Appendix B

Thermal Analyses

Thermal Resistance of Precast Concrete Wall Panels with Concrete Containing Recycled Glass and Carpet Fiber

Final Report

Prepared By:

Adrian Tuluca, RA and Ravi Gorthala, PH.D,
Steven Winter Associates, Inc.
50 Washington Street, Norwalk, CT 06850

I. Introduction

Steven Winter Associates, Inc. (SWA) was a subcontractor to Columbia University on the Project No. 4710-IABR-BR-98 sponsored by the New York State Energy Research and Development Authority. SWA performed thermal analyses of Thermal-Krete, a precast concrete foundation product of Kistner Concrete Products, Inc. The purpose of the analyses was to characterize the thermal bridging that occurs in the current configuration of the foundation system and to identify methods to reduce heat losses.

SWA first performed preliminary two-dimensional heat flow analyses using *THERM 2.0*[1] (developed by Lawrence Berkeley Laboratory) to assess the important parameters affecting the thermal resistance of the precast concrete wall panels, a cross-section of which is shown in Fig. 1. Since the 2-D models used by SWA took into account only the heat flow in the horizontal section, the resulting R-values were higher than the R-values later obtained from three -dimensional (3-D) analyses. 3-D analyses are more accurate since the concrete ribs act as thermal bridges to both horizontal and vertical heat flow. However, the 2-D modeling gave early insight into the relative importance of changes to each of the concrete panel components.

The three-dimensional heat flow analyses were subsequently performed using ALGOR, a commercial finite element software system. This report summarizes the results of the heat flow analyses of the precast concrete foundation.

II. Results

Two-Dimensional Heat Flow Analyses

The horizontal section of the wall, modeled in *Therm 2.0*, is depicted in Figure 1.
The parameters that were considered are as follows:

- cavity insulation thickness
- concrete conductivity
- stud channel conductivity

[1] *THERM 2.0* is a two-dimensional, finite element heat flow analysis software package developed by the Lawrence Berkeley National Laboratory.

Figure 2 illustrates that, as the thickness of the insulation increases, the effect of the thermal bridging created by the concrete web and its steel stud channel increases too. The cavity R-value is calculated by ignoring the effect of the concrete web. Assume a normal weight concrete currently used by Kistner, with the conductivity between 10 to13 Btu–in/(h–ft^2–^{o}F). For a foundation with 2-inch mineral fiber insulation and a metal stud channel, the overall R-value is about 40% lower than the cavity R-value. If the cavity insulation increases to 8 inches, the foundation R-value is about 70% lower than the cavity R-value (R-9 vs. R-32). The benefits of adding insulation to this particular wall configuration diminish rapidly.

Figure 3 shows how the overall R-value changes as the concrete conductivity is varied. The thermal conductivities of the concrete samples developed by Columbia University and tested by Holometrix, using the procedures of ASTM C 177-973 "Steady–State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus," are in the range of 8 to 5 Btu–in/(h–ft^2–^{o}F). Low conductivity concrete is most beneficial when the insulation has high R-value As the concrete conductivity decreases from 8 to 5, the overall R-value of the foundation system increases from R-11.5 to R-14, i.e., about 22% when 8 (eight) inches of insulation are installed. The same reduction in concrete conductivity results in about 5% increase in R-value when 2 inches of insulation are installed (R-5.95 to R-6.20). This outcome reflects the fact that thermal bridging has greater effect on higher insulation levels. Thus, when the short-circuiting effect of the concrete web decreases, the 8-inch insulation configuration benefits more than the 2-inch insulation configuration.

Figure 4 shows the effect of stud channel conductivity on overall R-value. Simulations to this point have used 0.0546-inch thick metal (ANSI 1040 mild steel), with a conductivity of 330 Btu–in/(h–ft^2–^{o}F). Since no information was available regarding the type of plastic that might be used, or the thickness that would be required, SWA made assumptions to characterize the magnitude of the change that can be expected. Two types of plastic were considered: polyethylene and polypropylene with conductivities of 2.29 and 1.11, respectively. It was assumed that the thickness of the stud channel would have to be doubled (to 0.11 inches), compared to the metal stud channel. Based on these assumptions, the use of plastic stud channels would increase the R-value of the foundation by 90% to 100%, with 8-inch insulation. With 2-inch insulation, the increase in R-value of the foundation due to the use of plastic stud channels would be 60% to 70%. As noted above, this outcome reflects the fact that thermal bridging has greater effect on 8-inch insulation than on 2-inch insulation. Consequently, mitigation of the thermal bridging benefits more the foundation with 8-inch insulation than the one with 2-inch insulation.

Conclusions from the 2-D analyses

The preliminary 2-D simulations indicate that (1) the stud channel conductivity has a greater effect on the thermal performance of the concrete foundation than the concrete conductivity, and (2) the conductivity of the stud channel and of the concrete has the most pronounced effect where the foundation uses higher levels of fibrous insulation. Three-dimensional simulations are presented in the next section.

