NISTIR 4991

Guidelines for Using Emulators to Evaluate the Performance of Energy Management and Control Systems

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NIST

United States Department of Commerce
Technology Administration
National Institute of Standards and Technology

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November 1992

U.S. Department of Commerce
Barbara Hackman Franklin, *Secretary*
Robert M. White, *Under Secretary for Technology*
National Institute of Standards and Technology
John W. Lyons, *Director*

Prepared for:
U.S. Department of Energy
Office of Conservation &
Renewable Energy
1000 Independence Ave., SW
Washington, DC 20585

ABSTRACT

A Building Energy Management System (BEMS) is that portion of a Building Automation System (BAS) that controls the heating, ventilation, and air conditioning (HVAC) systems in buildings. Its performance is directly related to the amount of energy consumed in a building and the comfort of the building occupants. One approach to evaluating the performance of an BEMS is through the use of an Emulator. This is a special computer/data acquisition system that is connected to the sensor inputs and command outputs of the BEMS. It replaces the HVAC system and building and uses a computer program to simulate their response to BEMS commands. The BEMS, through its supervisory and/or direct digital control algorithms, then controls the simulated building/HVAC system as if it were an actual one. At the same time the Emulator evaluates the performance of the BEMS in terms of the energy consumed by the simulated building, the degree of comfort maintained in the simulated space, response time, accuracy, etc..

This report contains guidelines for using Emulators to evaluate an BEMS. An overview of the hardware and software found in a typical BEMS is presented, followed by information on: setting up an BEMS and an Emulator, evaluating system/command and DDC software, and methodologies for testing BEMS application algorithms. Considerations are also presented for evaluating an BEMS' programming capabilities, DDC control loop performance, and for rating different aspects of an BEMS' performance.

KEY WORDS

Application Algorithms; Building/HVAC/Plant System; Building Energy Management System; Emulator; Energy Management and Control System; Performance Evaluation; Simulation; Test and Rating Methodology

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INTRODUCTION

An Emulator for Building Energy Management Systems (BEMS) applications consist of a computer-based simulation of a building and its mechanical system connected to a real BEMS (May and Park, 1985). It can be used to replace the entire building/HVAC/plant system or the emulation software can be interfaced with selected pieces of real HVAC hardware (such as coils, valves, a boiler or a chiller). The Emulator can then be used for evaluating the performance of a Building Energy Management System before or after purchase. By varying the number of tests performed, an Emulator can be used to evaluate either an BEMS that will be installed in a particular building or an BEMS that a large organization (e.g., a government agency) may be considering purchasing for installation in many different types of buildings in various climates.

An Emulator is connected to the BEMS being evaluated in place of the regular BEMS sensors and actuators. Since most BEMS sensors are electrical in nature, they can be replaced with voltage and current sources under the control of the Emulator. (In the few cases where resistive sensors are employed, it may be necessary to simulate the resistances of the real sensors with motorized resistors under the control of the Emulator.) The BEMS will be unable to distinguish between an actual sensor producing an electrical signal and the Emulator producing the same electrical signal. The BEMS, through its supervisory and/or direct digital control algorithms, then controls the simulated building/HVAC system as if it were an actual one. At the same time the Emulator evaluates the performance of the BEMS in terms of the energy consumed by the simulated building, the degree of comfort maintained in the simulated space, the response time, accuracy of control, etc. This allows the BEMS software algorithms to be evaluated directly without the effect of sensors distorting the results.

An advantage of using an Emulator is that an BEMS may be tested with any type of building/HVAC/plant system for which a simulation model is available, and tests can be repeated on different BEMS under identical conditions. In addition, it is not necessary to know the exact structure of the algorithms used in an BEMS to evaluate how well they perform. Since BEMS software is usually proprietary, this is a definite advantage.

In order to better understand the requirements associated with using Emulators to evaluate the performance of BEMS, the following sections provide: a brief description of the hardware found in a typical Building Automation System, an overview of the different kinds of BEMS software which a properly designed Emulator could be used to evaluate, a section on setting up the BEMS and the Emulator, information on evaluating system and command and DDC software, methodologies for operational testing and performance testing of BEMS application algorithms, considerations for evaluating an BEMS' programming capabilities and DDC control loop performance, and a suggested BEMS rating methodology. Obviously, since evaluation needs will vary on a case by case basis (depending, for example, on whether the BEMS is to be installed in a particular building or in many different types of buildings), the performance tests and evaluation methodology discussed in this chapter must be adapted to each specific use. Such decision should be made by an "evaluation team" that is specifically set up to plan, conduct, and analyze the results of all such BEMS performance tests.

1. DESCRIPTION OF BUILDING AUTOMATION SYSTEM HARDWARE

A typical Building Automation System (BAS) is shown in Figure 1. It consists of Host Local Area Network (LAN) whose primary function is data/word processing, a telecommunication system, a Building Energy Management System (BEMS), and a combined fire safety/security system. Common options include having separate systems for fire safety, security, lighting, and elevator control connected to the Host LAN. The BEMS Host computer, which may be either a minicomputer or a personal computer, is connected to Field Panels (sometimes called Outstations or Remote Stations) either using dedicated wiring or, as shown in Figure 1, by means of an BEMS control LAN.

These Field Panels may be classified, as shown in Figure 2, as either intelligent (active) or not intelligent (passive). In an BEMS that does not perform direct digital control (DDC), the Field Panels read sensors, perform open loop control of actuators and relays, and adjust the set points of pneumatic and/or electronic controllers that control the various local HVAC process loops. The Field Panels may carry out these tasks directly or through Multiplexers (MUXes) that multiplex sensor and control signals and perform analog-to-digital and digital-to-analog conversion. In a DDC based BEMS, the closed loop control of the final control elements is performed either by the Field Panels directly and/or by Unitary Controllers which are connected to a Field Panel or a Master Unitary Controller by means of a Unitary LAN.

Although an Emulator is primarily for evaluating BEMS software, the process of setting up the BEMS for testing and connecting it to the Emulator is an extremely valuable experience that should provide significant information on the capabilities of the BEMS hardware. Some typical hardware features to be considered during this process are listed in Appendix A.

2. DESCRIPTION OF BUILDING ENERGY MANAGEMENT SYSTEM SOFTWARE

In general, there are four basic types of software associated with BEMS that an Emulator can be used to evaluate. They are:

- System Software,
- Command Software,
- DDC Software for Local Loop Control, and
- Supervisory Application Software.

System software consists of the Operating Systems on the BEMS Host computer, the Field Panels, and any Unitary Controllers comprising the BEMS and various Utility Programs and Other Services. The BEMS Host Computer operating system coordinates the execution of the entire system, contains peripheral equipment drivers, database management, input/output control, communication controls, program execution controls, library computational routines, language interpretation, and system self-test routines, and runs system wide application programs. The Field Panels and Unitary Controller System Software support the execution of Application programs that provide both supervisory control of HVAC equipment and direct digital control of local loops either singularly and/or in a hierarchal manner. Utility programs include all programs which interface with the operating personnel to provide supervisory control of the entire operation of the control system. The output of these programs may be modified from the host computer keyboard to meet the needs of a particular application. More specifically the utility programs should include system monitoring and display of points, alarm summary

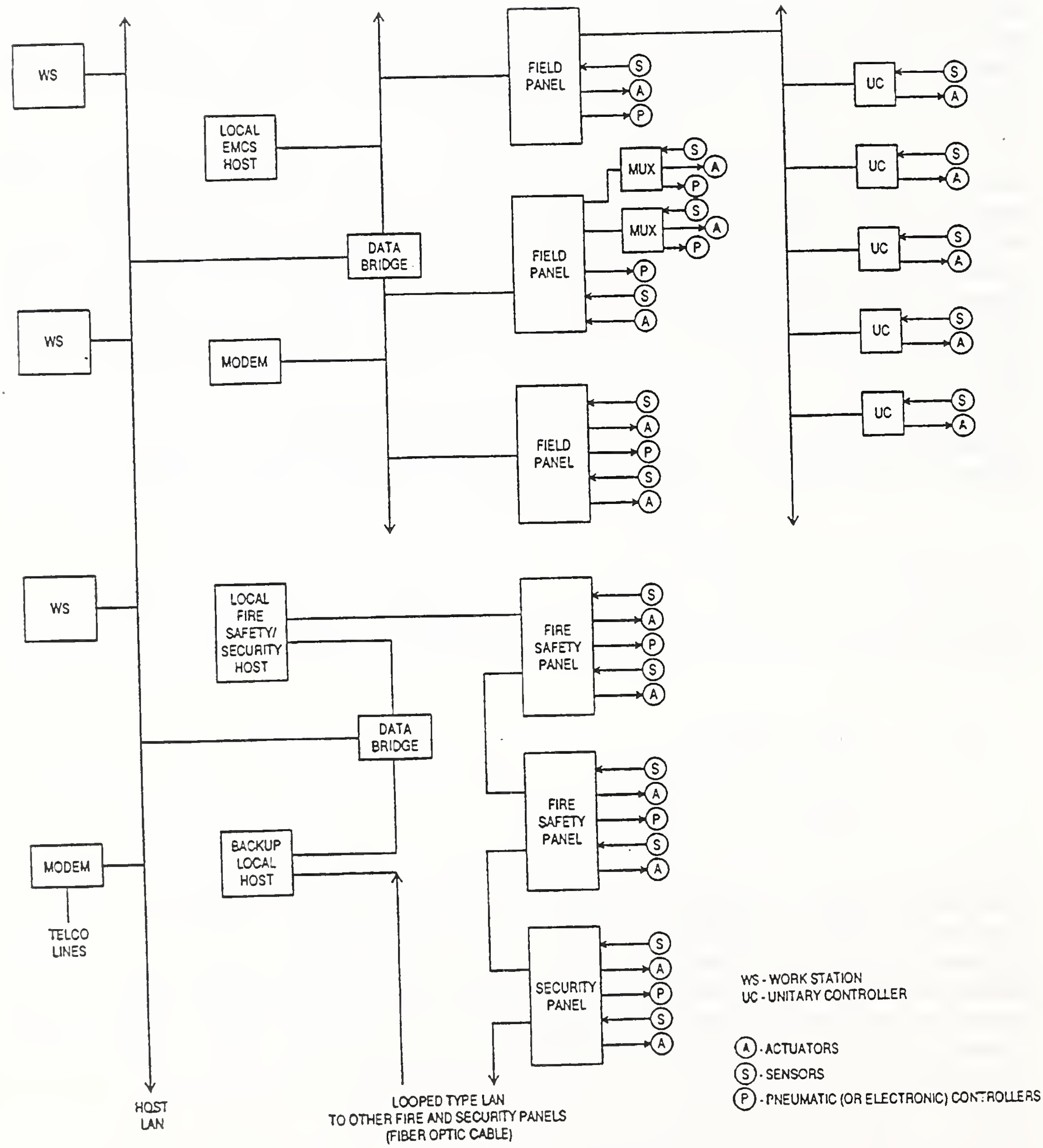

Figure 1. Typical Building Automation System (BAS)

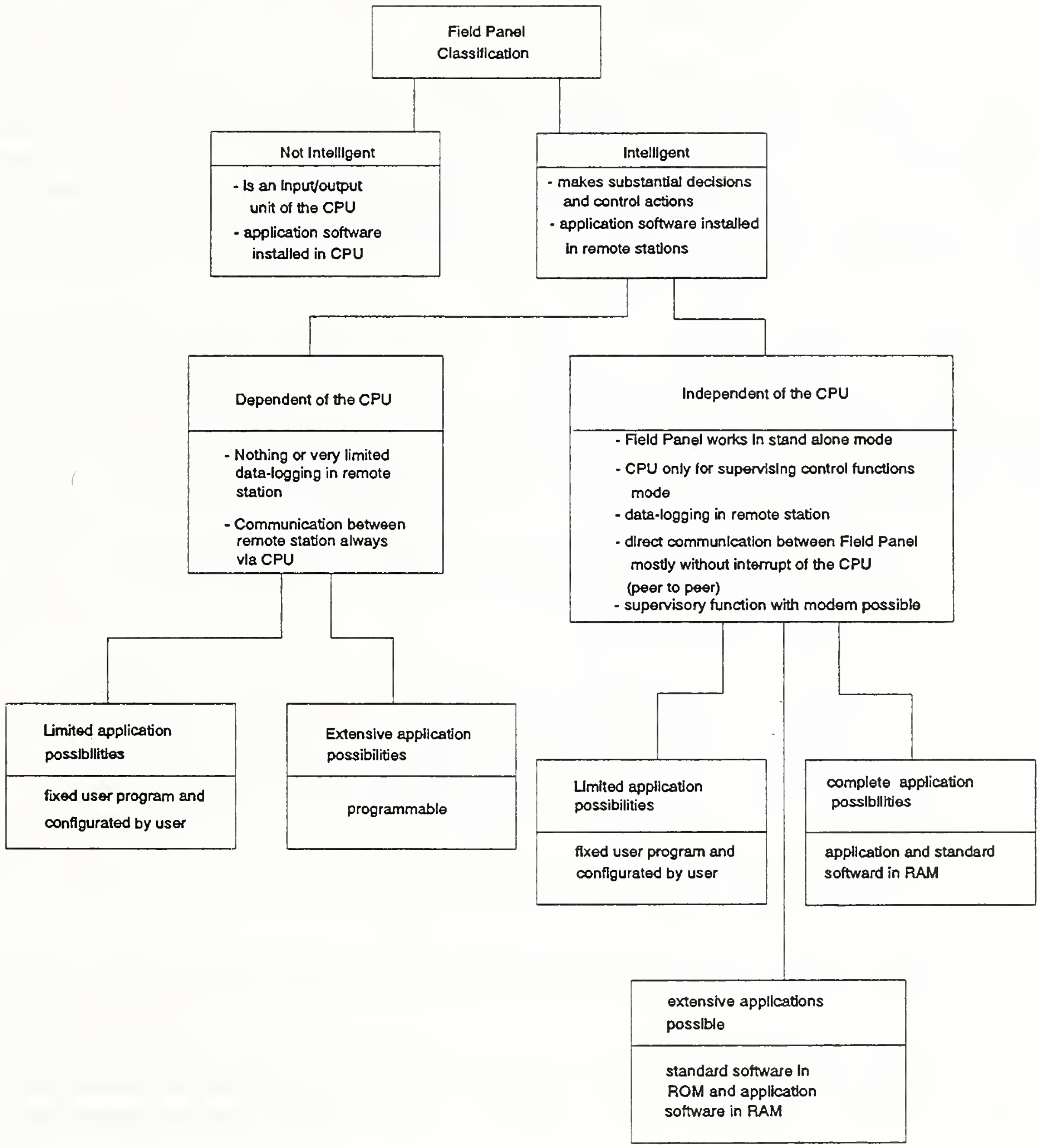

Figure 2. Classification of Field Panels (Remote Stations)

