EnergyPlus Testing with IEA BESTEST In-Depth Ground Coupled Heat Transfer Tests Related to Slab-on-Grade Construction

EnergyPlus Version 4.0.0.024

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1 TEST OBJECTIVES AND OVERVIEW

1.1 Introduction

This report describes the modeling methodology and results for testing done for the *IEA BESTEST In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction* (Neymark and Judkoff 2008) which were simulated using the EnergyPlus software. The specifications for the test suite are described in Section 1.3 Test Specifications of that report. The results of EnergyPlus are also compared with results from several other numerical models and whole building energy simulation programs which simulated the same test cases.

1.2 Test Type: Comparative - Loads

Comparative tests compare a program to itself or to other simulation programs. This type of testing accomplishes results on two different levels, both validation and debugging.

From a validation perspective, comparative tests will show that EnergyPlus is computing solutions that are reasonable compared to other energy simulation programs. This is a very powerful method of assessment, but it is no substitute for determining if the program is absolutely correct since it may be just as equally incorrect as the benchmark program or programs. The biggest strength of comparative testing is the ability to compare any cases that two or more programs can model. This is much more flexible than analytical tests when only specific solutions exist for simple models, and much more flexible than empirical tests when only specific data sets have been collected for usually a very narrow band of operation. The IEA BESTEST in-depth diagnostic G-C test procedures discussed below take advantage of the comparative test method and for the specific tests included in test suite have already been run by experts of the other simulation tools.

Comparative testing is also useful for field-by-field input debugging. Energy simulation programs have so many inputs and outputs that the results are often difficult to interpret. To ascertain if a given test passes or fails, engineering judgment or hand calculations are often needed. Field by field comparative testing eliminates any calculational requirements for the subset of fields that are equivalent in two or more simulation programs. The equivalent fields are exercised using equivalent inputs and relevant outputs are directly compared.

1.3 Test Suite: IEA BESTEST In-Depth Diagnostic G-C Test Suite for Slab-on-Grade Construction

The tests described in Section 1.3 of the *IEA BESTEST In-Depth Diagnostic Cases for Ground Coupled Heat Transfer Related to Slab-on-Grade Construction* (Neymark and Judkoff 2008) were performed using EnergyPlus. The test cases are designed to use the results of verified detailed numerical ground-coupled heat transfer models as a secondary mathematical truth standard for comparing the results of simplified and mid-level detailed ground-coupled heat transfer models typically used with whole-building energy simulation software. The test cases use an idealized uninsulated slab-in-grade configuration with both steady-state and harmonic boundary conditions applied with artificially constructed annual weather data, along with an adiabatic above-grade building envelope to isolate the effects of ground-coupled heat transfer.

The test cases are divided into three categories:

- Series “a” – for use with numerical methods programs
- Series “b” – for use with whole-building simulation programs
- Series “c” – uses boundary conditions that are compatible with the BASESIMP program to allow comparison of BASESIMP results with other programs

EnergyPlus was used to model the nine test cases in Series “b” and five test cases in Series “c”. Table 1 summarizes the characteristics of these test cases.

1.3.1 Base Case Building(Case GC30b)

The basic test building (Figures 1 and 2) is a rectangular 144 m2 single zone (12 m wide x 12 m long x 2.7 m high) with no interior partitions and no windows. The building’s exterior walls and roof are adiabatic and massless with energy transfer only through the floor slab which is contact with soil. There is no infiltration or ventilation and no internal gains.

Input Parameters

Slab length	12 m
Slab width	12 m
Wall thickness	0.24 m
Inside zone air temperature	30°C
Outside air temperature	10°C
Deep ground temperature	10°C
Deep ground boundary depth	15 m
Far field boundary distance	15 m
For other inputs see Table 1	

Soil and Slab Properties and Boundary Conditions

Thermal Conductivity	1.9 W/(m-K)
Density	1490 kg/m3
Specific Heat	1800 J/(kg-K)
Slab thickness	Use the smallest thickness that program will allow

Table 1 – In-Depth Ground Coupling Test Cases

Case	**Test Description**	**Dynamic**	**Slab Dimen. (m x m)**	**h,int (W/m2-K)**	**h,ext (W/m2-K)**	**Ground Depth (m)**	**Far-Field Boundary (m)**	**Cond. (W/m-K)**
Series "b" - Test Cases for Whole-Building Simulation Programs								
GC30b	Comparative Base Case	Steady State	12 x 12	100	100	15	15	1.9
GC40b	Harmonic Variation	Harmonic	12 x 12	100	100	15	15	1.9
GC45b	Aspect Ratio	Harmonic	36 x 4	100	100	15	15	1.9
GC50b	Large Slab	Harmonic	80 x 80	100	100	15	15	1.9
GC55b	Shallow Deep Ground Temp	Harmonic	12 x 12	100	100	2	15	1.9
GC60b	h,int	Steady State	12 x 12	7.95	100	15	15	1.9
GC65b	h,int and h,ext	Steady State	12 x 12	7.95	11.95	15	15	1.9
GC70b	Harmonic h,int and h,ext	Harmonic	12 x 12	7.95	11.95	15	15	1.9
GC80b	Ground Conductivity	Harmonic	12 x 12	100	100	15	15	0.5
Series "c" - Test Cases apply boundary conditions that are compatible with the BASESIMP program								
GC30c	Comparative Base Case for Series "c"	Steady State	12 x 12	7.95	Const T	15	8	1.9
GC40c	Harmonic Variation	Harmonic	12 x 12	7.95	Direst T	15	8	1.9
GC45c	Aspect Ratio	Harmonic	36 x 4	7.95	Direct T	15	8	1.9
GC55c	Shallow Deep Ground Temp	Harmonic	12 x 12	7.95	Direct T	5	8	1.9
GC80c	Ground Conductivity	Harmonic	12 x 12	7.95	Direct T	15	8	0.85

Notes:
h,int = interior surface convective coefficient
h,ext = exterior surface convective coefficient
Far-Field Boundary = distance from slab edge
Cond. = slab and soil conductivity
const T = direct input constant temperature
direct T = direct input temperature (varies hourly)

Surface Properties

No surface radiation exchange. Interior and exterior solar absorptances and infrared emittances are to set to 0 or as low as program will allow.

Mechanical System

The mechanical system is an ideal system that provides sensible heating only (no cooling) with the following characteristics:

Heat on if zone temperature <30°C; otherwise Heat = Off
Heating capacity set as needed to maintain zone air setpoint temperature of 30°C
Uniform zone air temperature, i.e. well mixed air
100% efficient
100% convective air system
Ideal controls, heating system cycles to maintain zone setpoint temperature

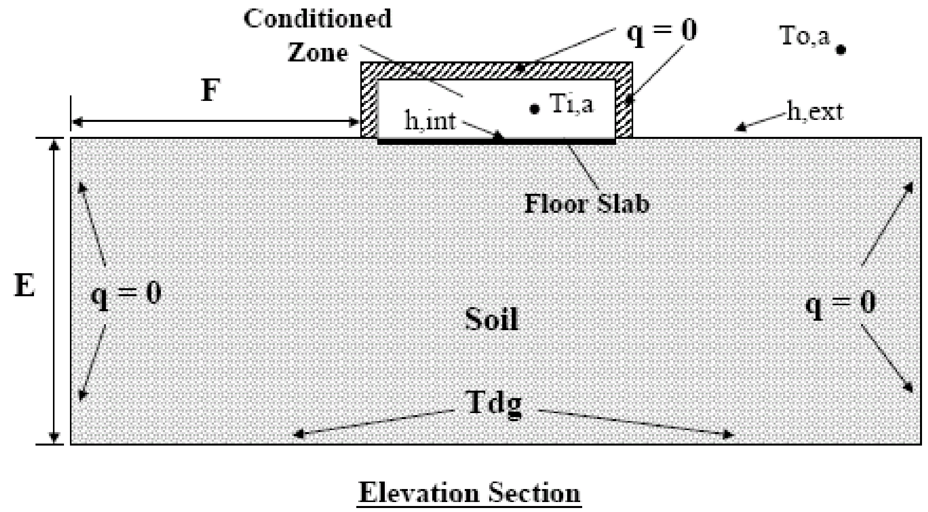
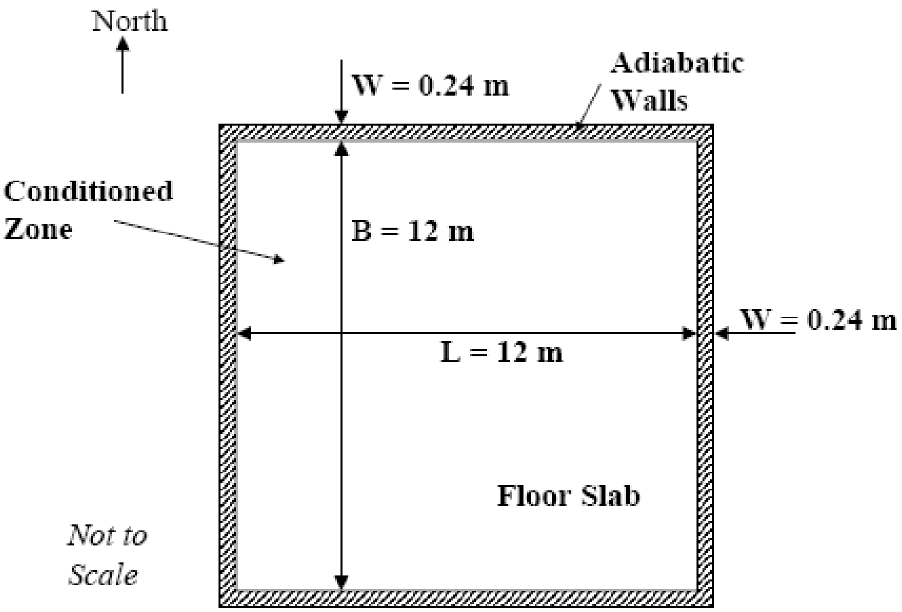
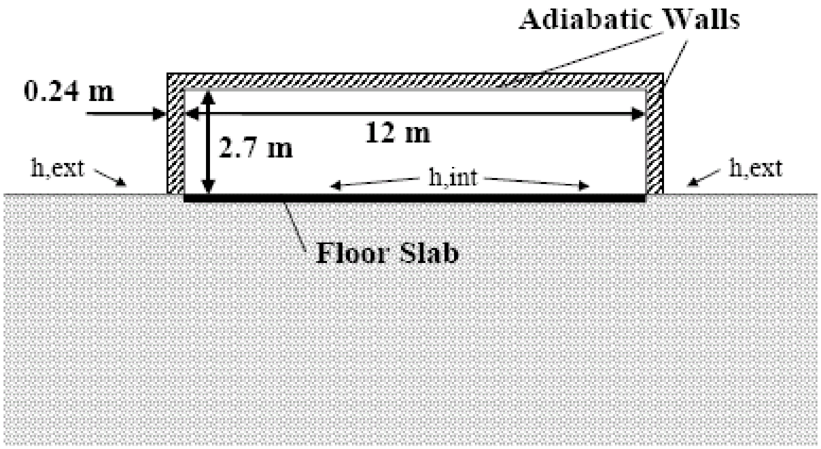


Figure 1 – Schematic Diagram of Test Building and Soil showing Boundary Conditions and Soil Dimensions (Excerpted from Neymark and Judkoff 2008)



Plan View



Elevation Section

Figure 2 – Schematic Diagram of Floor Slab and Conditioned Zone Adiabatic Wall Dimensions (Excerpted from Neymark and Judkoff 2008)

1.3.2 Weather Data

Six weather data files in TMY2 format were provided with the test suite in electronic format with characteristics as follows:

Weather Data Set	**Mean Ambient Dry-Bulb Temperature**	**Mean Ambient Relative Humidity**	**Constant Annual Wind Speed**
GCSS-W40.TM2	10°C, constant	0.09%, constant	40.0 m/s
GCSS-W20.TM2	10°C, constant	0.09%, constant	19.9 m/s
GCSS-W01.TM2	10°C, constant	0.09%, constant	1.0 m/s
GCSP-W40.TM2	10°C, harmonically varying	0.09%, harmonically varying	40.0 m/s
GCSP-W20.TM2	10°C, harmonically varying	0.09%, harmonically varying	19.9 m/s
GCSP-W01.TM2	10°C, harmonically varying	0.09%, harmonically varying	1.0 m/s

These weather files were to be used as indicated below for the various test cases. The TM2 versions of these weather files were converted to EnergyPlus format using the EnergyPlus 3.1.0.027 weather conversion program (version 1.04.0011 dated 4/9/2009).

Case	**Weather Data File**
GC30b	GCSS-W20.TM2
GC40b	GCSP-W20.TM2
GC45b	GCSP-W20.TM2
GC50b	GCSP-W20.TM2
GC55b	GCSP-W20.TM2
GC60b	GCSS-W20.TM2
GC65b	GCSS-W01.TM2
GC70b	GCSP-W01.TM2
GC80b	GCSP-W20.TM2
GC30c	GCSS-W40.TM2
GC40c	GCSP-W40.TM2
GC45c	GCSP-W40.TM2
GC55c	GCSP-W40.TM2
GC80c	GCSP-W40.TM2

1.3.3 *Simulation and Reporting Period*

Annual simulations were run for all cases for as many years as required such that a less than or equal to 0.1% change in floor slab conduction occurs over the year. The following outputs were provided for the last hour of the simulation:

- Conduction through the floor slab in W or Wh/h
- Zone load in W or Wh/h
- Zone air temperature in °C
- Duration of the simulation in hours

2 RESULTS AND DISCUSSION

2.1 Modeling Methodology

The difficulty behind linking ground heat transfer calculations to EnergyPlus is the fact that the conduction calculations in EnergyPlus (and in DOE–2 and BLAST before it) are one-dimensional and the ground heat transfer calculations are two or three-dimensional. This causes severe modeling problems irrespective of the methods being used for the ground heat transfer calculation. The basic heat balance based zone model is the foundation for building energy simulation in EnergyPlus. Thus, it is necessary to be able to relate ground heat transfer calculations to that model.

The heat balance zone model considers a single room or thermal zone in a building and performs a heat balance on it. A fundamental modeling assumption is that the faces of the enclosure are isothermal planes. A ground heat transfer calculation usually considers an entire building and the earth that surrounds it, resulting in non-isothermal face planes where there is ground contact.

The EnergyPlus development team decided to break the modeling into two steps with the first step being to partially decouple the ground heat transfer calculation from the thermal zone calculation to determine the ground-slab interface temperature and then the second step being the zone heat transfer calculation. The most important parameter for the zone calculation is the outside face temperature of the building surface that is in contact with the ground. Thus, this becomes a reasonable "separation plane" for the two calculations. It was further decided that the current usage of monthly average ground temperature was reasonable for this separation plane temperature as well, since the time scales of the building heat transfer processes are so much shorter than those of the ground heat transfer processes.

Using the separation plane premise, the 3D ground heat transfer program for slabs were developed by Bahnfleth (1989, 1990) and were modified by Clements (2004) to produce outside face temperatures. The program has been modified for use by EnergyPlus to permit separate monthly average inside zone temperatures as input. The program produces outside face temperatures for the core area and the perimeter area of the slab. It also produces the overall weighted average surface temperature based on the perimeter and core areas used in the calculation.

The independent EnergyPlus Slab program requires the use of the EnergyPlus whole-building simulation program in order to determine the space heating or cooling load and resultant space temperature for each time step of the simulation. Only In-Depth G-C test cases GC30b, GC40b, GC45b, GC50b, GC55b, GC60b, GC65b, GC70b, GC80b, GC30c, GC40c, GC45c, GC55c and GC80c were modeled with EnergyPlus. Each of these cases were simulated using the autogrid feature of the EnergyPlus Slab program.

The simulation of ground-coupled heat transfer is a two-step process with EnergyPlus. First, for each of the IEA BESTEST In-Depth G-C cases that were modeled, the characteristics and properties of the soil and slab along with boundary conditions, indoor film coefficients and monthly average indoor temperature setpoint were input to the EnergyPlus Slab program which is an auxiliary program that is part of the EnergyPlus suite. Using the slab Area-to-Perimeter ratio defined by the user, the Slab program generates an equivalent slab with appropriate perimeter and core areas and simulates the slab heat transfer for a period of years until the temperature convergence tolerance is reached. A set of monthly slab perimeter and core temperatures at the ground-slab interface and heat fluxes are output as shown in tables below. The second step then is to create the EnergyPlus whole building model (IDF file) which includes the monthly average ground temperature values from the Slab program analysis. In the EnergyPlus IDF file these monthly temperatures are input as part of the Site:GroundTemperature:BuildingSurface object. The whole building simulation is then performed using a one zone building where all surfaces except for the floor were adiabatic. This analysis process is then repeated for each case to be analyzed.

