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The Thermal Performance of a Two-Bedroom Mobile Home

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Final Report

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by

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ABSTRACT

Tests were conducted on a mobile home located in an Environmental Climatic Laboratory for the purpose of evaluating its thermal performance. The heating demand greatly affected the part-load efficiency of a gas-fired, forced-air, sealed-combustion furnace system. The practice of installing oversized heating plants was shown to result in low seasonal operating efficiencies. Air leakage measurements were performed using a pressurization technique to quantify the amount of air leakage through the various parts of the mobile home. Separate air infiltration tests using the SF_6 tracer-gas technique showed that somewhat higher air infiltration rates were induced by operation of the mobile home heating plant. A thermographic survey of interior surfaces showed that the technique used to install the wall insulation may allow wrinkles formed in the surface of the insulation to form air paths running the height of the wall cavity. Convective air flow through these paths may create heat leaks on the building surface which can have an impact on the overall heat-loss rate. Separate tests were also conducted to identify places in the mobile home envelope having high condensation potential.

Key Words: Air infiltration; energy conservation; mobile home; part-load efficiency; thermography.

1. INTRODUCTION

Rising energy prices and the necessity for conserving our nation's energy resources should provide a significant incentive to increase the effectiveness of energy utilization. For residential and commercial buildings this can be done by providing more efficient heating, ventilation, and cooling equipment, by more efficient operation and sustained maintenance of buildings and equipment, and by a building envelope with increased resistance to heat loss or gain. As in other types of buildings, energy conserving efforts in the mobile home industry and on existing mobile homes would result in a significant impact on energy savings. Currently, mobile homes represent more than 30 percent of new single-family detached housing, and this percentage is expected to increase over the next few years.

In order to accomplish savings in this significant segment of building energy consumption, it is necessary to provide the mobile home industry and present occupants of mobile homes with techniques and methods for predicting and evaluating energy utilization. As an effort to upgrade the standards with regard to energy conservation, the National Conference of States for Building Codes and Standards (NCSBCS) asked that the National Fire Protection Association Standard (NFPA) 501B (ANSI A119.1) Committee develop energy conservation requirements for mobile homes. NFPA formed an Energy Conservation Task Force to add such requirements to the mobile home standard and to a proposed new mobile home installation standard. As part of his initiative in the energy area, the President has directed the Secretary of the Department of Housing and Urban Development (HUD) to work in conjunction with the Federal Energy Administration (FEA) and the Department of Commerce (DoC) to ensure that energy conservation standards are included in the mobile home construction and safety standards.

The present report summarizes the findings of an experimental study conducted at the National Bureau of Standards (NBS) which was sponsored by FEA. The objective of this study was to observe measured vs. predicted thermal performance in order to aid in the establishment of energy conservation design standards with consideration to cost, size, weight, and performance of mobile homes. The test plan included the instrumentation and measurement of the thermal performance of a new furnished mobile home, built in accordance with the Mobile Home Standard, ANSI A119.1, 1974. The mobile home was installed in the large NBS Environmental Laboratory, where it was exposed to a variety of climatic conditions.

Because the final location of a mobile home may not be known at the time of manufacture and because of a number of variables such as altitude and heating value of the fuel that may affect the furnace output capacity, it is a common practice in the mobile home industry to install oversized heating plants in mobile homes. In most instances, the heating output capacity of the heating plant is much larger than the design heating load for the home in its final location. This study investigates the effect of heating demand on the part-load efficiency of a gas-fired forced-air heating plant.

Heat loss through air infiltration may represent one-third to one-half the heating load for a mobile home. Measures taken to reduce air leakage will unquestionably have a significant impact on reducing heating energy requirements. The points where air leakage occurs may not always be obvious and may sometimes occur in unsuspected places. A recent air leakage study performed on residential buildings [1]* showed that significant amounts of leakage occurred through solid walls and ceilings. These parts were previously thought to be essentially impervious to air leakage. Similar tests were also conducted on the mobile home of the present study to quantify the amount of air leakage occurring through different parts of the structure. Separate tests were also conducted to determine the effect of the operation of the heating plant on inducing additional air infiltration.

