AN EXPERIMENTAL INVESTIGATION OF THE EFFECT OF ADDED INSULATION ON WATER VAPOR CONDENSATION IN MOBILE HOME ROOF CAVITIES

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ABSTRACT

The influence of increasing thermal insulation in the attic space of mobile home roofs on water vapor transport and water damage was investigated. Two laboratory environmental test chambers were designed and constructed to simulate outside winter ambient and interior mobile home living space conditions. In addition the effect of roof skin heating due to sunlight was also simulated.

Two basic roof section designs, each with three thermal insulation configurations, were examined. These were a standard and a raised-heel bow truss. The test specimens were constructed using actual mobile home roof construction procedures and materials. Each test specimen was instrumented using thermocouples and humidity gages. Based on the objectives of the study and the results of the thermal analysis prior to testing, a representative daily skin temperature cycle was selected and used during the tests.

Each specimen was tested for 3 weeks or longer. The roof skin temperature was cycled daily from approximately -10°F to 70°F and the living space conditions were held constant at a temperature of approximately 70°F and a relative humidity of 50 percent. Each test specimen was disassembled after the test for complete visual inspection and weighing of the insulation.

Based on the measured test results and post-test visual observations, it was concluded that added levels of thermal insulation in the attic space of mobile home roofs will not increase condensation or water damage, provided an effective vapor barrier is installed above the ceiling board.

In addition, test results indicated that condensation may form between the vapor barrier and ceiling board for roof sections having either conventional insulating packages or increased insulation packages. It was observed that for all insulating systems, moisture condensation occurred on the warm side of the vapor barrier where the ceiling boards were fastened to the wooden trusses. Further examination of this problem is planned.

INTRODUCTION

Energy conservation has become a major area of concern in this country over the past few years. As a result, a major effort to upgrade insulation levels of new and existing residential structures, including mobile homes is being made. A major concern in the mobile home industry is whether the added levels of insulation will increase condensation in the roof cavity. This concern is based upon the fact that increased insulation levels will cause lower roof cavity temperatures and potentially longer periods of time at dew point. A common

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complaint of many mobile home dwellers in colder climates is water staining and seepage through the ceiling board in the mobile home. Many in the mobile home industry feel that this problem results from water vapor diffusing up into the roof plenum, condensing on or near the metal roof skin, and seeping back down through the insulation to the ceiling board. The amount of water vapor migration from the living space into the roof cavity is a function of the permeance of the structure (ceiling and roof components), the living space temperature and relative humidity, and the attic and outside air temperatures. Normally constructed mobile home roofs have a polyethylene sheet vapor barrier above the ceiling board. The polyethylene sheet, with a permeance coefficient of approximately 0.1, influences the composite permeance coefficient of the roof structure. Any damage to the polyethylene sheet will decrease its effectiveness as a vapor barrier and result in an increase in the water vapor transmitted and possibly accumulated in the roof cavity.

Because of these concerns, a study was conducted to assess the effects of increased insulation levels in mobile home roof cavities on condensation and water damage. To accomplish this, laboratory tests were conducted using six specimens of actual mobile home roof systems. The test specimens were exposed to realistic living room and ambient conditions in two test chambers designed and built specifically for this study. In these tests a reasonable approximation of the indoor and outdoor environmental conditions expected in mobile home service was established. The roof specimens were exposed to these conditions for 3 weeks or longer, and the nature of moisture condensation (possibly moisture damage), and relative differences for the various roof section configurations were noted.

TEST CONDITIONS

Test conditions were selected to simulate reasonably severe winter conditions while allowing potential problems to be identified in relatively short periods of test time. In addition, a freeze-thaw cycle, similar to that due to daily solar insolation was imposed on the roof section to increase potential water damage problems.

In order to test the roof structures under somewhat realistic cyclic temperature conditions, it was necessary to determine typical daily temperature variations in an outdoor winter environment. An existing Battelle computer model, SNAPS (System Network Analysis for Passive Systems), was used to accomplish this transient analysis for one basic type of mobile home roof under four combinations of weather conditions.

The four combinations of winter ambient conditions examined in the model consisted of a typical daily solar flux variation together with:

- Constant ambient temperature, -10°F; no wind.
- Constant ambient temperature, -10°F; constant wind speed, 7.5 mph
- Cyclic ambient temperature, varying from -10°F at 6 a.m. to 20°F at 2 p.m.; no wind.
- Cyclic ambient temperature (as above); constant wind speed, 7.5 mph.

Table 1 lists the solar flux variations that were used as input data for the computer model. The solar flux values represent the solar energy incident on a horizontal surface located at 40 degrees North latitude (Columbus, Ohio). They were calculated by multiplying the direct normal solar intensity for a typical day in January by the sine of the solar altitude angle (1)[1]. For the purposes of these calculations, the solar absorptivity of the roof was assumed to be 0.95. The minimum daily ambient temperature was assumed to be -10°F, which was the same as the selected design testing temperature. The maximum ambient temperature of 20°F was selected after reviewing typical weather data and daily temperature variations for Columbus, Ohio. (2)

The basic type of mobile home roof structure was assumed to consist of metal roof skin (22 gage, 0.030-in.), insulation at the roof skin (2-in., R-7), air space (3.5-in., unvented), ceiling insulation (6-in., R-19; or 12-in., R-38), gypsum ceiling panels (1/4 in.), and room air (70°F, constant indoor temperature).

