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AISI/DOE Technology Roadmap Program:
Development of Cost-effective, Energy-efficient Steel Framing

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Abstract:

Steel members in wall construction form a thermal bridge that interrupts the insulation layer of a wall. This causes higher rate of heat transfer by conduction through the wall framing than through other parts of the wall. One method to reduce the thermal bridging effect is to provide a break, such as insulating sheathing. A thermally efficient slit-web stud was developed in this program to mitigate the conductivity of steel. The thermal performance of the slit-web stud was evaluated at Oak Ridge National Laboratory using hotbox testing. The thermal test results showed that the prototype slit-web stud [3 _ " (89 mm)] performed 17% better than the solid-web stud, using R-13 fiber glass batts with exterior OSB sheathing and _" interior drywall. The structural behavior of this slit-web stud was evaluated in axial, bending, shear, shearwall, and stub-column tests. Test results indicated that the slit-web stud performed similarly or better than the solid-web stud in most structural performance characteristics investigated. Thus, the prototype slit-web stud has been shown to be thermally efficient, economically viable, structurally sound, easily manufactured and usable in a range of residential installations.

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AISI/DOE Technology Roadmap Program

Final Report

Development of Cost-Effective, Energy-Efficient Steel Framing

by

Nader R. Elhajj

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EXECUTIVE SUMMARY

Steel studs used in residential and light commercial wall construction form thermal bridges that interrupt the insulation layer of a wall. This causes higher rate of heat transfer by conduction through the wall framing than through other parts of the wall. One method to reduce the thermal bridging effect is to provide a break, such as insulating sheathing. This method, however, adds to the cost of construction, and is not economically viable. As a solution to this problem, a thermally efficient slit-web stud was developed in this TRP Program project to mitigate the conductivity of steel. Moreover, the second part of this project analyzed and designed components and systems for the construction of homes using cold-formed steel whose thermal performance meets energy code requirements in a cost-effective manner, and to document system performance through thermal testing.

The thermal performance of the slit-web stud was confirmed by thermal testing. Hot-box (thermal) testing was conducted at Oak Ridge National Laboratory. Thermal test results showed that the prototype slit web studs performed 17 percent better than the solid-web studs, giving an overall wall resisitivity of R-10.4 for the chosen slit-web stud (3-1/2" 18 gauge steel framing, 24" on center) wall, using R-13 fiberglass batts with exterior OSB sheathing and ½" interior drywall compared to an R-8.9 for solid web studs with the same configuration. [It may be mentioned here that the base line wood stud (2"x4", 24" on center) wall, with the same configuration has an overall wall resistivity of R-12.7.] Test results also proved that the best performing steel stud walls are those using slit web studs and angles (for top tracks), yielding a wall R-value of 11.4. Adding a thin layer of polyisocyanurate foam insulation on the exterior increases the wall R-value to 14.1; i.e., 28 percent improvement over solid web studs.

The structural behavior of 3-1/2 inch (89 mm) slit-web stud (perforated web) was evaluated and test results showed that the prototype slit web stud performed similar to or better than a solid-web stud in bending, axial, and shear tests. The shearwall test results indicated the importance of using multiple chord studs and the need to address the connection to the tension chord end stud where heavy connections are made and locally high compressive and tension forces must be transferred through connections or bearing of end studs. Tests also showed that the slit-web stud is very sensitive to the distortional buckling mode. The slit-web stud tested in this report was shown to be better than or essentially equivalent to a solid-web stud in most structural performance characteristics investigated. Web crippling was not investigated for the slit-web stud, as it is not considered a failure mode for wall studs that are fully sheathed with structural sheathing. Web crippling strength should be investigated when slit-web studs are used in non-sheathed wall applications.

The prototype slit-web steel stud successfully developed under this TRP project has been shown to be thermally efficient, economically viable, structurally sound, easily manufactured, and usable in a range of residential installations ("Buildable"). The details of these analyses and results were presented in the main body of the report.

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Part 1: Thermal Performance of Slit-Web Steel Wall Studs

INTRODUCTION

Cold-formed steel framing has seen some market growth in the housing market. However, due to concerns about the thermal performance of steel, the use of steel framing in the residential market is still low.

Steel members in wall construction form a thermal bridge that interrupts the insulation layer of a wall. This causes higher rate of heat transfer by conduction through the wall framing than through other parts of the wall. One method to reduce the thermal bridging effect is to provide a break, such as insulating sheathing. Recommended sheathing thicknesses for various steel wall sizes are given in the Thermal Design Guide [1]. The exterior insulation thickness can be as high as 2 inches to achieve a required (effective) R-value. This can be costly and inefficient. Thick exterior insulation typically requires longer (expensive and hard to find) screws and creates a challenge for siding installation.

Most builders currently use one or more of the following construction methods to create a thermally efficient steel stud wall system:

- Increasing the fiberglass batt insulation in the wall cavity (such as R-15 instead of the typical R-11).
- Increasing the spacing between the steel studs to 24 inches on center instead of the typical 16 inches on center (for wood studs).
- Adding exterior insulating sheathing (such as rigid foam).
- Using larger studs (such as 5-1/2" instead of the 3-1/2") spaced further apart so that more cavity insulation can be used.
- Adding thicker rigid foam insulation on the exterior without any cavity insulation.

Studies suggest that some of the options listed above may not be adequate to overcome the thermal bridging that steel creates in a framed wall [2]. Therefore, it is essential that builders use the appropriate insulation material and thickness or provide an adequate thermal break to effectively reduce the thermal bridging effect.

PURPOSE

The objective of this program is to improve the building envelope thermal performance in cold-formed steel-framed homes, by developing and analyzing new "thermally efficient steel stud". The performance of the promising stud was confirmed by thermal testing to determine acceptable solutions for residential and light commercial construction. A list of existing wall systems and/or components (options) that potentially reduce house energy use (specially for steel-framed buildings) was compiled. The options were then evaluated based on whether the wall systems and components are:

Thermally efficient
Economically viable
Structurally sound
Easily manufactured
Usable in a range of residential installations ("Buildable")

This evaluation has been conducted on dozens of types of wall systems that use such components as thermal breaks, modified studs, novel materials and new construction techniques. On a reduced set of promising technologies, this evaluation has been conducted quantitatively, using thermal finite element analysis and other techniques, as well as qualitatively.

This program was conducted in several stages as follows:

- **Review of Existing Solutions**

  Measures, systems, or materials were investigated and reviewed which might be used to improve the thermal performance of the conventional and non-conventional cold-formed steel framed wall assemblies, considering different regions (e.g. hot and hot & humid, cold climate, and transitional climate). The information obtained was analyzed and evaluated.

- **Evaluation of Existing Solutions**

  The systems and materials reviewed were then analyzed and evaluated to determine the best option. The selected configurations were evaluated using two-dimensional finite element analysis models to determine if the modeled performance warrants additional testing. In addition, constructability analysis was conducted to insure that the wall system could be manufactured and built prior to subjecting assemblies to testing.

- **Selection of Wall Configurations**

  An option was chosen from the results of the previous stages. The selected configuration was further evaluated using two-dimensional finite element analysis to determine if the modeled performance warrants additional testing. A total of 10 wall assemblies were selected for thermal testing.

- **Thermal Testing of Wall Assemblies – Phase I**

  Wall assembly tests, consisting of 8 foot by 8-foot wall samples, were executed in accordance with ASTM C1363 [3] with a hot side temperature of 70 °F and a cold side of 20 °F.

- **Thermal Testing of Wall Assemblies – Phase II**

  Thermal test results from Phase I tests were reviewed. Modifications were made and the final "thermally efficient" stud wall system was developed. Additionally, 12 wall assembly tests, consisting of 8 foot by 8-foot wall samples, were executed in accordance with ASTM C1363.

- **Structural Testing of Walls**

  Structural tests were conducted to assess the strength and stability of the recommended "thermally efficient" steel stud wall. The description and results of such tests are summarized in a separate report [4].

LITERATURE REVIEW

Researchers through out the world have investigated several techniques and proposed many ideas that mitigate the thermal concern of steel framing. Most of the methods and materials investigated were concentrated on increasing the thermal effectiveness of steel framed walls through:

- Reducing the contact area between the studs and the exterior sheathing materials,
- Reducing the steel stud web area,
- Placing foam insulation in locations where the thermal shorts are most critical, and,
- Modifying the stud web

Numerous papers, research reports and publications have been written about the thermal performance of cold-formed steel framing. Most of the reports and papers written address the negative performance of steel in cold climates. Table 1 lists a summary of the thermal options selected for review and evaluation in this report. The options in Table 1 are by no means inclusive. Figure 1 provides illustrations of some of the thermal options selected for review.

Researchers Bombino and Burnett concluded that a mere replacement of wooden studs with steel studs in a conventional wall assembly could result in halving the contribution of the insulation shown in Figure 2 [5]. Bombino and Burnett estimated the thermal efficiency of the steel-framed wall to be 55% compared to 89% for the wood-framed wall (taking into account the thermal effect of the studs). They further concluded that increasing the cavity batt insulation without adding exterior insulation produces nominal increase in the wall R-value but actually lowers the thermal efficiency of the wall from 55% to 51% (refer to Figure 3). Increasing the cavity insulation from R-11 to R-15 (a nominal increase of R-4) increases the average wall R-value by 1.1 and decreases the thermal efficiency of the wall to 47%. Bombino and Burnett also reported "the best strategy is a combination of cavity insulation and exterior sheathing." This is illustrated in Figure 4 and 5.

Table 1 – List of Thermal Options

Option No.	Description	Option No.	Description
1	Snap-Cap™ (2")	34	Struct. Insul (CBS) w/ Slot Web & 26
2	Astec Ceramic Ins. Coating	35	Struct. Insul (Celotex Thermax) w/ Slot Web
3	Double Wall Metal Track	36	Struct. Insul (E'NRG'Y 2 Nailboard)
4	Double Wall Insulated Track	37	Thermal Tape
5	Slotted Web (Delta™)	38	SuperTherm Insulating Coating
6	Rigid Sheathing (1") Polystyrene	39	Metal/Foam Laminate Sheathing
7	Rigid Sheathing (2")	40	Foil-Backed Wallboard
8	Rigid Sheating (2") with lathe/glue	41	Offset Framing
9	Rigid Sheating (2") without plywood	42	Broken Web
10	Rigid Sheathing (1") Isocyanurate	43	Hybrid Stud
11	Ridged Flange	44	Panelized Walls (Thermastructure)
12	Studs with Dimpled Flange	45	Panelized Wall w/ ExcelBoard less Plywood
13	Circular Slot Web Stud	46	Foamed Cement/Metal Framing
14	Circ. Slot Web Stud w/ Sprayed Foam	47	PVC Clip
15	Circ. Slot Web Stud w/ Ridge & Foam	48	PVC Clip w/ Spray-in Foam
16	Circ. Slot Web Stud w/ Interior Foam/Z	49	PVC Clip w/ Spray-in Cellulose
17	Circ. Slot Web Stud w/ Ridge & Cellulose	50	PVC Clip w/ Oversized Foil-Faced Batt
18	Circ. Slot Web Stud w/ Thermal Tape	51	Insulated Drywall
19	Circ. Slot Web Stud w/ Foil-backed Wallboard	52	Insulated Drywall w/ Slotted Web
20	Circ. Slot Web Stud w/ Foil-Faced Insulation	53	Spray-in Foam
21	Circ. Slot Web Stud w/ Therm Tape & Foil Insul	54	ExcelBoard Structural Insulation
22	Furring Strips	55	Diversitec Structural Insulation
23	Furring Strips w/ foil-backed ins.	56	Fiberglass Batt w/ Foil over Flange
24	Furring Strips w/ Urethane Foam	57	Fiberglass Batt w/ Foil over Slotted Web
25	Furring Strips w/ Spray-in Cellulose	58	Gentec Insulated Siding
26	Furring Strips w/ Cellulose & Slotted Stud	59	AmazingWall Insulated Siding
27	Furring Strips w/ Foam & Slotted Stud	60	TechWall Insulated Siding
28	Furring Strips w/ EESI-Stud	61	TechWall Ins. Siding w/ Batt over Flange
29	EESI-Stud (Tri-Chord™)	62	TechWall Ins. Siding w/ Slotted Web
30	EESI-Stud w/ Thermal Tape	63	TechWall Siding w/ Batt & Slotted Web
31	Struct. Insul - Cellulosic Hardboard	64	Interior Rigid Foam w/ Z Strip
32	Struct. Insul - CBS Sheathing (1")	65	Interior Rigid Foam w/ Hat Channel
33	Struct. Insul (CBS) w/ Slotted Web	66	Inter. Rigid Foam w/ Z & Foil-Faced Insul

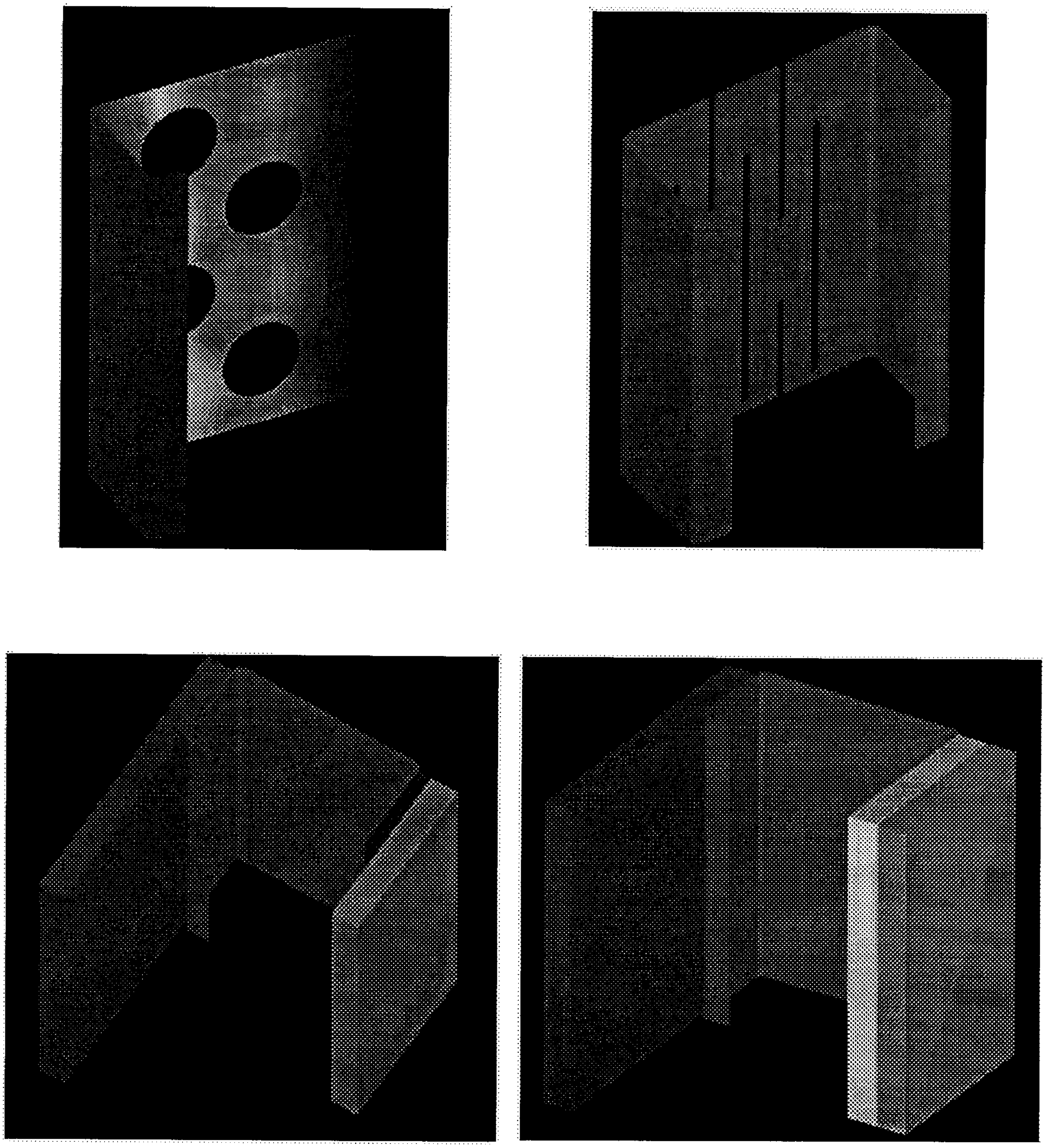

Figure 1 – Selected Thermal Options

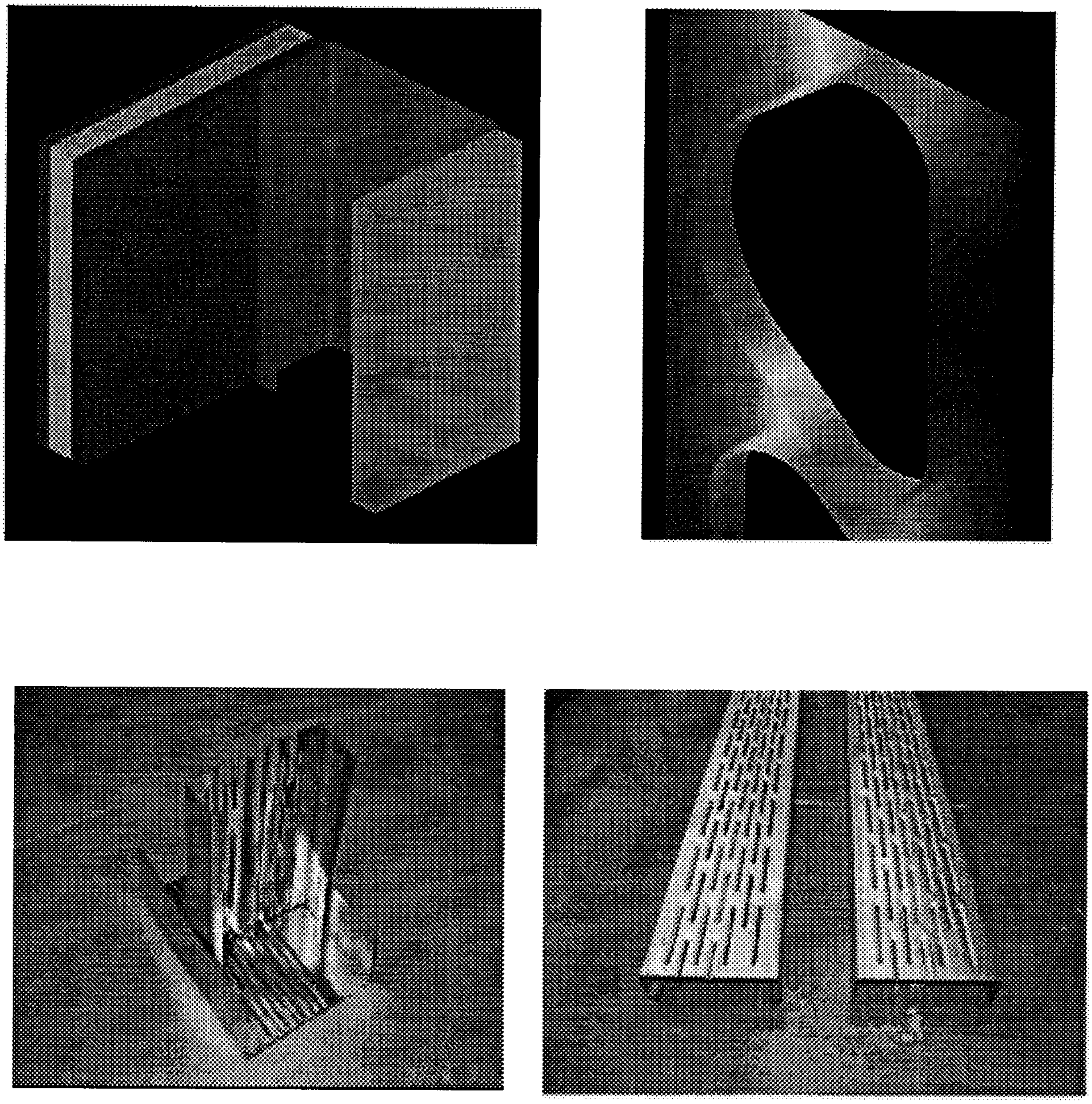

Figure 1 – Selected Thermal Options (cont.)

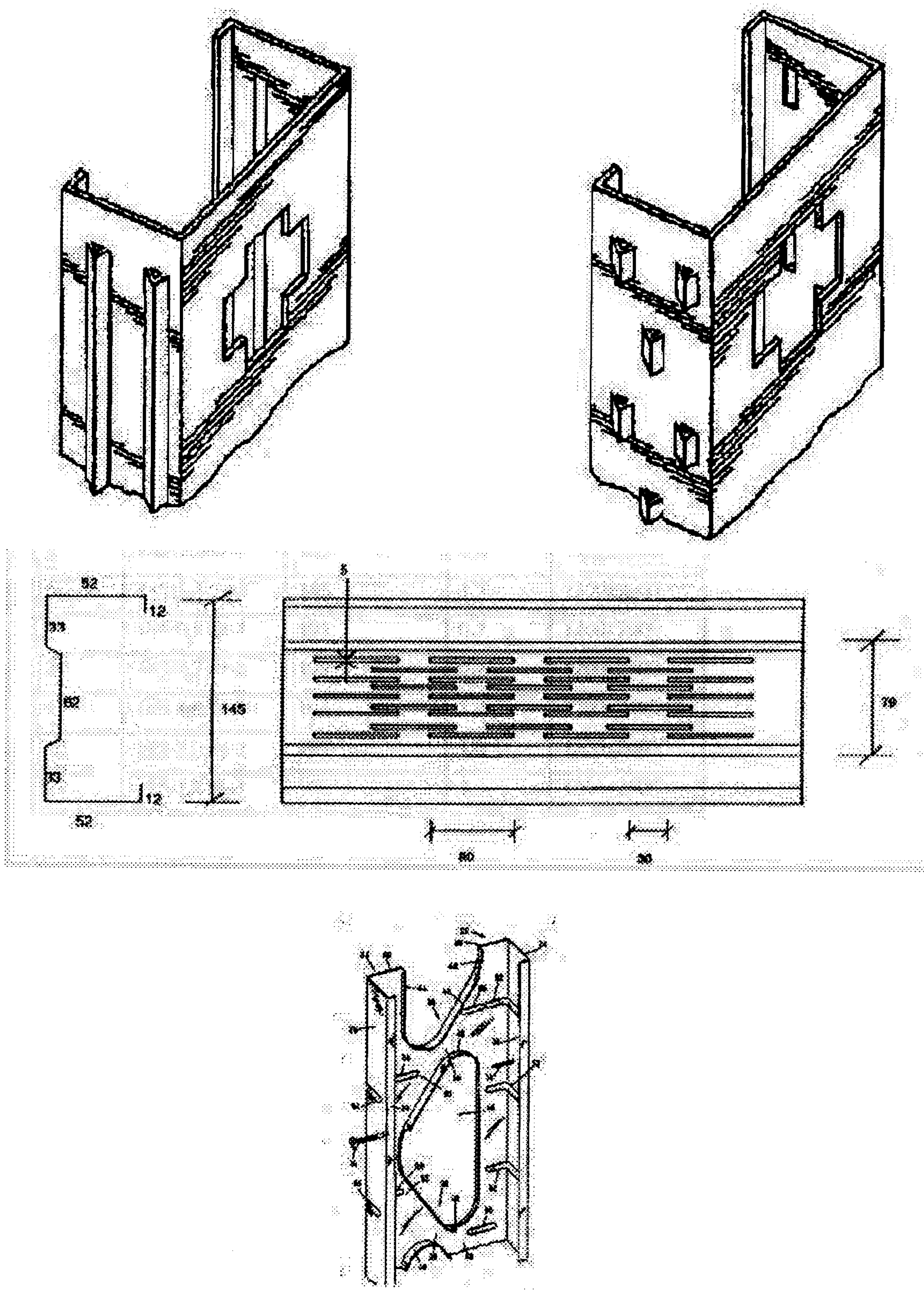

Figure 1 – Selected Thermal Options (cont.)

