A Low-Cost Building/HVAC Emulator

How the emulator was developed, how its proper performance was verified, and how it can be used to evaluate control products

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Manufacturers of energy management and control systems (EMCS) have a strong interest in developing new products quickly, minimizing the time required to install and commission new systems, and making sure that new control products and systems work in a reliable manner when installed in a variety of real applications. The last is of particular importance since it helps to minimize the risk and cost involved in bringing new products to market. A building/HVAC emulator[1] is a promising new tool that is likely to assist manufacturers in these areas and to provide many additional benefits.

A building/HVAC emulator (sometimes called a simulator) is a simulation of a building and its HVAC system running in real time on a computer along with a hardware interface that allows the simulation to be connected to a real control system. It can be used to replace the entire building and mechanical system or can be interfaced with selected pieces of real HVAC equipment, such as coils, valves, boilers, and chillers.

One of the first building/HVAC emulators was developed by the National Institute of Standards and Technology (NIST) in 1985.[2] It employed a personal computer connected to EMCS sensor inputs and actuator outputs of the EMCS. The EMCS controlled the simulated building/HVAC system as if it were real and evaluated the EMCS's performance in terms of energy consumption, comfort level in the simulated space, actuator activity, and accuracy of control. In 1988, the International Energy Agency (IEA) Annex 17 committee was formed with the participation of nine countries. The main mission of this committee was to conduct research on evaluating the performance of EMCS through simulation and emulation methods. As part of this committee's efforts, six countries developed their own emulators,[3] and a validation exercise was carried out using four of the emulators.[4] All of the emulators used a component-based simulation program—either TRNSYS[5] or HVACSIM^{+}.[6] This research project showed that an emulator was a flexible, convenient, and reliable tool for testing real EMCS. It also demonstrated the value of EMCS for product development and testing, training, tuning control algorithms, and research on the development of fault detection and diagnostic methods.

The emulator research carried out under IEA Annex 17 was aimed at proving the concept and value of emulators. The six emulators that were constructed employed either work stations or multiple personal computers and/or proprietary software. For the most part, they were also fairly expensive to build. For example, the NIST emulator (described below) cost approximately $27,000 and, in addition, involved the use of an existing local area network. NIST has subsequently fostered a project to make emulators more affordable and more usable by industry. NIST and Johnson Controls Inc. (JCI) entered into a cooperative research and development agreement (CRADA) in 1993 to transfer the knowledge learned about emulation in Annex 17 to JCI.

The NIST/JCI CRADA involved a number of steps. These included selecting and developing an inexpensive hardware platform for the new emulator, transforming the appropriate simulation software from the NIST emulator developed in Annex 17 to the inexpensive emulator, developing new user interface software, testing the new emulator against existing benchmark tests to validate its performance, using the NIST/JCI emulator in a typical product development application, and finally sharing the results with industry, especially with other U.S. control companies.

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[1]*Superscript numerals indicate references listed at end of article.*

This article describes the building/HVAC process that was emulated, NIST's Annex 17 emulator, the less costly NIST/JCI emulator, the validation exercise, and the use of the new emulator by JCI to evaluate different tuning procedures for a variable air volume (VAV) box controller.

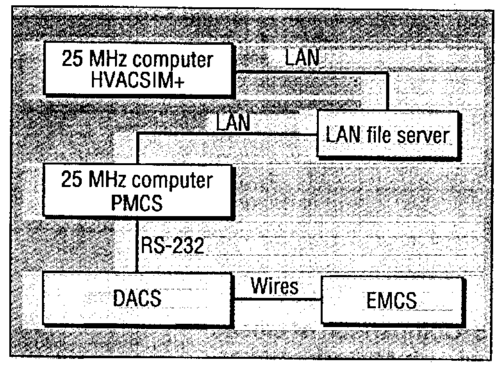
Building/HVAC emulation model

The building/HVAC system model, shown in Fig. 1, was used in this joint NIST/JCI research effort. It was basically the same model used in the Annex 17 emulation work[7] and consisted of a three-story office building with a VAV HVAC system. A single VAV air-handling unit served three zones, one on each floor. Each floor included an occupied space and a return air plenum. The air handler consisted of a mixing box, preheating coil, cooling coil, and supply fan. Each coil was served by a three-way flow control valve that was under the control of a PID controller in the EMCS. The outside, exhaust, and recirculating dampers were linked together and operated by an actuator that was controlled by a signal from the EMCS. A VAV box with reheat coils controlled the flow rate and temperature of the conditioned air for each zone. Control signals for the VAV boxes were also generated by PID loops in the EMCS. The central plant consisted of an oil-fired boiler, reciprocating chiller, and cooling tower. All the component models used in the building/HVAC emulation were TYPE subroutines in the HVACSIM+ program.