2.2 Modeling Difficulties

The boundary condition of zero-vertical heat flux implied for the soil surface just beneath the adiabatic exterior walls of the conditioned zone, as specified in the BESTEST Indepth G-C specification, was not modeled by the EnergyPlus Slab program. The slab program does not have the capability to model this effect. With the EnergyPlus Slab program the entire slab top surface is exposed to the interior zone condition. The slab configuration used in the slab program is a "slab-in-grade model." That is, the slab top surface is assumed to be level with the outside earth surface. The modeling capabilities of the EnergyPlus Slab program are shown in Figure 3. The insulation layers are optional and were not required for any of the G-C test cases.

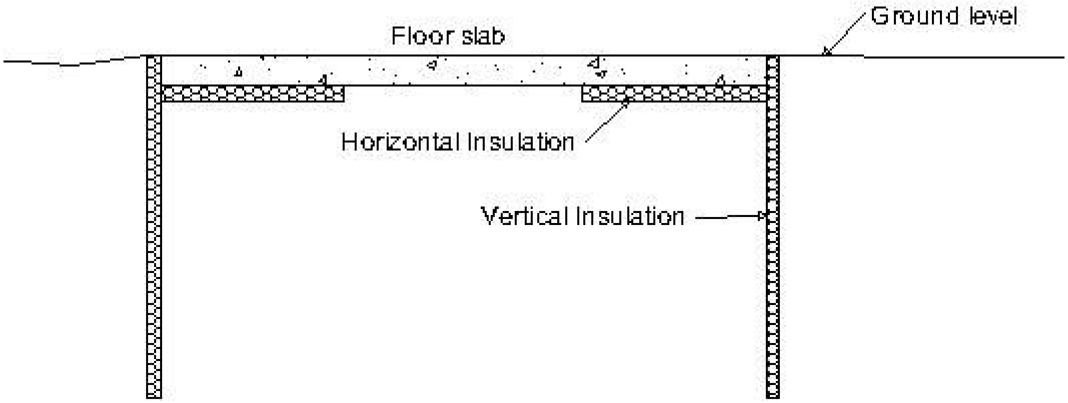


Figure 3 EnergyPlus Slab-In-Grade Illustration

2.3 Modeling Assumptions

Over the duration of the IEA BESTEST In-Depth Ground-Coupling test suite development in which EnergyPlus first participated in December 2004, the EnergyPlus auxiliary Slab program has had several upgrades with changes as summarized below:

- May 2003 Original version (EnergyPlus version 1.1.0.003) used to report results in EnergyPlus Modeler Report dated December 2004

- April 2004 Enhanced (EnergyPlus version 1.2.2.031) to allow optional user inputs for the lower deep boundary temperature and exterior ground heat transfer coefficient and was used to report revised results presented in EnergyPlus Modeler Report dated June 2005

- March 2006 Enhanced (EnergyPlus 1.3.0.007) to allow user input of the lower deep boundary depth and was used to report revised results presented in EnergyPlus Modeler Report dated March 2006.

Several of the inputs required by the EnergyPlus Slab program to simulate the IEA BESTEST In-Depth G-C test cases but not specified by the test specification are highlighted below.

1) Ground surface albedo for snow and no snow conditions – both set to 0.0

2) Ground surface emissivity for snow and no snow conditions – both set to 0.000001

3) Ground surface roughness for snow and no snow conditions – both set to 0.000001

4) Slab thickness - The EnergyPlus Slab program requires the user to specify the thickness of the slab. For the results reported in the EnergyPlus Modeler Report dated December 2004, the slab thickness was set to 0.1524 m (6 inch). In accordance with the IEA BESTEST In-Depth G-C specification released in June 2005 where it was requested that the thinnest slab allowable be used, all cases were revised to use a slab with thickness of 0.1285 m (5 inch).

5) Surface evapotranspiration – set to FALSE (off)

6) Convergence tolerance – The Slab program iterations continue until the temperature change of all modes are less than this value. For all test cases the convergence tolerance was set to 0.1 C.

7) For all cases the grid autosizing option was used.

8) For Cases GC30c, GC40c, GC45c, GC55c and GC80c the exterior ground surface temperature could not be fixed as required by the BESTEST Indepth G-C specification. To approximate this condition, as suggested in the specification, the exterior ground convective coefficient was set to 100 W/m2-K.

2.4 Results with Latest Release

2.4.1 *Slab Program Results*

The monthly ground/slab interface temperatures calculated by the EnergyPlus Slab Program for various cases are summarized in tables below. The temperatures listed in the column labeled “Taverage” were used by EnergyPlus to simulate the heat transfer between the slab and the zone interior space. It should be noted that the total slab area (perimeter area + core area) presented in the tables below will not necessarily agree with the total slab area specified for each case in the BESTEST Indepth G-C specification. This is particularly noticeable for Cases GC45b and GC45c. The EnergyPlus Slab program requests that the user input the Area-to-Perimeter (A/P) ratio for each case and not the actual dimensions or area of the slab. The EnergyPlus Slab program then constructs a square slab with an equivalent A/P ratio and then performs its analysis to determine the ground/slab interface temperatures. For those cases where the specification calls for a slab with dimensions of 12m by 12m (Cases GC30, GC 40, GC55, GC60, GC65 and GC70), the total floor area used by the Slab program happens to be approximately 144 m2. For the other cases however, where the specification calls for a rectangular floor (Case GC45 with a 36m by 4m floor and Case GC 50 with a 80m by 80m floor), the floor area used by EnergyPlus is not that called for in the specification. The resulting ground/slab interface temperatures calculated by the Slab program for these last two cases should be reliable since they are based on a floor with the same A/P ratio. The resulting monthly ground/slab interface temperatures are then specified in EnergyPlus using the Site:GroundTemperature:BuildingSurface object along with the actual slab dimensions from the specification for each test case. EnergyPlus then performs simulations based on the correct slab area.

Cases GC30b – Steady-State Comparative Test Base Case

Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00 Core Area: 64

Month	TAverage	TPerimeter	TCore	TInside	AverageFlux	PerimeterFlux	CoreFlux
1	28.57	27.99	29.31	30	18.39	25.94	8.95
2	28.57	27.99	29.31	30	18.39	25.94	8.95
3	28.57	27.99	29.31	30	18.39	25.94	8.95
4	28.57	27.99	29.31	30	18.39	25.94	8.95
5	28.57	27.99	29.31	30	18.39	25.94	8.95
6	28.57	27.99	29.31	30	18.39	25.94	8.95
7	28.57	27.99	29.31	30	18.38	25.94	8.95
8	28.57	27.99	29.31	30	18.38	25.94	8.95
9	28.57	27.99	29.31	30	18.38	25.94	8.94
10	28.57	27.99	29.31	30	18.38	25.94	8.95
11	28.57	27.99	29.31	30	18.38	25.94	8.94
12	28.57	27.99	29.31	30	18.38	25.93	8.95

Convergence has been gained.

Case GC40b – Harmonic Variation of Ambient Temperature

Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00   Core Area: 64

Month	TAverage	TPerimeter	TCore	TInside	AverageFlux	PerimeterFlux	CoreFlux
1	28.39	27.66	29.30	30	20.73	30.11	8.00
2	28.38	27.65	29.29	30	20.92	30.32	9.16
3	28.41	27.72	29.28	30	20.46	29.41	9.28
4	28.49	27.86	29.28	30	19.46	27.57	9.31
5	28.59	28.04	29.28	30	18.17	25.31	9.25
6	28.68	28.20	29.29	30	16.95	23.22	9.11
7	28.75	28.30	29.31	30	16.12	21.87	8.92
8	28.77	28.32	29.32	30	15.90	21.63	8.74
9	28.73	28.25	29.33	30	16.36	22.55	8.63
10	28.65	28.11	29.33	30	17.38	24.40	8.59
11	28.55	27.93	29.33	30	18.67	26.68	8.66
12	28.46	27.77	29.32	30	19.89	28.76	8.80

Convergence has been gained.

Case GC45b – Aspect Ratio

Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 41.60   Core Area: 10.24

Month	TAverage	TPerimeter	TCore	TInside	AverageFlux	PerimeterFlux	CoreFlux
1	27.65	27.32	28.99	30	30.30	34.58	12.95
2	27.62	27.29	28.97	30	30.59	34.85	13.32
3	27.68	27.37	28.95	30	29.83	33.84	13.54
4	27.81	27.53	28.95	30	28.16	31.75	13.55
5	27.98	27.74	28.96	30	26.04	29.17	13.34
6	28.13	27.92	28.99	30	24.04	26.76	12.96
7	28.24	28.04	29.03	30	22.69	25.19	12.52
8	28.26	28.07	29.06	30	22.36	24.88	12.12
9	28.20	27.99	29.08	30	23.14	25.91	11.90
10	28.07	27.83	29.08	30	24.83	28.01	11.89
11	27.91	27.62	29.06	30	26.96	30.61	12.11
12	27.75	27.44	29.03	30	28.96	33.01	12.49

Convergence has been gained.

Case GC50b – Large Slab

Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 624.00   Core Area: 5776.00

Month	TAverage	TPerimeter	TCore	TInside	AverageFlux	PerimeterFlux	CoreFlux
1	29.52	28.03	29.69	30	6.13	25.35	4.05
2	29.52	28.02	29.68	30	6.16	25.51	4.07
3	29.53	28.08	29.68	30	6.09	24.71	4.08
4	29.54	28.21	29.68	30	5.94	23.11	4.09
5	29.55	28.36	29.68	30	5.74	21.15	4.08
6	29.57	28.50	29.68	30	5.56	19.36	4.06
7	29.58	28.59	29.69	30	5.43	18.21	4.04
8	29.58	28.60	29.69	30	5.39	18.02	4.02
9	29.58	28.54	29.69	30	5.46	18.84	4.01
10	29.56	28.41	29.69	30	5.61	20.45	4.01
11	29.55	28.26	29.69	30	5.81	22.42	4.02
12	29.53	28.12	29.69	30	5.99	24.21	4.03

Convergence has been gained.

Case GC55b – Shallow Deep Ground Temperature

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
      Month     TAverage    TPerimeter         TCore        TInside   AverageFlux  PerimeterFlux      CoreFlux
          1        27.38         26.82         28.09             30         33.69          40.99         24.55
          2        27.40         26.84         28.09             30         33.54          40.74         24.55
          3        27.44         26.92         28.10             30         32.91          39.62         24.54
          4        27.52         27.06         28.10             30         31.94          37.88         24.50
          5        27.60         27.20         28.10             30         30.88          36.02         24.46
          6        27.67         27.32         28.10             30         30.04          34.53         24.42
          7        27.70         27.38         28.11             30         29.62          33.81         24.40
          8        27.69         27.36         28.11             30         29.76          34.05         24.39
          9        27.64         27.27         28.11             30         30.40          35.20         24.41
         10        27.56         27.13         28.10             30         31.38          36.93         24.44
         11        27.48         26.99         28.10             30         32.44          38.80         24.48
         12        27.42         26.87         28.10             30         33.28          40.29         24.52

Convergence has been gained.
```

Case GC60b – Steady State with Typical Interior Surface Convective Coefficient

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
      Month     TAverage    TPerimeter         TCore        TInside   AverageFlux  PerimeterFlux      CoreFlux
          1        27.02         25.86         28.45             30         15.43          21.38          7.99
          2        27.02         25.86         28.45             30         15.43          21.38          7.99
          3        27.02         25.86         28.46             30         15.43          21.38          7.99
          4        27.02         25.86         28.45             30         15.43          21.38          7.99
          5        27.02         25.86         28.46             30         15.43          21.38          7.99
          6        27.02         25.86         28.46             30         15.43          21.38          7.98
          7        27.02         25.87         28.46             30         15.43          21.38          7.99
          8        27.02         25.87         28.46             30         15.43          21.38          7.99
          9        27.02         25.86         28.46             30         15.42          21.38          7.98
         10        27.02         25.87         28.46             30         15.43          21.38          7.99
         11        27.02         25.87         28.46             30         15.42          21.38          7.98
         12        27.02         25.87         28.46             30         15.43          21.38          7.99

Convergence has been gained.
```

Case GC65b – Steady State with Typical Interior and Exterior Surface Convective Coefficients

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
      Month     TAverage    TPerimeter         TCore        TInside   AverageFlux  PerimeterFlux      CoreFlux
          1        27.83         27.14         28.68             30         11.24          14.78          6.82
          2        27.83         27.14         28.68             30         11.24          14.78          6.82
          3        27.83         27.14         28.68             30         11.24          14.77          6.81
          4        27.83         27.14         28.68             30         11.24          14.77          6.81
          5        27.83         27.14         28.68             30         11.24          14.77          6.81
          6        27.83         27.14         28.68             30         11.23          14.77          6.81
          7        27.83         27.14         28.68             30         11.23          14.77          6.81
          8        27.83         27.14         28.68             30         11.23          14.77          6.81
          9        27.83         27.14         28.68             30         11.23          14.77          6.81
         10        27.83         27.14         28.68             30         11.23          14.77          6.81
         11        27.83         27.14         28.68             30         11.23          14.77          6.81
         12        27.83         27.14         28.68             30         11.23          14.77          6.81

Convergence has been gained.
```

Case GC70b – Harmonic Variation of Ambient Temperature with Typical Interior and Exterior Surface Convective Coefficients

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
            Month       TAverage     TPerimeter          TCore          TInside    AverageFlux  PerimeterFlux       CoreFlux
                1          27.46          26.56          28.60               30          13.11          17.80           7.24
                2          27.44          26.53          28.58               30          13.23          17.96           7.32
                3          27.46          26.58          28.57               30          13.12          17.71           7.38
                4          27.52          26.69          28.57               30          12.80          17.12           7.40
                5          27.61          26.83          28.57               30          12.38          16.38           7.38
                6          27.69          26.97          28.58               30          11.96          15.67           7.32
                7          27.75          27.07          28.60               30          11.63          15.13           7.25
                8          27.78          27.12          28.61               30          11.46          14.89           7.17
                9          27.77          27.09          28.63               30          11.50          15.02           7.11
               10          27.72          26.99          28.63               30          11.78          15.55           7.07
               11          27.63          26.83          28.63               30          12.24          16.36           7.09
               12          27.54          26.67          28.62               30          12.73          17.19           7.15

Convergence has been gained.
```

Case GC80b – Reduced Slab and Ground Conductivity

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
            Month       TAverage         TPerim     eter TCore          TInside    AverageFlux  PerimeterFlux       CoreFlux
                1          28.60          27.95          29.41               30           5.26           7.69           2.21
                2          28.58          27.92          29.41               30           5.31           7.79           2.22
                3          28.60          27.96          29.40               30           5.24           7.65           2.24
                4          28.65          28.05          29.40               30           5.05           7.30           2.25
                5          28.72          28.17          29.40               30           4.80           6.84           2.25
                6          28.79          28.30          29.40               30           4.55           6.38           2.25
                7          28.84          28.38          29.40               30           4.36           6.06           2.24
                8          28.85          28.41          29.41               30           4.30           5.95           2.23
                9          28.83          28.37          29.41               30           4.37           6.09           2.21
               10          28.78          28.28          29.41               30           4.56           6.44           2.20
               11          28.71          28.16          29.41               30           4.81           6.90           2.20
               12          28.65          28.04          29.41               30           5.07           7.36           2.20

Convergence has been gained.
```

Cases GC30c – Steady-State Comparative Test Base Case with BASESIMP

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64
            Month       TAverage     TPerimeter          TCore          TInside    AverageFlux  PerimeterFlux       CoreFlux
                1          26.90          25.67          28.43               30          16.05          22.41           8.11
                2          26.90          25.67          28.43               30          16.05          22.41           8.11
                3          26.90          25.67          28.43               30          16.05          22.41           8.11
                4          26.90          25.67          28.43               30          16.05          22.40           8.11
                5          26.90          25.67          28.43               30          16.05          22.40           8.10
                6          26.90          25.67          28.43               30          16.05          22.40           8.10
                7          26.90          25.67          28.43               30          16.05          22.40           8.10
                8          26.90          25.67          28.43               30          16.05          22.40           8.10
                9          26.90          25.67          28.43               30          16.05          22.40           8.10
               10          26.90          25.67          28.43               30          16.05          22.40           8.10
               11          26.90          25.67          28.43               30          16.05          22.40           8.10
               12          26.90          25.67          28.43               30          16.04          22.40           8.10

Convergence has been gained.
```