When mobile homes are constructed, the technique for installation of insulation in the walls may cause the insulation to wrinkle, creating air paths running the full height of the wall cavity. In this instance, significant air flow can be induced due to the thermo-syphon effect which may decrease the insulation effectiveness. In the present study, heat leaks due to this phenomenon were investigated.

The condensation of moisture on exposed surfaces and within structural elements may eventually cause unsightly staining and even wood rotting which may significantly shorten the life of a mobile home. As part of the present study, observations were made to identify those parts of the mobile home that have a high condensation potential.

2. DESCRIPTION OF TEST SPECIMEN

The test specimen was a new, factory-produced two-bedroom mobile home of nominal dimensions of 50 feet by 12 feet with a 7-foot interior height. Nominal dimensions include a 4-foot hitch, making the actual length 46 feet.

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* Figures in brackets indicate the literature references at the end of this paper.

Figures 1 through 12 show construction phases for the mobile home, beginning with the chassis (fig. 1). Floor construction included R-4 insulation over 1/16-in asphalt-impregnated underlayment; 2 x 6-in floor joists and heating duct running the entire length, completed with carpet and vinyl floor covering. The next step was installation of interior partitions and bathroom and kitchen. Exterior wall sections were fabricated with R-7 insulation friction-fitted between 2 x 4-in framing, and placed on periphery of floor; the roof section using R-14 insulation between framing members and over a 6-mil polyethylene film and a 3/4-in fiberboard ceiling material was then lowered over the walls, and the factory construction was completed by the installation of corrugated aluminum siding on exterior walls, and the sheet metal roof.

The mobile home was manufactured in Ephrata, Pennsylvania, and transported by tractor to NBS (fig. 13). After it was placed in the NBS high-bay environmental laboratory of approximately 70,000 ft^3 in volume, the utilities--electricity, water, natural gas and drainage--were connected. Supports were placed at various locations under the chassis to take weight off of the tires, for leveling and to reduce vibration. Also, sheet metal skirting was installed at the outer periphery between the bottom of the mobile home and the ground, as shown in figure 14. The home was factory-furnished with refrigerator, stove, two beds, dining-room table and four chairs, couch and divan, and curtains and draperies at windows.

Figure 1. Chassis of mobile home.

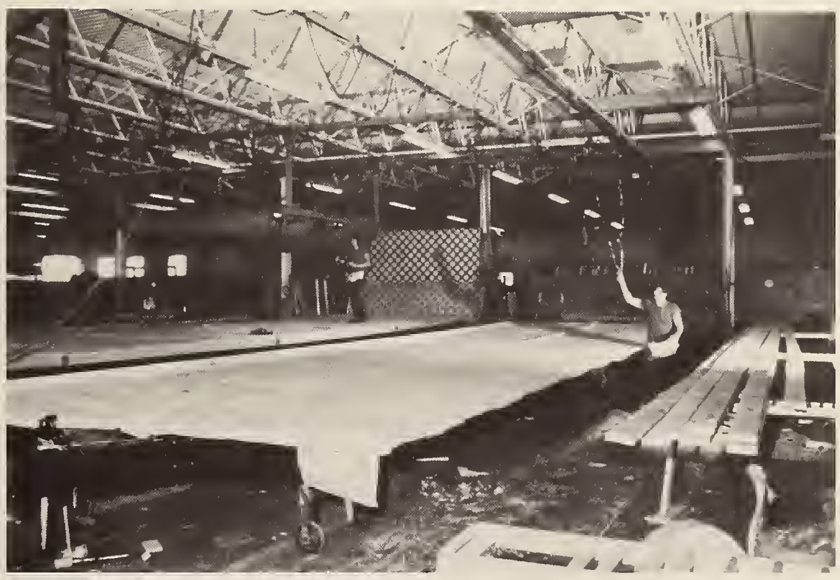

Figure 2. R-4 insulation over asphalt-impregnated underlayment.

Figure 3. Installation of 2 x 6 floor joists.

Figure 4. Longitudinal floor joists with heating duct in place.

Figure 5. Mobile home floor coverings in place.

