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HVAC BESTEST: A Procedure for Testing the Ability of Whole-Building Energy Simulation Programs to Model Space Conditioning Equipment

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HVAC BESTEST: A PROCEDURE FOR TESTING THE ABILITY OF WHOLE-BUILDING ENERGY SIMULATION PROGRAMS TO MODEL SPACE CONDITIONING EQUIPMENT

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ABSTRACT

Validation of Building Energy Simulation Programs consists of a combination of empirical validation, analytical verification, and comparative analysis techniques (Judkoff 1988). An analytical verification and comparative diagnostic procedure was developed to test the ability of whole-building simulation programs to model the performance of unitary space-cooling equipment that is typically modeled using manufacturer design data presented as empirically derived performance maps. Field trials of the method were conducted by researchers from nations participating in the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 22, using a number of detailed hourly simulation programs from Europe and the United States, including: CA-SIS, CLIM2000, PROMETHEUS, TRNSYS-TUD, and two versions of DOE-2.1E. Analytical solutions were also developed for the test cases.

INTRODUCTION

Increasing power and the attractive pricing of personal computers has engendered a proliferation of energy-analysis software for buildings. An on-line directory sponsored by the U.S. Department of Energy (*BETD*, 2000) lists more than 200 building-energy software tools developed worldwide that have thousands of users. It is important that the users of building energy simulation tools are confident about their utility and accuracy because using such tools offers great potential for energy savings and comfort improvements. Validation and testing is a necessary part of any software development process and is intended to ensure credibility by eliminating bugs, algorithm errors, physics errors, and documentation errors. Formal procedures that address quality control of building energy simulation software are just now appearing. One of these is the IEA BESTEST procedure—developed in conjunction with the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 12—that tests a simulation program's ability to model heat transfer associated with the building fabric, and basic thermostat controls and mechanical ventilation (Judkoff and Neymark 1995a).

A code language adapted version of the IEA BESTEST procedure was recently approved by the American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) as a Standard Method of Test for evaluating building energy analysis computer programs (ASHRAE 2000). In the United States, the National Association of State Energy Officials/ Residential Energy Services Network (NASEO/RESNET) has also adopted the HERS BESTEST procedure (Judkoff and Neymark 1995b) as the basis for certifying software to be used for Home Energy Rating Systems (HERS) under their National Guidelines. (NASEO/RESNET 2000). The BESTEST procedures are also being used as teaching tools for simulation courses at universities in the United States and Europe. The popularity of these BESTEST procedures is further evident from the large number of requests we have received for them (more than 800).

As part of IEA SHC Task 22, the previous IEA BESTEST work was expanded to include more evaluation of heating, ventilating, and air-conditioning (HVAC) equipment models. This new procedure, HVAC BESTEST (Neymark and Judkoff 2000), is presented in this paper.

APPROACH

There are only a few ways to evaluate the accuracy of a whole-building energy simulation program (Judkoff et al. 1983a):

- *Empirical Validation*—in which calculated results from a program, subroutine, or algorithm are compared to monitored data from a real building, test cell, or laboratory experiment.
- *Analytical Verification*—in which outputs from a program, subroutine or algorithm are compared to results from a known analytical solution or a generally accepted numerical method for isolated heat transfer mechanisms under very simple and highly defined boundary conditions.

- *Comparative Testing*—in which a program is compared to itself or to other programs that may be considered better validated or more detailed and, presumably, more physically correct.

Each of these approaches has different strengths and weaknesses. (Judkoff 1988; Neymark and Judkoff 2000)

In this project, the BESTEST comparative test method was extended for testing mechanical system simulation models. This extension, "HVAC BESTEST" cases E100–E200, consists of a series of steady-state analytical verification tests using a carefully specified mechanical system applied to a highly simplified near-adiabatic building envelope. The mechanical equipment load is driven by sensible and latent internal gains such that the sensitivity of the simulation programs to a number of equipment performance parameters are explored. Output values for the cases, such as compressor and fan electricity consumption, cooling coil sensible and latent loads, coefficient of performance (COP), zone temperature, and zone humidity ratio are compared and used in conjunction with diagnostic logic to determine the algorithms responsible for predictive differences.

In these steady-state cases, the following parameters are varied (as summarized in Table 1): sensible internal gains, latent internal gains, zone thermostat set point (entering dry-bulb temperature), and outdoor dry-bulb temperature. Parametric variations isolate the effects of the parameters singly and in various combinations, as well as the influence of: part-loading of equipment, varying sensible heat ratio, "dry" coil (no latent load) versus "wet" (with dehumidification) coil operation, and operation at typical Air-Conditioning and Refrigeration Institute (ARI) rating conditions. In this way, the models are tested in various regions of the performance map.

