# GENERALIZED ENGINEERING MODELING AND SIMULATION (GEMS)

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## ABSTRACT

A structured, generalized modeling and simulation software is described that enables development and analysis of control algorithms and systems and prediction of thermal performance and energy use in buildings. The basis for this tool is the state-space technique, which casts differential and algebraic equations describing the system into a vector-matrix form. An automated building modeling capability generates detailed and simplified models directly from building plans by using a library of construction element models (walls, floors, etc.). A closed-loop system simulation can be generated by interconnecting the building model with other component models selected from a library of HVAC equipment, controls, internal load schedules, and weather data. Theoretical considerations for the modeling methodologies implemented in GEMS are discussed. GEMS analysis results from an application are presented.

## INTRODUCTION

A few years ago, a significant effort was initiated to improve the computerized dynamic modeling and simulation capabilities for the development and analysis of control algorithms for HVAC applications. At that time, several sophisticated dynamic modeling and simulation and analysis tools were available for aerospace applications, and a substantial database existed for the dynamic modeling and simulation of buildings and their associated HVAC equipment and systems (Nelson 1965; Konar and Mahesh 1974; Shavit 1977; Bonne et al. 1978; Nelson and MacArthur 1978; Pejsa 1978). In trying to identify solution(s) incorporating both present and future needs, it was realized that within the space comfort control industry as a whole, methods for simulating dynamic building systems had not been formulated and/or documented sufficiently.

This assessment of needs led to the development of GEMS—Generalized Engineering Modeling and Simulation. Over the years, the GEMS library has grown to include HVAC equipment (furnaces, boilers, air conditioners, heat pumps, etc.), standard and advanced controls (both primary and secondary), buildings and their envelope construction elements (walls, windows, floors, etc.) for residential and commercial structures, comfort analysis routines (predicted mean vote (PMV), indoor air quality, etc.), and weather data for numerous cities. With the aid of existing and/or newly developed modules, complex systems can be constructed with GEMS, making rapid and inexpensive closed-loop system analysis possible. Since its introduction, GEMS has been used extensively in the development and analysis of control algorithms for a large number of existing and future products. With the proliferation of inexpensive microprocessors, control algorithms developed with the aid of GEMS can be directly embedded into microprocessor-based controllers. Furthermore, GEMS has also been used in emulators (or closed-loop simulations) for testing and analyzing product prototypes.

## WHY DYNAMIC MODELING & SIMULATION?

As a tool for engineering, dynamic modeling and simulation is invaluable in designing and evaluating new concepts. It allows the designer to readily identify acceptable methods, optimize the design, and predict its performance over a wide range of applications so that several concepts can be evaluated early in the hardware cycle to reduce iterations. In control synthesis, where product design is secondary to the effort of discovering the best control concept, the designer can quickly perform closed-form and sensitivity studies to get an intuitive sense of the system's behavior. Computer modeling and simulation is also a versatile and convincing capability that can supply detailed answers to any number of questions concerning the operation and performance of specific control devices in buildings or systems. The ability to verify product performance in different or unique applications is not general in nature, but is specific to the environmental control system and the building, location, weather conditions, and use patterns.

But beyond that, the ability to "build," test, and optimize new controllers early in the design cycle has several benefits. It provides direction by aiding the selection of the most "salable" product idea or product feature set prior to committing to a product development. Once a development is initiated, it makes for more efficient use of engineering resources and cuts down development time, since design reiterations are bypassed, allowing new products to be brought to the marketplace sooner. It helps ensure that product specifications are met and that the design provides adequately for the intended application, thus satisfying customer requirements. And it enables product development, introduction to the market, and promotions based on verifiable and predictable performance under a wide range of applications and conditions.