reports, historical data display, add or deletion of points, editing control parameters and time schedules, file transfer, and password management.

Command Software enables the BEMS operator to communicate with the system using words and acronyms. Commands may be entered directly, in an abbreviated form, or selected from a menu of command options, with the BEMS prompting the operator for input as required. Command software functions usually include an explanation of each command, an Index of all available commands, commands to define and modify physical parameters and constraints assigned to any point, commands to request reports, commands to request graphic displays of monitored and controlled equipment and systems, identification and description of alarms, and the ability to control operator access to specific command software based on levels of operator privilege.

Direct digital control (DDC) software is used to process information from analog and digital sensors for the purpose of determining the correct control action. The word "direct" implies that the outputs from the computer, which may be either analog or digital signals, has immediate control over the final control elements or actuators. This is in contrast to a "conventional" control system in which a computer acts only through pneumatic on analog controllers which actuate the final control devices. The DDC software performs all the automatic control necessary to control local HVAC processes, including:

a. Open loop control in which a DDC controller senses a variable, makes a control decision, and sends the output signal to an actuator without receiving any feedback.

b. On-off control, where the final control element has only two states, fully on and fully off.

c. Closed loop control where the DDC controller changes its output signal based upon up-dated feedback information from the process being controlled. Typical HVAC closed loop controls include proportional (P) control, proportional plus integral (PI) control, proportional plus integral plus derivative (PID) control, and adaptive control.

d. Cascade or multilevel control. In cascade control the first level directly controls the measured process variables, while the second level monitors the process and adjusts one or more set points used by the first control level.

The above system, command, and DDC based field panel software features are described in Appendix B.

Supervisory application software is usually stored in and executed by either the field panels or unitary controllers, with the exception of the duty cycling and load shedding programs which are usually executed by the host computer system because of their global nature. Typical application programs include:

* Duty Cycling
* Electric Equipment Restart
* Optimum Start/Stop
* Unoccupied Temperature Setback
* Dry-bulb Economizer Control
* Discriminator Control
* Building Pressure Control for VAV
* Coil Freeze Protection
* Demand Limiting (Load Shedding)
* Scheduled Start/Stop
* Outdoor Air Damper Control
* Summer/Winter Change-over
* Enthalpy Economizer Control
* Supply Fan Control for VAV
* VAV Terminal Unit Control
* Chiller Plant Control

* Heating Plant Control
* Steam/Hot Water Convertor Control
* Lighting Control
* Space Heating Water Circuit Control
* Finned Tube Radiator Control

Descriptions of the above application programs are included in Appendix C.

3. SETUP OF THE BEMS AND THE EMULATOR

This section contains a general description of the procedures to be followed in setting up both the BEMS and the Emulator. Obviously, details will vary with different Emulator designs and the type of BEMS functions that are selected for evaluation.

3.1. BEMS Preparation

The BEMS to be tested should be prepared before the actual connection of the Emulator. In most cases, the preparation should be performed by an BEMS evaluation team since detail knowledge of the features and the capabilities of a particular BEMS is best gained by actually setting up the BEMS database, setting parameters, selecting algorithms, saving and displaying data, developing software for particular applications, etc. Alternatively, the evaluation team may decide that for their particular needs it is better to let the BEMS supplier prepare the BEMS. This would provide an assessment of both the BEMS and the ability of a particular supplier to choose and implement good control strategies.

3.1.1. Specification of points for connection between the BEMS and the Emulator

The BEMS personnel should provide an BEMS field panel or panels with the required number of analog inputs, digital inputs, digital/command outputs, and analog outputs. The points in this panel should then be entered into the BEMS data base. The actual data points used should depend on the BEMS software that is to be evaluated and on the type of building system model to be emulated in the Emulator.

3.1.2. Specification of BEMS algorithm parameters

All parameters for operation of the BEMS algorithms to be tested shall be entered by the building personnel. Any special parameters not specified in this procedure shall be in accordance with the recommendations of the BEMS manufacturer. The exact parameters entered may in some cases depend on the exact building configuration chosen to test. The person specifying the parameters to enter into the BEMS must have previously determined which of the possible building/climate configurations is the best for the installation where the tests are to be conducted, and must be familiar with the test conditions required for the particular configuration.

3.2. Emulator Preparation

If the performance of an already installed BEMS is to be evaluated, the Emulator should, if possible, be located in or adjacent to the BEMS control room with all facilities for connection to an BEMS field panel located in the area. The BEMS field panel should have been previously connected to the BEMS and configured for the points to be attached to the Emulator. All BEMS algorithm parameters should have been entered except for ones which require the Emulator to be connected for determination. The Emulator preparation should begin with the physical connection of the sensor lines between the Emulator and the BEMS field panel.

3.2.1. Physical Connection

The Emulator must be physically connected to the BEMS by the attachment of signal cables between the BEMS field panel and the Emulator interface box. Care should be taken to assure that the polarity and range of the signals being connected are correct. The connections must be made so that the points configured in the BEMS are connected to the correct Emulator points. The terminal points of the BEMS shall be connected to the corresponding points on the Emulator interface device.

3.2.2. Verification of Points

The correct connection of the BEMS points to the Emulator points must be verified. For digital points, the points in the Emulator or BEMS should be switched on and off and an observation should be made to confirm that the corresponding point in the BEMS or Emulator has changed state. For analog points the verification should be termed calibration since the BEMS and Emulator must agree on the interpretation of analog values.

3.2.3. Calibration

The Emulator should contain software for the calibration of analog points. A typical procedure might involve holding the analog outputs at several values while readings are taken from the BEMS. These values could then be entered into the Emulator, which would calculate the appropriate conversions to use to convert internal values to analog values that can be read by the BEMS.

After connection and verification of the points are complete, the algorithm points should be verified by operation of the algorithm in a limited way. For start/stop, the start and stop times can be set for a few minutes past the current time.

3.2.4. Tuning Local Control Loops

After the sensor and control points are connected, it will be necessary to select the proper control parameters for the various HVAC control loops modeled on the Emulator. This may be done either by the BEMS manufacturer/installer or by the BEMS evaluation team. If the latter does it, valuable information can be obtained on the ease of programming the DDC software provided with the BEMS system. The evaluation of DDC control loop performance is discussed in section 7.

3.3. Test Condition Selection

The test conditions are those parameters that describe the simulated building and the environmental conditions it is exposed to, in order to emulate a real building system connected to the BEMS system. The test conditions should be locally set-up within the Emulator. In general, there are three types of test conditions that must be specified for the Emulator:

1. Weather: the most important variable is the outdoor dry-bulb temperature. Other variables are humidity ratio, wind speed, and solar gain.

2. Building system type: These are variables which affect the response of the building to the forces of weather and internal gains. Important variables are thermal mass, transmission/infiltration resistance, HVAC system type, HVAC system capacity, and air flow rates.

3. Building Use: These variables reflect how a building is used. Two buildings may be of the same type but have different uses. Variables are the number of occupants, internal gains (lights and machinery), and use schedules.

If the BEMS is to be installed in a particular building, the conditions specified would ideally describe the particular building in which the BEMS is installed. Unfortunately, this would involve a complicated process of determining exact values for the building descriptive parameters and input of weather data for the exact location. Also if the BEMS is to be installed in many different buildings located in different climates, using one fixed building at one location in the Emulator would be simple, but the results of the testing would not be very meaningful. One solution to both of these problems is to use some small number of possible combinations of conditions. All of the condition parameters should be previously selected, and stored within the Emulator. The Emulator operator (or evaluation team) should then be able to estimate which of the combinations of conditions most closely matched the particular site or range of sites where the BEMS will be installed.

The following sections specify a possible set of test conditions for an BEMS. Choices for weather, building type, and building use are considered.

3.3.1. Weather

Weather is the most difficult of the test conditions to select. The weather experienced by a building will vary with location and time of year, and should in general not be predictable except on a long term statistical basis.

There are two parts to the selection of weather conditions. The first part is associated with the location of the building and describes the general range of weather conditions or the climate that a building will be subjected to within a year. If the BEMS is to be installed (or is already installed) in a specific building at a given location, then the choice of climate to use in the performance evaluation is already determined. However, if the BEMS is to be installed in buildings in a variety of different geographical locations with vastly different climates, then performance tests may have to be conducted over the range of possible climates. In a large country, this range of climates could include regions with:

- a cold humid winter, hot humid summer, moderate sun,

- a cold humid winter, hot dry summer, strong sun,

- a mild winter, warm dry summer, strong sun,

- a moderate humid winter, hot humid summer, moderate sun,

- a mild winter, hot humid summer, weak sun,

- a warm winter, warm humid summer, moderate sun.

Of course, if the building is only heated or only cooled, the number of weather conditions that needs to be investigated could be reduced. For example, humidity would not be a significant variable if only heating was being performed.

The second part of weather condition selection is the characterization of annual performance of an BEMS algorithm without having to test the algorithm for a year. For the most complicated algorithms it should be sufficient to test the algorithm for one or more days in each season of the year. What is needed is a weather description for high load periods, moderate load periods, and low load periods. Such periods might correspond to the peak of summer and winter (July and January), early summer and early winter periods (May and October) and spring (April).

The variables to be included in a weather condition would definitely include the dry-bulb temperature. Next in importance might be the humidity. Other variables, such as solar gain, wind speed, and barometric pressure, could be included.

Within a single day the weather variables will change with time. There must be a specification of the way in which the variables change. A reasonably good approximation can be made using an outside air temperature which varies in a sinusoidal fashion. Another approximation is to use a constant humidity ratio for any particular day, but use different humidity ratios in different seasons. If five different weather conditions were used to approximate a range of yearly conditions, this would imply at least 5 days of testing. If the building emulated were of high mass, the transition between days at different conditions might require several days to allow the building structure temperature to reach a steady oscillation. This could be avoided by reinitializing the structure temperatures as the weather made a transition into the new season. If optimum start/stop were being tested, however, several days might be needed for an adaptive type algorithm to operate properly. For other algorithms this would not be necessary. If weather conditions needed to be run for one day, and five conditions were needed, then five days of testing would be required.

3.3.2. Building System Type

The building system type will characterize its response to environmental conditions. The conditions can be divided into those describing the building shell and those conditions describing the HVAC system type. The conditions for these two types can be decouple to some extent, since different HVAC system could be installed in the same building shell.

The building shell characteristics include resistance to thermal heat transfer, resistance to infiltration, thermal capacity (mass), solar heat gain areas/shading factors/transmissivities, and building/zone volume. These must be specified in terms of quantities usable by the emulator model. Since all building shells are not alike, there must be some ability in the Emulator to vary the shell characteristics of the building used for testing the algorithms if the BEMS is to be located in a specific building.

If the BEMS being evaluated is to be installed in a variety of building types, then tests may have to be conducted in which a number of different buildings with a range of characteristics are emulated. However, it would probably be undesirable to use a very large selection of characteristics. Instead, it may be preferable to limit the number of building shell types to something like three, which might be called heavy, medium, and light structures. The selection of characteristics for these could perhaps be based on the statistical percentage of various building types in the country of interest. The exact properties for a medium building might also vary with the climate choice, since a medium building in a warm climate might have less insulation than a medium building in a very cold climate.