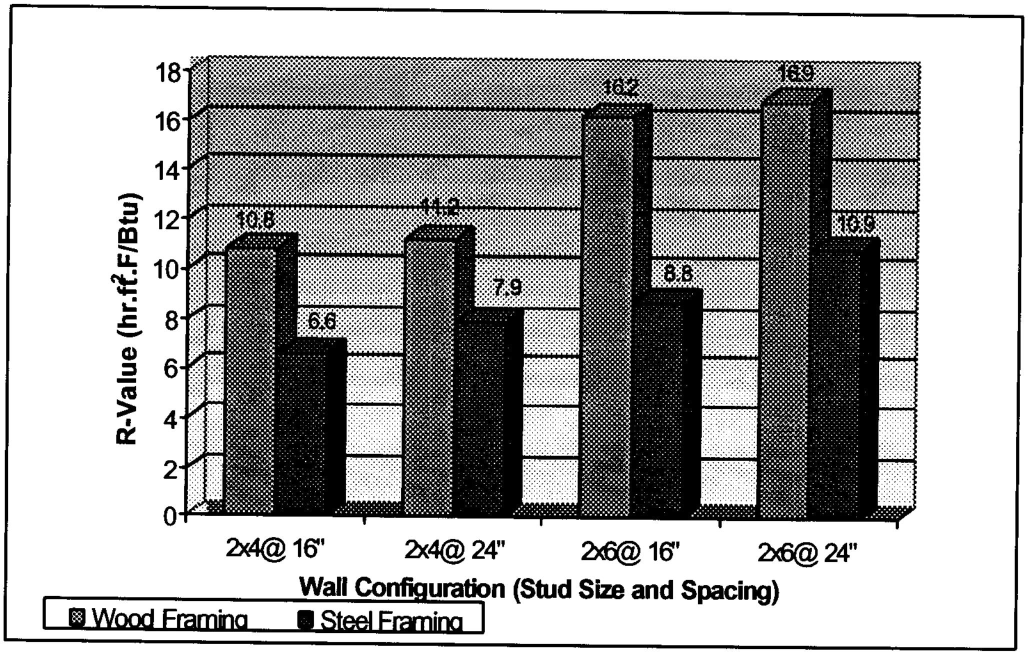

Figure 2 – Average R-Value for Various Wood- and Steel-Framed Walls
(Based on mere replacement of wooden studs with steel studs)

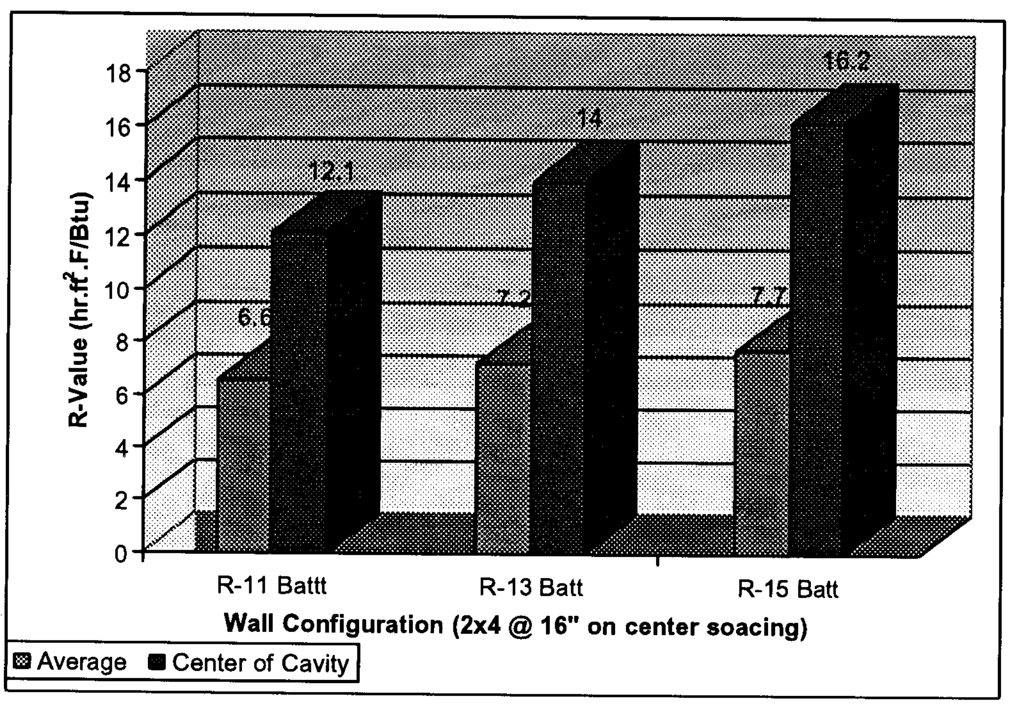

Figure 3 – Average Wall R-Value for Steel-Framed Walls with Different Levels of Cavity Insulation

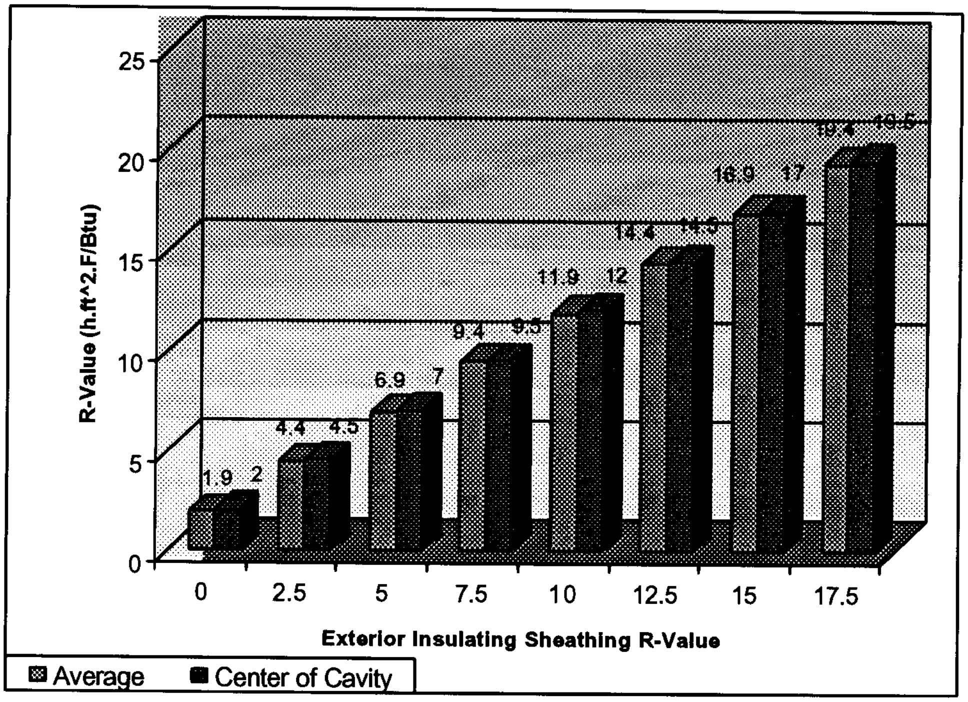

Figure 4 – Average Wall R-Value for Steel-Framed Walls with R-11 Cavity and Exterior Insulating Sheathing

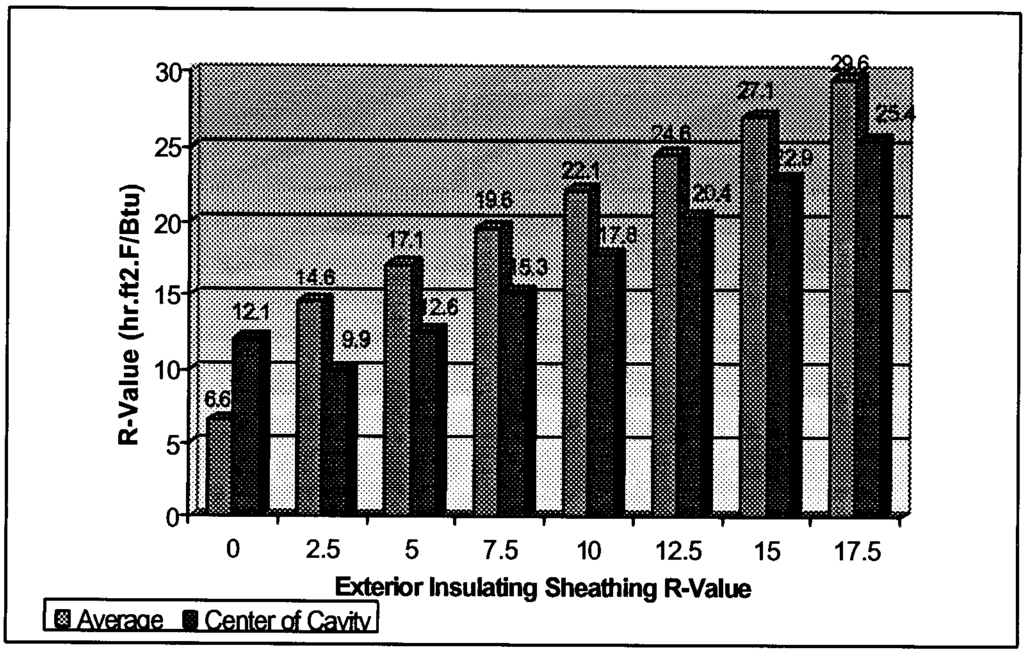

Figure 5 – Average Wall R-Value for Steel-Framed Walls with Different Levels of Exterior Insulating Sheathing

EVALUATION OF SELECTED THERMAL SOLUTIONS

Available technologies dealing with improving the thermal effectiveness of cold-formed steel framing were reviewed and grouped into five groups of options, representing several potential wall details as follows:

Frame Insulating Fitting	Thermal barriers on stud interior- or exterior-side flange under drywall, especially thin sections
Insulating Coating	Rigid insulation installed on interior or exterior side, with attention to cost and improving construction details
Stud Modification	Modified steel stud shapes, especially slotted or punched web designs
Wall System Modification	Complete wall sections that combine insulation and framing members
Structural/Insulating Panels	Use of sheathing with combined structural and insulation properties on outside of stud
Others	All others

A comprehensive review process was performed on the options listed in Table 1.

Design Option Review Process

Information on the options collected and created was summarized on a spreadsheet. The spreadsheet design allows either quantitative or qualitative input of such information as cost data, and calculates a benefit to cost ratio to help in the assessment and ranking of options. Assessment of the design options was based on:

- Approximate incremental effectiveness (R-value over base)
- Range of incremental cost (labor and materials)
- Impact on wall structural integrity
- Impact on ease of construction ("constructability")
- Suitability for various climate regions, other code issues
- Potential impact on ghosting
- Potential impact on condensation
- Other factors affecting market acceptance

Assessment of these qualities of the design options was made with respect to a "baseline" 4'X8' wall system of approximately R-7.9 overall, consisting of:

½" plywood sheathing
3 ½" 18 gauge steel framing, 24 inches on center
R-13 fiberglass batt insulation
½" gypsum board

Builders and other industry professionals were contacted for their input on the design options and their merits.

Specific information listed in the spreadsheet for each option is:

- Design option name and identification number
- Best available estimate of additional R-value over the baseline system (not the R-value of the material). The added R-value for each option was obtained from research reports, manufacturer's catalogs (where available), or finite element models.
- Whether the wall system with this option totals R-13 or greater.
- Whether the wall system with this option, plus 1" of XPS foam totals R-19 or greater.
- First cut estimates of material and labor cost premiums (cents/ft^2) over baseline, if available. The cost for each option was calculated using the 1998 RS Means.
- Total cost premium in a range of: none, low, medium, high or "value" (cost savings). These could be entered directly into the spreadsheet if quantitative data were not available. The spreadsheet translated these ranges into specific values to be used for the cost/benefit ratio.
- Thermal premium/cost premium ratio. If the cost premium is zero, disproportionately larger values of the ratio are assigned, to represent the much higher market attractiveness of the option.
- Structural impact – Positive, neutral or negative impact on structural strength with respect to the baseline system.
- Constructability impact – Impact of the option on the ease of construction, relative to the baseline system. This is intended to evaluate those construction-related factors that are not taken into account in the labor cost premium estimates. Constructability impact was done by obtaining builders' and framers input and experience.
- Condensation impact – Estimated impact of the option on the propensity toward collection of condensation inside the wall, relative to the baseline system. This judgment was not based on thermal analysis; generally, if a significant amount of insulation value was added to the outside of the wall, the option was judged to be positive in impact.
- Ghosting impact – The impact of the option on reducing the tendency of stripes to form over time on the inside surface of the wallboard. Generally, if significant insulation was added between the inside surface of the stud and the wallboard, the option was judged to have a positive impact. Analysis, comparison, research reports, or finite element models were used in determining the structural and ghosting impact.
- Zone suitability – Suitability of the wall with that option for use in either hot, cold or transitional climates, based on judgments on the clear wall R-values required for certain heating degree day climates. Note that if a wall using a particular option meets the requirements for a cold zone, for instance, it also meets (exceeds) the requirements for a transition zone or hot zone.
- Design category – The general type of design option, using the categories described above.

Using the spreadsheet and other information tools, both quantitative and qualitative information were taken into account to assess the most promising options and categories of options. Specifically, three distinct types of criteria were evaluated:

- Cost/benefit ratio (from the design option summary spreadsheet)
- Qualitative information on criteria such as constructability (from the spreadsheet and other sources)
- In what geographic zone the option, or set of options, would be suitable. An effort was made to

see that at least some options would be chosen for research that would be useful in cold geographic regions, using the criteria established in the spreadsheet.

The goal was not the selection of specific individual options which is necessary for testing phase, but rather a few select categories of options, or parts of categories, for evaluation and optimization during the analysis process. Also, options were not chosen if they were in common use and did not merit further research. For instance, the use of rigid foam insulation over outside sheathing was not chosen, since it is a common practice and it was felt that there were areas for further research that were more promising.

The results of the review process are listed in Tables 2 and 3. Two-dimensional finite element modelings were used to screen candidate assemblies prior to conducting hotbox testing. At the same time economic analysis were also conducted to determine the cost of the different approaches. The results were used to determine what wall sections will be constructed and tested in a calibrated hot box.

Rationale for Design Choices

The information on all the properties, for the selected wall sections, was put into table form to allow comparison between options. The figure of merit, "total cost premium" (as shown in Table 2) was calculated for all sections. From this data, a summary table with a narrower list of options was also developed, with a simplified system of ranking attributes (Ranked 1-5) (refer to Table 4). This facilitated easy comparison between different types of options. From observation, generalizations were made about the relative merits of the wall sections. For instance, it was judged that the most cost-effective "near wood equivalents" (neglecting constructability merit) were 1) a slit or slotted web and track; 2) 1" expanded polystyrene exterior sheathing; and 3) use of a foam cap on the flange. For an R-value of 18, the lowest cost option was use of a slit/slotted web stud with ½" exterior polyisocyanurate sheathing.

Using the above review process, four analysis topics were chosen representing the most promising research directions for thermal solutions to steel-framed wall heat transfer problems:

- Modified stud shapes & wall sections
- Wall systems using thermal tape-type configurations
- Wall systems using interior rigid foam
- Structural insulation systems

One of the most influential drivers in the choice of option groups was cost. The use of steel studs with modified shapes (slots, ridges), for instance, was not estimated to have a significant cost impact. Thermal tape has the potential for low cost, as does the use of interior foam sheets, if construction details are optimized. Structural insulation systems have the potential for actually lowering the construction cost, depending on material availability and the design, but there are many institutional and other barriers that would have to be overcome for widespread use.

Some of the groups of options chosen do not have the capability of meeting the overall clear wall R-value criteria used on their own. For example, the use of a slotted-web stud alone, according to the option summary spreadsheet, would increase the wall section thermal resistance by only R-2.0 or 2.5. However, significant potential exists for the use of multiple options ("hybrids") that together will add little or no cost, but provide significant additional R-value. For instance, the use of certain types of thermal tape along with slotted web studs could provide additional insulation of R-5 or so, with little additional cost (reference option 10 in Table 4).

Table 2 – Analysis Summary of Steel Frame Thermal Isolation Options

Option No.	Design Option/Combination	Thermal Premium (R-Value)	Wall Total of R-13	Wall Total of R-19 w/1" Foam	Material Cost Premium (cents/ft²)	Labor Cost Premium (cents/ft²)	Total Cost Premium	Thermal Premium/ Cost Premium
1	Snap-Cap (2")	7	Yes	Yes	7.5	18.0	Medium	0.2
2	Astec Ceramic Ins. Coating	0.1	No	No	0.0	50.0	Medium	0.0
3a	Double Wall Metal Track	5	Yes	No			High	0.1
3b	Double Wall Insulated Track	6	Yes	Yes			High	0.1
4	Slotted Web (Delta)	2.5	No	No	0.0	0.0	None	5.0
5a	Rigid Sheathing (1") Polystyrene	5	Yes	n/a	45.0	8.0	High	0.1
5b	Rigid Sheathing (2")	10	Yes	n/a			High	0.2
5c	Rigid Sheating (2") with lathe/glue	10	Yes	n/a			High	0.2
5d	Rigid Sheating (2") without plywood	9	Yes	n/a			High	0.1
5e	Rigid Sheathing (1") Isocyanurate	7.2	Yes	n/a			High	0.1
6	Ridged Flange	1.15	No	No	0.0	0.0	None	2.3
7	Dimpled Flange	0.6	No	No	0.0	0.0	None	1.2
8a	Circular Slot Web	2	No	No	0.0	0.0	None	4.0
8b	Circ. Slot Web w/ Sprayed Foam	3	No	No			High	0.0
8c	Circ. Slot Web w/ Ridge & Foam	5	Yes	No			High	0.1
8d	Circ. Slot Web w/ Interior Foam/Z	5.5	Yes	No			Medium	0.1
8e	Circ. Slot Web w/ Ridge & Cellulose	4	No	No			Low	0.3
8f	Circ. Slot Web w/ Thermal Tape	5	Yes	No	11.0	5.8	Low	0.4
8g	Circ. Slot Web w/ Foil-backed Wallboard	3	No	No	10.0	0.0	Low	0.2
8h	Circ. Slot Web w/ Foil-Faced Insulation	3	No	No	10.0	0.0	Low	0.2
8i	Circ. Slot Web w/ Therm Tape & Foil Insul	6	Yes	Yes	21.0	5.8	Medium	0.2
9a	Furring Strips	1	No	No			Low	0.1
9b	Furring Strips w/ foil-backed ins.	2	No	No			Medium	0.1
9c	Furring Strips w/ Urethane Foam	5	Yes	No			High	0.1

[1] Thermal premium is estimated R-value above that of a baseline steel stud wall of about R-8 (4'x8' section), using 1/2" plywood, 3 1/2" studs, R-13 fiberglass batts, 1/2" drywall.

[2] Cost premium is estimated cost of construction above baseline wall; if numerical data is shown, total cost premium is "High" if above 50 cents/ft^2, "Medium" if between 25 and 50 cents/ft^2, "Low" if below 25 cents/ft^2, "Value" if cost is less than baseline.

Table 2 – Analysis Summary of Steel Frame Thermal Isolation Options (cont.)

Option No.	Design Option/Combination	Thermal Premium (R-Value)	Wall Total of R-13	Wall Total of R-19 w/1" Foam	Material Cost Premium (cents/ft²)	Labor Cost Premium (cents/ft²)	Total Cost Premium	Thermal Premium/ Cost Premium
9d	Furring Strips w/ Spray-in Cellulose	3.5	No	No			Medium	0.1
9e	Furring Strips w/ Cellulose & Slotted Stud	5	Yes	No			Medium	0.1
9f	Furring Strips w/ Foam & Slotted Stud	8	Yes	Yes			High	0.1
9g	Furring Strips w/ EESI-Stud	4.7	No	No			Medium	0.1
10a	EESI-Stud (Tri-Chord)	3.7	No	No	2.5	5.0	Low	0.3
10b	EESI-Stud w/ Thermal Tape	6.2	Yes	Yes	13.5	10.8	Low	0.5
11a	Struct. Insul - Cellulosic Hardboard	2	No	n/a		0.0	Low	0.2
11b	Struct. Insul - CBS Sheathing (1")	6.6	Yes	n/a	50.0	0.0	Medium	0.2
11c	Struct. Insul (CBS) w/ Slotted Web	8.6	Yes	n/a	50.0	0.0	Medium	0.2
11d	Struct. Insul (CBS) w/ Slot Web & 26	9.6	Yes	n/a	50.0	0.0	Medium	0.3
11e	Struct. Insul (Celotex Thermax) w/ Slot Web	9	Yes	n/a	50.0	0.0	Medium	0.2
11f	Struct. Insul (E'NRG'Y 2 Nailboard)	6.6	Yes	n/a	50.0	0.0	Medium	0.2
12	Thermal Tape	2.5	No	No	11.0	5.8	Low	0.2
13	SuperTherm Insulating Coating	0.1	No	No	56.0	11.0	High	0.0
14	Metal/Foam Laminate Sheathing	6.6	Yes	n/a		0.0	Low	0.5
15	Foil-Backed Wallboard	1	No	No	10	0	Low	0.1
16	Offset Framing	3	No	No			High	0.0
17	Broken Web	4.5	No	No			High	0.1
18	Hybrid Stud	5	Yes	No			Medium	0.1
19a	Panelized Walls (Thermastructure)	6.1	Yes	Yes	0.0	0.0	None	12.2
19b	Panelized Wall w/ ExcelBoard less Plywood	7.8	Yes	Yes			None	15.6
20	Foamed Cement/Metal Framing	1.5	No	No			Low	0.1
21a	PVC Clip	3.4	No	No			Low	0.3

[1] Thermal premium is estimated R-value above that of a baseline steel stud wall of about R-8 (4'x8' section), using 1/2" plywood, 3 1/2" studs, R-13 fiberglass batts, 1/2" drywall.

[2] Cost premium is est'd cost of construction above baseline wall; if numerical data is shown, total cost premium is "High" if above 50 cents/ft², "Medium" if between 25 and 50 cents/ft², "Low" if below 25 cents/ft², "Value" if cost is less than baseline.

Table 2 – Analysis Summary of Steel Frame Thermal Isolation Options (cont.)

Option No.	Design Option/Combination	Thermal Premium (R-Value)	Wall Total of R-13	Wall Total of R-19 w/1" Foam	Material Cost Premium (cents/ft²)	Labor Cost Premium (cents/ft²)	Total Cost Premium	Thermal Premium/ Cost Premium
21b	PVC Clip w/ Spray-in Foam	5	Yes	No			High	0.1
21c	PVC Clip w/ Spray-in Cellulose	4	No	No			Medium	0.1
21d	PVC Clip w/ Oversized Foil-Faced Batt	5	Yes	No			Medium	0.1
22a	Insulated Drywall	7.2	Yes	Yes	50.0	0.0	Medium	0.2
22b	Insulated Drywall w/ Slotted Web	9.5	Yes	Yes	50.0	0.0	Medium	0.3
23	Spray-in Foam	1	No	No			High	0.0
24	ExcelBoard Structural Insulation	2	No	n/a	50.0	0.0	Medium	0.1
25	Diversitec Structural Insulation	4	No	n/a	30.0	0.0	Medium	0.1
26a	Fiberglass Batt w/ Foil over Flange	1	No	No	0.0	0.0	None	2.0
26b	Fiberglass Batt w/ Foil over Slotted Web	3	No	No	0.0	0.0	None	6.0
27a	Gentec Insulated Siding	3.8	No	No			Medium	0.1
27b	AmazingWall Insulated Siding	4.5	No	No			Medium	0.1
27c	TechWall Insulated Siding	4	No	No			Medium	0.1
27d	TechWall Ins. Siding w/ Batt over Flange	5	Yes	No			Medium	0.1
27e	TechWall Ins. Siding w/ Slotted Web	6	Yes	Yes			Medium	0.2
27f	TechWall Siding w/ Batt & Slotted Web	7	Yes	Yes			Medium	0.2
28a	Interior Rigid Foam w/ Z Strip	3.5	No	No			Medium	0.1
28b	Interior Rigid Foam w/ Hat Channel	3.5	No	No			Medium	0.1
28c	Inter. Rigid Foam w/ Z & Foil-Faced Insul	4.5	No	No			Medium	0.1

[1] Thermal premium is estimated R-value above that of a baseline steel stud wall of about R-8 (4'x8' section), using 1/2" plywood, 3 1/2" studs, R-13 fiberglass batts, 1/2" drywall.