Figure 1 shows thermal analysis results for a mobile home roof having 6 inches of insulation over the ceiling panels. Analyses for each of the four wind-temperature conditions are shown. Note the roof skin temperature cycles above the freezing point for three of the four conditions and reaches 95°F when the outdoor ambient temperature is approaching 20°F with no wind. These results illustrate the strong influence that solar radiation can have on the roof skin temperature, even with January weather conditions.

For these tests, a constant temperature, no wind condition was chosen. This profile results in a sufficiently large temperature variation to cause freeze and thaw conditions to occur in the insulation if sufficient water is retained within the roof section. During the tests, the roof section skin temperature was varied to closely match the estimated profile shown in Figure 1. Although the cyclic ambient temperature with a 7.5 mph wind may be more realistic, it was decided that thawing should be simulated.

Based on a general knowledge of living conditions in mobile homes and information from Slayter Associates (3), the room air conditions on the simulated living space side of the roof were controlled to a temperature of 70°F and a relative humidity of 50 percent. For an ambient temperature approximately -10°F and this living room condition, the water vapor pressure differential across the roof structure is approximately 0.2 psi. Again, these conditions simulate a rather severe winter condition.

DESCRIPTION OF TEST APPARATUS

Figure 2 depicts one of the two identical test chambers designed amd constructed for this program. Design requirements for these test chambers included:

- Maintaining a "living space" environment below the roof section at 70°F and 50 percent relative humidity
- Providing a temperature capability above the roof section of -10°F, as well as a heating capability and necessary controls to achieve a repeatable thermal cycle that would simulate daytime conditions in which the roof skin temperature could reach 100°F
- Providing for negligible water vapor movement from the "living space" through the side walls and floor, the "living space" into the space above the roof section, and outside into the space above the roof section
- Providing for measurement of water vapor transport into the roof section
- Providing for installation and removal of the roof sections with a closure design that provides a positive seal against water vapor movement into the space above the roof section
- Accommodating different sizes and configurations of roof sections

- Providing for instrumentation and power control systems that allow an essentially unmanned operation with only periodic monitoring

The test chambers are approximately 16 ft. x 11 ft. x 11 ft. They consist of an upper and lower section separated by the roof test specimen. The lower section contains a reinforced shelf 5 ft. from the floor that supports the roof section thus the "living space" height is 5 ft. The floor, side walls, and shelf support are all covered with a 6-mil thick polyethylene sheet vapor barrier on the inside surfaces. The floor and side walls are insulated with R-11 fiberglass batts. A small refrigerator unit is provided in the "living space" of the test cells for temperature and relative humidity control. The upper section of the test chamber serves includes:

- The structural upper part of the test cell, which enables the upper part to be removed when changing mobile home roof sections

- Support structure for the refrigeration and ducting systems that supplies refrigerated air to the space above the mobile home roof sections

- Support for the 12 infrared heat lamps that provide the thermal cycle

- A 200-cfm air handler and a 3-hp, water-cooled condensing unit and associated hardware

The upper section is clamped to the bottom section with an angle iron through-bolt system utilizing a closed-cell sponge rubber gasket, 1/2-in. thick by 3-1/2-in. wide, between 2 by 4-in. plates that extend around the periphery of the upper and lower sections.

TEST PROCEDURES

During tests, the relative humidity and temperature in the test chamber's simulated living room space were maintained at 50 percent $\pm$ 10 percent RH and $70^{\circ}F \pm 3^{\circ}F$. The conditions were controlled by a humidistat and thermostat.

The desired time history for roof skin temperature was obtained by controlling the on-off time periods of the refrigeration system and heater lamps. The specific times during the cycle (24-hour period) to activate or deactivate the refrigeration and heater lamps were determined during preliminary calibration. Figure 3 is a plot representing the actual test cycle of the roof section skin temperature as a function of time. Figure 3 also shows operating time periods for the refrigeration system and heating lamps.

Each roof section had a number of thermocouples and relative humidity gauges placed in the roof cavity. During the test, readings from these gauges were recorded on paper tape using a Fluke data acquisition system. After each test, the specimen was removed for observation and insulation samples were removed and weighed.

TEST SPECIMENS

Figure 4 illustrates the six mobile home roof specimens that were tested. Specimens 1, 3, and 5, measuring 8 ft. by 12 ft., utilize the standard bow truss that is used in the mobile home industry today. Specimens 1 and 3 represent a nonvented and vented roof system that has been reinsulated, in that the cavities have been completely filled with fiberglass batt insulation. The two layers of insulation measure 6 and 3-1/2 in. at the center. Specimen 5 is a standard roof configuration with a typical lower level of insulation (R=7). The insulation is just 2-in. thick. Specimens 2, 4, and 6 measuring 8 ft. by 14 ft., utilize a 12-in., raised-heel bow truss also commonly used in the industry. The raised heel allows for greater thickness of insulation at the roof edge. Specimens 2 and 4 are highly insulated (R-37, R-38), non-vented and vented systems. Specimen 2 has insulation layers measuring 9 and 3-1/2 in., and Specimen 4 a single 12-in. layer. Specimen 6 is a vented system, but with a lower level of insulation (R-19) provided by a 6-in. layer. The venting of roof cavities is accomplished by a 3-in. diameter hole in the metal roof skin. Venting in this experiment was for vapor diffusion only since forced ventilation and wind effects were not simulated.

