

# OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

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August 31, 2007

Daniel Harkins  
Vice President Operations R&D  
Thermal Design, Inc.  
P.O. Box 324  
Stoughton, Wisconsin 53589

Dear Mr. Harkins:

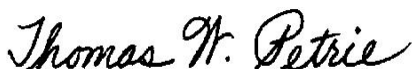
## **TESTS OF STANDING-SEAM METAL ROOF ASSEMBLIES**

Attached is a summary report on the tests of standing-seam assemblies that we did with you in 2006 and early 2007 under the terms of User Agreement UF-05-455 between Thermal Design, Inc. and UT-Battelle LLC, manager of the Oak Ridge National Laboratory (ORNL). My signature on this letter of transmittal affirms that I prepared the report and that it accurately presents the results of the tests.

The purpose of this report is to present the results and explain how they were obtained for the Simple Saver Systems™ and over-the-purlin systems covered by standing-seam metal roofs. Special procedures and analysis techniques were followed for these tests. They are explained in a common section before subsections devoted to each system.

Thank you for the opportunity to use the capabilities of the Large Scale Climate Simulator to demonstrate improved thermal performance of standing-seam metal roofs with your Simple Saver System™.

Sincerely,



Thomas W. Petrie  
Research Engineer

Attached: Tests of Standing-Seam Metal Roof Assemblies

## **Tests of Standing-Seam Metal Roof Assemblies**

### **Introduction**

The Buildings Technology Center at the Oak Ridge National Laboratory did steady-state guarded hot box tests in its Large Scale Climate Simulator (LSCS) in 2006 and early 2007 to compare the thermal performance of over-the-purlin insulation configurations and Thermal Design's Simple Saver System™ under standing-seam metal roofs with various purlin spacings. Test program design, construction of the test assemblies, and execution and analysis of the experiments were done under the terms of User Agreement UF-05-455 between Thermal Design, Inc. and UT-Battelle LLC, manager of the Oak Ridge National Laboratory (ORNL). Assemblies were constructed outside the LSCS by Thermal Design personnel to suit the 8 ft by 8 ft metered area of the LSCS. ORNL personnel moved the tests sections into the LSCS, insulated around their perimeters, instrumented them, and conducted the tests for thermal performance. No structural changes were made to the test sections as built by Thermal Design and no evaluation was made of them other than thermal performance as built. The Simple Saver configurations had blown-in cellulose insulation and R-30 fiberglass blanket insulation. Another configuration had a single R-19 fiberglass blanket over the purlins. The fourth insulation configuration had an R-11 blanket over the purlins with a layer of R-19 fiberglass added between the purlins, a so-called sag-and-bag configuration.

Post-test measurements were done of insulation thickness in the metered area and insulation thermal conductivity as a function of density. These measurements allowed the heat flow through the 8 ft x 8 ft metered area of the assemblies to be corrected to heat flow for an 8 ft long area with width corresponding to an integral number of purlin spacings nearest to 8 ft. The corrected heat flow yielded U-values corresponding to purlins spaced 60 in., 30 in. or 20 in. oc in the field of a large roof. Linear behavior of the U-values was observed when they were plotted vs. inverse of purlin spacing. This behavior allows interpolation of the U-values from the tests to other purlin spacings of possible interest.

### **Details of Test Section Construction**

The test assemblies used 14 gauge steel purlins nominally 8-in. high with 2-in.-wide flanges. The purlins were supplied with proper length by Behlen Manufacturing Company. Besides the purlins spaced 60 in., 30 in. or 20 in. oc within the metered area, purlins were installed at the two edges of each test section parallel to those inside the metered area. They served to provide structural support at these edges. They were not important for evaluation of the thermal performance of the assemblies. Under the other two edges of each test section, the ends of the purlins were attached to nominal 4x4 wood beams. For the Simple Saver configurations, a lattice of metal strips was installed under the purlins. Polyethylene fabric, about 6 mils thick, was unfolded over the lattice and under the purlins. It was stretched as taut as it is in the field and attached to the 4x4 wood beams. Metal spacer bars maintained purlin spacing and added stability. In field applications the high density reinforced fabric, with a water vapor transmission rating of 0.02 perms, is a vapor retarder and forms a liner for OSHA certification of protection against through fall and falling objects.

For the fiberglass-insulated Simple Saver configurations, the fabric supported nominal R-19 unfaced blanket insulation of proper width to fit between the purlins. An additional layer of nominal R-11 unfaced blanket insulation was installed over the entire assembly, including the purlins. To form the standing-seam system, 24 gauge steel roof panels, 2-ft wide, were attached at their edges to clips and to each other. The clips were attached by screws through compressed

R-11 insulation to the purlins. Standard expanded polystyrene (EPS) thermal blocks,  $\frac{3}{4}$  in. thick by 3 in. wide by 23 in. long, were laid over the purlins on top of the insulation between the clips. The R-11 insulation was also compressed between the purlins and the bottom of these thermal blocks in this assembly.

For the cellulose-insulated Simple Saver configurations, two roof panels were installed at one end of the assembly. Fiberglass insulation was fitted into the space at the edge to prevent cellulose from falling out. Cellulose was blown into the cavity under the roof panels. Blowing continued as progressively more panels were added. When the entire roof was in place, fiberglass insulation was installed at the other end of the assembly to prevent cellulose from falling out. To partially break the thermal bridge between the clips and the purlins, and more so between the metal roof and the purlins, the EPS thermal blocks were taped to the top of the purlins before the clips and roof panels were put in place. Fig. 1 is a photograph of the cellulose-filled Simple Saver configuration with purlins 60 in. oc, taken during disassembly after testing. Some roof panels are in place and the thermal blocks are visible on top of the purlins. The cellulose does not quite fill the cavity between the purlins in this assembly.



**Fig. 1 Simple Saver Configuration with Cellulose Insulation**

For the non-Simple Saver configurations, the insulation draped over the purlins was faced blanket insulation. In the assemblies with a single layer of insulation, the facing on nominal R-19 insulation was stretched tautly across the purlins and secured at the edges. Clips were attached by screws through the compressed R-19 insulation to the purlins. EPS thermal blocks were laid over the purlins on top of the insulation and roof panels were put in place. In the assemblies with sag-and-bag configurations, the facing on nominal R-11 insulation was stretched tautly across the purlins. Clips were attached by screws through the compressed R-11 insulation to the purlins. Unfaced R-19 insulation of the proper width was then laid between the purlins. EPS thermal blocks were laid over the purlins on top of the R-11 insulation and roof panels were put in place. Fig. 2 shows a sag-and-bag configuration with some roof panels in place. The thermal blocks are barely visible between the pieces of R-19 insulation. It is obvious from this picture that the fiberglass insulation was severely compressed between the roof and the liner.



**Fig. 2 Sag-and-Bag Configuration with Fiberglass Insulation**

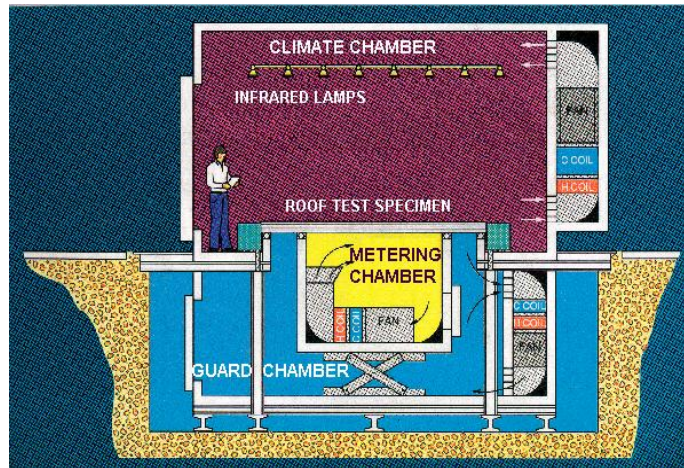
The same was true for the single layer of R-19 insulation in the other non-Simple Saver configurations.

Care was taken by Thermal Design personnel in all non-Simple Saver assemblies to achieve what they considered to be the typical amount of sag of the liner between purlins. The amount of sag was measured by Thermal Design at ten installations in the field and installed in the configurations as closely as possible. Measurement of the actual sag that was achieved was not done accurately until after the tests as part of the post-test analysis.

### **Instrumentation and Test Procedures**

Each test assembly was lifted by crane into the LSCS. A sketch of the LSCS is shown in Fig. 3 to illustrate the placement of an assembly with the climate chamber above it and the metering and guard chambers below it. Each assembly was fully instrumented with the same set of thermocouples on the upper and lower surfaces. Within the vertical projection of the metered area, nine thermocouples were fixed to the upper surface and another nine to the lower surface. An additional four thermocouples on the upper surface and four on the lower surface were placed outside the vertical projection of the metered area near the corners of the metering chamber walls. An array of 21 thermocouples measured metering chamber air temperature about 3 in. below the top of the metering chamber. Nine thermocouples in the air 3 in. below the bottom surface of each assembly augmented these data, especially when the bottom surface was near the top of the purlins in the over-the-purlin configurations. The thermocouples in the air under the assemblies were placed at the locations of the thermocouples on the bottom surface in the metered area. An array of 25 thermocouples measured the air temperature in the climate chamber about 3 in. above the roof surface.