[2] Cost premium is est'd cost of construction above baseline wall; if numerical data is shown, total cost premium is "High" if above 50 cents/ft², "Medium" if between 25 and 50 cents/ft², "Low" if below 25 cents/ft², "Value" if cost is less than baseline.

Table 3 – Evaluation Summary of Steel Frame Thermal Isolation Options

Option No.	Design Option/Combination	Structural Impact	Constructability Impact	Condensation Impact	Ghosting Impact	Zoning Suitability	Design Category
1	Snap-Cap (2")	Negative	Negative	Neutral	Positive	Cold	Frame Insulating Fitting
2	Astec Ceramic Ins. Coating	Neutral	Neutral	Neutral	Neutral	None	Insulating Coating
3a	Double Wall Metal Track	Negative	Neutral	Neutral	Positive	Transition	Wall System Modification
3b	Double Wall Insulated Track	Negative	Negative	Neutral	Positive	Cold	Wall System Modification
4	Slotted Web (Delta)	Neutral	Neutral	Neutral	Neutral	Hot	Stud Modification
5a	Rigid Sheathing (1") Polystyrene	Positive	Neutral	Positive	Positive	Transition	Structural/Insulating Panels
5b	Rigid Sheathing (2")	Positive	Negative	Positive	Positive	Cold	Structural/Insulating Panels
5c	Rigid Sheating (2") with lathe/glue	Positive	Negative	Positive	Positive	Cold	Structural/Insulating Panels
5d	Rigid Sheating (2") without plywood	Negative	Negative	Positive	Positive	Cold	Structural/Insulating Panels
5e	Rigid Sheathing (1") Isocyanurate	Positive	Neutral	Positive	Positive	Cold	Structural/Insulating Panels
6	Ridged Flange	Neutral	Negative	Neutral	Neutral	None	Stud Modification
7	Dimpled Flange	Neutral	Neutral	Neutral	Neutral	None	Stud Modification
8a	Circular Slot Web	Neutral	Neutral	Neutral	Neutral	Hot	Stud Modification
8b	Circ. Slot Web w/ Sprayed Foam	Positive	Neutral	Neutral	Neutral	Hot	Hybrid
8c	Circ. Slot Web w/ Ridge & Foam	Neutral	Negative	Neutral	Positive	Transition	Hybrid
8d	Circ. Slot Web w/ Interior Foam/Z	Neutral	Positive	Neutral	Positive	Cold	Hybrid
8e	Circ. Slot Web w/ Ridge & Cellulose	Neutral	Neutral	Neutral	Positive	Transition	Hybrid
8f	Circ. Slot Web w/ Thermal Tape	Neutral	Neutral	Neutral	Positive	Transition	Hybrid
8g	Circ. Slot Web w/ Foil-backed Wallboard	Neutral	Neutral	Neutral	Positive	Hot	Hybrid
8h	Circ. Slot Web w/ Foil-Faced Insulation	Neutral	Neutral	Neutral	Positive	Hot	Hybrid
8i	Circ. Slot Web w/ Therm Tape & Foil Insul	Neutral	Neutral	Neutral	Positive	Cold	Hybrid
9a	Furring Strips	Neutral	Neutral	Neutral	Positive	None	Wall System Modification
9b	Furring Strips w/ foil-backed ins.	Neutral	Neutral	Neutral	Positive	Hot	Hybrid
9c	Furring Strips w/ Urethane Foam	Positive	Neutral	Neutral	Positive	Transition	Hybrid

[1] Constructability impact is assessed based on whether significant additional time would be required to assemble framing or install utilities, which time is not accounted under labor cost.

[2] Condensation impact is generally assessed as positive if insulation value is being added to the outside of the wall.

[3] Ghosting impact is the affect the option has on wall "striping". It is assessed as positive if the option contributes at least R-3 or there is substantial insulation on the inside wall.

[4] Zone suitability indicates whether the option would render a wall suitable for use in one of three regions based on total R-value; "Cold" if total R-value of 13.5 or more, "Transition" of 11.5 - 13.5, 'Hot" if 9.5 - 11.5, "None" if less than 9.5.

Table 3 – Evaluation Summary of Steel Frame Thermal Isolation Options (cont.)

Option No.	Design Option/Combination	Structural Impact	Constructability Impact	Condensation Impact	Ghosting Impact	Zoning Suitability	Design Category
9d	Furring Strips w/ Spray-in Cellulose	Neutral	Neutral	Neutral	Positive	Transition	Hybrid
9e	Furring Strips w/ Cellulose & Slotted Stud	Neutral	Neutral	Neutral	Positive	Transition	Hybrid
9f	Furring Strips w/ Foam & Slotted Stud	Positive	Neutral	Neutral	Positive	Cold	Hybrid
9g	Furring Strips w/ EESI-Stud	Neutral	Negative	Neutral	Positive	Transition	Hybrid
10a	EESI-Stud (Tri-Chord)	Neutral	Negative	Neutral	Positive	Transition	Stud Modification
10b	EESI-Stud w/ Thermal Tape	Neutral	Negative	Neutral	Positive	Cold	Hybrid
11a	Struct. Insul - Cellulosic Hardboard	Negative	Neutral	Positive	Neutral	Hot	Structural/Insulating Panels
11b	Struct. Insul - CBS Sheathing (1")	Neutral	Neutral	Positive	Positive	Cold	Structural/Insulating Panels
11c	Struct. Insul (CBS) w/ Slotted Web	Neutral	Neutral	Positive	Positive	Cold	Hybrid
11d	Struct. Insul (CBS) w/ Slot Web & 26	Neutral	Neutral	Positive	Positive	Cold	Hybrid
11e	Struct. Insul (Celotex Thermax) w/ Slot Web	Neutral	Neutral	Positive	Positive	Cold	Hybrid
11f	Struct. Insul (E'NRG'Y 2 Nailboard)	Neutral	Neutral	Positive	Positive	Cold	Structural/Insulating Panels
12	Thermal Tape	Neutral	Neutral	Neutral	Neutral	Hot	Frame Insulating Fitting
13	SuperTherm Insulating Coating	Neutral	Neutral	Neutral	Neutral	None	Insulating Coating
14	Metal/Foam Laminate Sheathing	Neutral	Neutral	Positive	Positive	Cold	Structural/Insulating Panels
15	Foil-Backed Wallboard	Neutral	Neutral	Neutral	Neutral	None	Other - Rad/Conducting Coat
16	Offset Framing	0.0	Neutral	Neutral	Neutral	Positive	Hot
17	Broken Web	0.1	Negative	Neutral	Neutral	Positive	Transition
18	Hybrid Stud	0.1	Neutral	Neutral	Neutral	Positive	Transition
19a	Panelized Walls (Thermastructure)	12.2	Neutral	Negative	Positive	Positive	Cold
19b	Panelized Wall w/ ExcelBoard less Plywood	15.6	Neutral	Negative	Positive	Positive	Cold
20	Foamed Cement/Metal Framing	0.1	Neutral	Neutral	Neutral	Neutral	Hot
21a	PVC Clip	0.3	Neutral	Negative	Neutral	Positive	Hot
21b	PVC Clip w/ Spray-in Foam	0.1	Neutral	Negative	Neutral	Positive	Transition
21c	PVC Clip w/ Spray-in Cellulose	0.1	Neutral	Negative	Neutral	Positive	Transition

[1] Constructability impact is assessed based on whether significant additional time would be required to assemble framing or install utilities, which time is not accounted under labor cost.

[2] Condensation impact is generally assessed as positive if insulation value is being added to the outside of the wall.

[3] Ghosting impact is the affect the option has on wall "striping". It is assessed as positive if the option contributes at least R-3 or there is substantial insulation on the inside wall.

[4] Zone suitability indicates whether the option would render a wall suitable for use in one of three regions based on total R-value; "Cold" if total R-value of 13.5 or more, "Transition" of 11.5 - 13.5, "Hot" if 9.5 - 11.5, "None" if less than 9.5.

Table 3 – Evaluation Summary of Steel Frame Thermal Isolation Options (cont.)

Option No.	Design Option/Combination	Structural Impact	Constructability Impact	Condensation Impact	Ghosting Impact	Zoning Suitability	Design Category
21d	PVC Clip w/ Oversized Foil-Faced Batt	0.1	Neutral	Negative	Neutral	Positive	Transition
22a	Insulated Drywall	0.2	Neutral	Negative	Neutral	Positive	Cold
22b	Insulated Drywall w/ Slotted Web	0.3	Neutral	Negative	Neutral	Positive	Cold
23	Spray-in Foam	0.0	Positive	Neutral	Neutral	Neutral	None
24	ExcelBoard Structural Insulation	0.1	Negative	Neutral	Positive	Positive	Hot
25	Diversitec Structural Insulation	0.1	Neutral	Neutral	Positive	Positive	Transition
26a	Fiberglass Batt w/ Foil over Flange	2.0	Neutral	Neutral	Neutral	Positive	None
26b	Fiberglass Batt w/ Foil over Slotted Web	6.0	Neutral	Neutral	Neutral	Positive	Hot
27a	Gentec Insulated Siding	0.1	Neutral	Neutral	Positive	Positive	Transition
27b	AmazingWall Insulated Siding	0.1	Neutral	Neutral	Positive	Positive	Transition
27c	TechWall Insulated Siding	0.1	Neutral	Neutral	Positive	Positive	Transition
27d	TechWall Ins. Siding w/ Batt over Flange	0.1	Neutral	Neutral	Positive	Positive	Transition
27e	TechWall Ins. Siding w/ Slotted Web	0.2	Neutral	Neutral	Positive	Positive	Cold
27f	TechWall Siding w/ Batt & Slotted Web	0.2	Neutral	Neutral	Positive	Positive	Cold
28a	Interior Rigid Foam w/ Z Strip	0.1	Neutral	Positive	Neutral	Positive	Transition
28b	Interior Rigid Foam w/ Hat Channel	0.1	Neutral	Positive	Neutral	Positive	Transition
28c	Inter. Rigid Foam w/ Z & Foil-Faced Insul	0.1	Neutral	Positive	Neutral	Positive	Transition

[1] Constructability impact is assessed based on whether significant additional time would be required to assemble framing or install utilities, which time is not accounted under labor cost.

[2] Condensation impact is generally assessed as positive if insulation value is being added to the outside of the wall.

[3] Ghosting impact is the affect the option has on wall "striping". It is assessed as positive if the option contributes at least R-3 or there is substantial insulation on the inside wall.

[4] Zone suitability indicates whether the option would render a wall suitable for use in one of three regions based on total R-value; "Cold" if total R-value of 13.5 or more, "Transition" of 11.5 - 13.5, "Hot" if 9.5 - 11.5, "None" if less than 9.5.

Table 4 - Steel Frame, Whole Wall Thermal Isolation Design Options Assignment List

Option	Wall Construction	Thermal	Structural	Cost	Constructability	Manufacturing/ Risk	Average
1	1" Extruded Polystyrene Sheathing (XPS) Outside	4	3	2	2	5	3.2
2	2" Foam Cap	4	3	3	2	5	3.4
3	1/4" Fanfold Insulation on Flange	1	4	2	4	5	3.2
4	1/4" Foam Tape (R-3) on Flange	2	4	3	4	3	3.2
5	Slit Web Stud and Track (9 Row)	2	2	4	5	4	3.4
6	Slit Web Stud and Track, 50 ksi, 33 mil	2	4	5	5	3	3.8
7	Slit Web Stud & Track, 1 3/4" Flange, 5/8" Lip	2	4	4	5	3	3.6
8	Slit Web Stud & Track, 1 3/4" Flange, 5/8" Lip, 40 ksi	2	5	4	5	3	3.8
9	Slit Web Stud & Track, 1 3/4" Flange, 5/8" Lip, 50 ksi	2	5	4	5	3	3.8
10	Slit Web Stud and Track, 50 ksi, 33 mil + 1/2" Polyiso	5	4	2	4	3	3.6
11	Extruded Slot Stud/Track (7 Row)	2	4	4	4	2	3.2
12	Extruded Slot Stud/Track + Foam Tape	3	4	3	4	2	3.2
13	Extruded Slot Stud/Track + 1/2" Polyiso Sheathing	5	4	2	4	2	3.4
14	Extruded Slot Stud/ Track, 40 ksi + 1/2" Polyiso	5	5	2	4	2	3.6
15	1" Expanded Polystyrene Sheathing (EPS) Inside	2	4	1	1	5	2.6
16	CBS Board (Reinforced 1/2" Polyiso)	4	2	3	4	3	3.2

Notes:

1) 1 indicates "Worst"; 5 indicates "Best".

2) All walls 2x4, 24"o.c., 33 ksi, 43 mil, unless otherwise noted

3) Averages are calculated based on an even weighting of all attributes

4) R-values in thermal column range from about R-9.7 to R-17.4

ANALYSIS OF THERMAL OPTIONS SELECTED

Each of the four areas described in the previous section involved analyses tailored, both in their content and depth, to the type of option and its unique requirements. Although the focus of the investigations was on practical solutions, attention was paid to potential longer-term opportunities.

Analysis of Modified Stud Shapes and Wall Sections

A lot of emphasis was put on the analysis of modified stud shapes. Such modifications as slotted webs and modified flanges were covered, with an emphasis on those changes that would maintain or reduce price and enhance constructability. The research can be divided into three areas:

- Thermal evaluation of modified stud configurations. First, the thermal properties of steel studs alone – that is, not as part of a built-up wall – were evaluated using three-dimension finite element analysis (3-D FEA). Analysis of both existing and new designs were covered, including such modifications as slotted web designs, ridged flanges and dimpled flanges.
- Limited thermal, structural and cost optimization of selected modified studs. Promising designs from the above thermal work was examined to look for ways to simultaneously optimize thermal and structural properties, using FEA and other tools.
- Thermal and cost optimization of wall systems with modified studs, using 2D FEA, cost & constructability guidelines. The most attractive stud designs were evaluated in a number of configurations with other mitigation options in clear wall cross-sections.

Analysis of Thermal Tape-Type Wall Sections

Flexible, adhesive-backed, high-resistivity foam tapes that can be applied to the stud flanges were the focus of this analysis. However, other similar promising insulating systems, such as the application of strips of foam to flanges, were also investigated. There were two areas of research:

- Collection of thermal property data on newly developed materials. Some thermal tapes now under development were investigated, and other potential materials researched.

- Thermal and cost optimization of wall systems with thermal tape, using 2-D FEA, as well as cost and constructability guidelines.

Analysis of Interior Rigid Foam Wall Sections

Wall systems using rigid foam sheets and various installation configurations were investigated. The emphasis was on inexpensive materials and modifications to the systems and installation techniques that have the potential to reduce overall building cost or enhance constructability. The work involved thermal and cost optimization of wall systems using two-dimensional finite element analysis, cost & constructability guidelines.

Analysis of Structural Insulation Systems

Outside sheathing systems that carry both structural and insulating properties in one product have the potential to eliminate thermal concerns without significant cost or constructability impact. The evaluation of structural systems was composed of two subtasks:

- Limited thermal, structural and cost optimization of structural insulated sheathing systems (Evaluation was of the sheathing itself rather than wall cross-sections.) Products that are currently commercially available were evaluated, and a limited amount of analysis on potential new products performed.
- Thermal and cost optimization of wall systems with structural insulation, using 2-D FEA, cost & constructability guidelines. Wall cross-sections were analyzed, using the most promising sheathing products investigated above.

Table 5 contains a summary of the results of the analysis of the thermal options considered above.

Table 5 - Summary of Steel Wall Thermal Isolation Design Options

Option No.	Design Option/Combination	R-Value of Wall	R-Value w/1" XPS Foam	Material Cost ($/Wall)	Labor Cost ($/Wall)	Total Cost ($/Wall)	Added Cost per R-Value	Constructability Impact	Zone Suitability
1	Baseline Wood 2x4. 24"o.c.	12.7	18.7	$51.16	$65.70	$116.86	n/a	Small	Transition
2	Baseline Steel 350S162-43, 24"o.c.	8.0	14.0	$77.06	$81.76	$158.82	n/a	Small	None
3	1/2" EPS on Exterior	11.0	n/a	$83.72	$99.49	$183.21	8.1	None	Hot
4	1" EPS on Exterior	13.3	n/a	$89.20	$99.49	$188.69	5.6	None	Transition
5	2" EPS on Exterior	18.5	n/a	$100.12	$101.26	$201.38	4.1	None	Cold
6	1/2" XPS on Exterior	12.1	n/a	$92.19	$99.49	$191.68	8.0	None	Transition
7	1" XPS on Exterior	14.4	n/a	$95.14	$99.49	$194.63	5.6	None	Cold
8	2" XPS on Exterior	19.6	n/a	$113.03	$101.26	$214.29	4.8	None	Cold
9	1/2" Polyisocyanurate on Exterior	14.2	n/a	$91.17	$99.49	$190.66	5.1	None	Cold
10	1" Polyisocyanurate on Exterior	16.5	n/a	$102.56	$99.49	$202.05	5.1	None	Cold
11	2" Polyisocyanurate on Exterior	21.7	n/a	$120.19	$101.26	$221.45	4.6	None	Cold
12	2" Foam Cap on Exterior	15.3	21.3	$91.06	$90.90	$181.96	3.2	None	Cold
13	1/4" Fanfold on Interior	9.7	15.7	$78.22	$109.46	$187.68	17.0	Small	Hot
14	R-2 Foam Tape on Interior	10.2	16.2	$85.46	$97.79	$183.25	11.1	Small	Hot
15	R-3 Foam Tape on Interior	10.9	16.9	$85.46	$97.79	$183.25	8.4	None	Hot
16	R-5 Foam Tape on Interior	11.4	17.4	$85.46	$97.79	$183.25	7.2	None	Hot
17	Slit Web Stud, 3" 6 row slits, 4" solid end	10.2	16.2	$77.06	$81.76	$158.82	0.0	None	Hot
18	Slit Web Stud, 3" 9 row slits, 4" solid end	10.4	16.4	$77.06	$81.76	$158.82	0.0	None	Hot
19	Slit Web Stud, 3" 6 row slits, 2" solid end, 40ksi	10.5	16.5	$77.06	$81.76	$158.82	0.0	None	Hot
20	Slit Web Stud, 3" 9 row slits, 2" solid end, 40ksi	10.8	16.8	$77.06	$81.76	$158.82	0.0	None	Hot
21	Slit Web Stud & Track, 3" 9 row slits, 2" end,40ksi	11.7	17.7	$77.06	$81.76	$158.82	0.0	None	Transition
22	Slit Web Stud, 3" 9 row slits, 2" solid end, 50 ksi	10.8	16.8	$78.61	$81.76	$160.37	0.6	None	Hot
23	Slotted Web Stud, 3", 7 row, 2" solid end	10.6	16.6	$77.06	$81.76	$158.82	0.0	None	Hot
24	Slotted Web Stud, 3" 7 row, 2" solid end , 40ksi	10.6	16.6	$77.06	$81.76	$158.82	0.0	None	Hot
25	Slotted Web Stud, 4" 7 row, 2" solid end , 40ksi	10.8	16.8	$77.06	$81.76	$158.82	0.0	Small	Hot
26	Slotted Web Stud, 3" 7 row, 2" end, 40ksi, 33mil	10.9	16.9	$69.12	$75.13	$144.25	-5.0	Small	Hot
27	Slotted Web Stud, 4" 7 row, 2" end, 40ksi, 33mil	11.1	17.1	$69.12	$75.13	$144.25	-4.7	None	Hot

[1] Baseline steel stud wall is 8'x8' section using 1/2" plywood, 3 1/2" studs, R-13 fiberglass batts, 1/2" drywall.

[2] Constructability impact is assessed based on whether significant additional time would be required to assemble framing or install utilities, which time is not accounted under labor cost.

[3] Zone suitability indicates whether the option would render a wall suitable for use in one of three regions based on total R-value; "Cold" if total R-value of 13.5 or more, "Transition" of 11.5 - 13.5, "Hot" if 9.5 - 11.5, "None" if less than 9.5.

Table 5 - Summary of Steel Frame Thermal Isolation Options (cont.)

Option No.	Design Option/Combination	R-Value of Wall	R-Value w/1" XPS Foam	Material Cost ($/Wall)	Labor Cost ($/Wall)	Total Cost ($/Wall)	Added Cost per R-Value	Constructability Impact	Zone Suitability
28	Slotted Web/Slit Track, 3", 7 row, 2" end	11.6	17.6	$77.06	$81.76	$158.82	0.0	None	Transition
29	Slit Web #21 with R-2 Foam Tape	12.4	18.4	$85.43	$97.79	$183.22	5.5	Small	Transition
30	Slit Web #21 with R-3 Foam Tape	12.7	18.7	$85.43	$97.79	$183.22	5.2	Small	Transition
31	Slit Web #21 with 1/4" Fanfold	12.0	18.0	$78.22	$109.46	$187.68	7.2	Small	Transition
32	Slotted Web #28 with R-2 Foam Tape	12.3	18.3	$85.43	$97.79	$183.22	5.7	Small	Transition
33	Slotted Web #28 with R-3 Foam Tape	12.6	18.6	$85.43	$97.79	$183.22	5.3	Small	Transition
34	Slit Web#21 with 1/2" Polyiso on Exterior	17.5	n/a	$91.17	$99.49	$190.66	3.4	Small	Cold
35	Slit Web #21 with 1" XPS on Exterior	17.7	n/a	$95.14	$99.49	$194.63	3.7	Moderate	Cold
36	Slotted Web #28 with 1/2" Polyiso on Exterior	17.4	n/a	$91.17	$99.49	$190.66	3.4	Small	Cold
37	Slotted Web #28 with 1" XPS on Exterior	17.6	n/a	$95.14	$99.49	$194.63	3.7	Moderate	Cold
38	Slotted Web #28 w/ 1" XPS (5% steel premium)	17.6	n/a	$96.69	$99.49	$196.18	3.9	Moderate	Cold
39	Slit Web #21 w/ R-2 Tape and 1/2" Polyiso	18.2	n/a	$99.57	$115.52	$215.09	5.5	Moderate	Cold
40	Slit Web #21 w R-2 Tape and 1" XPS	18.4	n/a	$103.54	$115.52	$219.06	5.8	Moderate	Cold
41	Slotted Web #28 w/ R-2 Tape and 1/2" Polyiso	18.1	n/a	$99.57	$115.52	$215.09	5.6	Moderate	Cold
42	Slotted Web #28 w/ R-2 Tape and 1" XPS	18.3	n/a	$103.54	$115.52	$219.06	5.8	Moderate	Cold
43	20 ga., 50 ksi stud w/ 1" XPS (5% steel premium)	14.8	n/a	$88.38	$92.86	$181.24	3.3	Moderate	Cold
44	20 ga 50 ksi slit web #21 w/ 1" XPS	18.0	n/a	$88.38	$92.86	$181.24	2.2	Moderate	Cold
45	Slit web #21 with 3/4" lip (5% steel premium)	11.6	17.6	$78.61	$81.76	$160.37	0.4	None	Transition
46	Slit web #21 with 1 3/4" flange and 5/8" lip	11.6	17.6	$78.61	$81.76	$160.37	0.4	None	Transition
47	Slit web #21 with 1/4" added lip	11.6	17.6	$78.61	$81.76	$160.37	0.4	None	Transition
48	Slit web #21 w/ 1 3/4" flange and 1/8" added lip	11.6	17.6	$78.61	$81.76	$160.37	0.4	None	Transition
49	Slit web #21 with 1 3/4" flange, 5/8" lip, 50 ksi	11.6	17.6	$80.16	$81.76	$161.92	0.9	None	Transition
50	Slit web #21, 50 ksi, 33 mil, 1/2" CBS sheathing	17.2	n/a	$83.91	$93.82	$177.73	2.1	Small	Cold

[1] Baseline steel stud wall is 8'x8' section using 1/2" plywood, 3 1/2" studs, R-13 fiberglass batts, 1/2" drywall.