Case GC40c – Harmonic Variation of Direct-Input Exterior Surface Temperature with BASESIMP Boundary Conditions

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64
           Month      TAverage     TPerimeter          TCore         TInside    AverageFlux  PerimeterFlux       CoreFlux
               1         26.47          24.91          28.41              30          18.26          26.31           8.20
               2         26.44          24.89          28.38              30          18.40          26.42           8.37
               3         26.53          25.07          28.36              30          17.94          25.51           8.48
               4         26.72          25.40          28.36              30          16.97          23.76           8.49
               5         26.95          25.81          28.38              30          15.76          21.66           8.40
               6         27.17          26.18          28.41              30          14.63          19.75           8.23
               7         27.31          26.41          28.45              30          13.88          18.57           8.03
               8         27.35          26.44          28.48              30          13.72          18.42           7.85
               9         27.25          26.26          28.50              30          14.19          19.36           7.73
              10         27.07          25.91          28.51              30          15.17          21.12           7.72
              11         26.83          25.51          28.49              30          16.38          23.24           7.82
              12         26.61          25.14          28.46              30          17.51          25.13           7.99

Convergence has been gained.
```

Case GC45c – Aspect Ratio with BASESIMP Boundary Conditions

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 41.60    Core Area: 10.24
           Month      TAverage     TPerimeter          TCore         TInside    AverageFlux  PerimeterFlux       CoreFlux
               1         24.90          24.21          27.70              30          26.35          29.91          11.90
               2         24.86          24.18          27.63              30          26.55          30.07          12.27
               3         25.01          24.38          27.59              30          25.78          29.06          12.46
               4         25.32          24.76          27.60              30          24.19          27.09          12.42
               5         25.70          25.22          27.65              30          22.21          24.69          12.14
               6         26.06          25.64          27.74              30          20.38          22.52          11.71
               7         26.29          25.91          27.83              30          19.19          21.15          11.24
               8         26.33          25.95          27.90              30          18.96          20.96          10.85
               9         26.18          25.75          27.94              30          19.76          21.00          10.65
              10         25.87          25.36          27.93              30          21.36          23.99          10.71
              11         25.48          24.90          27.88              30          23.35          26.39          10.99
              12         25.13          24.48          27.79              30          25.17          28.55          11.42

Convergence has been gained.
```

Case GC55c – Shallow Deep Ground Temperature with BASESIMP Boundary Conditions

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
           Month      TAverage     TPerimeter          TCore         TInside    AverageFlux  PerimeterFlux       CoreFlux
               1         26.09          24.58          27.98              30          20.21          28.01          10.45
               2         26.07          24.56          27.94              30          20.34          28.11          10.63
               3         26.16          24.75          27.93              30          19.84          27.15          10.71
               4         26.36          25.10          27.93              30          18.82          25.33          10.68
               5         26.61          25.52          27.96              30          17.55          23.16          10.54
               6         26.83          25.90          28.00              30          16.37          21.21          10.32
               7         26.98          26.13          28.05              30          15.60          20.00          10.09
               8         27.01          26.15          28.08              30          15.45          19.88           9.91
               9         26.91          25.96          28.10              30          15.96          20.87           9.82
              10         26.71          25.61          28.09              30          16.99          22.70           9.86
              11         26.47          25.19          28.07              30          18.27          24.88          10.00
              12         26.24          24.81          28.02              30          19.44          26.82          10.22

Convergence has been gained.
```

Case GC80c – Reduced Slab and Ground Conductivity with BASESIMP Boundary Conditions

```
Monthly Slab Outside Face Temperatures, C and Heat Fluxes(loss), W/(m^2)
Perimeter Area: 79.00    Core Area: 64.00
           Month      TAverage          TPerim      eter   TCore           TInside    AverageFlux  PerimeterFlux        CoreFlux
               1         27.52           26.35             28.99                30           8.95          13.18            3.66
               2         27.50           26.32             28.98                30           9.02          13.28            3.70
               3         27.56           26.43             28.97                30           8.83          12.90            3.73
               4         27.67           26.64             28.96                30           8.41          12.13            3.75
               5         27.82           26.90             28.96                30           7.88          11.18            3.75
               6         27.96           27.15             28.97                30           7.37          10.29            3.73
               7         28.05           27.31             28.98                30           7.03           9.71            3.69
               8         28.07           27.34             28.99                30           6.95           9.60            3.65
               9         28.02           27.23             29.00                30           7.15           9.98            3.61
              10         27.90           27.02             29.01                30           7.57          10.76            3.59
              11         27.75           26.75             29.01                30           8.11          11.72            3.59
              12         27.62           26.51             28.00                30           8.61          12.60            3.61