The metering chamber could be raised at most to the bottom of the purlins. For the Simple Saver configurations, it was raised within about an inch of this limit to leave the same space between the liner and the purlins as in actual applications. A gauge block exactly an inch thick was placed under the purlins between the liner and the top of the metering chamber wall when the metering chamber was close to the fully-raised position for a given test. When there was some resistance to removing the block, the fully-raised position was declared. Masking tape was used to seal any small gaps between the liner and the metering chamber walls in order to prevent air leakage between the guard and metering chambers.



**Fig. 3 Sketch of the Large Scale Climate Simulator**

For the non-Simple Saver configurations, the metering chamber was raised against the purlins. This left a gap all around the perimeter of the metering chamber that required extensions of the metering chamber walls. Pieces of 2-in.-thick extruded polystyrene (XPS) foam with known R-value were cut to fit the contour of the draped insulation and were placed flush with the inside perimeter of the 4-in.-wide metering chamber walls. The area of each piece was measured and thermocouples were affixed to the inside and outside surfaces of each piece. Masking tape was used to seal the pieces of XPS to the liner, metering chamber walls and purlins.

The purpose of the metering chamber is to obtain the steady-state energy flow through the 64 ft<sup>2</sup> of open area at the top of the metering chamber. Energy flows due to the temperature difference imposed between the climate and metering chambers and across the test section. This energy flow is obtained by measuring all other energy flows into the metering chamber in accordance with ASTM C-1363, Standard Test Method for the Thermal Performance of Building Assemblies by Means of a Hot Box Apparatus. They include the amount across the metering chamber walls and floor due to any imbalance between the metering and guard chamber temperatures. The energy flow for the walls and floor was determined as a function of the measured surface temperature imbalance by previous use of a calibration panel, that is, a simple test section with known thermal resistance. Energy flow through the metering chamber walls and floor is given by the sum over all faces. On each wall and the floor, the average temperature difference measured by nine differential thermocouples is multiplied by the component's area and divided by its R-value. The same calibration panel is used periodically to establish the overall accuracy of energy balances for the metering chamber (1). The accuracy is generally of the order of  $\pm 10\%$ . The precision is generally of the order of  $\pm 1\%$  as a result of excellent control of imposed conditions by the control system. Proportional-Integral control is done under the direction of a Programmable Logic Controller.

The usual operation of a guarded hot box calls for minimizing the heat flow through the metering chamber walls and floor. This is accomplished in the LSCS by adjusting the air temperatures in the guard and metering chambers separately until there is nearly zero average surface temperature difference across the metering chamber walls and floor. However, despite the presence of fans to move air in the guard chamber, there are floor to ceiling gradients in the air temperature in the guard chamber. When the climate chamber is cooler than the metering and guard chambers and the average air temperatures in the metering and guard chambers are the

same, the guard chamber is cooler than the metering chamber near the top of the metering chamber walls. Therefore, even if there is no net heat flow between the guard and metering chambers through the walls and floor of the metering chamber, temperature differences exist. Heat flows from the metering chamber to the guard chamber near the top of the metering chamber walls and vice-versa near the bottom of the walls and across the floor. For these tests, this causes heat to flow horizontally through the purlins and, for the non-Simple Saver configurations, also through the XPS foam extensions of the metering chamber walls.

The heat flow through each foam extension, when used, was determined by measuring surface temperature difference across it, multiplying by its area and dividing by its R-value. Heat flow along the purlins cannot be measured easily or accurately. Unsuccessful attempts were made to get consistent temperature differences along the purlins where they crossed the metering chamber walls by placing thermocouples on or below the bottom of the purlins. A special operating procedure was adopted for all these tests. The average air temperature in the guard chamber was controlled at a higher level than in the metering chamber. For the Simple Saver configurations, the level was chosen to obtain nearly zero difference in liner surface temperatures from outside to inside the metering chamber on the two sides where purlins crossed the walls. For the non-Simple Saver configurations, the level was chosen to obtain nearly zero difference across the foam extensions on the two sides of the metering chamber where purlins crossed the walls.

For comparison, the standard operating procedure was also followed in which nearly zero net heat flow occurred across the metering chamber walls and floor. Not surprisingly, because of the unreported but significant heat flow along the purlins with the standard operating procedure, total heat flow reported for the test section was different by the special and standard procedures. This was despite the same imposed conditions in the climate and metering chambers. From use of the calibration panel, the heat flow through the metering chamber walls and floor has been observed to be linear with temperature difference across them. The difference in heat flows between the special and standard operating procedures was assumed to be linear with the difference from outside to inside the metering chamber in either liner surface temperatures or extension surface temperatures on the two sides where the purlins crossed the walls. Using this relationship, total heat flow for exactly zero difference was reported as the measured heat flow.

### **Post-Test Characterization of Test Sections**

At the conclusion of each test, before the test section was moved out of the LSCS, holes were drilled through the roof panels to admit a pin probe. It was used to determine depth from the bottom of the roof panels to the top of the liner or purlins. Eight holes were drilled parallel to the purlins at each location shown in Fig. 4. Each set was two holes in flat parts of each of the four roof panels within the vertical projection of the metered area. The numbers in Fig. 4 are the average of the eight measurements at each location for the cellulose-insulated and fiberglass-insulated Simple Saver configurations. As Fig. 1 showed, with purlins 60 in. oc (two purlins in the metered area), the cellulose settled during the tests and no longer filled the entire cavity. Depth of cellulose insulation was measured outside the LSCS after the roof panels were removed. The results are added to Fig. 4. With the three and four purlin configurations, there was no evidence that the cellulose settled. For fiberglass-insulated Simple Saver configurations, the entire cavity was assumed to be filled since the insulation was free to expand.

Care was taken with the Simple Saver configurations to raise the metering chamber so it barely touched the bottom of the liner. As explained earlier, a one inch gauge block was used so

as not to bring the metering chamber tight against the bottom of the purlins like in the non-Simple Saver configurations. Regardless, the metering chamber did compress the insulation slightly along the edges where the purlins crossed the wall and this compression was ignored in the analysis. The metering chamber also compressed the insulation where it pushed against the liner parallel to the purlins. This compression was taken out of the results by the analysis.

Table 1 lists the average distance from the bottom of the standing-seam roof to the top of the liner for the three purlin spacings and two insulations used for the Simple Saver configurations. This distance is the average of the seven to nine numbers for each insulation in the lower half of each sketch in Fig. 4. As stated above, each of the numbers shown in Fig. 4 is itself an average over eight locations from metering chamber wall to metering chamber wall parallel to the purlins. The first and last of the eight locations were within six inches of the walls. Next to the average over all eight locations in Table 1 is the average for the first and last locations. The difference between these two columns is given in the last column. The possible effect is 0.1 to 0.3 in. more insulation depth at the edges or an average of less than 0.2 in. if the compression was not present.