The simulated system was sequenced through a typical day's load conditions. The weather data used contained minute-by-minute data on the outside dry-bulb air temperature and the sol-air temperature on the external surfaces of the room and of the plenum. Hourly variations of the internal gains due to lights, equipment, and occupants in each of the three zones were considered. Changes in air pressure and variations in humidity were not accounted for. Two kinds of EMCS control algorithms were involved—local and supervisory. Local controls involved control of the preheat coil valve, cooling coil valve, mixing box dampers, VAV box dampers, and reheat coil valves in each zone. Firmware PID control algorithms on the EMCS were used for local control and were tuned for the system. The control logic for supervisory control was programmed using the programming language available on the EMCS.

NIST emulator for Annex 17

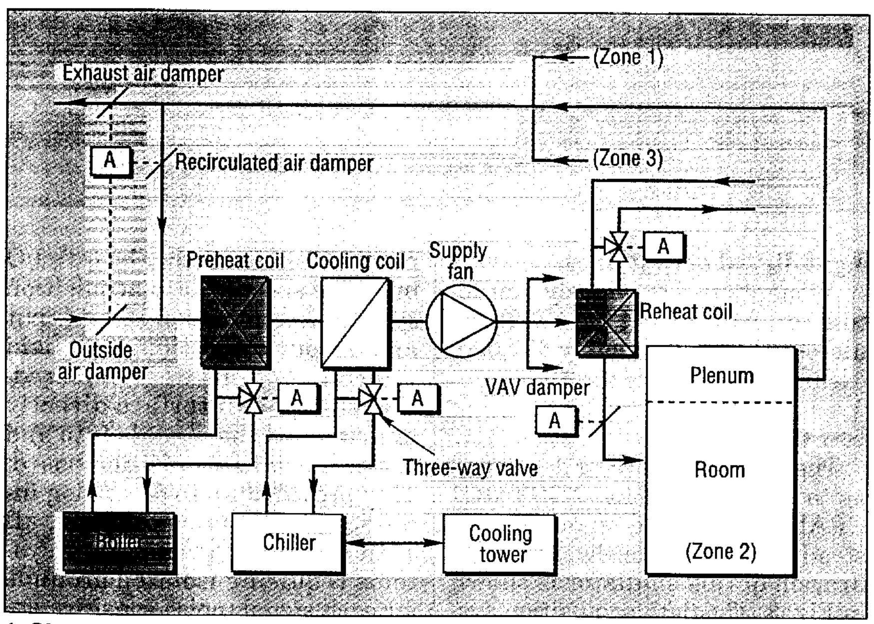
The NIST emulator developed as part of IEA Annex 17 activities formed the starting point for the low-cost emulator developed



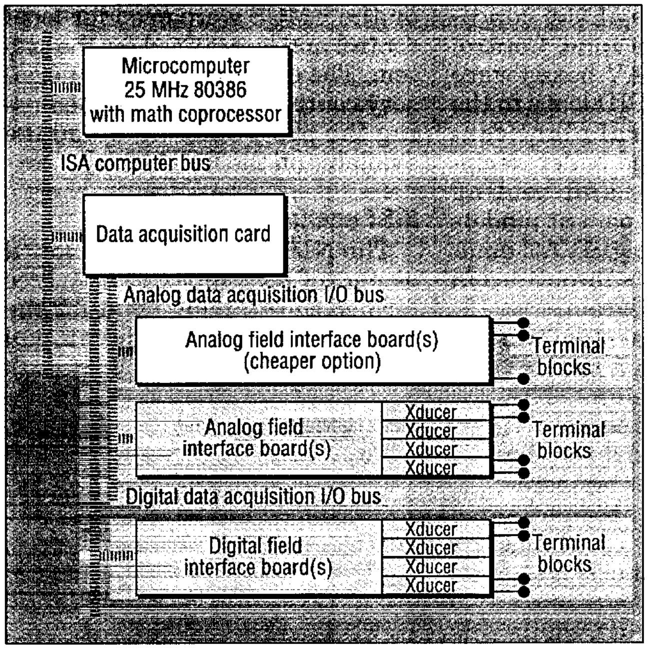
2 NIST emulator configuration.