Convergence has been gained.
```

2.4.2 Times to Reach Convergence

The accuracy of results produced by the EnergyPlus Slab program are controlled by the Convergence Tolerance input parameter specified by the user. Annual simulations by the EnergyPlus Slab program continue until the change in temperature for all nodes of the grid are less than this convergence tolerance. For all of the cases simulated as part of this test suite, the convergence tolerance was set to 0.1 C. Convergence for the cases occurred within the following time periods:

Case GC30b	7 years
Case GC40b	7 years
Case GC45b	7 years
Case GC50b	8 years
Case GC55b	3 years
Case GC60b	7 years
Case GC65b	8 years
Case GC70b	7 years
Case GC80b	16 years
Case GC30c	6 years
Case GC40c	6 years
Case GC45c	6 years
Case GC55c	3 years
Case GC80c	10 years

2.4.3 EnergyPlus Results

EnergyPlus results for the final round of testing done as part of the IEA task were submitted using EnergyPlus version 2.0.0.025 in September 2007 and are compared to the results of other programs that participated in the exercise in the IEA final report published in September 2008 (Neymark and Judkoff 2008). Table 2 summarizes the various programs that participated

Table 2 – Participating Organizations and Programs

Analytical Solution, Case 10a	Authoring Organization	Implemented by	Abbreviation
Delsante, Stokes and Walsh	Commonwealth Scientific and Industrial Research Organisation, Australia	NREL/JNA,[a,b] United States	Analytical Solution/CSIRO

Verified Numerical Model	Authoring Organization	Implemented by	Abbreviation
FLUENT 6.0.20	Fluent, Inc., United States	PAAET,[c] Kuwait	FLUENT/PAAET
MATLAB 7.0.4.365 (R14)	The MathWorks, Inc., United States	Dublin Institute of Technology, Ireland	MATLAB/DIT
TRNSYS 16.1	University of Wisconsin/TESS, [d] United States	TESS,[d] United States	TRNSYS/TESS

Simulation Program	Authoring Organization	Implemented by	Abbreviation
BASECALC V1.0e	CETC, [e] Canada	CETC,[e] Canada	BASECALC/NRCan
EnergyPlus 4.0.0.024	LBNL/UIUC/DOE-BT,[f,g,h] United States	GARD Analytics, Inc., United States	EnergyPlus/GARD
ESP-r/BASESIMP	CETC/ESRU,[e,i] Canada/United Kingdom	CETC, [e] Canada	ESP-r-BASESIMP/NRCan
GHT	NREL,[a] United States	NREL,[a] United States	GHT/NREL
SUNREL-GC 1.14.01	NREL,[a] United States	NREL, [a] United States	SUNREL-GC/NREL
VA114 2.20/ISO-13370	VABI Software BV, The Netherlands, CEN/ISO[j,k]	VABI Software BV, The Netherlands	VA 114-ISO 13370/VABI

a NREL: National Renewable Energy Laboratory, United States
b JNA: J. Neymark & Associates, United States
c PAAET: Public Authority for Applied Education and Training, Kuwait
d TESS: Thermal Energy Systems Specialists, United States
e CETC: CANMET Energy Technology Centre, Natural Resources Canada, Canada
f LBNL: Lawrence Berkeley National Laboratory, United States
g UIUC: University of Illinois Urbana/Champaign, United States
h DOE-BT: U.S. Department of Energy, Office of Building Technologies, Energy Efficiency and Renewable Energy, United States
i ESRU: Energy Systems Research Unit, University of Strathclyde, United Kingdom
j CEN: European Committee for Standardisation, Belgium
k ISO: International Organization for Standardization, Switzerland

in this IEA program. Although there have been subsequent new releases of EnergyPlus since the reporting of final results, i.e. October 2007 (version 2.1.0) through the current release October 2009 (version 4.0.0.024), the EnergyPlus results for the IEA BESTEST In-Depth G-C test suite have not changed.

The results for each of the IEA BESTEST In-Depth G-C test cases simulated with EnergyPlus version 4.0.0.024 are presented in Table 3. The EnergyPlus results compared to the other programs that participated in the IEA BESTEST In-Depth G-C test exercise are presented on a set of charts which can be found in Appendix A. The charts are presented in groups of three: Floor Conduction, Zone Heating Load and Zone Temperature first for the Steady-State cases, then for the Steady-Periodic cases, and finally for the Steady-State Annual Peak Hour.

Table 3 – IEA BESTEST In-Depth G-C Test Case Results with EnergyPlus Version 4.0.0.024

Software: EnergyPlus	**Version:** 4.0.0.024	**Date:** 22-Oct-09

Steady State Cases						**GC10 Only**	
