

USING *ENERGYPLUS* FOR CALIFORNIA TITLE-24 COMPLIANCE CALCULATIONS

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ABSTRACT

For the past decade, the non-residential portion of California's Title-24 building energy standard has relied on *DOE-2.1E* as the reference computer simulation program for development as well as compliance. However, starting in 2004, the California Energy Commission has been evaluating the possible use of *EnergyPlus* as the reference program in future revisions of Title-24. As part of this evaluation, the authors converted the Alternate Compliance Method (ACM) certification test suite of 150 *DOE-2* files to *EnergyPlus*, and made parallel *DOE-2* and *EnergyPlus* runs for this extensive set of test cases. A customized version of *DOE-2.1E* named *doe2ep* was developed to automate the conversion process. This paper describes this conversion process, including the difficulties in establishing an apples-to-apples comparison between the two programs, and summarizes how the *DOE-2* and *EnergyPlus* results compare for the ACM test cases.

BACKGROUND

California has had a set of comprehensive building energy standards (Title-24) since the late 1970's, all of which have been developed through use of computer simulations. For the non-residential portion of Title-24, the reference computer simulation program for the past decade has been *DOE-2.1E* (Winkelmann et al. 1993). To be certified as an Alternate Compliance Method (ACM), any commercial compliance software must be run through a rigorous suite of 150 test cases established by the California Energy Commission (hereafter referred to as the Commission) to demonstrate that the software produces results consistent with benchmark values maintained by the Commission.¹ To date, all candidate compliance programs use *DOE-2* for their simulation engine, so the primary function of the certification process is to ensure that the inputs and modeling procedures are as prescribed.

However, entering the latest round of revisions for 2008

¹ In actuality, the benchmark *DOE-2* files were also produced by one of the compliance software vendors, so that the ACM certification is not entirely a double-blind process.

Title-24 standards, the Commission has been evaluating the possible future replacement of *DOE-2.1E* by *EnergyPlus* as the reference building simulation program. The technical reasons for such a move are compelling. *DOE-2.1E* is now over 13 years old and no longer being maintained by the Department of Energy (DOE) or any other public or private entity, except for minor bug fixes. As newer technologies appear on the marketplace, there will be increasing difficulty in modeling them using *DOE-2.1E*.²

EnergyPlus is a major new building-energy-simulation program under development by DOE since 1996 (Crawley et al. 2004). In support of the Commission's interest in evaluating the use of *EnergyPlus* for Title-24, a previous project in 2004 compared the features and capabilities of *DOE-2.1E* and *EnergyPlus* for modeling Title-24 measures (AEC 2005). That project concluded, from an algorithmic point of view, there were numerous improvements and benefits in migrating from *DOE-2.1E* to *EnergyPlus*, but raised concerns about the usability of *EnergyPlus* and suggested a measured approach towards this transition.

The work described in this paper represents the first quantitative comparison of the two programs, using the ACM certification suite as a ready-made comprehensive set of tests for various changes in building shell, equipment, and operations in different California climates.

The Commission has a vested interest in knowing how much the calculated energy performance of different conservation measures would change should *EnergyPlus* replace *DOE-2.1E* as the reference program. A large amount of political capital has been invested over the years in promoting Title-24 as a rational building energy standard, and both the Commission staff and the building industry are now familiar with the compliance levels and trade-off procedures. A sudden change in the calculated results, particularly a sizeable shift in the relative performance of different conservation measures, will be problematic and may damage the integrity of the building standard.

² Even for the 2005 standards, there are already several energy features that are being modeled outside of *DOE-2.1E*.

ACM TEST SUITE

A full description of the 150 test cases is contained in Chapter 5 of the Commission's ACM manual (CEC 2004). Table 1 summarizes the different test series and what building aspects are being tested. In each test, the simulations are repeated, once for the *Proposed* option and once for the *Standard* or prescriptive code option.