through the NIST/JCI CRADA. As shown in Fig. 2, the EMCS was connected to the emulator through a stand-alone data acquisition and control system (DACS). Two personal computers were used—one to run the building/HVAC emulation model and the other to act as an interface with the human operator and with the DACS. The PCs communicated by means of file-passing through a file server on a local area network (LAN).

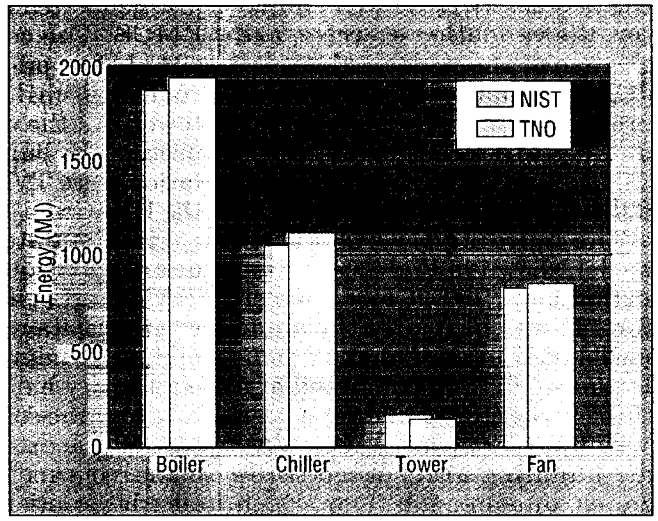
The building/HVAC system was emulated using the HVACSIM+ program running on a 25 MHz 80386 computer under a DOS operating system. This computer included a math coprocessor and 2 MB of RAM. A special component routine was written in FORTRAN and the C-language for data communication. A commercially available process management and control software (PMCS) program ran on a 20 MHz computer. This program served as the interface among the user, the HVACSIM+ program, and the DACS connected to an EMCS. A user-programmable portion of the



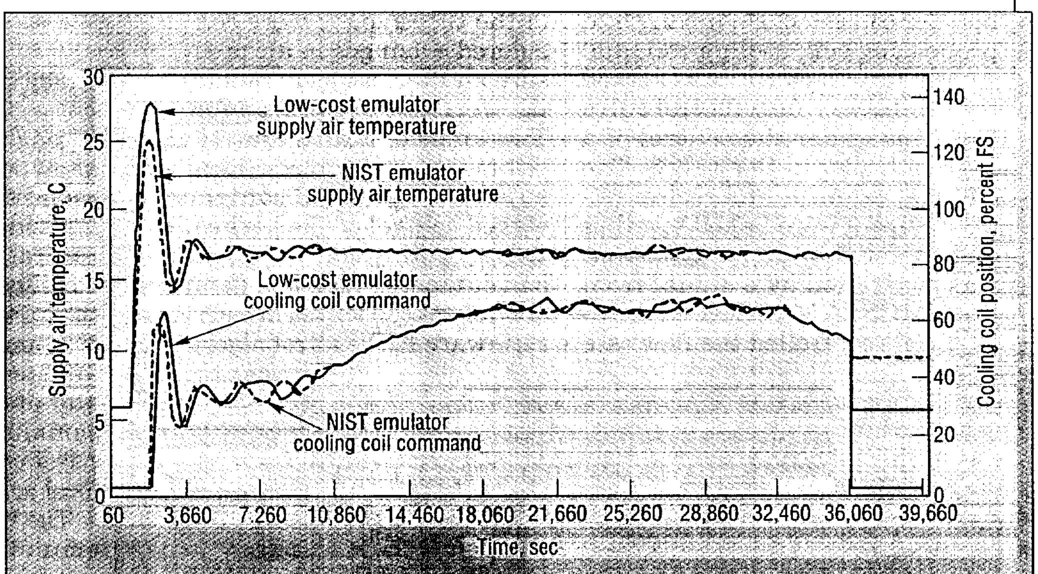
1 Simplified diagram of the building/HVAC system used in Exercise C1.