	q_{floor} (W)	q_{zone} (W)	T_{zone} (°C)	t_{sim} (hours)	$Q_{cumulative}$ (kWh)	E (m)	F (m)
GC10a		n/a	n/a		n/a		
GC30a							
GC30b	2652	2652	30	61320	69706		
GC30c	2308	2308	30	52560	60652		
GC60b	2219	2219	30	61320	58304		
GC65b	1616	1616	30	70080	42457		

Harmonic Cases	Annual Sums and Means				Annual Hourly Integrated Maxima and Minima									
												(first occurrence)		
	Q_{floor} (kWh/y)	Q_{zone} (kWh/y)	$T_{zone,mean}$ (°C)	t_{sim} (hours)	$q_{floor,max}$ (W)	Date	Hour	$q_{zone,max}$ (W)	Date	Hour	$T_{ODB,min}$ (°C)	Date	Hour	Number of hours at $T_{ODB,min}$
GC40a														
GC40b	23204	23204	30	61320	3005	02/02	02:00	3005	02/02	02:00	2.0375	01/08	04:00	15
GC45b	33415	33415	30	61320	4415	02/02	03:00	4415	02/02	03:00	2.0375	01/08	04:00	15
GC50b	324257	324257	30	70080	39570	01/01	01:00	39570	01/01	01:00	2.0375	01/08	04:00	15
GC55b	39932	39932	30	26280	4860	01/01	03:00	4860	01/01	03:00	2.0375	01/08	04:00	15
GC70b	15553	15553	30	61320	1906	02/03	09:00	1906	02/03	09:00	2.0375	01/08	04:00	15
GC80b	6059	6059	30	140160	766	02/10	02:00	766	02/10	02:00	2.0375	01/08	04:00	15
GC40c	20255	20255	30	52560	2650	02/03	07:00	2650	02/03	07:00	2.0375	01/08	04:00	15
GC45c	28707	28707	30	52560	3827	02/03	18:00	3827	02/03	18:00	2.0375	01/08	04:00	15
GC55c	22570	22570	30	26280	2926	02/03	05:00	2926	02/03	05:00	2.0375	01/08	04:00	15
GC80c	10073	10073	30	87600	1300	02/06	14:00	1300	02/06	14:00	2.0375	01/08	04:00	15

The IEA BESTEST In-Depth G-C final report refers to the results of the TRNSYS, FLUENT and MATLIB programs as quasi-analytical results since they are detailed 3-D models of the test cases and were rigorously verified versus the Case GC-10a analytical solution. A comparison of the EnergyPlus results to the mean of the results for the numerical programs is shown in Table 4.

Some of these differences may be explainable due to the less detailed modeling that the EnergyPlus Slab program does of slab-on-grade heat transfer compared to the more detailed modeling of numerical models. There were two input parameters for which the EnergyPlus results seemed to be more sensitive compared to the results of the numerical models and other programs.

a) Sensitivity to variation of ground surface heat transfer coefficient – this is demonstrated by comparing the results of Case GC60b with h,ext = 100 W/m2-K versus Cases GC65b and GC70b with h,ext = 11.95 W/m2-K (see Figure 4). This disagreement may be caused by the EnergyPlus Slab program not being able to model the presence of the adiabatic exterior wall which would create a shorter heat flow path underneath the exterior wall and would overestimate the slab perimeter heat flow for the test cases.

b) Sensitivity to variation of soil depth – this is demonstrated by comparing the results of Case GC40b with Soil Depth = 15m versus Case GC55b with Soil Depth = 2m (see Figure 5). This difference is again probably due to the more detailed modeling done by numerical programs versus the EnergyPlus method.

Additional "Delta Charts" are included in the IEA final report to compare the difference in results between certain cases in order to isolate the sensitivity of each program to changes in other features floor aspect ratio, ground conductivity, etc. The "Delta Charts" comparing EnergyPlus results with other programs are presented in Appendix B.

Table 4 – EnergyPlus In-Depth G-C Test Case Results Compared to Results of Numerical Models

Steady-State Conduction

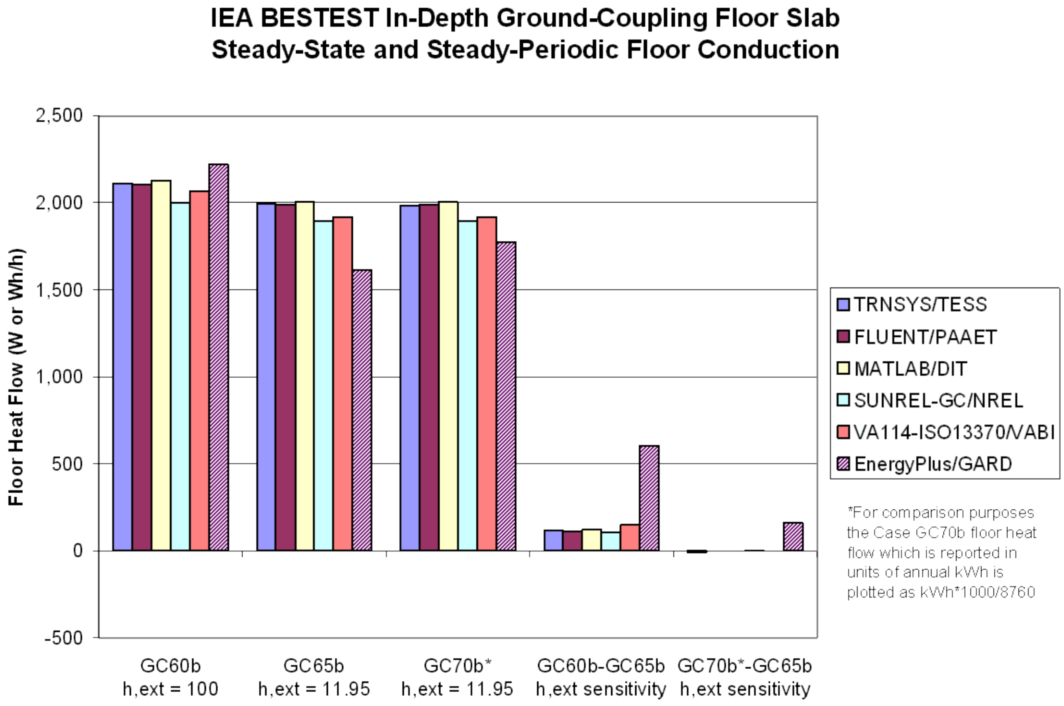
Floor Conduction (W or Wh/h)

	Verified Numerical Models					
Case	TRNSYS TESS	FLUENT PAAET	MATLAB DIT	Mean	EnergyPlus GARD	% Diff versus Mean
GC30b	2,533	2,504	2,570	2,536	2,652	4.6%
GC30c	2,137	2,123	2,154	2,138	2,308	7.9%
GC60b	2,113	2,104	2,128	2,115	2,219	4.9%
GC65b	1,994	1,991	2,004	1,996	1,616	-19.1%

Steady-Periodic Last-Simulation-Year Conduction

Floor Conduction (kWh)

	Verified Numerical Models					
Case	TRNSYS TESS	FLUENT PAAET	MATLAB DIT	Mean	EnergyPlus GARD	% Diff versus Mean
GC40b	22,099	21,932	22,513	22,181	23,204	4.6%
GC45b	32,758	32,456	33,483	32,899	33,415	1.6%
GC50b	277,923	277,988	281,418	279,110	324,257	16.2%
GC55b	35,075	34,879	35,491	35,148	39,932	13.6%
GC70b	17,396	17,434	17,552	17,461	15,553	-10.9%
GC80b	6,029	5,939	6,151	6,040	6,059	0.3%