[2] Constructability impact is assessed based on whether significant additional time would be required to assemble framing or install utilities, which time is not accounted under labor cost.

[3] Zone suitability indicates whether the option would render a wall suitable for use in one of three regions based on total R-value; "Cold" if total R-value of 13.5 or more, "Transition" of 11.5 - 13.5, "Hot" if 9.5 - 11.5, "None" if less than 9.5.

SELECTION OF POTENTIAL THERMAL SOLUTION

A number of steel studs with modified webs were evaluated thermally using Finite Element Analysis (FEA). The analysis included both the evaluation of several broad categories of web modifications, and evaluation of specific designs, some of which are commercially available. The conclusion based on modeling is that the most thermally effective designs use thin (high ratio of length to width) slots, staggered along the width of the stud, to lengthen the thermal path. Stud webs of this design have been modeled as reducing heat transfer by 90% or more (refer to Table 6).

Overall wall sections, comprised of standard studs, modified studs, thermal tape, and other components were also evaluated using Finite Element Analysis (FEA) and spreadsheet analysis. This has:

a) Enabled an evaluation of the most effective options,
b) Indicated the upper limits of the thermal effects of a given option on overall wall R-value, and
c) Indicated what level of component performance is required in order to meet desired overall wall R-values. For instance, a steel stud web with 90% reduced conductivity has been modeled as resulting in a wall section, given certain assumptions, with an R-value comparable to that of a wood-framed wall. Similarly, a thin thermal break between the stud flange and drywall with an R-value of 3 is modeled as being approximately equivalent to a wood-framed wall. Examination of the results of the hot box tests will allow confirmation and/or adjustment of the modeling results

Cost spreadsheets were constructed to evaluate and rank the costs of various wall sections. Lacking definitive information regarding the cost to manufacture new slotted web stud designs, certain assumptions were made to estimate the cost premiums for modified steel studs. Evaluations of wall section options were also made, or refined, in terms of how they affected aspects of house construction not accounted for directly in the cost spreadsheets, and what the potential manufacturing implications would be. Table 6 summarizes the results of the thermal modeling of the slit-web stud option with variable number of slits and size. The R-value for each option was determined using a finite element model.

Table 6 - Thermal FEA Buildup for Slotted Web Studs

No.	Stud Type	Stud End Btu/sec-in²	Stud Middle Btu/sec-in²	Stud Utility Hole Btu/sec-in²	Stud Overall Btu/sec-in²	% Thermal Reduction Over Solid
1	Baseline solid web	0.00957	0.00957	none	0.00957	0.0%
2	Slit web 3", 6 row, solid center, 4" solid end	0.003051	0.0007223	0.0006816	0.001491326	84.4%
3	Slit web 3", 6 row, solid center, 2" solid end	0.002073	0.0007223	0.0006816	0.001165326	87.8%
4	Slit web 3", 9 row, slit center, 4" solid end	0.00957	0.0004117	0.0006816	0.001222686	87.2%
5	Slit web 3", 9 row, slit center, 2" solid end	0.00957	0.0004117	0.0006816	0.000841091	91.2%
6	Slit web 3", 11 row, slit center, 4" solid end	0.00957	0.0002737	0.0004278	0.00107568	88.8%
7	Slit web 3", 11 row, slit center, 2" solid end	0.00957	0.0002737	0.0004278	0.00068833	92.8%
8	Slit web 3", 8 row, solid center, 4" solid end	0.00957	0.0004281	0.0004278	0.00118987	87.6%
9	Slit web 3", 8 row, solid center, 2" solid end	0.00957	0.0004281	0.0004278	0.00080896	91.5%
10	Slit web 4", 11 row, slit center, 4" solid end	0.00957	0.0001544	0.0002465	0.00095918	90.0%
11	Slit web 4", 11 row, slit center, 2" solid end	0.00957	0.0001544	0.0002465	0.00056686	94.1%
12	Slot web 4", 7 row, slit center, 4" solid end	0.00957	0.000315	0.0005534	0.0011384	88.1%
13	Slot web 4", 7 row, slit center, 2" solid end	0.00957	0.000315	0.0005534	0.00075278	92.1%
14	Slot web 4.5", 7 row, slit ctr, 4" solid end	0.00957	0.0002532	0.000402	0.00106525	88.9%
15	Slot web 4.5", 7 row, slit ctr, 2" solid end	0.00957	0.0002532	0.000402	0.00067705	92.9%
16	Slot web 4.5", 7 row, slit ctr, 1.5" solid end	0.00957	0.0002532	0.000402	0.00058	93.9%
17	Slot web 4", 9 row, full width slits,4" sol end	0.00957	0.0002135	0.0003107	0.00101447	89.4%
18	Slot web 4", 9 row, full width slits,2" sol end	0.00957	0.0002135	0.0003107	0.00062462	93.5%
19	Slot web 4", 5 row, full width slits,2" sol end	0.00957	0.0006532	0.0006930	0.00103346	89.2%
20	Slot web 4", 5 row, mods for mfg	0.00219	0.0007667	0.0007384	0.00093059	90.3%
21	5.5" Reinf slot 3", 9 row, mods for mfg	0.00347	0.0004691	0.0004811	0.00085084	91.1%
22	5.5" Reinf slot 3.5", 9 row, mods for mfg	0.00320	0.0003130	0.0003244	0.00068008	92.9%

EXPERIMENTAL APPROACH

Based on the evaluation and analysis of the information developed on the wall sections, an initial set of ten thermal hot box tests were chosen, to verify the estimated R-values. The tests, conducted cover the following types of wall sections:

- Baseline steel wall
- Steel wall with a high-R foam tape
- Steel walls with "knife slit" shapes in stud webs
- Steel walls with a newly developed "extruded slot" pattern in the stud webs
- Steel walls with 5 ½" and 3 ½" stud widths
- Combinations of the above options, including use of thin exterior rigid foam sheathing

After the test results of the initial ten wall assemblies were evaluated, a revised slit-web stud was developed and a prototype was fabricated. Twelve additional wall assemblies utilizing the refined slit-web stud were tested in the hotbox apparatus. The two phases of testing are summarized below:

Phase I: Testing of ten wall assemblies using the Lindab slit-web stud. The stud configuration used for testing (Lindab slit-web stud) offered the needed reduction in thermal conductivity for a potential thermal solution. Fabrication of such a stud was costly, and therefore, the Lindab stud was used to obtain an initial assessment of the estimated R-value of the steel wall.

Phase II: Testing of 12 wall assemblies using a refined slit-web stud. The stud used in Phase I was refined to improve its structural characteristics (strength) as the slit web stud with slits similar to those of the Lindab stud were reported to have a reduced axial strength of nearly 50% when compared to a solid web stud [6].

Test Apparatus and Test Method

Testing was conducted at Oak Ridge National Laboratory (ORNL). The test assemblies were tested in accordance with ASTM C 1363-97 [2], "Steady-State Thermal Performance of Building Assemblies by Means of a Guarded Hot Box" using the Oak Ridge National Laboratory Rotatable Guarded Hot Box (RGHB).

The test assemblies were installed into a specimen frame, which is mounted on a moveable dolly. The specimen frame has an aperture of 13-ft long by 10-ft high. The specimen frame/test assembly is inserted between two chambers of identical cross-section. The insertion of the test wall assembly between the chambers allows the chamber temperatures to be independently controlled. These chambers are designated as the climate (cold) and metering/guard (hot) chambers. A photograph, schematic of the RGHB and cross section of the RGB frame are shown in Figures 6, 7, and 8 respectively.

In the climate chamber, a full-size baffle is mounted approximately 10 in. from the test specimen assembly. Temperature control in this chamber is accomplished by the insertion of a refrigeration system and electrical resistance heaters in series with an array of air blowers. The external refrigeration system is operated continuously and cooled air is transferred from the refrigeration system through insulated flexible ducting into the rear of the climate chamber behind the baffle. Five centrifugal air blowers, installed in the climate chamber behind the baffle, are used to circulate the air through a bank of electrical resistance heaters and through the airspace between the baffle and test specimen assembly. Temperature control is accomplished by overcooling the air stream entering the climate chamber and then reheating this air stream with resistance heaters. The air velocity parallel to the climate side of the test specimen assembly is controlled by adjusting the input frequency to the air blowers. An anemometer continuously measures the wind speed in the airspace.

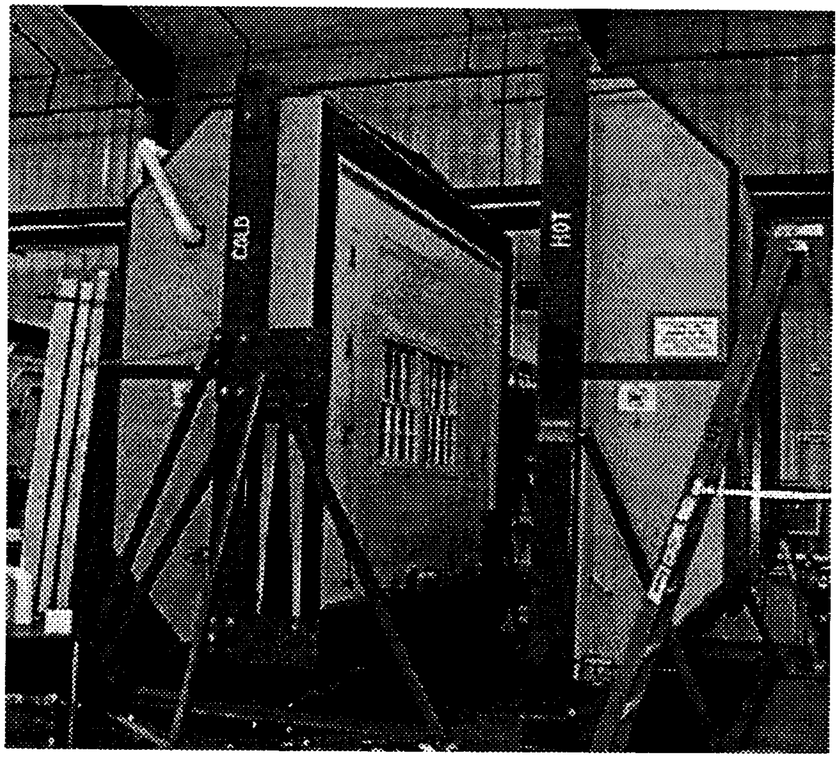

Figure 6 - Rotatable Guarded Hot Box

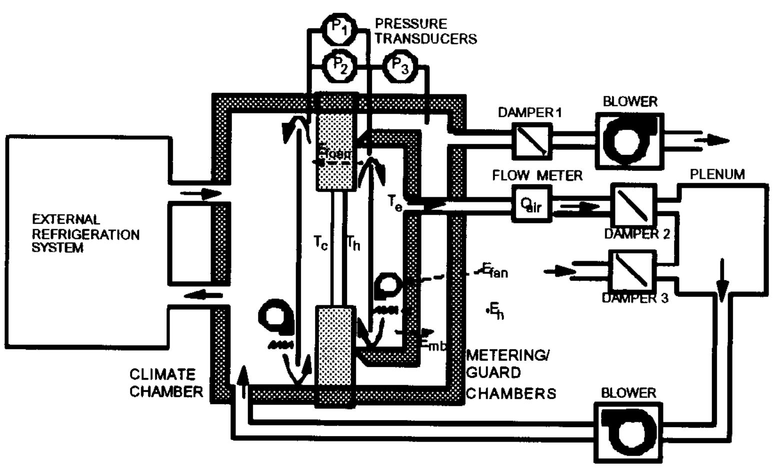

Figure 7 - Schematic of Rotatable Guarded Hot Box

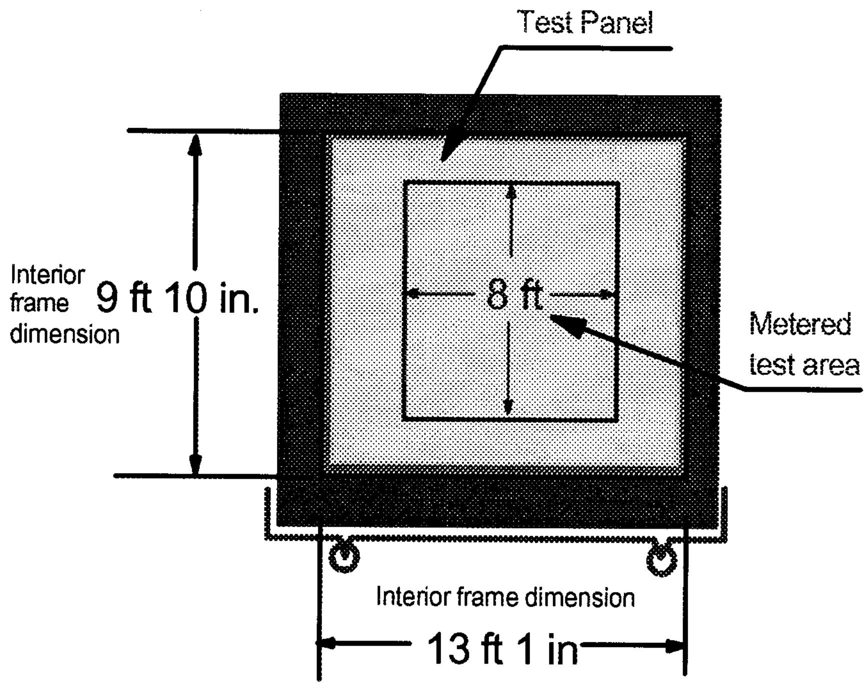

Figure 8 - Cross Section of RGHB Frame

In the center of the metering/guard chamber, a metering box is pressed against the test specimen assembly. The metering chamber is approximately 8-ft square by 1.3-ft deep. The walls of the metering chamber are constructed with 3-in. thick aged extruded polystyrene foam having an approximate thermal resistance of 15 hr•ft^2°F/Btu at 75° F. The walls of the metering box are reinforced with aluminum frames on the interior and exterior sides and are interconnected with fiberglass threaded rods. The edge of the metering chamber which contacts the test assembly is tapered to a thickness of 0.75-in. and a 0.5-in. square neoprene rubber gasket is affixed to this tapered edge. A baffle is mounted inside the metering box 6-in. from the exposed edge of the gasket. Behind the baffle, an array of eight fans and four electric resistance heaters is installed. These fans force air upward behind the baffle, through the resistance heaters, and downward through the airspace between the baffle and test assembly. The upper and lower rear corners of the metering box are tapered to minimize air impingement onto the metering box walls and to provide a smooth transition into the baffle space.

The guard box has four heaters and six fans that heat and circulate the air around the outside of the metering box. These heaters and fans are situated to achieve uniform temperatures throughout the guard box and not allow air to impinge directly onto the metering chamber.

A 96 junction (48 pair) differential thermopile is applied on the interior and exterior walls of the metering chamber to sense the temperature imbalance between the metering and guard chambers. Each thermopile junction is mounted in the center of one of the 48 equal areas into which the metering chamber is divided. The interior thermopile junction is mounted directly opposite the corresponding exterior junction. Additional arrays of temperature sensors are affixed to both the meter-side and climate-side surfaces of the foam panel surrounding the test specimen in the area covered by the metering chamber. All of the thermocouples that are attached to the surface of the foam are affixed with duct tape.

All temperature measurements were performed using Type T copper/constantan thermocouples calibrated to the special limits of error specified in ASTM E 230 [7]. All thermocouples were fabricated with No. 26 AWG (American Wire Gage) wire prepared from the same spool of wire.

Three differential pressure transducers were installed in the RGHB. Two of the transducers, P1 and P2, measure the pressure difference across the test assembly. These two transducers have different pressure ranges. The third transducer, P3, monitors the pressure difference between the metering and guard chambers.

In operation, the temperature of the climate chamber is set at the desired level. Separate programmable D.C. power supplies in conjunction with a temperature controller are used to energize and control the metering chamber heaters and fans. The power to the fans is adjusted to set the desired wind speed in the airspace between the baffle and the test wall assembly. An anemometer is used to monitor this wind speed. The power to the metering chamber heaters is adjusted to obtain the required metering chamber temperature. The output of the differential thermopile is used to energize the heaters in the guard chamber by using a differential temperature controller. By this technique, the temperature difference across the metering box walls is minimized, thereby permitting negligible heat leaks between the metering and guard chambers.

When an experiment requires air leakage, the blower connected to the metering chamber is energized, and the pressure difference across the test assembly is controlled by either adjusting the damper or the speed of the blower. The blower connected to the guard chamber is adjusted to minimize the pressure difference between the metering and guard chambers and thus the air leakage either through the metering chamber wall or past the seal between this chamber and the test assembly. Conditions are maintained until temperatures, heat flows, and pressure differences equilibrate. The heat flow generated by the metering chamber heaters is calculated from the voltage and current measurements taken from a precision shunt resistor. The energy dissipated by the metering chamber fans is metered with a precision resistor network. Once steady-state conditions have been achieved, the test period is continued until three successive four-hour periods produce results that vary non-monotonically by less than 1 percent. The data for each period is the average of one-minute scans for that period.

To verify the performance of the rotatable guarded hot box, a series of five verification experiments was performed on a homogeneous panel comprised of a 5-in. thick expanded polystyrene foam core faced on both sides with 0.12-in. high impact polystyrene sheet. In these experiments, the test conditions (temperatures of the metering and climate chambers) and the differential thermopile settings were varied. These experiments were performed to assess how closely we needed to maintain the null balance of the thermopile and to determine the precision of the RGHB. The metering chamber input heat flow is corrected for any losses through the metering chamber walls to determine the specimen heat flow. At mean temperatures of 50 and 75° F, the differential thermopile bias correction yields R-values that are within 0.05 and 0.02 hr•ft^2°F/Btu of the average values, respectively. To obtain a 10 Btu/hr bias from the metering chamber requires a 1.5° F temperature imbalance across the metering chamber walls.

Specimens of the EPS foam used to fabricate the verification panel were tested at Oak Ridge National Laboratory. The testing was done to determine the thermal resistance of the specimens in accordance with ASTM C 518-98 [8]. ASHRAE Handbook of Fundamentals [9] value for the thermal resistance of the polystyrene sheet (0.36 hrft^2°F/Btu) was used. Adding this thermal resistance to the R-value of the EPS foam, the R-value vs. temperature for the specimens of the verification panel was determined. These data were linearly regressed and compared to the data compiled in the RGHB.

The test results generated between the two test apparatus were in agreement; all five of the ASTM C 236 (Standard replaced by C1363) [10][3] experiments performed in the RGHB are within ± 0.2% of the ASTM C 518 results from the heat flow meter apparatus. Even if the thermal resistance of the polystyrene sheets estimate was in error by 50%, the results from the two procedures would still agree to within 1.1%. The need to estimate the R-value of the polystyrene sheets does not appreciably compromise the results that are presented.

Test Specimen

The specimen walls for both series of tests (phase I and phase II) were built and constructed at the NAHB Research Center laboratory. All test walls measured 96-in. x 96-in. Each assembled wall was positioned in the test frame such that the wall was centered both vertically and horizontally over the metering chamber opening. The area surrounding the test wall panel was filled with a thermally resistive foam insulation material, expanded polystyrene (EPS) and/or extruded polystyrene (XPS), to the same thickness as the tested wall. Excess polyisocyanurate was also used as fill material in the surround panel on some of the test walls. Since the surround is not part of the metered area, the type of insulation material used is inconsequential to the test results.

The R-13 batts used in the steel walls were Kraft paper faced while the R-19 batts were unfaced. To compensate for the lack of vapor barrier in the R-19 walls, polyethylene sheathing was applied between the insulation and the OSB. The drywall and OSB materials were fastened to the framing using standard No. 8 drywall and OSB screws, respectively. The screws were spaced at 6in. intervals around the perimeter of the wall and at 12-in. intervals on the center studs.

Phase I Tests

A summary of the tested wall configuration is shown in Tables 7 and 8.

The fiberglass batts were carefully installed in the cavities to minimize gaps between the insulation and the stud/track interface. The insulation used on the 35S162-33 framed walls was Kraft paper faced and the seams were taped with masking tape to provide a tighter air barrier. The insulation used on the 550S162-33 framed walls was unfaced and a continuous polyethylene sheathing vapor barrier was used on the warm side. This barrier covered the entire surface of the test wall and was taped to prevent air leakage through the specimen. The Tuff-R® polyisocyanurate insulation used on the exterior of the OSB in tests 6 and 8 was attached with building adhesive and roofing nails. The roofing nails were primarily used to assure good thermal contact with the OSB surface and to secure the insulation while the adhesive was curing. The Tuff-R® exterior sheathing was also taped around the perimeter to prevent air leakage between the sheathing and the OSB. In the tests using the exterior sheathing, the thermocouple array on the exterior of the OSB was moved to the exterior of the sheathing and four additional thermocouples were installed between the Tuff-R® and the OSB.

Because of the increase in cavity depth after addition of the foam tape between framing and the exterior OSB sheathing, the R-13 fiberglass batt was tested at two thicknesses, 3.44 inch and 3.56 inch. It was assumed that the batt would expand into the slightly deeper cavity created by adding the foam tape. The foam tape was supplied in a roll and was approximately 0.25 inch thick by 1.15 inch wide. This made it difficult to determine the R-value with the ASTM C518 test. The thickness of the foam tape used in tests 2 and 4 was compressed to approximately 0.125 inches after the OSB was screwed into place, hence the 3.44 inch original cavity and the 3.56 inch expanded cavity. Because of the difficulty in measuring the R-value of the tape, comparable material was obtained in the form of 0.588-inch thick sheet. This material was tested by the ASTM C518 method at its original thickness and then was compressed as much as possible between two nominal 0.5-inch thick plywood squares and retested. The plywood was also tested separately. The foam R-value was then calculated by subtracting the value of the two layers of plywood from the total sandwich value. The results are inconclusive as to whether this method of backing out the R-value for the compressed foam is representative of the foam tape actually used in the tests. Tuff-R polyisocyanurate was used for both the additional sheathing and the rigid foam strips between the metal framing and exterior OSB in tests 5, 6, and 8. The expanded polystyrene (EPS) and extruded polystyrene (XPS) were both used for the surround panel fill material needed to make up the difference between the test wall area and the metering box cross sectional face area.

