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LITERATURE REVIEW OF UNCERTAINTY OF ANALYSIS METHODS

(DOE-2 Program)

Report to the
Texas Commission on Environmental Quality

TCEQ

DRAFT

Jeff S. Haberl, Ph.D., P.E.
Soolyeon Cho

Energy Systems Laboratory
Texas A&M University System

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ENERGY SYSTEMS LABORATORY

Texas Engineering Experiment Station
Texas A&M University System

Disclaimer

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1 Executive Summary

This report reviews the reported uncertainty of the DOE-2 simulation program by reviewing the published accuracy of DOE-2 simulations versus: measured data (Empirical Validation), other simulation methods (Comparative Test), and analytical calculation (Analytical Verification). This report includes a review of the history of the DOE-2 simulation program. In summary, from the literature it was found that DOE-2 simulations versus measured data were shown to vary by 10% (i.e., as reported in 33 of 47 studies) to 26% (i.e., reported in 14 of 47 studies). DOE-2 simulations versus simulations by other programs showed agreement in the 1% to 30% range, and from 1% to 15% when weighted by building size. DOE-2 predictions of whole-building energy use versus analytical calculations were shown to vary from 0% to 5%. One report that focused on component modeling showed that DOE-2 versus analytical calculations varied from 0.2% to 18.7%.

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2 Introduction

This literature review covers the DOE-2 simulation program, which is one of the legacy programs in the ESL's Emissions Calculator (eCALC), a web-based emissions reductions calculator. The eCALC program is a tool for those who want to see how their energy savings have reduced NOx emissions, which are produced by on-site combustion of natural gas, or at fossil-fuel burning power plants that supply the electricity. This report includes a brief history of the development of the DOE-2 program, and includes an analysis of the reported accuracies of the DOE-2 program. For the validation of the DOE-2 program, peer-reviewed literature that presented case studies using one of three methodologies (empirical, comparative, or analytical) were reviewed and summarized.

3 History of the DOE-2 Simulation Program

DOE-2 is a computer simulation program for evaluating the energy performance and associated operating costs of buildings. The first version of DOE-2 was released by the Lawrence Berkeley Laboratory (LBL) in 1978 (Leighton et al., 1978). As shown in Figure 1, DOE-2 evolved from previous simulations developed in the public and private sectors.

The transient heat transfer calculation methods used in DOE-2 can be traced to the dynamic analysis method first introduced in the 1920's in France by Nessi and Nisolle (1925) who used the Response Factor Method (RFM) for calculating transient heat flow in their paper "Regimes Variables de Fonctionnement dans les Installations de Chauffage Central." In the U.S., this method was first published in an Electrical Engineering journal by Tustin (1947) entitled, "A Method of Analyzing the Behavior of Linear Systems in Terms of Time Series," which used time-series concept. This was followed by the paper by Brisken and Reque (1956) who presented a paper using the RFM that used rectangular pulses; and then by Hill (1957) who was the first to use the application of triangular pulses to improve the accuracy of the method. The RFM has also been referenced by several other authors (Stewart, 1948; Pipes, 1957; Holden, 1963; Muncey, 1963).

Of special importance to DOE-2, the RFM was demonstrated to be particularly efficient at calculating transient heat transfer through multi-layer walls in the series of papers by Mitalas et al. (1960), Mitalas (1965), Mitalas and Stephenson (1966; 1967), Stephenson and Mitalas (1967). These procedures were then incorporated into the computer programs by Kusuda (1969; 1970; 1971; 1974).

The first use of computers for the design and analysis of building systems began in the mid 1960s when a group of mechanical engineers organized the Automated Procedures for Engineering Consultants, Inc. (APEC). The first program developed by APEC was the APEC Heating and Cooling Peak Load Calculation (HCC) program (APEC, 1967), which was used for calculating hourly peak and annual heating-cooling loads for heating, ventilating, and air-conditioning (HVAC) systems in buildings. The APEC members were later formed into the ASHRAE Task Group on Energy Requirements (TGER), who then published the procedures for determining heating and cooling loads for computerizing energy calculations (Lokmanhekim ed., 1969; Stoecker ed., 1969;

Stoecker, 1975; ASHRAE, 1975). These publications included the procedures for simulating the dynamic heat transfer through building envelopes, procedures for calculating psychrometric properties, and the algorithms for simulating the primary and secondary HVAC system components.

When such procedures became known to design engineers, the General American Transportation Corporation (GATC) was commissioned by the U.S. Post Office to develop the first public domain energy analysis program (Lokmanhekim et al., 1971), which was based on the Response Factors Method and the Weighting Factor Method (WFM). The program developed for the U.S. Postal Service, called the "Post Office Program," was merged with the National Bureau of Standards Load Determination (NBSLD) program (Kusuda, 1974), which was then used for developing a life-cycle cost analysis of building components.

Four years after the development of the Post Office Program, the National Aeronautics and Space Administration (NASA) developed and released the NASA Cost Analysis Program (NECAP) (Henninger ed., 1975), which was an enhanced version of previously developed Post Office Program. In 1976, NECAP was significantly upgraded through a collaboration with the Lawrence Berkeley Laboratory, the Los Alamos Scientific Laboratory, the Argonne National Laboratory, and several private entities, including the Computation Consultants Bureau. In 1977, NECAP was renamed CAL-ERDA (Graven and Hirsch, 1977; Bennet et al., 1977), to recognize that the primary support for the program came from the State of California and the Energy Research and Development Administration – ERDA (which later became the Department of Energy).

Shortly thereafter, the California Energy Commission (CEC) adopted the CAL-ERDA program as the official building energy simulation program for California and briefly renamed it CAL/CON (Ayres and Stamper, 1995). After the Energy Research and Development Administration (ERDA) was renamed the U.S. Department of Energy (USDOE), the CAL/CON and CAL-ERDA programs were merged into DOE-1 (Leighton et al., 1978). One year later, the USDOE released version DOE-2 (Buhl et al., 1979). Since then, the DOE-2 program has been continually updated and improved by LBL (Buhl et al., 1981; 1983; 1984; 1989).

In 1993, LBL (renamed Lawrence Berkeley National Laboratory) released the most recent version, DOE-2.1e (Buhl et al., 1993). This version incorporated a number of new models, including: ice storage systems, evaporative cooling systems, desiccant cooling systems, variable-speed heat pumps, etc. Updates and improvements have been added in DOE-2.1e since 1993, with versions up to DOE-2.1e-121 (LBNL, 2003). The ESL's Emissions Calculator (eCALC), a web-based emissions reductions calculator, uses version DOE-2.1e-119 as the building simulation engine, with plans to migrate to DOE-2.1e-121 in 2005.

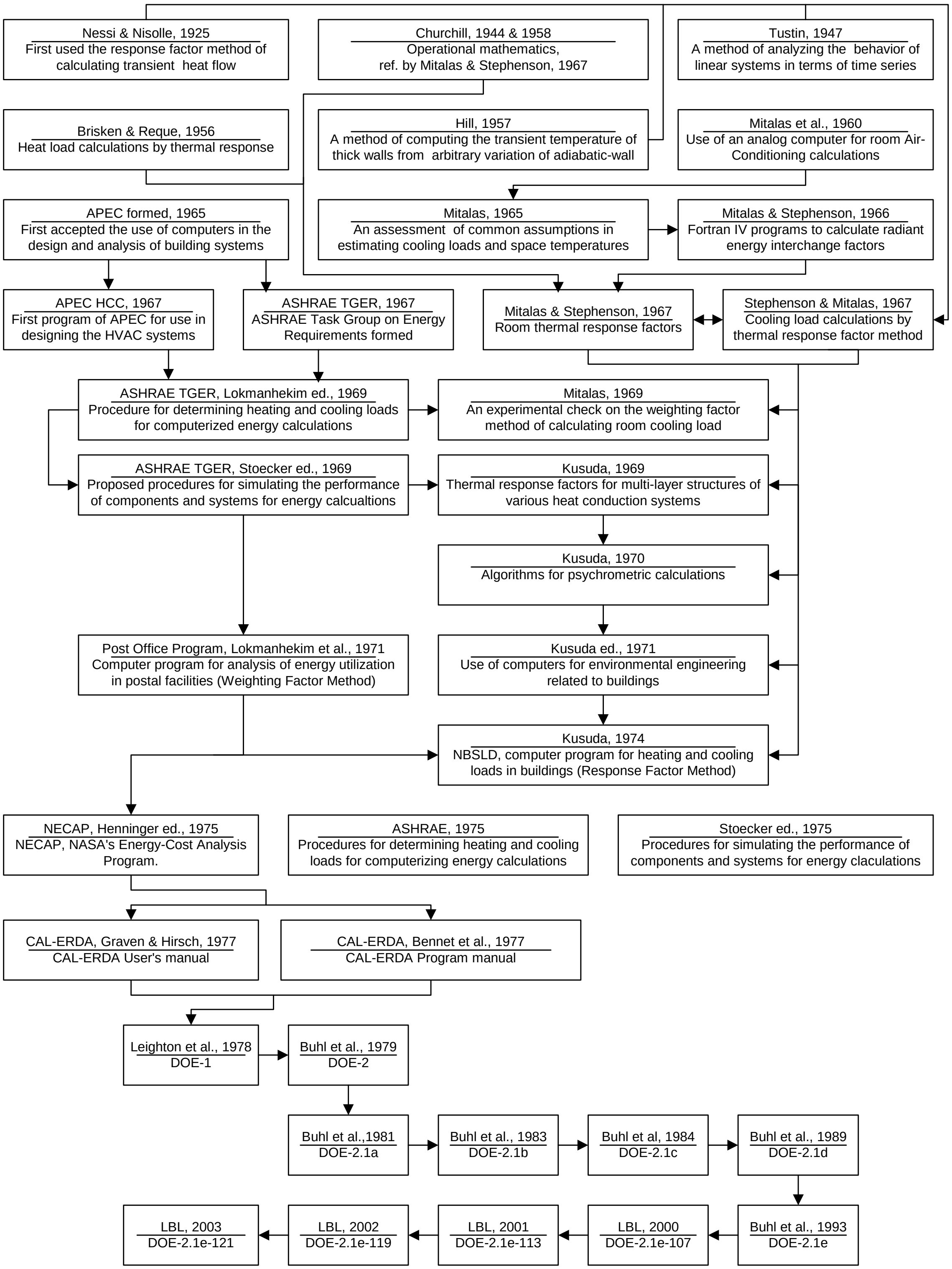


Figure 1. History Diagram of the DOE-2 Simulation Program.