GC40c	18,649	18,598	18,873	18,707	20,255	8.3%
GC45c	27,004	26,906	27,392	27,101	28,707	5.9%
GC50c	20,760	20,714	20,986	20,820	22,570	8.4%
GC80c	9,192	9,137	9,314	9,215	10,073	9.3%



*For comparison purposes the Case GC70b floor heat flow which is reported in units of annual kWh is plotted as kWh*1000/8760

Figure 4 EnergyPlus Slab Program Sensitivity to Ground Surface Heat Transfer Coefficient Compared to Other Models and Programs

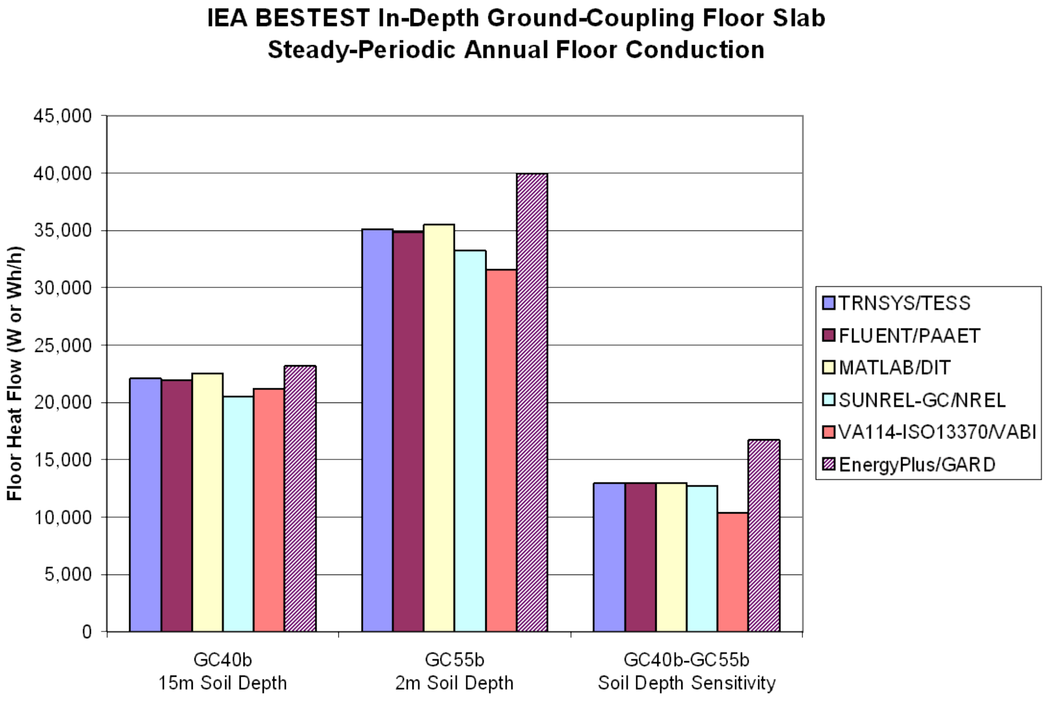


Figure 5 EnergyPlus Slab Program Sensitivity to Soil Depth Compared to Other Models and Programs

2.5 Enhancements to EnergyPlus Prompted by Using IEA BESTEST In-Depth G-C Test Suite

As was discussed in Section 2.3, a series of enhancements were made to the EnergyPlus Slab program in order to accommodate the range of variable testing required by the IEA BESTEST In-Depth G-C specification. The extreme range of some of these variables would never be seen in real buildings but are convenient for controlled comparative testing. A summary of these enhancements and there impact on results is presented below.

- User definition of a specific lower deep boundary temperature. This capability was required to ensure that all programs participating in the IEA BESTEST In-Depth G-C comparative testing exercise were using the same deep boundary temperature. Previous to this enhancement, this temperature was calculated for the user by the EnergyPlus Slab program and set to the annual mean outdoor dry-bulb temperature as determined from data on the weather file. Since the lower deep boundary temperature required by the specification was 10C for all test cases and each of the weather files used as part of the test suite already had annual mean ambient dry-bulb air temperatures of 10C, use of this new capability did not change any of the test results.

- User definition of ground surface heat transfer coefficient. This capability was required to ensure that all programs participating in the IEA BESTEST In-Depth G-C comparative testing exercise were using the same the same ground heat transfer coefficient. Most test cases the In-Depth G-C specification required that this parameter be set to 100 W/m2-K, a value far higher than typically seen in real situations. Cases GC65b and GC70b however, required that this parameter be set at 11.95 W/m2-K. In the original version of the EnergyPlus Slab program the user did not have the option of defining this parameter but rather it was calculated internally by the program as a function of the ambient temperature and wind speed from the weather file. Subsequent to this enhancement the ground heat transfer coefficient for each test case was set by input to that required by the specification.

- User definition of the lower deep boundary depth, including allowing the automated gridding option for various depths. This capability was required because the In-Depth G-C specification requested the simulation of shallow as well as deep boundary depths ranging from 2m to 30m. Previous to this enhancement, when the A/P ratio was 4.25 or less the deep boundary depth was automatically set to 15 m and if greater than 4.25 it was set to 20m. It is expected that once you reach 20m there would be little change in results beyond that distance. For all test cases except GC55b and GC55c, the deep boundary depth specified is 15 m, and since for all cases except GC50b the A/P ratio is less than 4.25, this new capability affected only three out of the 14 of the test cases modeled by EnergyPlus.

- With earlier versions of the EnergyPlus Slab program documentation there was some confusion about the input parameter “Distance from edge of slab to domain edge.” It was unclear if this was the horizontal far field distance or the deep boundary depth. Later EnergyPlus documentation changes cleared this up.

3 CONCLUSIONS