Table 1. HVAC BESTEST Case Descriptions

	Zone			Weather	
	Internal Gains*		Setpoint		
Case #	Sensible (W)	Latent (W)	EDB (°C)	ODB (°C)	Comments
dry zone series					
E100	5400	0	22.2	46.1	Base case, dry coil. High PLR.
E110	5400	0	22.2	29.4	High PLR. Tests low ODB versus E100.
E120	5400	0	26.7	29.4	High PLR. Tests high EDB versus E110. Tests ODB & EDB interaction versus E100.
E130	270	0	22.2	46.1	Low PLR test versus E100.
E140	270	0	22.2	29.4	Tests ODB at low PLR vs E130. Tests PLR at low ODB vs E110.
humid zone series					
E150	5400	1100	22.2	29.4	High PLR. High SHR. Tests latent load versus E110.
E160	5400	1100	26.7	29.4	High PLR. High SHR. Tests EDB versus E150.
E165	5400	1100	23.3	40.6	High PLR. High SHR. Tests ODB & EDB interaction with latent load versus E160.
E170	2100	1100	22.2	29.4	Mid PLR. Mid SHR. Tests low sensible load versus E150.
E180	2100	4400	22.2	29.4	High PLR. Low SHR. Tests SHR versus E150. Tests high latent load versus E170.
E185	2100	4400	22.2	46.1	High PLR. Low SHR. Tests ODB versus E180.
E190	270	550	22.2	29.4	Low PLR. Low SHR Tests low PLR at constant SHR vs E180. Tests latent load at low PLR versus E140.
E195	270	550	22.2	46.1	Low PLR. Low SHR Tests ODB at low PLR & SHR versus E190. Tests low PLR at constant SHR vs E185. Tests latent load at low PLR versus E130.
full load test at ARI conditions					
E200	6120	1817	26.7	35.0	Tests for ARI indoor wetbulb temperature at full sensible and latent loads.

Abbreviations: PLR = Part Load Ratio; ODB = outdoor drybulb temperature;
EDB = entering drybulb temperature; vs = versus;
SHR = Sensible Heat Ratio; ARI = Air Conditioning and Refrigeration Institute.

*Internal Gains are internally generated sources of heat and humidity that are not related to operation of the mechanical cooling system or its air distribution fan.

Given the underlying assumptions of the case definitions, analytical solutions are given that represent a mathematically provable and deterministic solution for each case. The underlying physical assumptions regarding the mechanical equipment are representative of typical manufacturer catalog data, normally used by building design practitioners, that many "whole-building" simulation programs are designed to work with. Two sets of analytical solutions were initially developed independently by different organizations and then compared and improved as described later.

SPECIFICATION OF THE TEST CASES

No two programs require exactly the same input information. Therefore, we have tried to describe the test cases in a fashion that allows many different building simulation programs (representing different degrees of modeling complexity) to be tested.

The configuration of the base-case building (Case E100) is a windowless, near-adiabatic rectangular single zone with only user-specified internal gains to drive cooling loads. The geometric and materials specifications are purposely kept as simple as possible to minimize the opportunity for input errors on the part of the user. Mechanical equipment specifications represent a simple unitary vapor-compression cooling system or, more precisely, a split-system, air-cooled condensing unit with indoor evaporator coil as shown in Figure 1.

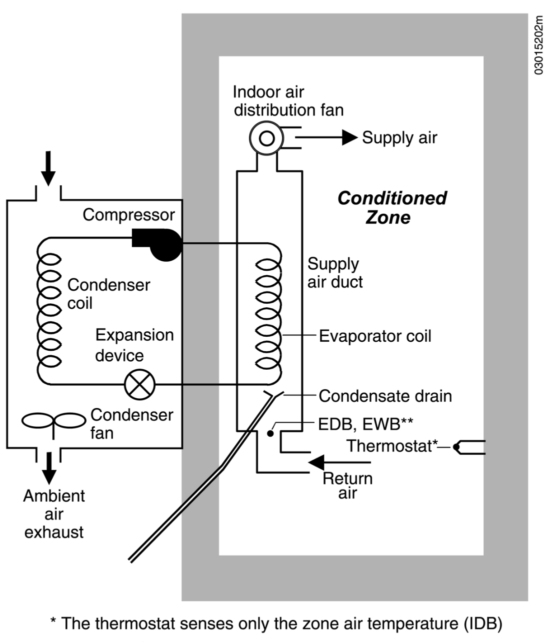

Figure 1. Unitary split system, air-cooled condensing unit with indoor evaporator coil