4 Accuracy of the DOE-2 Simulation Program

Typical building energy simulation programs contain many variables and parameters. Varying each of these parameters in combination creates an astronomical number of possible cases and, consequently, cannot practically be fully tested. For this reason, the validation methodology for the building energy simulation programs uses three primary kinds of tests: (1) empirical validation, (2) comparative test, and (3) analytical verification (Judkoff et al., 1983; Judkoff, 1988). Each of these verification methods has its own advantages and disadvantages. Other software testing methods have been developed by a number of researchers since NREL first developed the three test methods (Judkoff et al., 1983; Bloomfield, 1988; Bowman and Lomas, 1985; Irving, 1988; Judkoff, 1988; Judkoff and Neymark, 1995b; Lomas, 1991; Lomas et al., 1994). The sections that follow summarize the results of literature surveys about the validation of the DOE-2 simulation program based on three different methods.

4.1 Empirical Validation

Empirical tests are comparisons of simulation results against experimentally obtained data. This validation technique provides an accuracy measure within accuracy of the data acquisition system and complexity of measurement. The disadvantage of this method is the degree of input uncertainty from measurement, the high expense of performing detailed measurements of high quality, and the limitation of the number of data sites that are economically practical.

Figure 2 shows the literature that contain case studies of empirical validations of the DOE-2 simulation program. The figure shows the DOE-2 agreement with measured data numerically, and includes building types, building locations, the climate zones where the buildings were located (Figure 3).

A total of forty-eight cases have been reported from eighteen papers showing DOE-2 accuracy compared to the measured data. The main applications of these studies were to commercial construction that included office buildings, retail stores, restaurants, and hospitals, as reported in eighteen of the forty-eight cases. Thirteen case studies applied residential buildings, eleven cases school buildings, and six cases others. Climate zones varied from Zone 2 to Zone 6, but mainly in mild climate zones (Zone 3 to Zone 5). Nine cases for other climate zones are applications to the buildings located outside the United States.

As indicated in Figure 2, DOE-2 simulations versus measured data were shown to be within 10% in 33 of 47 case studies and within 26% from 14 of 47 case studies. Seven cases were reported with qualitative results saying that DOE-2 showed reasonable or excellent agreement to measured data.

Year	Author	Title	Building Type	Location	Climate Zone	Data Compred	Application	Accuracy	Accuracy (%) 5	10	15	20	25	30	Qualitative / Others Qual.	Oth.
1981	Diamond et al.	DOE-2 Verification Project Phase 1 Interim Report	School	Warwick, RI	4	Utility bills	Annual total energy consumption	Difference of 11%		11						
			School	Lincoln, NE	5	Utility bills	Annual total energy consumption	Difference of 2%	2							
			School	Glen Rock, NJ	4	Utility bills	Annual total energy consumption	Difference of 5%	5							
			School	Sioux Falls, SD	6	Utility bills	Annual total energy consumption	Difference of 14%			14					
			School	Langhorn, PA	4	Utility bills	Annual total energy consumption	Difference of 7%	7							
			School	Stevens Point, WI	6	Utility bills	Annual total energy consumption	Difference of 10%		10						
			School	Hindman, KY	4	Utility bills	Annual total energy consumption	Difference of 8%		8						
			School	Columbus, OH	5	Utility bills	Annual total energy consumption	Difference of 3%	3							
			School	Lubbock, TX	3	Utility bills	Annual total energy consumption	Difference of 13%			13					
1981	Diamond et al.	DOE-2 Verification Project Phase 1 Interim Report	Single-floor office building	Santa Clara, CA	3	Utility bills	Annual total energy consumption for seven buildings	Standard deviation of 7.9 %, 11.0 % for gas/fuel oil use and 9.2 % for electrical energy use		8						
			Multi-floor office building	Dayton, OH	4	Utility bills				9						
			Retail store	Albuquerque, NM	5	Utility bills				11						
			Restaurant	Downers Grove, IL	5	Utility bills	Monthly energy consumption for seven buildings	Standard deviation of 16.7 %, 26.3 % for gas/fuel oil use and 18.7 % for electrical energy use			17					
			Hospital	Chattanooga, TN	3	Utility bills						19				
			School	Kennewick, WA	4	Utility bills										
			National Security and Resources Study Center	Los Alamos, NM	5	Utility bills							26			
1981	Diamond & Hunn	Comparison of DOE-2 Computer Program Simulations to Metered Data for Seven Commercial Buildings	Single floor office building	Santa Clara, CA	3	Utility bills	Annual total energy use for seven buildings	Standard deviation of less than 8% & maximum difference of 12%		8						
			Multi floor office building	Dayton, OH	4	Utility bills				12						
			Retail store	Albuquerque, NM	5	Utility bills										
			Restaurant	Downers Grove, IL	5	Utility bills	Annual gas/fuel use for seven buildings	Standard deviation of 11%, ranging from 1% to 19%		11						
			Hospital	Chattanooga, TN	3	Utility bills										
			School	Kennewick, WA	4	Utility bills	Annual electric energy for seven buildings	Standard deviation of 9.2%, ranging from 1% to 15%		9						
			Solar-heated and cooled building	Los Alamos, NM	5	Utility bills										
1981	Fleming and Associates	A DOE-2.1A Comparison with CERL Data for VAV and REHEAT Systems	Test chambers	Laboratory	65F -80F	Monitored data	Fuel & electric energy use	Prediction within 5%	5							

Figure 2. Empirical Validation Studies for the Accuracy of the DOE-2 Program.

Year	Author	Title	Building Type	Location	Climate Zone	Data Compred	Applications	Accuracy	Accuracy (%)						Qualitative / Others	
									5	10	15	20	25	30	Qual.	Oth.
1983	Wagner & Rosenfeld	A Summary Report of Building Energy Compilation and Analysis (BECA) Part V: Validation of Energy Analysis Computer Programs	Commercial	Seven cities	3, 4, & 5	Utility bills	Annual total energy use	Standard deviation of 7.9%		8						
			Residential	Windsor, Ontario, Canada	Canada	Utility bills	Annual total heating energy	Agreement within 5%	5							
1983	Judkoff et al.	Measured Versus Predicted Performance of the SERI Test House: A Validation Study	Residential	Golden, CO	5	Monitored data	Whole-house heating load	Predictions within 7%	7							
							Interior air temperature	Prediction errors from 10% to 17%		10	17					
1984	Hall & Wilson	The Validation of DOE-2 for Application to Single-Family Dwellings	A house with a full basement	Windsor, Ontario, Canada	Canada	Monitored data	Natural gas consumption of heating system	Prediction within 5%	5							
			A house with a slab-on-grade construction	Windsor, Ontario, Canada	Canada	Monitored data	Natural gas consumption of heating system	Prediction within 1%	1							
			Seventy five similar houses	Unknown	n/a	Monitored data	Electric consumption of heating system	5% below the measured value	5							
			One zone passive solar house	Unknown	n/a	Monitored data	Electric consumption of heating system, space air temperature	Reasonable agreement for electric consumption and good agreement for space air temperature							x	
1984	Wagner	Comparisons of Predicted and Measured Energy Use in Occupied Buildings	Residential	Various	n/a	Utility bills		Differences of plus or minus 20%				20				
1985	Diamond et al.	User Effect Validation Tests of the DOE-2 Building Energy Analysis Computer Program	Single floor office building	Santa Clara, CA	3	Utility bills	Three levels of input control: (1) Uncontrolled input, (2) Refined input, and (3) Input by Standard evaluation technique	Uncontrolled input to refined input: Scatter reductions range from 19% to 63%								x
			Multi floor office building	Dayton, OH	4	Utility bills										
			Retail store	Albuquerque, NM	5	Utility bills		Refined input to SET input: Scatter reductions range from 22% to 48%								x
			Restaurant	Downers Grove, IL	5	Utility bills										
1985	Sorrell et al.	Validation of Hourly Building Energy Models for Residential Buildings	Test house	Gaithersburg, MD	4	Monitored data	Absolute energy use	Accuracy of 5% to 20%	5	--	--	20				
			ORNL ACES control house	Oak Ridge, TN	4	Monitored data	Low mass / high mass structure	More accurate for low mass structures / largest difference in small high mass structure							x	
			NBS test house	Houston, TX	2	Monitored data	Relative hourly energy use	Model's prediction within 10% to 20%		10	--	20				
1985	Robertson & Christian	Comparisons of Four Computer Models with Experimental Data from Test Buildings in Northern New Mexico	Test house (SWTMS)	Tesuque, NM	5	Monitored data	Cumulative heat loads	Agreement of +/- 10%		10						
						Monitored data	Interior temperatures	Least squares of 0.84 for the massive cells and 0.93 for the frame cells								x
						Monitored data	Wall heat flux	Least squares of 0.88 for the massive building and 0.94 for the insulated frame								x

Figure 2. Empirical Validation Studies for the Accuracy of the DOE-2 Program Continued.