Each roof specimen was constructed using standard mobile home material. The vapor barriers were made from 3 mil polyethylene with a 6 inch overlap at each seam. In every roof specimen the vapor barrier was penetrated due to bolt and wire chase holes needed to mount a standard ceiling light fixture. During construction of the roof sections, care was taken not to damage the vapor barrier. Instrumentation lines that were run from the living room space to inside of the roof sections penetrated the vapor barrier. Putty was used to seal around the instrumentation lines at two locations--inside the roof section at the vapor barrier and on the living space side of the ceiling board.

DISCUSSION OF TEST RESULTS

Figure 5 shows the time history of water supplied to the simulated living space over the 3 week test period, in order to maintain 50 percent R.H. for each test specimen. Water input ranged from 20 liters for Specimen 4 to 32 liters for Specimen 1. Moisture content in the thermal insulation and air space inside the roof specimens during the test period was directly measured with moisture probes (Thunder Scientific Gauge Model No. PC2000). Figures 6 through 11 illustrate the calculated relative humidity levels for all roof specimens at times corresponding to 1200 hours (noon) and 0200 hours (2 a.m.) for selected cycles during the test for each of the specimens. These are the times of maximum and minimum roof skin temperatures. Figure 10 shows the results of only one R.H. gauge because the second gauge failed to function part way through the test cycle.

If a significant amount of moisture were being transported and stored in the attic space, the relative humidity would increase during the test and reach 100 percent if condensation were occurring. A comparison of Figures 6, 7, and 8 (standard bow) and Figures 9, 10, and 11 (raised bow) shows no appreciable change in R.H. between the specimens with lower levels of insulation and those with increased levels. These results indicate that an insignificant amount of moisture was transmitted and stored in the attic. That amount appeared to be independent of the levels of insulation within the attic space.

If sufficient water vapor were transported and retained in the roof's insulation, condensation and freezing could occur. Under these circumstances, the temperature profile across the roof section would change due to local variations in the insulation's thermal conductivity. However, when thermocouple measurements were compared, there were no significant changes in the thermal profiles in either the low or higher insulated roof systems. Themocouples were also placed in the corners of each roof specimen, and examination of those thermal profiles at different times during the test period also indicated no change either.

Each test specimen was disassembled after removal from the test chamber. The roof's metal skin was removed and the interior portion of the roof was examined in detail. The thermal insulation in all of the specimens was dry to the touch. No local areas on the cold insulation side of the vapor barrier of any of the specimens showed signs of water accumulation that would subsequently lead to degradation of the insulation or to water damage. Samples of insulation were weighed after each test and showed no appreciable change from their original weight. The vapor barrier was inspected for tears that could have been caused during construction and installation of the test specimens. In all cases, the vapor barrier was in good condition. Inspection of the ceiling board indicated that some water had condensed on the warm side of the vapor barrier at various locations, corresponding to regions where the wooden trusses were in contact with the ceiling board. The attic side of the ceiling board on all specimens was water stained to about the same extent in all cases except Specimen 4, which was stained somewhat more. However, the water staining could not be observed on any of the specimens from the living room side of the ceiling. The ceiling board had absorbed sufficient water at a number of locations (near the wooden trusses) to become quite soft to the touch.

CONCLUSIONS

The results of this study indicate that for the laboratory conditions used, highly insulated mobile home roofs will not lead to condensation in the attic space or increase the potential of water damage to the ceilings. The degree of moisture condensation on the warm side of the vapor barrier (which caused water staining on the attic side of the ceiling board) appeared to be the same for both insulating package thicknesses. There was little or no water vapor transported from the living space region and stored in the insulation.

The results of the post-test visual observations suggested potential problem with moisture condensation on the warm side of the vapor barrier at the bow truss interface for both the conventional and highly insulated packages in both bow truss configurations. It was noted that at the junction of the ceiling board and wooden trusses, there was sufficient water condensation to cause water staining on the attic side of the ceiling board. This could, in time, cause staining on the living room side of the ceiling. Apparently, the local temperature in the vicinity of the wooden trusses (behind the ceiling board) is low enough to allow condensation to occur. If this local condensation is due to the higher thermal conductance through the wooden truss members and the air spaces along them, then increasing the thermal insulation in the roof cavity will increase the thermal insulation at these locations which could reduce the condensation problem. Until additional information concerning the local temperature variations near the truss is obtained, it is difficult to identify the problem in more detail. It is planned to examine this problem further both analytically and experimentally since it is anticipated that increasing the thermal ceiling insulation will reduce the amount of condensation that occurs at the truss locations.

The degree of roof ventilation due to air infiltration was minimized during these experiments. Polyethylene sheets were attached to the sides and ends of the test roof section to eliminate infiltration at these locations. A vent pipe was attached to four of the test specimens (3, 4, 5, and 6) to allow water vapor to vent from the attic space to the refrigerated space. Based on the results obtained from these tests, it is concluded that venting in this way does not influence the performance of the roof section with respect to the degree of water condensation and damage. Again, note that forced ventilation in the attic space by either ambient winds or blowers was not simulated during these tests.

REFERENCES

1. ASHRAE, 1977 Fundamentals Handbook, Chapter 26, Tables 7 and 22.

2. National Oceanic and Atmospheric Administration, Local Climatological Data, Monthly Summaries for Columbus, Ohio.

3. "Condensation in Mobile Homes," a report to Owens-Corning Fiberglas Corp., Exhibit 5, prepared by Slayter Associates, Inc., Elkhart, Indiana, October 28, 1971.