For a dynamic modeling and simulation tool to be useful in the development and synthesis of control algorithms, it must be capable of running the simulations at extremely small time steps, usually on the order of several seconds. This is an important feature of any such tool for two reasons: (1) the need to understand the effect of any control action on the operation of components and subcomponents within equipment such as a furnace, and (2) typical controllers have a cycle rate of less than a minute. Systems analysis tools with detailed models and small simulation time steps provide the ability to study the impact of control algorithms on the amplitude of room air temperature, equipment start-up and shutdown (on/off cycle), etc., and to identify issues such as short cycling, erratic equipment operations, and the like. All such micro- and macro-level behaviors have an impact on the overall operation and performance of a system. Even the system annual energy consumption attributed to a particular control feature can be estimated efficiently and accurately. Such fine-grained, detailed analysis of control systems and their impact on overall system performance is not possible with any other simulation tools.

## GEMS FEATURES

The GEMS computer program is a structured software tool that enables the development and analysis of control algorithms and systems and the prediction of thermal performance and energy use in buildings. It has evolved from other tools that have been used extensively for designing, developing, and analyzing digital flight control laws for aircraft, and hence has the ability to perform simulations at extremely small time steps, as well as a multi-rating capability under which different modules can be run at different time steps. The basis for this tool is the state-space technique, which casts differential and algebraic equations describing the system into a vector-matrix form. The user generates detailed models directly from building plans by using a library of construction element models (walls, floors, etc.). A closed-loop system simulation is then generated by interconnecting the building model with other component models selected from a library of HVAC equipment, controls, internal load schedules, and weather data. The software enables detailed dynamic analysis of the operation and performance of a building system using any desired time step.

GEMS differs from other building analysis tools such as DOE-2.x, BLAST, EnergyPlus, Trace, TranSys, ESP, and HVACSIM+ in that it is not merely an energy analysis tool based on hourly simulations. Instead, GEMS is a high-fidelity analysis tool because of the fine granularity with which the simulations can be performed. The importance of a systems analysis tool's ability to assist in dynamic simulations with small time steps (on the order of seconds or minutes) cannot be overstated when one considers the operation of a building's heating, ventilating, and air-conditioning (HVAC) system. The operating status (on/off, open/close) of HVAC system components (water valves on heating/cooling coils, boiler burner, etc.) is determined by the building controller(s) (or energy management system) in response to the imposed heating and cooling load. Since these loads vary with time (on the order of seconds or minutes, not hours), the HVAC system component status will need to be changed in order to maintain the desired set points—usually space temperature and building pressure. This then implies that any exhaust from a building (e.g., products of combustion from a boiler burner) will also be a function of time. This type of dynamic information can be utilized as data input to the "Plume Modeling" software used for predicting the composition and dispersion of building exhaust.

GEMS has been used extensively for several years, resulting in a broad experience base and development of a rich library of various building and HVAC system component models.

## STATE-SPACE REPRESENTATION

The key to GEMS is state-space system representation. One method of modeling the dynamics of a system is to cast the differential and algebraic equations describing the system into the general first-order state-space form:

$$\dot{\underline{x}} = [A(\underline{x},\underline{u},t)]\underline{x} + [B(\underline{x},\underline{u},t)]\underline{u} \qquad (1)$$

$$\underline{r} = [C(\underline{x},\underline{u},t)]\underline{x} + [D(\underline{x},\underline{u},t)]\underline{u} \qquad (2)$$

where Eq. 1 represents the N-coupled differential equations of the system with the vector of states, $\underline{x}$, and inputs, $\underline{u}$, and Eq. 2 represents the N-coupled algebraic equations for output, $\underline{r}$. These equations are commonly known as the state-space system representation, and the set of coefficient matrices [$A, B, C, D$] is called the system state-space quadruple.

When cast in this form, several powerful tools such as linear algebra, modern control theory, and vector-matrix numerical methods can be used to study the system. In modeling even a moderately detailed system, the state-space form presents an enormous bookkeeping and coupling problem. Moreover, each time the system is modified, the coupling among the equations necessitates a derivation of the entire state-space vector-matrix equations. Herein lies the power of GEMS, which contains the tools to automatically generate the state-space representation of the entire system from user input descriptions of the basic subsystem block dynamics and the interconnections of these blocks.