Because of the difficulty in maintaining a constant wall surface temperature across multiple test walls with varying surface and interior configurations, the controllers were adjusted to maintain constant air temperatures in the metering and climate chambers at 100°F and 50°F, respectively. Figure 9 shows the warm side (gypsum board) of one of the typical steel-framed walls positioned in the Rotatable Guarded Hot Box (RGHB) test frame. In addition to testing the steel-framed wall systems in the RGHB, samples were taken from each of the insulating materials used in the metered area of the test walls. These samples were tested in accordance with ASTM C 518-98, where the thermal resistance of each sample was measured. The specimens were subjected to mean temperatures of 50° F and 75° F matching the conditions tested in the RGHB

Table 7 – List of Phase I Tested Wall Assemblies [1]

Test No.	Test Name	Stud Size	Web Design		Sheathing			Modification
			Stud	Track	Interior	Exterior	Cavity Insulation	
1	W1T1	350S162-33	Solid	Solid	½" gypsum board	7/16-in. OSB	R-13	Base
2	W1T2	350S162-33	Solid	Solid	½" gypsum board	7/16-in. OSB[2]	R-13	Foam tape between stud/track and OSB
3	W2T1	350S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB	R-13	Slit web design
4	W2T2	350S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB[2]	R-13	Foam tape between stud/track and OSB
5	W2T3	350S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB[2]	R-13	½" ISO on exterior side of OSB
6	W2T5	350S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB	R-13	½" ISO on exterior side of OSB
7	W3T1	550S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB	R-19	Base
8	W3T2	550S162-33	Slit	Slit	½" gypsum board	7/16-in. OSB	R-19	½" ISO on exterior side of OSB
9	W4T2	350S162-33	Slit	Solid	½" gypsum board	7/16-in. OSB	R-13	Slit stud w/solid track
10	W3T3	550S162-33	Slit	Solid	½" gypsum board	7/16-in. OSB	R-19	Slit stud w/solid track

[1] All wall sections are constructed with five studs and two tracks
[2] Foam or polyiso. tape installed on the interior surface between stud and drywall

Table 8 – Phase I Test Walls Configurations Estimated R-Values

Test No.	Test Name	Stud Size	Stud	Track	Cavity Insulation	Interior Sheathing-Value	Exterior Sheathing R-Value	Modification R-Value
1	W1T1	350S162-33	Solid	Solid	13	0.45	0.62	Base
2	W1T2	350S162-33	Solid	Solid	13	0.45	0.62	1.7
3	W2T1	550S162-33	Slit	Slit	13	0.45	0.62	-
4	W2T2	350S162-33	Slit	Slit	13	0.45	0.62	1.7
5	W2T3	350S162-33	Slit	Slit	13	0.45	0.62	3.5
6	W2T5	350S162-33	Slit	Slit	13	0.45	0.62	3.5
7	W3T1	350S162-33	Slit	Slit	19	0.45	0.62	Base
8	W3T2	550S162-33	Slit	Slit	19	0.45	0.62	3.5
9	W4T2	550S162-33	Slit	Solid	19	0.45	0.62	-
10	W3T3	350S162-33	Slit	Solid	13	0.45	0.62	-

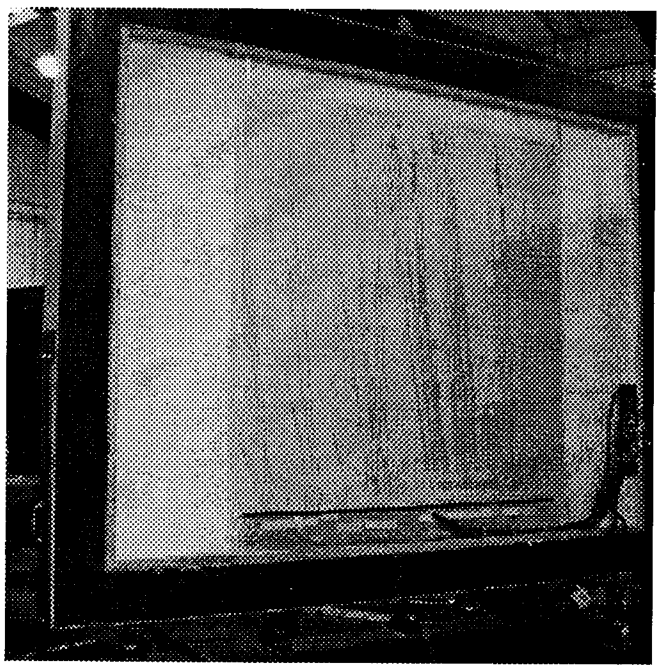

Figure 9 – Typical Test Wall in RGHB Frame

Arrays of thermocouples were used to measure the meter and climate chamber air temperatures. Table 9 provides a summary of the thermocouple locations for the test wall specimen. Figures 10, 11, 12, and 13 illustrate the locations of the thermocouples. Figure 14 shows a slit-web stud test wall assembly.

Table 9 – Location of Thermocouples Across Gypsum Surface (Phase I Tests)

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
1	6" right of stud center (outside)	11	2" left of stud center (inside)
2	2" right of stud center (outside)	12	1" left of stud center (inside)
3	1" right of stud center (outside)	13	Left stud edge (inside)
4	Right stud edge (outside)	14	Right stud edge (inside)
5	Left stud edge (outside)	15	1" right of stud center (inside)
6	1" left of stud center (outside)	16	2" right of stud center (inside)
7	2" left of stud center (outside)	17	6" right of stud center (inside)
8	6" left of stud center (outside)	18	Center of cavity left of stud
9	Center of stud (outside)	19	Center of cavity right of stud
10	6" left of stud center (inside)		

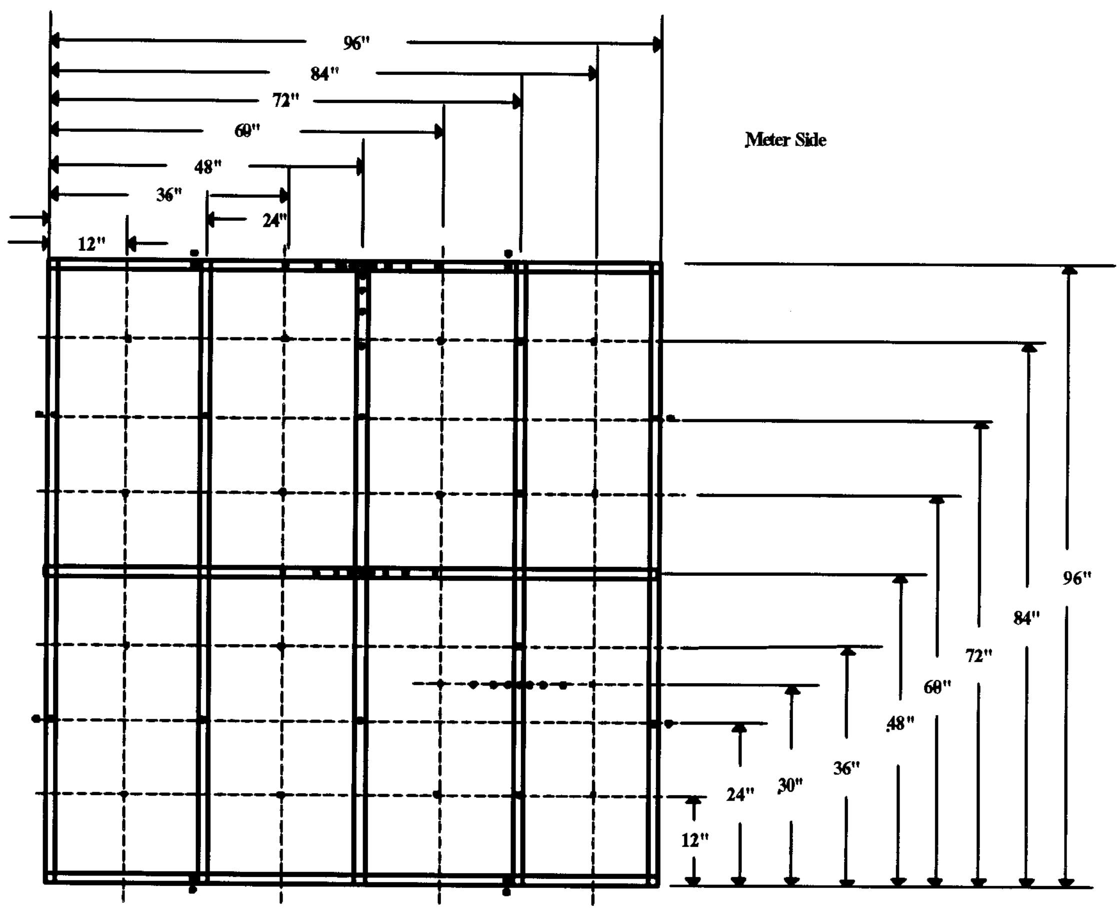

Figure 10 Wall Surface Thermocouple Detail

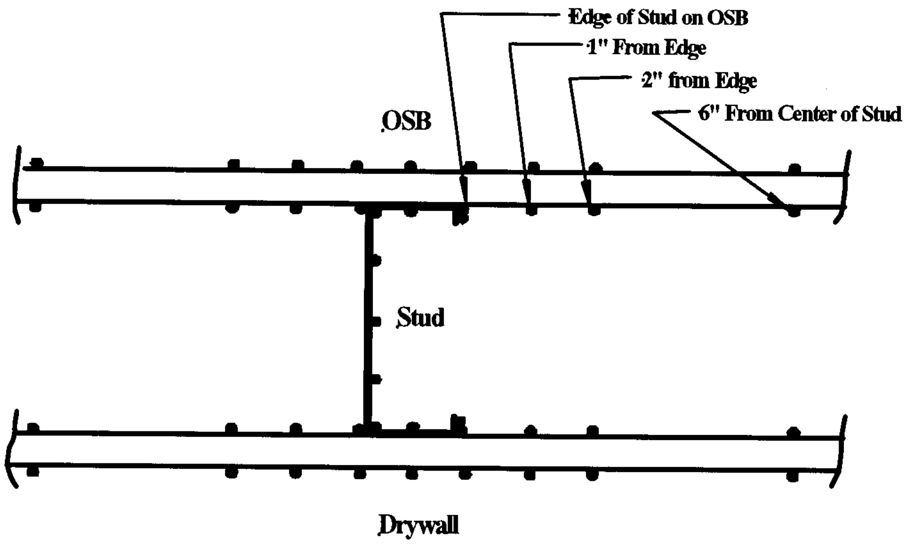

Figure 11 - Internal Stud TC Array Layout

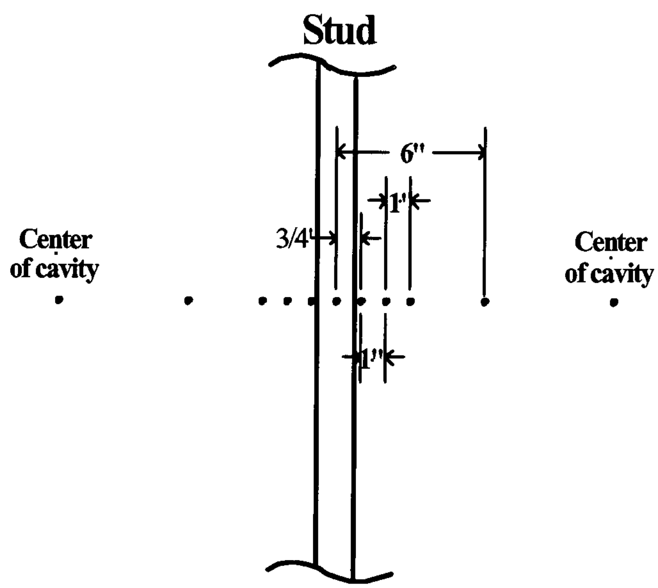

Figure 12 - Stud Array TC Layout

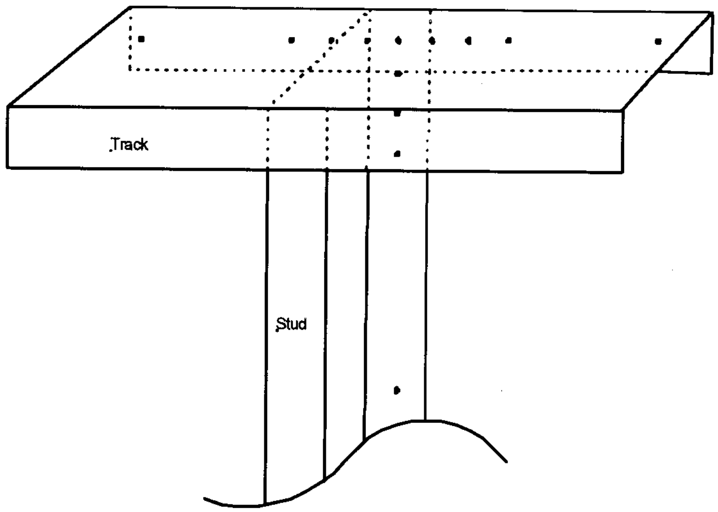

Figure 13 - Track TC Array

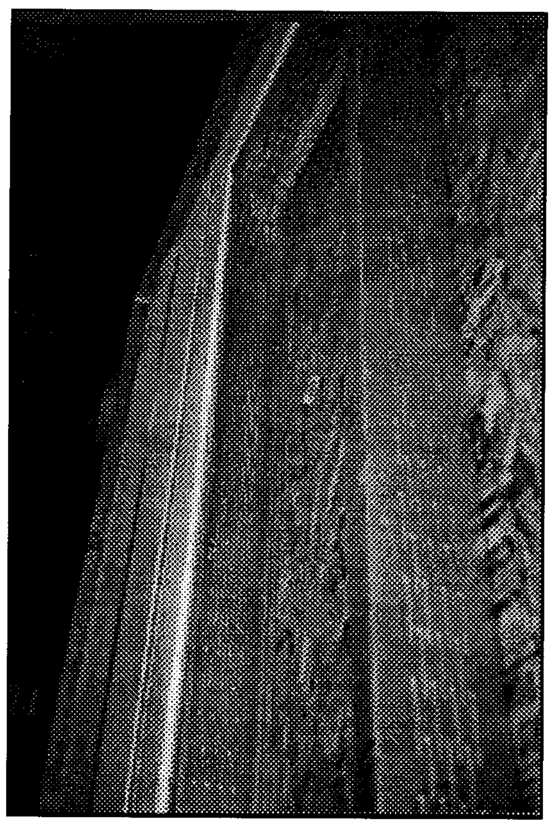

Figure 14 – Slit-Web Stud Wall Assembly

Phase II Tests

The slit-web stud was refined for this stage of testing. The refinement concentrated on enhancing the strength of the stud but maintaining its thermal characteristics. Figure 15 shows a photo of the prototype slit-web stud.

Figure 15 – Prototype of Slit Web Stud

The test configurations consisted of 350S162033 (nominal 2 x 4) cold-formed steel-framed wall assemblies and 350S162-33 (nominal 2 x 4) slotted-stud walls, with the common characteristics of 0.5-in. thick gypsum board on the warm side, 7/16 in. thick oriented strand board (OSB) on the cold side, and full-width R-13 craft-faced fiberglass batt insulation in the cavities. Wall 2 was an exception and utilized a 1-1/2-in x 1-1/2-in x 33 mil galvanized steel strap placed horizontally across the studs and 1-in Tuff-R polyisocyanurate insulation in place of the 1/2-in OSB on the exterior side. Wall 6 also varied from the other walls in that the OSB was replaced with 33-mil galvanized steel sheet and the cavity insulation was unfaced R-15 batts.

Variations of the base walls tested included modified track/stud combinations and application of foam sheathing on the exterior OSB wall surface. Walls 2 through 4 and 6 through 7 utilized a split track design (L-headers), which consisted of removing a portion of the center track web to within 1-in of each bend (see Figure 16). The missing center portion provided a thermal break in the conduction path of the track. The top track for wall 5 used a modification of the split track design. This modification was applied to the top track only and consisted of a split track mounted to a nominal 2 x 4 wood stud. The bottom track was identical to the split tracks used in walls 2-4. The 2 x 4 used in this wall was part of the metered area, causing the metal studs to be 1-1/2-in shorter than the studs in the other walls. Wall 3, used in tests 6 and 7, was fabricated from solid web studs. Figure 15 shows a picture of one of the typical slit studs used in tests 1 through 5 and 8 through 10 and Figure 16 shows the split track design used in walls 2 through 4. Tables 10 and 11 list the tested walls with their respective tests and configurations.

Figure 16 – Typical Split Track (Angles)

Some of the wall assemblies (test samples) were damaged during shipment to ORNL, necessitating a visit to the BTC by NAHBRC personnel to evaluate the damage and to make the necessary repairs. The biggest concern with the damage was the collapsing of the slits in the slotted studs, thereby reducing the effectiveness of the conduction break in the path across the stud flange. Care was taken to assure that all slits were opened to their original spacing. After repair, the walls nonetheless retained some minor cosmetic damage consisting primarily of small dimples and dents. NAHBRC and BTC personnel concluded that these cosmetic blemishes would have negligible affect on the thermal performance of the framing.

Because of the difficulty in maintaining a constant wall surface temperature across multiple test walls with varying surface and interior configurations, the controllers were adjusted to maintain constant air temperatures in the metering and climate chambers at 100°F and 50°F, respectively. In addition to testing the steel-framed wall systems in the RGHB, samples were taken from each of the insulating materials used in the metered area of the test walls. These samples were tested in accordance with ASTM C 518-98, where the thermal resistance of each sample was measured. The specimens were subjected to mean temperatures of 50° F and 75° F matching the conditions tested in the RGHB.

Table 10 – Phase II Test Walls Configurations

Wall No.	Test No.	Test Name	Web Design		Sheathing		Modification
			Stud	Track	Interior	Exterior	
1	1	W1T1	Slit web	Solid	½" gypsum board	7/16-in. OSB	Base
1	2	W1T2	Slit web	Solid	½" gypsum board	7/16-in. OSB	0.5-in thick ISO foam
1	3	W1T3	Slit web	Solid	½" gypsum board	7/16-in. OSB	1.0-in thick ISO foam
1	4	W1T4	Slit web	Solid	½" gypsum board	7/16-in. OSB	2.0-in thick ISO foam
2	5	W2T5	Slit web	1½" x 1½" Angle	½" gypsum board	1-½" x 20 ga steel strap + 1.0-in thick ISO foam	-
3	6	W3T6	Solid web	1½" x 1½" Angle	½" gypsum board	7/16-in. OSB	Base
3	7	W3T7	Solid web	1½" x 1½" Angle	½" gypsum board	7/16-in. OSB	0.5-in thick ISO foam
4	8	W4T8	Slit web	1½" x 1½" Angle	½" gypsum board	7/16-in. OSB	Base
4	9	W4T9	Slit web	1½" x 1½" Angle	½" gypsum board	7/16-in. OSB	0.5-in thick ISO foam
5	10	W5T10	Slit web	2x4 wood plate	½" gypsum board	7/16-in. OSB	-
6	11	W6T11	Slit web	1½" x 1½" Angle	½" gypsum board	7/16-in. OSB	(R-15 FG cavity)
7	12	W7T12	Slit web	1½" x 1½" Angle	½" gypsum board	33-mil sheet steel	-

Table 11 – Phase II Test Walls Configurations Estimated R-Values

Wall No.	Test No.	Test Name	Stud	Track	Cavity Insulation	Interior Sheathing R-Value	Exterior Sheathing R-Value	Modification R-Value
1	1	W1T1	Slit web	Solid	13	0.45	0.62	Base
1	2	W1T2	Slit web	Solid	13	0.45	0.62	4.2
1	3	W1T3	Slit web	Solid	13	0.45	0.62	7.8
1	4	W1T4	Slit web	Solid	13	0.45	0.62	15
2	5	W2T5	Slit web	1½" x 1½" Angle	13	0.45	3.6	-
3	6	W3T6	Solid web	1½" x 1½" Angle	13	0.45	0.62	Base
3	7	W3T7	Solid web	1½" x 1½" Angle	13	0.45	0.62	4.2
4	8	W4T8	Slit web	1½" x 1½" Angle	13	0.45	0.62	Base
4	9	W4T9	Slit web	1½" x 1½" Angle	13	0.45	0.62	4.2
5	10	W5T10	Slit web	2x4 wood plate	13	0.45	0.62	-
6	11	W6T11	Slit web	1½" x 1½" Angle	15	0.45	0.62	-
7	12	W7T12	Slit web	1½" x 1½" Angle	13	0.45	0	-

Similar to Phase I tests, arrays of thermocouples were used to measure the meter and climate chamber air temperatures. Tables 12 through 16 provide a summary of the thermocouple locations for the test wall specimen (refer to Figures 10 through 14 for illustration of thermocouples location).

Table 12 – Location of Thermocouples Across Gypsum Surface (Phase 2 Tests)

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
G-H2	6" right of stud center (exterior)	M-E3	6" right of stud center (interior)
G-H3	2" right of stud edge (exterior)	M-E4	2" right of stud edge (interior)
G-H4	1" right of stud edge (exterior)	M-E5	1" right of stud edge (interior)
G-H5	Right stud edge (exterior)	M-E6	Right stud edge (interior)
G-H6	Center of stud (exterior)	M-F1	Left stud edge (interior)
M-J6	Left stud edge (exterior)	M-F2	1" left of stud edge (interior)
M-K6	1" left of stud edge (exterior)	M-F3	2" left of stud edge (interior)
G-L6	2" left of stud edge (exterior)	M-F4	6" left of stud center (interior)
G-M6	6" left of stud center (exterior)		

Table 13 – Location of Thermocouples Across OSB Surface (Phase 2 Tests)

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
B3	6" right of stud center (exterior)	A1	6" right of stud center (interior)
B4	2" right of stud edge (exterior)	A2	2" right of stud edge (interior)
B5	1" right of stud edge (exterior)	A3	1" right of stud edge (interior)
B6	Right stud edge (exterior)	A4	Right stud edge (interior)
E1	Center of stud (exterior)	M-G6	Center of stud (interior stud surface)
E2	Left stud edge (exterior)	A5	Left stud edge (interior)
E3	1" left of stud edge (exterior)	A6	1" left of stud edge (interior)
E4	2" left of stud edge (exterior)	B1	2" left of stud edge (interior)
E5	6" left of stud center (exterior)	B2	6" left of stud center (interior)

Table 14 – Location of Thermocouples Across Steel Strap Surface (Phase 2 Tests)
Brace-OSB surface (inside) Looking from MC side

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
A1	6" right of stud edge	B4	6" above Brace-OSB (stud)
A2	2" right of stud edge	B5	2" above Brace-OSB (stud)
A3	1" right of stud edge	B6	1" above Brace-OSB (stud)
A4	Right stud edge	E1	Top stud/Brace-OSB interface (stud)
A5	Brace/stud interface, inside stud	E2	Bottom stud/Brace-OSB interface (stud)
A6	Left stud edge	E3	1" below Brace-OSB (stud)
B1	1" left of stud edge	E4	2" below Brace-OSB (stud)
B2	2" left of stud edge	E5	6" below Brace-OSB (stud)
B3	6" left of stud edge		

Table 15 – Location of Thermocouples Across Steel Strap Surface (Phase 2 Tests)
Brace-OSB surface outside

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
F1	6" right of stud edge	G4	6" above Brace-OSB (stud)
F2	2" right of stud edge	G5	2" above Brace-OSB (stud)
F3	1" right of stud edge	G6	1" above Brace-OSB (stud)
F4	Right stud edge	H1	Top stud/Brace-OSB interface (stud)
F5	Brace/stud interface, outside stud	H2	Bottom stud/Brace-OSB interface (stud)
F6	Left stud edge	H3	1" below Brace-OSB (stud)
G1	1" left of stud edge	H4	2" below Brace-OSB (stud)
G2	2" left of stud edge	H5	6" below Brace-OSB (stud)
G3	6" left of stud edge		

Table 16 – Location of Thermocouples Across Interior Stud Surface (Phase 2 Tests)

Thermocouple No.	Thermocouple Location	Thermocouple No.	Thermocouple Location
M-F5	Back fold (gypsum side)	M-G4	Web, 1" from flange (OSB side)
M-F6	Flange, center (gypsum side)	M-G5	Web/flange intersection (OSB side)
M-G1	Web/flange intersection (gypsum side)	M-G6	Flange, center (OSB side)
M-G2	Web, 1" from flange (gypsum side)	M-H1	Back fold (OSB side)
M-G3	Web, center		

RESULTS

Phase I Tests

Table 17 presents the results of the ASTM C518 tests for the insulation and sheathing materials used for the wall specimens.