Time of Day	Solar Radiation on Horizontal Surface, Btu/hr-ft^2
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	20
9	70
10	111
11	136
12 (noon)	147
13	136
14	111
15	70
16	20
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24 (midnight)	0

TABLE 1

DAILY VARIATION IN SOLAR RADIATION
FOR COLUMBUS, OHIO, IN JANUARY

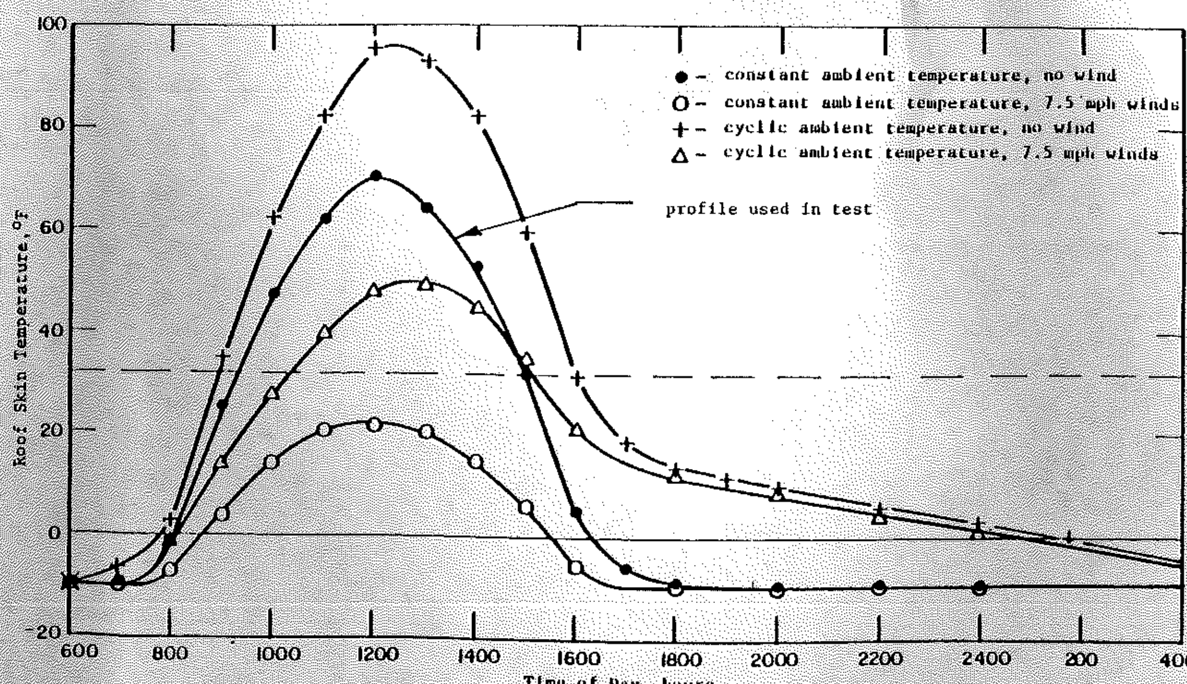

FIGURE 1.