## BUILDING STRUCTURE THERMAL REPRESENTATION

One way to model heat flow in buildings is to represent the thermal parameters by analogous electrical parameters: temperature = voltage, heat flow = current, thermal conductance = 1/electrical resistance, and thermal capacitance = electrical capacitance. For example, based on similitude, the wall construct shown in Figure 1 may be represented by the RC network, also shown in Figure 1. The user's task is to create a representative RC network for a section of the building (in this case a wall) and input it in a prescribed manner to create a software construct with an assigned mnemonic label. Subsequently, the construct can be used by specifying its label and other appropriately relevant parameters. In this manner, all the building constructs (walls, floors, roofs, ceilings, windows, air masses, furniture, etc.) are generated and evoked by using their label.

To use GEMS, the building under study must be in the form of an RC network. The RC network data may be entered on a node-by-node basis (which is both cumbersome and error prone) or by using a building construction element preprocessor in GEMS, which selects predefined networks for building constructs from a library. As shown in Figure 2, the building modeling task then becomes one of obtaining the floor plans, defining a construction element numbering scheme, selecting the desired library elements, and supplying orientation and area information. Reradiation between surfaces (walls, windows, etc.) is modeled in a similar manner. A room-by-room description of the building and geometric information are used to compute the shape factors. Then, using the specified areas and surface temperatures, linearized reradiation resistances are computed and stored in a data file to be accessed automatically. Next, the RC network modeling segment of GEMS generates the state-space model and presents it to the user as a "namelist" table (see Figure 3). This table identifies all the states of the model and the inputs and outputs of the overall system. The state-space quadruple of the model is stored in a data file.

## MODELING TECHNIQUES FOR GENERAL LINEAR SYSTEMS

In addition to the building structure, many other components and effects in a building system can be modeled as a linear or linearized system, for example, sensors, controllers, HVAC equipment and time delays (Pade approximation). Thus, to make it convenient to include these models in the building structure model, GEMS uses a preexisting model (Konar and Mahesh 1974) for casting these models into state-space form. These algorithms are capable of modeling systems described by: simulation equations such as systems implemented on an analog computer; general transfer functions; and interconnecting subsystems such as combining N Jth-order systems into a single N×J system.

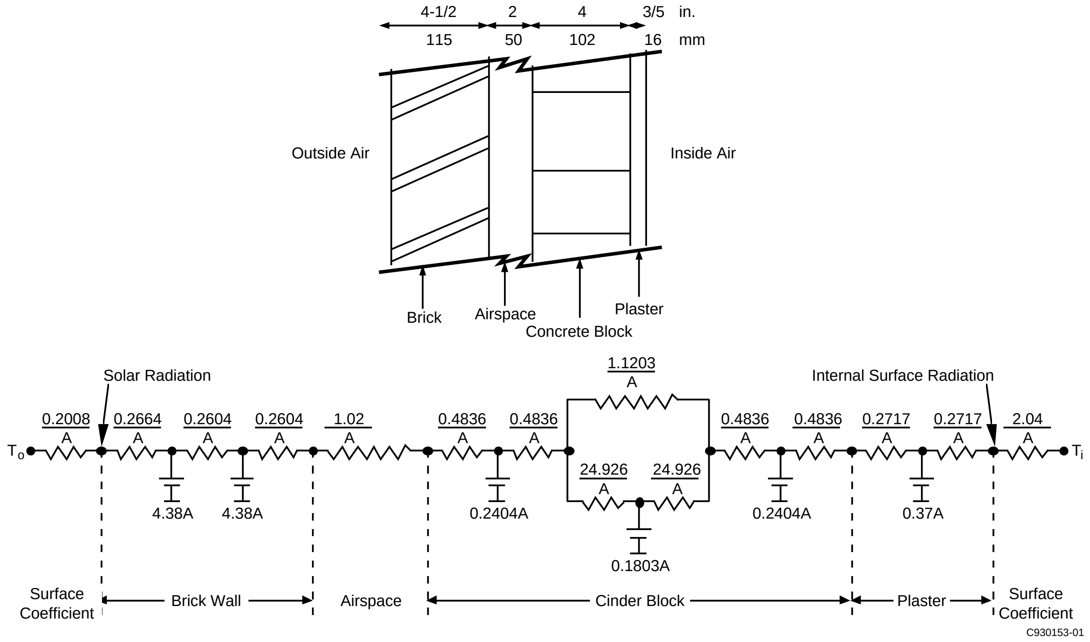
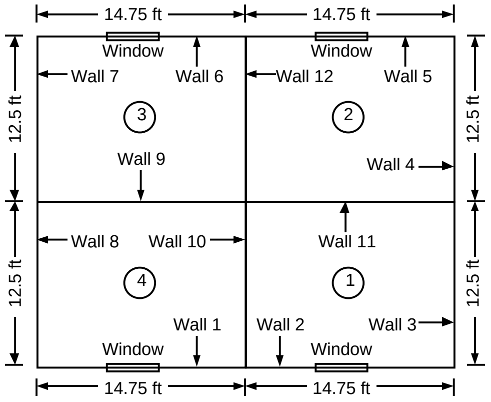


