ATTIC TESTING AT THE ROOF RESEARCH CENTER—INITIAL RESULTS

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In 1990, a series of tests was performed on residential attics using an attic test module built to permit research to be accomplished on a number of issues related to attics. This test module was used in the Large Scale Climate Simulator (LSCS) at the Roof Research Center (Center). This combination of test module and LSCS permitted the Center to perform a number of studies under closely controlled interior and climatic conditions, including:

- Evaluation of uninsulated attic performance and comparison with previously published results.
- Evaluation of the thermal performance of the attic with loose-fill fiberglass insulation.
- Identification of heat loss due to convective air movement through the loose-fill insulation under simulated winter conditions.

Testing, in general, showed reasonable agreement with previously published results for each of the above areas of investigation. Thermal performance improved markedly with the installation of the loose-fill insulation. However, the thermal performance of the loose-fill insulation tested under winter conditions declined by as much as a factor of two as the temperature difference across the insulation increased. This decline in thermal performance is attributed to the initiation of convection through the insulation as the temperature declines. These findings were documented by both energy low analysis using the LSCS guarded hot box and infrared scans of the insulation surface in the attic. It should be noted that the present experiments were performed with one type of loose-fill fiberglass insulation. Similar results would be expected for other products that have similar air flow and thermal properties. However, further testing is required to document the performance of the full range of insulations currently available.

KEYWORDS

Attic Test Module, Large Scale Climate Simulator, loose-fill fiberglass insulation, Roof Research Center.

BACKGROUND

Roof Research Center

The Roof Research Center was initiated by the U.S. Department of Energy (DOE) in 1984 at the Oak Ridge National Laboratory, located in eastern Tennessee near the city of Knoxville. The Center was conceived as a DOE User Facility to assist in the development of cost-effective improvements in the energy performance and durability of roofing systems.

The roofing industry has been heavily involved in the Center from its beginning. Currently fourteen experts from industry form an Industry Advisory Panel to review the Center's activities and research plans. In addition, a number of firms are sponsoring work at the Center.

Major Experimental Facilities

The Center has three major experimental facilities. The oldest and smallest is the Roof Thermal Research Apparatus (RTRA), which has been in use since 1985. In this facility, four low-slope roof panels [each 1.2m by 2.4m (4 ft. by 8 ft.)] are exposed to the rigors of Tennessee weather. The structure below these test panels is maintained at typical indoor temperatures of 24°C (75°F).

Another outdoor facility, the Roof Mechanical Properties and Foundation Research Apparatus (RMPFRA) was built in 1990 and provides a 9.8m by 22m (32 ft. by 72 ft.) roof test platform which simulates typical commercial construction practices. A description of the initial testing accomplished on the RMPFRA is included in the paper by Smith and Wendt found elsewhere in this proceedings.

The third experimental facility, the $2 million Large-Scale Climate Simulator (LSCS) is located within a 650m² (7000 ft.²) building which also houses the Center's test roof fabrication and storage facilities (see Figure 1). The LSCS, which has been in use since 1988, tests roofing materials under specific, artificially created climate conditions.

The upper portion of the LSCS (Figure 2) is the environmental chamber which simulates a wide range of climatic conditions in either a steady-state or dynamic (simulating diurnal conditions) mode. Temperatures in the environmental chamber can range from 66°C to −40°C (150°F to −40°F). Roof surface temperatures can be controlled with infrared heating up to 93°C (200°F).

The lower portion of the LSCS contains both a guard and metering chamber each of which can be controlled independently from 7°C to 66°C (45°F to 150°F). Both upper and lower chambers have controlled humidity and other capabilities which were not utilized in this set of experiments. The automatic control systems for guard and metering chambers are capable of maintaining temperatures to within ±0.06°C (±0.1°F). The control system for the climate chamber is also capable of maintaining the temperature to within ±0.06°C (±0.1°F), except when the infrared lamps are operating.

Attic Test Module

The Attic Test Module (Figure 3) was built to simulate typical residential construction practices and fit within the physical limitations imposed by LSCS. The gable attic is approximately 4.3m by 4.9m (14 ft. by 16 ft.) and is constructed of standard framing lumber, plywood roof deck and gypsum board ceiling. The roof (5 in 12 slope) is covered with roofing felt and medium grey asphalt shingles. Ventilation is mechanically controlled, entering through eave vents and exhausting through gable or ridge vents.

Instrumentation of the attic includes more than 130 thermocouples which feed their data into a collection system which monitors signals every four minutes. Air flow in the ventilation air supply ducts is monitored by hot-wire anemometers. The location of the instrumentation is shown in Figure 4.

In addition to conditions in the attic test module, complete data are also gathered on conditions in the environmental, guard and metering chambers of the LSCS.

Attic Testing Agenda

The initial testing agenda for the Attic Test Module includes the following primary objectives:

- Determine the experimental characteristics of the module.
- Compare test results from the module with results from other attic testing.
- Compare the performance of various types of insulations (reflective, radiant barrier and low density loose-fill) under similar conditions.
- Determine if convective heat loss occurs within low-density, loose-fill insulation.
- Determine if various forms of convective barriers are effective at controlling convective heat loss in low-density, loose-fill insulation.

An additional secondary objective was to evaluate the impact of varying the ventilation rate within the attic module for several of the tests performed.

Potential Future Attic Testing

As knowledge of the availability of the attic testing capability at the Roof Research Center increased, industry interest in performing additional tests has developed. Further potential tests in the Attic Test Module include:

- Thermal performance of other loose-fill insulations.
- Thermal performance of higher-density, loose-fill fiberglass insulation.
- Thermal performance of various batt insulations.
- Effectiveness of various types and configurations of vapor retarders.
- Thermal performance of various radiant barriers.

Experience gained in using the Attic Test Module has shown that additional capability should be developed to evaluate changes in the roof membrane (shingle color, differing materials), as well as changes in the roof deck construction such as would be experienced with a cathedral ceiling. Another test module has been proposed which will enable the Center to test additional attributes of shingle roofs.