Figure 1: Horizontal Cross Section of Precast Concrete Panel

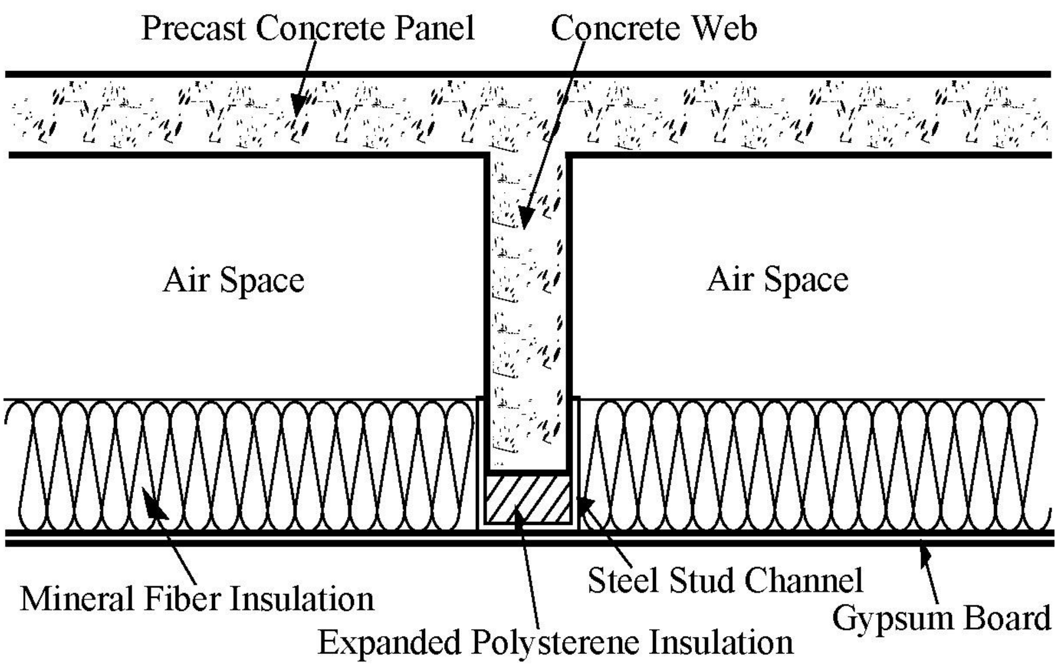
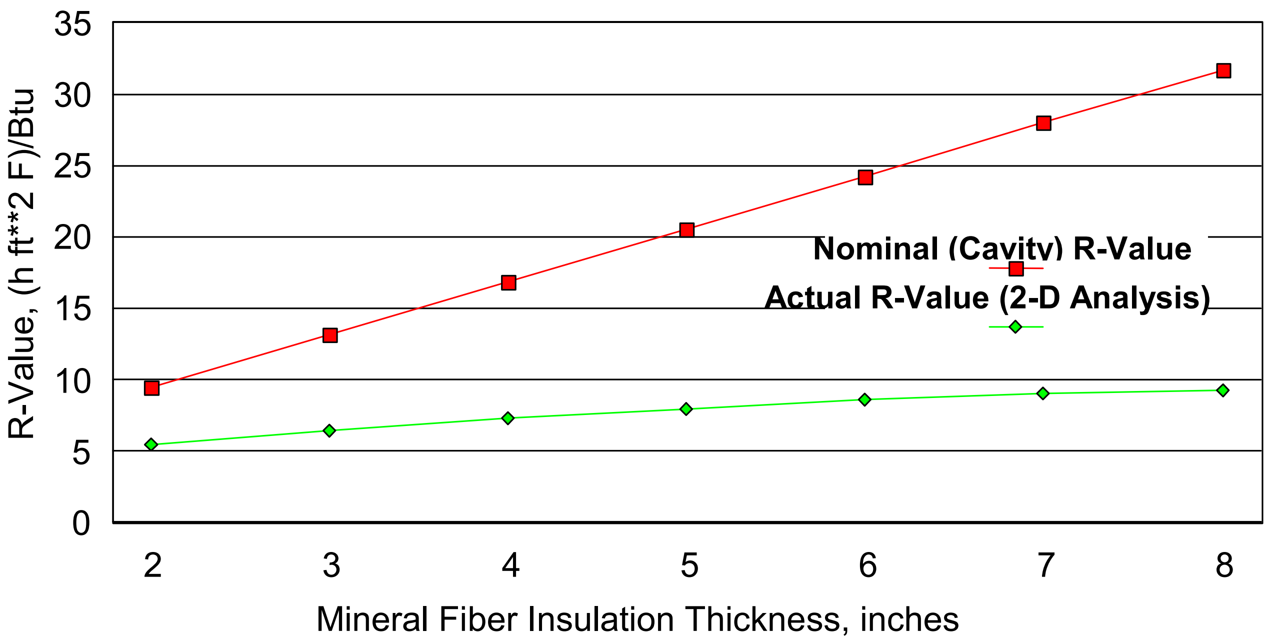


Figure 2: Foundation R-Value vs. Insulation Thickness (Metal Stud Channel) – 2D Model (Includes Internal & External Film Resistances)