**Figure 1. Predefined Resistance/Capacitance Network for a Typical European Outside Wall from Construction Element Library**



Wall 1 (Z1 = 0, Z2 = 4, AZ = 0, R = 0.0, A = 182.67, T = 2.0)

Wall 8 (Z1 = 0, Z2 = 4, AZ = 270.0, R = 0.0, A = 200.0, T = 2.0)

Wall 9 (Z1 = 4, Z2 = 3, R = 0.0, A = 232.0, T = 3.0)

Floor 1 (Z1 = 4, Z2 = 3, R = 0.0, A = 232.0, T = 3.0)

Ceiling 1 (Z1 = 4, Z2 = 3, R = 0.0, A = 232.0, T = 3.0)

Roof 1 (Z1 = 4, Z2 = 3, R = 0.0, A = 232.0, T = 3.0)

Air Mass 1 (Z = 1, Q = 1.0, C = 35.0, IZ4 = 0.0146)

Outputs (Z1, Z2, Z3, Z4, W1Z1)

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**Figure 2. Automated Building Modeling Procedure**

**States**
X(1) = Wall 1 Capacitor State – Node 3
X(15) = Wall 5 Capacitor State – Node 51
X(25) = Air Mass 2 Capacitor State – Node 73

**Outputs**
R(1) = Air Mass Temperature in Zone 1 – Node 8
R(2) = Air Mass Temperature in Zone 2 – Node 73
R(3) = Wall 1 Temperature in Zone 1 – Node 7
R(4) = Ceiling 1 Temperature in Zone 1 – Node 32

**Outputs**
U(1) = Prescribed Outside Temperature – Node 1
U(2) = Solar Radiation to Wall 1 – Node 2
U(3) = Solar Radiation to Floor 1 – Node 13
U(4) = Heat Input to Air Mass 1 – Node 8

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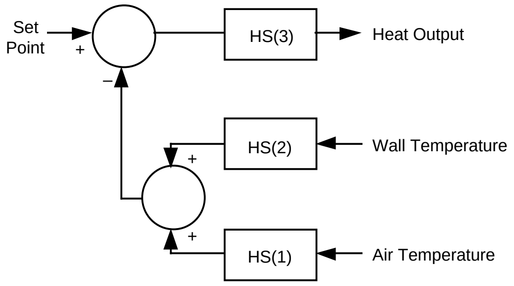
**Figure 3. "Namelist" Table for a Simple Residence Model**

To illustrate the use of transfer functions, consider the case of a continuous linear controller with a heat source (see Figure 4), where the controller is a thermostat controlling the room temperature by means of proportional and integral action. Control feedback is provided by a sensor responding to both room air and wall temperatures with some time lags. There are three transfer functions describing this controller with heat source, along with algebraic equations for specifying the interconnections between the inputs, outputs, and gains of the system. Figure 4 also shows how this model is input into GEMS. As mentioned previously, algorithms within GEMS use each of these transfer functions to create a state-space quadruple for each transfer function, an overall connection quadruple, and an overall linear state-space quadruple, which is then stored in the data file.



```
$TRANSFER FUNCTION DATA
C
C TRANSFER FUNCTION BLOCKS
C
HS(1) = 1.0/(0.33* S + 1.0)
HS(2) = 1.0/(0.33* S + 1.0)
HS(3) = 20000.0* (S + 1.0)/S
C
C INTERCONNECTION DATA FOR BLOCKS WHERE:
C     UI = INPUT TO BLOCKS
C     RI = OUTPUT OF BLOCKS
C     U = INPUT TO SYSTEM
C     R = OUTPUT OF SYSTEM
C
UI(1) = U(1)
UI(2) = U(2)
UI(3) = U(3) – RI(1) – RI(2)
R(1) = RI(3)
```