General specifications of the mechanical system are included with the full test procedure. Full-load performance data is given in the format typical of manufacturer catalog data. This data lists Total (Sensible + Latent) Capacity, Compressor Power, and Apparatus Dew Point as f(ODB, EWB). Additionally, the sensible capacity is given as f(ODB, EWB, EDB). Equivalent data is given in three formats that list gross capacities (including fan heat), adjusted net capacities (excluding fan heat of the specified fan), and original manufacturer net capacities (excluding fan heat assumed by the manufacturer—which is not the same as the actual fan heat). Space limitations prevent us from including an example performance data table here. Instructions are included that clarify how to properly use these tables to adapt them for use in simulations; such instructions are not normally included with the manufacturer's catalogs. A COP f(PLR) curve is given to account for performance degradation at partial loads caused by equipment cycling. Other equivalent input data are also included.

ANALYTICAL SOLUTION RESULTS

HVAC BESTEST cases E100–E200 include analytical solutions. These solutions represent a "mathematical truth standard." That is, given the underlying physical assumptions in the case definitions, there is a mathematically provable and deterministic solution for each case. In this context, the underlying physical assumptions regarding the mechanical equipment as defined in cases E100-E200 are representative of typical manufacturer data normally used by building design practitioners. Many "whole-building" simulation programs are designed to work with this type of data.

It is important to understand the difference between a "mathematical truth standard" and an "absolute truth standard." In the former, we accept the given underlying physical assumptions while recognizing that these assumptions represent a simplification of physical reality. The ultimate or "absolute" validation standard would be comparison of simulation results with a *perfectly performed* empirical experiment, the inputs for which are *perfectly specified* to the simulationists. In reality, an experiment is performed and the experimental object is specified within some acceptable range of uncertainty. Such experiments are possible, but fairly expensive. We recommend developing a set of empirical validation experiments in the future.

Two of the IEA participating organizations independently developed analytical solutions that were submitted to a third party for review. (Le and Knabe 2000; Durig *et al.*

2000; Glass 2000) Comparing the results indicated some disagreements, which were then resolved by allowing the solvers to review the third-party reviewers' comments and to review and critique each others' solution techniques. This process resulted in both solvers making changes to their solutions such that their final results are mostly within a <1% range of disagreement. Remaining differences in the analytical solutions are due in part to the difficulty of completely describing boundary conditions. In this case the boundary conditions are a compromise between full reality and some simplification of the real physical system that is analytically solvable. Therefore, the analytical solutions have some element of interpretation of the exact nature of the boundary conditions that causes minor uncertainty in the results. This may be less than perfect from a mathematician's viewpoint, but quite acceptable from an engineering perspective. Specific examples of remaining minor differences in the solutions are discussed in Part II of the full technical report. (Neymark and Judkoff 2000)

The remaining minor disagreement among the analytical solutions is small enough to identify bugs in software that would not otherwise be apparent from comparing software only to other software and, therefore, improves the diagnostic capabilities of the test procedure.

FIELD TRIAL RESULTS/ SIMULATION DIAGNOSTIC RESULTS

Errors Found in Simulation Programs

The analytical solution results and the simulation results presented here are intended to be useful for evaluating other detailed or simplified building energy prediction tools. The collective experience of the group has shown that when a program exhibits major disagreement with the analytical solution results, the underlying cause is usually a bug, faulty algorithm, or documentation problem. During the field trials, the HVAC BESTEST diagnostic methodology was successful at exposing such problems in every one of the simulation programs tested. This list is summarized in Table 2 (next page). A brief illustration of the diagnostic process used to find specific bugs is included below. Detailed discussion regarding using the HVAC BESTEST diagnostics on CA-SIS and CLIM2000 is presented in a separate paper for this conference by another of the IEA SHC Task 22 participants (Hayez et al. 2001).