In addition to thermal testing, a big area of concern to industry deals with moisture in attics. Improper materials, design or construction can lead to severe problems in some climates. The Center plans to adapt its test modules to study the location and extent of moisture concentration under various climatic and attic ventilation conditions.

RESEARCH RESULTS

Preparations for Attic Testing

LSCS Modes of Operation—The LSCS can be operated in two modes. In the heat flux transducer mode, the metering chamber hot box is kept in a lowered position (see Figure 2), and the lower chamber is used only to provide simulation of indoor conditions. Heat flows through the roof panel are measured with heat flux transducers attached to the panel. The guarded hot box mode uses the metering chamber as a guarded hot box. The metering chamber is raised so that it seals against the underside of the roof panel, and provides a measurement of the total heat flow through the 2.4m (8 ft.) by 2.4m (8 ft.) central area of the panel. The surrounding guard chamber is maintained at the same temperature as the metering chamber to minimize heat flow across the metering chamber walls.

Because of the complex heat flow paths in the attic, it is necessary to use the LSCS in the guarded hot box mode. In the guarded hot box mode, the heat flow through the panel is calculated from an energy balance on the metering chamber. Elements in this heat balance include energy supplied by the direct current circulation fans, energy supplied by an electric resistance heater, energy removed by a chilled-water coil, heat losses or gains through the walls of the metering chamber, and the heat flow through the roof panel. Fan and heater energies are obtained from DC current and voltage measurements. The energy removed by the chilled-water coil is obtained from a flow rate measured by a turbine flowmeter and from a temperature rise measured with a differential platinum resistance temperature device. Heat flows through the metering chamber walls are estimated from a number of differential thermocouples across the walls.

The chilled water coil must be operated when heat flows from the climate chamber into the metering chamber. It also must be used under some conditions when heat is flowing from the metering chamber into the climate chamber. These conditions arise when the heat flow through the roof is smaller than the energy input from the fans, and the chilled water must be used to remove the excess heat.

Efforts have been taken to reduce the uncertainties in individual measurements. All thermocouples used special limits of error wire, and all thermocouples used to obtain an average temperature on a given surface were taken from the same spool of wire, resulting in individual temperature measurements accurate to within ± 0.6°C (± 1°F). An independent calibration of the turbine flow meter established its accuracy at ± 0.0013 liters per second (± 0.02 gallons per minute), and an independent calibration of the differential resistance temperature device established its accuracy as ± 0.03°C (± 0.05°F).

All tests performed in the guarded hot box mode were conducted under essentially dry conditions, with no moisture sources in either the metering or climate chambers.

LSCS Tests with Calibration Panel—To check the overall operation of the LSCS in the guarded hot box mode, a set of experiments was performed using a roof panel that consisted of an 0.102m (4 in.) thick slab of expanded polystyrene foam insulation. The thermal resistance of the foam was determined independently using ORNL's unguarded thin-heater apparatus.[1] Thermal resistances were determined from the LSCS runs using the measured temperature differential across the panel, the area of the panel enclosed between the centerlines of the metering chamber walls, and the net heat flow deduced from the hot box energy balance.

The results of these experiments (see Table 1) show that the measured thermal resistance of the panel is usually within about five percent of the known value. Two tests were performed with the climate chamber at 7°C. For one of these tests, the chilled water coil in the metering chamber was activated, but was turned off for the other test. With the small heat flow for this test, the accuracy of the data is not as good with the chilled water activated (9.1 percent) as when the chilled water is turned off (5.2 percent). The larger discrepancy with the chilled water activated is probably due to the subtraction of two relatively large numbers (a cooling energy and a heating energy) to obtain a relatively small net heat flow through the panel. For this reason, data obtained with the chilled water coil activated are considered to be less accurate than those obtained with the chilled water turned off.

Attic Testing with No Insulation

The first set of experiments with the attic test module was conducted in February and March 1990, with no insulation in place. These runs provide a baseline for judging the impact of the addition of various types and levels of insulation. In addition, these runs provided an opportunity to compare results from the LSCS with results from another facility,[2] and were useful in diagnosing the characteristics of the attic module.

Test conditions and results are given in Table 2. LSCS tests 1, 2 and 3 were intended to duplicate conditions for tests reported in Wilkes and Rucker,[2] the results of which are also given in Table 2. For these three tests, the metering chamber was maintained at 24°C (75°F), and the climate chamber was maintained at either −18°C (0°F) to simulate winter conditions or 27°C (80°F) to simulate summer conditions. For the summer test, the roof temperature was controlled to 47°C (117°F) using the infrared lamps in the LSCS, while for the winter tests, the roof temperature was allowed to seek its equilibrium value.

LSCS tests 4, 5 and 6 were intended to provide baseline data for comparison with future tests with insulation installed in the attic. For the winter test (LSCS 4) with the climate chamber at −7°C (20°F), the roof temperature was allowed to seek its equilibrium value, while for the summer tests (LSCS 5 and 6) with the climate chamber at 32°C (90°F), the roof temperature was controlled at 71°C (160°F). Ventilation rates for all tests were controlled at the indicated values.

The two primary responses measured were the attic air temperature and the heat flux through the ceiling. The measured heat fluxes for LSCS 2 and 3 agree well with those reported in Wilkes and Rucker. However, the heat flux measured in LSCS 1 is about 40 percent higher than that reported in Wilkes and Rucker.

Two factors are thought to contribute to the difference in results from LSCS 1. First, the roof temperature in the LSCS test, 15°C (5°F), is much nearer the climate chamber temperature than was the case in Wilkes and Rucker, −7°C (19°F), presumably due to the higher air velocities in the LSCS. The lower roof temperature would result in a lower attic temperature and both of these lower temperatures would result in an increase in the heat flow through the ceiling. Another factor contributing to the difference may be inferred from a comparison of the results from LSCS 1 and 2, for which the only difference in test conditions was the imposed ventilation rate. The heat flux in the LSCS for these two tests is insensitive to ventilation rate, while the heat flux from Wilkes and Rucker increased significantly with increasing ventilation rate, as would be intuitively expected. It is thought that the LSCS attic may be subject to unintentional ventilation through openings in the gables which would not be apparent from airflow measurements in the ventilation air supply ducts. The effect of unintentional additional ventilation would be most important at very low imposed ventilation rates. Also, judging from the results of LSCS 3, unintentional venting appears to be less important for summer conditions where the roof temperature was controlled and where radiation between the roof deck and the attic floor is expected to be the dominant mechanism for heat transfer across the attic space. For the later tests with loose-fill insulation, openings in the gables were sealed to minimize unintentional ventilation.