Table 1. List of ACM Test Cases
(numbers in parenthesis indicate number of simulations)

<p><i>Partial Compliance Tests (3)</i> Partial compliance test for envelope, lighting, or envelope and equipment A1 series (3)</p> <p><i>Envelope Tests (18)</i> Wall assembly tests A2 series (7) Window-to-Wall Ratio tests B1 series (5) Glazing type with overhang tests B2 series (4) Display perimeter & skylight tests B3 series (2)</p> <p><i>Internal Loads Tests (23)</i> Single-occupancy tests C1 series (5) Mixed occupancy tests C2 series (2) Lighting tests D1 series (4) Ventilation tests E1 series (6) Process load tests E2 series (6)</p> <p><i>System Tests (35)</i> HVAC system type tests F1 series (5) System sizing tests G1 series (6) Optional compliance OC test series (1) Fan-powered VAV box tests O1 series (2) Supply and return fan tests O2 series (4) Economizer tests O3 series (3) HVAC control tests O4 series (1) Optional additional chiller tests O6 series (6) Optional additional HVAC tests O7 series (3) Optional evaporative cooling tests O9 series (4)</p>
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The test cases use one of four prototypical buildings – *A* is a small detached single-story building 9.14m x 22.86m (30ft x 75ft); *B* is a large two-story building 18.29m x 18.29m (60ft x 60ft); *C* is the same as *B* but has five stories; and *D* is a single-story attached office or store 6.10m x 18.29m (20ft x 60 ft) - in different California climates. The test cases provide a thorough sampling of different building shell, internal gains, and system characteristics. The most critical simulation results are not the total building energy uses, but the differences in building energy use between the *Proposed* and *Standard* cases, and the energy use trends stepping through the runs of a particular test series.

EXISTING DOE-2 FILES

At the beginning of the project, the Commission provided two sets of *DOE-2.1E* input files developed by different contractors for ACM certification, with the intention that these would provide the basis for the conversion to *EnergyPlus*. These two sets of *DOE-2* files were not developed independently, but rather different permutations of a basic set by one of the contractors. It was known that additional work would be needed to flush out the building descriptions to meet *EnergyPlus*' more stringent input requirements, but unanticipated concerns that arose during the course of creating the *EnergyPlus* files resulted in rewriting or restructuring the *DOE-2* files in their entirety.

There were numerous reasons for rewriting or restructuring the *DOE-2* files, of which the first was anticipated, but the following two were not:

1. The *DOE-2* files locate exterior walls only by azimuth and tilt and define interior walls only by area. Although such descriptions are acceptable in *DOE-2*, *EnergyPlus* requires that all walls be correctly located so that the view factors in the Heat Balance calculation are computed correctly. To maintain as much correspondence between the *DOE-2* and *EnergyPlus* files as possible, building geometry was added to the *DOE-2* files before the files were translated to *EnergyPlus*. Much of this effort was automated by assuming all building zones were rectilinear in shape, etc., but manual checking was essential to insure that the results were correct. For the occupancy tests (C1 and C2), physically plausible geometries had to be defined for the building zones, which were specified in the ACM manual only as fractions of the building floor area. For example, tests C11 and C12 specify the *C* building as a grocery with 82% of the floor area as sales, 8% storage, 5% office, and 6% support spaces. In the original *DOE-2* files, these spaces were modeled with the same fractional amounts of walls and windows, which was physically untenable. With realistic explicit geometry, the amounts of walls and windows in each zone differ substantially from those in the original *DOE-2* files.

The original *DOE-2* files were done for the 2001 version, not the current 2005 version of Title-24, which was not available at the time. Although this was not expected to affect the comparison between *DOE-2* and *EnergyPlus*, in the spirit of keeping current with the standard, the *DOE-2* input files

were updated to the 2005 Title-24 requirements. Instead of making incremental changes to the input files, which already bore evidence of numerous revisions by different people, completely new inputs were written for materials, layers, and schedules based on the Joint Appendices of the ACM (CEC 2004) following the modular structure described below.

2. A fundamental difficulty in working with the original *DOE-2* files was that they consisted of 150 separate files, frequently with inconsistencies and differences difficult for third parties to understand. To determine how a certain ACM test was being modeled required line-by-line comparisons between different files in the test series. To overcome this problem, the files were restructured to a manageable set of *include* files by building prototype, occupancy, and HVAC system, and used *DOE-2 macros* to specify parametric variations within each *include* file. This not only drastically reduced the number of files, but also conveniently highlighted the differences particular to each ACM test. Making this conversion, however, was time-consuming, but once it was done, proofreading the files and updating them for the 2005 Standard became much easier and consistent.

The final revised *DOE-2* files are more fully described in Huang et al. 2006, and provided to the Commission as reference for ongoing work in developing a more authoritative set of ACM certification input files.