3 Low-cost emulator hardware configuration.



4 The energy usage by the subsystems.



5 Comparison of closed loop performance.

PMCS was customized for handling the data flow and some data manipulations, including the conversion of engineering units to and from the electric current or voltage signals required by the connected EMCS. Up to four selected variables could be plotted simultaneously on the screen as trend plots. The displayed data could also be stored on a hard disk for future processing.

The DACS consisted of eight modules—one system power supply, one system control unit, two voltage modules, and four current transmitter modules. The PMCS manipulated the individual inputs and outputs by command strings sent over a RS232 connection. The voltage module contained eight analog input channels, eight digital inputs, and eight digital outputs. The current transmitter module had eight 0 to 50 mA current transmitter channels plus eight digital input and eight digital output lines.

As mentioned previously, the actual cost for building the NIST emulator was approximately $27,000, excluding the cost of the LAN.

Low-cost emulator

The low-cost emulator developed as a result of the NIST/JCI CRADA was based on one PC instead of two. The hardware configuration of this emulator is shown in Fig. 3. The data acquisition system was incorporated into the computer using the mother board's I/O bus. The specific data acquisition system used provided 12-bit input and output resolution. Two field interface options were explored. The cheapest interface directly multiplexed the signals into and out of the data acquisition board. This provided up to 64 analog inputs and 16 analog outputs, all with a common ground. For systems requiring isolated grounds for each signal (noise-sensitive applications), a second interface was developed that includes isolating transducers. If desired, a separate digital I/O module can be purchased or the software can be written to treat analog inputs and outputs as digital signals.

The computer used was a 25 MHz 80386 DOS-compatible system with a math coprocessor and 4 MB of memory. The mother board had several ISA bus connectors, and a data acquisition board was inserted in one of these slots. The cheaper field interface uses two analog field interface boards. The electrically isolated field interface uses a board with various transducer modules. The cost for the cheaper system, including the PC and 16 analog inputs and 8 analog outputs, was less than $3500. The cost of the system providing isolated grounds, including the PC and 16 analog inputs and 8 analog outputs, was less than $7000.

Validation exercise

One of the joint exercises (Exercise C1)[8,3] conducted as a part of Annex 17 involved the testing of the same EMCS by NIST and TNO in the Netherlands. Each participant used its own emulator. The same building/HVAC system model was used; however, NIST chose to employ the HVACSIM$^+$ program to perform the exercise while TNO used the TRNSYS program. Minor modifications of the component models were made to convert them from HVACSIM$^+$ to TRNSYS-based component models. As seen in Fig. 4, the energy usages by the different subsystems obtained using the NIST and TNO emulators appear to be in reasonably good agreement.

This same exercise was carried out with the low-cost NIST/JCI emulator, and the results were compared with those previously obtained with the NIST and TNO Annex 17 emulators. In this case, however, a different EMCS was evaluated using the NIST/JCI emulator. Fig. 5 compares the control performance obtained with the NIST Annex 17 emulator and the NIST/JCI emulator. The supply air temperature and control signal to the cooling coil can be seen to be in good agreement over an 11-hr period.

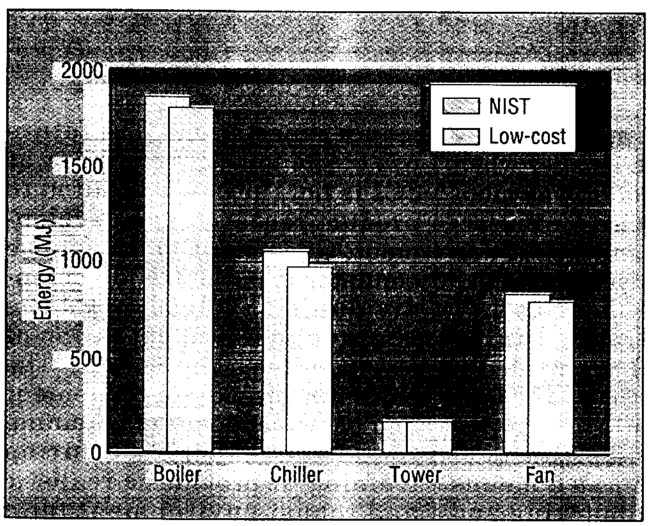
Table 1 gives a comparison of the energy usage, number of total starts/stops/reversals, and total distance traveled by all the actuators using the NIST Annex 17 emulator and the NIST/JCI emulator. In Fig. 6, a bar chart plot of the estimated energy usage by the different HVAC subsystems verifies that the low-cost emulator provided results similar to the more expensive NIST and TNO Annex 17 emulators.