ROOF SKIN TEMPERATURE VARIATION FOR VARIOUS AMBIENT CONDITIONS

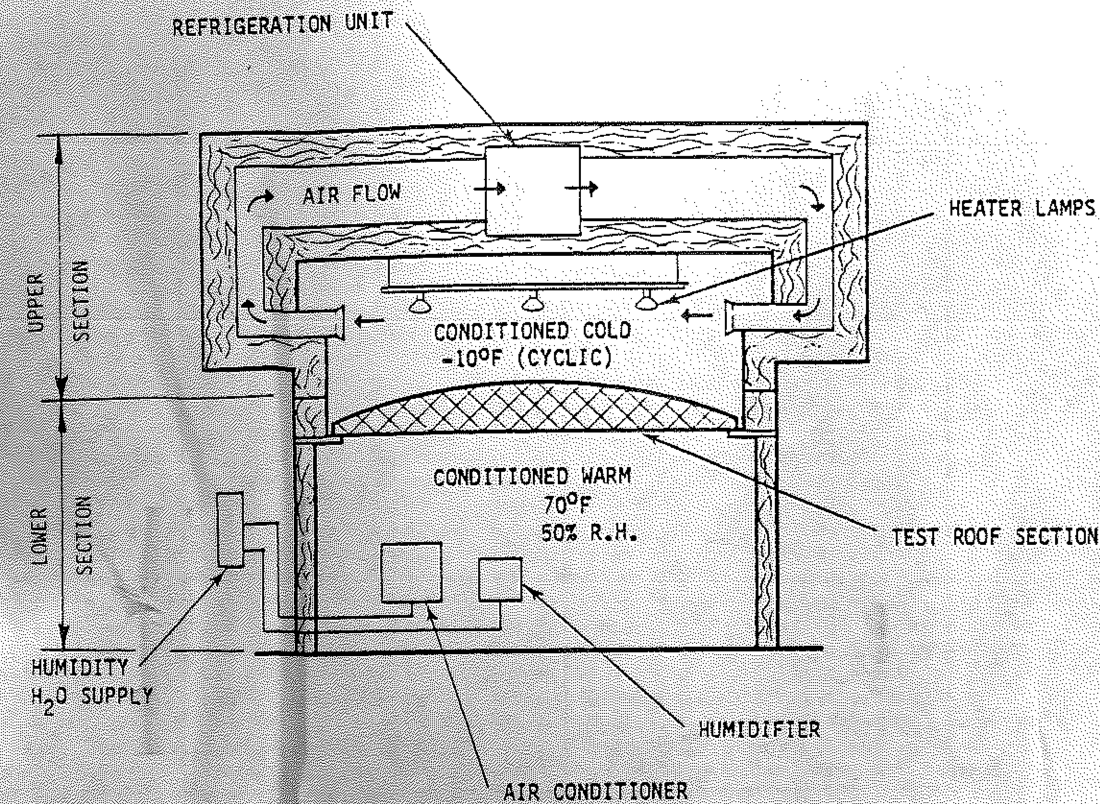

FIGURE 2

TEST CHAMBER SCHEMATIC

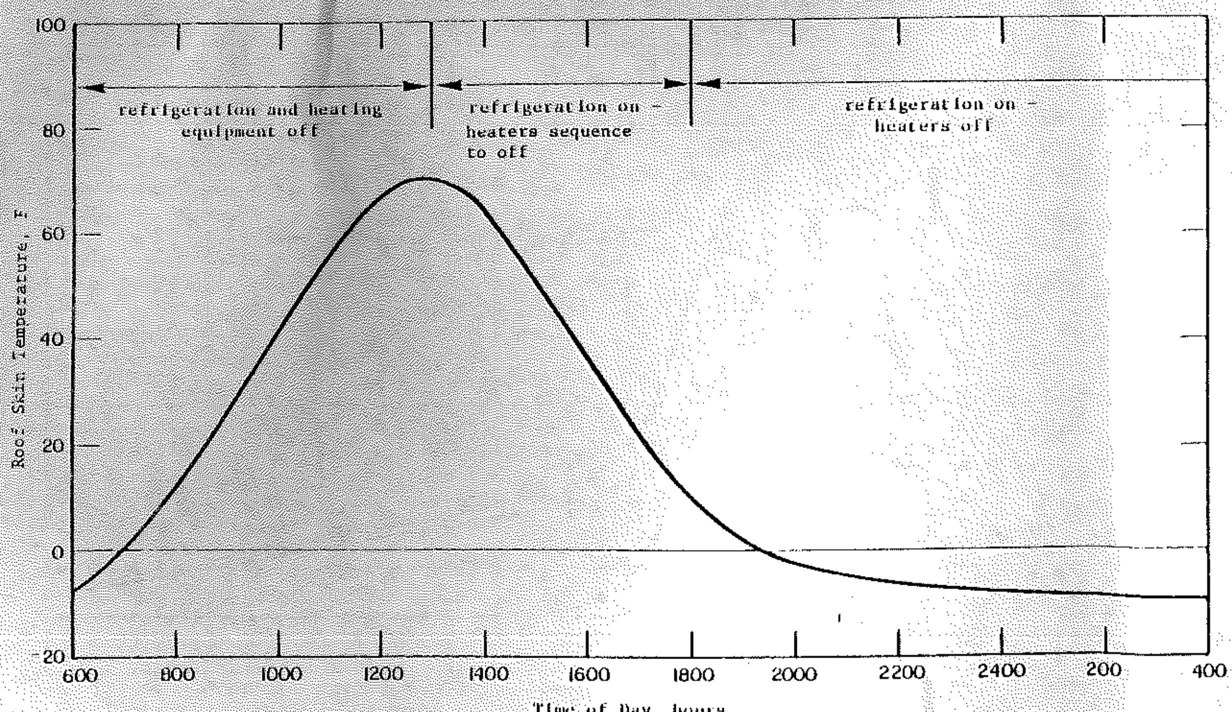

FIGURE 3.