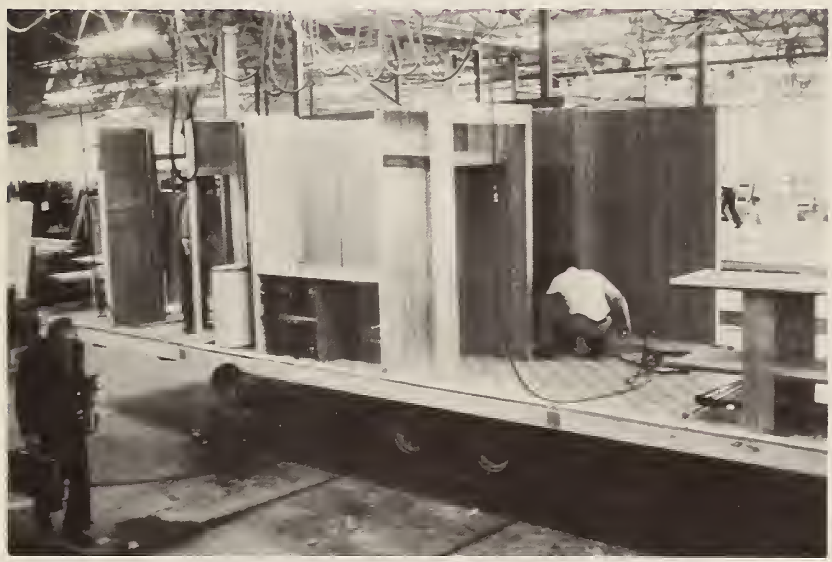

Figure 6. Installation of interior partitions.

Figure 7. Prefabricated insulated wall sections.

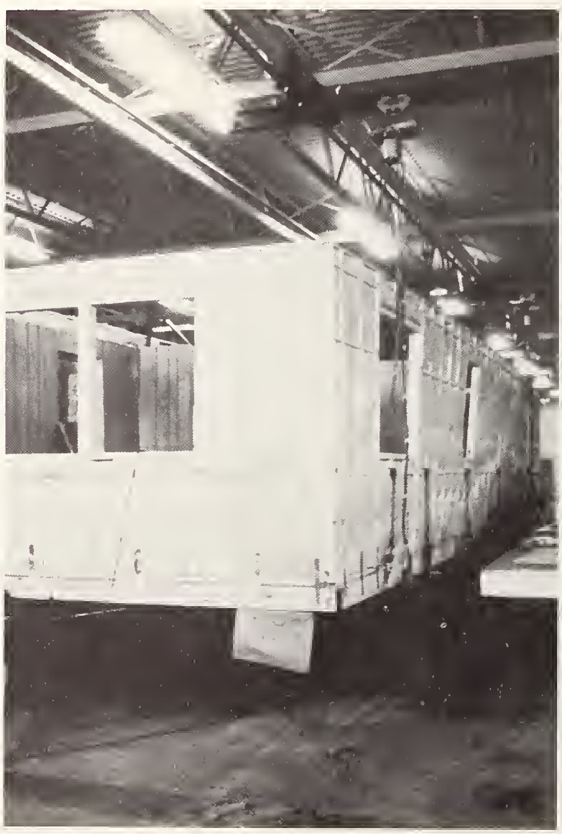

Figure 8. Installed wall sections.

Figure 9. Fabrication of roof section.

Figure 10. Roof section being lowered onto walls.

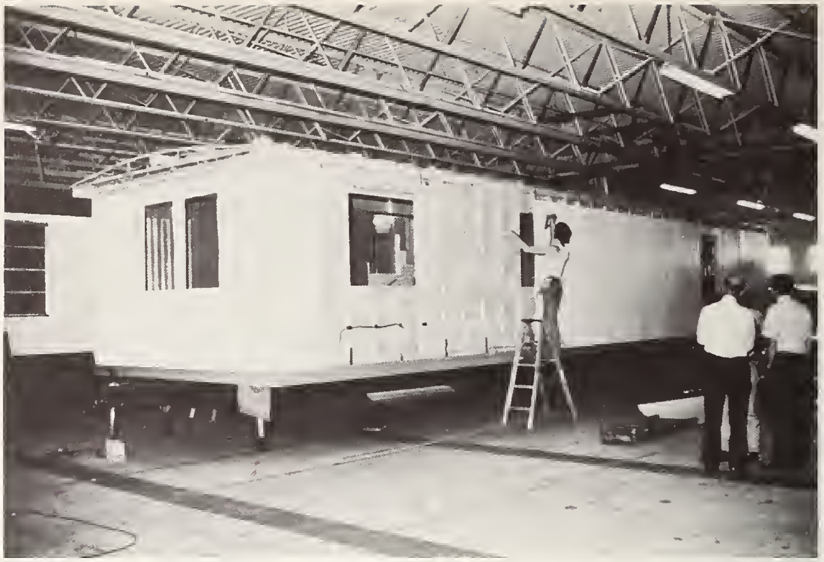

Figure 11. Installation of aluminum siding.

