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IEA BESTEST Multi-Zone Non-Airflow In-Depth Diagnostic Cases

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IEA BESTEST MULTI-ZONE NON-AIRFLOW IN-DEPTH DIAGNOSTIC CASES

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ABSTRACT

A set of in-depth diagnostic test cases for multi-zone heat transfer was developed. These are designed to test the ability of building energy analysis tools to model multi-zone conduction, multi-zone shading, including automated building self-shading and modeling of internal windows between zones. A methodological advancement for this work, which enhances the diagnostic capability of the tests, is that the multi-zone shading and internal window test cases were specified using building zones designed to be modeled as precise calorimeters. The basic principle is that all solar radiation incident on an exterior window is captured within a zone, such that the zone cooling load is equivalent to the solar radiation incident on that window.

INTRODUCTION

This paper documents a set of in-depth diagnostic test cases for multi-zone heat transfer models that do not include the heat and mass transfer effects of airflow between zones. The multi-zone non-airflow test cases represent an extension to IEA BESTEST (Judkoff and Neymark 1995a). This new work was conducted by the National Renewable Energy Laboratory (NREL), United States, in collaboration with a working group of international experts under International Energy Agency (IEA) Solar Heating and Cooling (SHC) Programme Task 34 and IEA Energy Conservation in Buildings and Community Systems (ECBCS) Programme Annex 43 (IEA 34/43).

Background: Building Energy Simulation Test and Diagnostic Method (BESTEST)

NREL has developed a number of building energy simulation test (BESTEST) suites for evaluating and diagnosing errors in software used for energy analysis of commercial and residential buildings. ASHRAE Standard 140, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* (ASHRAE 2007), either adopted the BESTEST test suites or are in the process of adopting them. Many entities have adopted or cited Standard 140 and/or the component BESTEST suites: the Internal Revenue Service (2008) (for certifying software used to determine tax deductions), ASHRAE building energy efficiency Standards 90.1 and 189.1 (ANSI/ASHRAE/IESNA 2007, ANSI/ASHRAE 2009), RESNET (2006, 2007), COMNET (Eley 2011), the International Energy Agency (Judkoff and Neymark 2009), and the European Community under its Energy Performance Directive (European Union 2002). These methods include software-to-software comparative testing, verification versus analytical solutions, and validation versus vetted empirical data. The theoretical basis for the BESTEST procedures is further described in the literature (ASHRAE 2009, Judkoff 1988, Judkoff et al. 2008, Judkoff and Neymark 2006).

Importance of the Multi-Zone Modeling Problem

Many buildings have multiple mechanical equipment control zones, and are therefore better modeled with multiple zones. Additionally, architectural features related to shading or that use internal windows are often applied in a multi-zone context. For example, a shading device associated with one zone of a model may cast a shadow on a window or wall associated with another zone of that model.

Current IEA BESTEST building thermal fabric test cases originally published by NREL in 1995 (Judkoff and Neymark 1995a, ASHRAE 2007) test the ability to model the thermal physics related to many typical building features such as thermal mass, windows, shading devices, orientation, internal gains, mechanical ventilation, and thermostat set point variation. These test cases are applied in a single-zone modeling context, except for one test case for modeling a sunspace that interacts with a conditioned zone via a common wall. HERS BESTEST (Judkoff and Neymark 1995b), also published by NREL, is designed to similarly test simplified tools commonly used with residential modeling. These test cases provide a more realistic, but less diagnostic context

than IEA BESTEST (Neymark and Judkoff 1997). HERS BESTEST includes the possibility for (but does not require) multi-zone modeling in all of its cases for an unconditioned attic, and in two of its cases that include a basement. However, the HERS BESTEST output requirements do not disaggregate results for separate zones, which inhibits multi-zone modeling diagnostics.

If a model has good agreement for the current set of building thermal fabric test cases that emphasize single-zone modeling, phenomena specific to multi-zone configurations are not necessarily being correctly modeled.