Comparing the winter test results, it is seen that the heat flux measured in LSCS 4 was about 36 percent less than those from LSCS 1 and 2. This difference in heat flux is directly proportional to the temperature difference between the metering chamber and the roof. Using this temperature difference and the measured heat flux to define an effective overall thermal resistance yields a value of 0.38 m²•K/W (2.2 hr•ft²•°F/Btu). This value is intermediate between similar resistances of 0.42 and 0.33 m²•K/W (2.4 and 1.9 hr•ft²•°F/Btu) derived from the results of Wilkes and Rucker.

Comparing the summer test results shows that the heat fluxes from LSCS 5 and 6 are 2.5 times as large as that from LSCS 3. These heat fluxes are almost in direct proportion to the temperature difference between the roof and the metering chamber. Defining an overall thermal resistance as was done for the winter tests yields values of 0.70, 0.61 and 0.60 m²•K/W (4.0, 3.5 and 3.4 hr•ft²•°F/Btu). A resistance of 0.60 m²•K/W (3.4 hr•ft²•°F/Btu) is obtained from the results of Wilkes and Rucker.

The thermal resistances for the summer tests are significantly larger than for the winter tests. The difference is thought to be due to a larger component of convection heat transfer across the attic space under winter conditions where the attic floor is warmer than the roof. Also, the thermal resistances for an uninsulated attic under either summer or winter conditions are much smaller than those obtained with an insulated attic, as given below.

In general, it is concluded that heat fluxes measured in an uninsulated attic in the LSCS agree fairly well with the results from Wilkes and Rucker. The exception is for winter tests with no intentional ventilation.

Convection in Loose-Fill Fiberglass Insulation

Wilkes and Rucker also reported data from attic tests with various levels of fiberglass batt insulation and with various levels of loose-fill fiberglass insulation. Under sufficiently cold winter conditions, the thermal resistance of the loose-fill insulation was significantly lower than expected based on results of small scale laboratory tests. The loss in thermal resistance was attributed to natural convection within the insulation. A similar loss in resistance for loose-fill fiberglass insulation was observed by Besant and Miller, using a test box.[3]

The insulating characteristics of fiberglass insulations have traditionally been considered to arise from the entrapment of still air within the insulation. Heat transfer through the insulation would then be a combination of conduction through still air, conduction through the glass fibers, and radiative transfer through an absorbing, scattering, and emitting medium. The results of Wilkes and Rucker suggested that an additional mechanism of heat flow by circulation of air through the insulation by natural convection may occur under certain conditions when the attic is colder than the space below the ceiling. With this mechanism, cold dense air in the attic space falls into the insulation, where it is warmed, becomes less dense and then rises back up into the air space carrying additional heat with it.

Two series of experiments were performed in the LSCS to determine whether the findings in Wilkes and Rucker could be corroborated. The major characteristic of natural convection is that the heat transfer rate is not proportional to the temperature difference across the system, as would be expected from Fourier's law, but increases at a faster rate than the temperature difference. In other words, the thermal resistance decreases with increasing temperature difference. Therefore, the LSCS experiments were designed to measure the thermal resistance over a wide range of temperature differences that might be encountered in a real house.

The first series of experiments was performed on Specimen 1 in May and June 1990. A local insulation contractor was hired to install a low-density, loose-fill fiberglass insulation in the attic to a nominal R-value of 3.35 m²•K/W (19 hr•ft²•°F/Btu). For this nominal R-value, the label thickness is 0.21m (8.25 in.) and the label density is 8 kg/m³ (0.5 pounds per cubic foot). Rulers were placed in several locations in the attic to allow an estimation of the installed thickness, which was about 0.23m to 0.25m (9 in. to 10 in.). After testing was concluded, the total weight of insulation in the metered area was determined to allow an estimate of installed density, which was about 7.2 to 8 kg/m³ (0.45 to 0.5 pounds per cubic foot).

Since the installed thickness was larger than the label value, the actual nominal installed R-value is also larger. Assuming a simple proportionality between thickness and R-value gives estimated nominal installed R-values between 3.7 and 4.0 m²•K/W (21 and 23 hr•ft²•°F/Btu). An additional adjustment would be needed to account for the variation of apparent thermal conductivity with density. Assuming that the apparent thermal conductivity is the sum of air and a radiation term that varies inversely with the density gives estimated nominal installed R-values between 3.7 and 3.8 m²•K/W (21 and 22 hr•ft²•°F/Btu).

Results for tests performed on Specimen 1 under winter conditions with a range of climate chamber temperatures are given in Table 3. This table shows the heat flux measured with the metering chamber, using the area between the centerlines of the hot box walls. The heat fluxes change by over a factor of six as the climate chamber temperature is lowered from 7°C to −28°C (45°F to −18°F). Comparing the test at a climate chamber temperature of −7°C (20°F) with the corresponding test with an uninsulated attic (LSCS 4) shows the addition of the loose-fill insulation has decreased the heat flow by nearly a factor of seven, from 65 to 9.4 W/m² (21 to 3.0 Btu/hr•ft²).

Table 3 also shows thermal resistances that were calculated using the measured heat flux, and the average temperature difference between the bottom of the gypsum wallboard and the top of the insulation. Thus, these thermal resistances include the effects of the gypsum wallboard and the 2 X 4 wood joists, as well as the insulation. The measured thermal resistances are seen to range from a high of 3.1 m²•K/W to a low of 1.6 (17.8 to 9.2 hr•ft²•°F/Btu), with the lower values corresponding to the lower climate chamber temperatures, or larger temperature differences. It should be noted that the resistances measured at the smallest temperature difference are about 15 to 20 percent lower than the estimated nominal R-value. Since these data were obtained with the chilled water coil activated, a part of this difference may be due to this experimental procedure.