Year	Author	Title	Building Type	Location	Climate Zone	Data Compred	Applications	Accuracy	Accuracy (%)						Qualitative / Others	
									5	10	15	20	25	30	Qual.	Oth.
1985	Birdsall	A Comparison of DOE-2.IC Prediction with Thermal Mass Test Cell Measurements	Test rooms (SWTMS)	Tesuque, NM	5	Monitored data	Energy use	Differences from 3% to 15%	3	--	15					
			NBS test house	Gaithersburg, MD	4	Monitored data	NBS test cell	Difficult to close within 20% of measured data				20				
1992	Akbari et al.	Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area	Residential	Sacramento, CA	3	Monitored data	Control, albedo, and vegetation modifications	Reasonable agreement							x	
1992	Bronson et al.	A Procedure for Calibrating the DOE-2 Simulation Program to Non-Weather-Dependent Measured Loads	Multipurpose	Central Texas	2	Monitored data	Non-weather-dependent loads	1% agreement after calibration	1							
1994	Lomas et al.	Empirical Validation of Thermal Building Programs Using Test Room Data	Test house	Milton Keynes, UK	UK	Monitored data	Radiator	Agreement within 5%	5							
1995	Meldem & Winkelmann	Comparison of DOE-2 with Measurements in the Pala Test Houses	Residential	San Diego, CA	3	Monitored data	Low mass house	Excellent agreement							x	
							High mass house	Excellent agreement							x	
1996	Vincent & Huang	Analysis of the Energy Performance of Cooling Retrofits in Sacramento Public Housing Using Monitored Data and Computer Simulations	Residential	Sacramento, CA	3	Monitored data	Evaporative coolers	Agreement within 8%		8						
							Ground source heat pumps	Agreement within 20%				20				
							Roof albedo	Good agreement							x	
							Building orientation	Same trends of temperatures							x	
1998	Pasqualetto et al.	A Case Study of Validation of an Energy Analysis Program: MICRO-DOE2.1E	Commercial	Montreal, Canada	Canada	Monitored data	Total energy consumption	Agreement within 12.1%		12						
							Peak demand	Agreement within 3.7%	4							

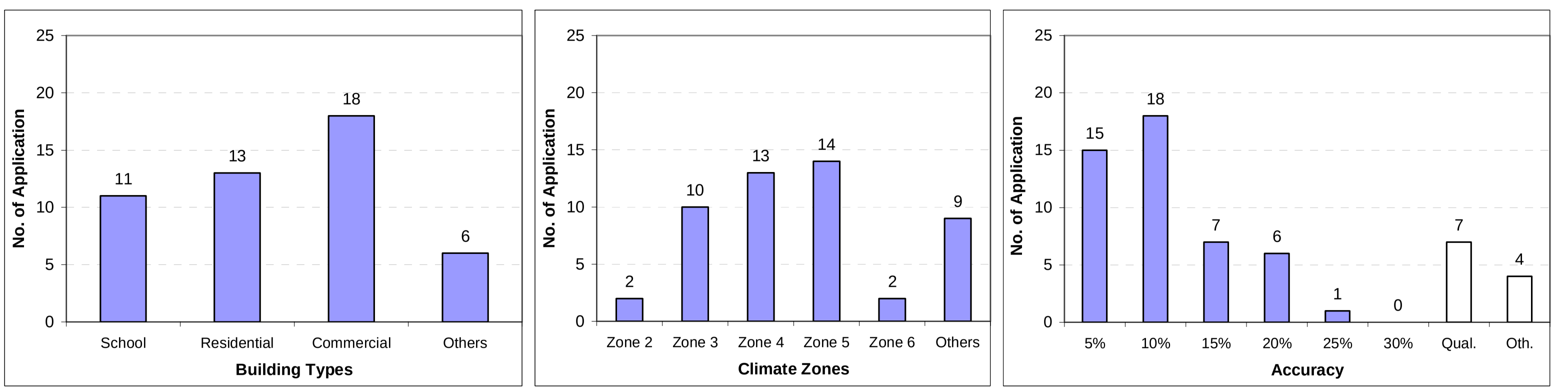


Figure 2. Empirical Validation Studies for the Accuracy of the DOE-2 Program Continued.

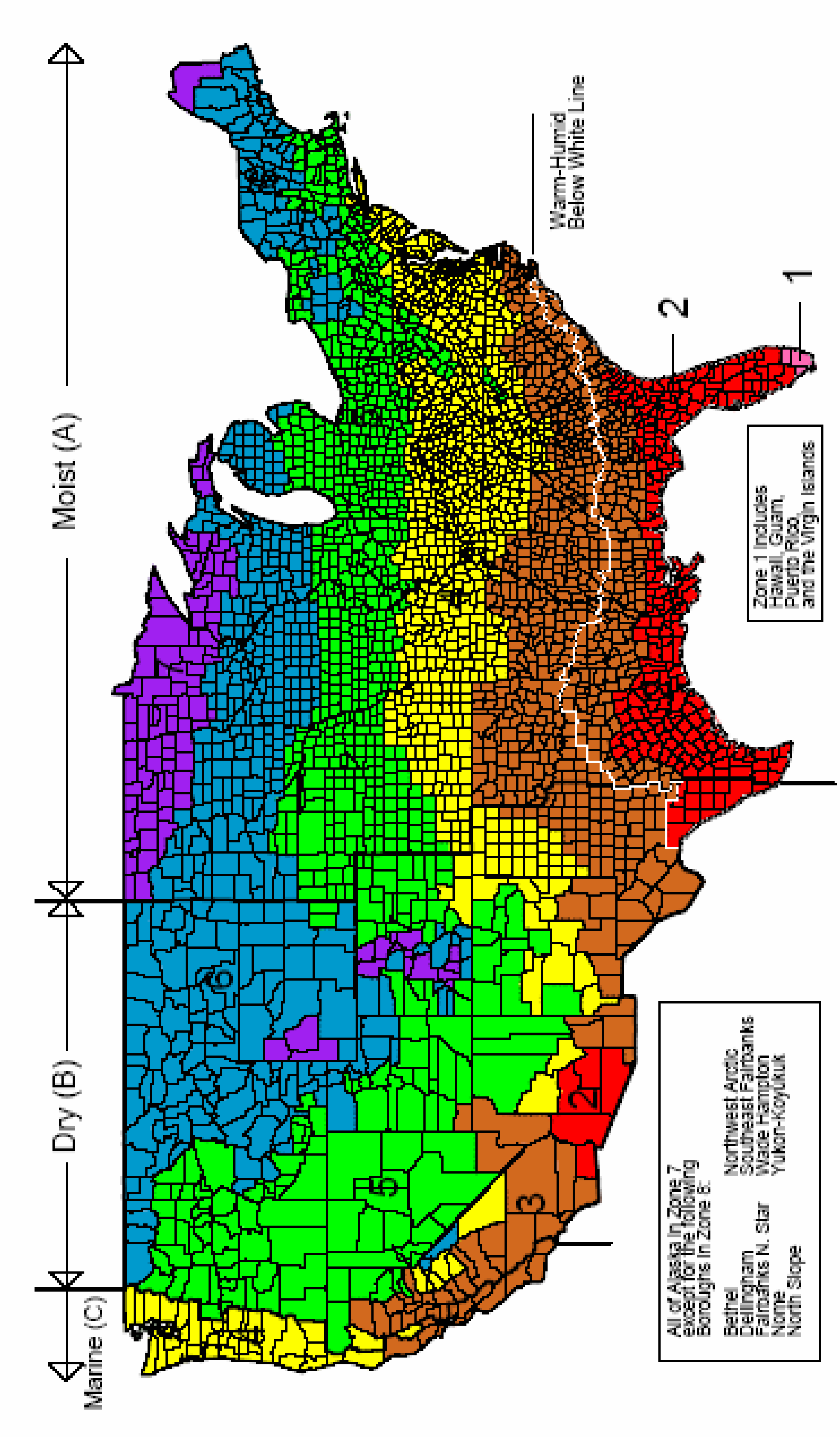


Figure 3. Map of DOE's Proposed Climate Zones (DOE, 2003).

4.2 Comparative Test

Comparative tests are comparisons of simulation results against other simulation programs. This method of validation has no input uncertainty or any adjustments for the level of complexity. Also, this test is less expensive, quicker to conduct, and therefore, covers a larger number of comparisons. Unfortunately, a comparative test has no truth standard, while the empirical verification can approximate the “truth”, as determined from accurate measurements.

The most widely cited comparative validation testing for building energy simulation programs was first conceived in the 1980s at the Solar Energy Research Institute (Judkoff et al., 1983). Since then, many efforts have been performed to develop standardized comparative procedures for evaluating and diagnosing a wide range of energy simulation tools (Judkoff, 1985a; Judkoff, 1985b; Judkoff and Neymark, 1995a; Judkoff and Neymark, 1995b; Judkoff, 1988; Neymark and Judkoff, 2001; Moinard et al., 1998; and Travesi, 1988).

In 1995, the International Energy Agency (IEA) released a comparative set of tests, the Building Energy Simulation Test (BESTEST) (Judkoff and Neymark, 1995a). Later, ASHRAE Standard Project Committee 140 adopted the IEA BESTEST, and incorporated it into ASHRAE’s Standard Method of Test (SMOT) in ASHRAE Standard 140-2001 (ASHRAE, 2001). ASHRAE Standard 140 includes reference results for eight different simulations to provide a comparison point for testing other simulation programs, including the ESP, BLAST, SRES/SUN, SERIRES, S3PAS, TRNSYS, TASE, and DOE-2 computer simulation programs. For each test case, results were compared for cooling and heating loads, peak heating and peak cooling loads, and for free-floating cases as well.

Table 1 is a summary of the simulation results from the eight different programs based on the results of case studies included in the ASHRAE Standard 140 (ASHRAE, 2001). The table shows DOE-2 simulation results along with average values from eight programs and DOE-2 deviations from average values of eight programs for each case and for an average of all cases as well. For the Annual Sensible Cooling Load, as shown in Table 1, the DOE-2 average deviation from the eight programs’ average was 30%, which includes cases where loads were very small compared to the modeling error. Therefore, the average values were restated based on weighted calculations, since the Standard 140 cases 400, 410, 420, 430, and 800 showed the largest deviations for the DOE-2 program in buildings with small cooling consumption numbers compared to the other cases, which were cases in the heating-dominant climate areas.

Figure 4 shows the summary of DOE-2 deviations from the average values of the eight programs. DOE-2 simulations versus simulations by other programs showed agreement in the 1% to 30% range (unweighted), and 1% to 15% (weighted). In the weighted comparisons for DOE-2, the annual heating and cooling load variations were 12% and 11%, respectively, and the weighted annual peak heating and cooling loads were 1% and 6%, respectively. Hourly heating and cooling load variations for DOE-2 (Case 600 and

Case 900) were 7% and 6%, respectively. Variations in cooling loads from solar radiation for DOE-2, which is important for evaluating low-e windows, were 3% to 15%.