CONVERTING *DOE-2* FILES TO *ENERGYPLUS*

Because of the large number of files in the ACM test suite, the project created the *EnergyPlus* input files by developing *doe2ep*, a modified version of *DOE-2.1E* that would automatically generate the corresponding *EnergyPlus* input files at the same time that it does a standard *DOE-2.1E* simulation. From the user's point of view, *doe2ep* is indistinguishable from standard *DOE-2.1E*, except that the outputs would also include *EnergyPlus* input files - a Loads *.idf and a Systems *.imf file that can be combined using *EPMacro* to a single *EnergyPlus* *.idf file. The advantage of basing *doe2ep* on *DOE-2.1E* is that by reading the building descriptions internal to *DOE-2*, all the default assumptions are properly passed, thus guaranteeing the *EnergyPlus* file would be as consistent as possible with the original *DOE-2* input file. The reason *doe2ep* requires a full *DOE-2* simulation is that a surprisingly large amount of the input information, including the coordinates of the surface vertices or the sizes and flow rates of the system and plant equipment, are handled in

the *doesim* simulation, and not the *doebdl* input processing, module.

Similar to *DOE-2*, *doe2ep* can be divided into two major modules: (1) the translation of LOADS, and (2) the translation of SYSTEMS and PLANT. The LOADS translation is more straightforward, involving the conversion of the *DOE-2* surface geometry data to the *EnergyPlus* coordinate system, and conversion of the various materials, layers, surfaces, and space-condition descriptions and schedules to *EnergyPlus*. An estimated 95% of the inputs in *DOE-2* LOADS can be handled by *doe2ep*.

The translation of *DOE-2* System and Plant inputs to *EnergyPlus* requires converting the simpler *DOE-2* lumped inputs to the more detailed air and water loops inputs required by *EnergyPlus*. This task relies on a set of template files by *DOE-2* system type that use *macro* expressions to expand the *EnergyPlus* objects depending on the number of zones and specified equipment options. For this project, template files were developed only for the following *DOE-2* system types used in the ACM test suite: (1) Packaged Single Zone (PSZ), (2) Packaged Variable-Air-Volume (PVAVS), (3) central Variable Air-Volume (VAVS), (4) Packaged Induction Unit (PIU) and (5) Four-Pipe Fan Coil (FPFC). For the packaged systems, the templates were also expanded to include a heat pump as the zone-level equipment. This covers the most commonly-used systems modeled in *DOE-2*, but still leaves 13 or so other, less commonly used, HVAC systems that currently cannot be translated by *doe2ep*. Further funding will be required to expand *doe2ep*'s capability to translating all *DOE-2* system types.

MODELING DIFFERENCES BETWEEN *DOE-2* AND *ENERGYPLUS*

doe2ep was found to be an indispensable tool in this project, because of the innumerable iterations between the *DOE-2* and *EnergyPlus* runs to resolve modeling differences and achieve, as much as possible, an "apples-to-apples" comparison between the two programs. Initially, the effort focused on insuring that the building descriptions in the two sets of input files were consistent, which was complicated by the different modeling approaches taken in the design of the two programs. *DOE-2* contains hundreds of default values meant to capture typical US building conditions, while *EnergyPlus* requires that all inputs be explicitly defined. Thus, *doe2ep* has to do more than just translate what's in the *DOE-2* files; it must also fill in additional inputs for *DOE-2*'s numerous explicit and implicit defaults. For example, *DOE-2*'s clock defaults assume daylight

savings and a US holiday schedule. These conditions must be explicitly defined in the *EnergyPlus* input file.

For some thermal processes, such as infiltration and ground heat transfer, *EnergyPlus* allows for two or more different modeling methods. For the test suite comparisons, the method that corresponded closest to the ACM specifications or original *DOE-2* input files (often the simpler method), was selected. In a later task, the impact of using the more detailed ground heat transfer model on the results was investigated.

For other thermal processes, notably window solar heat gain and shading, *EnergyPlus* uses more detailed models for which the simpler *DOE-2*-based specifications are insufficient. In these situations, attempts were made to match the bulk properties, or the input condition was eliminated from both the *DOE-2* and *EnergyPlus* runs (see items 2 and 3 later in this section).

It was expected in comparing the *DOE-2* to the *EnergyPlus* results that (1) the building loads would be more difficult to match than the system and plant effects, and (2) cooling energy use would be the most difficult to match, followed by heating, ventilation, lighting and other energy uses. Both of these expectations were wrong. Although it was frustrating and inconclusive in trying to compare building loads, due largely to significant differences in indoor temperatures, it became apparent that any differences were being swamped or magnified by differences in how the system responses were being modeled. It was also surprising that much closer correspondences were found in the cooling energy uses, while there continues to be significant, and difficult to explain, differences in heating energy use. Whereas in most of the country, heating can be characterized as more steady-state and cooling as more transient, in California both are equally transient because of the mild heating season and high thermal integrity of the buildings. In particular, heating energy use for the test suite cases seem very sensitive to free heat from internal sources and the economizer controls (see items 3 to 5 later in this section). As of June 2006, analysis is still underway to better understand and resolve those test cases where the *EnergyPlus* heating energy use is only 30-60% of that shown by *DOE-2*.