EnergyPlus Version 4.0.0.024 was used to model a range of ground-coupling models for a slab-on-grade configuration specified in *IEA BESTEST In-Depth Diagnostic Cases for Ground Coupled Heart Transfer Related to Slab-on-Grade Construction* (Neymark and Judkoff 2008). The ability of EnergyPlus and its Slab Program to model a slab-on-grade floor configuration and predict hourly floor conduction, zone loads and resulting zone temperatures was tested using a suite of 14 test cases which included varying slab aspect ratios, floor interior heat transfer coefficients, exterior ground heat transfer coefficients, ground depth, far field boundary distance, and steady-state and harmonic outdoor temperature. The results predicted by EnergyPlus for the 14 different cases were compared to 3 quasi-analytical numerical models and 5 other whole building simulation programs that participated in an International Energy Agency project which was completed in 2007. EnergyPlus results differed by 1.6% to 19.1% compared to the numerical models depending on the test case. Some of these differences may be explainable due to the less detailed modeling that the EnergyPlus Slab program does of slab-on-grade heat transfer compared to the more detailed modeling of numerical models and also due to the EnergyPlus Slab program's inability to model the presence of the adiabatic exterior walls of the conditioned zone as described in the IEA BESTEST In-Depth G-C specification.

4 REFERENCES

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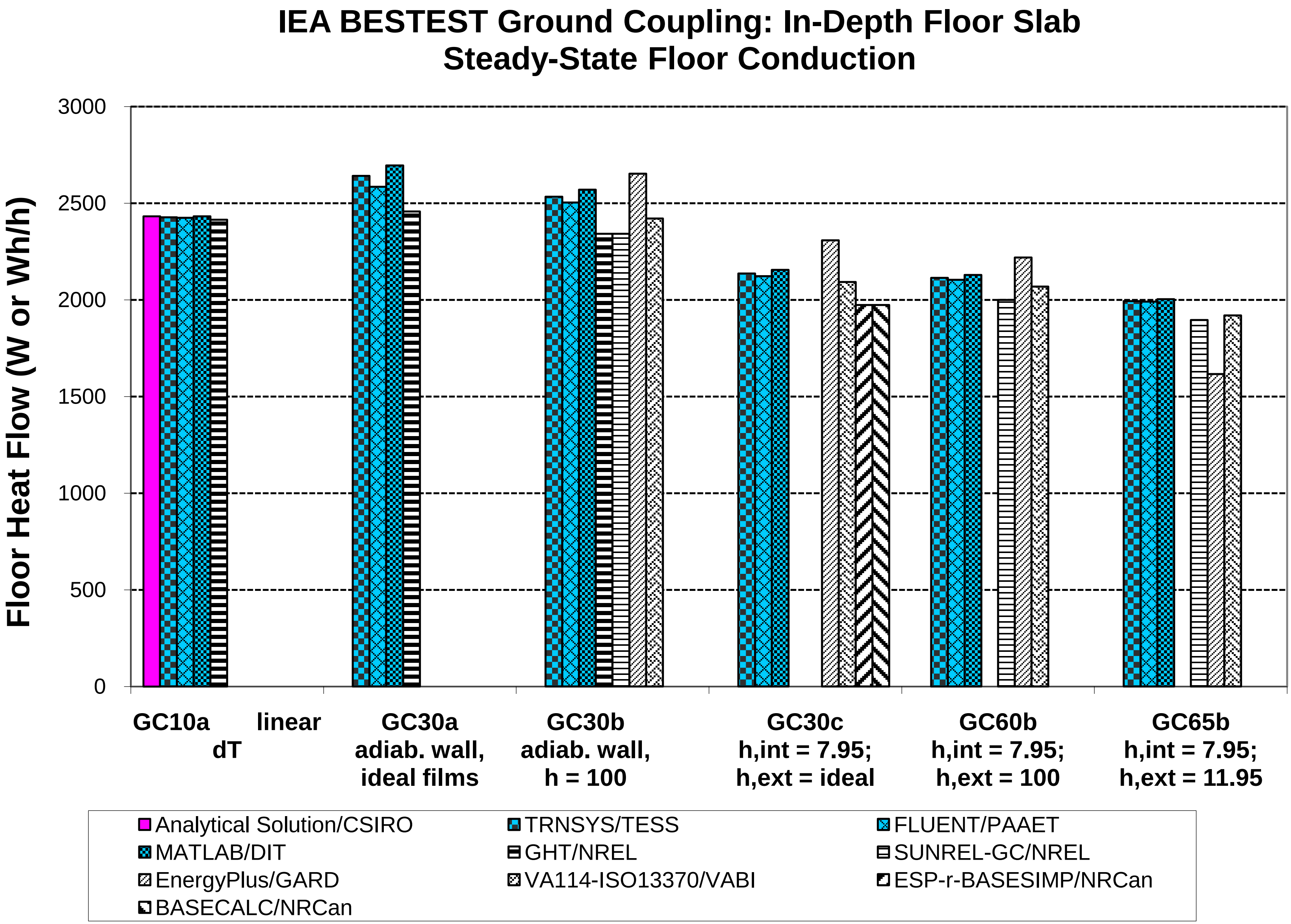
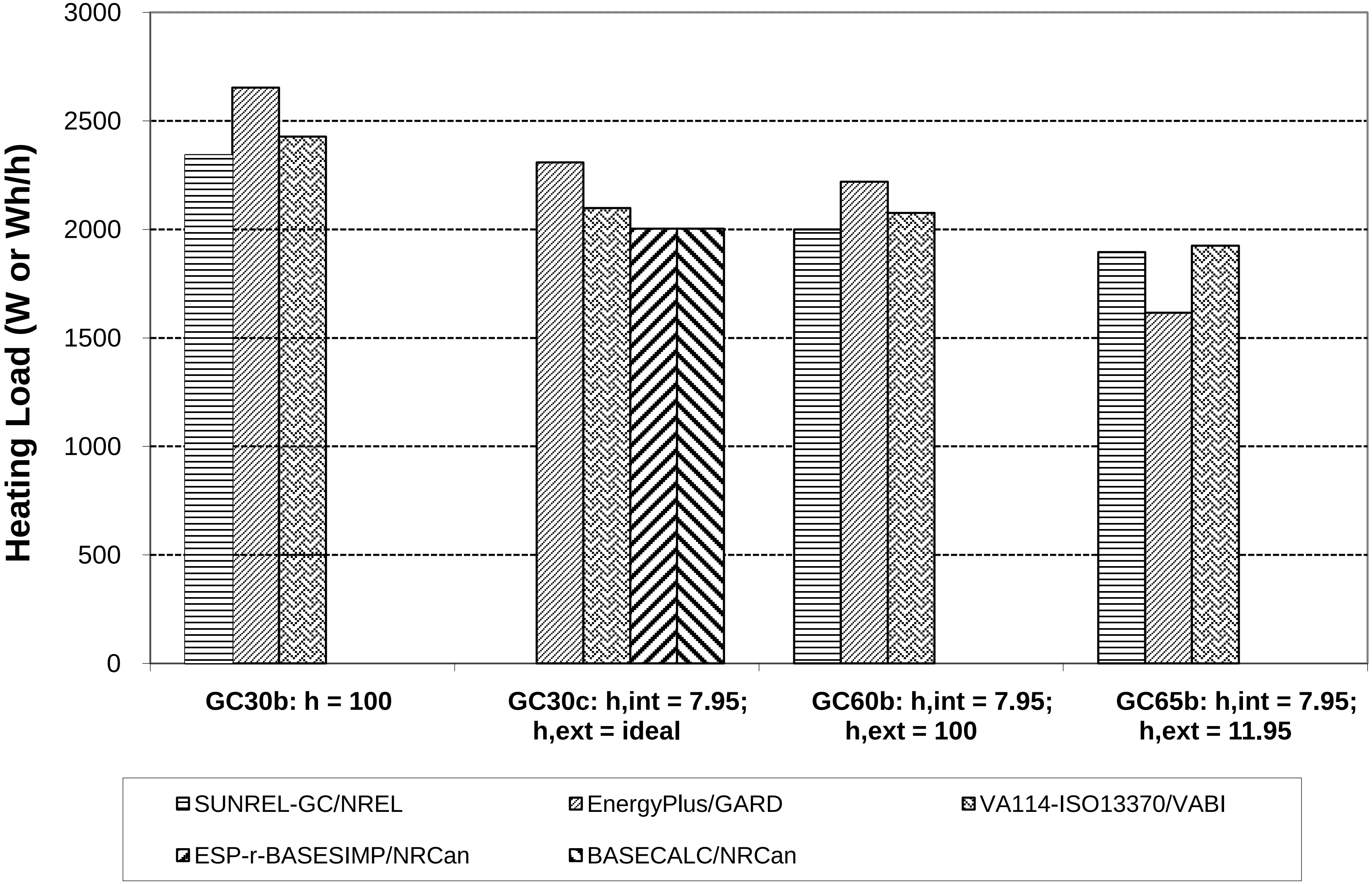
Appendix A

Charts Comparing EnergyPlus Version 4.0.0.024 Results with Other Whole Building Energy Simulation Programs

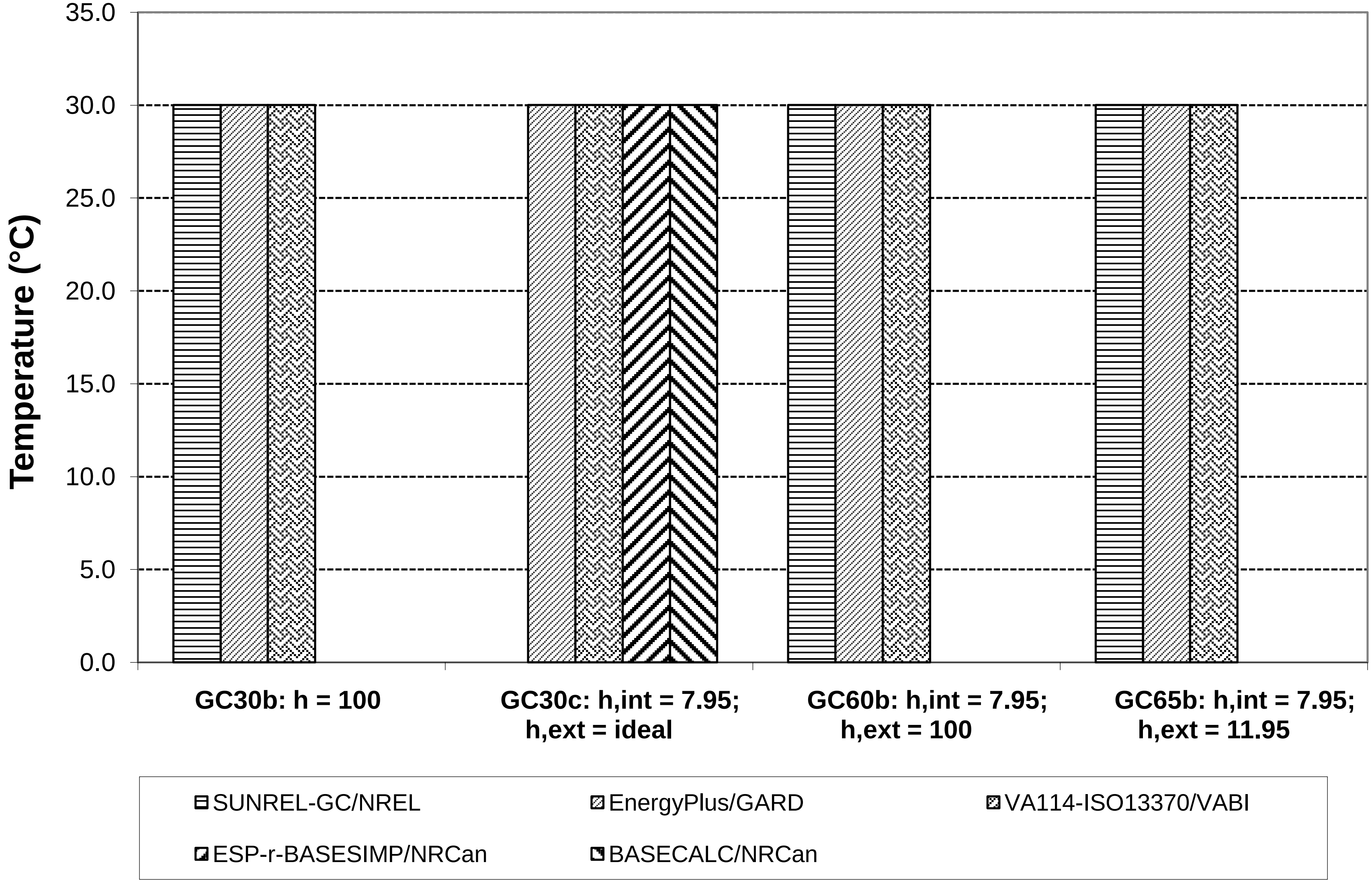
(Other Program Results Excerpted from Neymark and Judkoff 2008)

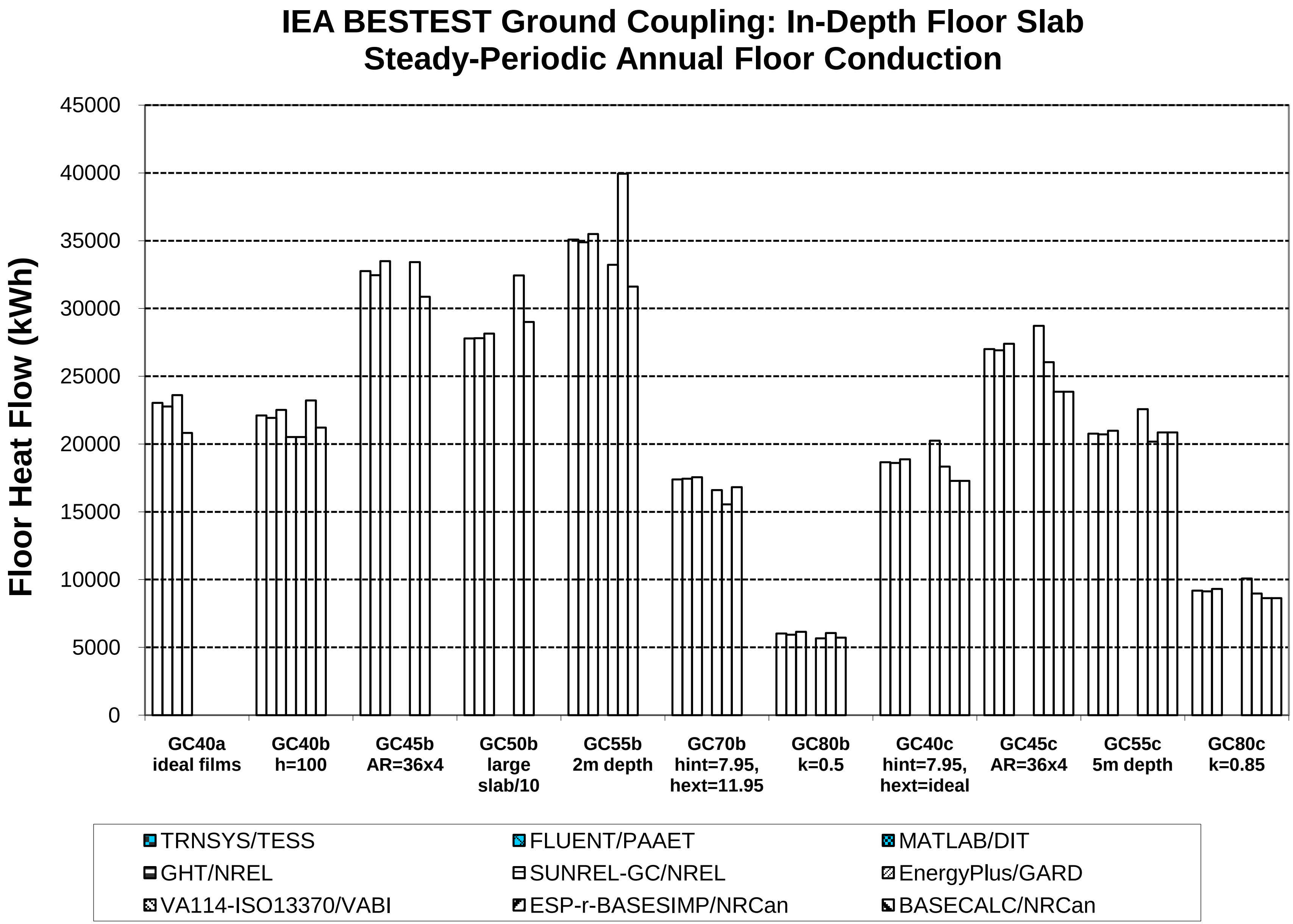

IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-State Floor Conduction
Floor Heat Flow (W or Wh/h)
0
500
1000
1500
2000
2500
3000
GC10a linear dT
GC30a adiab. wall, ideal films
GC30b adiab. wall, h = 100
GC30c h,int = 7.95; h,ext = ideal
GC60b h,int = 7.95; h,ext = 100
GC65b h,int = 7.95; h,ext = 11.95
Analytical Solution/CSIRO
TRNSYS/TESS
FLUENT/PAAET
MATLAB/DIT
GHT/NREL
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

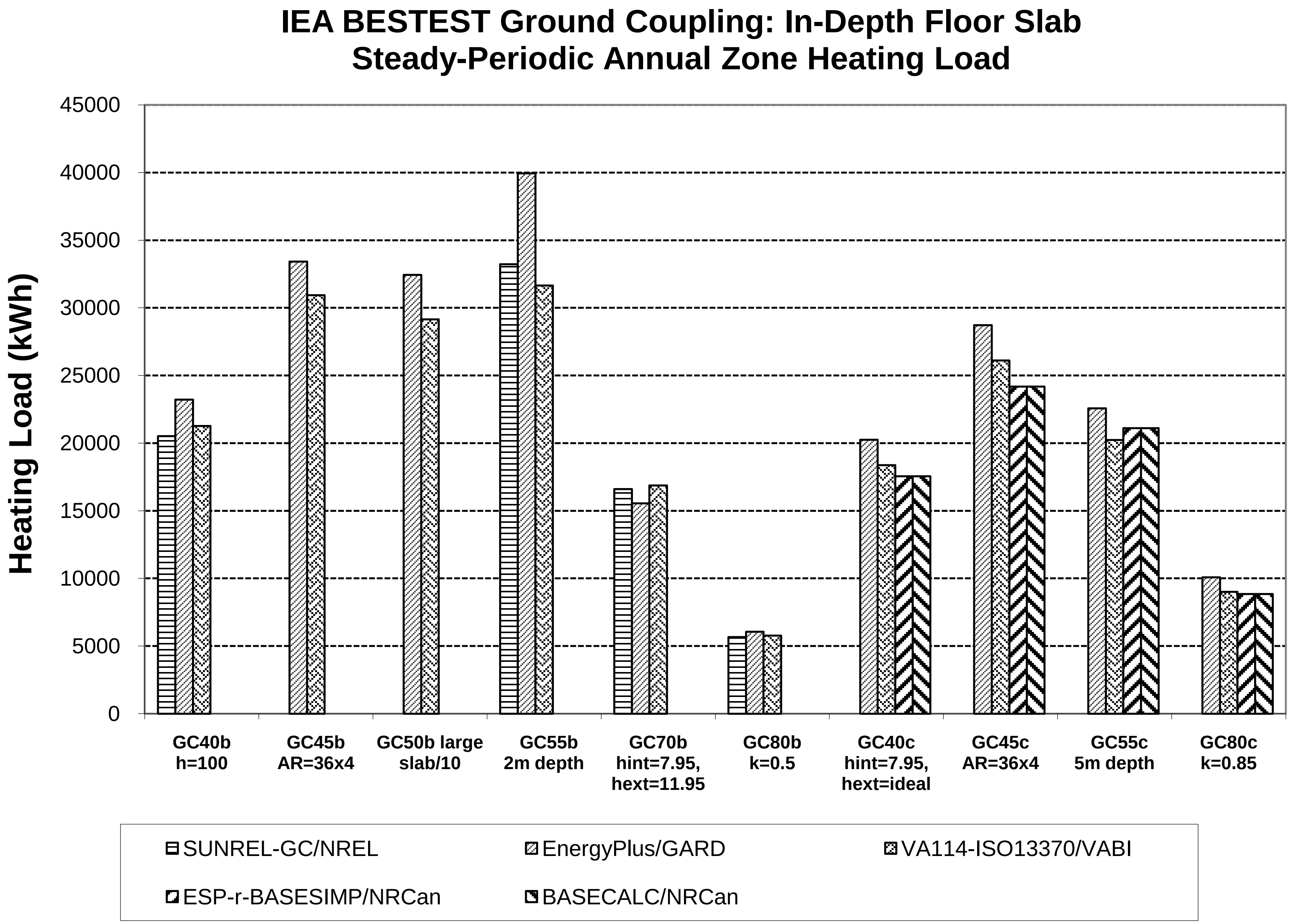
IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-State Zone Heating Load



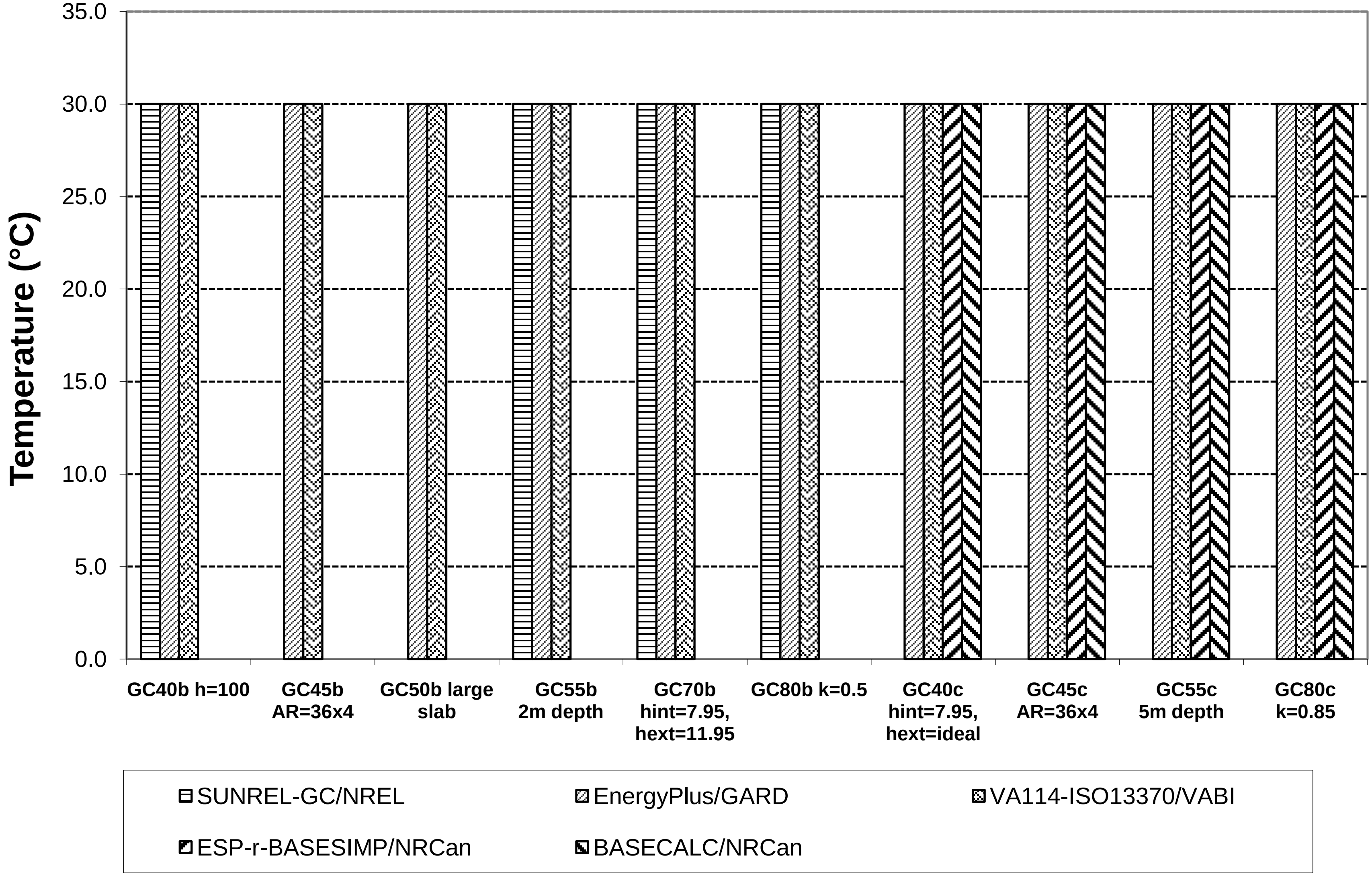
IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-State Zone Temperature



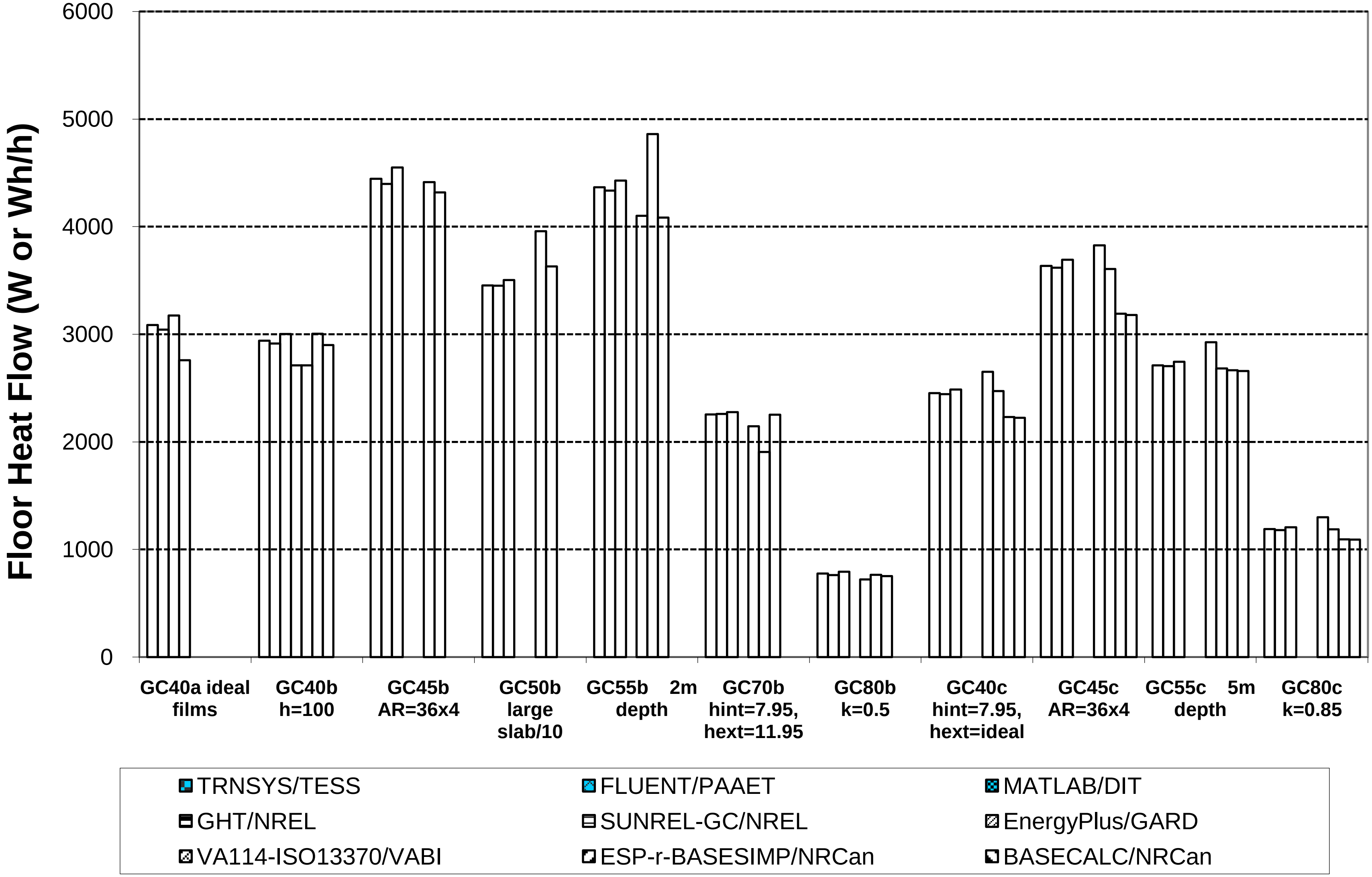

IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Floor Conduction
Floor Heat Flow (kWh)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
GC40a ideal films
GC40b h=100
GC45b AR=36x4
GC50b large slab/10
GC55b 2m depth
GC70b hint=7.95, hext=11.95
GC80b k=0.5
GC40c hint=7.95, hext=ideal
GC45c AR=36x4
GC55c 5m depth
GC80c k=0.85
TRNSYS/TESS
FLUENT/PAAET
MATLAB/DIT
GHT/NREL
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

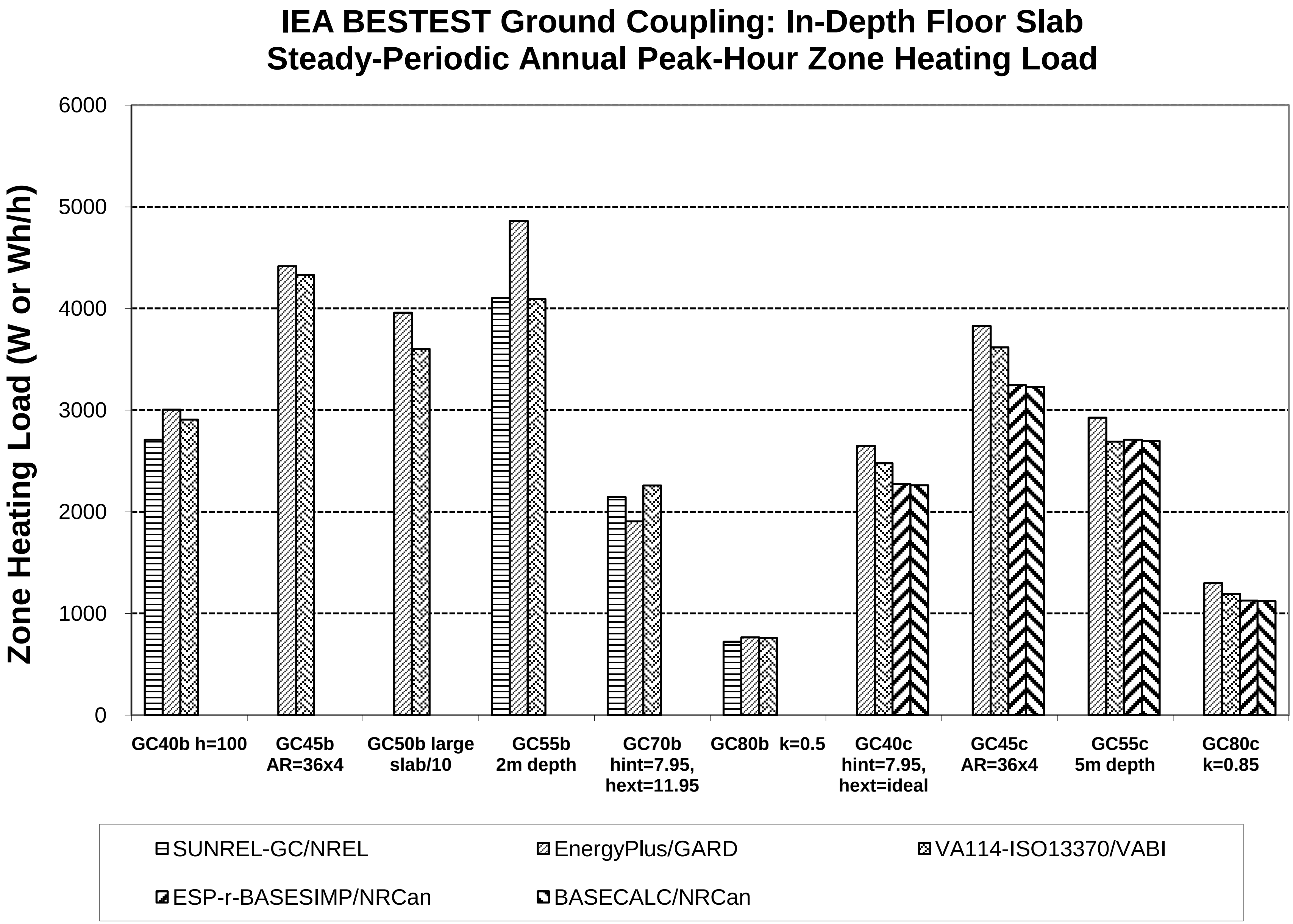


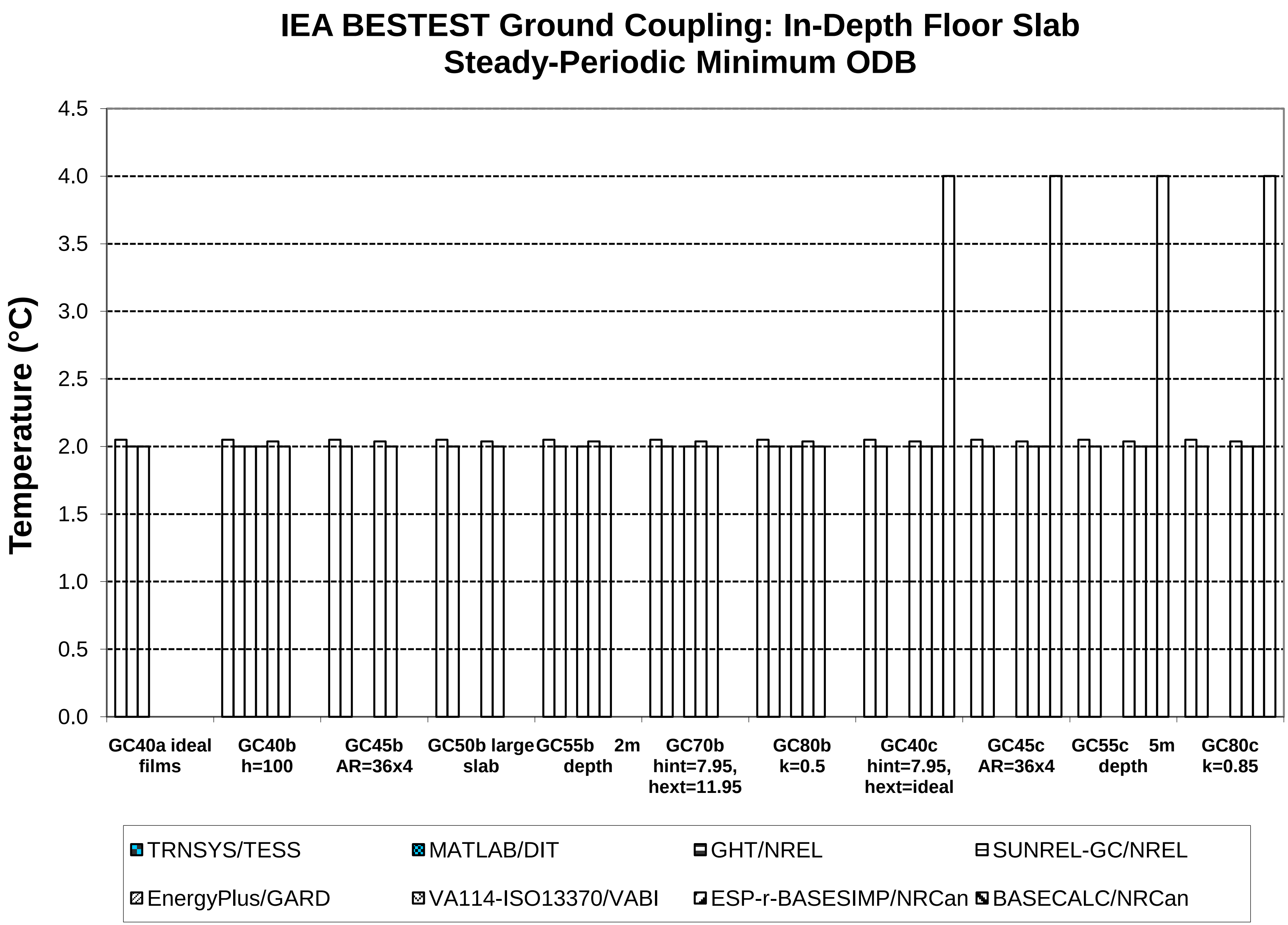
IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Zone Heating Load


IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Zone Temperature

IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Peak-Hour Floor Conduction




IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Peak-Hour Zone Heating Load
Zone Heating Load (W or Wh/h)
6000
5000
4000
3000
2000
1000
0
GC40b h=100
GC45b AR=36x4
GC50b large slab/10
GC55b 2m depth
GC70b hint=7.95, hext=11.95
GC80b k=0.5
GC40c hint=7.95, hext=ideal
GC45c AR=36x4
GC55c 5m depth
GC80c k=0.85
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

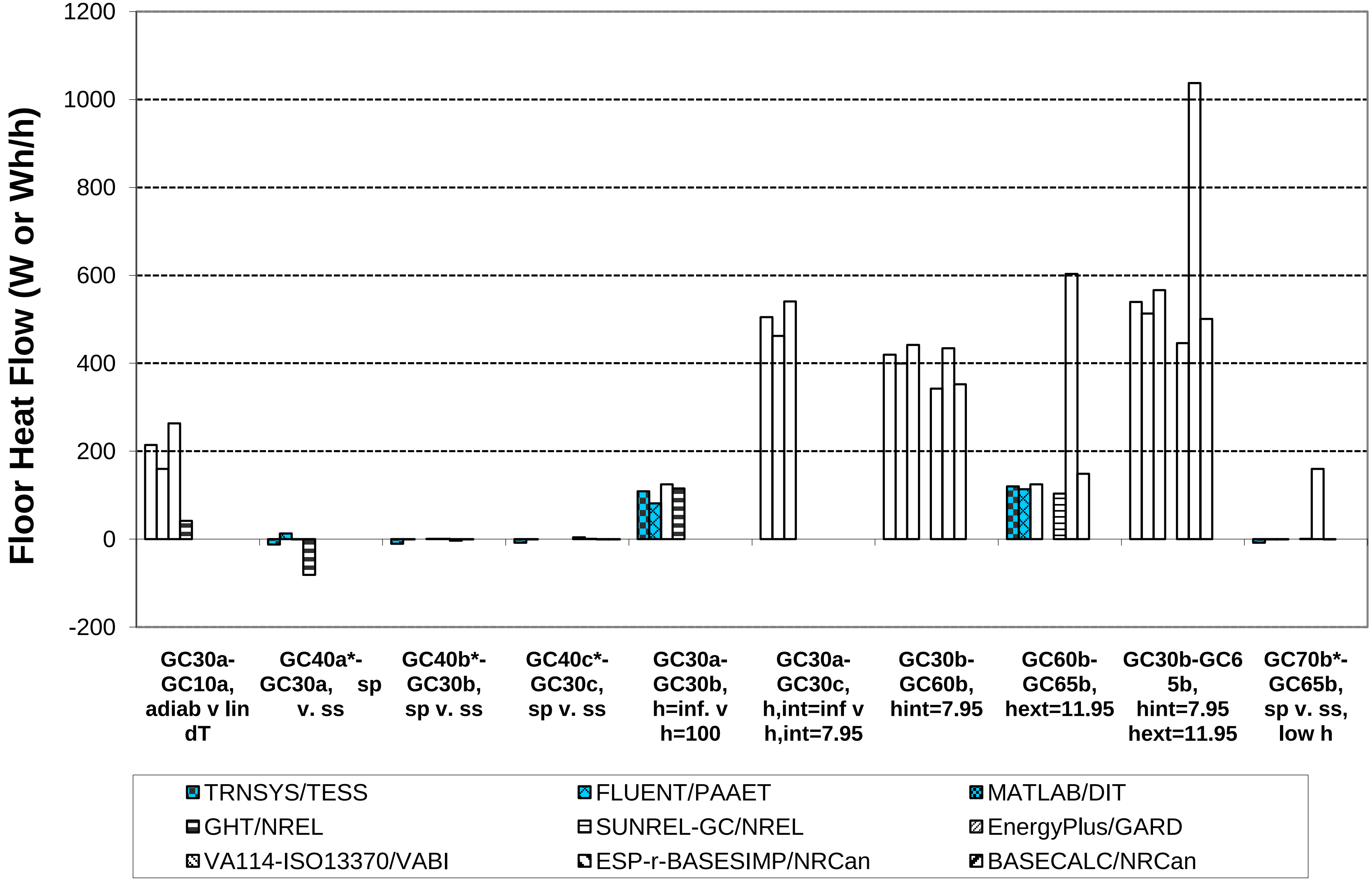

IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Minimum ODB
Temperature (°C)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
GC40a ideal films
GC40b h=100
GC45b AR=36x4
GC50b large slab
GC55b 2m depth
GC70b hint=7.95, hext=11.95
GC80b k=0.5
GC40c hint=7.95, hext=ideal
GC45c AR=36x4
GC55c 5m depth
GC80c k=0.85
TRNSYS/TESS
MATLAB/DIT
GHT/NREL
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

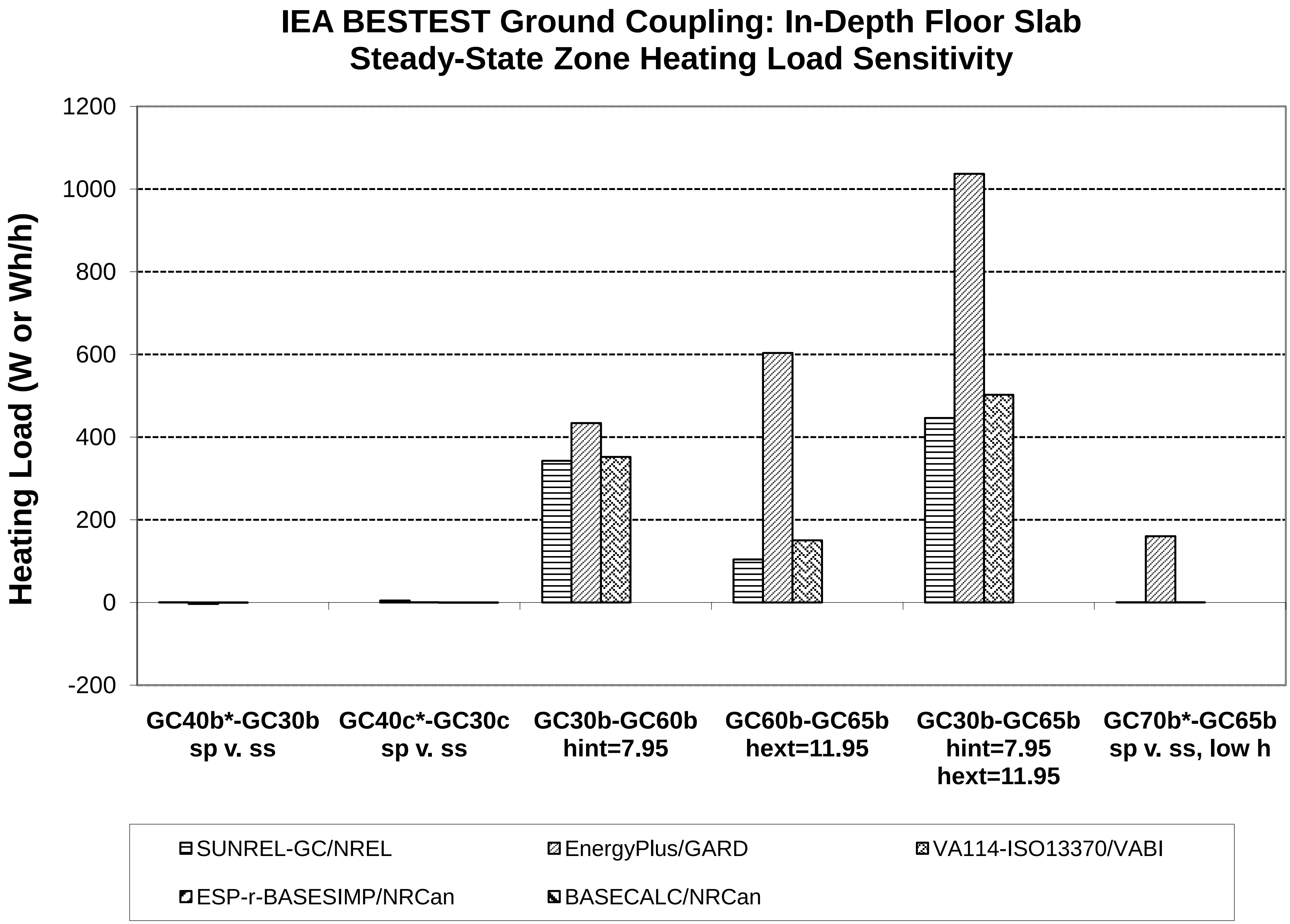
Appendix B

Delta Charts Comparing EnergyPlus Version 4.0.0.024 Results with Other Whole Building Energy Simulation Programs

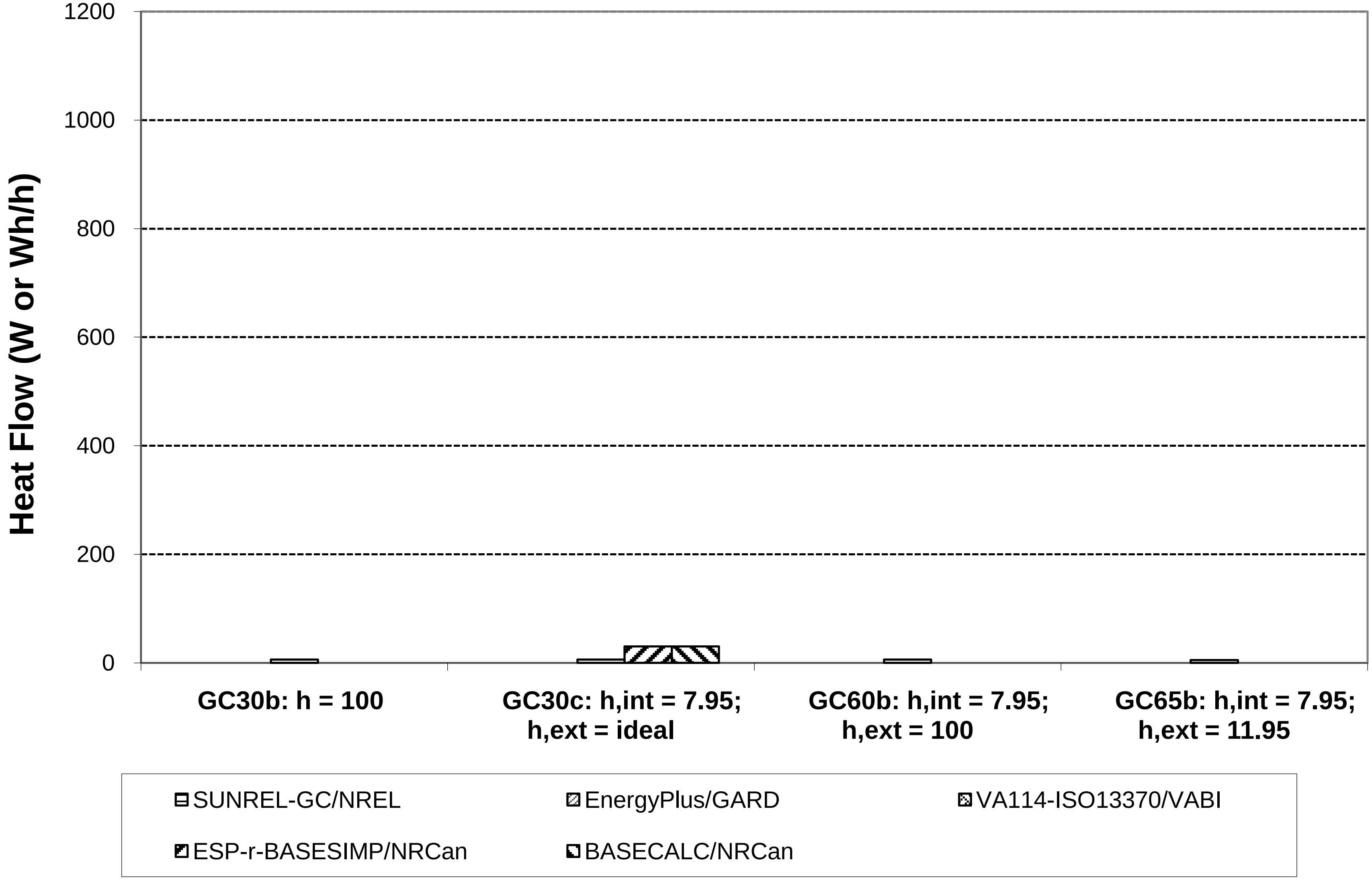
(Other Program Results Excerpted from Neymark and Judkoff 2008)

IEA BESTEST Ground Coupling: In-Depth Floor Slab Steady-State Floor Conduction Sensitivity

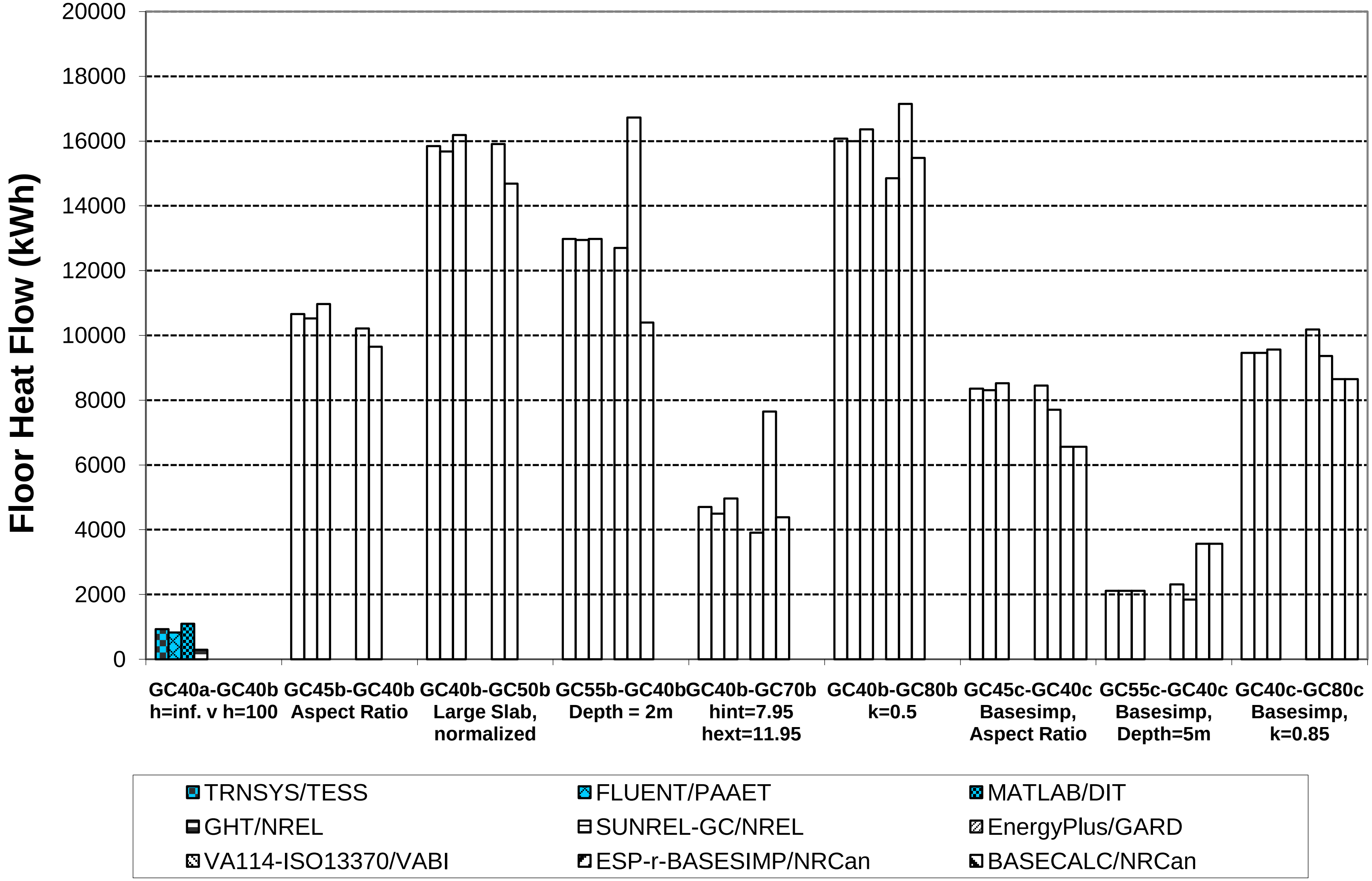



IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-State Zone Heating Load Sensitivity