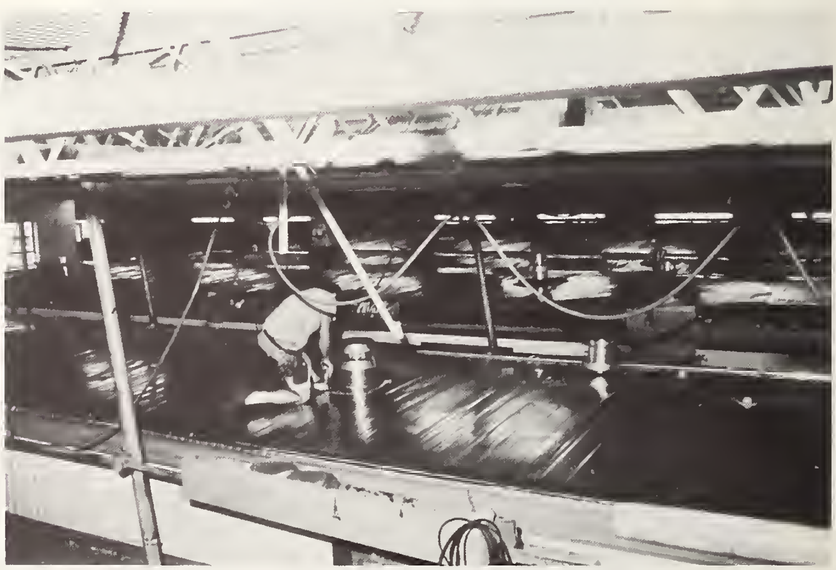

Figure 12. Installation of sheet metal roof.

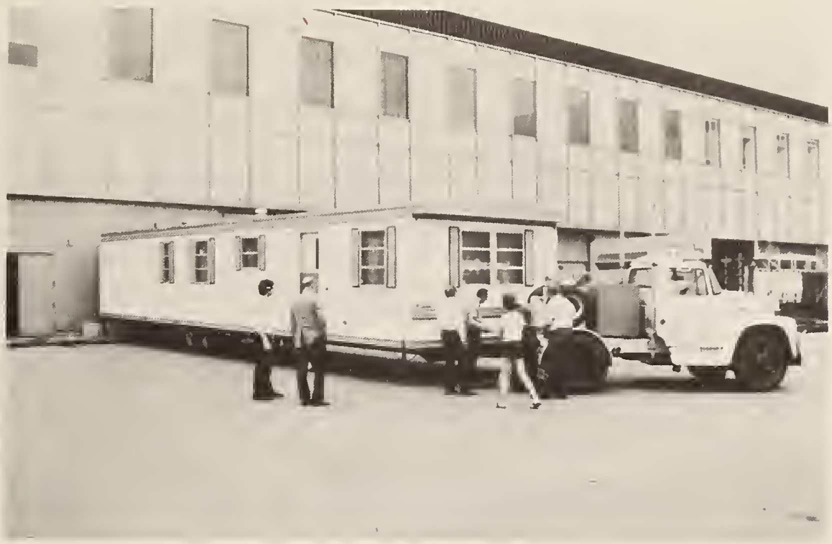

Figure 13. Mobile home delivered to NBS.

Figure 14. Mobile home in environmental chamber.

The warm-air, gas-fired, sealed-combustion furnace was rated at 56,500 Btu/h input and 45,200 Btu/h output at the bonnet. Air for combustion was taken from the outdoors at the roof through an outer annulus surrounding the flue pipe and into the combustion chamber. Combustion products were discharged to the outside through the inner annulus or flue. Air circulation within the mobile home was by a furnace fan forcing air down through the heat exchanger of the furnace to the heating duct located below the floor. Figure 15 shows air registers in the mobile home plan view. The thermostat was located in the hallway between the doors to the bedroom and furnace room. For special test purposes, the furnace plenum was used for the installation of electric resistance heating elements. The voltage supplied to the elements was controlled by a variable transformer for varying the electric heat input in tests where needed.