Following is a list of specific modeling issues that arose in the course of the comparison, and how these issues have been addressed:

1. *Window modeling.* The windows in the *DOE-2* test files are defined only by bulk properties of U-factor and Solar Heat Gain Coefficient (SHGC), as are the

window requirements in Title-24. *EnergyPlus*, however, requires that the thermal/optical properties be defined for the window assembly layer by layer. Hypothetical window layers were derived by iterative Window 5 calculations within *EnergyPlus* to produce a match to the specified U-factor and SHGC.³ To match the U-factor of a double-pane window, the gap thickness was first adjusted, then the inner glazing conductivity, and finally the outer glazing conductivity as necessary. To match the SHGC, the solar transmittance at normal incidence was adjusted, followed by the front and back solar reflectances at normal incidence as necessary. The hypothetical component window properties thus created were used to represent ACM test suite windows in the *EnergyPlus* simulations. This iterative procedure was done manually for the project, but will be eventually automated as a Compact Window object within *EnergyPlus*. A recommendation is also made to the Commission to specify Title-24 window requirements as layer-by-layer descriptions, in addition to listing their U-factor and SHGC.

2. *Window shading.* The original *DOE-2* input files assume a solar heat gain reduction of 0.80 due to the effects of drapes, curtains, or other window shading devices. In *DOE-2*, this is modeled simply as a 20% reduction in the incoming solar radiation. *EnergyPlus* models window interior blinds much more rigorously, making it very difficult to model a shading device with the right thermal properties resulting in the same 0.20 solar reduction across the board. For the ACM test suite, the decision was made to simulate the windows in both *EnergyPlus* and *DOE-2* with no solar heat gain reduction, and a recommendation forwarded to the Commission that the definition of the base case window shading condition be clarified.
3. *Infiltration.* As mentioned earlier, the *DOE-2* infiltration inputs in air-changes per hour were translated into the comparable Simple Air Flow model in *EnergyPlus*. However, when the resultant air flow rates were compared, those in the *EnergyPlus* runs were consistently higher by 30%. This discrepancy was found to be due to *DOE-2*'s reduction of the wind speed on the weather tape to account for local terrain effects. Although *EnergyPlus* also adjusts for wind speed in some of

³ The iterative search procedure was tested using a stand-alone *Window 5* program (Windows and Daylighting Group 2001), but the final search procedure was done using the *Window 5* algorithms in *EnergyPlus* to avoid potential differences in results between the two versions of *Window 5*.

its thermal calculations, this adjustment was not used in the Simple Air Flow model. This oversight was referred to the *EnergyPlus* development team with the expectation that it will be corrected in the near future. In the interim, *doe2ep* was modified to eliminate the wind speed reduction in *DOE-2*, so that the calculated infiltration rates will be equivalent between the two programs.

4. *Thermostat throttling range.* The original *DOE-2* runs contain a large throttling range of 2.2°C (4°F), leading to zone temperatures that on average were 1°C higher than the thermostat setting. *EnergyPlus* does not model throttling ranges. Since PID controls are becoming more widespread in use and do not have throttling ranges, the decision was made to reduce the throttling-range in *DOE-2* to 0.20.
5. *Inconsistent fan inputs in DOE-2.* *DOE-2* permits redundant fan inputs for SUPPLY-CFM, SUPPLY-DELTA-T, and SUPPLY-KW. *doe2ep* uses the first two of these to compute the *EnergyPlus* inputs for fan static pressure and design flow rate. For many of the ACM test suite files, this resulted in fan energy consumptions in *EnergyPlus* that differ greatly from what *DOE-2* calculated using the input SUPPLY-KW. The reason for this discrepancy is that the *DOE-2* inputs for SUPPLY-DELTA-T and SUPPLY-KW were contradictory. This inconsistency was resolved by overwriting the SUPPLY-KW in the *DOE-2* files with values consistent with the input SUPPLY-DELTA-T.
6. *Heating to the cooling setpoint.* Temperature plots revealed that at times during the shoulder seasons, *EnergyPlus* had difficulty in picking between the heating or cooling season control logic. This resulted in the supply air being heated to the cooling, rather than the heating, setpoint during the morning hours. This problem was corrected by improving the setpoint manager in *EnergyPlus*.
7. *Faulty economizer operating logic.* The *EnergyPlus* heating energies were more than 50% higher for those test runs with PSZ (Packaged Single Zone) systems in climates with substantial economizer usage. The economizer control in *EnergyPlus* was found to cause overcooling during the swing season, which then necessitated heating to bring temperatures back up to the thermostat setpoint. This problem was corrected by improving the economizer control in *EnergyPlus*.
8. *Abnormally low boiler temperatures.* For many weeks, it was difficult to understand why the