ANNUAL HEATING LOADS				
Program	DOE2	Average of 8 Programs (MWh)	DOE2 Deviation from	Weighted Average
Country	USA			
CASE #	MWh			
600	5.709	5.127	11%	0.50%
610	5.786	5.184	12%	0.52%
620	5.944	5.455	9%	0.42%
630	6.469	5.826	11%	0.56%
640	3.543	3.241	9%	0.26%
650	0			
900	1.872	1.790	5%	0.07%
910	2.254	2.105	7%	0.13%
920	4.255	4.019	6%	0.20%
930	5.335	4.782	12%	0.48%
940	1.239	1.192	4%	0.04%
950	0			
960	2.928	2.895	1%	0.03%
195				
200				
210				
215				
220	8.787	7.670	15%	0.96%
230	12.243	11.200	9%	0.90%
240	7.448	6.402	16%	0.90%
250	7.024	6.076	16%	0.82%
270				
280				
290				
300				
310				
320				
395	5.835	5.057	15%	0.67%
400	8.77	7.552	16%	1.05%
410	10.506	9.306	13%	1.04%
420	9.151	8.016	14%	0.98%
430	7.827	6.755	16%	0.93%
440				
800	7.228	6.184	17%	0.90%
810				
Average Deviation			**11%**	**12%**

ANNUAL SENSIBLE COOLING LOADS				
Program	DOE2	Average of 8 Programs (MWh)	DOE2 Deviation from Average	Weighted Average
Country	USA			
CASE #	MWh			
600	7.079	6.897	3%	0.36%
610	4.852	5.062	4%	0.42%
620	4.334	4.280	1%	0.11%
630	2.489	2.902	14%	0.82%
640	6.759	6.659	1%	0.20%
650	5.795	5.535	5%	0.51%
900	2.455	2.743	10%	0.57%
910	0.976	1.525	36%	1.09%
920	2.44	2.611	7%	0.34%
930	1.266	1.706	26%	0.87%
940	2.34	2.637	11%	0.59%
950	0.538	0.634	15%	0.19%
960	0.428	0.639	33%	0.42%
195				
200				
210				
215				
220	0.399	0.686	42%	0.57%
230	0.692	0.981	29%	0.57%
240	0.66	1.050	37%	0.77%
250	2.177	2.827	23%	1.29%
270				
280				
290				
300				
310				
320				
395	0			
400	0.002	0.042	95%	0.08%
410	0.01	0.061	84%	0.10%
420	0.051	0.144	65%	0.18%
430	0.422	0.651	35%	0.45%
440				
800	0.055	0.218	75%	0.32%
810				0.00%
Average Deviation			**30%**	**11%**

ANNUAL HOURLY INTEGRATED PEAK HEATING LOADS				
Program	DOE2	Average of 8 Programs (MWh)	DOE2 Deviation from Average	Weighted Average
Country	USA			
CASE #	MWh			
600	4.045	4.053	0%	0.01%
610	4.034	4.050	0%	0.02%
620	4.046	4.117	2%	0.09%
630	4.025	4.058	1%	0.04%
640	5.943	6.161	4%	0.26%
650	0			
900	3.557	3.566	0%	0.01%
910	3.564	3.574	0%	0.01%
920	3.805	3.858	1%	0.06%
930	3.832	3.847	0%	0.02%
940	5.665	5.658	0%	0.01%
950	0			
960	2.727	2.720	0%	0.01%
195				
200				
210				
215				
220	3.465	3.401	2%	0.08%
230	4.994	5.022	1%	0.03%
240	3.282	3.213	2%	0.08%
250	3.465	3.400	2%	0.08%
270				
280				
290				
300				
310				
320				
395	2.328	2.262	3%	0.08%
400	3.476	3.401	2%	0.09%
410	4.233	4.206	1%	0.03%
420	4.05	4.019	1%	0.04%
430	4.05	4.021	1%	0.03%
440				
800	3.909	3.860	1%	0.06%
810				
Average Deviation			**1%**	**1%**

ANNUAL HOURLY INTEGRATED PEAK COOLING LOADS				
Program	DOE2	Average of 8 Programs (MWh)	DOE2 Deviation from Average	Weighted Average
Country	USA			
CASE #	MWh			
600	6.656	6.512	2%	0.2%
610	6.064	6.026	1%	0.1%
620	4.43	4.424	0%	0.0%
630	3.588	3.683	3%	0.1%
640	6.576	6.464	2%	0.2%
650	6.516	6.375	2%	0.2%
900	3.458	3.451	0%	0.0%
910	2.336	2.794	16%	0.7%
920	3.109	3.150	1%	0.1%
930	2.388	2.548	6%	0.2%
940	3.458	3.451	0%	0.0%
950	2.664	2.738	3%	0.1%
960	1.057	1.256	16%	0.3%
195				
200				
210				
215				
220	0.937	1.142	18%	0.3%
230	1.455	1.657	12%	0.3%
240	1.119	1.327	16%	0.3%
250	2.605	3.180	18%	0.9%
270				
280				
290				
300				
310				
320				
395	0			
400	0.265	0.525	50%	0.4%
410	0.413	0.648	36%	0.4%
420	0.631	0.864	27%	0.4%
430	1.427	1.829	22%	0.6%
440				
800	0.743	1.067	30%	0.5%
810				
Average Deviation			**13%**	**6%**

Table 1. Comparison of DOE-2 Simulation Results with Average Values from Eight Simulation Programs (ASHRAE, 2001).

HOURLY HEATING & COOLING LOAD DATA			
CASE 600 JAN 4			
[USE (-) FOR COOLING]			
Program	DOE2.1D	Average of 8 Programs (kWh)	DOE2 Deviation from Average
Country	USA		
HOUR	kWh		
1	3.926	3.915	0%
2	4.035	4.035	0%
3	4.013	4.017	0%
4	4.041	4.017	1%
5	4.045	4.026	0%
6	4.036	4.028	0%
7	4.045	4.029	0%
8	3.857	3.883	1%
9	2.559	2.717	6%
10	0.843	1.191	29%
11	0		
12	-1.552	-1.043	49%
13	-2.854	-2.576	11%
14	-3.398	-3.125	9%
15	-3.116	-2.796	11%
16	-1.82	-1.555	17%
17	0		
18	0.775	0.860	10%
19	2.232	2.270	2%
20	2.933	2.892	1%
21	3.323	3.263	2%
22	3.487	3.413	2%
23	3.514	3.496	1%
24	3.561	3.529	1%
Average Deviation			7%

HOURLY HEATING & COOLING LOAD DATA			
CASE 900 JAN 4			
[USE (-) FOR COOLING]			
Program	DOE2.1D	Average of 8 Programs (kWh)	DOE2 Deviation from Average
Country	USA		
HOUR	kWh		
1	3.101	3.165	2%
2	3.237	3.302	2%
3	3.279	3.335	2%
4	3.377	3.399	1%
5	3.446	3.464	1%
6	3.498	3.516	1%
7	3.557	3.564	0%
8	3.516	3.542	1%
9	2.974	3.001	1%
10	2.202	2.274	3%
11	1.034	1.113	7%
12	0.232	0.309	25%
13	0		
14	0		
15	0		
16	0		
17	0		
18	0.739	0.991	25%
19	1.14	1.367	17%
20	1.429	1.603	11%
21	1.7	1.839	8%
22	1.894	2.017	6%
23	2.028	2.151	6%
24	2.193	2.281	4%
Average Deviation			6%

SOLAR RADIATION			
ANNUAL INCIDENT TOTAL (Case 600)			
Program	DOE2.1D	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
Country	USA		
Surface	kWh/m2		
NORTH	434	428.533	1%
EAST	1155	1083.717	7%
WEST	1079	1007.667	7%
SOUTH	1566	1486.450	5%
HORZ.	1831	1828.967	0%
Average Deviation			4%

ANNUAL FREE-FLOAT TEMPERATURE OUTPUT			
MAXIMUM ANNUAL HOURLY ZONE TEMPERATURE (C)			
Program	DOE2	Average of 8 Programs (MWh)	DOE2 Deviation from Average
Country	USA		
CASE #	MWh		
600FF	69.5	66.140	5%
900FF	42.7	43.165	1%
650FF	68.2	64.601	6%
950FF	35.9	36.670	2%
960	49	50.704	3%
Average Deviation			3%

SOLAR RADIATION			
UNSHADED ANNUAL TRANSMITTED			
Program	DOE2.1D	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
Country	USA		
CASE#	kWh/m2		
920WEST	735	665.855	10%
900SOUTH	1051	956.495	10%
Average Deviation			10%

MINIMUM ANNUAL HOURLY ZONE TEMPERATURE (C)			
Program	DOE2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
Country	USA		
CASE#	TEMP (C)		
600FF	-18.8	-17.780	6%
900FF	-4.3	-4.558	6%
650FF	-21.6	-22.764	5%
950FF	-18.6	-19.684	6%
960	3.9		
Average Deviation			6%

SOLAR RADIATION			
SHADED ANNUAL TRANSMITTED			
Program	DOE2.1D	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
Country	USA		
CASE#	kWh/m2		
930WEST	481	480.760	0%
910SOUTH	831	788.977	5%
Average Deviation			3%

AVERAGE ANNUAL HOURLY ZONE TEMPERATURE (C)			
Program	DOE2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
Country	USA		
CASE#	TEMP (C)		
600FF	24.6	25.061	2%
900FF	24.7	25.134	2%
650FF	19.1	18.668	2%
950FF	14.3	14.428	1%
960	28	28.035	0%
Average Deviation			3%

Table 1. Comparison of DOE-2 Simulation Results with Average Values from Eight Simulation Programs (ASHRAE, 2001), Continued.