Low-cost emulator application

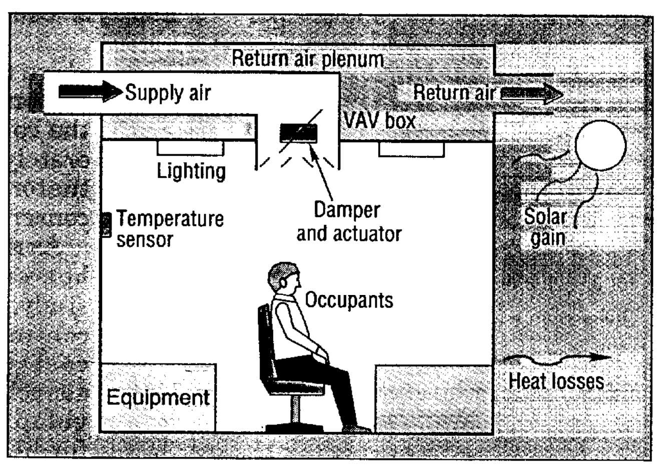
Subsequent to its development, the low-cost building/HVAC emulator has been employed at JCI to test several new products. In one application, the emulator was used by JCI to verify an optimal tuning procedure for a VAV box controller. A portion of HVAC system modeled for a zone is shown in Fig. 7. Fig. 8 shows a schematic of the test configuration for the VAV emulation model.

Trade-offs between VAV box actuator wear and occupant comfort were studied in these tests. Using an emulator rather than a real unit was preferable because the emulator provided a means of conducting a significant number of repeatable tests in a short period of time. The emulator also allowed the tests to be conducted under "typical" operating conditions. For these tests, a data set of a typical day's supply air conditions entering a VAV box was extracted from the data produced in the Annex 17 (C1) experiment described above. The dry-bulb temperatures and humidity ratios of the air entering the VAV box are displayed in Fig. 9 for a 10-hr period. The central plant and air-handling unit outputs in the C1 experiment were replaced by this typical daily profile.

The emulator was used to evaluate the performance of different tuning procedures. The zone air temperatures and the damper po-