Additional work published during IEA SHC Task 12/ECBCS Annex 21 by Tampere University of Technology (Haapala et al. 1995) developed six test cases in a realistic commercial building/multi-zone context using two conditioned zones separated by a conditioned or unconditioned corridor zone, where only walls with windows are exposed to ambient conditions. NREL reviewed this work and observed the following (Neymark et al. 2008):

- Although the cases use a multi-zone configuration, multi-zone modeling effects are not well isolated.
  - The only discernible multi-zone modeling observation was that an unconditioned corridor caused disagreement among simulation results to expand, versus a conditioned corridor.
  - Other than that, because of many simultaneously acting phenomena, it was difficult to make specific conclusions regarding multi-zone interactions.
- No found bugs were documented for the simulation programs that ran the field trials of these early stage multi-zone test cases, whereas several found bugs were documented and fixed during field trials of the IEA BESTEST single-zone test cases that were also developed during IEA SHC Task 12.

As none of the test suites described above adequately isolates phenomena specific to multi-zone modeling, test cases were developed to address such phenomena.

THE IEA 34/43 MULTI-ZONE NON-AIRFLOW DIAGNOSTIC TEST CASES

A set of five diagnostic test cases for multi-zone non-airflow heat transfer models were developed. The test cases cover modeling of:

- Interzonal conduction heat transfer, assuming one-dimensional conduction (see Figure 1)
- Multi-zone shading, including building self-shading (see Figure 2)
- Internal windows between zones (see Figure 3).

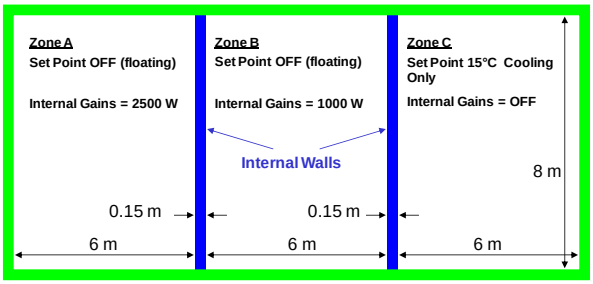


Figure 1 Multi-zone conduction schematic (Neymark et al. 2008)

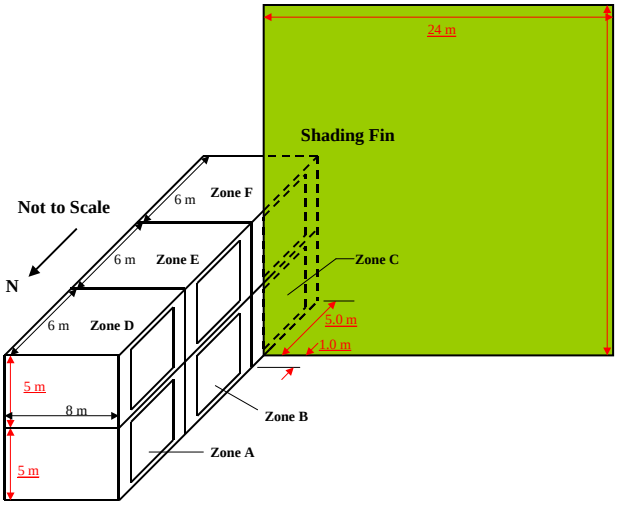


Figure 2 Multi-zone shading schematic (Neymark et al. 2008)

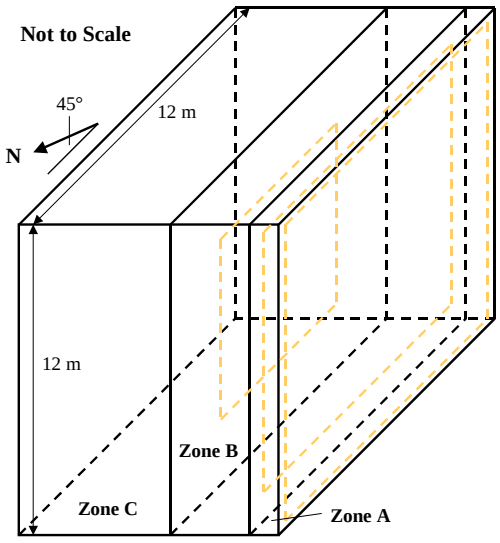


Figure 3 Multi-zone internal window schematic (Neymark et al. 2008)

We began the test cases by developing a relatively simple steady-state analytical solution (analytical verification test) for multi-zone conduction. Good agreement between simulation program results and the multi-zone conduction analytical solution was obtained early in the project. This provided a good starting point for developing diagnostic comparative test cases that test multi-zone shading models and internal window models.