For expelling exhaust furnace flue gases, a 12-in diameter flexible hose was installed over the flue-gas stack located on the roof and connected to the laboratory outdoor exhaust system. The flexible hose installation is shown in figure 14.

3. INSTRUMENTATION AND TRANSDUCERS

The electric energy supplied to the mobile home electrical distribution system was measured using a calibrated 3-wire watt-hour meter equipped with an impulse generator--a photoelectric device which generated pulses from revolutions of the disk inside the meter. The pulses were registered by a counter and printed out at preset time intervals. The same system was used to measure electric energy input to the electric resistance heating elements installed in the furnace plenum.

The volume of natural gas consumed by the furnace was measured with a domestic gas meter that was specially modified, so that the passage of 1 ft^3 of gas caused an electric pulse to be generated. This was accomplished by placing an excitation voltage across a micro-switch that rode on the cam shaft of the counter and printed out at preset time intervals.

Ambient air and surface temperatures were measured with 24- gage copper-constantan thermocouples. Thermocouple strings, suspended by 3/16-in diameter polycarbonate rods, were placed in each room. The location of these strings is shown in figure 15. Four thermocouples were attached to each rod and located at 3, 30, 60, and 81 inches above the floor. Outside air temperature in the environmental chamber was measured by eight thermocouples placed one foot from outside surfaces of walls and roof. Two thermocouples placed one foot below the chassis of the mobile home measured the air temperature in the space enclosed by the sheet metal skirting. Other thermocouples measured temperatures at inside window surfaces, and temperatures of the supply and return air to the furnace.

4. PROCEDURE, RESULTS AND DISCUSSION

In the following sections, procedure, results and discussion are presented for the various aspects of testing.

4.1 Thermal Testing Under Steady-State Conditions

A. Instrumentation

This series of tests was conducted in an environmental chamber having the capability of individually controllable temperature and relative humidity from -50 F to 150 F and from 15 percent to 85 percent RH, respectively. The temperature

