAC unit or "1" to turn it on. The operator can respond with only one entry at a time, e.g.

Enter command and RETURN. Press RETURN again after last command: AWP1(CR)

Enter command and RETURN. Press RETURN again after last command: BWV0(CR)

After all commands have been entered, a second carriage return is entered.

Enter command and RETURN. Press RETURN again after last command: (CR)

A "time" prompt will then be presented.

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Change Seasonal Condition (S)

The EMS is initially set to a winter condition. To change the seasonal condition, the operator responds the "command" prompt with "S", e.g.

Type of command: S(CR)

To select the seasonal condition type S for summer or W for winter:

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Change Maximum Demand Limit (D)

The maximum demand limit for the EMS is initially set at 480 KW per 30 minute interval or 960 KWH. To change the demand limit, the operator responds to the "command" prompt with "D", e.g.

Type of Command: D(CR)

Enter MAX ALLOWABLE DEMAND LIMIT in multiples of 48:

Entering a figure evenly divisible by 48 resets the demand limit, other entries, such as 820, not evenly divisible by 48 will not successfully reset the demand limit. The "time" prompt will then be presented.

Type of Command: D(CR)

Enter MAX ALLOWABLE DEMAND LIMIT in multiples of 48:
480

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Change the Thresholds for Load Shed Routines (G)

Load shed routines attempt to prevent power demand from exceeding set maximum limits by periodically shutting down circulating pumps. This is used only as a last resort, therefore, thresholds for these routines are usually set high.

Thresholds are expressed as percentages of maximum demand limit. There are lower and upper thresholds. The lower threshold is initially set at 80 percent of the maximum demand limit, and the upper threshold is set at

half the difference between the lower and the maximum demand limit or 90 percent, initially. The operator responds to the "command" prompt with "G", e.g.

Type of Command: G(CR)

Enter percent of MAX DEMAND LIMIT for LOAD SHED:

The operator responds with the lower threshold entry. The upper threshold is set automatically. Afterwards, the "time" prompt will be presented.

Type of Command: G(CR)

Enter percent of MAX DEMAND LIMIT for LOAD SHED: 70(CR)

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Change Off-times of Circulating Pumps, Front Air Handlers and Ventilators (P, F or V)

Front air handlers and ventilators are cycled off during normal working hours. Circulating pumps are cycled off only during load shed routines. Off-times are expressed in minutes and initially set at 30 minutes, e.g. 30 minutes off, 30 minutes on, etc. Off-times for the three types of equipment are changed individually. To change the off-time the operator responds to the "command" prompt with "P", "F" or "V" corresponding to the type of equipment, e.g.

Type of Command: V(CR)

Enter the number of minutes:

After entering the appropriate time, the "time" prompt is presented.

Type of Command: V(CR)
Enter the number of minutes: 45(CR)

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Change Temperature Limits (U, L or K)

The temperature limits, upper winter, lower winter and lower summer, define the range within which the HVAC will operate. There is no upper summer temperature limit obviously, because the higher the temperature the more cooling that is needed. The lower winter temperature limit is used to activate heating when HVAC is normally off. This is needed to prevent pipe freeze-ups. To change the temperature limits, the operator responds to the "command" prompt with "U", "L" or "K" corresponding to the limit to be changed, e.g.

Type of Command: K(CR)
Enter the limit in degrees Fahrenheit:

After the new limit is set, the "time" prompt is presented.

Type of Command: K(CR)
Enter the limit in degrees Fahrenheit: 76(CR)

At what time is this to be done?

Response to the "time" prompt will be discussed at the end of this section.

Enter Time

The "time" prompt determines the time commands to be

executed. They may be executed immediately by entering
TODAY

or scheduled for some time in the future using the format
12-JAN-1983:12:13:59

For example,

At what time is this to be done? 11-DEC-1986:12:00:00(CR)

After entering the time, CONTROL registers the commands
with the EMS.

VITA

Charles Bryan Alexander, III, was born in Rome, Georgia, on December 11, 1946. The son of a United States Air Force officer, he attended many different schools and lived in places including Orlando, Florida; Keflavik, Iceland; Los Angeles, California; Abilene, Texas; Tullahoma, Tennessee, and Wiesbaden, West Germany. He graduated from Tullahoma High School in June, 1964, traveled to West Germany and enrolled at The University of Maryland Extension branch at Munich. There he attended school and traveled about Europe for two years. He was awarded a Navy Reserve Officer Training Corps Scholarship to Marquette University in Milwaukee, Wisconsin and in May, 1969, graduated with a Bachelor of Arts degree in Economics.

After a four-year tour of duty with the United States Marine Corps he returned to college at The University of Tennessee, Knoxville in September, 1973, and there earned a Bachelor of Architecture degree.

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The author plans to continue his research with computer controls of building systems and will enter employment with Fuel Computer Corporation of New Haven, Connecticut after graduation.