EnergyPlus heating energies were in some runs less than half, and yet in other runs 50% more than the *DOE-2* heating energies. The low heating energy use was finally traced to *doe2ep* passing to the *EnergyPlus* inputs an abnormally low boiler heating temperature of only 16°C (60.8 °F). *DOE-2* actually does not model the boiler water temperature, but uses this low default temperature to pass the loop temperature for a water-source heat pump. Of course, when *EnergyPlus* attempts to model a boiler operating at such a low temperature, there is very little heat capacity, and hence very little delivered heat to the building. This problem was corrected by having *doe2ep* overwrite the *DOE-2* boiler temperature with a value of 48°C (120 °F).

9. *Excessive pump heat displacing mechanical heating.* This was probably the most unusual problem encountered in this project. The puzzling “symptoms” were a few runs that showed substantial heating in January, a small amount in February, and then no heating for the rest of the year. The test runs specified a hot water loop with a fixed-speed pump. Since *DOE-2* does not size water loop pumps, *EnergyPlus* was used to size the pumps. For relatively mild California climates, *EnergyPlus* returned a pump size that was several times too large. Since the pump is specified as fixed-speed, it would add a constant amount of heat to the loop whenever it ran. Furthermore, *EnergyPlus* keeps track of the water loop temperature without any distribution losses. Thus, over time the pump heat gain was sufficient to meet the building’s heating load without the boiler ever having to come on. There are several possible solutions to this phenomenon – (1) improve the *EnergyPlus* sizing routine, (2) change the pumps from fixed to variable speed, or (3) add a loss coefficient in the loop (*DOE-2* assumes 1%). The *EnergyPlus* development team were notified of this situation, but in the comparison runs the water loop pump was simply downsized.

COMPARISON OF RESULTS

The complete results for all 150 runs in the Test Suite are provided in Huang et al. 2006. This paper summarizes the results for five representative test series – A2 (wall assembly), B1 (window-to-wall ratio), D1 (lighting), E1 (ventilation) and F1 (HVAC system type).⁴

⁴ The run names shown in the following plots indicate the run series (2 letters), run number, prototype (1 letter), and climate

The A2 series covers variations in the wall assembly for the 2-story B prototype building with an office occupancy in four different climates. Runs 1, 5, and 7 have individual PSZ (Packaged Single Zone) systems, while runs 2, 3, 4, and 6 have central PVAV (Packaged Variable Air Volume) systems. The *EnergyPlus* results compare closely to the *DOE-2* results, with cooling