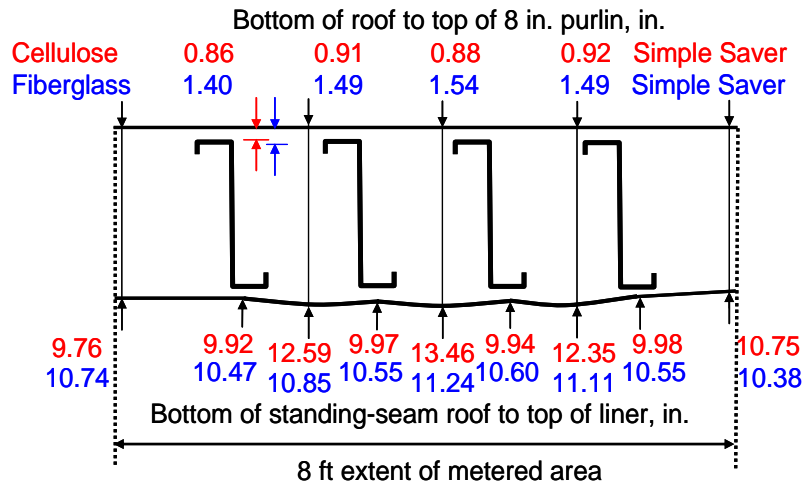
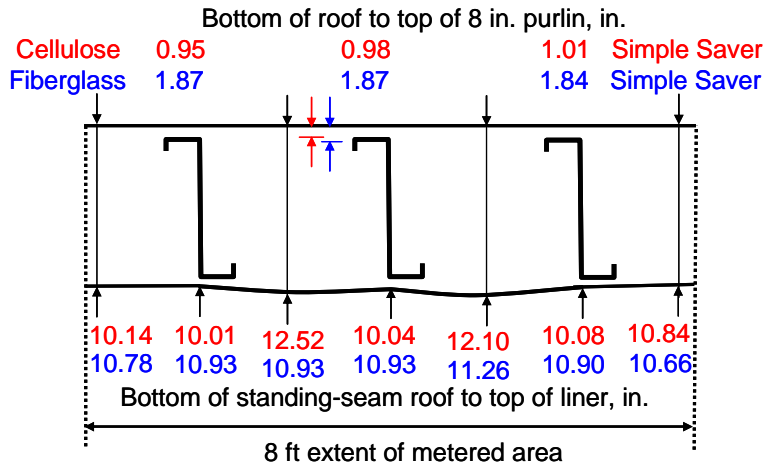
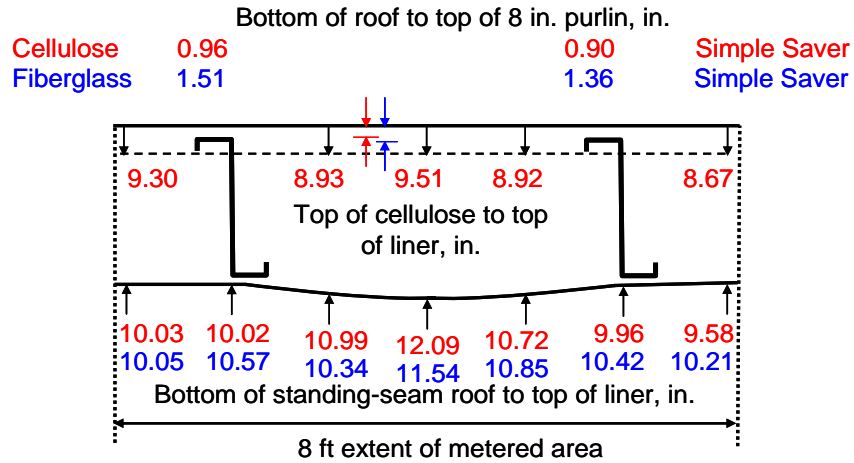
Table 1. Compression of insulation along the edges where the purlins crossed the metering chamber walls.

Simple Saver Configuration	Average Fig. 4, in.	Average edge, in.	Difference, in.
Cellulose, two purlins	10.49	10.29	0.20
Fiberglass, two purlins	10.57	10.40	0.17
Cellulose, three purlins	10.82	10.53	0.29
Fiberglass, three purlins	10.91	10.79	0.12
Cellulose, four purlins	10.97	10.72	0.25
Fiberglass, four purlins	10.72	10.60	0.12
AVERAGE DIFFERENCE			0.19

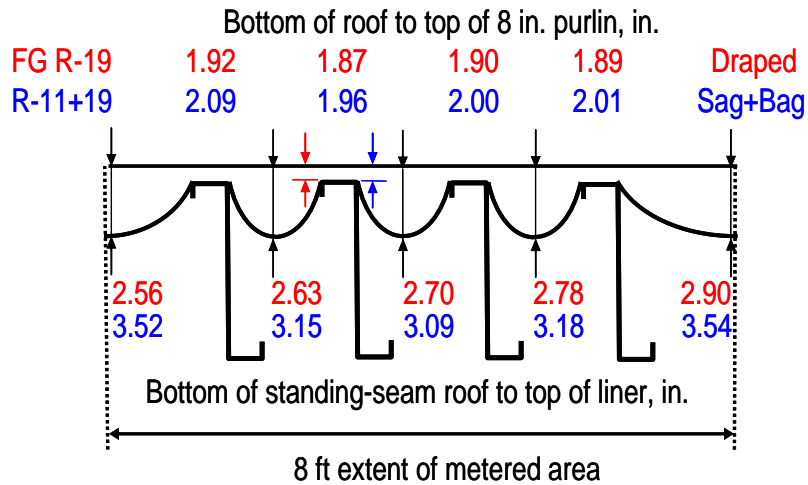
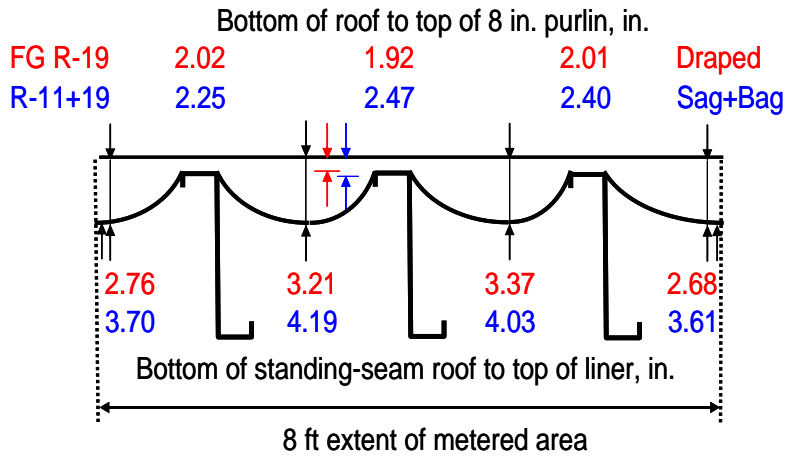
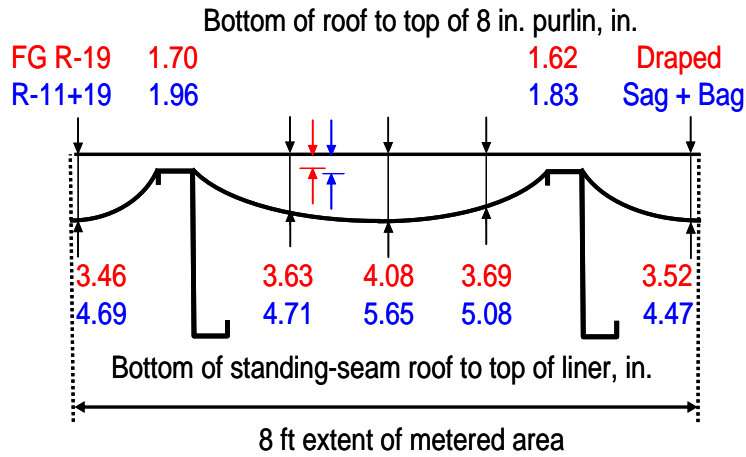
Figure 5 shows the depth from the bottom of the roof panels to the top of the liner for the non-Simple Saver configurations. Again, eight holes were drilled parallel to the purlins at each location shown in Fig. 5, with two of each set in flat parts of each of the four roof panels in the metered area. The numbers in Fig. 5 are the average of the eight measurements at each location for these configurations with fiberglass insulation. Unlike for fiberglass-insulated Simple Saver configurations, the insulation between purlins is severely compressed between the roof panels and the tightly stretched liner.

### Characterization of Insulation Used in the Test Sections

After the tests of the Simple Saver configurations insulated with cellulose, the amount blown in the metered area was removed from the test section and weighed. Depth from the pin probe measurements and extracted area yielded volume of insulation as tested. The resulting density was 2.00, 1.99 and 2.72 lb/ft<sup>3</sup> for the two, three and four purlin configurations, respectively. A sample of the cellulose was loaded into a heat flow meter apparatus to determine thermal conductivity at 75°F mean temperature by ASTM C-518, Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus. The sample had a density of 2.19 lb/ft<sup>3</sup> and the test yielded a thermal conductivity of 0.2738 Btu·in./(h·ft<sup>2</sup>·°F). A correlation of heat flow meter results by D.W. Yarbrough of R&D Services



**Fig. 4 Results of Pin Probe Measurements for the Simple Saver Configurations**



**Fig. 5 Results of Pin Probe Measurements for the non-Simple Saver Configurations**

on samples of the same brand of cellulose insulation was corrected to the thermal conductivity measured for this sample at its density. It gives thermal conductivity at 75°F as a function of density:

$$k_{\text{cellulose}} = 1/(2.7313 + 0.5437\rho - 0.0563\rho^2) \quad (1)$$

where,

$k_{\text{cellulose}}$  is thermal conductivity of the cellulose in Btu·in./(h·ft<sup>2</sup>·°F), and  $\rho$  is its density in lb/ft<sup>3</sup>.

For example, a density in the test section of 2.00 lb/ft<sup>3</sup> for the two purlin configuration yields thermal conductivity of 0.2783 Btu·in./(h·ft<sup>2</sup>·°F). For the average thickness of 9.07 in. measured for the two purlin configuration in the metered area, thickness divided by thermal conductivity yields R-value of 32.6 h·ft<sup>2</sup>·°F/Btu for the cellulose insulation in the metered area of this test section.