Heating Load (W or Wh/h)
1200
1000
800
600
400
200
0
-200
GC40b*-GC30b sp v. ss
GC40c*-GC30c sp v. ss
GC30b-GC60b hint=7.95
GC60b-GC65b hext=11.95
GC30b-GC65b hint=7.95 hext=11.95
GC70b*-GC65b sp v. ss, low h
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

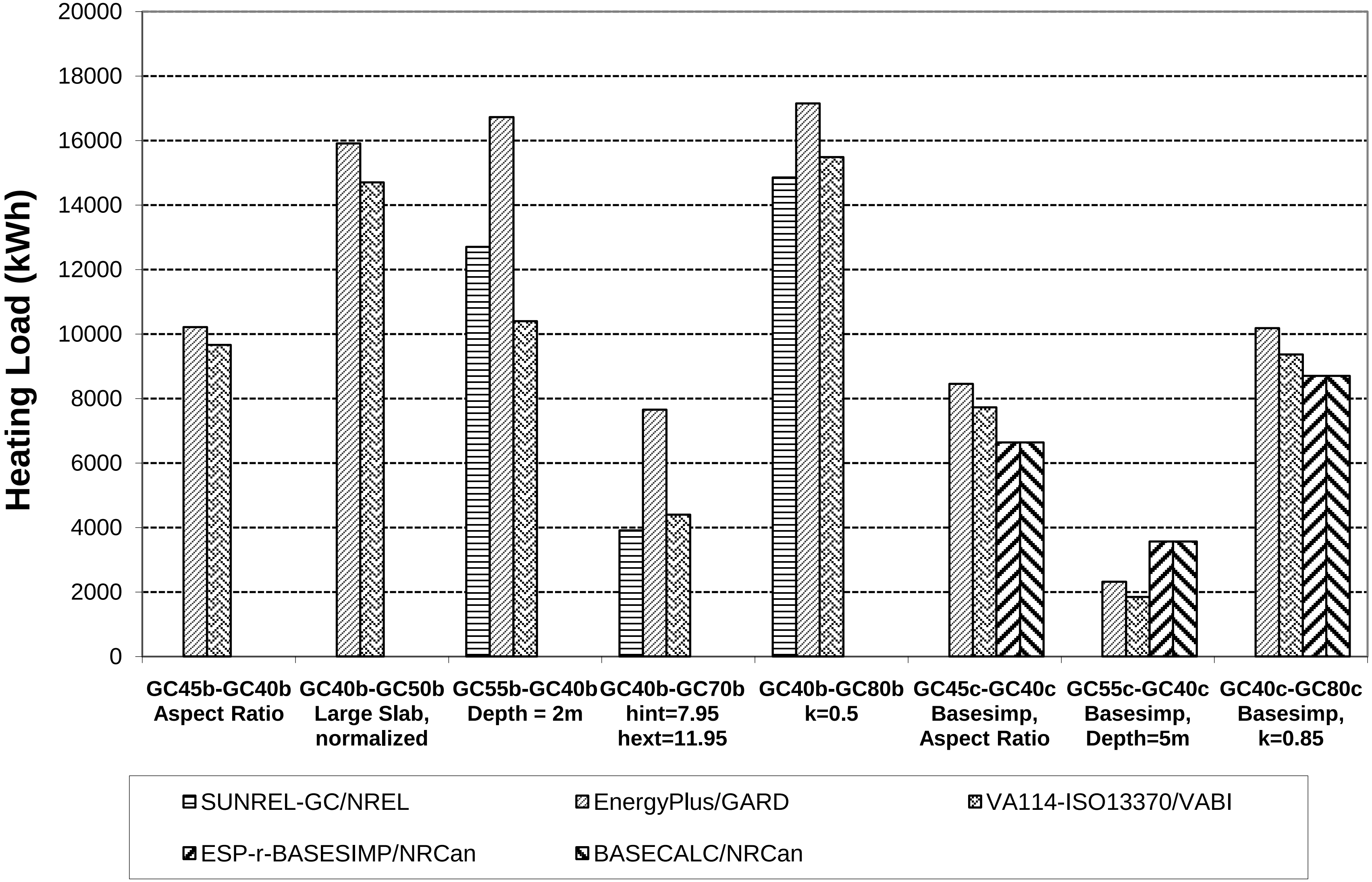
IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-State (Zone Heating Load) - (Floor Conduction)

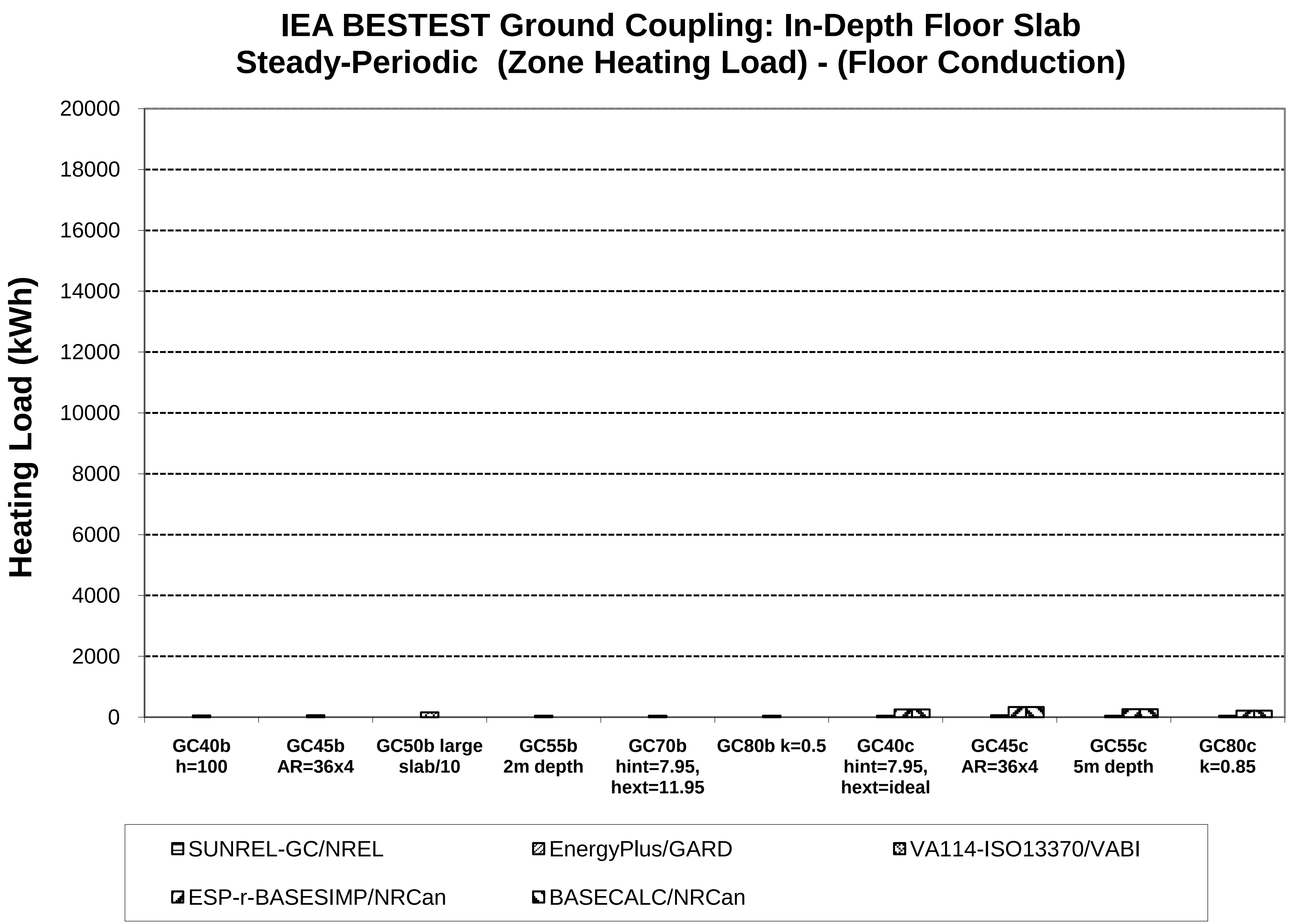


IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Floor Conduction Sensitivity

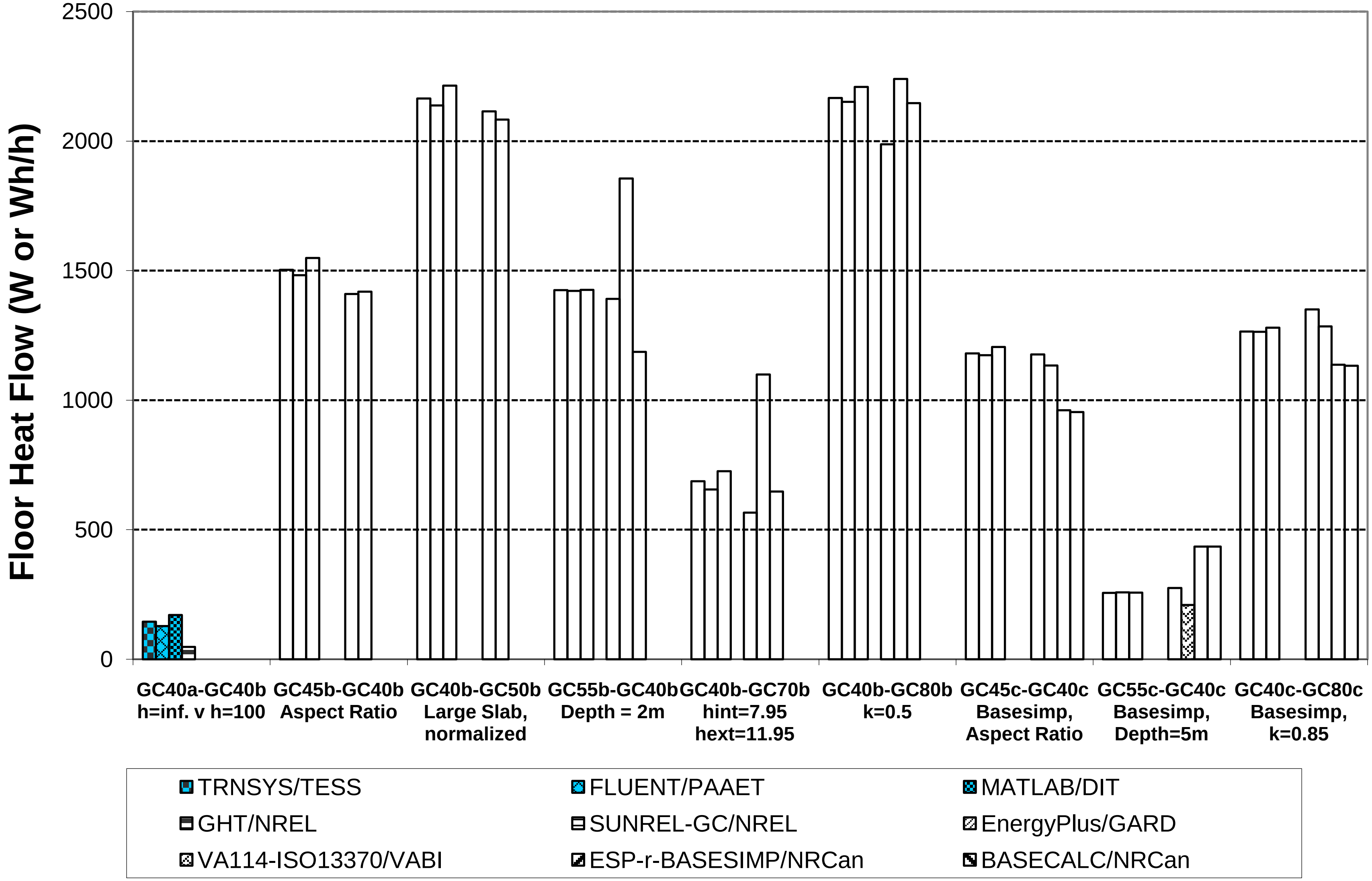


IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Zone Heating Load Sensitivity

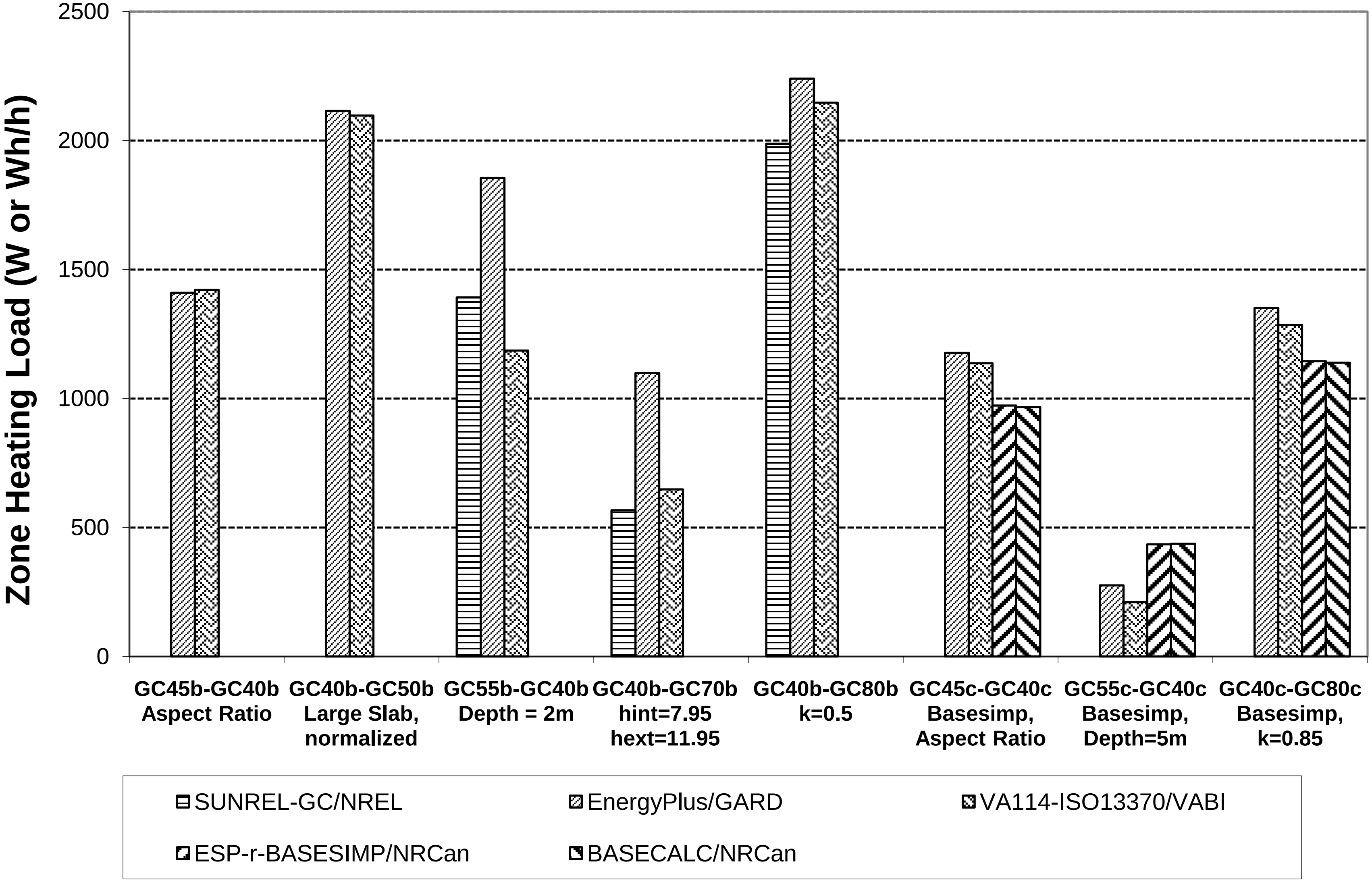



IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic (Zone Heating Load) - (Floor Conduction)
Heating Load (kWh)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
GC40b h=100
GC45b AR=36x4
GC50b large slab/10
GC55b 2m depth
GC70b hint=7.95, hext=11.95
GC80b k=0.5
GC40c hint=7.95, hext=ideal
GC45c AR=36x4
GC55c 5m depth
GC80c k=0.85
SUNREL-GC/NREL
EnergyPlus/GARD
VA114-ISO13370/VABI
ESP-r-BASESIMP/NRCan
BASECALC/NRCan

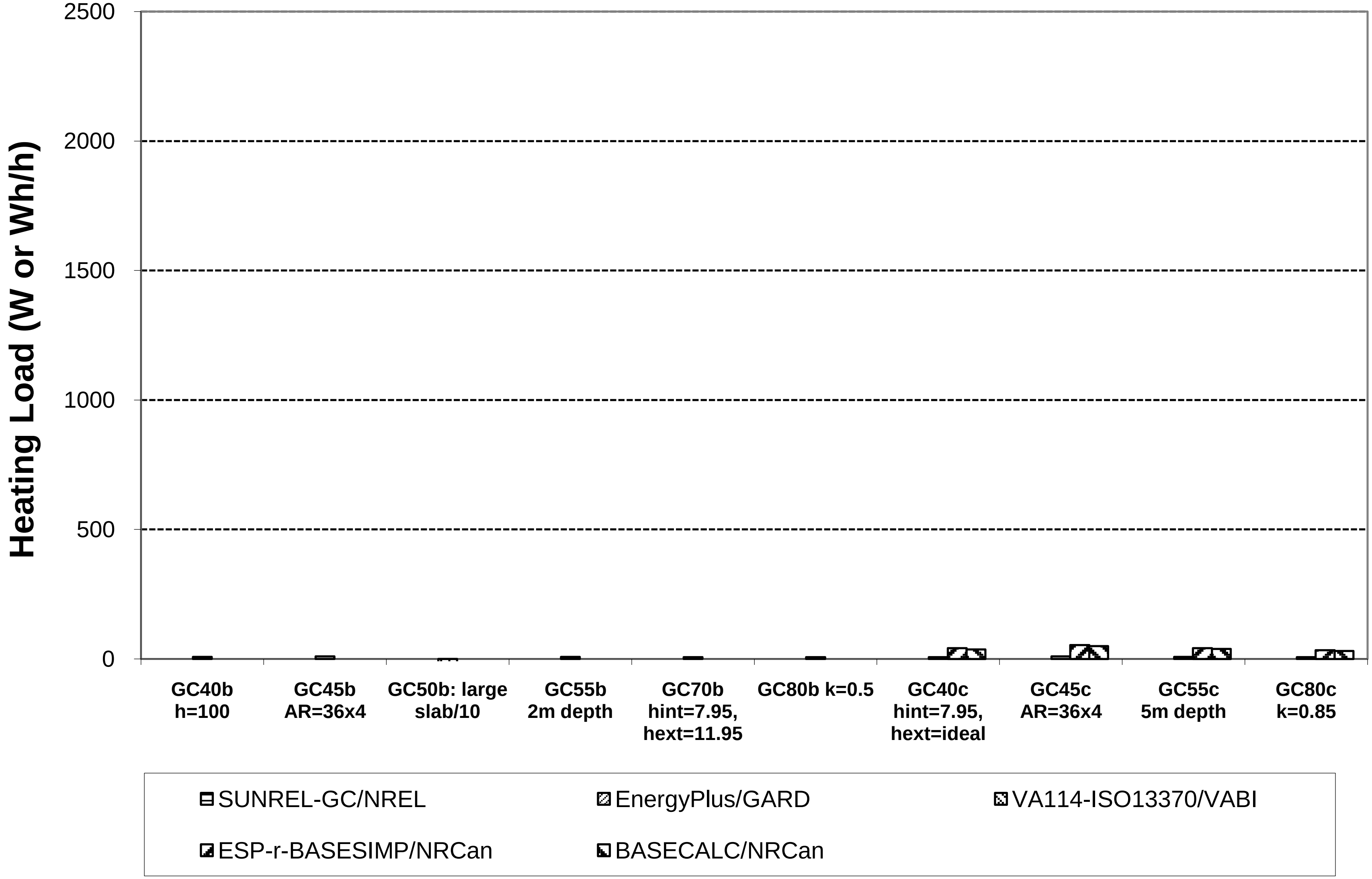
IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Peak-Hour Floor Conduction Sensitivity



IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic Annual Peak-Hour Zone Heating Load Sensitivity



IEA BESTEST Ground Coupling: In-Depth Floor Slab
Steady-Periodic (Peak Zone Heating Load) - (Peak Floor Conduction)



Appendix C

EnergyPlus Model Geometry and Thermal Property Allowed Inputs (pro forma)

Model and Version:	EnergyPlus Auxiliary Slab Program						Insulation Components		
	Below-Grade High-Mass Components				Low-Mass Components		Horizontal Edge Insulation	Vertical Interior Edge Insulation	Vertical Exterior Edge Insulation
	Slab	Foundation Wall	Footer	Soil	Sill Plate	Above Grade Wall			
GEOMETRY*									
Floor Slab **In (below) Grade** ("yes" or "no")	yes	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Floor Slab **On (above) Grade** ("yes" or "no")	no	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Floor Slab Minimum Thickness (cm)	set by stability	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Floor Slab Maximum Thickness (cm)	15m	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Minimum *x*-Thickness or Width (cm)	n/a	0	0	n/a	0	0	0	0	0
Maximum *x*-Thickness or Width (cm)	n/a	0	0	n/a	0	0	200	0	0
Minimum *z*-Thickness (cm)	n/a	n/a	0	n/a	0	n/a	0	n/a	n/a
Maximum *z*-Thickness (cm)	n/a	n/a	0	n/a	0	n/a	0	n/a	n/a
Minimum Bottom-Edge Depth Below Grade (*z*, cm)	set by stability	0	0	n/a	n/a	n/a	n/a	20	0
Maximum Bottom-Edge Depth Below Grade (*z*, cm)	1500	0	0	n/a	n/a	n/a	n/a	300	0
Minimum Top-Edge Height Above Grade (*z*, cm)	0	0	n/a	n/a	n/a	n/a	n/a	0	0
Maximum Top-Edge Height Above Grade (*z*, cm)	0	0	n/a	n/a	n/a	n/a	n/a	0	0
Minimum Soil Depth (E, m)	n/a	n/a	n/a	0	n/a	n/a	n/a	n/a	n/a
Maximum Soil Depth (E, m)	n/a	n/a	n/a	15	n/a	n/a	n/a	n/a	n/a
Minimum Soil Far-Field Distance (F, m)	n/a	n/a	n/a	0	n/a	n/a	n/a	n/a	n/a
Maximum Soil Far-Field Distance (F, m)	n/a	n/a	n/a	15	n/a	n/a	n/a	n/a	n/a
THERMAL PROPERTIES*									
Minimum Conductivity (W/(mK))	0	0	0	0	0	0	0	0	0
Maximum Conductivity (W/(mK))	0	0	0	0	0	0	0	0	0
Minimum R-Value (m^{2}K/W))	0	0	0	0	0	0	0	0	0
Maximum R-Value (m^{2}K/W))	0	0	0	0	0	0	0	0	0
Minimum Density (kg/m^3)	0	0	0	0	0	0	0	0	0
Maximum Density (kg/m^3)	0	0	0	0	0	0	0	0	0
Minimum Specific Heat (kJ/(kgK))	0	0	0	0	0	0	0	0	0
Maximum Specific Heat (kJ/(kgK))	0	0	0	0	0	0	0	0	0
COMMENTS									
Uninsulated detail (Figure A-1) ok? ("yes" or "no")	yes								
Insulated detail (Figure A-2) ok? ("yes" or "no")	yes								
If no, include additional assumptions of your model not covered here (add rows as needed)									
Include other clarfications and/or comments here (add rows as needed)	Many of the limits are set by stability considerations and cannot be specified in isolation.								

NOTES

"n/a": not applicable

**** If a listed input does not apply to your model, enter "0" in the relevant cells.***

***** For below grade high-mass components, only list R-value input limits if there is some difference versus what would be calculated based on listed conductivity and thickness limits***