HOURLY INCIDENT SOLAR RADIATION, CLEAR DAY, JULY 27			
CASE 600			
SOUTH SURFACE			
Program Country HOUR	DOE2.1D USA Wh/m2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
6	20.11	26.247	23%
7	70.22	72.669	3%
8	108.13	99.966	8%
9	219.58	204.276	7%
10	343.67	326.168	5%
11	435.54	415.069	5%
12	475.37	453.290	5%
13	488.49	462.691	6%
14	443.66	412.761	7%
15	367.07	332.691	10%
16	246.71	209.968	17%
17	119.19	110.256	8%
18	68.86	72.627	5%
19	19.75	19.023	4%
Average Deviation			**8%**

HOURLY INCIDENT SOLAR RADIATION, CLEAR DAY, JULY 27			
CASE 600			
WEST SURFACE			
Program Country HOUR	DOE2.1D USA Wh/m2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
6	19.96	26.235	24%
7	65.86	72.297	9%
8	97.11	92.419	5%
9	116.89	109.989	6%
10	128.97	123.231	5%
11	138.05	136.068	1%
12	141.34	140.456	1%
13	243.51	254.611	4%
14	462.83	458.745	1%
15	664.62	640.457	4%
16	786.35	733.552	7%
17	649.05	537.452	21%
18	243.11	165.633	47%
19	43.19	29.784	45%
Average Deviation			**13%**

Clear Day South & West Average Deviation:	**11%**

HOURLY INCIDENT SOLAR RADIATION CLOUDY DAY, MARCH 5			
CASE 600 OR 900			
SOUTH SURFACE			
Program Country HOUR	DOE2.1D USA Wh/m2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
7	1.5	2.777	**46%**
8	12.59	19.467	35%
9	30.01	37.566	20%
10	46.23	53.432	13%
11	59.31	63.211	6%
12	65.05	69.045	6%
13	66.98	69.741	4%
14	63.11	64.360	2%
15	51.79	53.454	3%
16	37.13	38.133	3%
17	19.14	20.257	6%
18	4.62	3.049	52%
Average Deviation			**16%**

HOURLY INCIDENT SOLAR RADIATION CLOUDY DAY, MARCH 5			
CASE 600 OR 900			
WEST SURFACE			
Program Country HOUR	DOE2.1D USA Wh/m2	Average of 8 Programs (kWh/m2)	DOE2 Deviation from Average
7	1.8	2.781	35%
8	13.92	19.076	27%
9	31.75	36.860	14%
10	45.24	52.001	13%
11	56.63	61.465	8%
12	61.58	67.037	8%
13	63.7	68.153	7%
14	61.46	63.651	3%
15	51.67	53.463	3%
16	37.2	38.763	4%
17	16.72	20.862	20%
18	2.52	3.007	16%
Average Deviation			**13%**

Cloudy Day South & West Average Deviation:	**15%**

Table 1. Comparison of DOE-2 Simulation Results with Average Values from Eight Simulation Programs (ASHRAE, 2001), Continued.

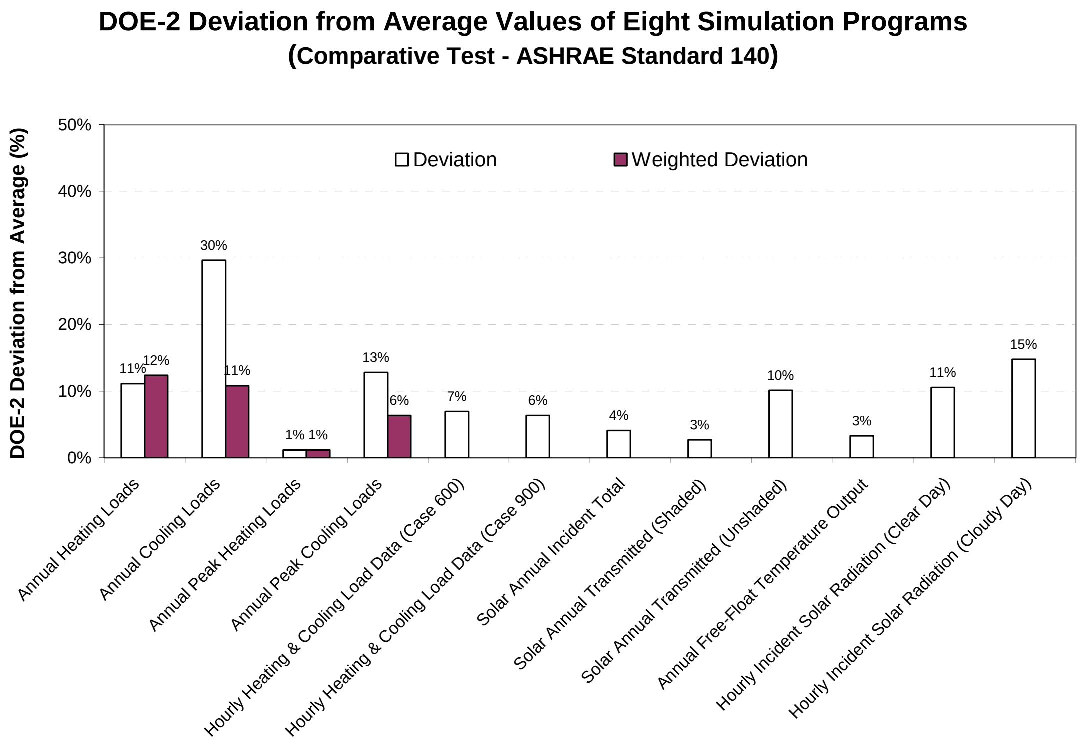


Figure 4. Summary Chart for the Comparison of DOE-2 Simulation Results with Average Values from Eight Simulation Programs.

4.3 Analytical Verification

Analytical verification, one of three validation methods for building simulation programs, compares the output from a computer program, subroutine, or algorithm to the result from a known analytical solution or accepted numerical solution for specific heat transfer cases under very rigid boundary conditions. This validation technique has an exact truth standard, less complex models, and no input uncertainty. However, it does not test the entire model, and is limited to cases for which analytical solutions can be derived (Judkoff and Neymark, 1999).

The Building Energy Performance Analysis Club (BEPAC) in the United Kingdom published a test suite for validating building simulation programs (Bland, 1992; 1993), including FORTRAN routines for calculating the validation. Earlier, a set of analytical solutions for testing key heat transfer mechanisms in the codes were produced (Judkoff et al., 1983; Wortman et al., 1981). In 2002, IEA developed the HVAC BESTEST report as an extension of the HVAC BESTEST for testing mechanical system simulation models, including analytical solutions (Neymark and Judkoff, 2002).

Table 2 shows comparisons between DOE-2 test results from two organizations, Centro de Investigaciones Energéticas, Medioambientales y Technologicas (CIEMAT), the National Renewable Energy Laboratory (NREL), and analytical test results from two other organizations, Technische Universität Dresden (TUD) and Hochschule Technik + Architektur Luzern (HTAL), where two different tests were performed (Neymark and Judkoff, 2002). In these tests comparisons were made to the energy consumption of compressors and fans used for cooling, to the Coefficient of Performance (COP), to the indoor temperatures, the humidity ratio, to the sensible and latent cooling loads, and to the sensible and latent zone loads.

Figure 5 is a summary of comparisons from this report that show the deviations of the DOE-2 results from the results of the analytical calculations. In the majority of cases the DOE-2 agreement with analytical calculation was within 1%. DOE-2 showed a 4.9% deviation for the fan cooling energy consumption and a 1.8% deviation for both the COP and humidity ratio deviations.

Further studies have been performed and reported. In one study an analytical verification test suite was developed for building fabric models in whole-building energy simulation programs (Rees et al., 2002). However, applications were made to the BLAST program, not to the DOE-2 program. In another validation suite fuel-fired furnace models were developed for analytical and semi-analytical solutions (Purdy and Morrison, 2003). In this study DOE-2 results were compared to analytical and semi-analytical calculations along with other programs (ESP-r/HOT3000 and EnergyPlus) and showed very good correlation to the analytical/semi-analytical solutions as well as to the other programs.

Space Cooling Energy Consumption								
Energy Consumption, Total (kWh,e)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	1530	1521	1526	1531	1531	1531	1531	0.4%
E110	1089	1061	1075	1076	1077	1077	1077	0.2%
E120	1012	1011	1012	1013	1011	1011	1012	0.0%
E130	109	105	107	111	110	110	110	3.0%
E140	69	65	67	69	69	68	69	2.4%
E150	1207	1202	1205	1206	1207	1207	1207	0.2%
E160	1139	1138	1139	1140	1139	1139	1139	0.1%
E165	1501	1499	1500	1498	1500	1500	1499	0.0%
E170	638	629	634	641	638	638	639	0.9%
E180	1082	1077	1080	1083	1082	1082	1082	0.3%
E185	1543	1541	1542	1545	1543	1543	1544	0.1%
E190	164	160	162	165	164	164	164	1.4%
E195	250	245	248	252	250	250	251	1.3%
E200	1464	1468	1466	1476	1477	1477	1477	0.7%
						Average Deviation		0.8%

COP								
Mean COP								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	2.43	2.41	2.42	2.39	2.39	2.39	2.39	1.3%
E110	3.46	3.41	3.44	3.38	3.38	3.38	3.38	1.6%
E120	3.61	3.62	3.62	3.59	3.59	3.59	3.59	0.7%
E130	1.98	1.95	1.97	1.89	1.91	1.91	1.90	3.2%
E140	2.92	2.85	2.89	2.75	2.77	2.77	2.76	4.4%
E150	3.67	3.7	3.69	3.63	3.63	3.63	3.63	1.5%
E160	3.87	3.95	3.91	3.83	3.84	3.84	3.84	1.9%
E165	2.95	2.99	2.97	2.93	2.93	2.93	2.93	1.4%
E170	3.44	3.48	3.46	3.37	3.39	3.39	3.38	2.3%
E180	4.08	4.03	4.06	4.04	4.04	4.04	4.04	0.4%
E185	2.87	2.82	2.85	2.85	2.85	2.85	2.85	0.2%
E190	3.49	3.46	3.48	3.39	3.41	3.41	3.40	2.1%
E195	2.36	2.34	2.35	2.29	2.31	2.31	2.30	2.0%
E200	3.67	3.71	3.69	3.62	3.62	3.62	3.62	1.9%
						Average Deviation		1.8%