Table 17 – ASTM C518 Test Results (Phase I Tests)

Specimen	Thickness (in.)	?t (°F)	T_{mean} (°F)	K (Btu-in/h.ft^2. °F	R_{in} (hr.ft^2.°F/Btu)	R_{total} (hr.ft^2.°F/Btu)
R-13FG	3.56	50.1	50.0	0.2692	3.715	13.23
	3.56	50.0	75.0	0.2892	3.458	12.32
R-13FG	3.44	50.1	50.0	0.2642	3.785	13.04
	3.44	50.1	75.1	0.2857	3.50	12.06
R-19FG	5.5	60.1	50.0	0.2897	3.45	18.98
	5.5	50.1	75.1	0.3170	3.16	17.38
Tuff-R® Polyiso.	0.479	40.4	19.8	0.1258	7.949	3.81
	0.479	50.1	75.0	0.1389	7.199	3.45
Black Foam	0.588	50.1	50.0	0.2657	3.67	2.21
	0.588	50.1	75.1	0.2754	3.63	2.13
Black Foam plus Plywood	1.544	60.0	50.0	-	-	1.709
	1.544	50.0	75.0	-	-	1.660
Plywood	0.475	60.0	50.0	0.5945	1.682	0.799
	0.475	50.0	75.0	0.7047	1.419	0.674
Black Foam (Calc.)	0.1875	60.0	50.0	1.6892	0.5920	.111
		50.0	75.0	0.601	1.664	.312
XPS	2.06	60.0	50.0	0.1990	5.025	10.4
	2.06	50.0	75.0	0.2058	4.796	9.9
EPS	5.0	50.1	75.1	0.2528	3.96	19.80
	5.0	50.1	50.1	0.2362	4.23	21.15

Table 18 summarizes the calculated wall systems' R-values. The R-values were calculated based on the heat flow and temperature data that was measured during the tests. The temperatures and heat flows used were average for the time interval for each test after steady state had been achieved. When multiple temperature sensors are used to define a temperature, those sensors are averaged for each scan and then integrated over the time interval. The heading row in Table 16 lists the test designation number; e.g. W1T1 designates wall 1, test 1. The surface-to-surface R-values from Table 16 are shown graphically in Figure 17. Stud array temperatures data are shown graphically in Figure 19.

Table 18 - Summary of Phase I Test Data and Calculations

Test No.	1	2	3	4	5	6	7	8	9	10
Test Name	W1T1	W1T2	W2T1	W2T2	W2T3	W2T5	W4T2	W3T1	W3T2	W3T3
?t [1]	54.5	54.9	56.5	56.7	57.1	58.2	56.3	67.2	67.7	66.5
R_{wall} [2]	8.1	8.2	10.2	10.4	11.1	13.9	9.5	13.4	17.3	11.4
$R_{ms\ air}$ [3]	0.616	0.603	0.636	0.630	0.646	0.651	0.604	0.652	0.663	0.581
$R_{cs\ air}$ [4]	0.218	0.197	0.192	0.175	0.158	0.180	0.236	0.279	0.329	0.245
$R_{u\ wall}$ [5]	8.9	9.0	11.0	11.2	11.9	14.7	10.4	14.3	18.3	12.2
% Change in R_{wall} from Base	350S162-33 Base	1.2%	25.9%	28.4%	37.0%	71.6%	17.3%	550S162-33 Base	29.1%	-14.9%

[1] ?t is the temperature difference across sample wall.
[2] R_{wall} is the surface to surface R-value of the wall (hr.ft^2.°F/Btu).
[3] $R_{ms\ air}$ is the meter side air film resistance (hr.ft^2.°F/Btu).
[4] $R_{cs\ air}$ is the climate side air film resistance (hr.ft^2.°F/Btu).
[5] $R_{u\ wall}$ is overall R-value of sample wall, $R_{ms\ air}$ + R_{wall} + $R_{cs\ air}$ (hr.ft^2.°F/Btu).

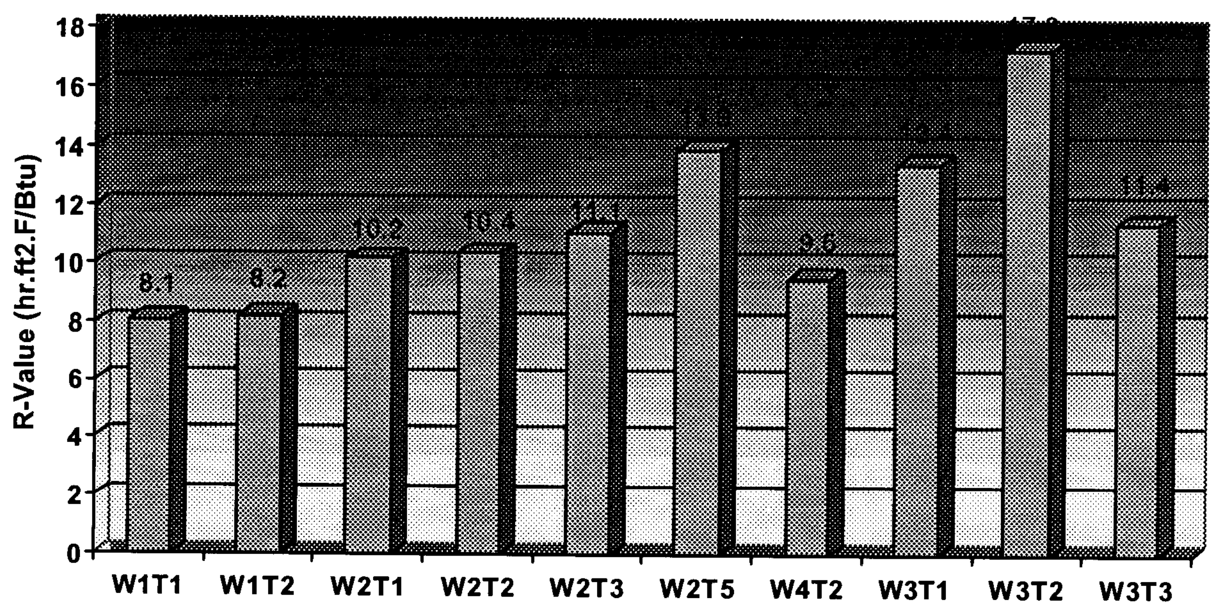

Figure 17 - Surface-to-Surface R-Values (Phase I)

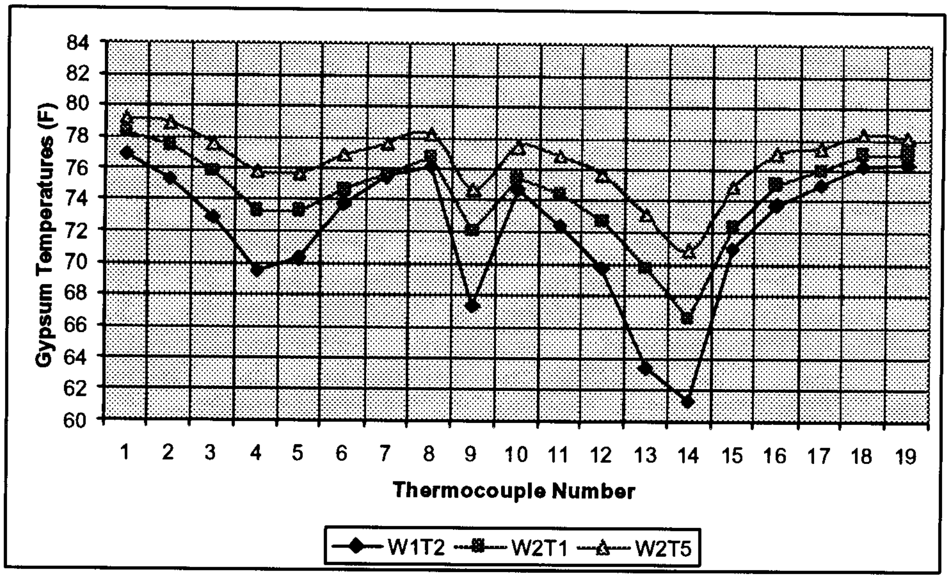

Figure 18 – Plot of Gypsum Surface Temperatures on 3-1/2" Steel Stud Walls

Phase II Tests

Table 19 presents the results of the ASTM C518 tests for the different materials used in the test specimens. Table 20 presents the R-values for each of the walls tested. The heading row in Table 18 lists the test designation number; e.g. W1T1 designates wall 1, test 1. Table

Table 21 was added as a continuation of Table 19 and shows data for two additional test runs at CC=20°F, MC=80°F made on wall 1, tests 1 and 4 (W1T1a and W1T4a). The primary purpose of these runs was to provide some additional data for comparison to Phase I test conditions.

The surface-to-surface R-values from Table 19 are shown graphically in Figure 19. Only the values for the standard chamber test conditions of MC= 100°F and CC= 50°F are shown. Stud array temperature data (refer to Table TC Locations in Tables 12 through 16) are shown graphically in Figures 20 and 21 with Figure 20 displaying the warm side (gypsum) data and Figure 21 displaying the cold side (OSB) data. These data are arranged in order to position the thermocouples in the chart as one would view from left to right if facing the gypsum board side of the wall. Figure 22 is a plot of the gypsum surface temperatures at the top track array.

Table 19 - ASTM C518 Test Results (Phase II Tests) [1,2]

Specimen	Thickness (in.)	Density (lb/ft³)	T (°F)	T_{mean} (°F)	K (Btu-in/h.ft².°F)	R_{in} (hr.ft².°F/Btu)	R_{total} (hr.ft².°F/Btu)
R-13 FG Batt # 1	3.5	0.791	50.0	75.0	0.2964	3.37	11.81
			60.0	50.0	0.2707	3.69	12.93
R-13 FG Batt # 2	3.5	0.759	50.0	75.0	0.2926	3.42	11.96
			60.0	50.1	0.2672	3.74	13.10
R-13 FG Batt # 3	3.5	0.757	50.0	75.0	0.2835	3.53	12.35
			60.0	50.0	0.2628	3.81	13.32
R-15 FG Batt # 1	3.5	1.409	50.0	50.0	0.2224	4.50	15.74
			60.0	75.0	0.2377	4.21	14.72
R-15 FG Batt # 2	3.5	1.570	50.0	50.0	0.2185	4.58	16.02
			60.0	75.0	0.2328	4.30	15.03
R-15 FG Batt # 3	3.5	1.589	50.0	50.0	0.2183	4.58	16.03
			60.0	75.0	0.2329	4.29	15.03
Tuff-R® polyiso 1/2-in Thick	0.567	2.281	50.0	75.0	0.1493	6.70	3.80
			60.0	50.0	0.1398	7.16	4.06
Tuff-R® polyiso 1-in Thick	0.970	2.093	50.0	75.0	0.1457	6.86	6.66
			60.0	50.0	0.1356	7.37	7.16
Tuff-R® polyiso 2-in Thick	2.211	1.898	50.0	75.0	0.1446	6.92	15.29
			60.0	50.0	0.1338	7.47	16.52

Table 20 - Summary of Phase II Test Data and Calculations

Test No.	1	2	3	4	5	6	7	8	9	10	11	12
Test Name	W1T1	W1T2	W1T3	W1T4	W2T5	W3T6	W3T7	W4T8	W4T9	W5T10	W6T11	W7T12
?t [1]	45.1	45.9	46.4	47.4	46.5	44.5	45.8	45.3	46.2	45.2	45.4	44.8
R_{wall} [2]	9.4	12.9	15.1	20.3	16.3	8.5	12.2	10.4	14.0	10.5	10.9	9.7
$R_{ms\ air}$ [3]	0.698	0.701	0.710	0.708	0.700	0.683	0.687	0.706	0.703	0.752	0.720	0.729
$R_{cs\ air}$ [4]	0.342	0.451	0.435	0.407	0.456	0.355	0.418	0.353	0.456	0.350	0.329	0.447
$R_{u\ wall}$ [5]	10.4	14.1	16.2	21.5	17.4	9.6	13.3	11.4	15.1	11.6	12.0	10.9
% Change in $R_{u\ wall}$ from Base (350S162-33 Solid web)[5]	16.85	58.43	82.02	141.6	95.51	7.87	49.44	28.09	69.66	30.34	34.83	22.47

[1] ?t is the temperature difference across sample wall.
[2] R_{wall} is the surface to surface R-value of the wall (hr.ft².°F/Btu).
[3] $R_{ms\ air}$ is the meter side air film resistance (hr.ft².°F/Btu).
[4] $R_{cs\ air}$ is the climate side air film resistance (hr.ft².°F/Btu).
[5] $R_{u\ wall}$ is overall R-value of sample wall, $R_{ms\ air} + R_{wall} + R_{cs\ air}$ (hr.ft².°F/Btu).
[6] Base stud R-value of 8.9 is taken from Table 16.

Table 21 - Summary of Phase II Test Data and Calculations with CC=20° and MC=80° [1,2]

Test Name	W1T1a	W1T1	W1T4a	W1T4
?t [1]	54.0	45.1	56.9	47.4
R_{wall} [2]	9.7	9.4	20.7	20.3
$R_{ms\ air}$ [3]	0.702	0.698	0.656	0.708
$R_{cs\ air}$ [4]	0.363	0.342	0.373	0.407
$R_{u\ wall}$ [5]	10.7	10.4	21.8	21.5

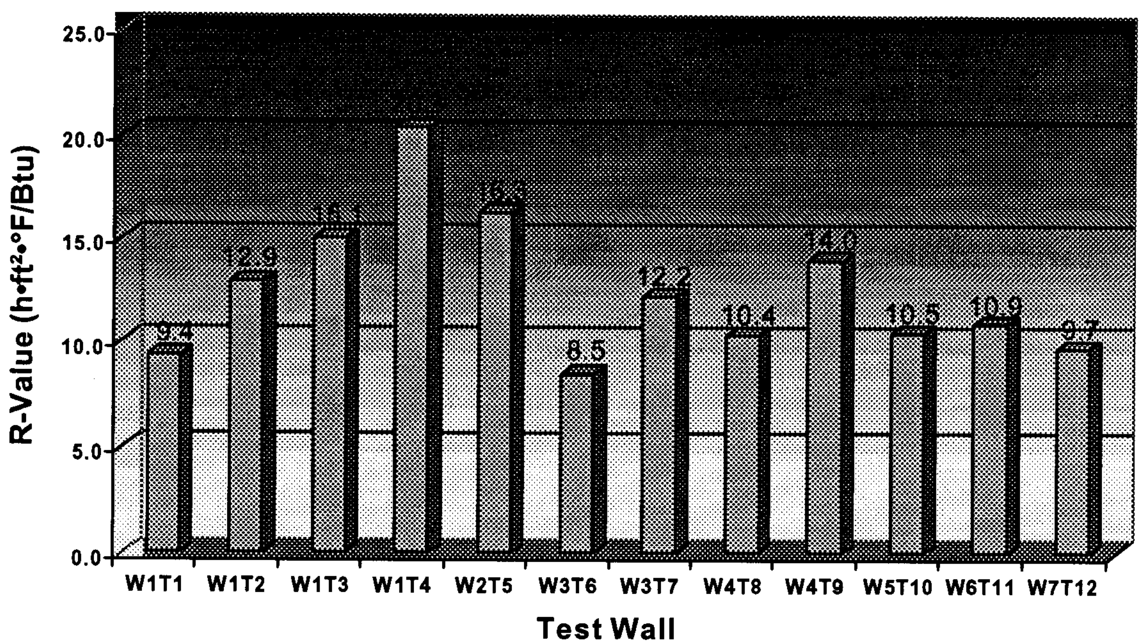

Figure 19 - Surface-to-Surface R-Values (Phase II)

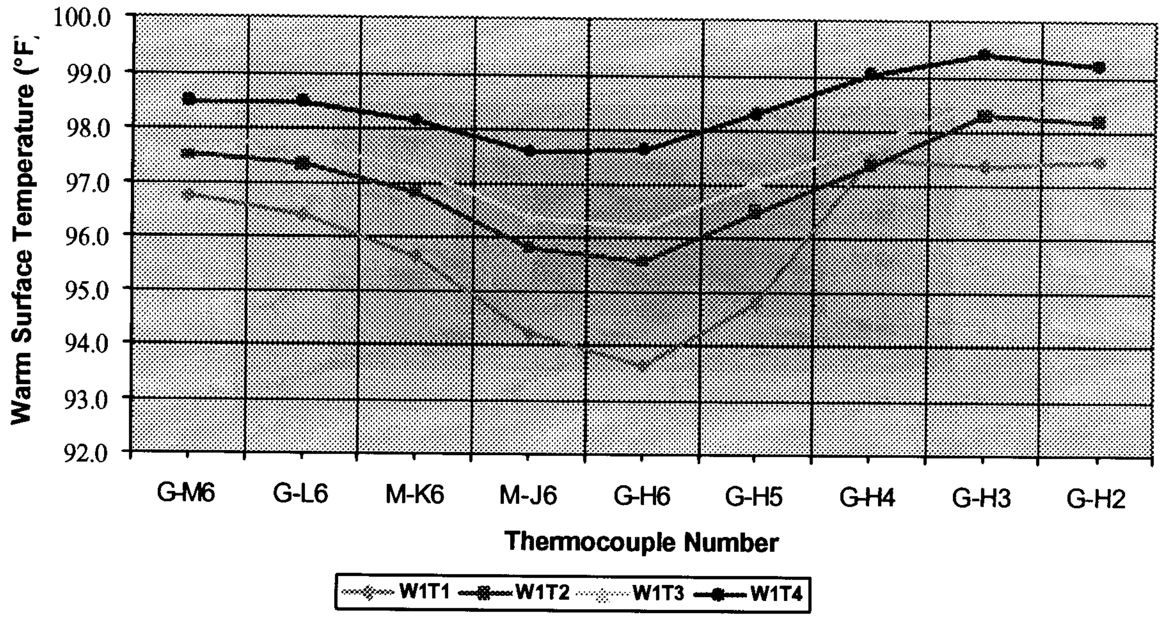

Figure 20 - Stud Array Temperatures at Gypsum Surface

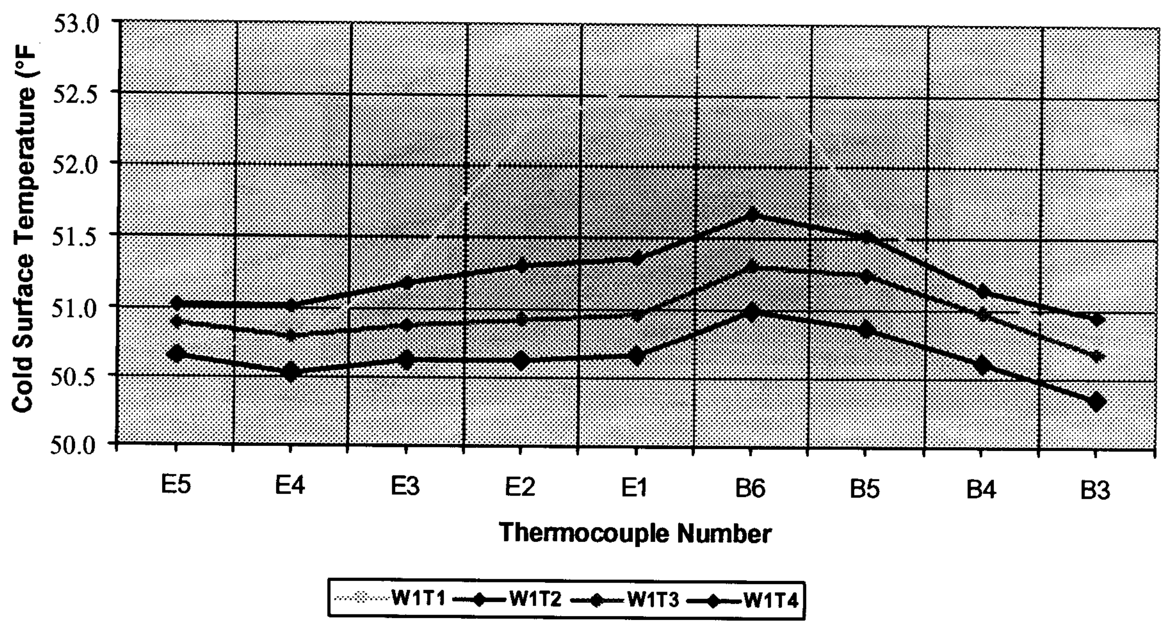

Figure 21 - Stud Array Temperatures at OSB Surface

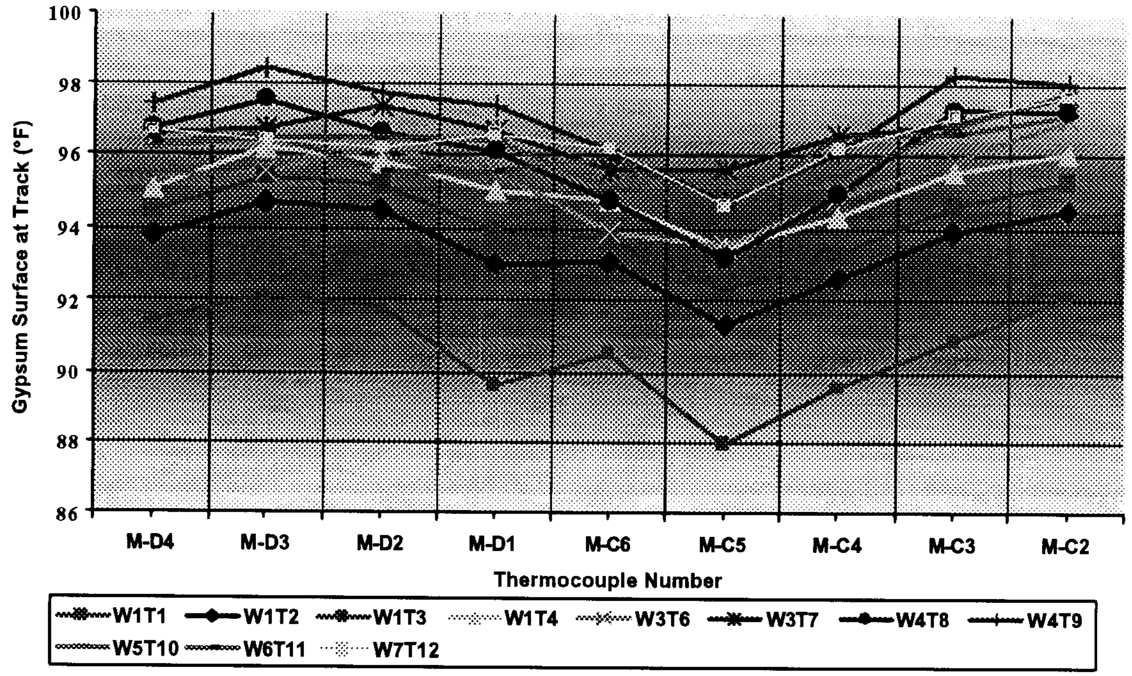

Figure 22 - Stud Array Temperatures at Gypsum Surface

Overall Results

Tables 22 and 23 compare the R-values for the slit-web studs and the solid-web studs with those of comparable wood studs (Table 22 only). It should be noted that the R-values for the solid-web studs were obtained from previous tests [1] that were conducted at a 50 °F mean temperature, R-11 cavity insulation, and polystyrene (XPS) exterior foam insulation while the tests conducted in this report were done at 75 °F mean temperature, R-13 cavity insulation and polyisocyanurate exterior foam insulation. The wood wall R-values shown in Table 22 were calculated using the Parallel-Path Flow Method [9].