TRNSYS is the main program for active solar systems analysis supported by the U.S. Department of Energy; TRNSYS-TUD is a version with custom algorithms developed by Technische Universitat Dresden (TUD), Germany. For the initial set of TRNSYS-TUD results at low part loads (cases E130, E140, E190, and E195), there were large (43%–48%) errors in sensible and latent coil loads, which also propagated through to energy consumption predictions. For the mid-PLR Case E170, the error was also high at 14% for energy consumption. Diagnostic logic indicated that the problem could be with the application of the part-load curve. Upon further review, the code authors discovered a problem with using single precision variables in one of the calculation subroutines associated with their model that applies a realistic system controller. This caused rounding errors, which became worse as PLR (and resulting fraction of operation-time per hour) decreased.

Figure 2 documents the results of TUD's simulations before and after fixing this problem and includes a comparison with TUD's analytical solution results (later verified by HTAL's analytical solution results). The figure shows that when the appropriate variables were changed to double precision variables, the simulation results were substantively improved.

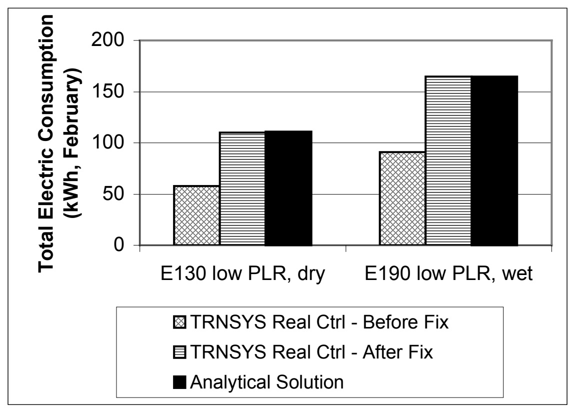

Figure 2. TRNSYS-TUD single precision variable problem

Evaluation of Simulation Programs

Improvements to the simulation programs are evident from comparing the initial results set to the current results set. Initial simulation results for COP obtained after the first round of simulations, prior to developing analytical solutions, are shown in Figure 3. (Abbreviations at the bottom of this table's x-axis are shorthand for the case descriptions; see Table 1 for full case descriptions.) These results indicate 2%–30% *average* disagreement versus the mean of the simulated COP results; corresponding disagreement of energy consumption results was 4%–40%.

Table 2. Summary of Software Problems found with HVAC BESTEST

Software	Error Description	% Disagreement	Resolution
CASIS	No extrapolation of performance data	Possibly up to 10% power (E110, E100)	Manually fixed*
CASIS	Convergence Algorithm	E200 would not run (convergence problem)	Fixed
CASIS	Fan heat added to coil load	4% sensible coil load ([4% power f(SHR))	Fixed
CASIS	ID & OD fan power did not include COP f(PLR)	2% power (mid PLR)	Fixed
CLIM2000	Verification of new model improvements	up to 50% COP for earlier model	Fixed
CLIM2000	Compressor/fan power does not include COP f(PLR)	20% power (low PLR) 13% power (mid PLR)	Fixed
CLIM2000	Performance map extrapolation problem	9% power (E110)	Fixed
DOE-2.1E (JJH ver < W54)	Minimum supply temperature coding error in early RESYS2 system	36% COP (base case)	Fixed
DOE-2.1E (JJH ver 133)	Coil/Zone load difference inconsistent with fan power for RESYS2 at low SHR.	5% sensible coil load (at low SHR)	Authors notified
DOE-2.1E (JJH ver 133)	COIL-BF-FT insensitivity	1% power (E185)	Authors notified
DOE-2.1E (JJH ver 133 & ESTSC ver 088)	Fan power does not include COP f(PLR) degradation (RESYS2 and PTAC).	2% power (mid PLR)	Authors notified
DOE-2.1E (ESTSC v 088)	Coil/Zone load difference inconsistent with fan power for PTAC at low SHR.	2% sensible coil load (at low SHR)	Authors notified
PROMETHEUS	Compressor COP f(PLR) calculated externally	20% power (low PLR) if no external calc	Authors plan to fix
TRNSYS-TUD (realistic ctrl)	Use of some single precision variables in the code.	45% power (low PLR) 14% power (mid PLR)	Fixed
TRNSYS-TUD (realistic ctrl)	Wrong data compiled for Coil Latent Load output.	4% power (E150) 3% lat. coil (E170)	Fixed

*Current results include non-automated version of the fix.