Alternatively, many detail tests could be done using one particular building type and a limited number of tests could be done on a range of other building types to determine if different building characteristics significantly effect the results. For example, the major portion of the tests (e.g., evaluating different application algorithms) could be performed on medium buildings (medium mass, medium insulation, medium glazing ratio) and them some partial studies performed using the six buildings defined below:

BLDG. MASS	INSULATION	GLAZING RATIO
Medium	Medium	Low
Medium	Medium	High
Medium	Low	Medium
Medium	High	Medium
Low	Medium	Medium
High	Medium	Medium

There remains the question of building size characterization. BEMS with different capabilities are likely to be installed in different size buildings. The BEMS evaluation team will have to decide if building size will effect the performance of the BEMS or the BEMS algorithms to be evaluated and select the building characteristics accordingly. In many cases, size may not be a necessary parameter if the air volume, wall area, HVAC system capacity, and local equipment capacity can be scaled accordingly.

The HVAC system type(s) must also be selected. In the case of central air systems, it is useful to subdivide the system into one or more central air handling systems and the local equipment type. Since the simulation of such systems should be relatively straight forward, there is no need to be extremely detailed in specifying the system characteristics. For example, the most important gross characteristics are likely to be: the central system may be constant volume or variable air volume; it may have a single deck or a dual deck; it will have heating and cooling coils of a certain maximum capacity; and it will have a rated air flow rate (which may vary for a VAV system). The plant for heating and cooling could include one or more boilers, chillers, and cooling towers.

The equipment in a building zone will likely be one of three major types. It will either be some sort of local heating and/or cooling device, a non-energy consuming control which either controls air volume entering the room or the mix of hot and cold air from a dual deck system, or a combination of the previous two types.

The control strategies and associated evaluation procedures discussed in this chapter deal mostly with central air systems. However, the ideas and concepts that are presented could be easily generalized to heating only, hydronic systems.

3.3.3. Building Use

The building use conditions determine the characteristics of the building occupancy. These characteristics determine the magnitude and scheduling of the building internal loads. The internal loads are of two types: fixed, such as computers, equipment, and lights that are present or operating 24 hours a day, and scheduled, such as people and lights that are not present or operating during some hours of the day. In terms of general categories, there could be two types of building uses specified. One would be a building with low internal gains and the other would be a high internal gain building. A building without scheduled internal gains could be included, but a number of BEMS algorithms depend on the existence of an unoccupied period (scheduled start/stop, optimum start/stop, unoccupied temperature setback, etc.).

3.3.4. Derived Conditions

There are some additional conditions for the BEMS and/or Emulator which depend on the specifications for climate, building system type, and model specifications. These are likely to include:

1. nominal off-time for duty cycling.

2. time required after building start-up until occupied conditions are reached, and time required after building shut-down until conditions drift out of the comfort zone.

3. setpoints for air handling unit supply air temperatures.

4. space zone setpoints for occupied and unoccupied conditions.

These conditions should be determined after the other conditions have been selected and must be derived using tables or equations.

3.3.5. Total Possible Sets of Test Conditions

The total number of possible states of a model is the product m(1) * m(2) * ... m(n), where n in the number of variables (such as climate, building shell, HVAC system type, etc.) in the model and the i-th variable has m(i) possible states. This number can become very large if a lot of different variables and states are to be evaluated. For example, if the following five variables having the following number of states are tested:

climate = 6
building shell = 3
building size = 2
HVAC system type = 3
building use = 2

then the total number of discrete conditions is 6 * 3 * 2 * 3 * 2 = 216. Obviously, this level of testing is impractical and the set of test conditions must be carefully chosen to minimize the number of variables and the number of states of the variables in order to keep the testing time within reasonable limits.

4. EVALUATING OPERATING SYSTEM, COMMAND, AND DDC SOFTWARE

The evaluation of system software, command software, and DDC software for local loop control is a straight forward process. It involves selecting one set of the test conditions described in section 3.3 to be simulated in the Emulator and exercising each of the BEMS functions which fall into these three categories. The evaluation criterion is simply whether or not the software works as expected and how difficult it is to use. No specific tests for these categories of software are described in this chapter. Instead, Appendix B contains a listing of many of the features one would expect to find in an BEMS. The person conducting the BEMS performance evaluation should easily be able to devise a test that exercises a particular software feature. For example, testing if a data point can be read or a control parameter changed and with what degree of difficulty on a particular BEMS, involves simply reading a data point and changing a control parameter.

5. OPERATIONAL TESTING AND PERFORMANCE TESTING BEMS APPLICATION ALGORITHMS

An Emulator can be a useful tool for evaluating all of the categories of BEMS software described in section 2. For example, alarms can be generated by the Emulator under different loading conditions and the response time of the BEMS measured. The response of valves and dampers in simulated HVAC systems could be used to evaluate the performance of various Direct Digital Control algorithms and their implementation on a particular BEMS. However, where an Emulator is really valuable is in evaluating the supervisory application software. This type of testing should generally fall into two categories: operational testing and performance testing. In discussing these two categories of tests, it will be assumed that the application algorithms being evaluated are supplied as "canned" software by the BEMS manufacturer. If this is not the case and the application algorithms are programmed by the installer, the BEMS purchaser, or the evaluation team, the same performance tests may still be used but the evaluation team must keep in mind the fact that the results will be a measure of both the BEMS performance and the programming skill of the installer/purchaser/evaluation team. In such an instance, the suggested rating procedure in section 8 may also be need to be modified to provide a fair comparison between different BEMS.

5.1. Operational Testing

Operational testing of BEMS application algorithms consists mainly of exercising the different logical branches that one might expect to exist in each algorithm and determining if they operate as expected. Like the evaluation of operating system, command, and DDC software (section 4), operational testing of supervisory control algorithms, in most cases, is likely to involve tests of limited duration. However, tests are likely to include a variety of test conditions linked together to exercise the logic built into the application software. Although operational tests should usually be conducted on each application algorithm individually, they may also be performed on a combination of algorithms to determine if they interact in an acceptable manner. The BEMS evaluation team should have no difficulty selecting sequences of test conditions for an Emulator that would operationally test most of the "typical" application algorithms found on today's BEMS. More advanced algorithms, that are likely to come along in the future that optimize overall building system performance, might best be evaluated using the performance testing methods discussed below in section 5.2.

5.2. Performance Testing

An Emulator is absolutely essential for evaluating application programs that involve complex control over long periods of time or where there is strong interactions between such programs. To illustrate this, several supervisory control algorithms have been selected and a scenario is developed in this section for how an Emulator might be used to evaluate their performance. The approach could easily be generalized to include any of the application programs or combination of application programs listed in section 2 and described in Appendix C. Suggestions for performance testing some of these application programs are presented in Appendix D.

5.2.1. Selecting Application Algorithms For Performance Testing

One of the most important steps in evaluating the performance of an BEMS is selecting the application algorithms of interest and then deciding which combination of these algorithms are to be tested. These must be carefully selected and will be strongly dependent on the particular building/HVAC system being emulated. For example, the evaluation team might decide that the Emulator should be used to evaluate the performance of the following six BEMS application programs involving control of a building air handling system:

1. Scheduled Start/Stop
2. Duty Cycling
3. Demand Limiting
4. Optimum Start/Stop
5. Economizer
6. Ventilation/Recirculation

To shorten the testing process and produce reasonably realistic tests for algorithms which must normally interact with each other, the testing procedures should test some algorithms concurrently. It will be assumed that the Scheduled and Optimum Start/Stop algorithm should turn an air handling unit on during occupied periods and off during unoccupied periods. During occupied periods only, the duty cycling algorithm should turn an air handler off and on. Also during occupied periods, the demand limiting algorithm should cut off the air handler for short periods of time. If these strategies are not coordinated or prioritized, their control of the same load can cause problems. These problems, if they exist for a specific system under test, are likely to appear during the concurrent tests. The economizer and ventilation/recirculation algorithms both control the outside air damper operation and could be logically grouped together for concurrent testing. Thus the tests to be conducted might be reduced to the following combination of algorithms:

1. Scheduled start/stop, duty cycling, and demand limiting
2. Optimum start/stop, duty cycling, and demand limiting
3. Economizer and ventilation/recirculation

It is likely that the demand limiting algorithm will have to be tested in a partial manner, since the true electrical demand of the building may not be known. In this case, a "simulated demand meter" might be connect to the BEMS for the purpose of simulating a demand level sufficient to cause the demand limiting algorithm to shut down the air handling unit.

If the Emulator includes the capability of performing concurrent testing, an important consideration is how many independent concurrent tests to run at the same time. If the Emulator had sufficient computational power, more than one building could be emulated at the same time. The BEMS could then be configured to run the strategies on different physical buildings. The disadvantage of this approach is that more physical points must be connected to the Emulator. The advantage is that the BEMS is loaded more completely, and more tests can be completed in less time. The number of concurrent tests possible will depend on the number of points available to the Emulator and on the model used to emulate the building. More than one test will require multiple copies of the model programs, and will require more memory and more computer execution time. The number of concurrent tests will depend on the power of the computer which the Emulator is based upon.

5.2.2 Summary of Test Characteristics and Test Period

It is important to understand how different variables effect different application algorithms (or combination of application algorithms), since this will determine the type and nature of the tests which need to be performed.
For example, if a particular algorithm is unaffected by weather, it would be a waste of time and effort to evaluate its performance in different climates. For the example given in section 5.2.1, the following table might be developed:

	Sch S/S	Opt S/S	D. Cyc.	D. Lim.	Econ.	Vent.
control actions	stop start	stop start	stop start	stop start	lock unlock	vent stop close
seasons used	all	all	all	all	spring summer	all summer
actions affected by weather?	no	yes	yes	no	yes	yes
savings affected by weather?	yes	yes	yes	no	yes	yes
savings affected by length of testing at same conditions?	no	yes	no	no	no	yes

The test period must also be determined for each algorithm or combination of algorithms being evaluated. As indicated previously, some algorithms (such as scheduled start/stop) may be evaluated over a relatively short test period (e.g., a few hours) while others (such as optimal start/stop) will require a much longer test period (several days to a week). A typical test period is likely to be one or two days. In addition, the evaluation team will have to decide if, for the algorithm(s) being evaluated, it is necessary to test during both occupied and unoccupied periods of the day. Often it is only necessary to test algorithms during the occupied period plus one or two hours on each side of occupied period (i.e., a 10 or 12 hour day) to give results suitable for comparison.

Regardless of the length of the test period, however, careful attention must be given to the initial conditions of the building (e.g., temperature of the building mass) at the start of each test period.

5.2.3. Performance Test Procedure

The algorithm test procedures should basically consist of letting the Emulator run and the BEMS operate with the algorithms active for a period of time. The Emulator should compile information for producing performance ratings. The test procedures must basically provide a range of situations to allow the algorithm under test to produce control actions in response to the conditions likely to be found in the building where the algorithm is to be used.

5.2.3.1. Verification of Correct BEMS Operation

Before test initiation, the BEMS should be checked to insure that it is operating properly. If it is not operating, the condition must be corrected before the test is started.

5.2.3.2. Selection of Specific Time to Start Test

After the BEMS and the Emulator are properly prepared, the system is ready for testing. When all preparations are complete, a test starting time can be selected. The test should be started at the time when the Emulator operator can be available to re-start the Emulator, if necessary, after a failure of a test. If no test failures occur, subsequent test periods should automatically start at the same time on the appropriate day. For BEMS already installed in a real building, a good starting time is 10:00.

5.2.3.3. Time Synchronization

Since the some of the BEMS application programs selected depend upon the time of day, time synchronization must be made between the BEMS and the Emulator. This can be done by reading the current clock value from the BEMS and entering the value into the Emulator, reading the internal clock in the Emulator and entering the time in the BEMS, or some other time synchronization method can be applied.

5.2.3.4. Test Initiation

The BEMS software should be used to start the test by command. The BEMS should control the tests. The Emulator should remain a passive state in terms of controls. The test start command should start the first set of tests, which are grouped together. For the example given in section 5.2.1, these would be scheduled start/stop, duty cycling, and demand limiting.

5.2.3.5. Duration of Tests

Normal running of the test procedure should require no operator intervention until the end of each test segment.

If each test segment in the example in section 5.2.1 requires a two day test period for each climate condition, then the tests would be run for five two-day periods or a total of 10 days if five different climate conditions were studied.

5.2.3.6. Test Failure

There are two possible types of failure which could occur during the time period of a test. In one case, the observation of the Emulator indicates a failure by messages on the CRT screen of the Emulator. In the other case, no messages appear on the Emulator screen because the BEMS system has failed and is no longer performing control actions. This latter failure must be detected by observation of the BEMS system.

5.2.3.7. Test Failure Indication Observed on the Emulator

Two types of indications of failure should be visible on the Emulator CRT screen. One is due to a hardware or software failure within the Emulator. The failure should be indicated by a hardware or software error message, or in certain cases by the observation that the information normally periodically updated on the screen has failed to appear. This type of problem could be caused by an inherent flaw in the hardware or software or by an external event such as an electric power failure or voltage dip.