6 Comparison of estimated energy usage.

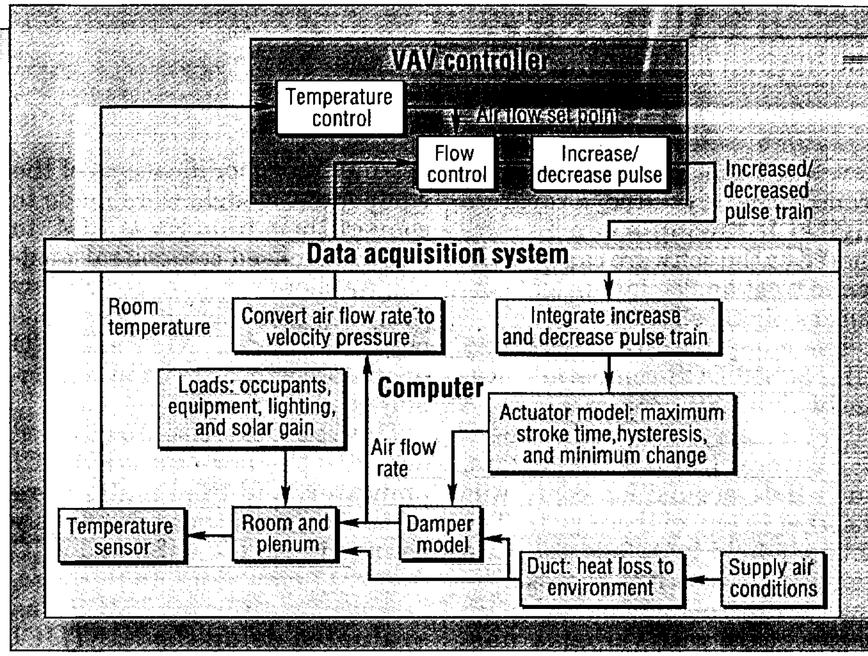


7 Portion of HVAC system modeled for a zone.

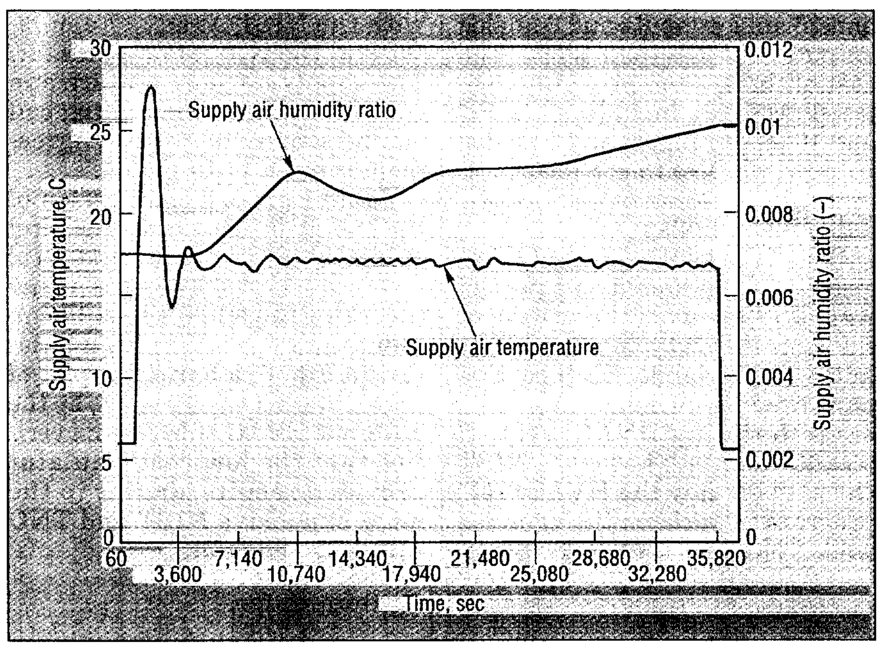
sitions over the 10-hr period are shown in Fig. 10 for the cases of aggressive, moderate, and conservative tuning. For each of these tuning cases, the number of actuator starts/stops/reversals and the integrated error squared of the zone air temperature are shown in Tables 2 and 3 for VAV box damper actuators having travel times of 1 and 2 min. These quantities were used by JCI as approximate measures of actuator wear and occupant comfort.

For the actuator with a travel time of 1 min, it is apparent from Fig. 10 and Table 3 that the different tuning procedures had a negligible effect on the zone air temperature. However, there were significant differences among the tuning procedures in the numbers of starts/stops/reversals and the total distances traveled by the actuators (Table 2). Based on these two measures of performance, moderate and conservative tunings are clearly preferable to aggressive tuning. Moderate tuning was only slightly better than conservative tuning in reducing the total number of starts/stops/reversals and distances traveled.

For the actuator with a travel time of 2 min, moderate tuning also resulted in the lowest number of starts/stops/reversals and the smallest total distances traveled (Table 2). In addition, as shown in Table 3, the integrated error squared of the zone temperature was approximately 14 percent smaller when the controller was moderately tuned for this actuator than when it was conservatively tuned.



8 Block diagram of emulation test configuration.



9 Supply air condition profile.

TABLE 1—Comparison of performance measures.

	NIST emulator	Low-cost emulator
Total starts/stops/reversals for all actuators	357.0	350.0
Total distance traveled for all actuators	23.7	10.6
Boiler energy usage (MJ)	1861.5	1794.2
Chiller energy usage (MJ)	1046.5	982.5
Cooling tower energy usage (MJ)	145.2	144.0
Supply fan energy usage (MJ)	813.1	799.4
Total cooling energy usage (MJ)	2004.8	1925.9

As a result of this VAV box controller tuning study, JCI has decided to continue to use the low-cost emulator in research and product development as a means for benchmarking and verifying system performance expectations. The future use of the low-cost emulator at JCI is not, however, limited to product research and development. One potential use for the emulator is in the training of individuals involved with the maintenance and operation of HVAC systems and controls. The emulator provides a convenient and portable means of obtaining "hands-on" experience during training. It provides a realistic and robust environment for a person to learn from mistakes and successes without the risk of damaging expensive equipment or adversely affecting the comfort of building occupants. Control experience can be gained in typical and abnormal situations before having to deal with those situations in real buildings.