Space Cooling Energy Consumption								
Energy Consumption, Compressor (kWh,e)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	1318	1307	1313	1319	1319	1319	1319	0.5%
E110	899	866	883	888	889	889	889	0.7%
E120	840	850	845	841	839	839	840	0.6%
E130	94	93	94	95	94	94	94	0.9%
E140	57	55	56	57	57	56	57	1.2%
E150	999	1007	1003	999	999	999	999	0.4%
E160	949	963	956	950	949	949	949	0.7%
E165	1281	1291	1286	1279	1280	1280	1280	0.5%
E170	530	539	535	533	530	530	531	0.7%
E180	908	914	911	908	908	908	908	0.3%
E185	1339	1343	1341	1340	1339	1338	1339	0.1%
E190	138	139	139	138	138	138	138	0.4%
E195	217	219	218	219	217	217	218	0.2%
E200	1239	1249	1244	1249	1250	1250	1250	0.5%
						Average Deviation		0.5%

Indoor Drybulb Temperature: Mean and (Max-Min)/ Mean								
Mean IDB (°C)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	22.3	22.3	22.30	22.2	22.2	22.2	22.20	0.5%
E110	22.3	22.3	22.30	22.2	22.2	22.2	22.20	0.5%
E120	26.8	26.7	26.75	26.7	26.7	26.7	26.70	0.2%
E130	22.1	22.1	22.10	22.2	22.2	22.2	22.20	0.5%
E140	22.1	22.1	22.10	22.2	22.2	22.2	22.20	0.5%
E150	22.3	22.3	22.30	22.2	22.2	22.2	22.20	0.5%
E160	26.8	26.7	26.75	26.7	26.7	26.7	26.70	0.2%
E165	23.4	23.4	23.40	23.3	23.3	23.3	23.30	0.4%
E170	22.2	22.2	22.20	22.2	22.2	22.2	22.20	0.0%
E180	22.3	22.3	22.30	22.2	22.2	22.2	22.20	0.5%
E185	22.3	22.3	22.30	22.2	22.2	22.2	22.20	0.5%
E190	22.1	22.1	22.10	22.2	22.2	22.2	22.20	0.5%
E195	22.1	22.1	22.10	22.2	22.2	22.2	22.20	0.5%
E200	26.8	26.8	26.80	26.7	26.7	26.7	26.70	0.4%
						Average Deviation		0.4%

Space Cooling Energy Consumption								
Energy Consumption, Supply Fan (kWh,e)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	144	145	145	144	144	144	144	0.3%
E110	129	133	131	128	128	128	128	2.3%
E120	117	110	114	117	117	117	117	3.0%
E130	10	8	9	10	10	10	10	10.0%
E140	8	7	8	8	8	8	8	6.3%
E150	141	133	137	141	141	141	141	2.8%
E160	129	119	124	129	129	129	129	3.9%
E165	150	142	146	149	149	149	149	2.0%
E170	73	61	67	74	73	73	73	8.6%
E180	119	111	115	119	119	119	119	3.4%
E185	139	135	137	139	139	139	139	1.4%
E190	18	14	16	18	18	18	18	11.1%
E195	23	18	21	23	23	23	23	10.9%
E200	153	149	151	154	155	155	155	2.4%
						Average Deviation		4.9%

Humidity Ratio: Mean and (Max-Min)/ Mean								
Mean Humidity Ratio								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	0.0076	0.0074	0.01	0.0074	0.0073	0.0073	0.01	2.3%
E110	0.007	0.0064	0.01	0.0065	0.0064	0.0064	0.01	4.1%
E120	0.0078	0.0078	0.01	0.0079	0.0079	0.0079	0.01	1.3%
E130	0.0076	0.0073	0.01	0.0074	0.0073	0.0073	0.01	1.6%
E140	0.0071	0.0064	0.01	0.0065	0.0064	0.0064	0.01	4.9%
E150	0.0082	0.0083	0.01	0.0082	0.0082	0.0082	0.01	0.6%
E160	0.0097	0.0099	0.01	0.01	0.0099	0.0099	0.01	1.3%
E165	0.009	0.0092	0.01	0.0093	0.0092	0.0092	0.01	1.4%
E170	0.0105	0.0105	0.01	0.0104	0.0105	0.0105	0.01	0.3%
E180	0.0166	0.0164	0.02	0.0162	0.0162	0.0162	0.02	1.9%
E185	0.0164	0.0162	0.02	0.0161	0.0161	0.0161	0.02	1.2%
E190	0.0163	0.0159	0.02	0.0158	0.0159	0.0159	0.02	1.5%
E195	0.0158	0.0155	0.02	0.0154	0.0154	0.0154	0.02	1.6%
E200	0.0109	0.0111	0.01	0.0111	0.0111	0.0111	0.01	0.9%
						Average Deviation		1.8%

Table 2. Comparison of DOE-2 Simulation Average Results with Average Values from Three Analytical Solutions (Neymark and Judkoff, 2002).

Coil Loads								
Coil Load, Total (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	3841	3794	3818	3800	3800	3800	3800	0.5%
E110	3804	3756	3780	3765	3765	3765	3765	0.4%
E120	3763	3739	3751	3749	3749	3749	3749	0.1%
E130	216	215	216	219	219	219	219	1.6%
E140	196	195	196	198	198	197	198	1.1%
E150	4543	4528	4536	4518	4517	4518	4518	0.4%
E160	4516	4508	4512	4501	4500	4500	4500	0.3%
E165	4567	4549	4558	4537	4537	4538	4537	0.5%
E170	2226	2237	2232	2232	2232	2233	2232	0.0%
E180	4510	4535	4523	4495	4495	4494	4495	0.6%
E185	4565	4583	4574	4535	4535	4534	4535	0.9%
E190	573	579	576	578	577	578	578	0.3%
E195	595	602	599	601	601	601	601	0.4%
E200	5534	5522	5528	5498	5498	5498	5498	0.5%
						Average Deviation		0.5%

Zone Loads								
Zone Load, Total (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	3654	3655	3655	3656	3656	3656	3656	0.0%
E110	3636	3637	3637	3637	3637	3637	3637	0.0%
E120	3630	3632	3631	3632	3632	3632	3632	0.0%
E130	207	208	208	209	209	209	209	0.7%
E140	189	188	189	190	190	190	190	0.8%
E150	4375	4376	4376	4376	4376	4376	4376	0.0%
E160	4370	4371	4371	4371	4371	4371	4371	0.0%
E165	4386	4387	4387	4388	4388	4388	4388	0.0%
E170	2157	2158	2158	2159	2159	2159	2159	0.1%
E180	4375	4376	4376	4376	4376	4376	4376	0.0%
E185	4394	4395	4395	4396	4396	4396	4396	0.0%
E190	558	558	558	559	559	559	559	0.2%
E195	577	577	577	579	579	579	579	0.3%
E200	5342	5343	5343	5343	5343	5343	5343	0.0%
						Average Deviation		0.2%

Coil Loads								
Coil Load, Sensible (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	3841	3794	3818	3800	3800	3800	3800	0.5%
E110	3804	3756	3780	3765	3765	3765	3765	0.4%
E120	3763	3739	3751	3749	3749	3749	3749	0.1%
E130	216	215	216	219	219	219	219	1.6%
E140	196	195	196	198	198	197	198	1.1%
E150	3804	3786	3795	3778	3778	3779	3778	0.4%
E160	3777	3769	3773	3761	3761	3761	3761	0.3%
E165	3828	3809	3819	3798	3798	3799	3798	0.5%
E170	1487	1498	1493	1493	1493	1493	1493	0.0%
E180	1553	1607	1580	1538	1538	1538	1538	2.7%
E185	1608	1653	1631	1578	1578	1578	1578	3.3%
E190	203	212	208	208	208	208	208	0.2%
E195	226	235	231	232	232	232	232	0.6%
E200	4313	4303	4308	4277	4277	4277	4277	0.7%
						Average Deviation		0.9%

Zone Loads								
Zone Load, Sensible (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	3654	3655	3655	3656	3656	3656	3656	0.0%
E110	3636	3637	3637	3637	3637	3637	3637	0.0%
E120	3630	3632	3631	3632	3632	3632	3632	0.0%
E130	207	208	208	209	209	209	209	0.7%
E140	189	188	189	190	190	190	190	0.8%
E150	3636	3637	3637	3637	3637	3637	3637	0.0%
E160	3630	3632	3631	3632	3632	3632	3632	0.0%
E165	3647	3648	3648	3649	3649	3649	3649	0.0%
E170	1418	1419	1419	1420	1420	1420	1420	0.1%
E180	1418	1419	1419	1420	1420	1420	1420	0.1%
E185	1437	1437	1437	1439	1439	1439	1439	0.1%
E190	188	188	188	190	190	190	190	1.1%
E195	207	208	208	209	209	209	209	0.7%
E200	4121	4122	4122	4122	4122	4122	4122	0.0%
						Average Deviation		0.3%

Coil Loads								
Coil Load, Latent (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	0	0	0	0	0	0	0	0.0%
E110	0	0	0	0	0	0	0	0.0%
E120	0	0	0	0	0	0	0	0.0%
E130	0	0	0	0	0	0	0	0.0%
E140	0	0	0	0	0	0	0	0.0%
E150	739	742	741	739	739	739	739	0.2%
E160	739	739	739	739	739	739	739	0.0%
E165	739	740	740	739	739	739	739	0.1%
E170	739	739	739	739	739	739	739	0.0%
E180	2957	2928	2943	2957	2957	2956	2957	0.5%
E185	2957	2930	2944	2958	2957	2956	2957	0.5%
E190	370	366	368	370	370	370	370	0.5%
E195	370	367	369	370	370	370	370	0.4%
E200	1221	1219	1220	1221	1221	1221	1221	0.1%
						Average Deviation		0.2%

Zone Loads								
Zone Load, Latent (kWh,thermal)								DOE-2.1e Deviation from Anal.
	DOE-2.1e			Analytical				
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E100	0	0	0	0	0	0	0	0.0%
E110	0	0	0	0	0	0	0	0.0%
E120	0	0	0	0	0	0	0	0.0%
E130	0	0	0	0	0	0	0	0.0%
E140	0	0	0	0	0	0	0	0.0%
E150	739	739	739	739	739	739	739	0.0%
E160	739	739	739	739	739	739	739	0.0%
E165	739	739	739	739	739	739	739	0.0%
E170	739	739	739	739	739	739	739	0.0%
E180	2957	2958	2958	2957	2957	2957	2957	0.0%
E185	2957	2958	2958	2957	2957	2957	2957	0.0%
E190	370	370	370	370	370	370	370	0.0%
E195	370	370	370	370	370	370	370	0.0%
E200	1221	1221	1221	1221	1221	1221	1221	0.0%
						Average Deviation		0.0%

Table 2. Comparison of DOE-2 Simulation Average Results with Average Values from Three Analytical Solutions (Neymark and Judkoff, 2002), Continued.