We specified the multi-zone shading and internal window test cases by using idealized building zones designed to be modeled as precise calorimeters, where the only thermal mass is that of the zone air. The basic principle is that all solar radiation incident on an exterior window is captured within a zone, such that the zone cooling load is equivalent to the solar radiation incident on that window. Causes of disagreements are therefore limited to either an issue with the specific model being tested (the shading or internal window model), modeling of incident solar radiation, inability to precisely model the idealizations defining the zone as a calorimeter, or an input error. Additionally, sensitivity "delta" cases allow intermodel comparison of the difference between zone cooling loads with a shading device and without shading. This allows better isolation of shading model effects, as differences among models not related specifically to shading models should cancel out.

The effects of thermal mass were not tested in these new cases because the original IEA BESTEST (Judkoff and Neymark 1995a) comparative cases explored building envelope thermal mass effects in detail in a single-zone context (and in a two-zone case with a sunspace). By excluding thermal inertia and minimizing other simultaneous effects, the current specialized multi-zone cases maximize diagnostic power, and also minimize the number of cases required to address the tested phenomena. In the absence of multi-zone mass interaction test cases for the current configurations, if a simulation model demonstrates agreement for the original IEA BESTEST cases with thermal mass and demonstrates agreement for the new multi-zone test cases, this would suggest that such tested simulations may provide agreement where aspects of both types of test cases are combined. As thermal mass interactions (and other interactions) are important to test explicitly, our recommendations for future activities include developing multi-zone cases with thermal mass.

RESULTS

Field trials of the new IEA BESTEST cases were conducted with a number of detailed state-of-the-art whole-building energy simulation programs from around the world, including:

- For all cases: EnergyPlus (2008), ESP-r (2008), HTB2 (2008), TRNSYS-16 (2005), TRNSYS-TUD (2008), VA114 (2008)
- For conduction only: CODYRUN (2005), COMFIE (Peuportier and Sommereaux 1994), KoZiBu (2005).

The simulation-trial process was iterative in that executing the simulations led to refinement of the BESTEST cases, and the results of the tests led to improving and debugging the models. Improvements to simulation programs or simulation inputs made by participants must have a mathematical and a physical basis, and must be applied consistently across tests. Arbitrary modification of a simulation program's input or internal code just for the purpose of more closely matching a given set of results is not allowed. All improvements were required to be documented and justified in modeler reports, which are included in the final report (Neymark et al. 2008).

The multi-zone conduction case is a steady-state system of three zones in series with a conditioned zone on one end adjacent to two adjacent unconditioned (free floating temperature) zones, where the interior and exterior walls are conductive (see Figure 1). This case has a relatively simple analytical solution, as documented in the final report. For the Zone C cooling load all models tested agreed with the analytical solution within 0.3% except for one program (CODYRUN), which is within 1.9%.

For the multi-zone shading and internal window test cases, improvements to the simulation programs are evident when initial results are compared to final results, as shown in Figures 4 and 5, respectively, for the multi-zone shading cases, and Figures 6 and 7, respectively, for the internal window cases. These results indicate that there was initially 20%–90% and 40%–155% disagreement among annual cooling loads for various zones for the multi-zone shading and internal window cases, respectively, with substantial scatter among the programs. Here, disagreement is the difference between the maximum and minimum results for each case, divided by the mean of the results for each case ((max-min)/mean). After correcting software and modeling errors using BESTEST diagnostics – there were 31 fixes documented during the simulation trials – the remaining disagreements among results for various zones for multi-zone shading are 5%–13%, and for a single internal-window configuration are 7%–34%. For the most challenging configuration of the internal window cases, with a second internal window in series, disagreement for annual cooling load for the zone located interior to the second internal window is 112% (see bars for Zone C in Figure 7), thus indicating further refinement of models for this configuration may be warranted. Scatter among results was reduced for all the cases.