The other possible failure state is due to the gross failure of an BEMS algorithm under test. In this case, the Emulator software should indicate through messages that the BEMS algorithm is performing in an unexpected manner.

In both cases of failure, the Emulator software must be stopped. If the failure is in the BEMS algorithm, the problem must be corrected before proceeding. If the failure is in the Emulator, the problem may require attention to the Emulator hardware, or in the simplest case, the Emulator may be restarted or reset to correct the problem. If the total test is divided into test segments, the test can be restarted with the segment that was under way at the time of the failure. Test results for the previous segments should have been stored in disc files on the Emulator. The BEMS software can be used to restart the test.

5.2.3.8. Test Failure Indication Observed on BEMS

If the BEMS partially or completely fails, then the algorithms under test may no longer be running properly. Observation of the Emulator may give no indication of the failure. The BEMS operator console or an auxiliary console must be monitored during the test to determine if the system is still operating properly. This may involve periodically entering commands into the BEMS. In case of failure, the Emulator software must be stopped. The problem must be corrected before proceeding. The BEMS problem may require attention to the hardware, or in the simplest case, the BEMS may be restarted or reset to correct the problem. As discussed in the previous section, dividing the total test time into test segments will allow the testing to be resumed with the segment that was under way at the time of the failure.

5.2.3.9. Ending Tests

After the time duration of a subtest (a test segment) has elapsed, the Emulator should automatically store the intermediate results. If a forced stop is required before the completion of the subtest, the Emulator software should have a provision to stop the test.

5.2.3.10. Sequence of Tests - Different Climate Conditions

If there are five subtests to be run with different climate conditions, the Emulator operator may select two options for running the five subtests. The options are to either have the Emulator software start the subsequent subtests automatically or to require a manual start of the other subtests. The other climate condition subtests must be started at the same time of day as the original subtest.

After all subtests are successfully completed, the BEMS algorithms being tested by the Emulator should be stopped or disabled. The Emulator should then be used to determine the test ratings. After ratings have be correctly obtained, the Emulator may be turned off and disconnected from the BEMS. If no further tests are planned, the BEMS field panel may be removed and the points in this panel deleted from the BEMS point data base.

5.2.3.11. Generation of Test Results

When all climate subtests have been completed, the test ratings must be obtained to determine the performance of the algorithms tested. After each subtest, the energy consumed by the cooling and heating systems, as predicted by the building simulation in the Emulator, should be stored on the Emulator's disc storage. Also stored should be information on occupant comfort levels and maintenance requirements. In addition, reports of all of the command events generated by the BEMS and the times that they occurred should be stored on the disc. This information should be used to determine the algorithm rating.

5.2.4. Criteria For Evaluation

The main purpose for installing BEMS algorithms for control of a building is to reduce energy consumption below that of a building without BEMS algorithms. Therefore energy savings should be the primary criteria by which an algorithm is judged. However, use of an algorithm may result in a net energy savings and yet produce occupant discomfort, incorrect or inconvenient activation or deactivation of equipment, or increased maintenance costs. The four main criteria by which the BEMS algorithms may be judged are then:

1. Energy savings
2. Occupant comfort
3. Maintenance requirements
4. BEMS algorithm errors

An additional criteria for evaluation of one particular algorithm, demand limiting, is the reduction of electrical demand. This algorithm must be evaluated in terms of monetary savings rather than energy savings. Due to the difficulty of simulating electrical demand and demand billing structures, as defined by the local electric utility, only partial testing of the demand limiting algorithm may be possible.

5.2.4.1. Energy Savings

The energy saved by an algorithm can be estimated by determining the energy used by a building for two cases: with and without the BEMS algorithm in use. The savings is based on the difference in energy use between the two cases. Unfortunately, an algorithm will not yield the same savings for all buildings in all locations. Energy savings will depend on the weather to which the building is exposed, the characteristics of the building, the use to which the building is put (the internal loads), and the type of heating, ventilation, and air conditioning (HVAC) system used to condition the building space.

In order to evaluate energy savings of algorithms, the Emulator software must contain a model of a building and its HVAC system, and sequences of weather conditions and occupancy schedules to which the model is subjected. The energy used by the building can be determined from the model output and can be categorized as follows:

1. energy used by the fans in the air handling unit (the power used by the fans should be constant unless a variable air volume system is used, in which case fan power will vary as a function of air flow).

2. energy used to heat or cool the air passing through the air handling unit (this would not include cooling by outside air).

3. energy used by local space heating or cooling equipment (reheat coils, heat pumps, fan coils, perimeter radiation, air conditioners).

4. total energy used by the building system.

The energy amounts reported may or may not be in terms of fuel consumption based upon assumed or measured plant efficiencies. In the later case the energies reported may represent the energy added to the air and extracted from steam/hot water for heating or the energy extracted from the air by chilled water or refrigerant for cooling.

The percentage energy savings attributable to a particular algorithm or combination of algorithms can be calculated from:

$$S = \left(\frac{E_0 - E}{E_0} \right) (100)$$

where

S percentage energy savings (%)
E energy consumption with algorithm(s) (KJ)
E_0 energy consumption without algorithm(s) (KJ)

The energy used by the building without the algorithm(s) could be previously determined and stored in the Emulator, or, the test could include a period of testing with the algorithm deactivated. This would involve more time but might produce better results. Public domain algorithms could also be tested for a specific set of building types, use, and climate and energy savings published as a set of tables or graphs for use in specifying minimum standards for algorithms.

5.2.4.2. Occupant Comfort

The specification of occupant comfort has not been well defined in the HVAC industry, yet is important in testing BEMS algorithms. Two possible comfort criteria could be used. One is a statistical type of measure that predicts the percentage of people occupying a space who should be uncomfortable under given conditions. The predicted percentage of dissatisfied (PPD) is widely used for this type of measurement. Another possibility is the use of a comfort zone approach. The comfort zone method would allow two states of comfort. Inside a range of dry-bulb temperatures and humidity ratios, the comfort would be acceptable. Outside this range, the comfort would be unacceptable. Other criteria for the comfort zone method would be a range of mean radiant temperatures and a maximum rate of change of temperature or humidity. Eventually, it may be desirable to include air quality or fresh air flow rates.

Due to the simplicity of the comfort zone approach, the comfort zone criteria may be the most suitable approach when control of different building systems are tested with an Emulator. During a test of an algorithm, the predicted values of the temperature and humidity from the emulation could be monitored by the Emulator. If these values exceeded limits for the comfort levels specified by ASHRAE standard

55-81 or its equivalent, the number of times and the average and maximum amount of time outside of the limits as well as the degree of excursion could be stored and reported at the conclusion of the test.

When different control algorithms are tested, the PPD can be a good index to use for the thermal comfort measurement.

5.2.4.3. Maintenance Requirements Due to Wear

While it is not possible to measure the cost of maintenance as a result of "wear and tear" directly, the hourly average number of starts, stops, and reversals of every actuator and the distance travelled by all the actuators can be used as an indicator of probable future maintenance needs.

5.2.4.4. BEMS Algorithm Errors

This type of criteria is basically a functional test of an algorithm or a set of algorithms. The Emulator or its operator must look for the wrong load being turned on or off, loads being turned on and off with too small an interval between the actions, or control actions taken at inappropriate times. The errors and their times can be logged and reported at the end of the test, or as they happen. If there is an error, it is possible that the best action is to abort the test since the results may not have meaning after the error occurs.

5.2.5. Test Results

When all the subtests have been completed, test ratings need to be obtained to determine the performance of the algorithms tested. After each subtest, the energy use in the various energy categories, as predicted by the building simulation model in the Emulator, must be stored. Also stored should be information on comfort and maintenance, as discussed in sections 5.2.4.2 and 5.2.4.3. In addition, reports of all of the command events generated by the BEMS and the times that they occurred should be saved to a file. This information should be used to determine the algorithm rating.

5.2.5.1. Energy Results

For the example in 5.2.1, at least four energy totals for the five seasonal periods could be made available from the Emulator in a tabular form. A typical summary of results might resemble the following table.

	mid winter		1. winter		spring		e. summer		mid summer	
electrical energy										
	HEAT	COOL	HEAT	COOL	HEAT	COOL	HEAT	COOL	HEAT	COOL
cooling coil load										
reheat energy										
total thermal energy										

Total energy data should also be available. These results are not directly useful for comparison purposes with specifications and other algorithms since the absolute energy use is not in the form of energy per year but is energy per subtest. Thus, the energy values must be used to generate energy savings ratings for the algorithms. A group of data similar to that shown in the above table would also have to be available for the same building, climate, and test period without the operation of any BEMS algorithms. This is known as the baseline data. The baseline can come from three possible sources. First, a book containing the baseline data for all possible combinations of the test conditions can be used to calculate the energy savings. The disadvantage of this is that if the number of possible configurations is large, the book will be quite large. A disc file containing the information in the book could also be present on the Emulator and used for calculating the savings. The book baseline data would have to be generated in computer runs of the Emulator internal model at some previous time and would assume that the algorithm test had started at a particular time of day. If the actual test started several hours later than the time used for the reference baseline data, this could introduce errors in the savings data.

A second option for the baseline data is to calculate the baseline energy use concurrently with the running of the tests, using additional Emulator models, but not connected to the BEMS system, and not influenced by any algorithms. This would require roughly twice the computations required for the basic testing and might be impossible due to the speed constraints of the Emulator.

A third, and most likely, option is to store the exact starting and ending times of the tests and run the baseline simulation after the algorithm tests are complete. After the baseline simulation is completed, the baseline data may then be used to determine the savings data.

Whichever option is selected, a table such as the one above, but containing energy savings, represents the test results. Savings can be negative, indicating that more energy was used with the algorithm than without it. The exact use of the results depends on the exact purpose of the algorithm test. If the test is used to check algorithms against a contract specification, the specification should spell out the exact minimum savings desired, and how the numbers in the savings chart are to be combined. For example, a specification might read that an algorithm must save an average of at least 15% of the total energy over all five seasonal tests.

5.2.5.2. Comfort Results

In addition to the energy savings results, the test results must also include comfort results. During the tests, the current space conditions should be compared to a pre-specified comfort envelope. Any excursions beyond the envelope should be recorded with the time of day, maximum excursion, and length of excursion. These results should be available for reporting at the end of the test. Another option would be to calculate the comfort during excursions in terms of an accepted comfort parameter such as predicted percentage of dissatisfaction (PPD).

5.2.5.3. Maintenance Indicators

Information on the average number of starts, stops, and reversals per hour for each actuator should be reported. This will hopefully provide a rough indicator of future maintenance requirements due to wear for different BEMS.

5.2.5.4. Event Logs

The fourth test result required is a report on the events that the BEMS commanded and the times that the commands were given. This information could then be compared to the parameters entered for the BEMS.

An BEMS algorithm specifications should have standards for incorrect or badly timed BEMS command actions. If actions are incorrect or badly timed, they should fail the specification.

6. EVALUATING BEMS PROGRAMMING CAPABILITIES

Once an BEMS operator has learned how to operate both the BEMS system and the building, he will need to be able to write and check out his own control algorithms. There are many reasons for this, including the fact that the canned software provided with many BEMS systems is often very limited, building systems (for both good and bad reasons) are rarely operated as the designer intended, equipment and systems are removed, replaced, or upgraded over time, and the use/occupancy of a building is often continuously changing. How difficult this is to do will depend on the capabilities and ease of use of both the BEMS and the programming language provided by the BEMS manufacturer.

To evaluate the BEMS programming capabilities, the BEMS evaluation team should develop his/her own application and local loop control program(s) and use them to control a hypothetical HVAC system running on the Emulator. The control program developed could be an original one for a unique building application or it could be a "home spun" version of one of the application programs listed in section 2. Invariably, problems will be found and the experience should be an "eye opening" one. There is, however, no better way of determining whether the process of programming a particular BEMS is going to be a nightmare or a reasonably pleasant experience than by actually developing software on the BEMS being evaluated. An Emulator should allow programming bugs to be quickly detected and fixed and enable the user developed program to be run without endangering any expensive equipment or interfering with normal building operations.

Criteria for evaluating the programming capabilities of an BEMS include:

* the ease of use of the programming language,
* the amount of the "canned" software provided with the BEMS and the difficulty of employing it in user developed programs,
* the quality of local loop control achieved,
* the convenience of using hierarchal control loops,
* the capabilities of the editor, compiler, linker, and debugger routines provided with the BEMS,
* the ability to create user developed graphics and to display data on the graphics in real time, and
* the ease of starting, stopping, editing, and changing parameters in user developed programs.

7. DDC CONTROL LOOP PERFORMANCE

Most BEMS systems come with "canned" software for performing proportional (P), proportional plus integral (PI), and proportional plus integral plus derivative (PID) control. Some should employ algorithms that will tune themselves upon command. A few may contain "adaptive" algorithms that continuously monitor and adjust to changes in load, actuator characteristics, etc. Most, however, will require the BEMS operator to go through a tuning process to select the appropriate gains for a particular control loop.