Table 23 provides a summary comparison between the slit-web and solid-web steel studs with different cavity insulation.

Table 22 – Wall R-Value Comparison

Wall Parameter	Wall Detail	Slit Web Stud (R-Value)	Solid-Web Stud (R-Value)	Wood Stud (R-Value)
Cavity Insulation	R-13	10.4	8.9	12.7
Exterior Insulation	0			
Top Track/Plate	Solid Track			
Interior Drywall	½"			
Exterior Sheathing	7/16" OSB			
Cavity Insulation	R-13	14.1	11.4 (1)	16.3 (4)
Exterior Insulation	½" Polyiso Foam			
Top Track/Plate	Solid Track			
Interior Drywall	½"			
Exterior Sheathing	7/16" OSB			
Cavity Insulation	R-13	16.2	13.9 (2)	19.9 (4)
Exterior Insulation	1" Polyiso Foam			
Top Track/Plate	Solid Track			
Interior Drywall	½"			
Exterior Sheathing	7/16" OSB			
Cavity Insulation	R-13	21.5	18.9 (3)	28.7 (4)
Exterior Insulation	2" Polyiso Foam			
Top Track/Plate	Solid Track			
Interior Drywall	½"			
Exterior Sheathing	7/16" OSB			
Cavity Insulation	R-13	17.4	-	12.2 (4)
Exterior Insulation	1" Polyiso			
Top Track/Plate	150L150-33 Angles			
Interior Drywall	½"			
Exterior Sheathing	1-1/2" Steel Strap			
Cavity Insulation	R-13	11.6	-	12.7 (4)
Exterior Insulation	0			
Top Track/Plate	2x4 Wood			
Interior Drywall	½"			
Exterior Sheathing	7/16" OSB			

1 Value taken from [1] with R-11 cavity insulation, 362S162-43 studs and ½" XPS.
2 Value taken from [1] with R-11 cavity insulation and 1" XPS.
3 Value taken from [1] with R-11 cavity insulation, 362S162-43 studs, and 2" XPS.
4 R-values are calculated using the ASHRAE Parallel-Path Flow Method.

Table 23 – Wall R-Value Comparison

Wall Parameter	Wall Detail	Slit Web Stud (R-Value)	Solid-Web Stud (R-Value)
Cavity Insulation	R-13	11.4	9.6
Exterior Insulation	0		
Top Track/Plate	150L150-33 Angles		
Interior Drywall	½"		
Exterior Sheathing	7/16" OSB		
Cavity Insulation	R-13	15.1	13.3
Exterior Insulation	½" Polyiso Foam		
Top Track/Plate	150L150-33 Angles		
Interior Drywall	½"		
Exterior Sheathing	7/16" OSB		
Cavity Insulation	R-15	12.0	-
Exterior Insulation	0		
Top Track/Plate	150L150-33 Angles		
Interior Drywall	½"		
Exterior Sheathing	7/16" OSB		
Cavity Insulation	R-13	10.9	-
Exterior Insulation	0		
Top Track/Plate	150L150-33 Angles		
Interior Drywall	½"		
Exterior Sheathing	33 mil sheet steel		
Cavity Insulation	R-19	12.2 [1]	-
Exterior Insulation	0		
Top Track/Plate	Solid		
Interior Drywall	½"		
Exterior Sheathing	7/16" OSB		

[1] R-value for 550S162-33 slit-web stud wall.

Table 24 - Impact of Cavity Insulation and Web Design

Wall Parameter	Slit Web Stud (1)		Solid-Web Stud (1)		Solid-Web Stud	
	Cavity Insulation	R-Value	Cavity Insulation	R-Value	Cavity Insulation	R-Value
Cavity Insulation	R-13	10.4	R-13	8.9	R-11	8.3 (1)
Exterior Insulation	None		None		None	
Interior Covering	½" drywall		½" drywall		½" drywall	
Exterior Sheathing	½" OSB		½" OSB		½" Plywood	
Cavity Insulation	R-13	14.1			R-11	11.4 (2,3)
Exterior Insulation	½" Polyiso. Foam				½" XPS	
Interior Covering	½" drywall				½" drywall	
Exterior Sheathing	½" OSB				½" Plywood	
Cavity Insulation	R-13	16.2			R-11	14.5 (2,3)
Exterior Insulation	1" Polyiso. Foam				1" XPS	
Interior Covering	½" drywall				½" drywall	
Exterior Sheathing	½" OSB				½" Plywood	

[1] Studs are 350S162-33, spaced at 24" on center.
[2] Studs are 362S162-33, spaced at 24" on center.
[3] R-values are taken from reference 1.

CONCLUSION

Test results show the prototype slit web studs performed 17 percent better than the solid-web studs, giving an overall wall resisitivity of R-10.4 for the 350S162-33 slit-web stud wall using R-13 fiberglass batts with exterior OSB sheathing and ½" interior drywall compared to an R-8.9 for solid web studs with the same configuration.

The best performing walls are those using slit web studs and angles (for top tracks), yielding a wall R-value of 11.4. Adding a thin layer (1/2") of polyisocyanurate foam insulation on the exterior increases the wall R-value to 14.1; i.e., 28 percent improvement over solid web studs.

Tests also showed that increasing the cavity insulation from R-11 to R-15 does not significantly increase the total wall R-value (from R-11.4 to R-12). This result agrees with the findings of Bombino and Burnett [5].

Tests indicated that adding foam tape on the solid web stud flanges provides very little additional R-value (R-Value increases from 8.1 to 8.2, see Figure 19). A slit-web stud with wood top plate produces an R-value (R-11.6) that is equivalent to that of a slit-web stud with double angle (R-11.4) top track (see Tables 22 and 23). Tests also showed that the overall wall R-value for walls with exterior sheathing could be estimated by adding the exterior insulation R-value to the base slit-web stud R-value.

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Part 2: Structural Performance of Slit-Web Wall Studs

INTRODUCTION

Cold-formed steel framing has seen some market growth in the housing market most probably due to its similarity to wood stick framing. However, due to concerns about the thermal performance of steel, the use of steel framing in the residential market is still relatively low.

The American Iron and Steel Institute (AISI) initiated a multi-year program with funding from the U.S. Department of Energy (DOE) through the Technology Roadmap Program (TRP) to investigate the thermal conductivity of cold-formed steel framed walls in residential construction and develop a thermally efficient stud. Prior to this program, the only nonproprietary commercially available thermal break for steel-framed walls was the use of rigid foam on the exterior of a steel-framed wall as specified in the *Thermal Design Guide* [11]. Other available products and construction methods and materials are mostly proprietary products, not widely available, or too costly. Even the exterior rigid foam insulation requirements specified in the *Thermal Design Guide* can be costly and inefficient in colder climates as the foam thickness can be up to 2 inches (51 mm) to achieve a required (effective) R-value.

The *Thermal Performance of Slit-Web Steel Wall Studs* report [12] investigated available options that mitigate the thermal conductivity of steel framing and developed and tested a slit-web stud that is thermally efficient. The newly developed stud can provide a solution to users once its structural characteristics are proved to be equivalent to that of a solid-web stud.

PURPOSE

The objective of this report is to document the structural performance of the slit-web stud (SWS) as developed in the thermal report [12]. The testing includes axial, bending and web crippling. This report also compares the test results of the SWS to those of a solid web stud.

LITERATURE REVIEW

Numerous papers have been written about the structural behavior of slit-web studs. The most comprehensive study was done by Bethlehem Steel Corporation in 1974 [13]. The Bethlehem Steel study investigated slit-web stud wall systems (4 ft. x 8 ft.) (1219 mm x2438 mm) under concentric compression, eccentric compression, transverse load, and racking load. The primary components of the wall systems were cold-formed channel C-shaped 3-1/2" x 1-1/2" x 0.36" (20 gauge) (89 x 38 x 9 mm) studs which snap-lock into a top and bottom steel track (see Figure 23). The studs were spaced at 24 inch on center. The studs had slits in the webs and ¾" (19 mm) diameter utility holes. Wall assembly sheathing arrangement is described in Table 25.

Table 25 – Wall Assembly Sheathing Arrangement

Test No.	½" Drywall/ ½" Gyplab	½" Drywall/ ½" Drywall	Gyplab One Side	No Sheathing	½" Plywood/ ½" Drywall
1,2,3,5	v				
4,6,7,10		v			
8				v	
9			v		
12,13	v				
11,14,15					v

The study concluded that the design of the thermal slits in the studs, particularly when they extend to the ends of the studs, significantly reduce the strength of the wall panels. Summary of test results is shown in Figures 24 through 26. The stud pullout test results shown in Figure 26 were based on single studs.

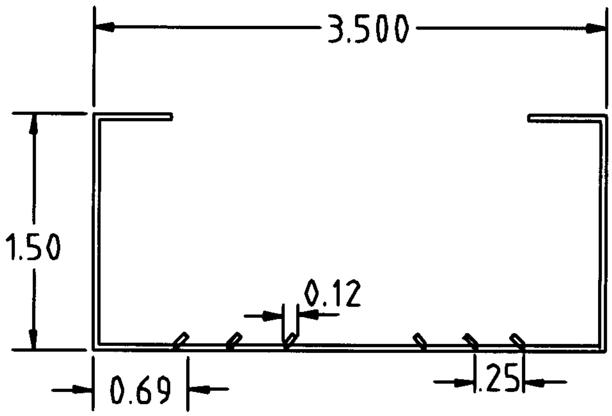

Figure 23 – Bethlehem Steel Slit-Web Stud
(Dimensions in inches)

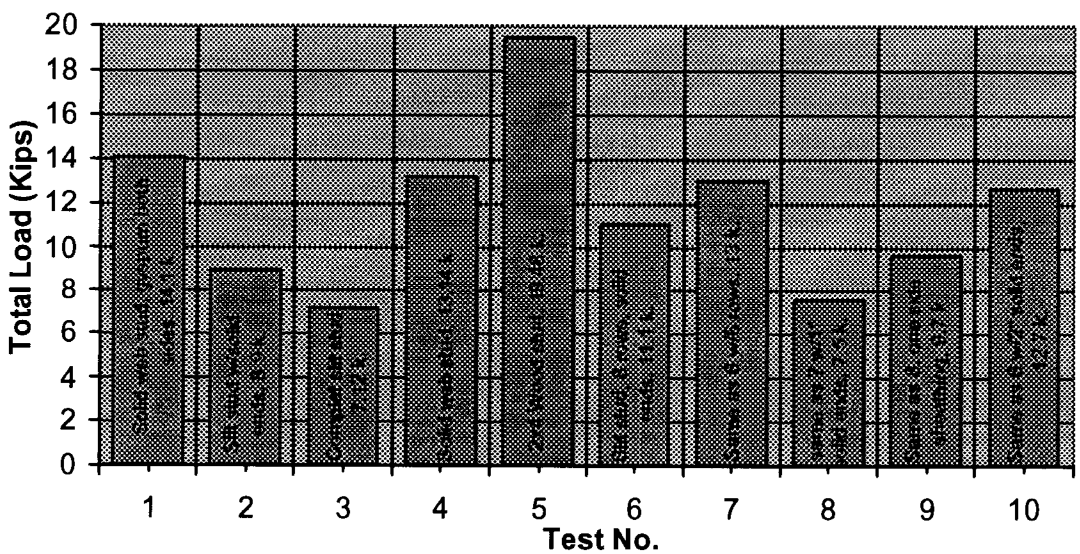

Figure 24 – Concentric Compression Tests

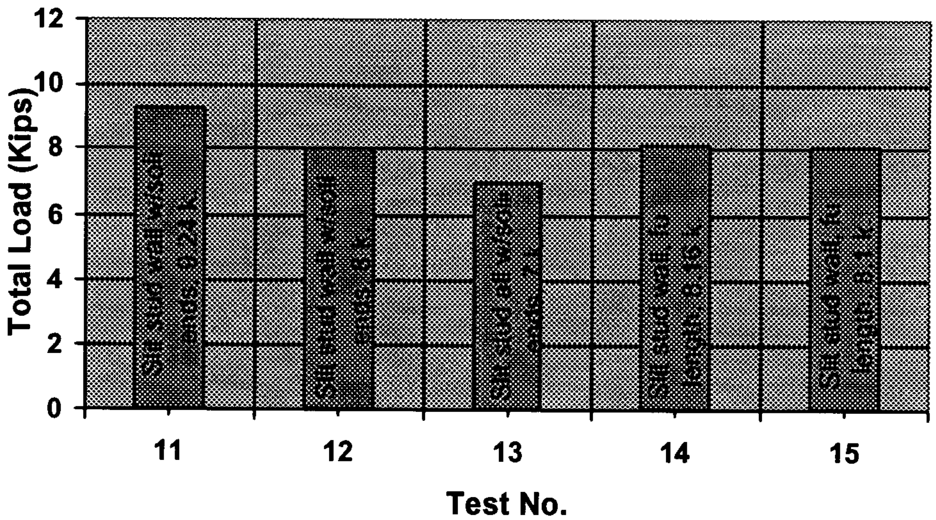

Figure 25 – Eccentric Compression Tests

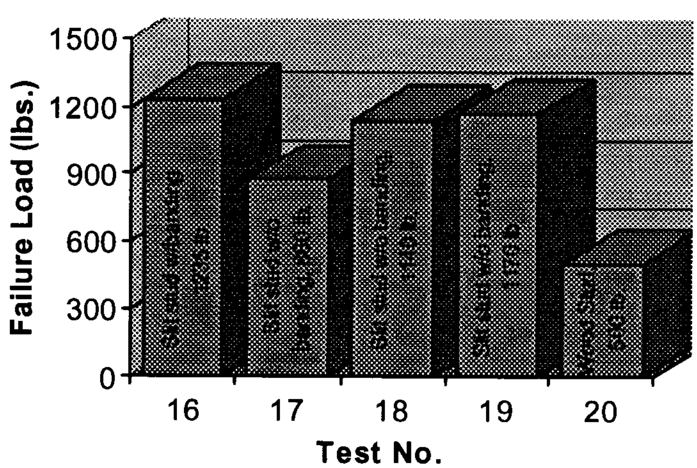

Figure 26 – Stud Pullout Test Results

Ratliff and Roeder conducted full-scale structural tests on steel wall panels constructed of slit-web studs [14]. Test results showed that the full scale compression-load tests of 4-foot (1219 mm) wide wall panels made with slit studs supported 12.8 kips (56.93 kN) compared with 12.2 kips (54.27 kN) for 4-foot (1219 mm) wide panels made with standard unslit studs. The results of the full-scale wind load tests showed that 4-foot (1219 mm) wide wall panels made with slit web studs supported a uniform load of 150 psf. The results of the short-column compression tests indicated that the compression load capacity of light-gauge steel stiffened channel section with slit webs was about 17 percent less than that of similar sections with un-slit webs.

Kesti investigated the structural capacity of web-perforated steel wall studs (see Figure 27) at Helsinki University [15]. Kesti concluded that the perforation changes the behavior of the stud under compressive and lateral loading, reduces the shear stiffness and shear strength of the stud, and also decreases the bending stiffness of the web causing decreased distortional buckling strength. Kesti investigated structures consisting of studs with perforated cold-formed sigma-profiles and gypsum wallboards attached to the stud flanges. The aim was to determine compression and bending moment capacities by full scale testing. The wall stud assemblies were subjected to combined axial and lateral loading. Kesti reported that the test specimens failed by distortional buckling of the upper (tension) flange while fasteners pulled through the sheathing boards. Stub column tests were conducted to evaluate the local and distortional buckling behavior of the stud sections.

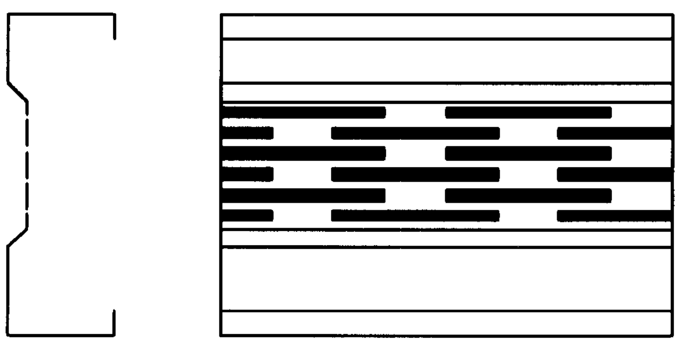

Figure 27 – Web Perforated Steel Stud Tested by

A slotted light-gauge steel stud was developed in Sweden for load-bearing external walls in single-family homes and infill walls in blocks of flats (see Figure 28). The slots are about 2.75 inches in length, and the distance between them in the longitudinal direction is 0.8-1 inch (20.3 – 25.4 mm) and in the transverse direction 1/4 - 3/8 inch (6.4 – 9.5 mm). The edges of the slots are folded inward and form edge stiffeners, which increase the buckling strength. In order to increase the strength further, the web is sometimes folded or given a longitudinal groove in the center. In most cases, the web has two panels with five rows of slots between them, while in smaller sections there are fewer rows of slots.

The Swedish Institute of Steel Construction [16][17] reported that several failure modes have been observed in tests of steel wall panels constructed with slotted steel studs, such as:

1. Flexural buckling in the plane of the web.
2. Lateral buckling of flanges in compression.
3. Shear failure of the slotted web.
4. Failure due to support reaction.
5. Failure under concentrated force.
6. Buckling of the edges of the flanges in the span (axial force and bending moment).
7. Buckling of the edges of the flanges at the supports (axial force).

In all cases, the capacity of the wall panel is affected by shear deformation of the slotted web and by the reduced transverse bending stiffness of the web.

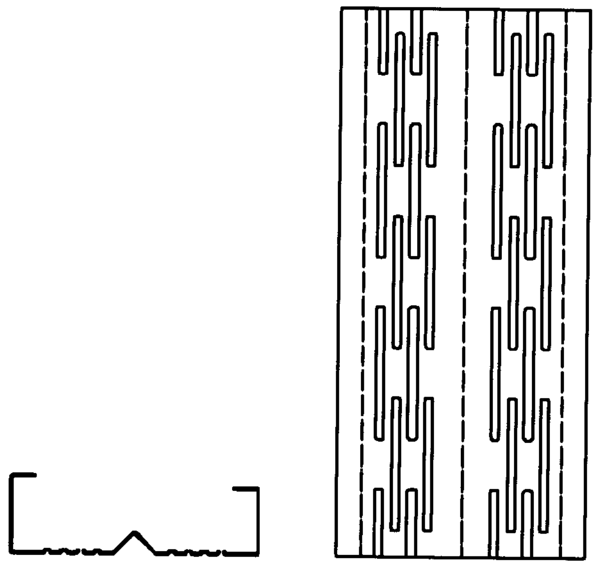

Figure 28 – Swedish Slit-Web Stud Profile

A Finnesteel Programme developed a thermoprofile stud in which the perforations were located in the middle part of the stud web in order to increase the bending stiffness (see Figure 29). In addition, longitudinal stiffeners stiffened the web to increase the overall buckling resistance of the profile [18]. Design guidance and design charts were developed for the thermoprofile stud.

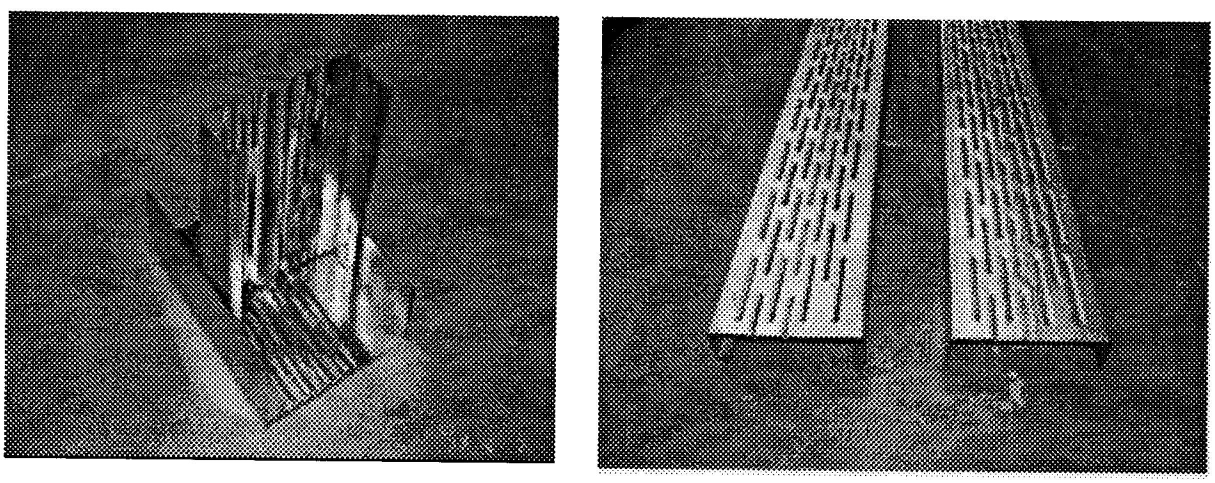

Figure 29 – Thermoprofile Stud

EXPERIMENTAL APPROACH

The slit-web stud (see Figure 30) that was thermally tested in Part 1 [12] was structurally evaluated in this report. Axial and bending tests were performed on single studs and the resulting capacity was compared to that of solid-web studs. All steel materials had a minimum specified tensile strength of 33 ksi (228 MPa) as verified by tensile tests in accordance with ASTM A370 [19]. Tensile tests were performed on a sample of three specimens for each stud thickness. Base steel thicknesses were measured in accordance with ASTM A90 [20]. Mechanical properties were based on coupons cut longitudinally from the center region of the specimen's web.

Figure 30 – Prototype of Slit Web Stud

Bending Tests

Test Procedure

The specimens were tested in the NAHB Research Center's Universal Testing Machine (UTM). No standard ASTM test procedure is specifically detailed for testing cold-formed steel beams subjected to third point loading or to steel wall studs subjected to axial loads. Therefore, the test set-up was similar to that specified in ASTM D198 [21] using simple beams with third-point loading. The standard requires specimens to be mounted in a testing apparatus capable of applying measurable loads at a constant load rate.

The following information was recorded and reported for each test:

- Depth, width, and return lip of specimens,
- Built-up member length,
- Loading configuration,
- Rate of load application,
- Support condition and any lateral supports used,
- Actual physical and mechanical properties of cold-formed steel materials, including thickness, yield strength, ultimate strength (coupon tests), and a statistical measure of variability of these values
- Description of observed failure mode, and,
- Ultimate loads and deflections.

Test Specimen and Test Configuration

The crosshead of the UTM was fitted with an apparatus capable of applying the total load at two points equidistant from the reactions. The locations of the two point loads and end reactions divide the specimen (bending test) into three equal sections. The load was applied by the UTM and transmitted to the load plates and roller (pivots) by a crossbeam.

The purpose of this test was to investigate the bending capacity of slit-web stud member (350S162-33) stabilized against lateral-torsional buckling. To stabilize the specimen against lateral-torsional buckling, each test specimen consisted of two slit-web studs inter-connected by 7/16-inch (11 mm) thick oriented-strand-board (OSB) or plywood and 33 mil (0.81 mm) tracks. The 10-inch x 12-inch x 7/16-inch (254 mm x 305 mm x 11 mm) wood strips were spaced at 16-inches (406 mm) on center and fastened to top and bottom flanges with No. 8 self-drilling, tapping screws (two screws per flange). The 33 mil (0.84 mm) tracks were fastened to ends of the studs (two track sections per assembly) using No. 8 self-drilling tapping screws. The test set up is shown in Figures 31 and 32. The assembly was restrained at each end from moving laterally and rotating. Rollers and bearing plates were used at each end of the assembly. Two concentrated loads were applied at third point locations of each specimen through a 1-5/8 inch (42.5 mm) thick bearing plate and roller. This loading arrangement provided a pure moment region in the central portion of the beam while the two end sections experienced a linearly increasing bending moment with increasing distance from the ends. A deflection gage was placed under the assembly at mid-span to measure the vertical deflection of the test specimen.