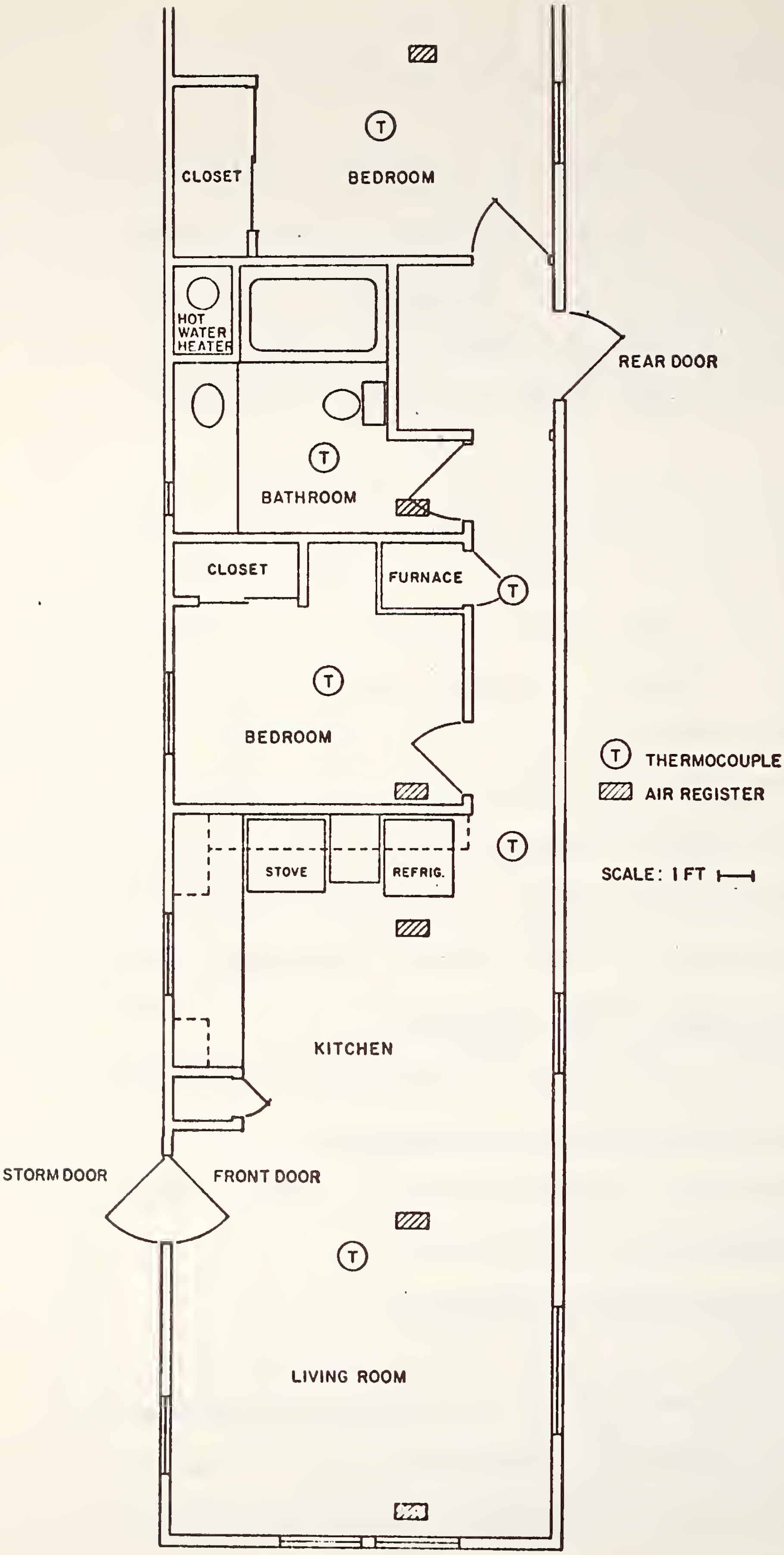

Figure 15. Plan view of 46 ft long by 12 ft wide mobile home showing location of thermocouple strings

and relative humidity can be held constant or caused to cycle on a predetermined schedule. The air within the chamber is circulated at a high-change rate (one air change every two minutes) in order to control the temperature within the chamber. Control thermocouples are located in the supply and return air.

Forty-eight 24-gauge copper constantan thermocouples were located throughout the interior and exterior of the mobile home so that temperature measurements could be used for heat flow calculations. For location of these thermocouples, refer to section 3 of this report.

Although the gas meter provided the gross energy input to the gas-fired furnace, it was necessary to measure the efficiency of the furnace in order to determine the energy input to the mobile home. The continuous operating efficiency was determined using a CO_2 combustion gas analyzer.

The furnace on-and-off cycles were observed using clocks and strip-chart recorders connected by relays to the furnace. A separate strip-chart recorder was used to show furnace blower on-time and furnace burner (or electrical resistance elements) on-time. These recorders were used to determine the number of cycles per hour. Two electric clocks were also connected to the strip-chart circuitry so that one clock recorded total on-time of the furnace fan during a test and the other clock recorded total burner on-time. These clocks were used to provide accurate percent on-time for the fan and the furnace for each test condition.

b. Test methods and conditions

For this series of tests, the chamber and mobile home interior temperatures were held constant and the mobile home energy consumption was recorded. It was necessary to hold the test chamber at test conditions for at least 16 hours prior to each test to allow the mobile home to reach equilibrium. A further check on equilibrium conditions was made at the end of each test by comparing energy consumption for each hour. Any irregularity of energy demand resulted in test invalidation.

The mobile home was tested under several outside air temperature conditions, with both natural gas and electric energy inputs and with and without storm windows. The various steady-state tests are denoted by the x's in the following schedule.

		Approximate Chamber Temperature, F				
		-15	0	15	30	45
Electric Furnace	With Storm Windows		x	x	x	x
	Without "			x	x	x
Original gas Furnace	With Storm Windows	x	xx	xx	xx	xxx
	Without "			x	x	x
Modified gas Furnace	With Storm Windows		x	x	x	x
	Without "					

The average inside air temperature was about 70°F for all tests. Tests were conducted with the furnace modified to a lower natural gas input to show the effect of this variable. Tests with the original gas furnace were repeated to show reproducibility of data. One test was made at -15 F in order to extend trends established. The chamber temperatures are described as being approximate since the chamber controls were set at the value shown but equilibrium was often established with a ± 2 F deviation from the set point. Actual temperatures were used for all calculations.