For those algorithms that tune themselves or are adaptive in nature, the Emulator should be used to evaluate their performance for a variety of control loops typically found in building applications. For example, different types of coils, dampers, and actuators could be emulated. Different values of process gain, dead time, hysterisis, stiction, and sensor mass could also be emulated, along with different degrees of non-linearity. The time it takes to tune each loop and the quality of control achieved should be monitored to determine how well the algorithms perform.

For algorithms requiring manual tuning, the operator should actually perform the tuning process using the trial-and-error method, closed loop tuning method, or one of the other methods described in Stoecker (1989). The Emulator should be used to emulate a variety of control loops having the different characteristics described above.

The criteria for evaluating the performance of different BEMS at local loop control include:

* control resolution obtained with different ranges of sensor input,
* control stability,
* control accuracy and repeatability,
* ease-of-use,
* flexibility of cascading control loops,
* hourly number of the starts/stops/reversals of the actuator

8. SUGGESTED BEMS RATING METHODOLOGY

Because each BEMS application is different and different evaluators will have different opinions of what is important and what is not, it is not possible to give any "hard and fast" rating scheme for comparing the performance of different BEMS. The following is offered for consideration by the evaluation team as one possible approach or as a starting point for a more extensive rating methodology. It should be edited and modified as required. Note that this suggested rating methodology assumes that the application algorithms are supplied as canned packages by the BEMS manufacturer. If this is not the case, the rating scheme should be altered to reflect the fact that the test results are an indication of both the performance of the BEMS <u>and</u> the skill of the person(s) (e.g., the installer, BEMS operator, or evaluation team) programming the application algorithms.

Rating Factor	Weight (Sum of Individual Weights should = 100)	Score (Between 1 - 10)	Rating (Weight X Score)
1. Does the BEMS contain the appropriate Hardware discussed in 5.1 and Appendix A.	______	______	______
2. Do the system, command, and DDC field panel software discussed in 5.4 perform as expected?	______	______	______

Is it easy to use?

Are commands easy to remember? Are menus and help provided?

Is data shared between field panels?

Are report and display features adequate?

Is editing of parameters, schedules, graphics, etc. easy to do?

Alarm levels and alarm reporting procedures are adequate?

Trend reports and graphic displays work well?

Energy totals, operating time, etc. are calculated?

Diagnostics are included?

Outstanding features include:

____

____

Inadequate features are:

____

____

____

3. All the application algorithms operate correctly.

Operational tests were performed on the following algorithms and their control logic was found to be correct:	______	______	______

____

____

____

Problems were found with the operation of the following algorithms:

4. Performance testing of application algorithms indicate optimal energy savings and occupant comfort, with no major errors detected.

   Performance tests were performed on the following application algorithms and/or combination of application algorithms:

Algorithm/Combination	Duration of Test

   Were energy and comfort results compiled and compared for all of the above algorithms or combination of algorithms?

   Were interaction problems detected between or among different application algorithms? If so, list them:

   The following errors were detected during the above performance tests:

5. The BEMS performance capabilities were evaluated and found to be excellent. Evaluation factors considered included:

   ease-of-use

   quantity/quality of software "tools"

quality of control

hierarchal control loops

adequate editor, compiler, linker, and debugger

user can easily develop graphic displays and show data in real time

ease of starting, stopping, and editing user developed programs and making changes in assigned parameters

6. DDC software works as expected. ______ ______ ______

The following control loops were emulated and controlled using DDC software provided with the BEMS:

____

____

____

____

Evaluation factors included:

control resolution

control stability

accuracy and repeatability

ease of use

cascade control capabilities

number of start/stop/reversal of the actuator

Total Score: (Max. value equals 1000) ______

NOTE: In addition, **ALL** critical performance factors must meet minimum performance criteria, regardless of the Total Score achieved above. These critical factors mostly involve safety features of the BEMS (i.e., BEMS errors which might endanger personnel or damage equipment).

REFERENCE

May, W.B., and Park, C., "Building Emulation Computer Program for Testing of Energy Management and Control System Algorithm," NBSIR 85-3291, NBS, 1985.

Stoecker, W. F., and Stoecker, P.A., 1989, Microcomputer Control of Thermal and Mechanical Systems, Van Nostrand Reinhold, New York

APPENDIX A SUGGESTED HARDWARE CONSIDERATIONS

The following hardware items are offered for consideration by the BEMS evaluation team. They are given with the intention of stimulating thought and/or discussion on the particular needs of a given installation. They should not be misinterpreted as recommendations or minimum requirements. Each installation is unique and has unique hardware requirements. In addition, building controls is a rapidly changing field and what is considered state-of-the-art hardware one year is looked on as being obsolete the next.

A.1 General:

1. Is the BEMS a microprocessor based system where the process variables are continuously monitored by digital computers which perform control solution calculations and loop control to accomplish the intended control functions?

2. Is the system fully modular to allow future expansion of application software, computer memory, field panel, and other components?

3. Is the BEMS a true distributed control system? Does the system have stand-alone microprocessor based field panels, a communications network? If fire safety and security systems are provided for, are separate host computers employed?

4. Are the field panels connected through a communication network to share common data and report to host computers? Are the host computers capable of being programmed to supervise the field panels? Is the system capable of down-loading and up-loading of programs between host computer and field panels?

5. Does the system allow all host computers to share information and to communicate among the host computers? Are operators with proper access level able to access any point of the BEMS from any host computer? In the event any host computer system fails, does system control continue to be performed?

6. Is the compatibility to connect the BEMS to building telecommunication system provided for? Is there any interference between the two systems?

7. Are the field panels capable of receiving signals from industry standard sensors, transmitters, and other input devices?

8. Does the BEMS perform closed loop automatic control using proportional, proportional plus integral, or proportional plus integral and derivative as applications require.

9. Is the BEMS capable of monitoring HVAC operation, building energy consumption, and equipment maintenance? What about fire safety and security?

A.2 **Host Computers:**

1. Are general purpose personal computers and associated equipment employed? Does the computer system provide monitoring, control, and system management over the entire BEMS system in spite of stand-alone control loops?

2. As a minimum, does each host computer system have a color video display, a printer, necessary communication equipment, software, and other supporting equipment?

3. Do host computer systems operate properly in an environment of 15.6 to 32.2 C (60 to 90 F) and 10% to 80% RH?

4. Does the host computer system have sufficient computational power and RAM memory? Is disk space sufficient for current and future needs? Is there a clock/calendar with a backup battery and charger, a suitable floppy disk drive, and a keyboard with standard typewriter keys and special function keys? Is the resolution of the video display adequate for the graphic display needs of the installation?

5. Are the host computer systems able to perform:

   Automatic initialization of system?

   Real-time data transfer and manipulation?

   Real-time graphic display?

   Password security protection?

   Interactive operation of data and graphic editing?

   Full English data addressing and presentation?

   Operating and maintenance data storage?

   Data trend display and manipulation?

   Menu format with on-line help message?

6. Are operators with the appropriate access level able to perform the following from the host computer:

   Enable/disable control loops to a system?

   Enable/disable points to a system?

Assign sensors and/or actuators to a control strategy?

Add, delete, or change setpoint values and point alarm

values?

7. Are the video displays compatible with the host computers? Do they have at least 80-character width columns, 16 colors, and minimum 640-pixel X 350-line resolution? Are the display screens 19" or wider and have non-glare surfaces? Do the video displays have adjustable bright and contrast controls?

8. Are the printers tabletop units with sprocket pin-feed tractors that use standard fanfold 9.5" X 11" paper? Do they have a 96 standard ASCII character set and print 80 characters per line under standard mode at a speed of at least 150 characters per second? Are they able to print an original and up to two copies at one time? Do they have paper runout warning and self-test provisions?

A.3 Field Panels:

1. Do field panels include microprocessor based controllers, power supply, input/output modules, communication devices, and other necessary components to function as a stand alone unit to perform required processing, memory, communication and field input/output functions?

2. Do field panels operate properly in an environment of 0 to 48.9 C (32 to 120 F) and 10% to 90% RH?

3. Do field panels operate properly from +10% to -15% of nominal voltage rating?

4. Do fire safety and security systems have separate field panels from HVAC systems?

5. Are set points, analog output values, and binary output differentials adjustable? Do all controllers have test connections for measuring input and output signals?

6. Does a field panel contain more than one controller for multiple control loops?

7. Does each field panel have battery backup with an automatic battery charger? Are batteries able to support all random access memories (RAM) and the clock/calendar for a minimum of 72 hours?

8. Is each field panel capable of automatic, unattended restart in the event of electrical power failure? In the event of electrical power failure, do all controlled devices move to their fail-safe positions? Upon the restoration of

electrical power, does the field panel automatically restart and provide control to its controlled devices?

9. Does each panel have at least 25% spare capacity for future expansion?

10. Are field panels of modular construction having interchangeable components, circuit cards, and power supplies to facilitate quick repair and easy expansion of monitoring/control points and additional control loops?

11. Are field panels able to communicate with other field panels and host computers through communication wires or non-dedicated telephone wires?

12. Does the program firmware and the microprocessor operating system reside in non-volatile memory?

14. Do field panels have built-in keypads or plug-in portable units for altering programs, control parameter values, and diagnosing control functions?

15. Do field panels or plug-in units have an alphanumeric display to assist operators in entering data, adjusting parameters, viewing alarm indications, and diagnosing systems?

16. Is the operator able to obtain the current sensor values for all connected sensors, the current operating status of controlled equipment, and is he/she able to issue control commands by use of the keypad or plug-in unit?

17. Is access to the control system through keypads or plug-in units security protected?

18. Can the operator in the field perform the following functions:

    Display the value of a measured variable?

    Start or stop equipment?

    Monitor the status of equipment being controlled?

    Display the setpoint of a control loop?

    Enable/disable control sequences?

19. Are the following field panel functions provided:

    Are local loop control functions executed by the field panels with direct digital control algorithms?

    Do field panels receive analog, binary, or other inputs from sensors, transmitters, switch closures, or transistor-transistor-logic signals, perform multiplexing, analog-to-digital or digital-to-analog conversion, perform signal conditioning, and store data in their memories for future interrogation?

Except for unitary equipment, do all analog-to-digital conversion have a minimum of 12 bit resolution?

Do microprocessors process the input signals based on the stored instructions of the software programs and make control decisions?

Do field panels issue analog and/or binary output signals to electrical relays, solenoid valves, motor speed controllers, and other actuators to perform loop control of HVAC equipment?

Do systems generate output signals to actuators utilizing pulse width modulation (PWM) in lieu of true analog output? Do all analog outputs have analog feedback to control logic cards of the actual output to the actuator?

Do field panels have isolation protection against 180 VAC minimum input? Are all logic circuits protected from high voltage surges?

When multiple outdoor temperature and humidity sensors are required for DDC logic, are one or multiple master sets of sensors processed by field panels provided? Is the data transmitted to other systems through the communication network?

20. Are the following construction features provided:

Are field panels capable of being securely mounted on walls? If field panels are free-standing, is there adequate structural steel support?

Are field panel cabinets constructed of sheet steel or plastic? Are cabinet doors hinged and lockable? Does a master key fit all field panels for the project?

Are field panels listed by Underwriters Laboratories for fire and shock hazard and do they conform to NEMA 1 standard?

Do field panels comply with Part 15 of F.C.C. rules?

Are electrical power disconnect switches provided inside the field panels to disconnect all external power to the cabinet during maintenance and repair?

Are screw type terminal strips provided in the field panel for the termination of all field wiring? Can each termination be labeled?

Is there adequate space provided for terminal connections and for wiring entrance?

Are all indicating lights, meters, and selector switches flush mounted on the cabinet doors?

A.4 Field Panels for Unitary Equipment:

1. Are field panels for unitary equipment factory packaged, programmed in non-volatile memory, and tested before delivered to the job site?

2. Does each panel accept time schedule inputs via the communication trunk and provide a facility for local backup?

3. Are all analog-to-digital conversions done with a minimum of 8 bit resolution?

4. Are field panels containing controllers for VAV terminal units mountable on the associated VAV boxes or remotely mountable on walls or floor? Do they connect to the building automation system so that operators can monitor and modify control operation of the VAV box without the need of reaching the individual boxes?

A.5 Communication Network:

1. Does the BEMS have microprocessor based communication processing devices and a multidrop digital transmission network to communicate between field panels and host computer systems?

2. Are the communication lines either twisted shielded pairs or coaxial cables?

3. Are two spare communication conductors provided over and above those conductors required for the system operation?

A.6 Fire Safety System:

1. Does the fire safety system have the capability to monitor all smoke detectors (in space, in air handling units and ductwork), sprinkler system flow valves, pull stations, alarm bells and other required devices?

2. Is it important that the host computer and central control panel communicate with all detectors and addressable devices to verify their proper function and status?

3. Should smoke detectors and other input/output contacts be connected to the system in addressable loops? In the event of a single wire trouble in the loop, does the system continue to detect any alarm conditions?

4. Is the fire safety system approved by Underwriters Laboratories, Inc.? Does it comply with the latest edition of UL Standard 864 (Standard for Control Units for Fire Protective Signaling Systems) and local fire codes?