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**Figure 4. Modeling Procedure for a System Described by Transfer Functions**

## MODELING NONLINEAR SYSTEMS

The system models discussed so far have been a subset of the general state equations, i.e., linear and time invariant, where the [*A*, *B*, *C*, *D*] quadruples are constants. Many processes in building systems, such as heat exchangers, distribution systems, moist air thermodynamics, or controllers, are best modeled by nonlinear, ordinary, or partial differential equations. Such continuous processes may be cast into the state-space form of Eqs. 1 and 2 by discretizing and integrating the governing partial differential equations, or by dividing the calculation field into a series of nodes and applying the appropriate conservation equations to each. An example of this is the single-flow uniform-sink heat exchanger (Figure 5), which may be used to represent a distribution network such as air ducts or hot water pipes. The temperature response of each fluid node is governed by

$$\left(C_p \rho A\,\Delta x\right)_f \frac{dT_{f_i}}{dt} = C_p \rho A V\left(T_{f_{i-1}} - T_{f_i}\right) - h_{in}\left\{V, T_{f_i}\right\} P\,\Delta x\left(T_{f_i} - T_{hx_i}\right) \tag{3}$$

Similar conservation equations can be formed for each heat exchanger node. The resulting set of equations for all the nodes can be arranged into the form of Eq. 1, with the matrix coefficients no longer constants but functions of time and/or other state variables.

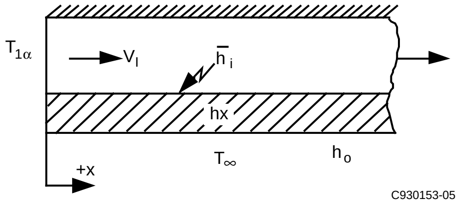

**Figure 5. Diagram of a Single-Flow Uniform Sink Temperature Heat Exchanger**

Discontinuous processes such as relays, hysteresis, friction, temperature-activated switching, etc., may be handled with discontinuous functions that “select” appropriate piecewise continuous equations based on $x^{\cdot}$, $\underline{x}$, $\underline{u}$, $\underline{r}$ (Takahashi et al. 1972).

While a unified and generalized method of performing nonlinear state-space *modeling* does not exist, a generalized method of *simulation* does exist: Calculate $x^{\cdot}$ using $\underline{x}$, $\underline{u}$, $t$; integrate $\dot{\underline{x}}$ ; and calculate $\underline{r}$.

## MODELING AND SIMULATION

State-space modeling techniques permit development of highly structured, modular, and automated software such as GEMS, in which the vector-matrix form is easily handled with arrays and software modules are defined by state-space models, with interfaces to other modules defined completely by input and output vectors. GEMS consists of several program segments, some of which are invariant in that they operate on input data to generate models and to select data and subroutines from modeling libraries. The information passed between the program segments is primarily state-space data. The system to be analyzed is constructed in the simulation program by interconnecting the input and output vectors of the various subsystem modules through indirect addressing of the appropriate arrays. Simulation output data is specified and handled similarly. A user-oriented interface based on alphanumeric mnemonic and namelist data help alleviate potential bookkeeping problems.

The steps involved in the building modeling task have already been described (Figure 2). Simulation equations are specified as any combination of $\dot{\underline{x}}$ , $\underline{x}$, $\underline{y}$, $\underline{u}$ and are then used to generate the state-space model. As previously demonstrated, transfer functions can also be modeled. Interconnection of subsystem models created by any of the program segments is identical, and the namelist data from each subsystem is carried along to identify the reordered variables of the overall system. Simulations are performed by entering data to: (1) select desired components, (2) modify parameter values if desired, (3) interconnect components, and (4) specify desired outputs. The simulation proceeds as shown in Figure 6. The derivative computation, integration, and output update for all components are synchronized to avoid erroneous phase shifts. This is made possible by the structure of the simulation modules. Simulations of any complexity are performed identically.