Summary

Building upon the research done under IEA Annex 17, NIST and JCI have collaborated to develop a low-cost emulator that can be used in product research and development and in the training of maintenance and operating personnel. After validating the performance of the emulator by carrying out the same joint exercise performed by participants in Annex 17, JCI used the emulator to study different tuning techniques for VAV box controllers. This experience, along with the many benefits of using emulators for training, has led to a commitment on the part of JCI to continue to employ emulators in these and other applications. With the reduction in the cost of emulators and the documentation of the many benefits that they can provide, we expect that building/HVAC emulators will, in the near future, have a significant impact on how building control products are developed and tested. **HPAC**

TABLE 2—Summary of actuator wear measures.
(Percentage reductions are relative to aggressive tuning case.)

Actuator travel time, min	Tuning Procedure	Number of starts/stops/ reversals	Total distance traveled	Reduction of starts/stops/ reversals, percent	Reduction of starts/stops/ reversals, percent
1	Aggressive	248	388	—	—
1	Moderate	54	331	–78.2	–14.7
1	Conservative	55	335	–77.8	–13.6
2	Agressive	94	410	—	—
2	Moderate	77	384	–18.1	–6.3
2	Conservative	83	395	–11.7	–3.7

TABLE 3—Comparison of zone temperature control measures.
(Integrated error squared was taken in the period form 2.5 to 10 hr. Percentage reductions are relative to aggressive tuning case.)

Actuator travel time, min	Tuning procedure	Integrated error squared of zone temperature	Increase in integrated error squared, percent
1	Aggressive	2748	—
1	Moderate	2702	–1.7
1	Conservative	2753	0.2
2	Aggressive	2546	—
2	Moderate	2624	3.1
2	Conservative	3045	19.6

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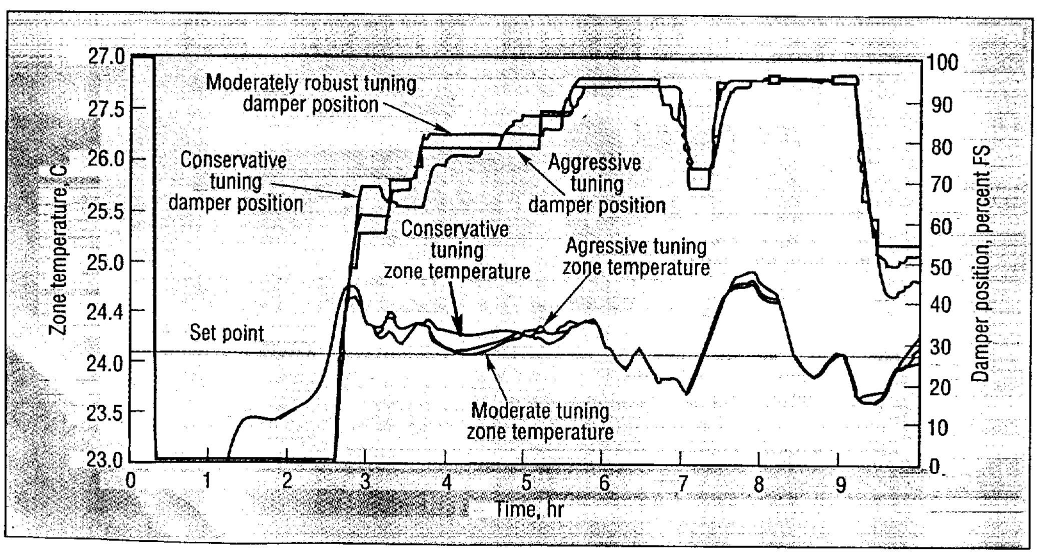

10 Zone temperatures and damper positions for different tunings with the actuator having travel time of 1 min.