5. How is the power to all the fire safety system components provided?

6. Does a central control panel receive data from detectors and process the data to determine normal, alarm, or trouble conditions?

7. Do all smoke and fire control programs reside in non-volatile programmable memory and not lost when all power fails?

8. Can the panel be mounted on a wall in a cabinet with indicators on the face of the panel? Is the panel modular in design for future expansion? Are locks with keys provided?

9. Are there LEDs or other means used to indicate power-on, alarm, system trouble, and other pertinent conditions?

10. How is programming of control panel parameters (such as alarm/trouble type assignments, point descriptor assignments, and alarm messages) accomplished?

11. Can the elevators be controlled under the fire safety system during smoke conditions? Is this control through the BEMS or by some other means?

A.7 Building Security System (If Applicable):

1. Should the building security system be capable of monitoring and controlling entrance card units at all entrances and intrusion alarms at emergency exits and all ground and second floor operable windows?

2. Is the system listed by Underwriter Laboratories, Inc. and does it comply with the latest edition of UL Standard 1076 (Standard for Proprietary Burglar Alarm Units and Systems)?

3. Are entrance card units microprocessor based units and capable of reading entrance cards and controlling entrance doors? Can these units be supervised by the security system host computer? In the event that communication with the host computer is interrupted, does entrance control remain in effect without indication at the units of communication interruption? Are they surface mounted?

4. Are addressable contact closure type alarms at each emergency exit and ground floor operable window provided. Does the security host computer communicate with all detectors to verify their proper function and status? Can individual alarms be set at enable/disable positions from the host computer?

A.8 - Transient Protection of System:

1. Is all equipment protected from power line surges? Does equipment meet the spike susceptibility requirements of MIL-STD-461 Part 7, CS06 and/or appropriate UL standards?

2. Are all sensors and control wiring protected against induced surges in accordance with the IEEE 472 surge withstand capability test?

3. Is all communications equipment protected against surges induced on any communications link? Do all cables and conductors, which serve as communications links between field panels and between field panels and host computers, have surge protection installed at each end that conform to the IEEE 472 surge withstand capability test?

APPENDIX B. BEMS SOFTWARE FEATURES

B.1 General BEMS Software Capabilities

The following software items are offered for consideration by the BEMS evaluation team. They are given with the intention of stimulating thought and/or discussion on the particular needs of a given installation. They do not represent recommendations or minimum requirements. Each installation is unique and has unique software needs.

1. Software of the host computer systems should have supervisory, file manipulation, energy management, and maintenance management capabilities.

2. Software of intelligent field panels should have stand-alone local loop control and monitoring capabilities and should operate independently of the host computers. Failure of the host computers should not inhibit the operation or program execution of the field panels.

3. All software programs which interface with operators should use plain spoken language format, be windows-based, and should have the option to be menu-driven or mouse-driven with prompts to accommodate easy use. When acronyms are used, they should be descriptive for easy learning.

4. All video display and data printing should include date and time.

B.2 System Software Features

System software should include operating systems and certain utility programs on the host computers, the field panels, and unitary controllers.

1. The host computer operating system should be a real-time multi-task system. The system should coordinate the execution of the entire system and should contain peripheral equipment controls, database management, input/output control, communication controls, program execution controls, library computational routines, language interpretation, system self-test routines, and should run system wide application programs.

2. Field panel and unitary controller software should support the application programs that provide both supervisory control of field equipment and direct digital control of local loops either singularly and/or in a hierarchial manner.

    a. Field panels should have self-test routines to continuously check microprocessor operation, communication with I/O devices, and status of the system. During startup, restart after power restoration, and shutdown, field panels should go through programmed routines to monitor the system, detect and report errors.

    b. Fail-safe conditions of equipment should be initiated or maintained regardless of the nature of the system failure.

c. The microprocessor operating system should be stored as firmware. Essential default values should be stored in non-volatile memories.

d. Data in field panels should be shared by other field panels through an interconnecting network. An operator through one field panel should have access to other field panels without going through the host computer.

B.3 Command Software Features

1. Command and utility software should include all programs which enable the operating personnel to communicate with the BEMS through the host computer keyboards using words and acronyms. More specifically these programs should include, but not be limited to, the following functions:

   a. System monitoring:

      Display of points on request to show a single point, or a group of points

      Update the displayed data automatically

      Display and print alarms automatically

      Alarm summary report

      Report trend of selected point at selected time intervals

      Energy usage report

      Historical data display

      Time and date display

   b. System control:

      Control of system access by operators

      Override of setpoint and programmed operation by operators

      Add or delete points from scan

      Adjustment of setpoint values

      Edit control parameters

      Edit alarm limits

Add, delete, and edit programs

Edit graphics

Set time and date

Edit time schedules

Start and stop motors

File transfer - upload and download

Copy data to back-up storage media

2. Commands should be capable of being entered directly in abbreviated forms or selected from a menu of command options. The system should prompt the operator for input as required. The command function should include, but not be limited to:

   a. An index of all available commands.

   b. An explanation of each command.

   c. Commands to define and modify physical parameters and the constraints assigned to the points.

   d. Commands to request reports.

   e. Commands to request graphic displays of equipment and systems.

   f. Identification and description of alarms.

   g. Ability to restrict access level of operators to specific software.

3. Commands should over-ride automatic functions in emergency.

4. The video display screens should have dedicated areas to show:

   a. Logging data, including date, time, and operator.

   b. Alarm data, including point of alarm, kind of alarm, time alarm detected, and advisory information.

5. Whenever a point exceeds preset limits or status, an alarm condition should be triggered.

6. An alarm summary should be provided at the command of the operator to display the current alarms or alarms in a specified period up to 24 hours.

7. Points should be grouped logically by location, or purpose. Each point should be identified and displayed for current value or state, setpoint, engineering unit, alarm limits, hardware address, etc. Points which are detected to be erroneous by the system should be noted to warn the operator.

8. The trend report should prompt the operator to give a time interval for display. The time interval should be between 5 minutes to 24 hours. Trend data should be displayed either in graphic or tabular form at the operator's selection.

9. Operators may select systems and points randomly for display on video displays and print on printers. Format of display should be in plain spoken language. Changing of format should be from a computer keyboard and should be allowed only by personnel with higher accesses.

10. For HVAC monitoring, the video display should show graphics of operator selected systems or zones with all sensing points and their real-time values, and graphics of all major components of the system or zone and their real-time states. The graphics should show, but not be limited to, pumps, fans, coils, dampers, chillers, boilers, cooling towers, engine generators, major valves, electrical switch gears, and major circuit breakers. The zone, system, and location of equipment should be labeled.

11. Floor plans should be available for graphic display. Floor plans should include mechanical and electrical equipment spaces.

12. All point values and states shown on display screens should be dynamically updated at least once every 30 seconds.

13. Provide diagnostic programs allowing operator's command to test the computer system.

14. Calculate energy flow amounts if available. The program should allow the operator to display energy consumption of selected equipment at selected time intervals from 1/2 to 24 hours. Required energy calculation points are:

    a. Air handling unit preheat coils, heating coils, cooling coils and fans.

    b. Steam to hot water heat exchangers.

    c. Condenser water and chilled water energy flow and compressor input of refrigeration machines. COP of refrigeration machines.

    d. Cooling plant energy flow.

    e. Boiler energy flow and boiler efficiency.

    f. Heating plant energy flow.

15. When calculated points are displayed, the equations and constants should be available to the operators.

16. Operator should be able to modify the database stored and should be able to perform on-line programming. At the operator's command, all database entries can be printed.

17. Inventory and preventive maintenance schedules should be provided. For example, the computer should accumulate run-time totals and issue reminder messages to the printer. The following equipment maintenance schedules might be considered:

    a. Air handling units: 2000 hours run time

    b. Water chillers: 2000 hours run time

    c. Air prefilters: 500 hours run time

    d. Final filters: 1000 hours run time

    e. Fans and pumps: 4000 hours run time

    f. Cooling towers and convertors: 3 months calendar time

    g. Calibration of instrumentation: 1 year calendar time

    The schedule of equipment maintenance should be distributed throughout the year initially. The reminder message should include point description, maintenance instructions, and other pertinent information. The schedule should be easily edited by the operators at the keyboard.

18. System Access Protection

    a. Access to the BEMS should be restricted by use of passwords and codes.

    b. Operators of the most restrictive access level should have the capability to assign, delete, or change passwords or codes for access.

    c. All access data such as time, date, password, and operator's name should be recorded. A summary of access records should be available.

    d. Do not print passwords when they are being used for system access.

B.4 DDC Based Field Panel Software Features

1. Software of field panels and unitary controllers should allow HVAC equipment to operate independently through local loop control of DDC algorithms.

2. The system should independently monitor and control all points under the field panels.

3. Field panels should accept global controls from host computers.

4. Field panels should accept downloading of programs from host computers.

5. Field panels and unitary controllers should have PID algorithms. Proportional, integral, and derivative constants should be resettable. The errors between the sensed and setpoint values should be kept to a minimum while maintaining system stability. The actual operation of the control loops should be determined by the nature of the equipment applications.

APPENDIX C TYPICAL BEMS APPLICATION PROGRAMS

The following is a brief description of typical application programs likely to be found on today's BEMS.

1. Duty cycling: Fan energy is conserved by periodically shutting down the fan system for a portion of its normal operating period. Typical algorithms use either a fixed off period (per "time cycle" period) or a modulated off period based upon space temperature and/or outdoor temperature.

2. Load shedding: Non-essential electric load should be shed in accordance with a priority list:

   This program will depend on the method used by the utility company to calculate demand charges. The minimum and maximum "off" period should be selected in accordance with load character and need of the equipment. Minimum "on" periods should also be provided. The control algorithm should predict continuously the energy consumption at the end of the demand interval. An alarm message should be shown on the video display and print on the printer when all sheddable loads have been shed and demand exceeds the prediction.

3. Electric equipment restart: Electric motors should be restarted sequentially after power failure. The starting sequence should be similar to that of the load shedding schedule except that certain equipment, such as refrigeration compressors, are added to and lighting loads are deleted from the schedule.

4. Scheduled start/stop control: Start and stop the equipment according to the list provided.

5. Optimum start/stop controls: The operation time of the air handling unit, refrigeration machine, heating system, or hot water convertor should be no more than necessary. The time of morning start and evening stop of this equipment should be controlled by the start/stop program which should be based on the outdoor temperature, the indoor temperature of a representative zone, the occupancy schedule, the response time of the building and contents, the system capacity, the load size and schedule, and the system thermal response time so that the desired temperature at the beginning and at end of the occupied periods will be met. The optimizing algorithm should adapt to the data of recent building heating/cooling history. A learning period should be used to accumulate historic data.

6. Outdoor air damper control during warm-up/cool-down period: Depending on the outdoor temperature and humidity, the position of the outdoor damper should be fully closed or fully open during the warm-up and the cool-down periods before scheduled occupancy so that the maximum potential of energy savings will be realized. The return air damper should be appropriately positioned to maintain building pressure.

7. Unoccupied temperature setback: There should be no heating energy dispensed during the unoccupied period (night, weekend, and holidays) unless the lowest temperature of any zone within the system (air handling or heating) reaches 10 C (50 F). During the setback period, the outdoor air damper should be fully closed and the return air damper should be fully open.

8. Summer/winter change-over: Based on outdoor temperature, change operating parameters and alarm limits from summer to winter operation and vise versa. Large enough differentials should be programmed to prevent frequent change-over.

9. Dry bulb economizer control: A fixed changeover temperature should be used for determining the positions of the outdoor air and the return air dampers during the cooling season. When the outdoor air temperature is higher than the changeover temperature, the outside air damper should be at its minimum position. When the outdoor temperature is between the changeover temperature and the supply air temperature, the outdoor damper should be fully open and the cooling coil should supplement the cooling requirements. When the outdoor temperature is below the supply air temperature, the outdoor damper should be modulated to provide the desired supply air temperature and the cooling coil should be deactivated. Upon further decreasing of the outdoor air temperature until the outdoor air damper reaches the minimum position, the heating coil should be modulated to maintain the desired supply air temperature. The outdoor air, return air, and relief air dampers should be coordinated to give the required building pressure level. The cooling coil, dampers, and heating coil should be acting in sequence following the control algorithm. When the heating coil is located in the outside air stream, it should be protected to maintain a minimum temperature of 1.67 C (35 F).

10. Enthalpy economizer control: When the outdoor temperature is below the desired leaving air temperature of the cooling coil, the outdoor air and the return air dampers should modulate to supply the desired air temperature and the cooling coil should be deactivated. When the outdoor temperature is above the desired leaving air temperature of the cooling coil, the enthalpies of the outdoor air and the return air should be calculated and compared. If the outdoor air enthalpy is less than the return air enthalpy and the outdoor temperature is between the desired leaving air and the return air temperature, the outdoor damper should be fully open. Otherwise, the outdoor air damper should be at the minimum air position. The measurement of temperature and humidity of the outdoor air may be done locally or through the network from a central location. The outdoor air, return air, and relief air dampers should be coordinated to give the required building pressure level. The cooling coil, dampers, and heating coil should be acting in sequence following the control algorithm.