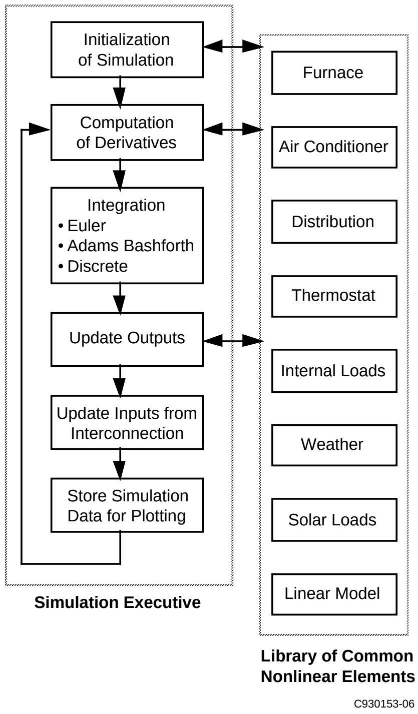

**Figure 6. Flow Diagram of Simulation Software**

## AN APPLICATION AND RESULTS

Electric utilities seek to influence the way customers use electricity because many find it difficult to meet peak load during the hottest (or coldest) days of the year when air conditioning (or electric heating) is in greatest demand. Finding ways to shift electricity usage to off-peak hours and reduce peak power demand benefits both the utility and the consumer. Using GEMS, a precooling load control strategy was analyzed to illustrate the use of simulation in quickly and effectively evaluating this and other concepts. Parameters of interest were peak demand reduction, overall energy use, and occupant comfort in terms of both temperature and PMV.

For this example, the simulated house from the GEMS library was a single-family, two-story house with basement, located in Eden Prairie, Minnesota. This house, which has been used extensively by researchers for testing new prototype HVAC control products, consists of three occupied zones, an unconditioned basement zone, and an attic zone. A forced-air distribution system model from the GEMS library was enhanced specifically for this house, with the ducts located in the basement and within walls and floors/ceilings. Duct thermal losses and air leakage were proportionately distributed into the zones through which the ducts ran. Internal gains were those due to people, lights, and appliances. In addition to lights, appliances contributing to the overall demand for electric power included a refrigerator, range, microwave oven, dishwasher, clothes washer and dryer, and water heater. A single-speed 3-ton air conditioner with a SEER of 11.0 was also used from the GEMS library. External influences to which the simulated house and HVAC systems were subjected were hourly weather data (ambient temperatures, wind speed and direction, solar insolation, etc.) from the typical meteorological year (TMY) database and adjacent earth temperatures.

The control strategy analyzed was one of precooling the house with thermostat setback prior to the peak-load period such that the cooling plant is operated to reduce the space temperature below the normal set point to permit cool storage within the building's thermal mass. However, before simulating the load management strategy, a baseline simulation was performed to establish a basis of comparison for the precooling strategy. The space dry-bulb temperature, indoor relative humidity, 15-min sliding-window average power, and PMV were used to evaluate the effectiveness of alternative strategies.

Results from the base case simulation on a hot and somewhat humid day are shown in Figures 7 and 8. Figure 7 shows that the space temperature is controlled as expected with a PI thermostat. The relative humidity is maintained near 45% except during periods of peak activity. In Figure 8, note that a single peak power demand occurs between 08:00 and 08:15 and two similar peaks occur in the late afternoon (17:00 to 17:25 and 18:00 to 19:00). These peaks are due to air conditioner, water heater, and cooking loads occurring simultaneously. The total energy used for the day was 45.6 kWh.