For the fiberglass used in the Simple Saver configurations, samples of the R-19 and the R-11 blankets were cut to the size needed in the heat flow meter apparatus (approximately 2 ft x 2 ft). Area and weight of each sample were measured. The samples were tested at mean temperature of 75°F and various thicknesses, resulting in values of thermal conductivity at 75°F for different densities. A correlation by K.E. Wilkes (2) for many samples of fiberglass batts and blankets gives thermal conductivity as a function of density at 75°F as follows:

$$k_{\text{fiberglass}} = 0.19815 + 0.001573 \rho/\rho_{\text{nom}} + 0.11686 \rho_{\text{nom}}/\rho \quad (2)$$

where,

$k_{\text{fiberglass}}$  is thermal conductivity of fiberglass in Btu·in./(h·ft<sup>2</sup>·°F),  $\rho$  is its density in lb/ft<sup>3</sup>, and  $\rho_{\text{nom}}$  is its nominal density in lb/ft<sup>3</sup>.

Equation (2) yields 0.3166 Btu·in./(h·ft<sup>2</sup>·°F) at  $\rho/\rho_{\text{nom}}=1$ . Table 2 gives the results of measurements on the two samples. The values for the Wilkes' correlation in Table 2 are the result of multiplying the result of Equation (2) by the nominal thermal conductivity for each sample and dividing by 0.3166. Nominal properties for each sample are taken to be the thickness and thermal conductivity that yield R-19 and R-11, respectively. With this adjustment, the agreement between thermal conductivity from the measurements and the correlation is excellent, no worse than ±0.003. More tests were done on the R-11 sample than the R-19 sample because

Table 2. Results of thermal conductivity measurements on samples of the R-19 and R-11 fiberglass blanket insulation and comparison to a correlation by Wilkes (2). *Tests selected for nominal thermal conductivity and density are in italics.*

Thermal conductivity, Btu·in./(h·ft <sup>2</sup> ·°F)	Thickness, in.	R-value, h·ft <sup>2</sup> ·°F/Btu	Density, lb/ft <sup>3</sup>	$\rho/\rho_{\text{nom}}$	Wilkes Correlation
R-19 blanket					
0.3132	6.25	19.96	0.617	0.920	0.3120
<i>0.3024</i>	<i>5.75</i>	<i>19.01</i>	<i>0.671</i>	<i>1.000</i>	<i>0.3024</i>
0.2500	3.125	12.50	1.234	1.840	0.2527
R-11 blanket					
0.2994	3.50	11.69	0.651	0.907	0.2989
<i>0.2881</i>	<i>3.174</i>	<i>11.02</i>	<i>0.717</i>	<i>1.000</i>	<i>0.2881</i>
0.2821	3.00	10.63	0.759	1.058	0.2823
0.2420	1.75	7.23	1.301	1.814	0.2415
0.2211	1.00	4.52	2.277	3.174	0.2184

an extra test was required to find the nominal conditions and because it was desired to verify the correlation at high density. The R-19 and R-11 fiberglass blankets in the non-Simple Saver configurations were assumed to behave the same as the R-19 and R-11 blankets in Table 2.

### **Correction of Measured Heat Flows to Yield Results for the Field of a Roof**

The heat flows from the metering chamber energy balance are for the 8 ft x 8 ft metered area of the LSCS. The post-test characterization of the test sections was used to correct to heat flows for an 8 ft by (2x60) in. or (3x30) in. or (4x20) in. area in the field of a large roof, that is, heat flow for an integral number of purlin spacings. These heat flows can then be used to generate R-values and U-values that apply to the field of roofs of similar construction and purlin spacing. These R-values and U-values account for the thermal bridges due to the purlins and compressed insulation but not those due to edge effects, penetrations, supports for equipment, *etc.*, on the roof.

Ignoring the slight compression where the purlins cross the metering chamber walls, three corrections are necessary. One accounts for the two-dimensional heat flow around the perimeter of any test section in the LSCS because of the flat top of its metering chamber walls, or extensions if used. Another subtracts the heat flow outboard from the purlins to the metering chamber walls, using the insulation depth measured from the purlins to the metering chamber walls. The third adds heat flow outboard from the purlins to a half purlin spacing on each side, using insulation depth measured between the purlins. Details about these corrections follow.

Two-dimensional and three-dimensional heat flow occurs when test specimens rest on the flat-topped walls or extensions of the metering chamber. One-dimensional heat exchange between the test specimen and the guard and metering chambers is distorted. Modeling only two-dimensional heat flow over the 4-in.-wide metering chamber walls has been verified to accurately correct metering chamber heat flow. Model results were used with the calibration panel for the LSCS. The modeling results are generalized in terms of a multiplier for the metering chamber opening of 64 ft<sup>2</sup>:

$$M = 0.012379 \cdot \ln(R) + 1.04582 \quad (3)$$

where,

M is effective area for heat transfer into the metered area divided by 64 ft<sup>2</sup>, and

R is the R-value in h-ft<sup>2</sup>·°F/Btu of the insulation over the metering chamber walls.

For low R-value test sections the multiplier tends to 1.00; for high R-value test sections the multiplier extends the effective area for heat flow into the metering chamber as far as the middle of the metering chamber walls. In order to not exceed the area out to the middle of the metering chamber walls, the maximum allowed value of the multiplier is 1.085.

The procedure followed for all test sections was to compute the multipliers by Equation (3) separately for the edges parallel to the purlins (clear edges) and for the edges where the purlins crossed the metering chamber walls. For the clear edges, average thickness of insulation measured at the metering chamber walls parallel to the purlins was used with Equations (1) and (2) to generate insulation R-value there. For the edges where purlins crossed the walls, the measured air-to-air R-value in the tests was diminished by the measured R-values of the top and bottom air films to get an R-value that included the effects of the purlins along the edges where purlins crossed the walls.

For the Simple Saver configurations, each multiplier minus one was multiplied by half of 64 ft<sup>2</sup> to yield the extra area on the clear or purlin-crossed edges of the 4-in.-wide walls. This area was effectively included in the measured heat flow. For the 2-in.-wide metering chamber

extensions used with the non-Simple Saver configurations, the extra area was taken to be half of what was figured for 4-in.-wide walls. Each area multiplied by the temperature difference across the insulation and divided by the appropriate R-value yields the heat flow included in the measured heat flow that is due to the two-dimensional effects. It would not be present in the field of a roof so was subtracted from the measured heat flow.

For all test sections to yield data applicable to the field of a roof, it is also necessary to subtract heat flow at the clear edges to account for differences in insulation thickness outside the purlins compared to thickness between the purlins. In the LSCS these differences are due primarily to the effects of bringing the metering chamber in contact with the bottom of the test section. In addition, heat flow must be added at the clear edges to get heat flow for an area of 8 ft by an integral number of purlin spacings.

For these corrections, data in Figs. 4 and 5 were used along with Equations (1) and (2). The average insulation R-values from purlins to metering chamber walls were estimated based on average insulation depths measured there. Average insulation R-values between the purlins in the metered area were estimated similarly. The heat flow to subtract is the area from each outboard purlin to the metering chamber wall, multiplied by the temperature difference across the insulation and divided by the appropriate R-value. The heat flow to add is the area between a pair of purlins multiplied by the temperature difference across the insulation and divided by average insulation R-value between the outboard purlins in the heart of the test section. By subtracting and adding only the effect of insulation, the effect on heat flow of the thermal bridges due to the purlins is not affected. It remains in the heat flow reported for the area of 8 ft by an integral number of purlin spacings.

## Test Results and Discussion:

### a) Simple Saver Configurations Insulated with Cellulose

The average gaps from the roof to the purlins for the Simple Saver configurations insulated with blown-in cellulose were 0.93 in. with two purlins, 0.98 in. with three purlins and 0.89 in. with four purlins. Only EPS thermal blocks are between the roof and purlins in these Simple Saver configurations. It is reasonable that the gap is only slightly larger than the 0.75 in. thickness of the thermal blocks. The variation from configuration to configuration is random and small. The measured depth of insulation and its thermal conductivity as a function of density yielded average insulation R-values in the test sections of R-32.8 with two purlins 60 in. oc, R-39.3 with three purlins 30 in. oc and R-42.4 with four purlins 20 in. oc.

Table 3a gives detailed results from the tests of the Simple Saver configurations insulated with blown-in cellulose. They include the system R-values obtained from the difference in air temperatures across each test section, multiplied by the nominal 64 ft<sup>2</sup> of metering chamber area exposed to the test section, and divided by the heat flow from the metering chamber energy balance. This heat flow is the value for exactly zero temperature difference between the guard and metering chambers at the top of the metering chamber walls. The R-value of the cellulose in the configuration with purlins 60 in. oc was inconsistently low so heat flow for this test was inconsistently high.

Table 3a. Detailed test results for Simple Saver configurations insulated with blown-in cellulose. All temperatures are in °F. Heat flows out of the metering chamber are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). Results are averages for 24 to 60 hours after steady-state was achieved in each test.