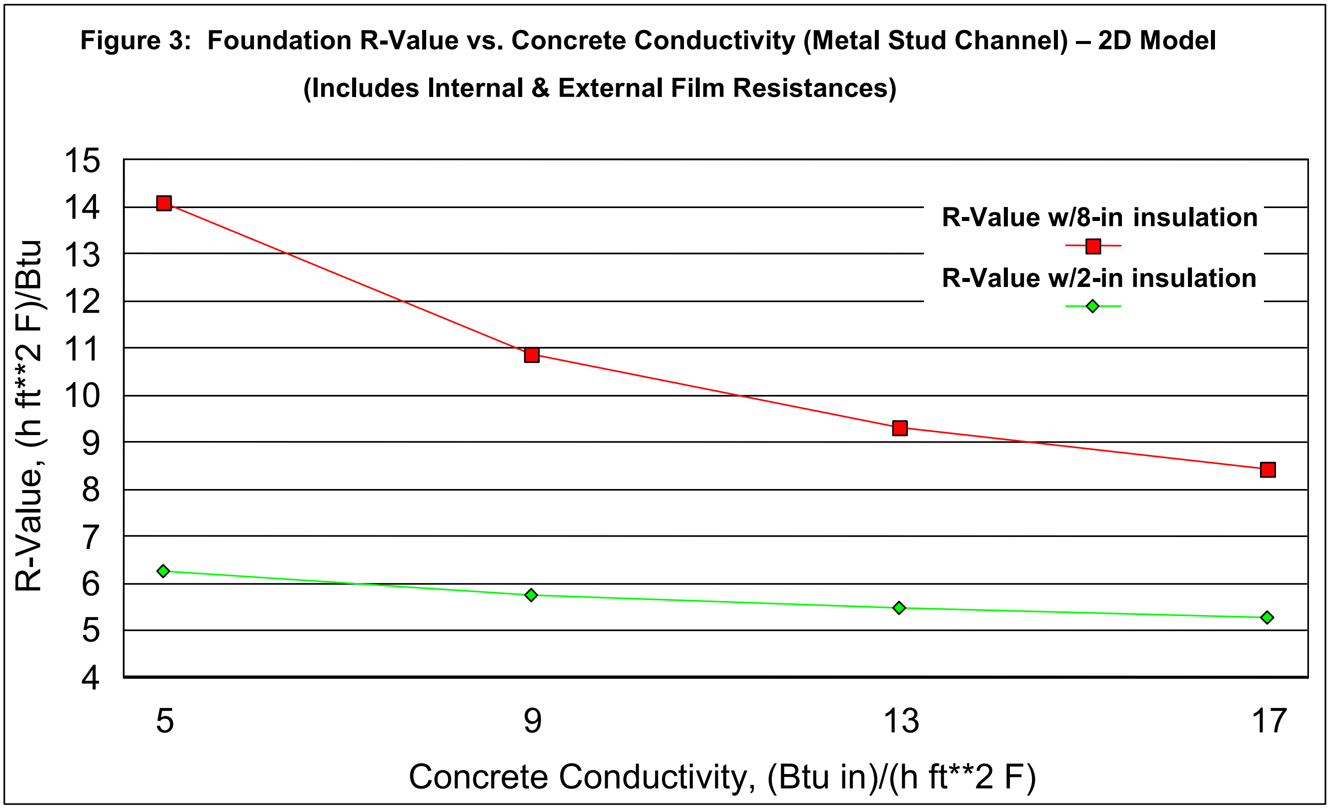


Figure 3: Foundation R-Value vs. Concrete Conductivity (Metal Stud Channel) – 2D Model
(Includes Internal & External Film Resistances)
15
14
13
12
11
10
9
8
7
6
5
4
R-Value, (h ft**2 F)/Btu
R-Value w/8-in insulation
R-Value w/2-in insulation
5
9
13
17
Concrete Conductivity, (Btu in)/(h ft**2 F)

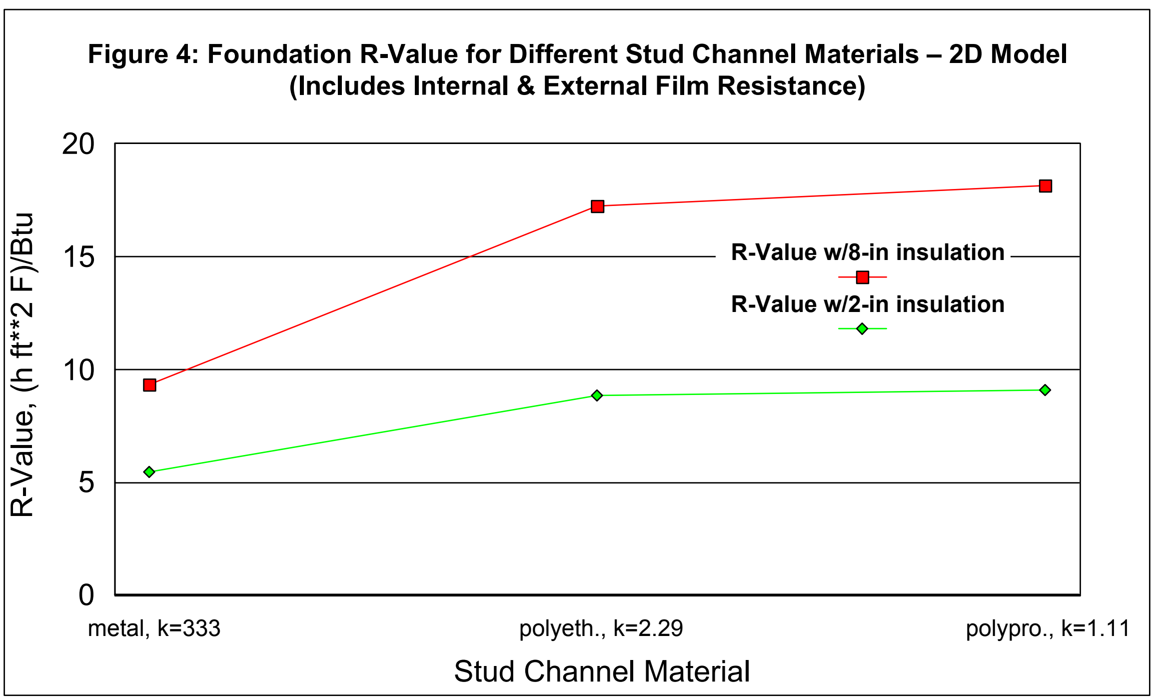


Figure 4: Foundation R-Value for Different Stud Channel Materials – 2D Model
(Includes Internal & External Film Resistance)
20
15
10
5
0
R-Value, (h ft**2 F)/Btu
R-Value w/8-in insulation
R-Value w/2-in insulation
metal, k=333
polyeth., k=2.29
polypro., k=1.11
Stud Channel Material

Three-Dimensional Heat Flow Analyses

Figure 5 shows the geometry of the Thermal-Krete foundation system as modeled with the three dimensional (3-D) finite element software ALGOR. The 3-D model developed is more realistic than the 2-D *Therm* models because it includes heat flow from the Thermal-Krete foundation system (1) to soil, (2) to outdoor ambient air, and (3) to/from the wood stud exterior wall that is located above the foundation. Boundary conditions in ALGOR included an indoor air temperature of 70^{o}F, an outdoor air temperature of 30^{o}F, and a soil temperature of 42^{o}F.