The second series of experiments was performed on Specimen 2 in November and December 1990. This specimen was installed by the same local insulation contractor, using material from the same lot as was used for Specimen 1. This specimen was installed to a thickness of about 0.24 m (9.5 inches). Using the total weight of installed insulation gives an installed density of about 6 kg/m³ (0.38 pounds per cubic foot), while core samples taken from the region outside the metered area give a density of about 7.5 kg/m³ (0.47 pounds per cubic foot). A more exact density of the insulation in the metered area will be determined when it is removed from the attic at the conclusion of testing (which was ongoing when this paper was written). These two estimates of density give estimated nominal R-values between 3.2 and 3.7 m²•K/W (18 and 21 hr•ft²•°F/Btu).

In order to avoid any extra uncertainty due to the use of the metering chamber chilled water coil, all data for Specimen 2 under winter conditions were obtained with the chilled water coil turned off. Results of these tests are given in Table 4. The heat fluxes change by a factor of five as the climate chamber temperature is lowered from 7°C to −28°C (45°F to −18°F). The thermal resistances range from a high of 3.1 m²•K/W to a low of 2.0 (17.7 to 11.1 hr•ft²•°F/Btu). As with Specimen 1, the thermal resistance values decrease as the temperature difference increases. Comparing the results of Specimen 2 and Specimen 1 shows that at the large temperature differences where both sets of data should be most accurate, the resistance of Specimen 2 is about 20 percent higher than that of Specimen 1. The reason for this difference has not as yet been identified.

For each of the two specimens, one test was performed with no ventilation in the attic space. The results from these tests are in very good agreement with results obtained under similar conditions, but with the attic ventilated. These results indicate that the imposed ventilation of the attic space does not alter the thermal resistance of the insulation.

The results in Wilkes and Rucker were presented in terms of dimensionless Nusselt and Rayleigh numbers. However, sufficient property information was presented to allow a calculation of the thermal resistance and the temperature difference between the bottom of the gypsum wallboard and the air in the attic. Their results are plotted in Figure 5, along with the results of the present tests. This figure shows that the trends of the two experiments are very similar, with a large decrease in thermal resistance being observed as the temperature difference across the insulation is increased. This trend is consistent with natural convection within the insulation in addition to radiation and conduction.

Further evidence for heat transfer by natural convection was obtained from infrared scans of the top surface of the insulation. After the heat flow measurements on Specimen 1 were concluded, an infrared camera was mounted in an opening in one gable end in order to view a large portion of the insulation surface. Scans were started when the climate chamber was at −20°C (−5°F) and were continued as the climate chamber was gradually warmed up to 7°C (45°F). Figure 6a shows a scan at −20°C (−5°F). The temperature along the horizontal line in Figure 6a is plotted in Figure 6b, which shows the light colored areas are about 0.8°C to 1.1°C (1.5°F to 2°F) warmer than the darker areas. The observed pattern is very reminiscent of the hexagonal cell patterns observed by Benard[4] for natural convection in a fluid layer heated from below, as shown in Figure 7. The darker areas on the scan appear to correspond to areas where cold, dense air from the attic space flows down into the insulation. This air is warmed by heat flow from below, and the warmer, less dense air appears to travel from the insulation into the attic air space at the lighter colored areas. When the attic was warmed up, the cellular patterns disappeared, as illustrated in the scan and temperature plot in Figure 8. Warm and cool areas were also observed with infrared scans in Wilkes and Rucker.

The quantitative differences between the present thermal resistances and those from Wilkes and Rucker may be due to several causes. Among these are differences in the type of insulation tested. The present insulation is a bonded cubed product, while their insulation was a bonded milled product. The present insulation specimens have a density of 6 to 8 kg/m^3 (0.38 to 0.5 pounds per cubic foot), while their insulation had a density of 12.0 kg/m^3 (0.75 pounds per cubic foot). The tests by Wilkes and Rucker were performed with a constant mean temperature of 3°C (37.5°F), while the present tests were performed with a constant metering chamber temperature of 21°C (70°F), resulting in a mean temperature that decreased with increasing temperature difference. Higher mean temperatures tend to stabilize against natural convection because the viscosity and thermal conductivity of air increase with increasing temperature.

A series of experiments was underway in 1990 and early 1991 to investigate the effectiveness of various materials that may be laid on top of the insulation to provide barriers to the exchange of air between the attic space and the insulation. Results from these tests will be reported in another paper.

SUMMARY AND CONCLUSIONS

Testing of residential attics in the Large Scale Climate Simulator has begun. Heat flow results have been obtained for the attic with no insulation and for the attic with loose-fill fiberglass insulation. Heat flows measured with no insulation are in reasonable agreement with previously published results.

The addition of loose-fill fiberglass insulation to the attic resulted in large reductions in the heat flow through the ceiling. However, the thermal resistance of the loose-fill fiberglass insulation was found to decrease by as much as a factor of two as the climate chamber temperature was lowered from 7°C to −28°C (45°F to −18°F). The variation of thermal resistance with temperature difference follows the same trends as seen in previously published results. This variation, along with infrared scans, confirm the theory of an additional heat flow mechanism due to circulation of air by natural convection through the insulation.

The lowest resistances were observed at the lower temperatures at which the heating loads on a house will be the greatest. This effect would be expected to have a significant impact on heating loads under design conditions. However, only a limited amount of time will be experienced at the coldest temperatures, depending upon the climatic conditions. Further analyses are needed to determine the net impact of the convective heat loss in loose- fill fiberglass insulation on the seasonal heating load of a house.

Finally, it should be noted that the present experiments were performed with one type of loose-fill fiberglass insulation. Similar results would be expected for other products having similar air flow and thermal properties. However, further testing is required to document the performance of the full range of insulations currently available.