Figures 9 and 10 show results from using the precooling strategy of reducing the set point by 4°F (from 78° to 74°F) for 2 hours prior to the period of peak demand and then raising it to 80°F during the peak period (17:00 to 20:00). Figure 9 shows that the room air dry-bulb temperature is reduced to 75°F during the precooling (setback) period and then drifts up to 81°F during the 3-hour peak period. The indoor relative humidity peaks at 57% in the morning and again at 56% in the afternoon from a nominal 40% to 45%. When compared to the baseline case (Figure 8), Figure 10 shows that since no precooling strategy is applied for the morning hours, the morning peak demand of 7.3 kW occurs in both cases; however, the afternoon peak demands are reduced to 5.5 and 4.9 kW from 8.3 and 7.1 kW, respectively. The total energy used for the day decreases from 45.6 kWh for the baseline case to 44.8 kWh. This corresponds to a reduction in peak power demand of more than 30% during the time period of interest and a 2% reduction in the daily energy used.

The PMV profiles for the cases are shown in Figure 11. The index varies from +0.5 and +0.7 for the baseline case and from +0.5 to +1.1 for the simulated precooling strategy.

## CONCLUSIONS

GEMS was developed on the basis of state-space system modeling techniques, providing a highly structured, automated, and efficient means with which to design, develop, and analyze control algorithms and systems and to predict thermal performance and energy use in buildings and associated HVAC systems and components. In many instances, specifically in the development of control systems, a high level of detail and the ability to simulate at extremely small time steps is mandatory in predicting system response accurately to effectively perform closed-loop analysis. This level of detailed modeling and simulation capability provided by GEMS continues to be applied to the development and performance analysis of a wide range of control products.

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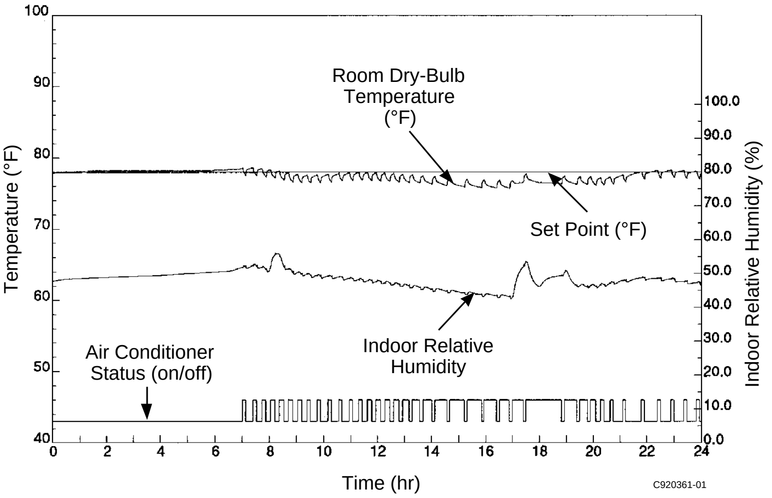