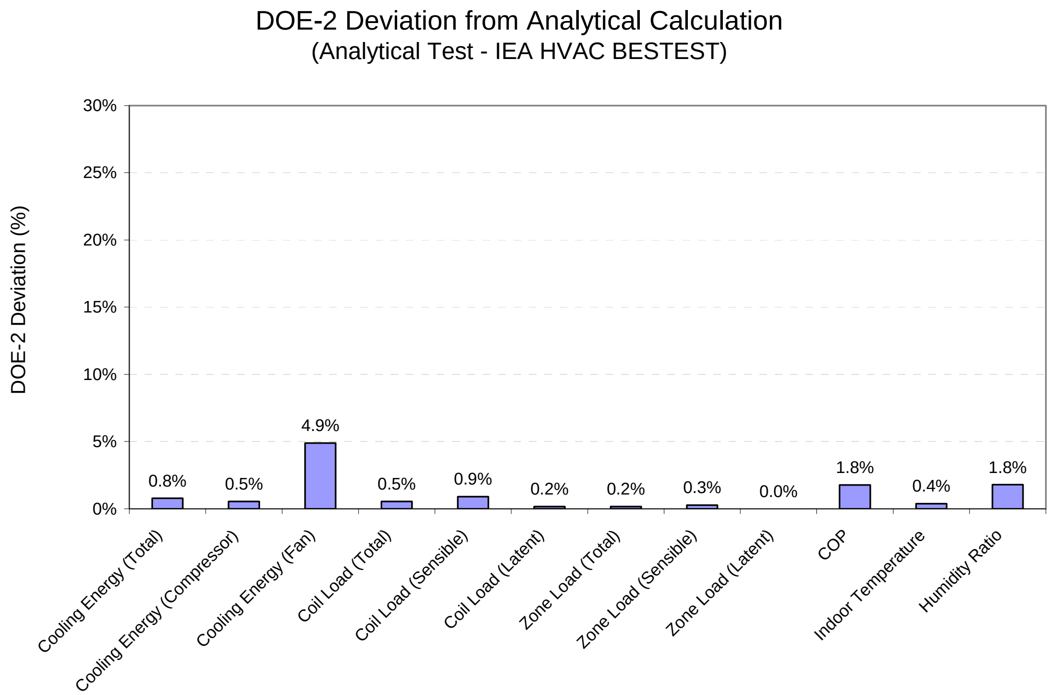


Figure 5. Summary Chart of Analytical Tests for the Accuracy of the DOE-2 Program.

Sensitivity tests were also performed by the same organizations for both DOE-2 (CIEMAT and NREL) and analytical solutions (TUD and HTAL), and the results were included in the HVAC BESTEST (Neymark and Judkoff, 2002). Table 3 shows comparisons between the DOE-2 sensitivity test results and analytical sensitivity solutions. Sensitivity comparisons were made to the energy consumption of compressors and fans used for space cooling, to the Coefficient of Performance (COP), and to the sensible and latent loads for coil.

A summary of the sensitivity tests is shown in Figure 6 where the DOE-2 deviations of sensitivities from the sensitivities of analytical solutions are depicted. The DOE-2 sensitivity deviations from the sensitivities of analytical solutions are shown to be within 20%. Sensitivity of indoor fan (supply fan) load calculation from DOE-2 showed 17.7%, which is the extreme in the category of space cooling loads, while total space cooling loads showed the least deviation of 3.4%. In the sensitivities for COP and coil loads, the sensible coil load showed the highest deviation of 18.7%, while the latent coil load is the lowest at 0.2%.

Sensitivities for Space Cooling Electricity Consumption

Delta Qtot (kWh,e)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-460	-454	-457	-454	-454	-453	-454	0.7%
E120-E110	-50	-62	-56	-64	-66	-66	-65	14.3%
E120-E100	-510	-516	-513	-518	-520	-520	-519	1.2%
E130-E100	-1415	-1413	-1414	-1420	-1421	-1421	-1421	0.5%
E140-E130	-40	-40	-40	-42	-41	-41	-41	3.2%
E140-E110	-996	-999	-998	-1007	-1009	-1009	-1008	1.1%
E150-E110	141	118	130	130	129	129	129	0.1%
E160-E150	-65	-76	-71	-66	-67	-68	-67	5.2%
E165-E160	362	363	363	357	360	361	359	0.9%
E170-E150	-573	-563	-568	-565	-569	-569	-568	0.1%
E180-E150	-125	-103	-114	-124	-124	-125	-124	8.3%
E180-E170	448	460	454	442	445	444	444	2.3%
E185-E180	464	467	466	462	461	461	461	0.9%
E190-E180	-917	-920	-919	-917	-918	-918	-918	0.1%
E190-E140	95	94	95	96	96	96	96	1.6%
E195-E190	85	86	86	87	86	86	86	1.0%
E195-E185	-1296	-1301	-1299	-1292	-1293	-1293	-1293	0.5%
E195-E130	140	140	140	142	141	141	141	0.9%
E200-E100	-53	-79	-66	-55	-53	-54	-54	22.2%
						Average Deviation		3.4%

Sensitivities for Space Cooling Electricity Consumption

Del Qcomp (kWh,e)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-442	-428	-435	-431	-430	-430	-430	1.1%
E120-E110	-16	-45	-31	-47	-50	-50	-49	37.8%
E120-E100	-457	-473	-465	-478	-480	-480	-479	3.0%
E130-E100	-1214	-1218	-1216	-1224	-1225	-1225	-1225	0.7%
E140-E130	-38	-37	-38	-38	-38	-38	-38	1.3%
E140-E110	-811	-827	-819	-831	-833	-833	-832	1.6%
E150-E110	141	99	120	111	110	110	110	8.8%
E160-E150	-44	-56	-50	-49	-50	-50	-50	0.7%
E165-E160	329	330	330	328	331	331	330	0.2%
E170-E150	-468	-459	-464	-466	-469	-469	-468	1.0%
E180-E150	-93	-70	-82	-91	-91	-92	-91	10.8%
E180-E170	375	389	382	375	378	378	377	1.3%
E185-E180	428	432	430	432	431	431	431	0.3%
E190-E180	-775	-774	-775	-770	-770	-770	-770	0.6%
E190-E140	85	82	84	82	81	81	81	2.7%
E195-E190	79	79	79	80	79	79	79	0.4%
E195-E185	-1124	-1127	-1126	-1121	-1122	-1121	-1121	0.4%
E195-E130	126	124	125	123	122	123	123	1.9%
E200-E100	-58	-93	-76	-70	-69	-69	-69	8.9%
						Average Deviation		4.4%

Sensitivities for Space Cooling Electricity Consumption

Del Q IDfan (kWh,e)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-12	-19	-16	-16	-16	-16	-16	3.1%
E120-E110	-23	-12	-18	-11	-11	-11	-11	59.1%
E120-E100	-36	-31	-34	-27	-27	-27	-27	24.1%
E130-E100	-137	-133	-135	-134	-134	-134	-134	0.7%
E140-E130	-1	-2	-2	-2	-2	-2	-2	25.0%
E140-E110	-126	-116	-121	-120	-120	-120	-120	0.8%
E150-E110	0	14	7	13	13	13	13	46.2%
E160-E150	-14	-15	-15	-12	-12	-12	-12	20.8%
E165-E160	23	24	24	20	20	20	20	17.5%
E170-E150	-72	-73	-73	-68	-68	-68	-68	6.6%
E180-E150	-22	-24	-23	-22	-23	-23	-23	1.5%
E180-E170	49	49	49	45	45	45	45	8.9%
E185-E180	24	25	25	21	21	21	21	16.7%
E190-E180	-97	-98	-98	-101	-101	-101	-101	3.5%
E190-E140	7	8	8	10	10	10	10	25.0%
E195-E190	4	4	4	5	5	5	5	20.0%
E195-E185	-117	-119	-118	-117	-117	-117	-117	0.9%
E195-E130	9	10	10	12	12	12	12	20.8%
E200-E100	4	10	7	10	11	11	11	34.4%
						Average Deviation		17.7%

Sensitivities for Space Cooling Electricity Consumption

Del Q ODfan (kWh,e)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-6	-7	-7	-7	-7	-7	-7	7.1%
E120-E110	-11	-5	-8	-5	-5	-5	-5	60.0%
E120-E100	-17	-12	-15	-13	-13	-13	-13	11.5%
E130-E100	-64	-62	-63	-63	-63	-63	-63	0.0%
E140-E130	-1	-1	-1	-1	-1	-1	-1	0.0%
E140-E110	-59	-56	-58	-56	-56	-56	-56	2.7%
E150-E110	0	5	3	6	6	6	6	58.3%
E160-E150	-7	-5	-6	-6	-6	-6	-6	0.0%
E165-E160	11	9	10	9	9	9	9	11.1%
E170-E150	-34	-31	-33	-32	-32	-32	-32	1.6%
E180-E150	-10	-9	-10	-11	-11	-11	-11	13.6%
E180-E170	23	22	23	21	21	21	21	7.1%
E185-E180	11	10	11	10	10	10	10	5.0%
E190-E180	-45	-48	-47	-47	-47	-47	-47	1.1%
E190-E140	3	4	4	5	5	5	5	30.0%
E195-E190	2	3	3	2	2	2	2	25.0%
E195-E185	-55	-55	-55	-55	-55	-55	-55	0.0%
E195-E130	4	6	5	6	6	6	6	16.7%
E200-E100	2	4	3	5	5	5	5	40.0%
						Average Deviation		15.3%