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Metering Chamber Temperature, °C	Climate Chamber Temperature, °C	Roof Heat Flux, W/m²	Measured Resistance m²•K/W	Known Resistance m²•K/W	Percent Difference**
21[a]	49	−9.75*	2.62	2.66	−1.5
21[a]	49	−9.69	2.64	2.66	−0.8
21[a]	35	−4.54	2.82	2.72	+3.7
21[a]	7	4.71	2.60	2.86	−9.1
21[b]	7	4.48	2.71	2.86	−5.2
21[b]	−28	15.2	2.92	3.06	−4.6
21[b]	−28	15.1	2.95	3.06	−3.6

*Positive values are heat flows from the metering chamber to the climate chamber.
**100 X (Measured R-Known R)/Known R
a. Chilled water activated.
b. Chilled water off.

Table 1 Results of LSCS metering chamber calibration.

	Temperatures, °C					
	Metering Chamber	Climate Chamber	Attic Air	Roof	Ventilation Rate, m/s*	Ceiling Heat Flux, W/m²
LSCS - 1W	24	−18	−4	−15	0	101**
Wilkes & Rucker	24	−18	2	−7	0	73
LSCS - 2W	24	−18	−5	−15	0.0025	103
Wilkes & Rucker	23	−18	−8	−11	0.0025	102
LSCS - 3S	24	27	33	47	0	−33
Wilkes & Rucker	24	27	34	45	0	−35
LSCS - 4W	21	−7	2	−4	0.0005	65
LSCS - 5S	21	32	42	72	0	−83
LSCS - 6S	21	32	42	71	0.0005	−83

*Ventilation rate is cubic meters per second per square meter of ceiling area.
**Positive values are heat flows from the metering chamber to the climate chamber.
Note: "W" denotes a winter simulation; "S" denotes a summer simulation.

Table 2 LSCS results on uninsulated attic.

Applied Temperatures, °C						
Metering Chamber	Climate Chamber	Temperature Difference, K°(F)	Ventilation Rate, m/s**	Ceiling Heat Flux, W/m²	Thermal Resistance m²•K/W	(hr•ft²•°F/Btu)
21	7	12(22)	0.0008	3.73*	3.14*	(17.8)
21	7	12(22)	0.0005	3.77*	3.07*	(17.4)
21	0	18(32)	0.0005	6.35*	2.84*	(16.1)
21	−7	23(41)	0.0008	9.4*	2.48*	(14.1)
21	−13	28(50)	0.0005	13.5	2.11	(12.0)
21	−20	34(61)	0.0005	18.1	1.87	(10.6)
21	−20	34(61)	0.0005	15.8*	2.13*	(12.1)
21	−20	34(61)	0	16.5*	2.06*	(11.7)
21	−20	34(61)	0.0005	18.7*	1.82*	(10.4)
21	−28	39(70)	0.0005	24.1	1.61	(9.2)

*Tests performed with chilled water coil in metering chamber activated.
Results are less accurate than other tests with chilled water turned off.
**Ventilation rate is cubic meters per second per square meter of ceiling area.
Note: Temperature difference is measured between bottom of gypsum wallboard and top of insulation.
Thermal resistance is calculated using this temperature difference and measured heat flux.

Table 3 LSCS results for winter conditions with loose-fill fiberglass insulation specimen 1.

Applied Temperatures, °C						
Metering Chamber	Climate Chamber	Temperature Difference, K(°F)	Ventilation Rate, m/s*	Ceiling Heat Flux, W/m²	Thermal Resistance m²•K/W	(hr•ft²•°F/Btu)
21	7	12(21)	0.0003	3.86	2.99	(17.0)
21	0	18(32)	0.0005	5.81	3.12	(17.7)
21	−7	24(42)	0.0005	8.2	2.87	(16.3)
21	−13	29(52)	0.0006	11.4	2.54	(14.4)
21	−13	29(53)	0	11.6	2.52	(14.3)
21	−20	34(62)	0.0006	16.0	2.14	(12.2)
21	−28	40(72)	0.0007	20.6	1.95	(11.1)

Note: All tests performed with chilled water coil in metering chamber turned off.
*Ventilation rate is cubic meters per second per square meter of ceiling area.
Note: Temperature difference is measured between bottom of gypsum wallboard and top of insulation. Thermal resistance is calculated using this temperature difference and measured heat flux.

Table 4 *LSCS results for winter conditions with loose-fill fiberglass insulation specimen 2.*

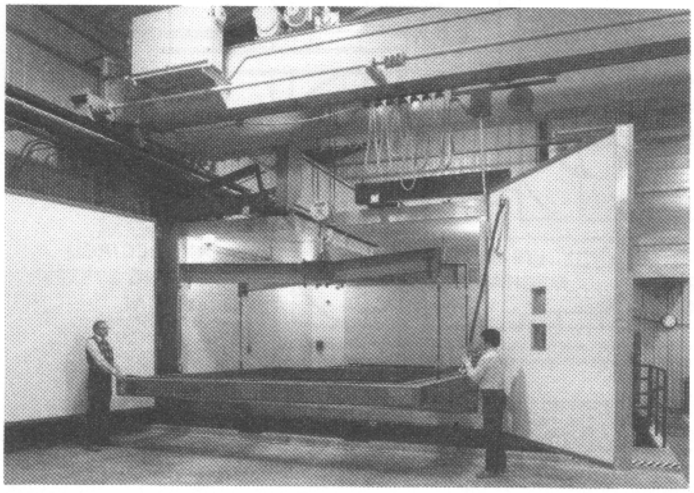

Figure 1 *The Large Scale Climate Simulator (LSCS) provides the opportunity to test a wide range of roofing systems under carefully controlled and monitored environmental conditions.*