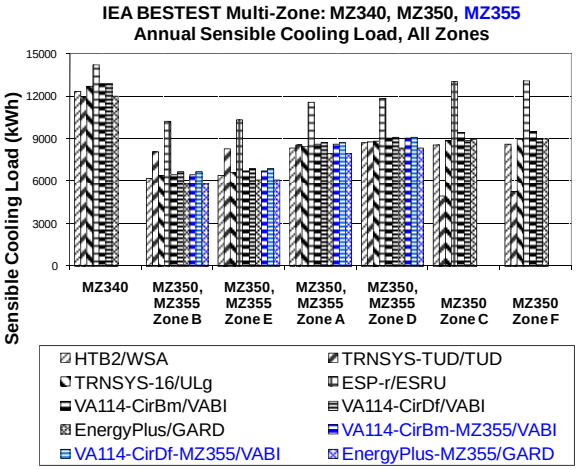


Figure 4 BESTEST multi-zone shading cases – sensible cooling load, before BESTESTing (Abbreviations along the x-axis are shorthand for the case descriptions, see Nomenclature; building self-shading results are three rightmost bars for zones B, E, A, and D.) (Neymark et al. 2008)

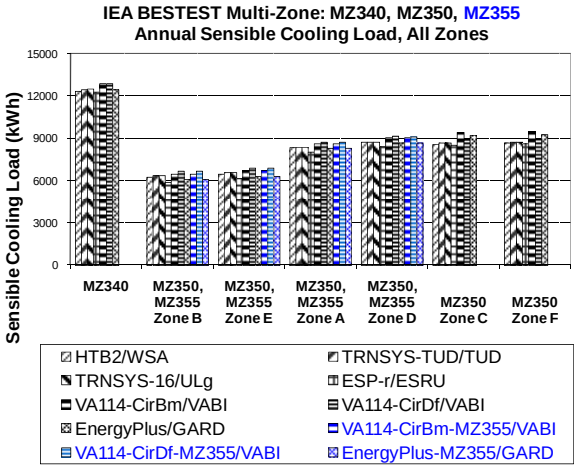


Figure 5 BESTEST multi-zone shading cases – sensible cooling load, after BESTESTing
(Abbreviations along the x-axis are shorthand for the case descriptions, see Nomenclature; building self-shading results are three rightmost bars for zones B, E, A, and D.) (Neymark et al. 2008)

Improvements in Shading Diagnostics Versus Previously Published Test Cases

Improvement in the ability to diagnose shading models is evident from comparing final disagreement ranges for the original single-zone IEA BESTEST shading cases for more realistic constructions, versus the final range of disagreement for the new in-depth diagnostic multi-zone shading cases. For the more realistic original single-zone cases with shading devices, the range of annual cooling load

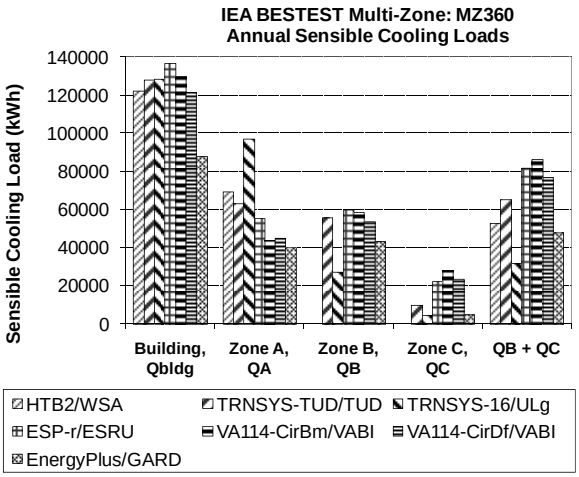


Figure 6 BESTEST internal windows – sensible cooling load, before BESTESTing (Abbreviations along the x-axis are shorthand for the output descriptions; see Nomenclature.) (Neymark et al. 2008)