First, two cases were simulated: 1) R-11 cavity insulation with steel stud (Base Case) and 2) R-11 cavity insulation with plastic stud (Alternate 1). Temperature contours for these cases are shown in Figs. 6 and 7, respectively. Heat loss for the foundation with plastic stud channel at the web was 39% lower than for the foundation with steel stud channel. These were preliminary three- dimensional heat flow simulations to develop an understanding of the overall procedure.

Then, 3-D heat flow parametrics were performed for a total of 17 different configurations of Thermal-Krete. Parameters considered included:

- Location of insulation
- Insulation thickness
- Insulation type
- Concrete conductivity
- Stud channel material: steel vs. plastic
- Mitigation of the thermal bridging caused by the steel stud channel

Unless otherwise noted the conductivity of concrete was 10 Btu–in/(h–ft^{2}–^{o}F), corresponding to current practice by Kistner Concrete Products.

The geometry of the Base Case for both steel and plastic stud was same as that shown in Fig. 5. Results are shown in Fig. 8 (steel stud) and Fig. 9 (plastic stud). Note that in the labels for different wall configurations the “S” notation stands for “steel” while the “P” notation stands for “plastic”. Thus in Fig. 8 “S-Base Case” means the Base Case configuration with a steel stud, while in Fig. 9 “P-Base Case” means the same Base Case configuration with a plastic stud. For all scenarios, using a plastic stud resulted in a lower heat loss for the foundation panel and hence in a higher R-value than for the corresponding steel stud case.

Location of insulation

Compare Base Case vs. Alt-1 for R-11 insulation, and Alt-2 vs. Alt-3 for R-19 insulation (Figs. 8 and 9 for both steel stud and plastic stud configurations). The concrete webs short-circuit the insulation placed between them. As a result, insulation installed against the gypsum board reduces heat loss to a greater extent than when it is installed against the concrete foundation wall.

Specifically, if the insulation is moved from the concrete panel to the gypsum board, the overall R-value of the foundation system increases by about 14-17% for R-11 insulation and by about 65-70% for R-19 insulation.