11. Discriminator control: When one control system with multiple sensors serves an HVAC system with multiple zones, the control system should provide the

highest temperature, within an allowable limit, to satisfy the zone calling for the greatest cooling, and should provide the lowest temperature, within an allowable limit, to satisfy the zone calling for the greatest heating.

12. Supply air fan control for VAV systems: The [variable speed drive] [inlet vanes] should vary the capacity of the supply fan as required to maintain the set static pressure setpoint of the duct pressure sensor. The static pressure setpoint should be reset with system load variations according to a reset schedule.

13. Building pressure control for VAV system: The total supply air and the total return air of the air handling system should be measured by air flow rate measuring stations in ducts. The difference between the supply air and return air quantities should be maintained as specified whenever the system is in operation. When the difference exceeds 5% of the specified difference, the variable speed drive or inlet vanes of the return air fan should be modulated to provide the specified difference. A minimum air velocity of 3.56 m/s (700 fpm) should be maintained.

14. VAV terminal unit control

    a. The terminal unit control should maintain space temperature at the setpoint or within the deadband as specified. The unit control should use a PI algorithm.

    b. The air flow rate of the unit should be measured and should be maintained between the maximum and minimum flow rates, except when the damper is closed as specified.

    c. There should be separate cooling and heating set temperatures with a deadband in between. There should be temperature setup for cooling and setback for heating during the unoccupied period. For the temperature setting, morning warmup should be considered as part of the occupied period.

    d. When the space temperature is above the cooling set temperature, the air flow rate should be modulated to give higher flow rate at higher cooling demand. When the space temperature is below the heating set temperature, the air flow rate should be maintained at the minimum flow rate.

    e. When the space temperature is in the deadband, the air flow should be at the minimum rate during the occupied period. The air damper should be at its minimum open setting during the unoccupied period.

    f. Provisions should be made to give occupants the capability of overriding the occupied/unoccupied schedule at the room sensors.

The override should revert to the automatic program after an 8-hour duration.

g. Software access to field panels of the terminal units should be through the host computer and at the room temperature sensors. Access should enable operators to reset device addresses, setpoints, operating parameters, operating schedules, and PI constants.

h. Sequence of operation for units with reheat hot water coils: The air damper and hot water valve should operate in sequence. Upon increasing heating demand, the air flow rate should decrease until the minimum flow rate limit is reached. Then the hot water heating valve should open until the space temperature is satisfied. The reverse should occur when space cooling load is increasing. When heating is required during warmup period, air damper should be at maximum position.

15. Coil freeze protection: A sensor located after the heating coil should maintain the set temperature of the heating coil at all times. A remote bulb type freeze protection sensor located in front of the cooling coil should stop the supply air fan and close the outdoor dampers when the coil face reaches 1.67 C (35 F). The heating coil control valve should be fail-safe at a full open position when any part of the heating control fails. A Level 2 alarm should be generated when any of these conditions occur.

16. Chiller plant control

a. The condenser water pump and chilled water pump should be started by the operator through the host computer keyboard or at the field panels. Upon verification of water flow through the condenser and evaporator, the chiller should be started manually at the chiller control console.

b. The chiller temperature controller should be adjustable at the field panel. Each chilled water pump and condenser water pump should have differential pressure sensors to monitor pump status. A Level 2 alarm should be generated within 20 seconds, if no flow is indicated after a pump-start command is given.

c. The condenser water bypass valve, the air flow rate of cooling tower fans, and/or the number of cooling tower fans in operation should be operating in sequence by maintaining [18.3] C ([65] F) minimum temperature in the condenser water main. When the chiller load is increasing, the following sequence should take place: bypass valve to allow more water from towers to chillers, cooling tower fans to be turned on in turn at the lowest air flow rate, and air flow rates of the cells to be increased uniformly until full flow.

d. The software should allow the operators to alter the lead-lag sequence of operating the chillers and tower cells.

e. The pressure differential between the chilled water supply and chilled water return should be maintained by controlling the chilled water bypass valve at the chillers.

f. Level 2 alarms should be generated when the following events occur:

Chillers are malfunctioning

Chilled water temperature is above setting

Condenser water supply temperature is above 29.4 C (85 F) or below [18.3] C ([65] F)

Differential pressure across chilled water and condenser water pumps drop to indicate malfunctioning of pumps

Level of cooling tower basin too high or too low

g. The automatic condenser water treatment pump should operate only when the refrigeration machines are off line and the condenser water pumps are in operation. The operation/control of the water treatment pump should be part of the BEMS system. The BEMS subcontractor should coordinate with the condenser water treatment subcontractor.

17. Heating plant control

a. The hot water pumps should be started by the operator through the host computer keyboard or at the field panels. Upon verification of water flow through the boilers, the boilers should be started manually at the boiler control console.

b. The boiler temperature controller should be adjustable at the field panel or from the host computer keyboard. The field panel and the host computer system should monitor the [hot water entering and leaving] [the steam and entering water] temperature at the boiler, burner status, forced or induced draft fan status, the stack temperature, the stack CO2 concentration, the fuel consumption rate, the heat output rate, and other pertinent data of each boiler. Also monitored should be the [hot water supply and hot water return temperature] [steam pressure or temperature] [condensate temperature] at the plant main pipes, flow and energy rate of [hot water] [steam and condensate] for the entire plant.

c. See Boiler Section for requirements on capacity and safety controls.

18. Space heating water circuit control: Space heating served by each pump should be controlled as follows:

  a. Pump should be activated automatically when outdoor temperature drops below the setpoint.

  b. Water flow should be verified by differential pressure sensors across the pump. Whenever the verification is negative while the outdoor temperature is below setpoint, an alarm should be generated. A command from the host computer keyboard or at the field panel should start the standby pump.

  c. A pressure reducing (choke) valve or variable speed pump should maintain the differential pressure setting.

19. Steam to hot water convertor control

  a. When the hot water circulation pump is not in operation, the convertor control system is deactivated and steam valves should be closed.

  b. Steam valves should be operated in sequence [1/3 and 2/3 of full capacity] to maintain the leaving water temperature setpoint.

  c. The operation of the water circulation pump and adjusting of leaving water temperature setpoint should be from the host computer system keyboard or at the field panel.

20. Finned tube radiation control

  a. Space temperature sensor should control the hot water valve.

  b. When the outdoor temperature is above [18.3 C ([65] F), the hot water valve should remain closed.

  c. The space temperature and low limit temperature set points should be adjustable from the host computer keyboard.

21. Lighting control: Lights should be turned on and off in areas as scheduled. A local switch should allow occupants to override the automatic on/off. However, the override should revert to the automatic program after an 8-hour duration.

APPENDIX D FACTORS TO BE CONSIDERED IN THE PERFORMANCE TESTING OF SELECTED BEMS SUPERVISORY ALGORITHMS

D.1 Scheduled Start/Stop

The Scheduled Start/Stop algorithm should cause two basic actions. These are: (1) turn on an air handling unit, and (2) turn off an air handling unit. The action of turning a unit on and off may be no more than turning on and off a fan, or it may involve two fans, opening/closing vortex damper, starting/stopping pumps, and opening/closing valves and dampers.

The points required for testing can be for one air handling unit connected to a single zone. Required inputs to the Emulator will be the start/stop signal from the BEMS. The clock time of the BEMS has to be synchronized with the time in the Emulator, or vice versa.

D.2 Duty Cycling

The actions caused by the duty cycling algorithm will be almost the same as for the start/stop algorithm, starting and stopping the air handler. One difference between the duty cycling actions and the start/stop actions is that the duty cycling actions depend upon the load, while the start/stop actions depend upon the time of day. Another difference is that the start/stop algorithm will shut off the air handler for approximately 10 to 15 hours, while duty cycling might shut off the air handler for 5 to 15 minutes. Also different is the frequency which the start/stop air handler action occurs. The scheduled start/stop algorithm will typically stop and start the air handler once per day. The duty cycling algorithm will stop and start the air handler perhaps 20 to 100 times per day. The building responses to duty cycling will be the same as for start/stop, but the space temperatures will typically not reach a steady-state condition as they will in response to the start/stop algorithm.

The current weather conditions will affect the response of the building to the duty cycling algorithm. If outside conditions or internal loads are severe, duty cycling may result in occupant discomfort. Therefore it is important to test a duty cycling algorithm at large space loads. The maximum energy saving potential of duty cycling occurs at small space loads such as during spring or fall. Therefore, it is also important to test the algorithm during mild load conditions. This would imply a minimum of three days of testing, with winter, spring/fall, and summer conditions.

Since the start/stop and duty cycling algorithms have the same control actions, the BEMS should have a scheme to prevent duty cycling from continuing after the air handler has been turned off by the start/stop algorithm. A full day of testing should verify this.

D.3 Demand Limiting

The demand limiting algorithm control actions closely resemble those of the duty cycling algorithm, with the exception that the number of times that the air handler is stopped and started should not be as large. This algorithm will only stop the air handler when the electrical demand, measured by a meter which has the air handler as a subsidiary load, exceeds or is predicted to exceed a desirable value, and the air handler is specified as a load that can be shed. The air handler may be cycled off and on with a minimum off time and minimum on-time until the demand is reduced. The ability of the demand limiting algorithm to effectively reduce demand must be tested by simulation of the change in electrical demand in a building with time and the connection of a number of loads which can be shed.

Since this is a different task than the simulation of the space condition change with time, the demand limiting algorithm will be treated as a sort of duty cycling algorithm which will start cycling during periods of high cooling load (due to electric chiller loads). The demand meter reading will have to be empirically simulated, and only one load will be connected to the algorithm. The same considerations for test timing and point requirements apply as with duty cycling. Also, concurrent testing of start/stop, duty cycling, and demand limiting should test the ability of the BEMS to prioritize the air handler control.

D.4 Optimum Start/Stop

The optimum start/stop algorithm is basically an enhanced scheduled start/stop algorithm. The control actions produced by the algorithm are the same as for scheduled start/stop. Only the timing of the actions will change. The scheduled start/stop actions will occur at the same time every day. The start and stop times ordered by the optimum start/stop algorithm will change with the weather conditions.

Optimum start/stop algorithms will usually be of two types, fixed, and adaptive. A fixed optimum start/stop algorithm will have a fixed formula for the start/stop time as a function of the outside and inside temperatures. This assumes that building characteristics will not change with seasons and that warm up and cool down times are only a function of the indoor-outdoor temperature difference. The fixed algorithm requires the entering of constants by the BEMS operator to "tune" the algorithm to a particular building.

The adaptive start/stop algorithm requires no tuning, but will usually need to run for two or three days to adapt to the building behavior. This means that in testing an adaptive start/stop algorithm, the test must be of sufficient duration to allow the algorithm to determine the building characteristics. Three days at a given climate would probably be required.

The points required for optimum start/stop will be the same as for scheduled start/stop with the addition of an outside air temperature point.

D.5 Economizer

The purpose of the economizer algorithm is to decide whether or not to use outside air for cooling the air passing through the air handling unit. This decision is made by comparing, in some manner, the enthalpies of the return and outside air streams. The determination of enthalpy can either be by direct measurement, as with the enthalpy economizer D.5.1, or by approximating enthalpy with dry bulb temperature, as with a dry bulb economizer. In either case, it is assumed that the local control of the damper is performed by some other device or algorithm. The control action of the economizer algorithm is either to allow or not allow the dampers to be opened.

The testing of the economizer algorithm should be carried out under various weather conditions. These would be:

1. outside air too cold for safe operation of economizer
2. outside air too hot or humid for effective economizer operation
3. outside air usable for cooling but air handler load cannot be met completely by economizer and mechanical cooling must also be used

4. outside air usable for cooling and entire air handler load can be met with economizer operation.

These conditions could be met by testing in mid-winter, mid-summer, early summer, and spring, respectively. The points required for testing would include outside and return air temperatures for a dry bulb economizer and outside air temperature and humidity and return air temperature and humidity for an enthalpy economizer.

D.5.1 Enthalpy Economizer Cycle

In an enthalpy economizer cycle program, the air temperature and humidity are used as indices to determine whether or not outside air should be used for free cooling. For HVAC systems without sprayed cooling coils (i.e.: air washers), the minimum amount of outside air necessary to maintain the space's fresh air requirement should be used when either the enthalpy or the dry-bulb temperature of the outside is greater than or equal to the enthalpy or dry-bulb temperature of the return air, respectively. The maximum amount of outside air should be used whenever the dry-bulb temperature of the outside air is greater than or equal to the cooling coil discharge air temperature set point, T_{CASP}, and both the dry-bulb temperature and enthalpy of the outside air is less than the dry-bulb and enthalpy of the return air, respectively. Controlled mixing of the outside and return air should be done when the outside dry-bulb temperature is less than T_{CASP} and the requirement for minimum outside air is not met. For systems with preheating coils, controlled mixing should be overridden and the dampers positioned to admit the minimum amount of outside air when the outdoor dry-bulb temperature is equal to or below some assigned minimum value to prevent freezing of the coils. A logical flow diagram of a typical enthalpy economizer algorithm is given in Figure 3.