	Climate Air	Meter Air	MC Heat Flow	R-value top film	R-value bottom film	R-value air to air	U-value air to air
Purlins 60 in. oc	50.03	100.01	127.94	0.71	0.44	25.00	0.0400
Purlins 30 in. oc	50.13	100.04	105.73	0.63	0.48	30.22	0.0331
Purlins 20 in. oc	50.04	100.00	113.06	0.57	0.40	28.29	0.0353
	Insulation Average	Insulation Bottom-Top	Surface Top	Purlin Top	Surface Bottom	Purlin Bottom	Air Bottom
Purlins 60 in. oc	75.28	47.68	51.4	52.7	99.1	97.5	100.0
Purlins 30 in. oc	75.21	47.98	51.2	52.2	99.2	98.0	100.0
Purlins 20 in. oc	75.17	48.25	51.0	51.9	99.3	99.0	100.1

Table 4a summarizes the corrections to the heat flow for the cellulose-insulated Simple Saver configurations. The results for thermal performance in the field of a roof are then presented. Note that the different field areas for the different purlin spacings makes the heat flow through these areas appear to be inconsistent with the increased thermal bridging as number of purlins increases. For purlins 60 in. oc the R-values and U-values are for the same level of cellulose insulation as for the test with purlins 30 in. oc. This is to eliminate the effect of too little insulation in the two purlin configuration. Appendix A shows how the surface-to-surface R-value increases from 27.0 to 31.2 using the Modified Zone Method that was developed for walls with metal studs. It was applied to the configuration as tested in order to establish the effective width of the flanges. With Z-shaped metal purlins, more distortion of the heat flow than occurs with C-shaped metal studs is reasonable. Trial-and-error established that an effective width of 2.08 in. rather than the nominal 2 in. width of the flanges duplicated the measured surface-to-

surface R-value of 27.0 with insulation yielding R-value of 32.8. This effective width was then used with insulation yielding R-value of 39.3 to predict surface-to-surface R-value of 31.2.

Table 4a. Corrections to heat flow and resulting thermal performance in the field (area = 8 ft by integral number of purlin spacings nearest to 8 ft) of a standing-seam roof over Simple Saver configurations insulated with blown-in cellulose. Heat flows are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). ASHRAE (3) summer R-values use 0.25 for the top film (7.5 mph wind over the roof) and 0.92 for the bottom film (free convection downward from non-reflective surfaces). ASHRAE winter R-values use 0.17 for the top film (15 mph wind over the roof) and 0.61 for the bottom film (free convection upward to non-reflective surfaces). These film R-values are specified in §9.4.1 of ASHRAE 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (4).

	R-value clear edge	Heat Flow clear edge	R-value purlin edge	Heat Flow purlin edge	Heat Flow purlin to wall	Heat Flow outside purlins	Heat Flow for field area
Purlins 60 in. oc	32.3	-4.02	23.8	-5.44	-35.49	58.19	141.18
Purlins 30 in. oc	37.7	-3.46	29.1	-4.48	-31.24	24.41	90.96
Purlins 20 in. oc	38.9	-3.37	27.3	-4.80	-30.20	15.16	89.85
	R-value surf-to-surf	R-value meas. films	U-value meas. films	R-value summer films	U-value summer films	R-value winter films	U-value winter films
Purlins 60 in. oc	31.2*	32.3	0.0309	32.3	0.0309	32.0	0.0313
Purlins 30 in. oc	31.6	32.8	0.0305	32.8	0.0305	32.4	0.0308
Purlins 20 in. oc	28.6	29.6	0.0338	29.8	0.0336	29.4	0.0340

\*With same insulation level as test for purlins 30 in. oc. See Appendix A

Figure 6a shows the behavior of the winter ASHRAE U-values in Table 4a as a function of the inverse of purlin spacing. This figure is useful for estimating U-value at other purlin spacings than in Tables 3a and 4a, despite the lack of much dependence on purlin spacing for this system.

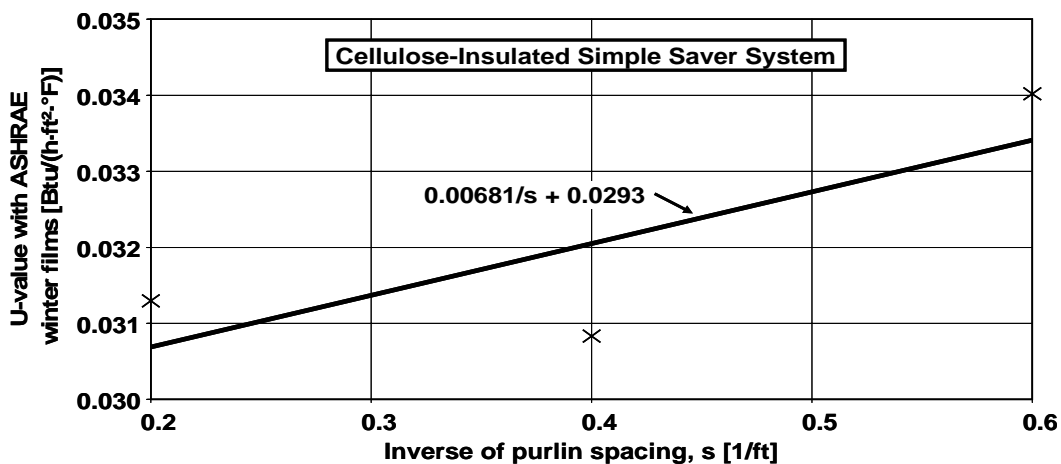


Fig. 6a ASHRAE Winter U-values for a Simple Saver System Insulated with Cellulose

**Test Results and Discussion:**

**b) Simple Saver Configurations Insulated with Fiberglass**

The average gaps from the roof to the purlins for the Simple Saver configurations insulated with fiberglass blankets were 1.44 in. with two purlins, 1.86 in. with three purlins and 1.48 in. with four purlins. These configurations had a compressed R-11 blanket between the clips and purlins. Apparently, the clips in the configuration with two and four purlins were screwed down to the purlins more tightly than they were in the three purlin configuration. The measured depth of insulation and its thermal conductivity as a function of density yielded average insulation R-values in the test sections of R-33.6 with two purlins 60 in. oc, R-33.6 with three purlins 30 in. oc and R-33.2 with four purlins 20 in. oc. Such uniformity is the result of using fiberglass blanket insulation that is allowed to fully expand between the purlins.

Table 3b gives detailed results from the tests of the Simple Saver configurations insulated with fiberglass blankets. They include the system R-values obtained from the difference in air temperatures across each test section, multiplied by the nominal 64 ft<sup>2</sup> of metering chamber area exposed to the test section, and divided by the heat flow from the metering chamber energy balance. This heat flow is the value for exactly zero temperature difference between the guard and metering chambers at the top of the metering chamber walls. The heat flow increases almost linearly with the number of purlins in the metered area, that is, in response to the linearly increasing thermal bridging.

Table 3b. Detailed test results for Simple Saver configurations insulated with fiberglass blankets. All temperatures are in °F. Heat flows out of the metering chamber are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). Results are averages for 24 to 60 hours after steady-state was achieved in each test.

	Climate Air	Meter Air	MC Heat Flow	R-value top film	R-value bottom film	R-value air to air	U-value air to air
Purlins 60 in. oc	49.98	100.01	126.74	0.73	0.44	25.26	0.0396
Purlins 30 in. oc	50.05	100.02	148.84	0.58	0.48	21.49	0.0465
Purlins 20 in. oc	50.08	100.04	162.71	0.57	0.46	19.65	0.0509
	Insulation Average	Insulation Bottom-Top	Surface Top	Purlin Top	Surface Bottom	Purlin Bottom	Air Bottom
Purlins 60 in. oc	75.28	47.71	51.4	51.9	99.1	96.4	99.9
Purlins 30 in. oc	75.15	47.51	51.4	51.9	98.9	96.9	99.8
Purlins 20 in. oc	75.21	47.36	51.5	51.9	98.9	97.2	99.8

Table 4b summarizes the corrections to the heat flow for the fiberglass-insulated Simple Saver configurations along with the results for thermal performance in the field of a roof. Note that the different field areas for the different purlin spacings makes the heat flow through these areas appear to be inconsistent with the increased thermal bridging as number of purlins increases.

Table 4b. Corrections to heat flow and resulting thermal performance in the field (area = 8 ft by integral number of purlin spacings nearest to 8 ft) of a standing-seam roof over Simple Saver configurations insulated with fiberglass blankets. Heat flows are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). ASHRAE (3) summer R-values use 0.25 for the top film (7.5 mph wind over the roof) and 0.92 for the bottom film (free convection downward from non-reflective surfaces). ASHRAE winter R-values use 0.17 for the top film (15 mph wind over the roof) and 0.61 for the bottom film (free convection upward to non-reflective surfaces). These film R-values are specified in §9.4.1 of ASHRAE 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (4).