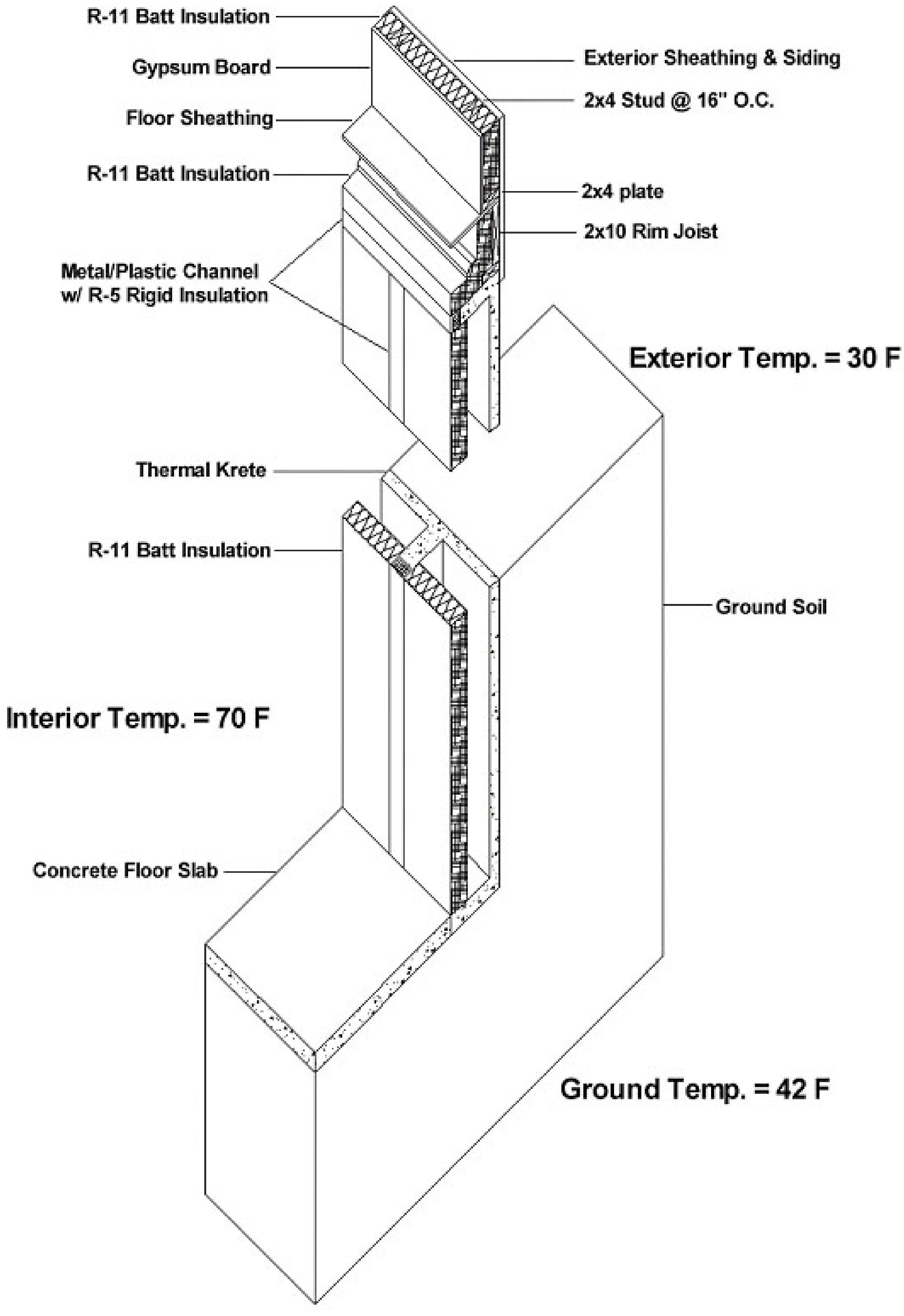


Figure 5. Geometry of the Thermal-Krete Foundation in the ALGOR 3D Model

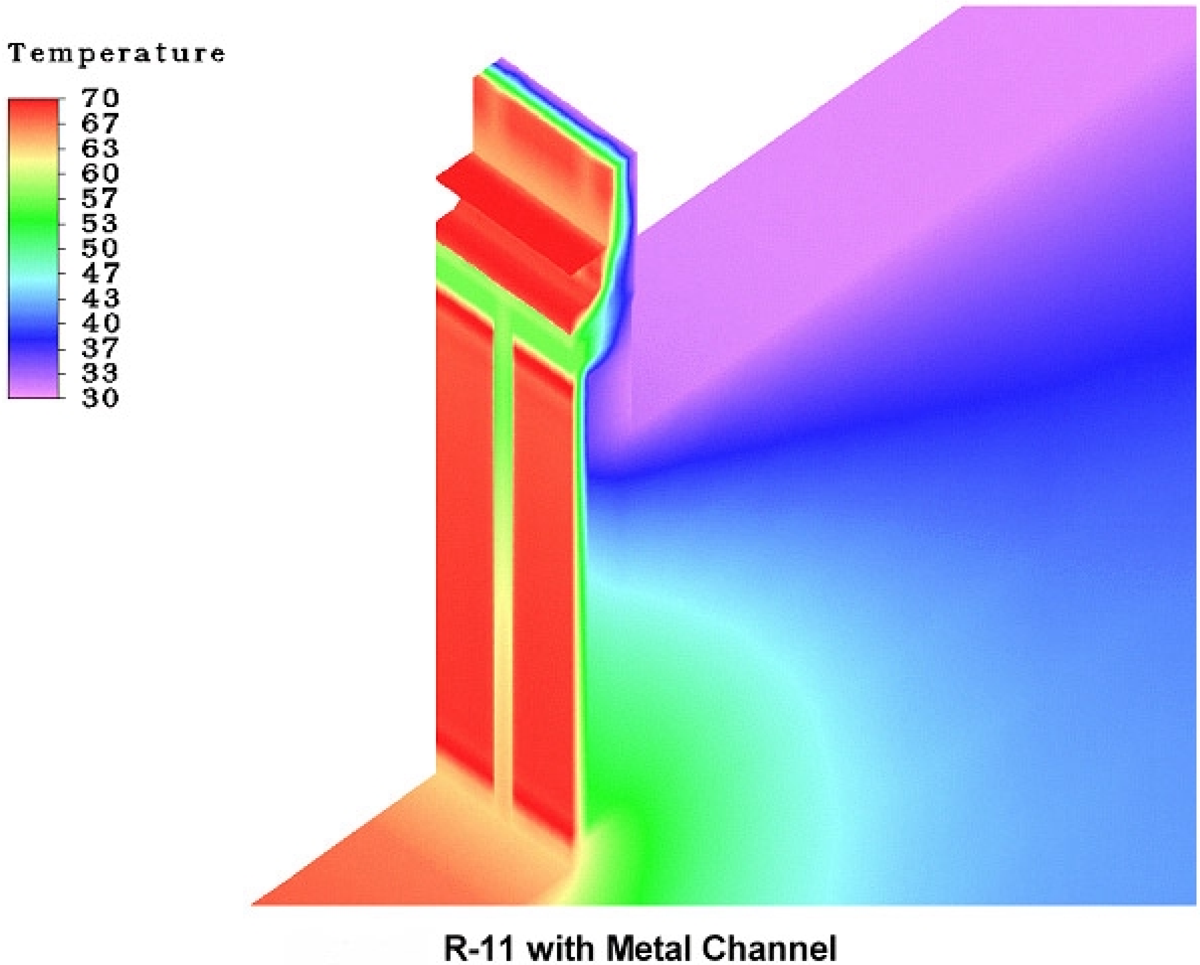


Fig. 6 Temperature Contours for Thermal-Krete with Steel Stud and R-11 Insulation--3D Model