Sensitivities for COP and Coil Loads

Delta COP (kWh,t)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	1.03	1.01	1	0.99	0.99	0.99	1	3.0%
E120-E110	0.16	0.21	0	0.21	0.21	0.21	0	11.9%
E120-E100	1.18	1.22	1	1.2	1.2	1.2	1	0.0%
E130-E100	-0.46	-0.45	0	-0.5	-0.48	-0.48	0	6.5%
E140-E130	0.94	0.9	1	0.86	0.86	0.86	1	7.0%
E140-E110	-0.54	-0.56	-1	-0.63	-0.61	-0.61	-1	10.8%
E150-E110	0.21	0.29	0	0.25	0.25	0.25	0	0.0%
E160-E150	0.2	0.25	0	0.21	0.21	0.21	0	7.1%
E165-E160	-0.91	-0.96	-1	-0.9	-0.91	-0.91	-1	3.1%
E170-E150	-0.23	-0.22	0	-0.26	-0.24	-0.24	0	8.8%
E180-E150	0.42	0.33	0	0.42	0.41	0.41	0	9.3%
E180-E170	0.64	0.55	1	0.68	0.65	0.65	1	9.8%
E185-E180	-1.21	-1.2	-1	-1.2	-1.19	-1.19	-1	1.0%
E190-E180	-0.6	-0.57	-1	-0.66	-0.63	-0.63	-1	8.6%
E190-E140	0.57	0.6	1	0.64	0.64	0.64	1	8.6%
E195-E190	-1.13	-1.12	-1	-1.09	-1.1	-1.1	-1	2.6%
E195-E185	-0.51	-0.49	-1	-0.55	-0.54	-0.54	-1	8.0%
E195-E130	0.38	0.38	0	0.4	0.4	0.4	0	5.0%
E200-E100	1.24	1.3	1	1.23	1.23	1.23	1	3.3%
						Average Deviation		6.0%

Sensitivities for COP and Coil Loads

Del Q coil,t (kWh,t)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-38	-38	-38	-35	-35	-35	-35	8.6%
E120-E110	-40	-16	-28	-16	-16	-17	-16	71.4%
E120-E100	-78	-55	-67	-51	-52	-52	-52	28.7%
E130-E100	-3626	-3579	-3603	-3581	-3581	-3581	-3581	0.6%
E140-E130	-20	-21	-21	-21	-21	-22	-21	3.9%
E140-E110	-3608	-3561	-3585	-3567	-3567	-3568	-3567	0.5%
E150-E110	739	772	756	752	752	753	752	0.4%
E160-E150	-26	-19	-23	-17	-17	-18	-17	29.8%
E165-E160	51	40	46	36	37	38	37	23.0%
E170-E150	-2317	-2291	-2304	-2285	-2286	-2286	-2286	0.8%
E180-E150	-33	7	-13	-22	-23	-25	-23	44.3%
E180-E170	2284	2298	2291	2263	2263	2261	2262	1.3%
E185-E180	55	48	52	40	40	40	40	28.8%
E190-E180	-3937	-3956	-3947	-3918	-3918	-3916	-3917	0.7%
E190-E140	377	384	381	380	379	380	380	0.2%
E195-E190	23	23	23	24	24	24	24	4.2%
E195-E185	-3970	-3981	-3976	-3934	-3934	-3933	-3934	1.1%
E195-E130	379	387	383	382	382	382	382	0.3%
E200-E100	1693	1728	1711	1697	1697	1697	1697	0.8%
						Average Deviation		13.1%

Sensitivities for COP and Coil Loads

Del Q coil,s (kWh,t)

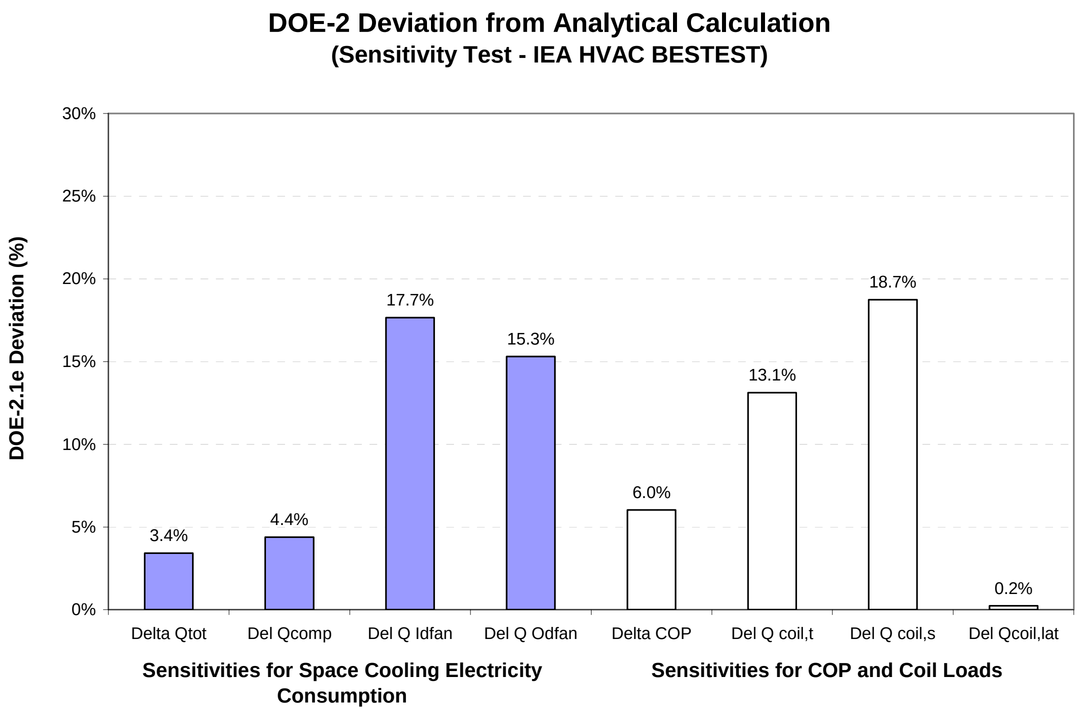
	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	-38	-38	-38	-35	-35	-35	-35	8.6%
E120-E110	-40	-16	-28	-16	-16	-17	-16	71.4%
E120-E100	-78	-55	-67	-51	-52	-52	-52	28.7%
E130-E100	-3626	-3579	-3603	-3581	-3581	-3581	-3581	0.6%
E140-E130	-20	-21	-21	-21	-21	-22	-21	3.9%
E140-E110	-3608	-3561	-3585	-3567	-3567	-3568	-3567	0.5%
E150-E110	0	30	15	13	13	14	13	12.5%
E160-E150	-26	-17	-22	-17	-17	-18	-17	24.0%
E165-E160	51	40	46	36	37	38	37	23.0%
E170-E150	-2317	-2288	-2303	-2285	-2286	-2286	-2286	0.7%
E180-E150	-2250	-2179	-2215	-2241	-2240	-2241	-2241	1.2%
E180-E170	66	109	88	45	45	45	45	94.4%
E185-E180	55	46	51	40	40	40	40	26.3%
E190-E180	-1350	-1394	-1372	-1330	-1330	-1330	-1330	3.2%
E190-E140	7	18	13	10	10	11	10	21.0%
E195-E190	23	23	23	24	24	24	24	4.2%
E195-E185	-1382	-1418	-1400	-1346	-1347	-1346	-1346	4.0%
E195-E130	10	20	15	12	12	12	12	25.0%
E200-E100	472	509	491	476	476	476	476	3.0%
						Average Deviation		18.7%

Sensitivities for COP and Coil Loads

Del Qcoil,lat (kWh,t)

	DOE-2.1e			Analytical				DOE-2.1e Deviation from Anal.
	CIEMAT	NREL	Avg.	TUD	HTAL-1	HTAL-2	Avg.	
E110-E100	0	0	0	0	0	0	0	0.0%
E120-E110	0	0	0	0	0	0	0	0.0%
E120-E100	0	0	0	0	0	0	0	0.0%
E130-E100	0	0	0	0	0	0	0	0.0%
E140-E130	0	0	0	0	0	0	0	0.0%
E140-E110	0	0	0	0	0	0	0	0.0%
E150-E110	739	742	741	739	739	739	739	0.2%
E160-E150	0	-2	-1	0	0	0	0	
E165-E160	0	1	1	0	0	0	0	
E170-E150	0	-3	-2	0	0	0	0	
E180-E150	2218	2186	2202	2218	2218	2217	2218	0.7%
E180-E170	2218	2189	2204	2218	2218	2217	2218	0.6%
E185-E180	0	2	1	0	0	0	0	
E190-E180	-2587	-2562	-2575	-2588	-2587	-2586	-2587	0.5%
E190-E140	370	366	368	370	370	370	370	0.5%
E195-E190	0	0	0	0	0	0	0	0.0%
E195-E185	-2587	-2563	-2575	-2588	-2587	-2587	-2587	0.5%
E195-E130	370	367	369	370	370	370	370	0.4%
E200-E100	1221	1219	1220	1221	1221	1221	1221	0.1%
						Average Deviation		0.2%

Table 3. Analytical Verification: Sensitivity Tests for the Accuracy of the DOE-2 Program.



(Note: Qtot=Total Load, Del=Delta, Q_{Idfan}=Indoor fan (Supply fan) load, Q_{Odfan}=Outdoor fan (Condenser fan) load, COP=Coefficient of performance, t=Total, s=Sensible, and lat=Latent)

Figure 6. Summary Chart of Sensitivity Tests for the Accuracy of the DOE-2 Program.

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