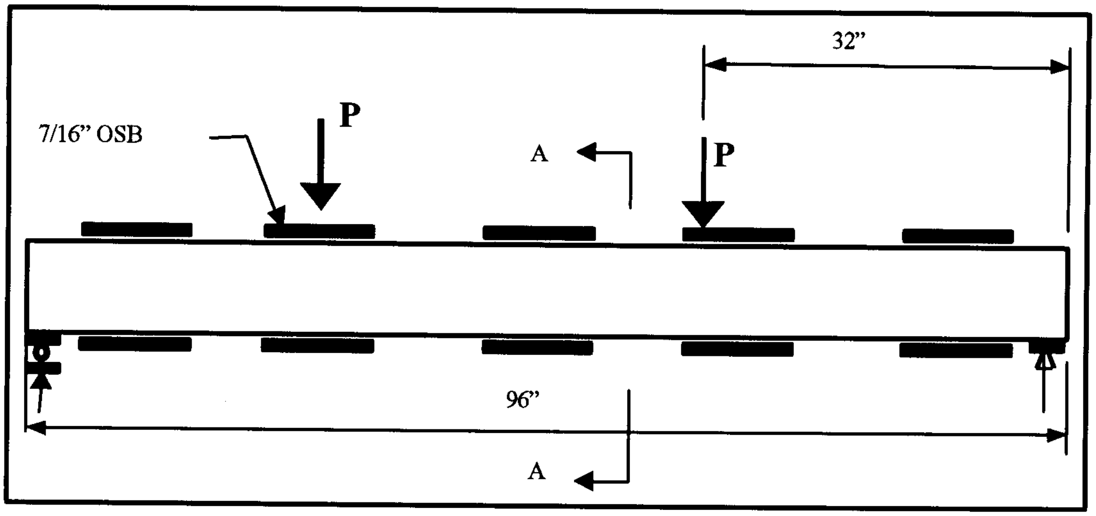

Figure 31 - Bending Test Setup

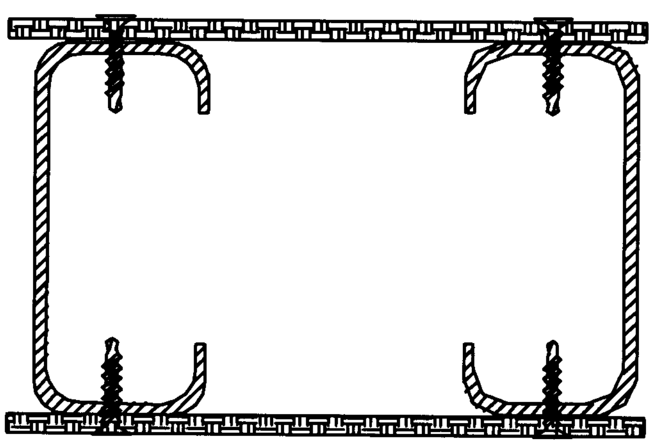

Figure 32 – Section A-A

Axial Tests

Test Procedure

The specimens were tested in the NAHB Research Center's Universal Testing Machine (UTM). No standard ASTM test procedure is specifically detailed for testing cold-formed steel columns subjected to pure axial loads. The AISI Design Specification [22] provides a test method for steel stub column tests. ASTM E72 [23] provides a standard test method for wall panels subject to axial load. The ASTM E72 test method was used to establish the axial load capacity of the slit-web stud.

Test Specimen and Test Configuration

The purpose of this test was to investigate the axial capacity of a slit-web stud member (350S162-33) stabilized against lateral-torsional buckling. To stabilize the specimen against lateral-torsional buckling, each test specimen consisted of two slit-web studs inter-connected by 7/16-inch (11 mm) thick oriented-strand-board (OSB) and plywood and 33-mil (0.84 mm) tracks as shown in Figure 33. The 10-inch x 12-inch x 7/16-inch (254 mm x 305 mm x 11 mm) wood strips were spaced at 16-inches (406 mm) on center and fastened to top and bottom flanges with No. 8 self-drilling, tapping screws (two screws per flange). The 33-mil (0.84 mm) tracks were fastened to ends of the studs (two track sections per assembly) using No. 8 self-drilling tapping screws. The axial load was applied through a pivot and thick steel plate to distribute the axial loads equally between both members. A deflection gage was placed at mid-span on one side of the assembly to measure out-of-plane deflection.

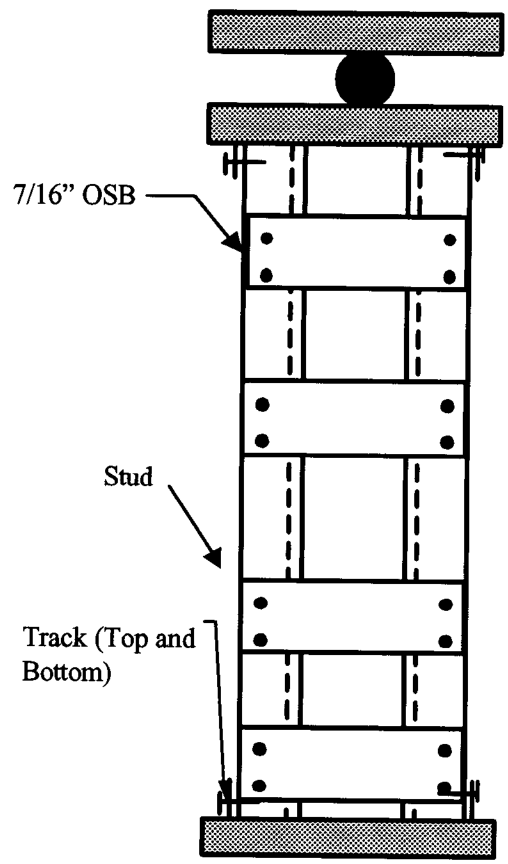

Figure 33 – Axial Load Test Setup

Stub-Column Test

Test Procedure

Stub-column specimens were tested in the NAHB Research Center's Universal Testing Machine (UTM). The AISI Design Specification [22] stub-column test method was used to determine the effective cross-sectional area of the slit-web stud.

Test Specimen and Test Configuration

Three identical stub-column specimens (350S162-33 slit web stud) were tested as required by the AISI Design .02Specification. The length of the specimens were determined to be sufficiently short to eliminate overall column buckling effects and sufficiently long to minimize the end effects during loading. The test set up is shown in Figure 34.

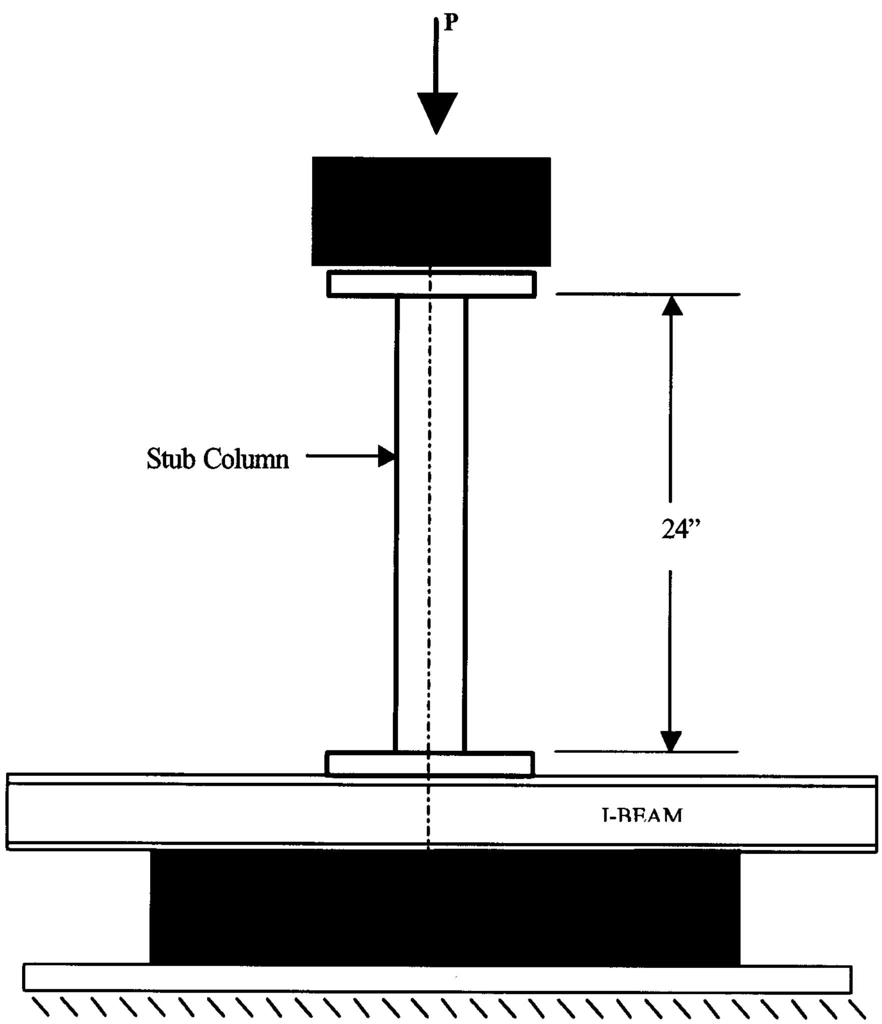

Figure 34 – Stub-Column Test Setup

Shear Wall Test

Test Procedure

The specimens were tested in the NAHB Research Center's "Racker" test apparatus utilizing the ASTM E564 [24] test method. The monotonic (with no load reversal on release) load protocol was used.

Test Specimen and Test Configuration

The main purpose of the test is to determine the shear capacity, stiffness, and failure mode of the slit-web stud wall assembly. One 8 ft x 8 ft (2438 x 2438 mm) shear wall using 5 thermal studs spaced at 24 inches (610 mm) on center was constructed and tested according to the ASTM E 564 test set-up. The top and bottom tracks were standard cold-formed steel, 33-mil (0.84 mm) material. The wall was sheathed on one side with 7/16 OSB (11.11 mm) (fastened at standard 6" edge / 12" (152/305 mm) field screw spacing using No. 8 counter-sink head self-drilling, tapping screws or sharp point). The opposite side was sheathed with ½" (12.7 mm) gypsum wallboard (drywall), fastened using No. 6 sharp point drywall screws spaced at 12 inches (305 mm) on center. The drywall was not taped and mudded with joint compound. Test setup is shown in Figure 35.

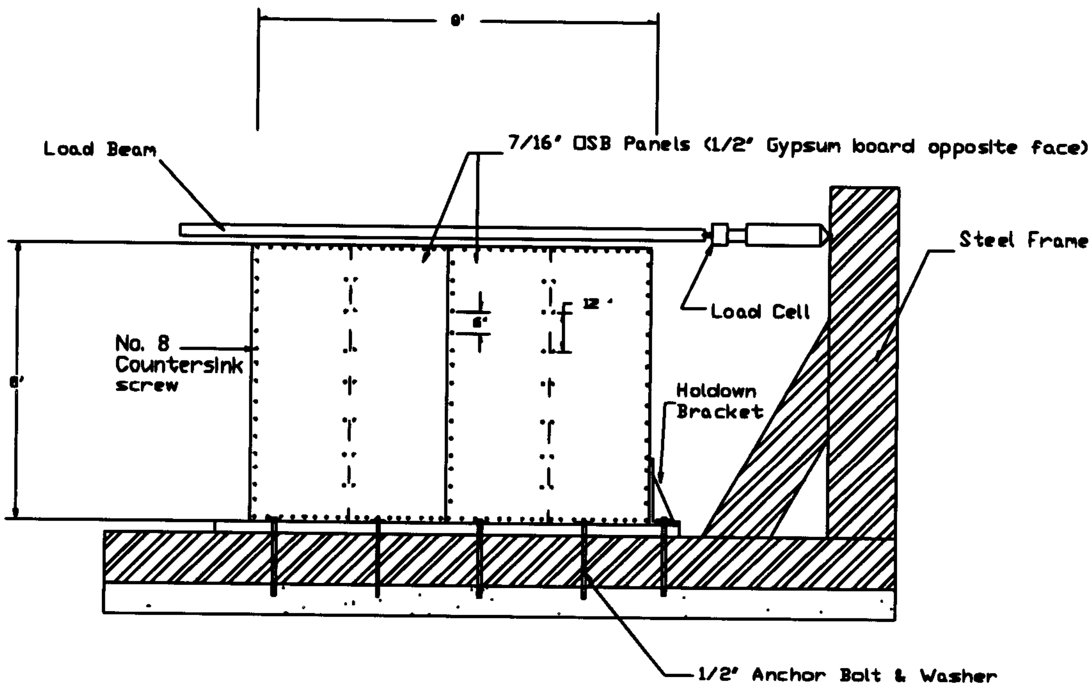

Figure 35 - Shearwall Test Setup

Shear Tests

Test Procedure

The specimens were tested in the NAHB Research Center's Universal Testing Machine (UTM). No standard ASTM test procedure is specifically detailed for testing cold-formed steel beams for shear. The shear test setup shown in Figure 36 is a typical setup that is widely used by the steel industry.

Test Specimen and Test Configuration

The main purpose of the test is to determine the shear strength of the slit-web stud. Each test specimen consisted of two slit-web studs connected to 33-mil (0.84 mm) tracks at the ends, with No. 8 self-drilling tapping screws. The load was applied through a pivot and thick steel plate to distribute the loads equally between both members. A deflection gage was placed under the point load between the supports to measure vertical deflection.

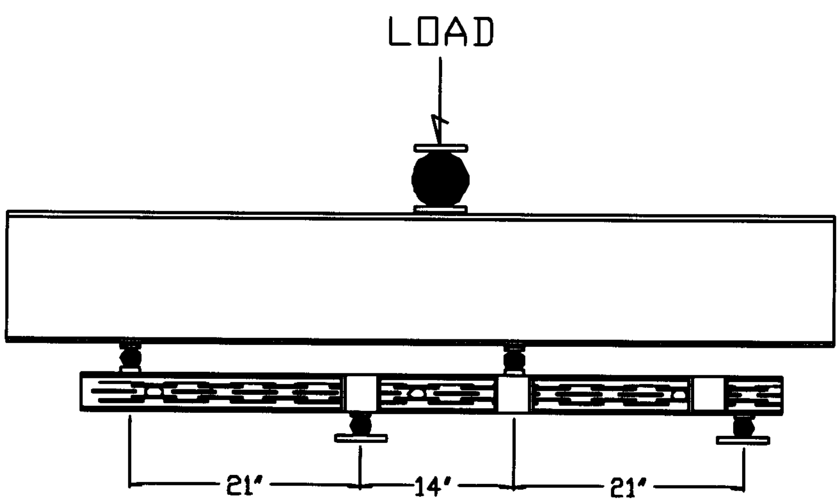

Figure 36 – Shear Test Setup

RESULTS

The results of the structural tests are summarized in this section.

Tensile Tests

Summary results of coupon tests on the slit-web studa are shown in Table 26.

Table 26 – Average Tensile Test Results

Stud Size	Stud Thickness (mil)	Stud Web Type	Yield Strength (psi)	Ultimate Strength (psi)	Thicknes s (inches)
350S162-33	33	Slit Web	43,650	60,320	0.0341
350S162-33	33	Solid Web	34,400	46,500	0.0340

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 psi = 0.0703 kg/cm^2

Bending Tests

Table 27 presents the results of the bending load tests for the slit web stud and similar solid web studs. The solid web studs were tested in the same manner and configuration as the slit web studs.

Table 27 - Bending Load Test Results

Test No.	Stud Size	Stud Thickness (mil)	Stud Web Type	Ultimate Load (lb.)
1	350S162-33	33	Slit Web	519
2	350S162-33	33	Slit Web	496
3	350S162-33	33	Slit Web	517
Average				**511**
Standard Deviation				**12.74**
COV				**0.02**
4	350S162-33	33	Solid Web	348
5	350S162-33	33	Solid Web	310
6	350S162-33	33	Solid Web	361
Average				**340**
Standard Deviation				**26.50**
COV				**0.08**

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

Axial Tests

Table 28 presents the results of the axial load tests for the slit-web stud and solid web studs. The solid web studs were tested in the same manner and configuration as the slit-web studs.

Table 28 – Axial Load Test Results

Test No.	Stud Size	Stud Thickness (mil)	Stud Web Type	Ultimate Load (lb.)
7	350S162-33	33	Slit Web	3,882
8	350S162-33	33	Slit Web	3,950
9	350S162-33	33	Slit Web	4,250
Average				**4,027**
Standard Deviation				**195.81**
COV				**0.05**
10	350S162-33	33	Solid Web	2,900
11	350S162-33	33	Solid Web	2,875
12	350S162-33	33	Solid Web	2,550
Average				**2,775**
Standard Deviation				**195.26**
COV				**0.07**

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

Stub-Column Tests

Table 29 presents the results of the stub-column tests for the slit web stud.

Table 29 – Stub-Column Test Results

Test No.	Stud Size	Stud Thickness (mil)	Stud Web Type	Ultimate Load (lb.)
13	350S162-33	33	Slit Web	4,163
14	350S162-33	33	Slit Web	4,249
15	350S162-33	33	Slit Web	3,788
Average				**4,067**
Standard Deviation				**245.13**
COV				**0.06**

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

ShearWall Test

Table 30 presents the results of the shearwall tests.

Table 30 – Shearwall Test Results

Test No.	Stud Size	Stud Thickness (mil)	Stud Web Type	Test Method	Ultimate Load (lb.)	Stud Thickness (in.)
16	350S162-33	33	Slit Web	ASTM E564	4,114	0.0341
17	350S162-33	33	Slit Web	ASTM E72	4,865	0.0341

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

Test No. 16 was done in accordance with the ASTM E564 [24] test setup. The hold-down was mounted externally to the side of the wall stud. During the test, the hold down connection tore out of the slotted web of the end (tension chord) stud and was considered to be the limiting failure mode (premature failure before the panel capacity was reached). The test was repeated (Test No. 17) using the ASTM E72 [23] test setup in an attempt to eliminate the source of the premature failure and to observe secondary failure modes.

Shear Tests

Table 31 presents the results of the shear tests for the slit-web stud.

Table 31– Shear Test Results

Test No.	Stud Size	Stud Thickness (mil)	Stud Web Type	Ultimate Load (lb.)
18	350S162-33	33	Slit Web	881
19	350S162-33	33	Slit Web	951
20	350S162-33	33	Slit Web	924
Average				**919**
Standard Deviation				**28.83**
COV				**0.0314**

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

FAILURE MODE

Bending Tests

The observed failure mode of the slit-web studs in all bending tests was mainly local buckling under the point load with some distortional buckling. The failure mode was similar to that of the solid-web stud.

Axial Tests

The observed failure mode of the slit-web studs was mainly buckling of the webs between the OSB sheets (for all tests). The failure mode was similar for the solid-web stud. The OSB sheets prevented overall column buckling..

Stub-Column Tests

The observed failure mode of the slit-web stud stub-column tests was mainly distortional buckling at mid-height of the stud.

Shearwall Tests

The first shearwall test (Test No. 16) was tested in accordance with ASTM D564 test method. The hold-down tore the slotted section of the stud out before the panel's capacity was reached. The test was repeated under the ASTM E72 test method with one end stud (compression stud). Again, the wall failed prematurely at the tension chord before the panel's capacity was reached. No failure in the screws or the sheathing was observed during both tests.

Shear Tests

Specimens tested for shear failed in localized buckling of the flanges under the point load.

DISCUSSION

The bending and axial tests showed that a slit-web stud outperformed a solid web stud (higher by 50% and 45% respectively). A portion of the increase in bending and axial capacity can be attributed to the higher yield and ultimate strengths of the slit-web stud (higher by 27% and 30% respectively). The failure modes for both the slit-web and solid-web studs were similar indicating that the louvered slits and edge stiffeners of the slit-web stud caused it resist higher loads.

The shear strength of the slit-web stud is compared to the calculated shear strength of a solid web stud in Table 32. The ultimate shear strength of the solid-web stud was determined in accordance with the AISI Specification using a factor of safety of 1.67. Furthermore, the average thickness, yield strength, and ultimate strength for the slit-web stud were used in calculating the shear capacity of the solid web stud.

Table 32– Shear Load Comparison

Stud Size	Stud Thickness (mil)	Stud Web Type	Ultimate Shear Strength [1] (lb.)	Stud Thickness (in.)
350S162-33	33	Slit Web	919[2]	0.0341
350S162-33	33	Solid Web	825	0.0340

For SI: 1 mil = 1/1000 inch = 0.0254 mm, 1 lb = 4.448 N

[1] The ultimate shear strength of the solid-web stud (punched) was calculated in accordance with the AISI Specification using a factor of safety of 1.67 to adjust up to ultimate load.

[2] Average tested value (see Table 31).

From the above comparison, it is concluded that the shear value for both studs are similar.

Comparison of the slit-web stud shearwall test results to those of a solid-web stud could not be made because the slit-web stud test specimen failed prematurely before the panel's ultimate capacity was reached. The International Building Code (IBC) [25] gives the ultimate (unfactored) shear value for a steel-framed wall (350S162-33 steel studs) of 910 pounds per linear foot (13.28 kN/m). The 910 plf (13.28 kN/m) nominal shear value can be increased by 30% if fully blocked gypsum board is applied to the opposite side of the wall. Therefore, the total shear value of the wall specimen should be 1,183 plf (17.26 kN/m). The IBC shear values are based on double studs at shearwall ends. The ultimate shear load achieved for the slit-web stud tests is 4,865 lb (21.64 kN), which is equivalent to 608 plf (8.87 kN/m). It is believed that the IBC code shear value could have been achieved if double chord studs were used in this test program.

The average effective area at the ultimate load, A_{eua}, of the slit-web stud is derived from the results of the stub-column tests in accordance with Part VII of the AISI Specification.

$$A_{eua} = P_{ua}/F_{ya}$$

Where,

A_{eua} = Effective area.

P_{ua} = Stub-column test ultimate load.

F_{ya} = Measure yield strength of steel.

$A_{eua} = 4{,}067/38{,}700 = 0.1051\ in^2$.

CONCLUSION

In this report, the behavior of 3-1/2 inch (89 mm) slit-web stud (perforated web) was studied. Test results showed that the prototype slit web stud performed similar to or better than a solid-web stud in bending, axial, and shear tests. The shearwall test results indicated the importance of using multiple chord studs and the need to address the connection to the tension chord end stud where heavy connections are made and locally high compressive and tension forces must be transferred through connections or bearing of end studs. Tests also showed that the slit-web stud is very sensitive to the distortional buckling mode. The stub-column tests provided an effective area for the slit-web stud. The effective area is approximately 50% of the gross area.

The 350S162-33 slit-web stud developed and tested in this report was shown to be better than or essentially equivalent to a 350S162-33 solid-web stud in most structural performance characteristics investigated. The reduction in capacity due to the presence of the slots in the web is compensated for by the addition of the draw-in hole (along the centerline of the web), the edge stiffeners, and the bent (louvered) slits.

The application of split-web studs in shearwalls where heavy connections are needed and locally high compressive and tension forces are developed and must be transferred through connections or bearing of end studs should be investigated.

Web crippling was not investigated for the slit-web stud, as it is not considered a failure mode for wall studs constructed within the applicability limits of the Prescriptive Method (fully sheathed walls) [26]. Web crippling strength should be investigated when slit-web studs are used in non-sheathed wall applications.

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