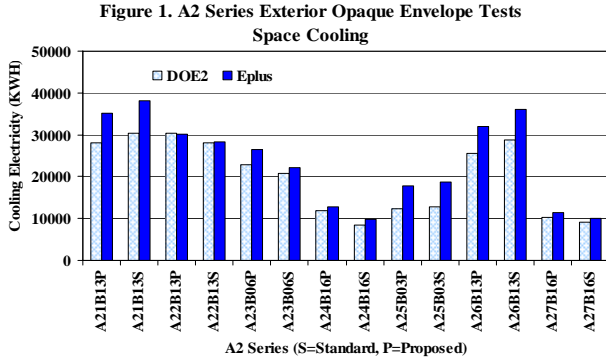


Figure 2. A2 Series Exterior Opaque Envelope Tests Space Heating

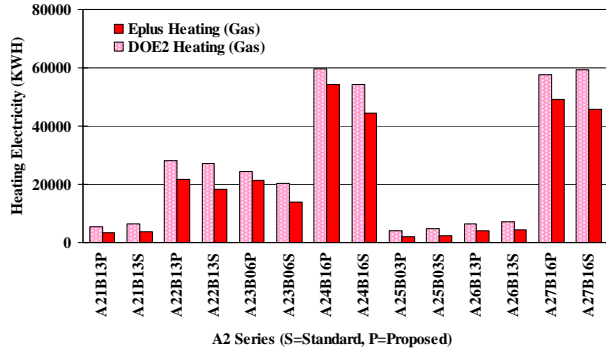
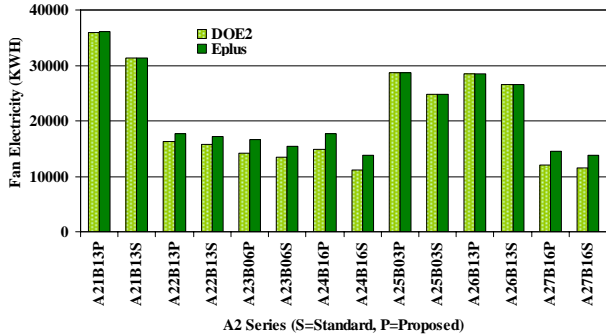


Figure 3. A2 Series Exterior Opaque Envelope Tests Ventilation Fans



slightly higher but within 10% and heating somewhat lower but within 20%. The fan energy consumptions are virtually the same.

zone (2 numbers). For example, A21B13 indicates the A2 series, run 1, B prototype, in Climate Zone 13.

The B1 series covers changes in the Window-to-Wall Ratio (WWR) for the 2-story Prototype B with a retail occupancy and a central PVAV system in 3 different climates. The *EnergyPlus* results are virtually identical to the *DOE-2* results for cooling energy use, and slightly higher but within 10% for fan energy use. These runs were affected by modeling issues 8 (low boiler

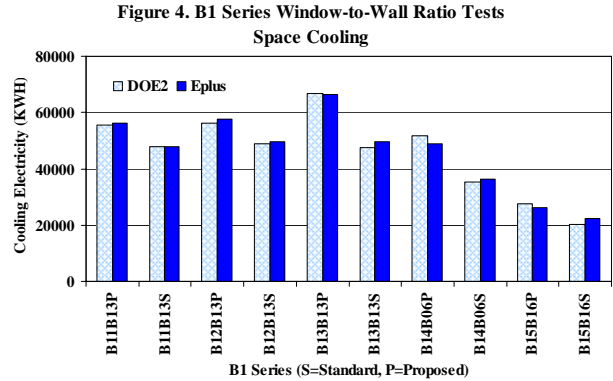


Figure 5. B1 Series Window-to-Wall Ratio Tests Space Heating

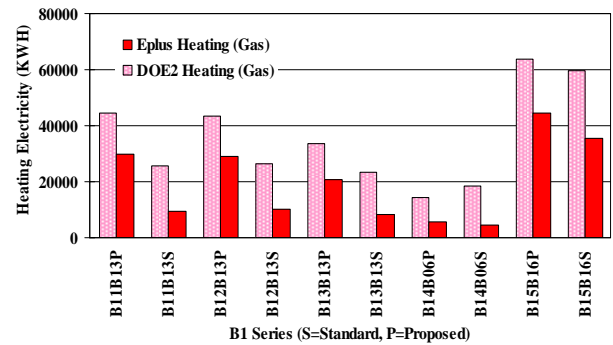
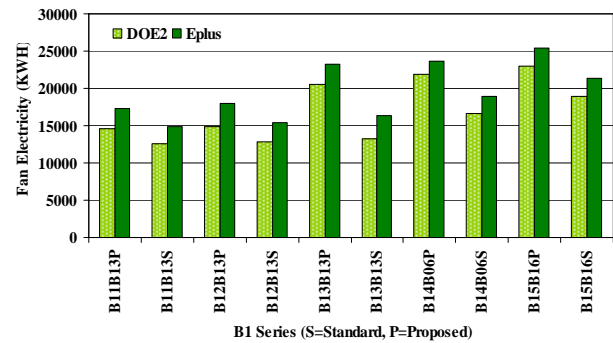
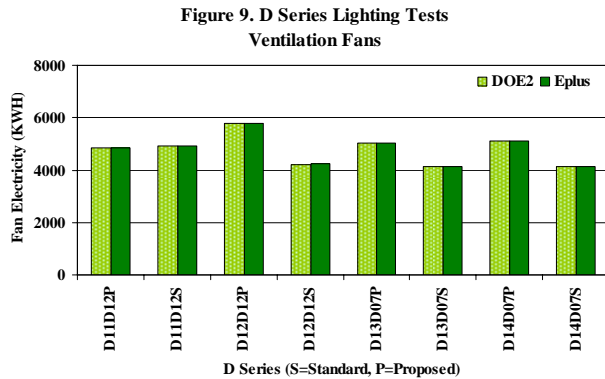
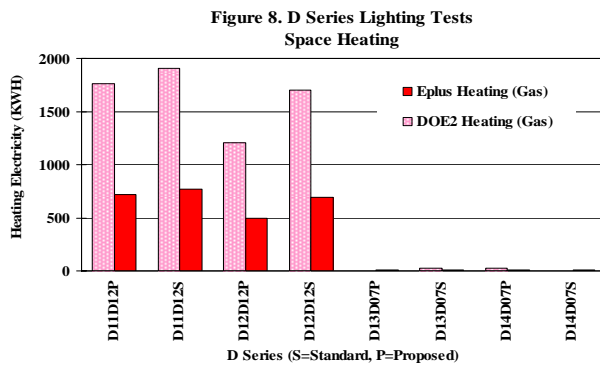
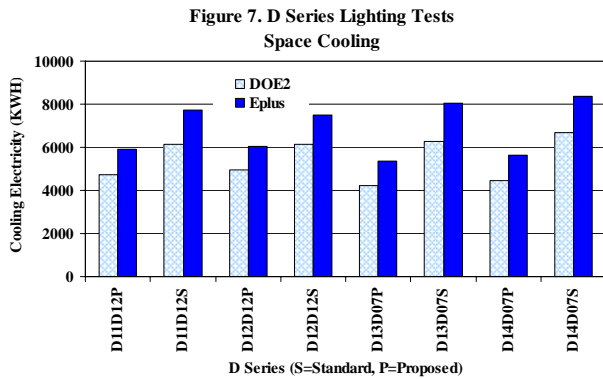