DUTY CYCLE FOR REFRIGERATION AND HEATING EQUIPMENT OVER A 24-HOUR PERIOD

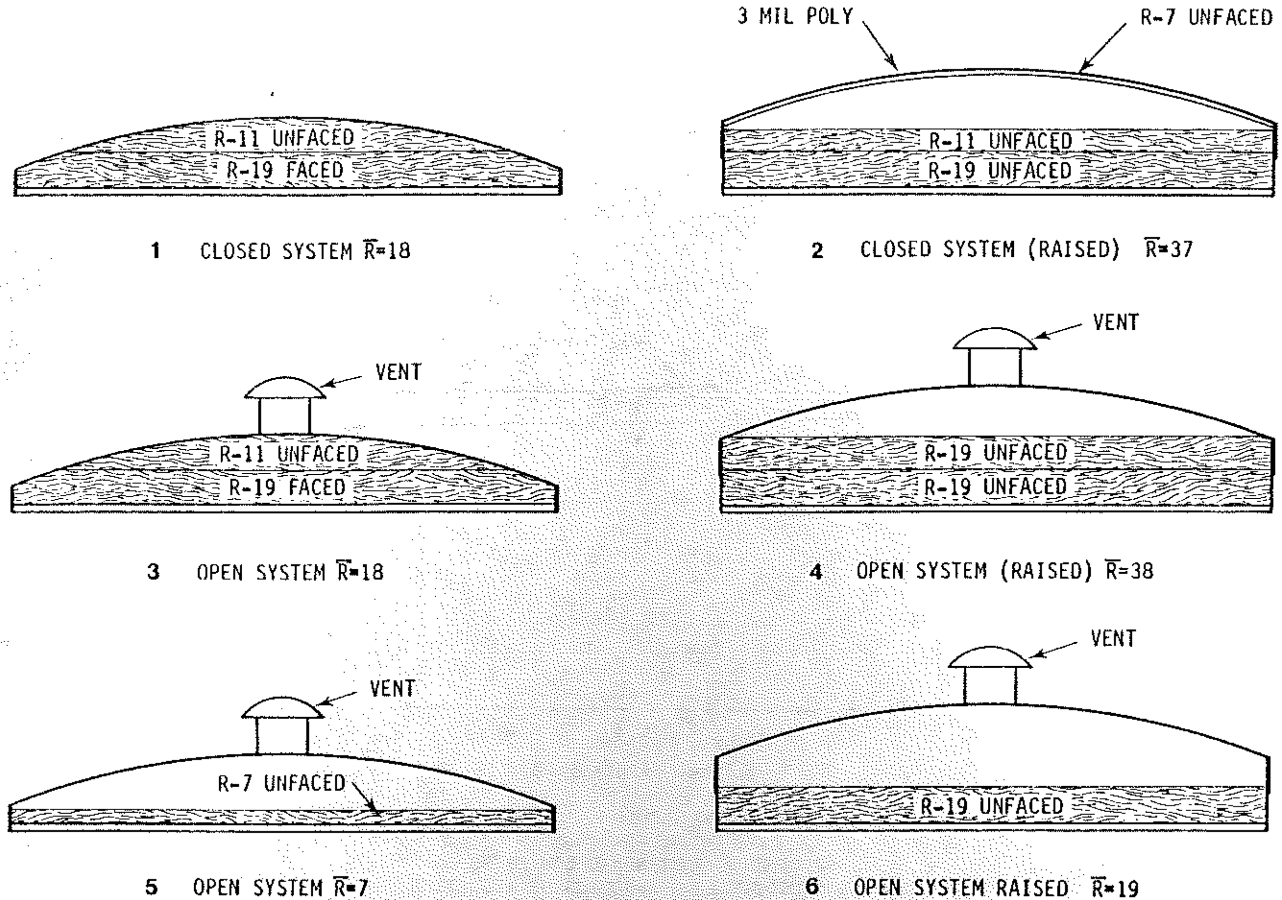

FIGURE 4

MOBILE HOME ROOF TEST SPECIMENS

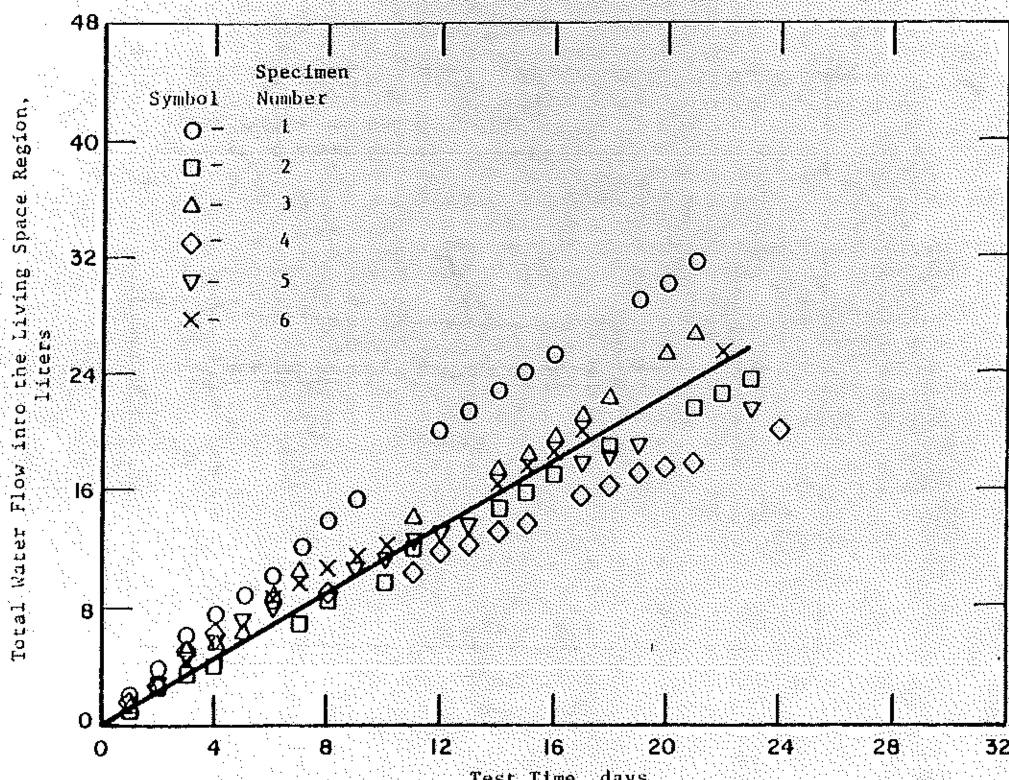

FIGURE 5. TOTAL WATER FLOW TO THE LIVING SPACE REGION AS A FUNCTION OF TIME FOR EACH SPECIMEN TEST

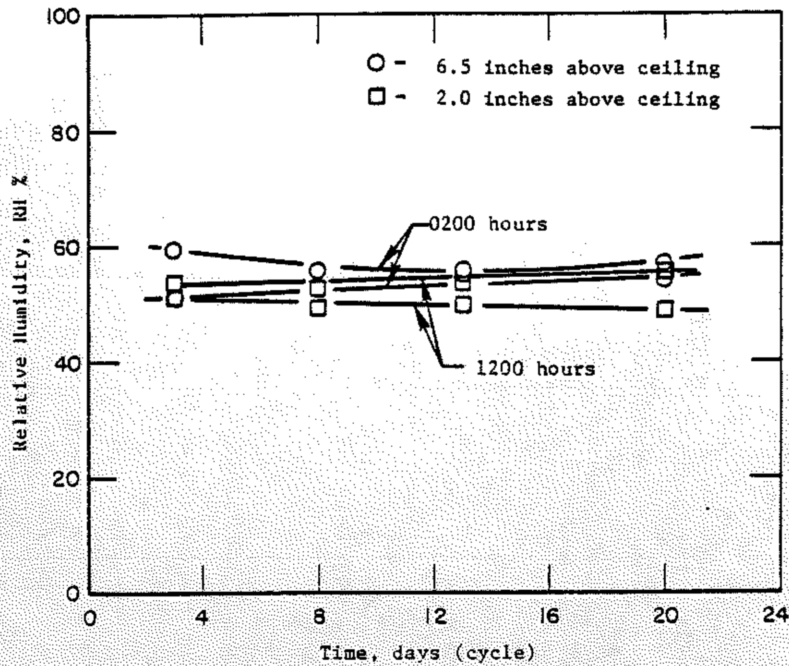

FIGURE 6