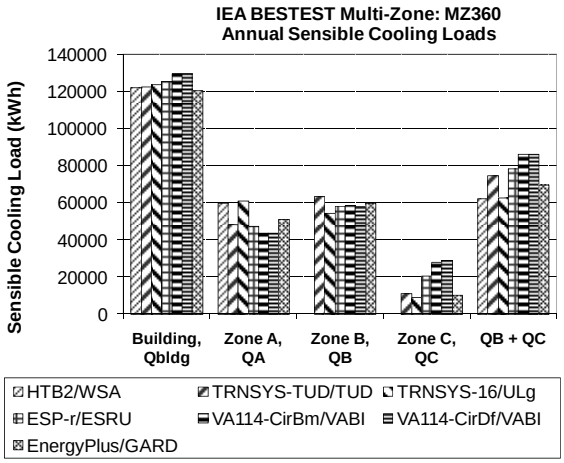


Figure 7 BESTEST internal windows – sensible cooling load, after BESTESTing
(Abbreviations along the x-axis are shorthand for the output descriptions; see Nomenclature.) (Neymark et al. 2008)

disagreement is 38%–73% for the absolute results (cases considered alone), and 46%–63% for the delta results (sensitivity results to isolate shading model effects, e.g., Case 630–620) (ANSI/ASHRAE 2007; Judkoff and Neymark 1995a). A graphic example of original single-zone shading case disagreement in the delta context, excerpted from IEA BESTEST, is provided in Figure 8. Disagreement ranges for final delta results of the current multi-zone cases are smaller relative to mean sensitivities (see Figure 9), ranging from 5%-6% for shading by the front side of the fin (zones B, E, A, D) to 20%-21% for the back side of the fin (zones C, F).

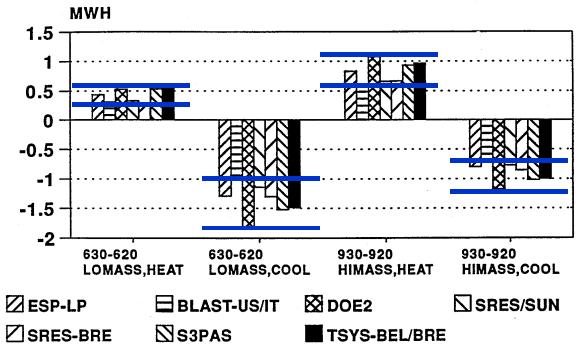


Figure 8 IEA BESTEST single-zone east- and west-shaded window delta sensitivity, annual heating and sensible cooling loads (Judkoff and Neymark 1995a)

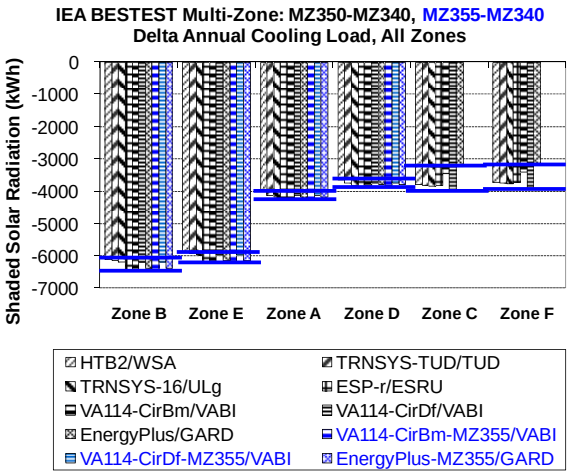


Figure 9 In-depth diagnostic multi-zone delta sensible cooling loads (Neymark et al. 2008)

CONCLUSIONS

A number of important test method and software improvements were made as a result of this work:

- The improved final agreement for shading cases using idealized/modeled calorimetry enabled us to identify disagreements and diagnose errors that may have been missed using the original IEA BESTEST shading cases (Judkoff and Neymark 1995a). The level of disagreement in the original IEA BESTEST cases related to a number of simultaneous effects such as modeling realistic optical properties of glazing and interior opaque surfaces, along with realistic wall conduction and thermal mass. These simultaneous effects may have obscured disagreements caused by shading models.
- Of 49 disagreements found during the simulation trials, 31 were diagnosed and fixed, 11 were planned for investigation by the software authors, 3 were judged as acceptable by the software authors, and 4 were awaiting notification of the software developer by the modeler. Several of the found errors affected some individual results by > 20%. A list of the problems found among the tested models, along with supporting details, are included in Part II of the final report (Neymark et al. 2008).