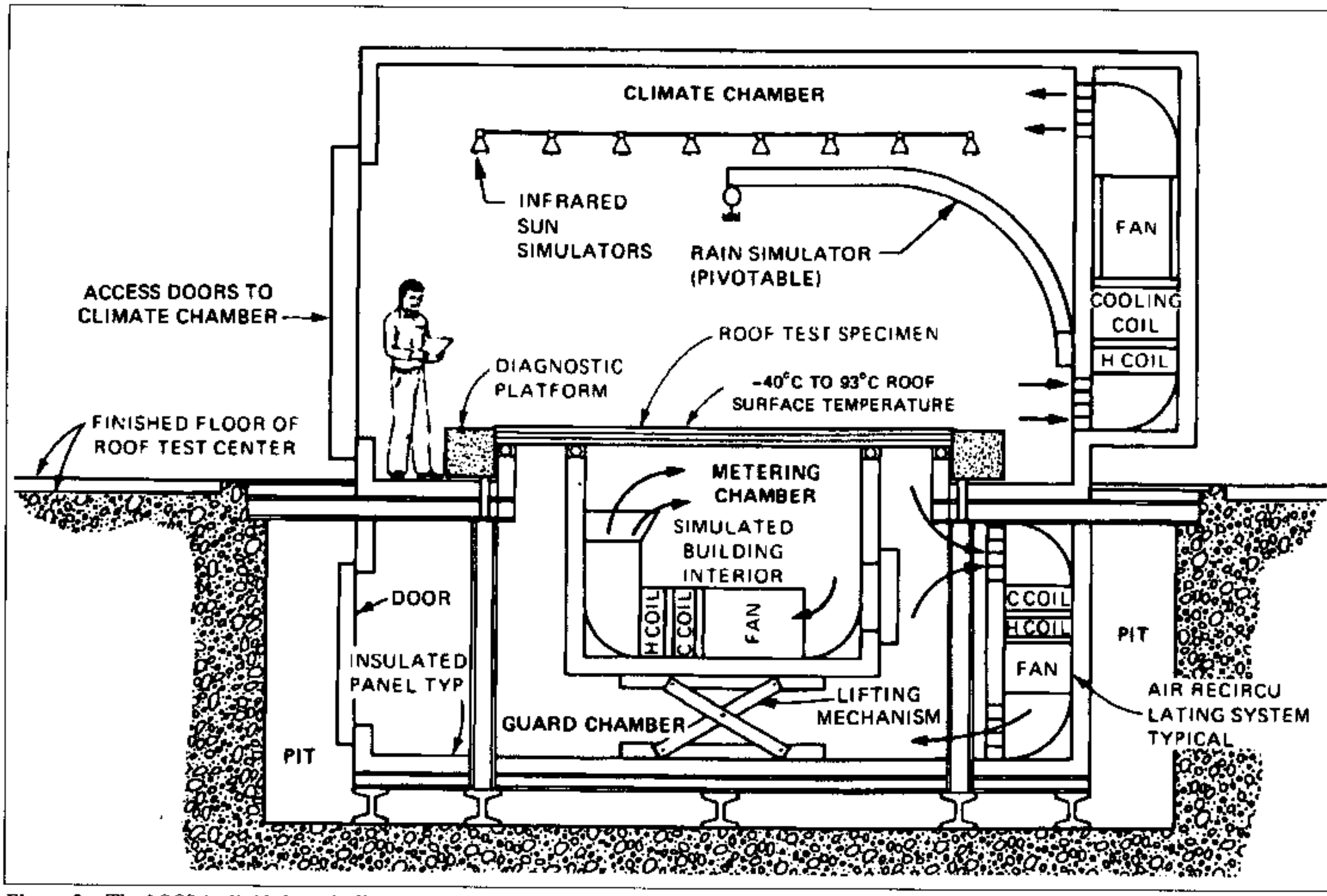

Figure 2 *The LSCS is divided vertically into a climate chamber to simulate outdoor conditions at the top and metering/guard chambers at the bottom to simulate indoor conditions.*

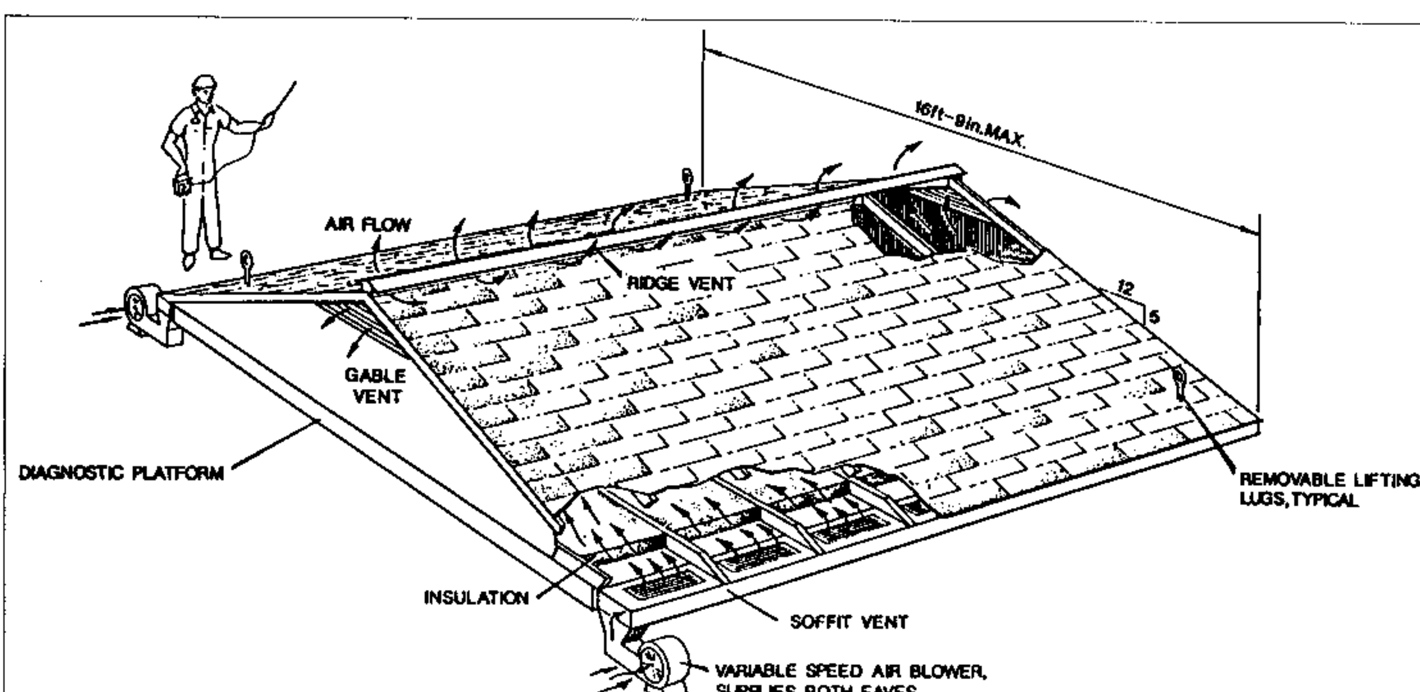

Figure 3 *The Attic Test Module was designed and built to simulate the common characteristics of residential roofing shingles.*