	R-value clear edge	Heat Flow clear edge	R-value purlin edge	Heat Flow purlin edge	Heat Flow purlin to wall	Heat Flow outside purlins	Heat Flow for field area
Purlins 60 in. oc	32.5	-3.99	24.1	-5.39	-34.87	56.71	139.20
Purlins 30 in. oc	33.1	-3.90	20.4	-6.19	-34.25	28.27	132.77
Purlins 20 in. oc	32.8	-3.92	18.6	-6.68	-34.68	19.02	136.45
	R-value surf-to-surf	R-value meas. films	U-value meas. films	R-value summer films	U-value summer films	R-value winter films	U-value winter films
Purlins 60 in. oc	27.4	28.6	0.0350	28.6	0.0350	28.2	0.0355
Purlins 30 in. oc	21.5	22.5	0.0444	22.6	0.0442	22.2	0.0449
Purlins 20 in. oc	18.5	19.5	0.0512	19.7	0.0508	19.3	0.0518

Figure 6b shows the behavior of the winter ASHRAE U-values in Table 4b as a function of the inverse of purlin spacing. This figure is useful for estimating U-value at other purlin spacings than in Tables 3b and 4b.

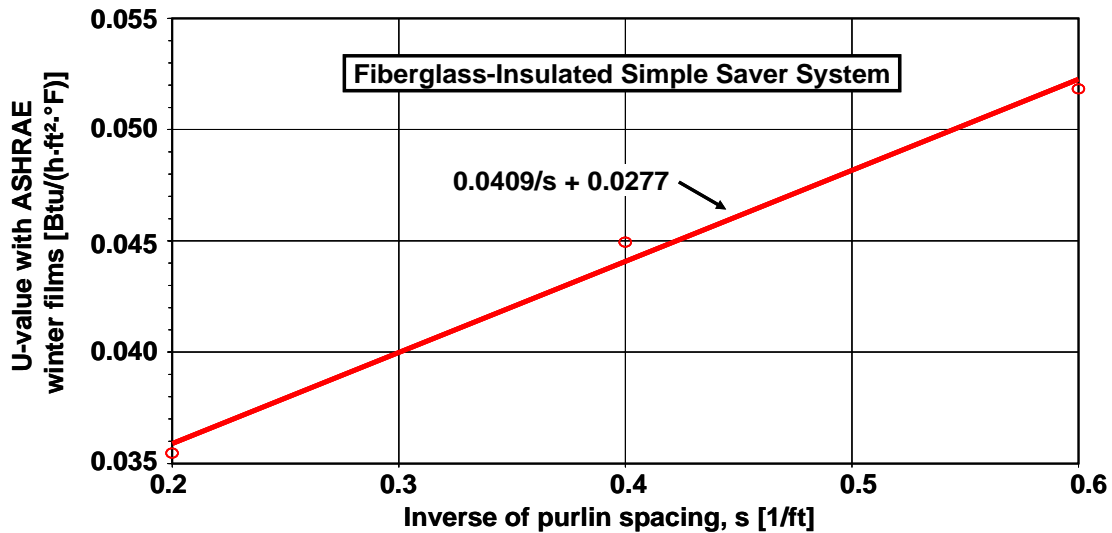


Fig. 6b ASHRAE Winter U-values for a Simple Saver System Insulated with Fiberglass

**Test Results and Discussion:**

**c) Configurations Insulated with R-19 Fiberglass Blankets Over the Purlins**

The average gaps from the roof to the purlins for the configurations insulated with a single layer of R-19 fiberglass blankets over the purlins were 1.66 in. with two purlins, 1.98 in. with three purlins and 1.90 in. with four purlins. These configurations had the R-19 blanket severely compressed between the clips and purlins. Apparently, the clips in the configuration with two purlins were screwed down to the purlins more tightly than they were in the other two configurations. The measured average depth of insulation between purlins and its thermal conductivity as a function of density yielded average insulation R-values in the test sections of R-12.4 with two purlins 60 in. oc, R-10.8 with three purlins 30 in. oc and R-9.7 with four purlins 20 in. oc. The closer the spacing of the purlins, the smaller the average depth of insulation, leading to the decreasing insulation R-value as number of purlins increases.

Table 3c gives detailed results from the tests of the configurations insulated with a single layer of R-19 fiberglass blankets over the purlins. They include the system R-values obtained from the difference in air temperatures across each test section, multiplied by the nominal 64 ft<sup>2</sup> of metering chamber area exposed to the test section, and divided by the heat flow from the metering chamber energy balance. This heat flow is the value for exactly zero temperature difference between the guard and metering chambers at the top of the metering chamber walls. The heat flow increases more from three to four purlins than from two to three purlins because of the smaller average depth of insulation as number of purlins increases.

Table 3c. Detailed test results for over-the-purlin configurations insulated with a single layer of R-19 fiberglass blankets. All temperatures are in °F. Heat flows out of the metering chamber are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). Results are averages for 24 to 60 hours after steady-state was achieved in each test.

	Climate Air	Meter Air	MC Heat Flow	R-value top film	R-value bottom film	R-value air to air	U-value air to air
Purlins 60 in. oc	50.07	100.04	270.80	0.64	0.45	11.81	0.0847
Purlins 30 in. oc	50.02	99.97	298.40	0.63	0.49	10.71	0.0934
Purlins 20 in. oc	50.02	100.01	320.30	0.55	0.53	10.00	0.1000
	Insulation Average	Insulation Bottom-Top	Surface Top	Purlin Top	Surface Bottom	Purlin Bottom	Air Bottom
Purlins 60 in. oc	75.45	45.36	52.8	54.1	98.1	99.4	99.9
Purlins 30 in. oc	75.31	44.73	52.9	53.7	97.7	99.4	99.4
Purlins 20 in. oc	75.07	44.60	52.8	53.2	97.4	99.4	99.8

Table 4c summarizes the corrections to the heat flow for the over-the-purlin R-19 fiberglass-insulated configurations along with the results for thermal performance in the field of a roof. Note that the different field areas for the different purlin spacings makes the heat flow through these areas appear to be inconsistent with the increased thermal bridging as number of purlins increases. The U-values for these configurations are sensitive to the amount of sag allowed between purlins, which Thermal Design built into the configurations based on their measurements on installed roofs.

Table 4c. Corrections to heat flow and resulting thermal performance in the field (area = 8 ft by integral number of purlin spacings nearest to 8 ft) of a standing-seam roof with a single layer of R-19 fiberglass blankets over the purlins. Heat flows are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). ASHRAE (3) summer R-values use 0.25 for the top film (7.5 mph wind over the roof) and 0.92 for the bottom film (free convection downward from non-reflective surfaces). ASHRAE winter R-values use 0.17 for the top film (15 mph wind over the roof) and 0.61 for the bottom film (free convection upward to non-reflective surfaces). These film R-values are specified in §9.4.1 of ASHRAE 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (4).

	R-value clear edge	Heat Flow clear edge	R-value purlin edge	Heat Flow purlin edge	Heat Flow purlin to wall	Heat Flow outside purlins	Heat Flow for field area
Purlins 60 in. oc	13.4	-4.21	10.7	-5.09	-102.63	146.47	305.34
Purlins 30 in. oc	11.1	-4.88	9.6	-5.51	-108.36	82.89	262.54
Purlins 20 in. oc	11.1	-4.85	8.9	-5.83	-109.89	61.51	261.24
	R-value surf-to-surf	R-value meas. films	U-value meas. films	R-value summer films	U-value summer films	R-value winter films	U-value winter films
Purlins 60 in. oc	11.9	13.0	0.0771	13.0	0.0766	12.7	0.0790
Purlins 30 in. oc	10.2	11.3	0.0882	11.4	0.0878	11.0	0.0909
Purlins 20 in. oc	9.1	10.2	0.0982	10.3	0.0973	9.9	0.1012

Figure 6c shows the behavior of the winter ASHRAE U-values in Table 4c as a function of the inverse of purlin spacing. This figure is useful for estimating U-value at other purlin spacings than in Tables 3c and 4c.