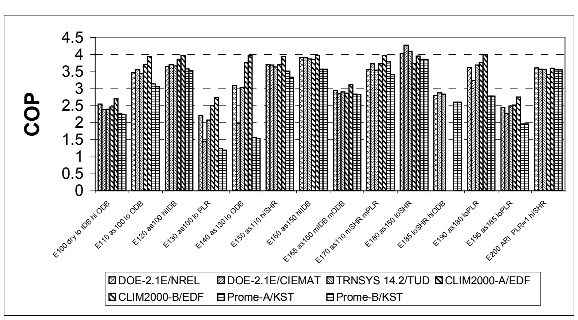

Figure 3. HVAC BESTEST — mean COP, initial results

The current set of COP results for all the simulations and analytical solutions are included in Figure 4. After correcting software errors using HVAC BESTEST diagnostics, the mean results of COP and total energy consumption for the programs are on average within <1% of the analytical solution results, with variations of up to 2% for the low PLR dry coil cases (E130 and E140). Ranges of disagreement are further summarized in Table 3 for predictions of various outputs, disaggregated for dry coil performance (no dehumidification) and for wet coil performance (dehumidification moisture condensing on the coil). This range of disagreement is defined as the difference between the maximum and minimum for the simulation results, divided by the mean of the analytical solution results. The Table 3 summary excludes results for the PROMETHEUS participants; they suspected an error(s) in their software, but were not able to complete the project.

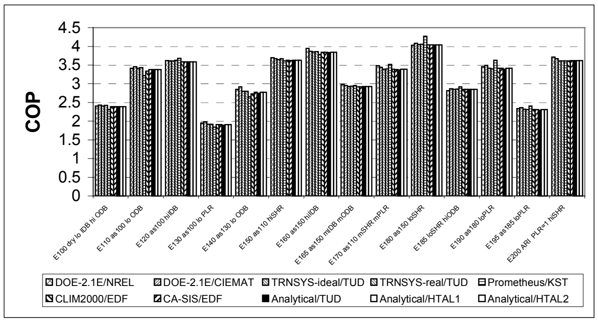

Figure 4. HVAC BESTEST — mean COP, current results

Table 3. Ranges of Disagreement Among Simulation Results

Cases	Dry Coil (E100-E140)	Wet Coil (E150-E200)
COP and Total Elec. Consumption	0% - 6%	0% - 3%
Zone Humidity Ratio	0% - 11%	0% - 7%
Zone Temperature	0.0°C - 0.7°C	0.0°C - 0.5°C

The higher level of disagreement in the dry coil cases occurs for the case with lowest PLR and is related to some potential problems that have been documented for DOE-2.1E (ESTSC version 088 and Hirsch Associates (JJH) version 133) in both the Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas (CIEMAT) and National Renewable Energy Laboratory (NREL) results (see Table 2). The larger disagreements for zone humidity ratio are caused by disagreements for the CLIM2000 and DOE-2.1E/CIEMAT results. The disagreement in zone temperature results is primarily from the TRNSYS-TUD results applying a realistic controller on a short time-step (36 seconds); all other simulation results apply ideal control.

Based on results after "HVAC BESTESTing", the programs appear reliable for performance-map modeling of space-cooling equipment when the equipment is operating close to design conditions. In the future, HVAC BESTEST cases will explore modeling at "off-design" conditions and the effects of using more realistic control schemes.

CONCLUSIONS AND RECOMMENDATIONS

The BESTEST procedures have been expanded to include HVAC BESTEST. This is an analytical verification and comparative diagnostic procedure, developed to test the ability of whole-building simulation programs to model the performance of unitary space-cooling equipment that is typically modeled using manufacturer design data presented as empirically derived performance maps.

Two of the IEA participating organizations independently developed analytical solutions that were submitted to a third party for review. After resolving disagreements, the final analytical solution results agree within about a <1% range. This remaining disagreement is small enough to offer a powerful tool for identifying even subtle bugs in software.

During the field trials, the HVAC BESTEST diagnostic methodology successfully exposed a number of bugs and faulty algorithms in every one of the simulation programs tested. The more prominent bugs and faulty algorithms caused errors of up to 20%–45% in predicting energy consumption or COP. A number of errors with smaller effects on predictions were also found. Checking a building energy simulation program with HVAC BESTEST should require about one week for an experienced user, assuming that any bugs found are easily fixable. Because the simulation programs have taken many years to produce, HVAC BESTEST provides a very cost-effective way of testing them. As we continue to develop new test cases, we will adhere to the principle of parsimony so that the entire suite of BESTEST cases may be implemented by users within a reasonable span of time.