Based on results *after* several iterations of BESTESTing, and resulting model improvements, all the tested programs now appear to have reliable models for phenomena isolated by the test cases including interzonal conduction, multi-zone shading, and internal windows where there are no multiple internal windows in series. These test cases did not address thermal inertia interactions for the modeled phenomena. Some remaining disagreements should be addressed, especially with respect to deficiencies identified for three of the models related to modeling a second internal window in series. The simulation results (with the noted exceptions) may therefore be useful as a reference or benchmark against which other software can be tested.

With respect to the value of the test cases to software developers, a software-developer/vendor participant made the following comment about this IEA project:

"Bestest and IEA-34/43 tests brought a number of new errors to the surface. This shows the importance of these test [cycles]!! And still there will be errors in the software!! Development of new, specific test cases is of big importance!!" (Wijsman 2008).

Finally, the authors wish to acknowledge that the expertise available through the IEA and the dedication of the participants were essential to the success of this project. Over the four-year field trial effort, there were several revisions to the BESTEST specifications and subsequent re-executions of the computer simulations. This iterative process led to the refining of the new BESTEST cases, and the results of the tests helped us improve and debug the simulation models. 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, were much more cost effective with the participation of the IEA-34/43 experts.

Test Cases for Future Work

This project developed a set of idealized in-depth diagnostic test cases for multi-zone conduction, multi-zone shading, and internal window models. During this project, participants discussed a number of important test case configurations that could not be included with the current test cases because of resource constraints. These test cases would include:

- Shading case parametric variations, including:
  - Shading fin surface reflectance > 0

    - Modeling of multiple shading projections on a shaded area
- Internal window parametric variations in a two-zone context, including:
    - Two-zone version of Case MZ360 (idealized calorimeter)
    - Zero-conductance walls with realistic interior solar reflectance, with ideal windows
    - Realistic windows, with ideal walls (zero-conductance; interior solar absorptance = 1)
    - Realistic windows and zero-conductance walls with realistic interior solar absorptance
    - Realistic windows with realistic thermally conducting walls
- Shading/internal window interaction.
- Multi-zone shading and internal windows with thermal mass interactions.

Additional cases to consider are described in Section 2.5.3 of the final report (Neymark et al. 2008).

ACKNOWLEDGEMENTS

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The project participants who provided most of the early simulation-trial work, preliminary sensitivity tests, and feedback on the test specification are listed as coauthors. We also gratefully acknowledge the contributions from modelers and authors of sections on additional computer programs used in this effort, including:

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- Julien L'Hoest, Christophe Adam, Philippe André and Corinne Rogiest; University of Liege, Belgium: TRNSYS-16
- Harry Boyer, Frederic Miranville, and Alain Bastide; University of Reunion Island, France: CODYRUN
- Bruno Peuportier; Paris School of Mines, France: COMFIE
- Jean Noel; JNLOG, France: KoZiBu.

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NOMENCLATURE (FOR RESULTS FIGURES)

EnergyPlus/GARD: EnergyPlus run by GARD Analytics, U.S.

ESP-r/ESRU: ESP-r run by Energy Systems Research Unit, University of Strathclyde, U.K.

HIMASS,COOL: high mass, cooling

HIMASS,HEAT: high mass, heating

HTB2/WSA: HTB2 run by Welsh School of Architecture, Cardiff University, U.K.

LOMASS,COOL: low mass, cooling

LOMASS,HEAT: low mass, heating

MZ340: six-zone, unshaded

MZ350: six-zone, external shading device

MZ355: seven-zone, building self-shading

MZ360: three-zone, internal windows

QA: cooling load for Zone A

QB: cooling load for Zone B

QB + QC: sum of cooling loads for Zones B and C

Qbldg: cooling load for total building

QC: cooling for Zone C

TRNSYS-TUD: TRNSYS-TUD run by Dresden University of Technology, Germany

TRNSYS-16/ULg: TRNSYS-16 run by University of Liege, Belgium

VA114-CirBm/VABI: VA114 with circumsolar radiation modeled as beam radiation, run by VABI Software, The Netherlands

VA114-CirDf/VABI: VA114 with circumsolar radiation modeled as diffuse radiation, run by VABI Software, The Netherlands

630-620: difference between shaded and unshaded east/west window configurations, low mass construction

930-920: difference between shaded and unshaded east/west window configurations, high mass construction

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