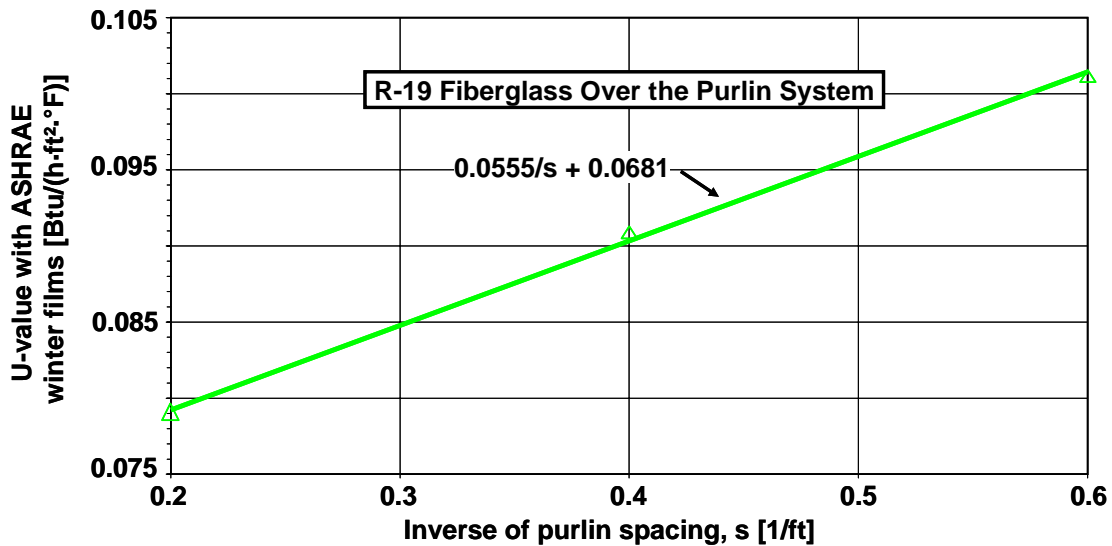


Fig. 6c ASHRAE Winter U-values for an Over the Purlin System Insulated with R-19 Fiberglass

**Test Results and Discussion:**

**d) Sag-and Bag Configurations Insulated with R-11+R-19 Fiberglass Blankets**

The sag-and-bag configurations were insulated with a layer of R-11 fiberglass blankets over the purlins and an additional layer of R-19 fiberglass blankets between them. Average gaps from the roof to the purlins were 1.90 in. with two purlins, 2.37 in. with three purlins and 2.02 in. with four purlins. These configurations had the R-11 blanket severely compressed between the clips and purlins. Apparently, the clips in the configuration with three purlins were screwed down to the purlins less tightly than they were in the other two configurations. The measured average depth of insulation between purlins and its thermal conductivity as a function of density yielded average insulation R-values in the test sections of R-17.3 with two purlins 60 in. oc, R-14.1 with three purlins 30 in. oc and R-11.6 with four purlins 20 in. oc. The closer the spacing of the purlins, the more the roof compressed the R-19 blanket when the roof panels were put in place. Therefore, the average insulation R-value decreases significantly as number of purlins increases despite the same nominal R-value of installed insulation in all three assemblies.

Table 3d gives detailed results from the tests of the R-11+R-19 sag-and-bag configurations. They include the system R-values obtained from the difference in air temperatures across each test section, multiplied by the nominal 64 ft<sup>2</sup> of metering chamber area exposed to the test section, and divided by the heat flow from the metering chamber energy balance. This heat flow is the value for exactly zero temperature difference between the guard and metering chambers at the top of the metering chamber walls. The heat flow increases more from three to four purlins than from two to three purlins because of the smaller average depth of insulation as number of purlins increases.

Table 3d. Detailed test results for R-11+R-19 sag-and-bag configurations. All temperatures are in °F. Heat flows out of the metering chamber are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). Results are averages for 24 to 60 hours after steady-state was achieved in each test.

	Climate Air	Meter Air	MC Heat Flow	R-value top film	R-value bottom film	R-value air to air	U-value air to air
Purlins 60 in. oc	50.09	99.96	225.65	0.71	0.40	14.15	0.0707
Purlins 30 in. oc	50.07	99.97	252.75	0.53	0.41	12.64	0.0791
Purlins 20 in. oc	50.10	99.96	281.05	0.50	0.44	11.35	0.0881
	Insulation Average	Insulation Bottom-Top	Surface Top	Purlin Top	Surface Bottom	Purlin Bottom	Air Bottom
Purlins 60 in. oc	75.57	45.96	52.6	54.0	98.6	99.4	99.9
Purlins 30 in. oc	75.24	46.19	52.2	53.2	98.3	99.5	99.8
Purlins 20 in. oc	75.17	45.77	52.3	53.5	98.0	99.4	99.9

Table 4d summarizes the corrections to the heat flow for the R-11+R-19 sag-and-bag configurations along with the results for thermal performance in the field of a roof. Note that the different field areas for the different purlin spacings makes the heat flow through these areas appear to be inconsistent with the increased thermal bridging as number of purlins increases. The U-values for these configurations are sensitive to the amount of sag allowed between purlins, which Thermal Design built into the configurations based on their measurements on installed roofs.

Table 4d. Corrections to heat flow and resulting thermal performance in the field (area = 8 ft by integral number of purlin spacings nearest to 8 ft) of a standing-seam roof with R-11+R-19 sag-and-bag fiberglass blanket insulation. Heat flows are in Btu/h. R-values are in h·ft<sup>2</sup>·°F/Btu and reciprocal U-values are in Btu/(h·ft<sup>2</sup>·°F). ASHRAE (3) summer R-values use 0.25 for the top film (7.5 mph wind over the roof) and 0.92 for the bottom film (free convection downward from non-reflective surfaces). ASHRAE winter R-values use 0.17 for the top film (15 mph wind over the roof) and 0.61 for the bottom film (free convection upward to non-reflective surfaces). These film R-values are specified in §9.4.1 of ASHRAE 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (4).

	R-value clear edge	Heat Flow clear edge	R-value purlin edge	Heat Flow purlin edge	Heat Flow purlin to wall	Heat Flow outside purlins	Heat Flow for field area
Purlins 60 in. oc	18.7	-3.23	13.0	-4.38	-78.34	106.47	246.17
Purlins 30 in. oc	15.6	-3.79	11.7	-4.82	-84.24	65.34	225.24
Purlins 20 in. oc	15.2	-3.84	10.4	-5.26	-88.56	52.86	236.25
	R-value surf-to-surf	R-value meas. films	U-value meas. films	R-value summer films	U-value summer films	R-value winter films	U-value winter films
Purlins 60 in. oc	14.9	16.0	0.0623	16.1	0.0621	15.7	0.0636
Purlins 30 in. oc	12.3	13.2	0.0755	13.5	0.0742	13.1	0.0764
Purlins 20 in. oc	10.3	11.3	0.0887	11.5	0.0869	11.1	0.0900

Figure 6d shows the behavior of the winter ASHRAE U-values in Table 4d as a function of the inverse of purlin spacing. This figure is useful for estimating U-value at other purlin spacings than in Tables 3d and 4d.

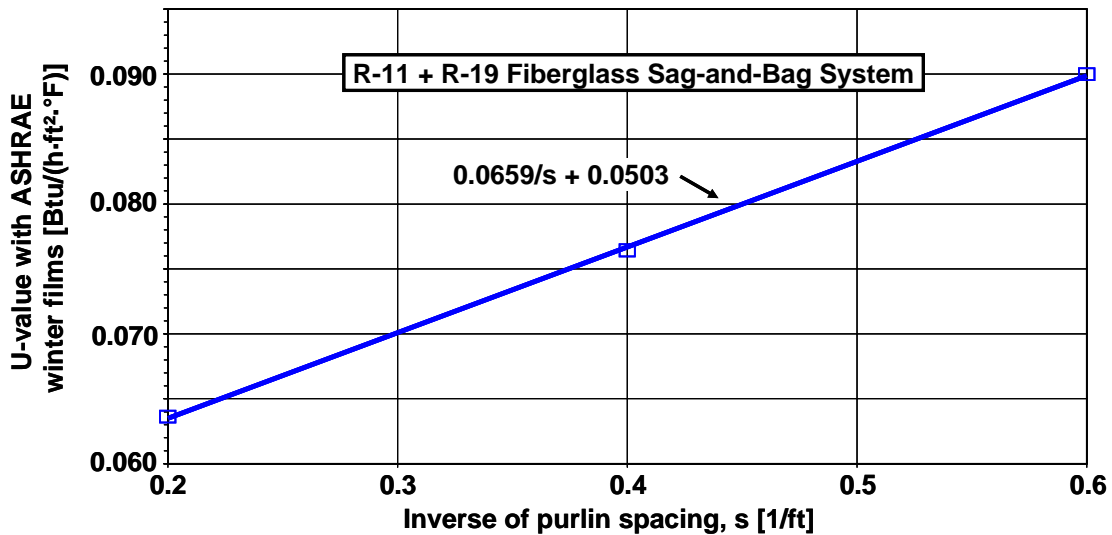
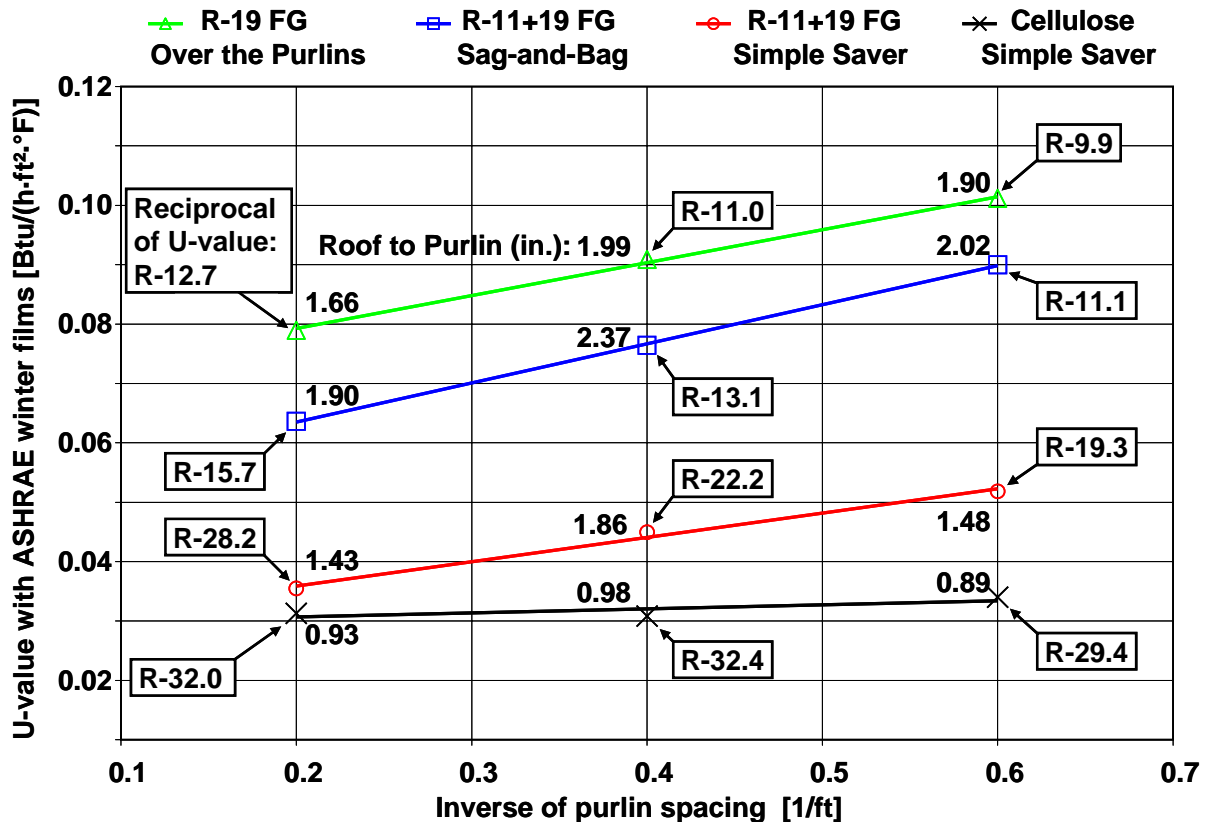