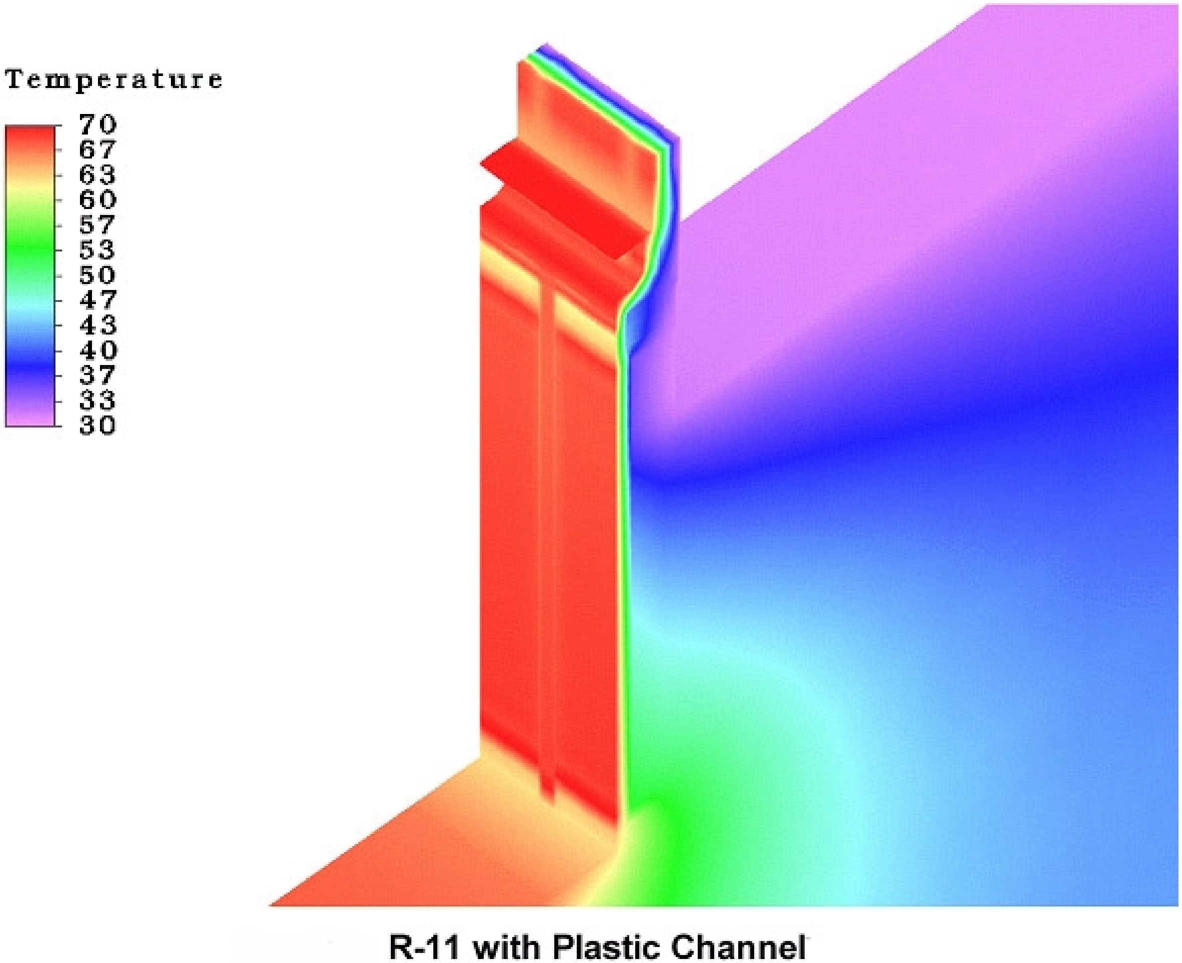


Fig. 7 Temperature Contours for Thermal-Krete with Plastic Stud and R-11 Insulation--3D Model

This conclusion, based on conduction heat flow only, holds true only if convective airflow between room and wall cavity is insignificant. To this end the gypsum board must be sealed at both ceiling and floor, and receptacles must have airtight enclosures. It is not particularly difficult to achieve an airtight gypsum board sheet and the advantage accrued by the higher R-value of the foundation is significant. However, please note that the advantage gained by moving the insulation against the gypsum board will be somewhat reduced if the concrete has lower conductivity, in the 5-8 range shown possible by Columbia University experiments.

Insulation thickness

When the insulation is installed against the gypsum board, heat losses are significantly reduced by replacing R-11 batts with R-19 batts. This decrease in heat loss is especially significant for the plastic stud construction shown in Fig. 9. It is less effective to increase the insulation thickness if this insulation is installed between webs capped by steel studs (about 40%). In fact, of all the cases modeled in Fig. 8 and 9, P-ALT-2 (R-19 insulation installed against the gypsum board with plastic stud) has the highest R-value (21.2).

Insulation type

Of the steel stud models simulated, S-ALT-5 performed the best (foundation fully covered with two inches R-10 exterior insulation made of extruded polystyrene, see Fig. 8). Its effective R-value of 14.86 is just 2% lower than the corresponding plastic stud case (P-ALT-5). More important, the R-10 exterior insulation yields higher overall R-value than R-11 fibrous insulation, whether this fibrous insulation is installed against the concrete panel or against the gypsum wallboard.

An additional advantage of the exterior insulation is that it maintains the entire concrete panel at higher temperature, greatly reducing the risk of moisture condensation. Fibrous insulation decreases the temperature of the concrete panel and this creates more opportunity for moisture condensation.

However, with an effective R-value of 15.13, P-ALT-5 falls significantly short of P-ALT-2's R-value of 21.2. (P-Alt-2 has R-19 fibrous insulation.) The thickness of the extruded polystyrene insulation can be increased to about 3 inches to surpass the performance of P-Alt-5. While 3-inch extruded polystyrene is more expensive than R-19 fibrous insulation, the requirements for airtight gypsum board associated with P-ALT-5 have their own cost. In addition, the exterior rigid insulation has the advantage of reducing the risk of moisture condensation, as noted above.

If exterior rigid insulation is considered, it is important to realize that if this insulation ends at grade level without covering the entire foundation, the effective R-value drops by about 50% for both the steel and plastic stud models (see S-ALT-4 and P-ALT-4). In certain geographic locations only the ALT-4 configuration is possible, because of the need to create a termite gap. In such situations the fibrous insulation, placed to the winter-warm surface of the concrete or to winter-cold surface of the gypsum board is more advantageous.

The configurations S-ALT-6 and P-ALT-6 have R-5 sprayed or glued insulation on the winter-warm surfaces of the concrete panel. The R-values achieved are in the range of those obtained with R-11 fibrous insulation. While the thermal performance of this R-5 configuration is unremarkable, the configuration has two advantages: (1) If the spray-on insulation is AirKrete (a cementitious, low-density compound) or cellulose, the moisture condensation potential is significantly reduced. This is because both AirKrete and sprayed cellulose leave no air space near the concrete, and therefore eliminate moisture transport through air convection. (2) If the insulation is made of plastic sheets formed from recycled carpets, the recycled content of the insulating material becomes very high. In addition it is possible that the plastic sheets have a low vapor permeance, acting as effective vapor retarders.