**Figure 7. House and HVAC System Response for a Hot and Humid Day (high = 98°F, dewpoint high = 60°F)**

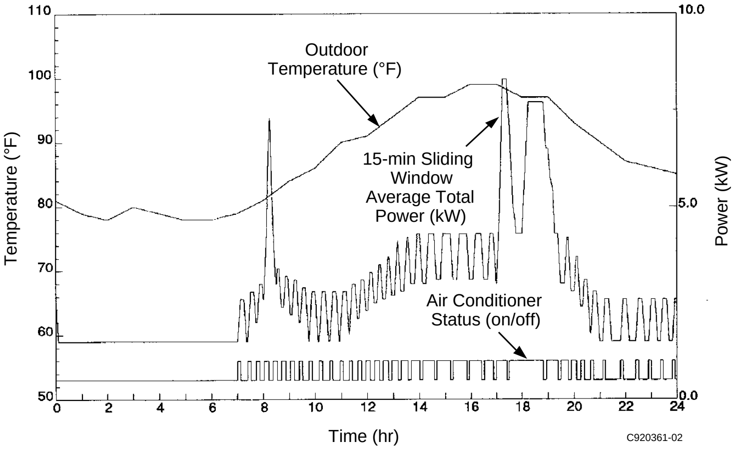

**Figure 8. 15-Min Sliding Power Average for a Hot and Humid Day (high = 98°F, dewpoint high = 60°F)**

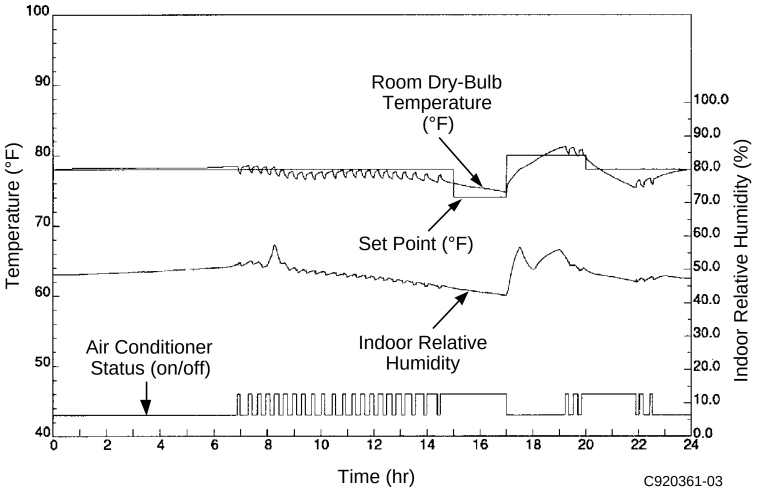

**Figure 9. House and HVAC System Response for a Hot and Humid Day (high = 98°F, dewpoint high = 60°F)—Precooling from 3:00 to 5:00 p.m.**

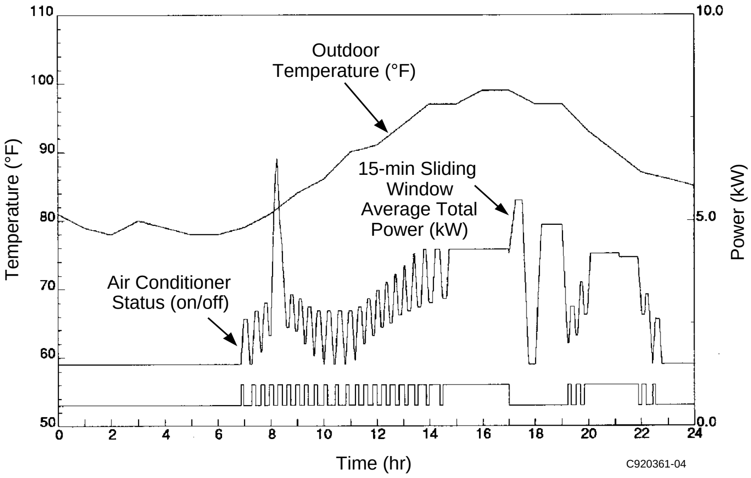

Figure 10. 15-Min Sliding Power Average for a Hot and Humid Day (high = 98°F, dewpoint high = 60°F)—Precooling from 3:00 to 5:00 p.m.

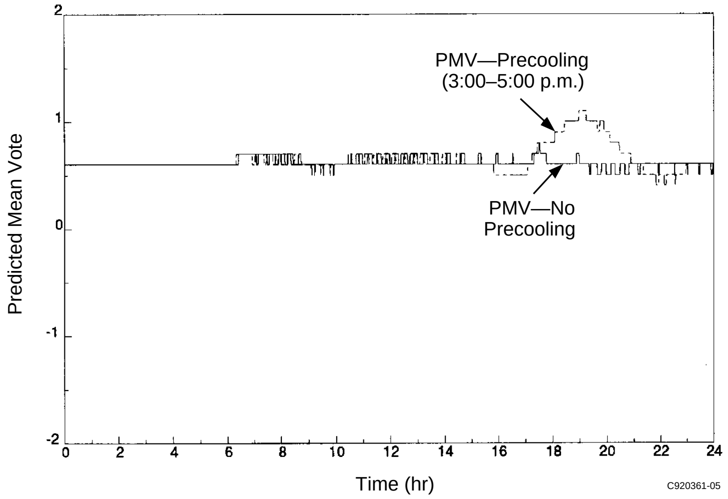

Figure 11. Predicted Mean Vote—Constant Set Point vs. Precooling (3:00 to 5:00 p.m.)