Figure 6. B1 Series Window-to-Wall Ratio Tests Ventilation Fans



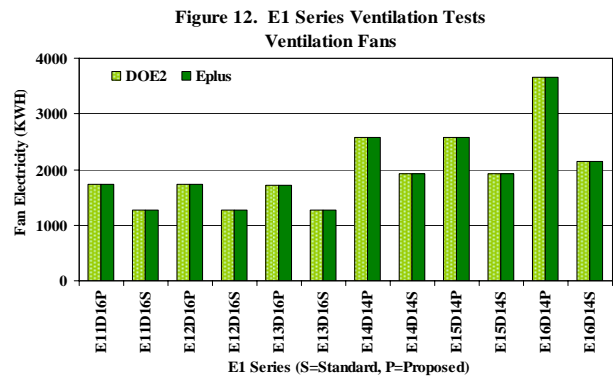
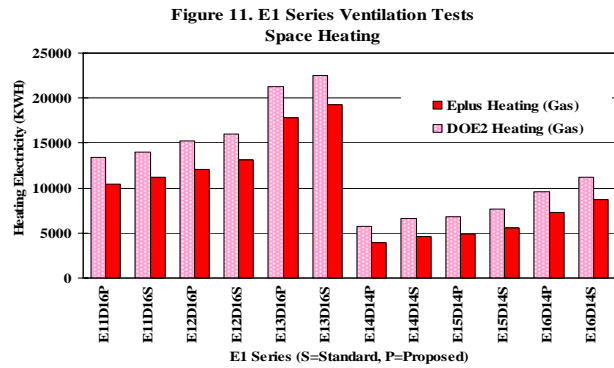
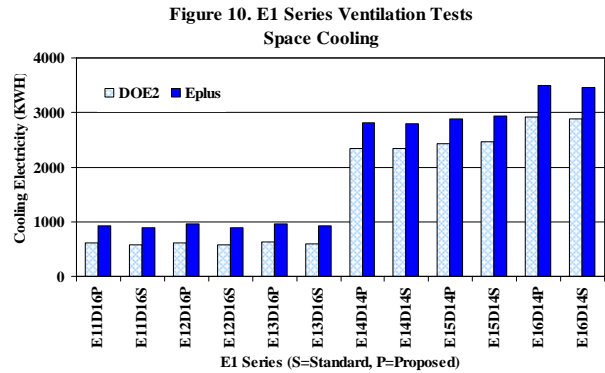
temperatures) and 9 (excessive pump heat gain) mentioned previously. Correcting these produced a closer match, but the *EnergyPlus* heating results are still consistently lower by 30% to 60% compared to *DOE-2*. These runs are still being analyzed to make sure that the modeling is consistent between the two programs.