Concrete Conductivity

To determine the effect of Thermal-Krete's conductivity on the effective R-value of the foundation, SWA performed a parametric analysis that is presented in Fig. 10. The concrete conductivity for model P-ALT-2 (R-19 insulation placed against the gypsum board) was varied from 4 to 10. The result is a minor increase in effective R-value of the foundation system from 21.20 (conductivity of 10) to R-23.65 (conductivity of 4), or 12%. Concrete with a conductivity of 4 is lightweight and probably unfit for foundation use. It was included in the analysis as a limit case. The thermal conductivity tests showed that concrete with glass and carpet fibers has conductivities in the 5-8 range. The K=6 yields a 6% increase in overall R-value. The K=8 yields only a 2% increase in R-value. Therefore, given the most likely achieved conductivity range, Thermal-Krete's conductivity will not significantly affect the overall R-value of the foundation.

Mitigation of the thermal bridging at the steel stud

Since the use of steel stud is the current practice for the Thermal-Krete foundation system, another three alternatives with steel stud were simulated. These three alternatives, presented in Fig.11, were:

1. S-BASE CASE-A
2. S-AL-2-A
3. S-ALT-7

S-BASE CASE and S-ALT-2-A are the same as S-BASE CASE and S-ALT-2, respectively, except that a ½-inch (R-2.5) strip of extruded polystyrene was placed between the steel stud and the gypsum board in order to reduce thermal bridging. S-ALT-7, the new alternative, utilizes a continuous layer of 1-inch (R-5) extruded polystyrene insulation, which fully covers the winter-cold surface of the gypsum board (no fibrous insulation).

The R-value of the foundation system significantly increases when installing extruded polystyrene insulation between the steel stud and gypsum board. The R-value of S-BASE CASE (R-11 insulation) increases from R-8.88 to R-17.82 (101%) Similarly the R-value of S-ALT-2A (R-19 insulation) has an R-value of 21.57 compared to R-12.45 for the S-ALT-2 (73% increase). S-ALT-7 achieves an R-value of 15.08, which is higher than S-ALT-1 (R-11 with steel stud) at R-8.88 by 70%, and is even higher than the R-14.4 of P-ALT-1 (R-11 with plastic stud) by 5%. Note that the continuous rigid insulation is also helpful in achieving an airtight enclosure. If extruded polystyrene is not acceptable for fire rating reasons, similar results can be obtained with slightly thicker semi-rigid mineral fiber board (R-4.2/inch).

III. Conclusions

The findings of the study are listed as below:

- The steel stud that covers the edge of the concrete web in the Thermal-Krete concrete foundation system is responsible for significant thermal bridging. The thermal performance of Thermal-Krete improves significantly by replacing the steel stud with a plastic stud or a wood stud.
- If an extruded polystyrene insulation strip is added between the steel stud and the gypsum board, the thermal performance of the foundation system is substantially improved. This seems to be an appropriate approach if the steel stud is not replaced by a plastic or wood stud in the Thermal-Krete foundation system.
- R-5 rigid or semi-rigid insulation placed continuously on the winter-cold surface of the gypsum board performs better than R-11 insulation placed between the concrete webs.
- Placing the batt insulation against the gypsum board is better than placing it against the concrete wall, if the gypsum board is installed in an airtight manner, and if all receptacles have airtight enclosures.
- Exterior insulation significantly reduces the risk of moisture condensation if it fully covers the foundation. Exterior insulation is significantly less effective if it stops at grade level, since its thermal performance will be lowered by 50% due to thermal bridging.
- Thermal conductivity of concrete has a relatively small effect on the thermal performance of the concrete foundation system.
- Spray-on or glued insulation on the winter-warm surface of the concrete panel can significantly reduce the risk of moisture condensation, while providing overall R-values similar to those of the fibrous insulation (R-5 spray-on or glued compares with R-11 fibrous). The technique may allow the use of recycled carpet fiber as insulation, acting as a waste stream sink.

THERMAL PERFORMANCE OF THERMAL KRETE WITH DIFFERENT INSULATION OPTIONS AND STEEL STUD AT CONCRETE WEB

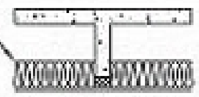
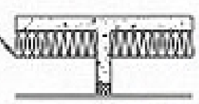
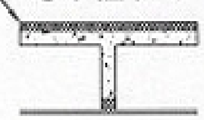
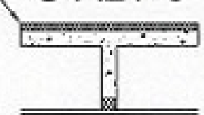
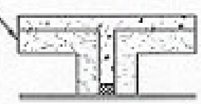
Case	Insulation	Section	TOTAL HEAT FLOW (Btu/h)	EFFECTIVE R-VALUE INCLUDING SOIL
S-BASE CASE	BATT INSULATION	 R11	68.41	R8.88
S-ALT-1	BATT INSULATION	 R11	78.07	R7.78
S-ALT-2	BATT INSULATION	 R19	48.79	R12.45
S-ALT-3	BATT INSULATION	 R19	56.90	R10.67
S-ALT-4	RIGID INSULATION	 R10	96.24	R6.31
S-ALT-5	RIGID INSULATION	 R10	40.86	R14.86
S-ALT-6	SPRAY-ON PLASTIC COATING MADE FROM RECYCLED CARPETS	 R5	70.00	R8.67

Figure 8. Thermal Performance of Thermal-Krete with Different Insulation Options and Steel Stud at Concrete Web –3D Model