After correcting software errors using HVAC BESTEST, the current generation of programs appears reliable for performance-map modeling of space-cooling equipment when the equipment is operating close to design conditions. Mean results of COP and total energy consumption for the programs are generally within <1% of the analytical solution results. Some isolated COP disagreements outside of the range remain; the appropriate simulation authors have been notified. Disagreements for zone humidity ratio predictions are generally a bit greater than for other outputs, and isolated disagreements also exist for this output; the appropriate simulation authors were notified.

The current cases only check equipment performance over a limited range of operation. Additional cases have been defined for future work to further explore the issue of modeling equipment performance at “off-design” conditions that are not typically included within performance data provided in manufacturer catalogs. These cases include:

- Quasi-steady-state performance using dynamic boundary conditions (dynamic internal gains loading and dynamic weather data)
- Latent loading from infiltration
- Outside air mixing
- Periods of operation away from typical design conditions
- Thermostat setup (dynamic operating schedule)
- Undersized system performance
- Economizer with a variety of control schemes
- Variation of Part-Load Ratio (using dynamic weather data)
- ODB and EDB performance sensitivities (using dynamic loading and weather data)

Other cases under consideration for future development are listed in the full HVAC BESTEST document.

The previous IEA BESTEST procedure (Judkoff and Neymark 1995a), developed in conjunction with IEA SHC Task 12, that primarily tests envelope modeling capabilities, has been code-language adapted and approved as a Standard Method of Test for evaluating building energy analysis computer programs - BSR/ASHRAE Standard 140P (ASHRAE 2001). We anticipate that after code language adaptation, HVAC BESTEST will be added to that Standard Method of Test. In the United States, the NASEO/RESNET has also adopted HERS BESTEST (Judkoff and Neymark 1995b) as the basis for certifying software to be used for Home Energy Rating Systems under their National Guidelines. The BESTEST procedures are also being used as teaching tools for simulation courses at universities in the United States and Europe. We hope that as the procedures become better known, developers will automatically run the tests as part of their normal in-house quality control efforts. The large number of requests for the envelope BESTEST reports we have received (over 800) indicates that this is beginning to happen. Developers should also include the test input and output files with their respective software packages to be used as part of the standard benchmarking process by the user.

ACKNOWLEDGEMENTS

The expertise available through IEA, and the dedication of the participants were essential to the success of this project. Over the three-year field trial effort, there were several revisions to the HVAC BESTEST specifications and subsequent re-execution of the computer simulations. This iterative process led to the refinement of HVAC BESTEST, and the results of the tests led to the improvement and debugging of the programs. The process underscores the leveraging of resources for the IEA countries participating in this project. Such extensive field trials, and resulting enhancements to the tests, would not have occurred without the participation of the IEA SHC Task 22 experts. Contributions from the modelers and the authors of sections on the computer programs used in this effort are gratefully acknowledged as follows:

- CA-SIS V1: S. Hayez; Electricité de France, France.
- CLIM2000 V2.4: G. Guyon, J. Féburie, and R. Chareille; Electricité de France, France.
- DOE-2.1E ESTSC Version 088: J. Travesi; Centro de Investigaciones Energéticas, Medioambientales y Tecnologicas, Spain.
- PROMETHEUS: M. Behne; Klimasystem-technik, Germany.

We also appreciate the support and guidance of Dru Crawley, DOE Program Manager for Task 22 and DOE representative to the IEA Solar Heating and Cooling Programme Executive Committee.

MEMORIAM

We wish to honor the passing of our colleague Dave Wortman last year. He was one of the pioneers involved with NREL’s building energy simulation validation work, and was an active member of the building energy analysis community. He is missed.

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NOMENCLATURE

COP: Coefficient Of Performance
EDB: Entering Drybulb Temperature
EWB: Entering Wetbulb Temperature
ODB: Outdoor Drybulb Temperature
PLR: Part Load Ratio
SHR: Sensible Heat Ratio

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13. ABSTRACT *(Maximum 200 words)* Validation of Building Energy Simulation Programs consists of a combination of empirical validation, analytical verification, and comparative analysis techniques (Judkoff 1988). An analytical verification and comparative diagnostic procedure was developed to test the ability of whole-building simulation programs to model the performance of unitary space-cooling equipment that is typically modeled using manufacturer design data presented as empirically derived performance maps. Field trials of the method were conducted by researchers from nations participating in the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 22, using a number of detailed hourly simulation programs from Europe and the United States, including: CA-SIS, CLIM2000, PROMETHEUS, TRNSYS-TUD, and two versions of DOE-2.1E. Analytical solutions were also developed for the test cases.			
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