The D1 series covers changes in the lighting level in the small Prototype D strip store with a PSZ system in two mild climates. The *EnergyPlus* results for cooling energy use are consistently higher by 15-20%, while the fan energy uses are identical to those from *DOE-2*. These runs were affected by modeling issues 6 (heating to the cooling setpoint) and 7 (faulty economizer control) mentioned previously. Correcting these dropped the *EnergyPlus* heating energy use from more than double to now 60-70% less than those shown by *DOE-2*. It appears likely that the increased cooling and decreased heating in *EnergyPlus* is due largely to differences in the economizer control logic.



The E1 series covers variations in the ventilation rate in the small building model as in D1, but with an

industrial-storage occupancy and simulated in an extreme heating and an extreme cooling climate. The *EnergyPlus* results for cooling energy use are similarly higher by 15% compared to *DOE-2*, but those for heating energy use are here lower by only 15-20%. Since the building model is very similar to that in D1, this difference must be because of climate differences, and further suggests that the economizer controls are the cause for the large heating differences in the D1 series. The *EnergyPlus* and *DOE-2* fan energies for the E1 series are identical.



The F1 series tests the sensitivity of the building models to alternative HVAC system types. Runs 1 and 2 are for the small 1-story A Prototype building modeled with a heat pump, while runs 3 and 4 are for the 2-story B

Prototype building modeled with a PVAV system with resistance heating. The *EnergyPlus* results for the heat pump runs are missing from this draft, but those for PVAV system show similar cooling energy use as do DOE-2, but double the heating energy use for both gas and electricity. The fan results are again very similar between *EnergyPlus* and *DOE-2*. As with the B1 and D1 series, these differences in heating energy use are still under study in hopes of achieving a better reconciliation.

Figure 13. F Series HVAC System Tests
Space Cooling

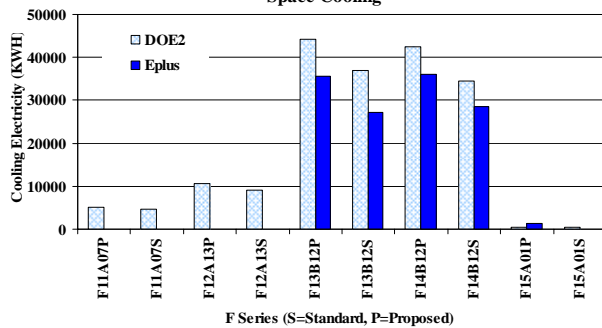


Figure 14. F Series HVAC System Tests
Space Heating

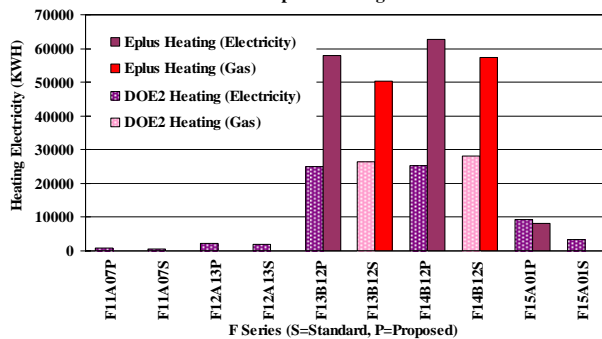
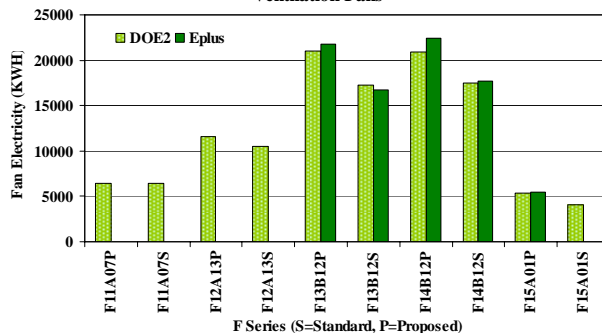


Figure 15. F Series HVAC System Tests
Ventilation Fans



CONCLUSIONS

Experience on this project has convinced the authors that a rigorous automated translation tool such as *doe2ep* is essential to insuring consistency between the

DOE-2 and *EnergyPlus* input files. The high sensitivity of the results from seemingly minor differences in input values or control algorithms has been continuously surprising. This may be partly due to California's mild climates and partly to the high thermal integrity required by Title-24. The sheer number of test cases in the ACM Test Suite was at times overwhelming, resulting in some test cases that are still under study as of June 2006. However, the Test Suite itself has proven to serve its intended purpose quite well in identifying discrepancies and problem areas for both simulation programs. It is the authors' intention to clear up the remaining questions, as well as finalize the current draft of *doe2ep* so that it can be offered as a program within the library of *EnergyPlus* utility tools.

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