By gradually increasing or decreasing the emulated dry-bulb temperature and/or humidity of the outside air, the Emulator can be used to quickly check out the operation of the enthalpy economizer cycles under conditions corresponding to minimum and maximum outdoor air use and the mixing of outdoor and return air. A psychometric chart of a typical enthalpy economizer cycle for systems without sprayed cooling coils is given in Figure 4. Of particular interest is how the application algorithm under test handles transitions from one region to another. For example, does the control of the outdoor air dampers hunt or oscillate as the outdoor air conditions approach the boundary between region I and region II (i.e. switching between minimum and maximum outdoor air) in Figure 4 from either side?

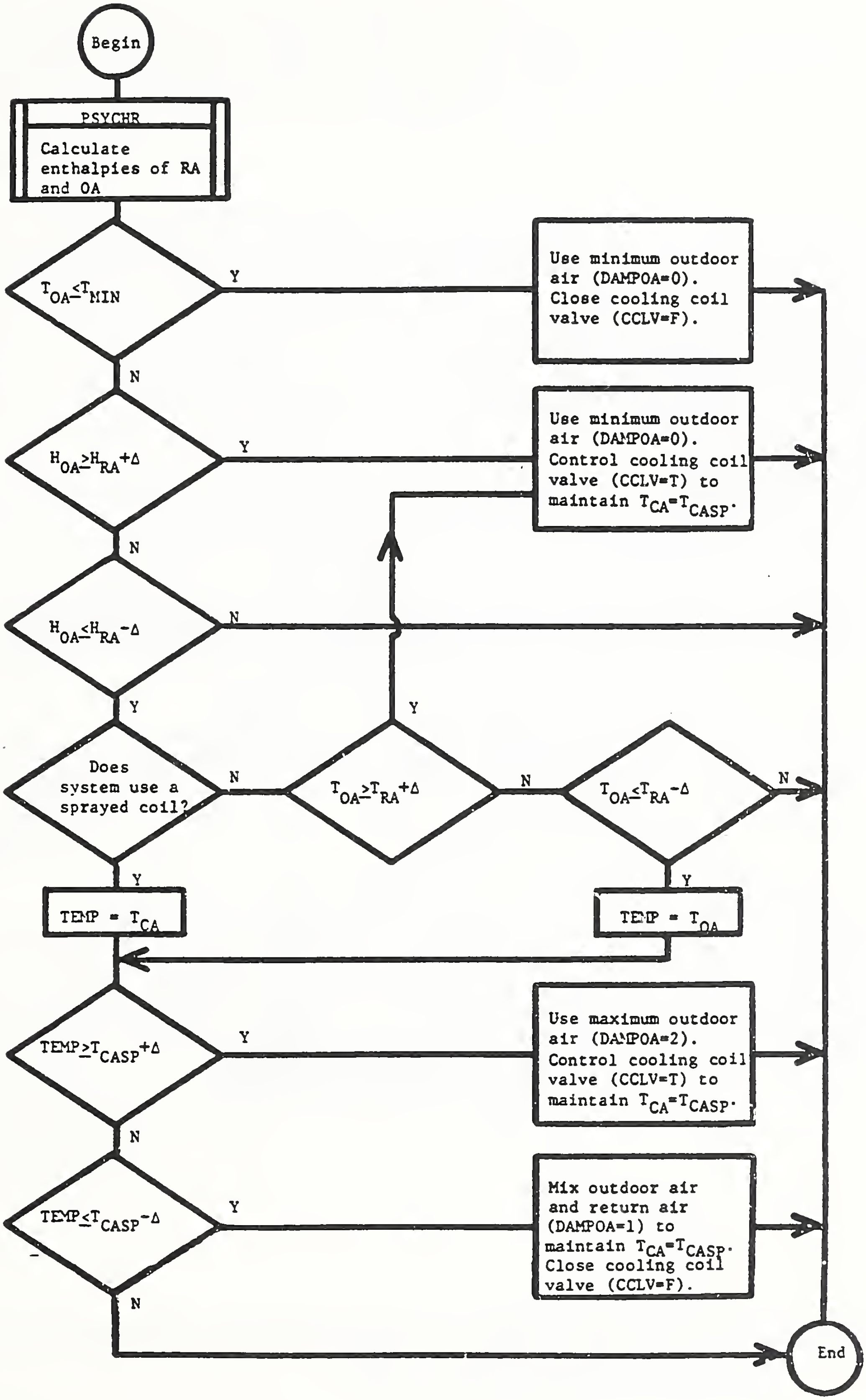

Figure 3. Logic flow diagram of the enthalpy ecnomizer cycle

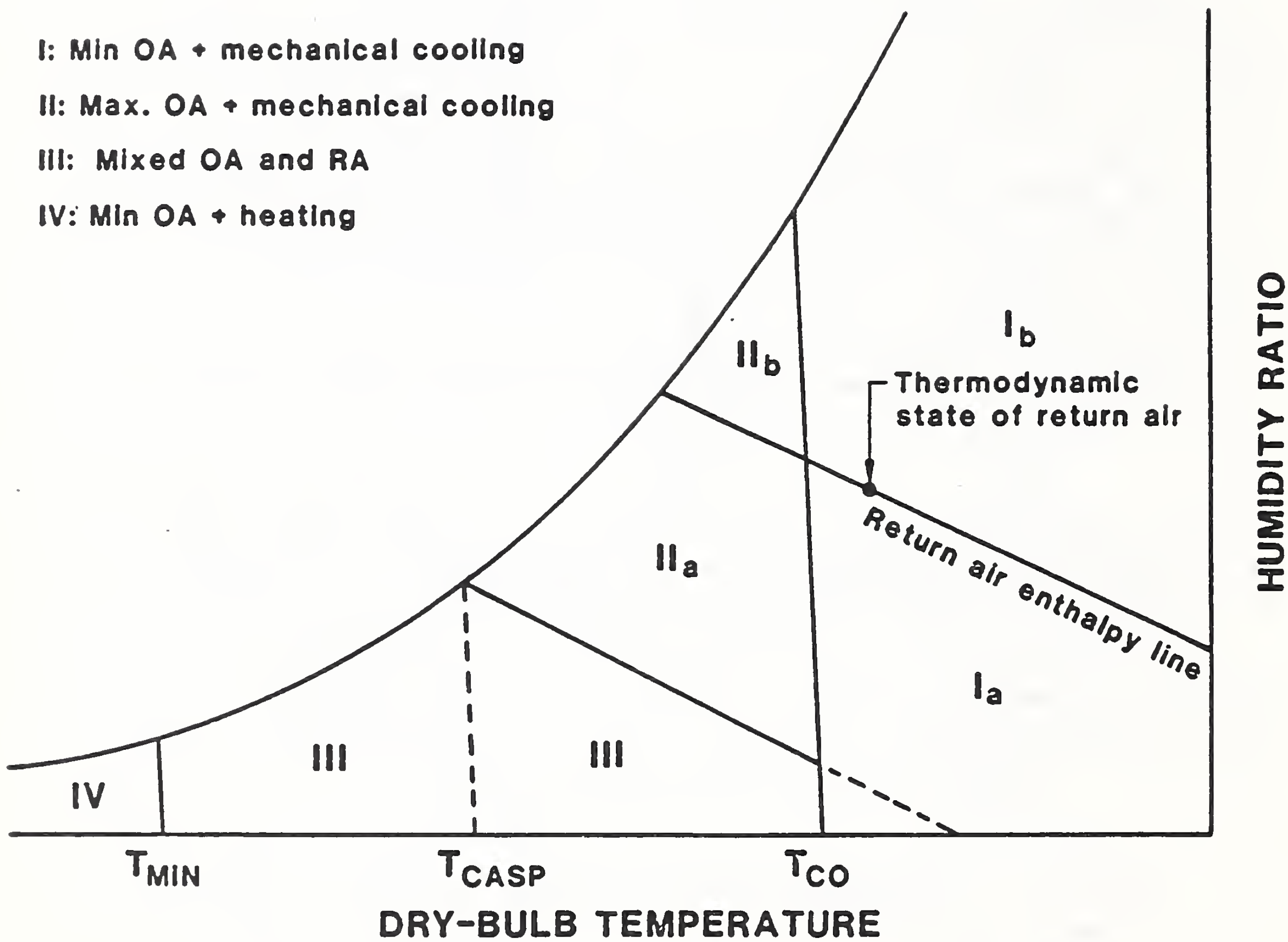

Figure 4. Psychrometric chart of enthalpy economizer algorithm for systems which do not employ sprayed cooling coils or air washers

For systems employing direct digital control (DDC) of the outdoor, relief, and return air dampers, the quality of control provided by the BEMS during the mixing operation (region III in Figure 4) can also be monitored. This can be done under a variety of weather conditions and cooling loads to determine if there are any undesirable interactions between different control loops.

D.6 Ventilation/Recirculation

Ventilation/recirculation algorithms may have several purposes. Some are designed to close outdoor air dampers during warm up periods. Others might be used in buildings in which the fans cannot be shut down and the algorithm closes the outdoor and ventilation air dampers during periods when the building is unoccupied. A third use of ventilation/recirculation algorithms is to allow outside air to be used to lower cooling requirements. This is usually done under special conditions when the outside air temperature is low at night and there is a building cooling load in the daytime. The cool outdoor air can be used to lower cooling loads through pre-cooling the building by running air handler fans and opening outside air dampers. This is sometimes called ventilation purging.

The ventilation/recirculation algorithms can be tested by running them under several weather conditions. Purging should only take place under certain conditions, so a purging algorithm should be tested under both favorable and unfavorable purging conditions. Warm-up damper control should take place at all times of the year, but the energy saved will depend on the weather. Closing of ventilation dampers during the unoccupied period is subject to the same restrictions. The idea of testing with a spring, fall, and winter condition should be adequate for testing these algorithms, as long as at least one condition is favorable for purging (large temperature swings from night to day, as in the spring).

Points required for testing would include space temperature and humidity, outside air temperature and humidity, air handler status, and start/stop air handler fan control and minimum and outside air damper open/close control points.

D.7 Chiller Sequencing Program

The function of a chiller sequencing algorithm is to sequence chillers in a multi-chiller plant under a variety of load conditions for the purpose of achieving optimal plant efficiency. By emulating the operation of a chiller plant under different load conditions, the Emulator can be used to simulate the response of a specific chiller plant to the control actions of the BEMS chiller sequencing application program. The observed control actions can then be compared with either those in the contract specification or with information provided by the BEMS supplier on the operation of the chiller sequencing algorithm. Weather patterns corresponding to high, medium, and low cooling load days could also be emulated to determine how well the chiller plant is controlled under a variety of conditions expected to be encountered
over a cooling season.

NIST-114A (REV. 3-90)	U.S. DEPARTMENT OF COMMERCE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY	1. PUBLICATION OR REPORT NUMBER NISTIR 4991
		2. PERFORMING ORGANIZATION REPORT NUMBER
	BIBLIOGRAPHIC DATA SHEET	3. PUBLICATION DATE NOVEMBER 1992

4. TITLE AND SUBTITLE

Guidelines for Using Emulators to Evaluate the Performance of Energy Management and Control Systems

5. AUTHOR(S)

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6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

U.S. Department of Energy
Office of Conservation & Renewable Energy
1000 Independence Ave., SW
Washington, DC 20585

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A Building Energy Management System (BEMS) is that portion of a Building Automation System (BAS) that controls the heating, ventilation, and air conditioning (HVAC) systems in buildings. Its performance is directly related to the amount of energy consumed in a building and the comfort of the building occupants. One approach to evaluating the performance of an BEMS is through the use of an Emulator. This is a special computer/data acquisition system that is connected to the sensor inputs and command outputs of the BEMS. It replaces the HVAC system and building and uses a computer program to simulate their response to BEMS commands. The BEMS, through its supervisory and/or direct digital control algorithms, then controls the simulated building/HVAC system as if it were an actual one. At the same time, the Emulator evaluates the performance of the BEMS in terms of the energy consumed by the simulated building, the degree of comfort maintained in the simulated space, response time, accuracy, etc.

This report contains guidelines for using Emulators to evaluate BEMS. An overview of the hardware and software found in a typical BEMS is presented, followed by information on: setting up an BEMS and an Emulator, evaluating system/command and DDC software, and methodologies for testing BEMS application algorithms. Considerations are also presented for evaluating an BEMS' programming capabilities, DDC control loop performance, and for rating different aspects of a BEMS' performance.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

Application Algorithms; Building/HVAC/Plant System; Building Energy Management System; building technology; Emulator; Energy Management and Control System; Performance Evaluation; Simulation; Test and Rating Methodology

13. AVAILABILITY

X	UNLIMITED	
	FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).	
	ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.	
X	ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.	

14. NUMBER OF PRINTED PAGES 58

15. PRICE A04

ELECTRONIC FORM