SPECIMEN 1 - STANDARD BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME

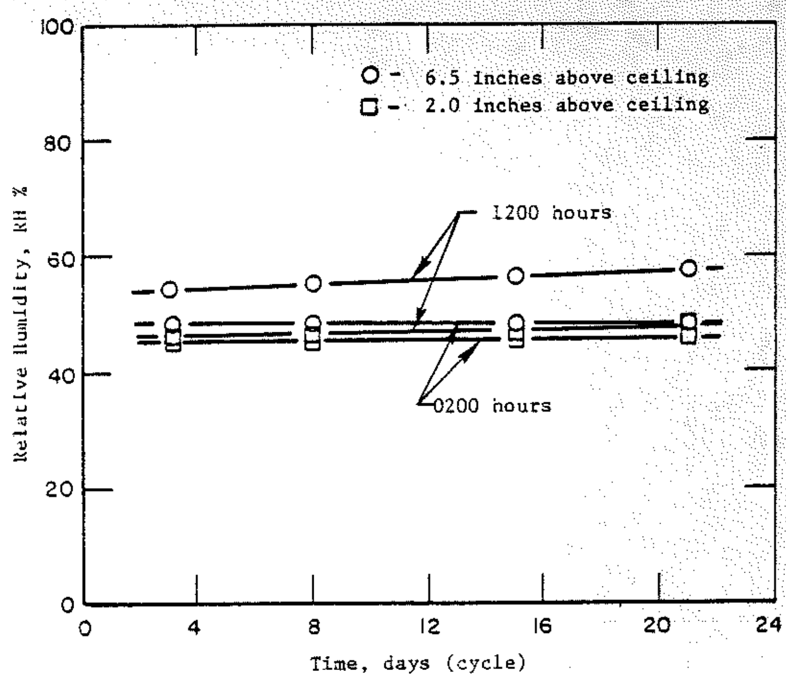

FIGURE 7

SPECIMEN 3 - STANDARD BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME

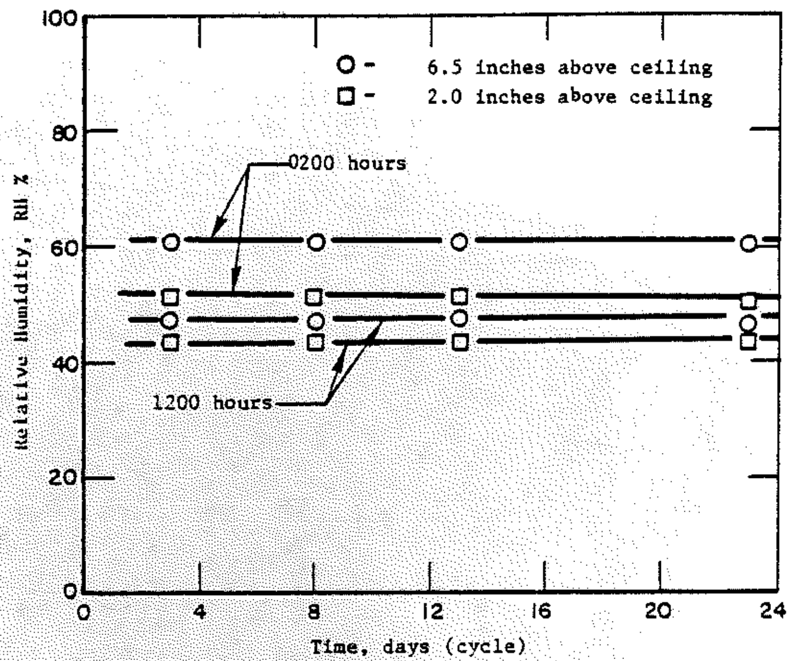

FIGURE 8

SPECIMEN 5 - STANDARD BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME

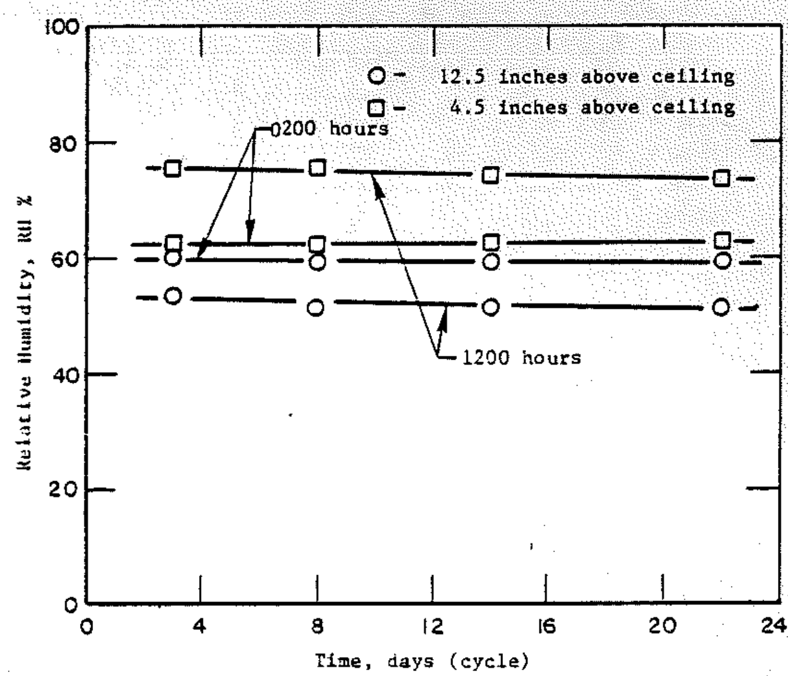