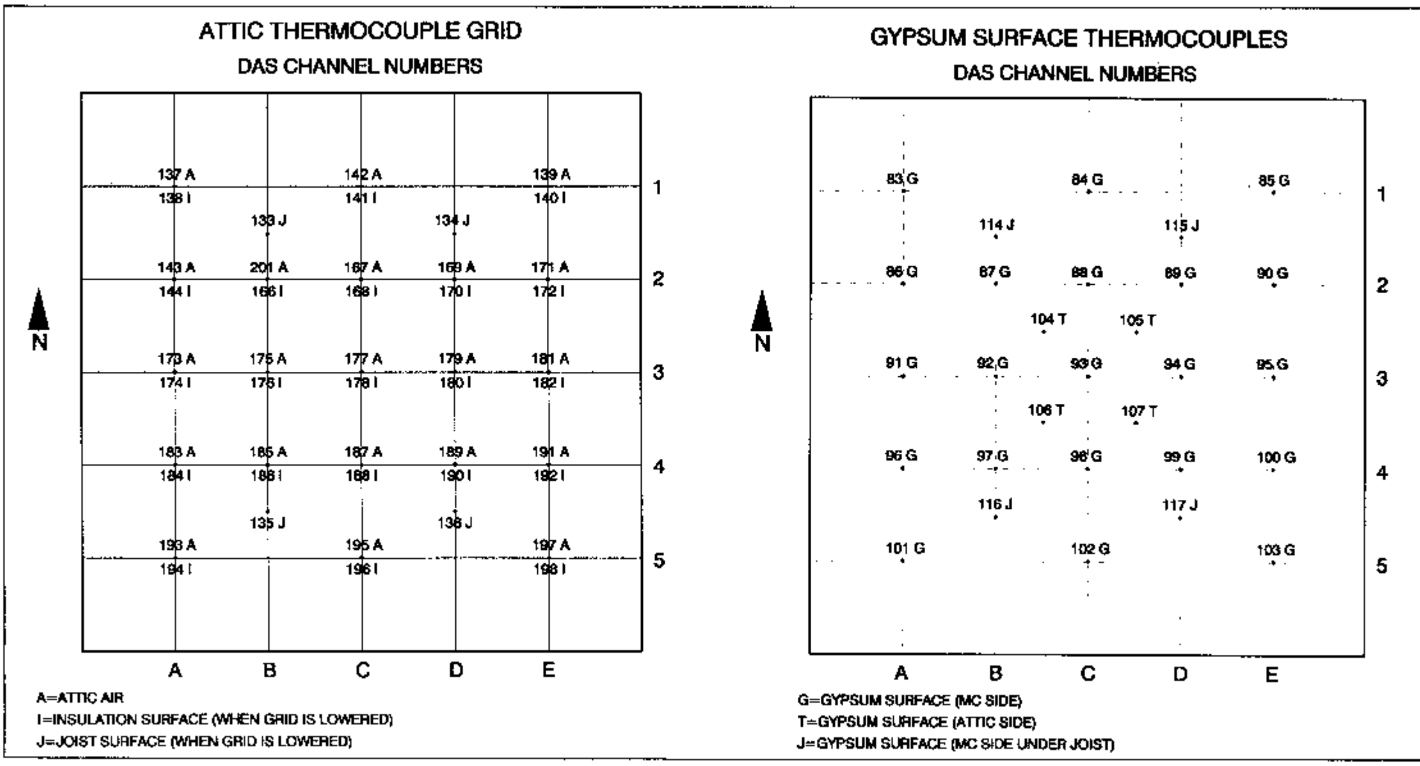

Figure 4 *Instrumentation in the Attic Test Module includes several arrays of thermocouples to monitor temperatures throughout the attic. Illustrated are the array located above and below the gypsum board ceiling and the array located at the upper surface of the insulation placed in the attic.*