THERMAL PERFORMANCE OF THERMAL KRETE WITH DIFFERENT INSULATION OPTIONS AND PLASTIC STUD AT CONCRETE WEB

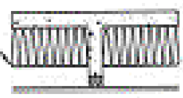
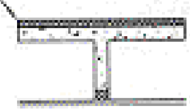
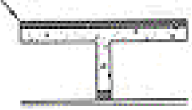
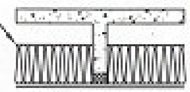
Case	Insulation	TOTAL HEAT FLOW (Btu/h)	EFFECTIVE R-VALUE INCLUDING SOIL
P-BASE CASE 	BATT INSULATION R11	42.18	R14.40
P-ALT-1 	BATT INSULATION R11	72.89	R8.33
P-ALT-2 	BATT INSULATION R19	28.64	R21.20
P-ALT-3 	BATT INSULATION R19	47.88	R12.68
P-ALT-4 	RIGID INSULATION R10	91.00	R6.67
P-ALT-5 	RIGID INSULATION R10	40.13	R15.13
P-ALT-6 	SPRAY-ON PLASTIC COATING MADE FROM RECYCLED CARPETS R5	56.52	R10.74

Figure 9. Thermal Performance of Thermal-Krete with Different Insulation Options and Plastic Stud at Concrete Web –3D Model

PARAMETRIC ANALYSIS OF P-ALT-2



BATT INSULATION R19	U-VALUE OF THERMAL KRETE	EFFECTIVE R-VALUE INCLUDING SOIL
P-ALT-2	10.0	R21.20
P-ALT-2a	8.0	R21.64
P-ALT-2b	6.0	R22.40
P-ALT-2c	4.0	R23.65

Figure 10. Thermal Performance of Thermal-Krete with Different Concrete Conductivities for P-ALT-2 – 3D Model

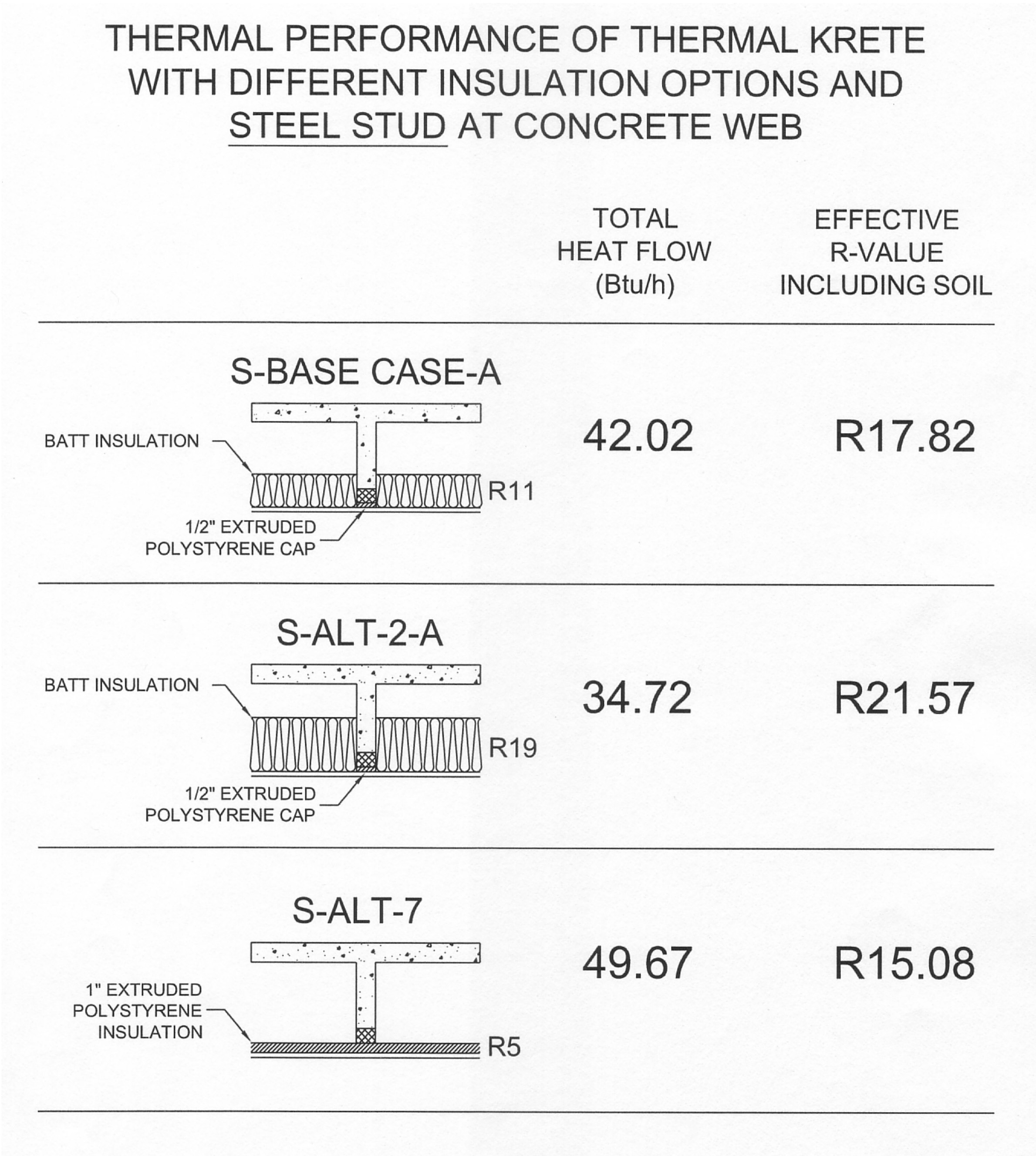


Figure 11. Thermal Performance of Thermal-Krete with Different Insulation Options and Extruded Polystyrene at Steel Stud – 3D Model