Fig. 6d ASHRAE Winter U-values for a Sag-and-Bag System Insulated with R-11 + R-19 Fiberglass

## Summary and Comparisons

The assemblies were tested as constructed by Thermal Design. No evaluation was made of the assemblies other than thermal performance. Figure 7 summarizes the results for all assemblies. The U-value with ASHRAE winter films is plotted as a function of the inverse of purlin spacing. Each configuration shows linear behavior of U-value as a function of the inverse of purlin spacing. The level of the U-value and the slope of the relationship are different from configuration to configuration. Labels are added for each configuration to show the roof to purlin spacing and the R-value corresponding to the U-value with ASHRAE winter films.



**Fig. 7 Thermal Performance of Various Insulation Configurations under Standing-Seam Metal Roofs**

The best performance is shown by the cellulose-insulated Simple Saver configuration because of the high R-value of insulation in these assemblies. The relatively small roof-to-purlin spacing does not affect the thermal bridging when insulation is below the purlins as it was in these assemblies. The worst performance is shown by the R-19 over-the-purlin configuration because the nominal R-value of the insulation is lower than in the other configurations and the insulation was severely compressed. Adding R-11 insulation in the sag-and-bag configuration did not help much because both the R-11 layer over the purlins and both layers between the purlins were severely compressed. The use of R-11 over the purlins and an additional R-19 between the purlins in the Simple Saver configuration yielded much better thermal performance because both layers between the purlins were free to expand to full depth.

## References

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- (2) Wilkes, K.E., “Thermophysical Properties Data Base Activities at Owens-Corning Fiberglass,” pp. 662-677, Proceedings of the 1979 ASHRAE/DOE-ORNL Conference on the Thermal Performance of the Exterior Envelope of Buildings, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA, 1979.
- (3) 2005 ASHRAE Handbook–Fundamentals, Table 1, pg. 25.2. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
- (4) ASHRAE/IESNA Standard 90.1-1999: Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Appendix A. Using the Modified Zone Method to Adjust the R-value of Cellulose in the Simple Saver Configuration with Purlins 60 in. oc [See 2005 ASHRAE Handbook of Fundamentals, pp. 25.11-25.12 for nomenclature and formulas]

Modified Zone Method: Simple Saver with Cellulose Insulation and Purlins 60 in. oc: insl. does not fill cavity

Measured R<sub>surf-surf</sub>=27.05 for 8 in. 14 gauge purlins + 1 in. block with R-32.8 insulation in cavity

Purlin spacing s (in.)	60	
Purlin thickness d <sub>ii</sub> (in.)	0.0747	14 ga=0.0747 in.
Purlin height d <sub>i</sub> (in.)	7.9131	Total height (nominal+1/16) less 2*thickness of flanges
Over purlin d <sub>A</sub> (in.)	0.93	Measured foam block + cellulose
Under purlin d <sub>B</sub> (in.)	1	Purlin to scrim distance (1 in. in experiments)
Flange width (in.)	<b>2.08</b>	Trial and error to match R-27.05 (actual width approx. 2 in.)

Sections	Material	Thickness (in.)	Resistivity (h·ft <sup>2</sup> ·°F)/(Btu·in.)	k(Btu·in)/(h·ft <sup>2</sup> ·°F)	rho (pcf)
A1	EPS	0.75	4.0000		
A2	Cellulose	0.18	3.5936	0.2783	2
B	Cellulose	1.00	3.5936	0.2783	2
I,II	Steel	0.0747	0.003181		
I+2*II	Cavity Insl	8.0625	3.1677		

Adjust to get correct total cavity R-value

Additional parameters

rs <sub>sheath</sub> /rc <sub>cavity</sub> =	1.238	
z <sub>f</sub> =	<b>2.71</b>	Use estimate for rs/rc and purlin height from graph in ASHRAE Fundamentals
w=L+z <sub>f</sub> *d <sub>A</sub>	4.597	For rs/rc = 1.24:
R-value of section A	3.647	Depth
R-value of section B	3.594	3.5
R-value insl in I	25.066	4
R-value insl in II	0.237	6
R-value of metal in I	0.0252	8
R-value of metal in II	0.000238	extrapolate

Calculations

R I	1.460	
R II	0.000524	
Total R cavity	<b>32.78</b>	
Total R in width w	8.702	
Overall surf to surf R-value	<b>27.05</b>	ASHRAE films winter: 0.17+0.61
Framing factor (R <sub>overall</sub> /R <sub>cav</sub> )	0.825	Roof R-value 27.83 U-value 0.0359

Modified Zone Method for Simple Saver System with Cellulose Insulation and Purlins 60 in. oc:

Increase cavity insulation to 3 purlin value for 8 in. 14 gauge purlins + 1 in. block: **R-39.3 insulation in cavity**

Purlin spacing s (in.)	60				
Purlin thickness dii (in.)	0.0747	14 ga=0.0747 in.			
Purlin height di (in.)	7.9131	Total height (nominal+1/16) less 2*thickness of flanges			
Over purlin dA (in.)	0.93	Measured foam block + cellulose			
Under purlin dB (in.)	1	Purlin to scrim distance (1 in. in experiments)			
Flange width (in.)	<b>2.08</b>	Use Flange Width to match measured insulation			
Sections	Material	Thickness (in.)	Resistivity (h-ft <sup>2</sup> ·°F)/(Btu-in.)	k (Btu-in)/(h-ft <sup>2</sup> ·°F)	rho (pcf)
A1	EPS	0.75	4.0000		
A2	Cellulose	0.18	3.5936	0.2783	2
B	Cellulose	1	3.5936	0.2783	2
I,II	Steel	0.0747	0.003181		
I+2*II	Cavity Insl	8.0625	3.9789		
				Adjust to get correct total cavity R-value	
Additional parameters					
rsheath/rcavity=	0.986				
zf=	<b>2.53</b>	Use estimate for rs/rc and purlin height from graph in ASHRAE Fundamentals			
w=L+zf*dA	4.436	For rs/rc = 1.0:	Depth	Read zf	Linear Fit
R-value of section A	3.647		3.5	1.55	1.57
R-value of section B	3.594		4	1.7	1.68
R-value insl in I	31.485		6	2.1	2.10
R-value insl in II	0.297		8	extrapolate	2.53
R-value of metal in I	0.0252				
R-value of metal in II	0.000238				
Calculations					
R I	1.428				
R II	0.000506				
Total R cavity	<b>39.32</b>	Increase to 39.3			
Total R in width w	8.669				
Overall surf to surf R-value	<b>31.17</b>	ASHRAE films winter: 0.17+0.61			
Framing factor (Roverall/Rcav)	0.793	Roof R-value	31.95	U-value	0.0313