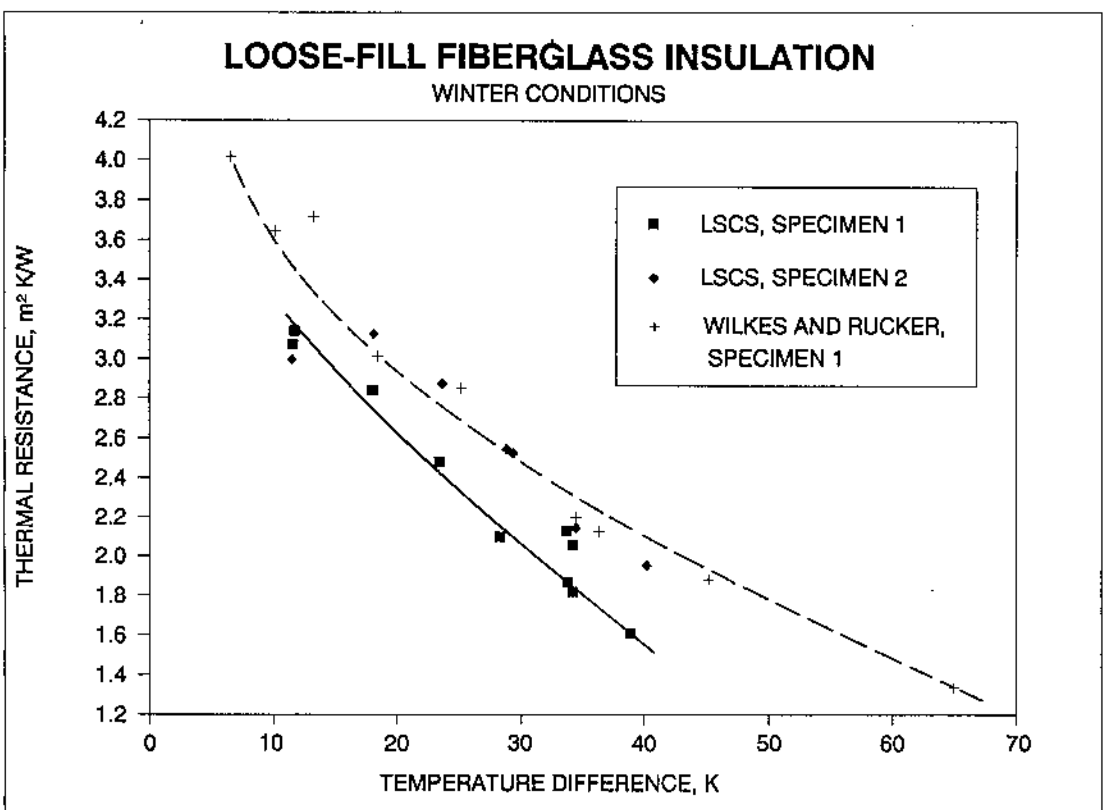

Figure 5 *Thermal resistance of loose-fill fiberglass insulation. The abscissa is the temperature difference between the bottom of the gypsum wallboard and either the attic air (Wilkes and Rucker) or the top of the insulation (LSCS).*

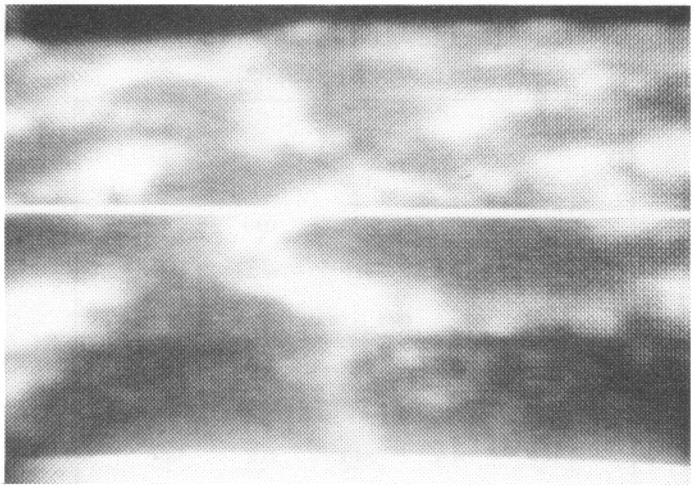

Figure 6a *Infrared picture of top of insulation with climate chamber near – 20°C. Light regions are warmer, dark regions are cooler.*

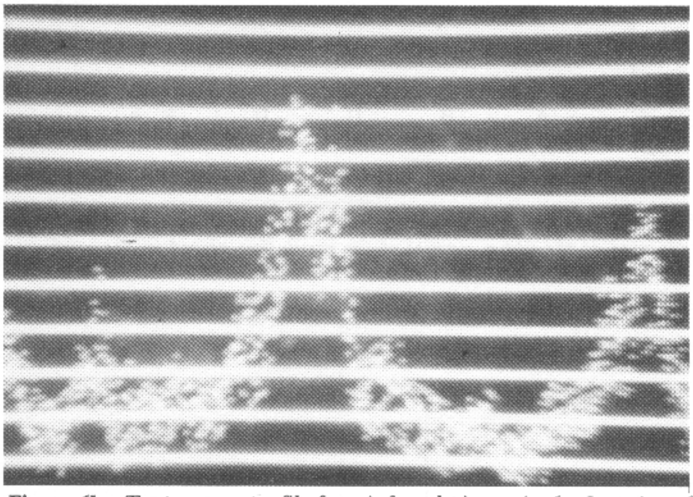

Figure 6b *Temperature profile from infrared picture in 6a. Location of scan corresponds to horizontal line in 6a. Full scale is 1.4°C.*

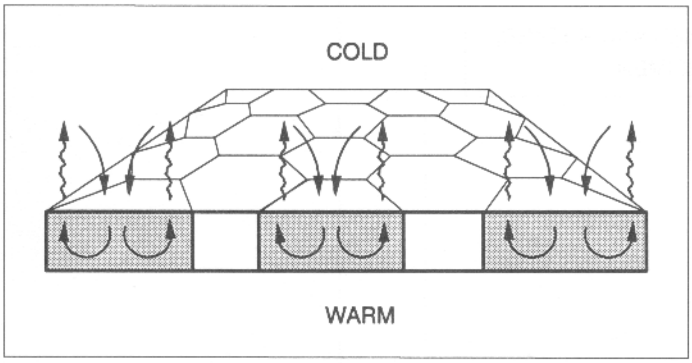

Figure 7 *Hexagonal Benard cell pattern for fluid layer heated from below.*

Figure 8a *Infrared picture of top of insulation at mild temperatures.*

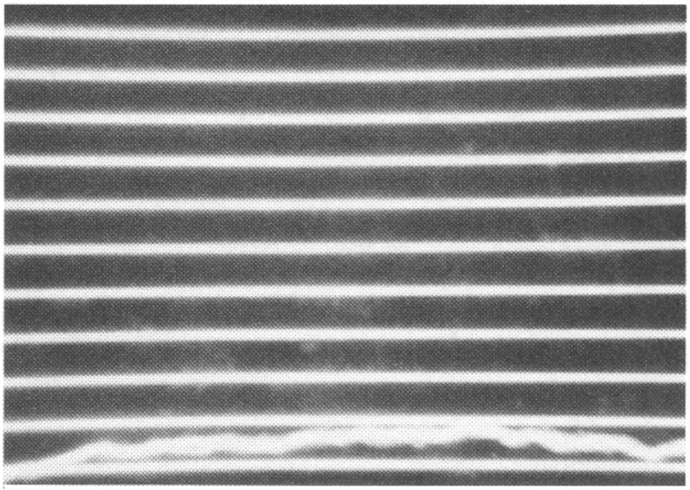

Figure 8b *Temperature profile from infrared picture at mild temperature. Full scale is 1.4°C.*