FIGURE 9

SPECIMEN 2 - RAISED BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME

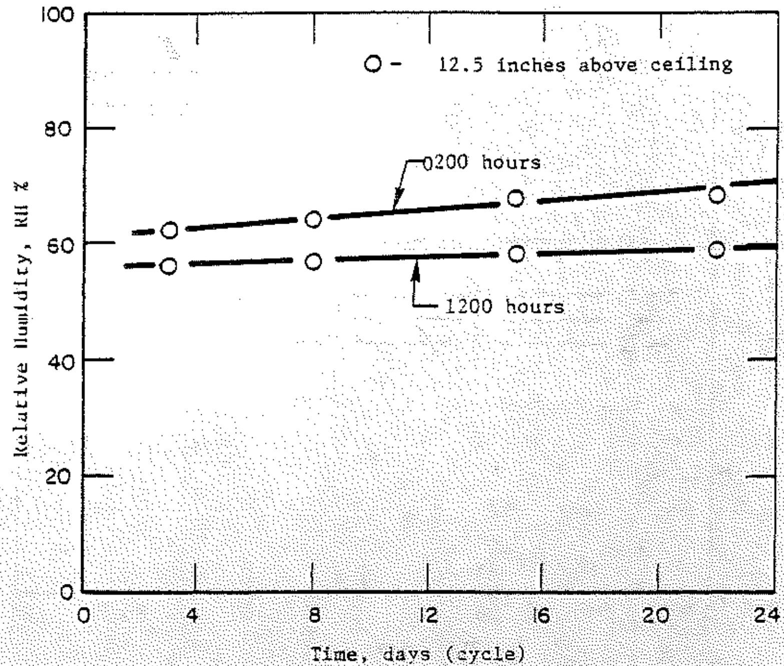

FIGURE 10

SPECIMEN 4 - RAISED BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME

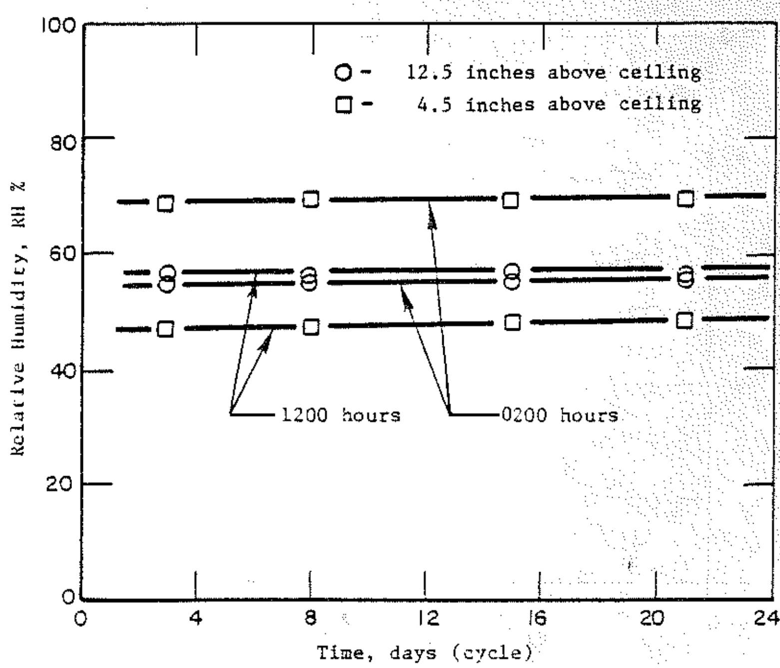

FIGURE 11

SPECIMEN 6 - RAISED BOW TRUSS
RELATIVE HUMIDITY AS A FUNCTION OF TEST TIME