After reaching equilibrium, each steady-state test was continued for a period of seven hours. A complete set of data was recorded every 30 minutes for the duration of the test.

One series of tests was run with the furnace modified to a lower input capacity. The original equipment gas furnace was rated at a 56,500 Btu/h input and a bonnet capacity of 45,200 Btu/h. On special request, the manufacturer provided a replacement burner orifice to reduce the input capacity to 30,000 Btu/h or a bonnet capacity of 24,000 Btu/h. In order to keep the furnace efficiency nearly the same as the original furnace, the manufacturer also provided a small plate which was used to partially block the burner chamber draft outlet opening. After installing the new burner orifice and plate, the continuous running efficiency was found to be 75 percent (365 F and 4.5 percent CO_2) as compared to 72 percent (517 F and 4.5 percent CO_2) as determined for the original equipment. For sealed combustion furnaces the air for combustion is heated by the flue jacket, whereby the flue jacket losses for the computation of efficiency are ignored. The efficiency is then computed on the assumption of complete combustion of the fuel and the temperature and carbon dioxide content of the combustion products in the flue.

The method used to evaluate the effect of reducing the furnace capacity oversizing in comparison with the heating load was a comparison of energy consumption with the two different furnace capacities. The comparative comfort derived from the two furnace sizes was evaluated by determining air temperature gradient from floor to ceiling under the different test conditions.

c. Results and Discussion

The actual energy input was observed over 7-hour test periods and averaged to obtain energy input data. The observed energy readings were adjusted to reflect efficiency losses associated with the combustion heating systems. The electrical resistance furnace was assumed to operate at 100 percent efficiency and all other electrical inputs were converted directly to heat. The natural gas energy was based on a heat content of 1027 Btu/ft^3. This figure was obtained from the local natural gas utility and was reported to be applicable for the period of time when the tests were run. The efficiency of the gas furnace was measured using the CO_2 gas analyzer previously described. This efficiency could not be used directly, however, because of the indeterminate stack losses occurring during the off-cycle. In order to estimate the efficiency of the gas furnace under cyclical running conditions, the energy input to the combustion furnace was compared to the input to electrical resistance heating under the same test conditions. The relationship between the measured energy demands in Btu/h as a function of the inside-to-outside air temperature difference, ΔT, for the electric heating tests was found to be:

for mobile home with storm windows

$$Q_e = 471.3 + 149.2\ \Delta T + 1.076\ \Delta T^2$$

for mobile home without storm windows

$$Q_e = 120.35 + 177.1\ \Delta T + 1.081\ \Delta T^2$$

where Q_e = total heating load satisfied by combination of electric resistance heating elements, lights, and furnace fan.

From tests with the gas-fired furnace, the total rate of gas energy consumption, Q_g, rate of electrical energy consumption from lights and furnace fan, Q_m, and the temperature difference as measured, the efficiency, e, is calculated from the expression:

$$e = \frac{Q_e - Q_m}{Q_g}$$

where Q_e is determined from the relationships given above. These apparent efficiencies as a function of inside-to-outside temperature differences are shown in figure 16. These efficiencies were used to calculate net energy input to the mobile home for each test condition and compared with the predicted values.

The measured energy input to the mobile home for each of the test conditions is shown in table 1.

For comparison purposes, the predicted heat loss was calculated for each of the test conditions. These calculations as shown in Appendix A were made using the formula, U factors, and areas shown on table A-1. The construction of the building elements is shown in section 2 of this report. In these calculations the ASHRAE design resistances for interior still-air films were not used in the calculations. This is because of the geometry of the mobile home and its effect on the radiative heat transfer. Appendix B discusses reasons for the interior air film resistances used.

Actual temperature differences observed during each test were used in the heat transfer predictions. Separate temperature differences were used for transmission losses through walls and roof, and floor areas.

In order to predict heat flow under test conditions, air infiltration rates had to be considered. The air infiltration rates used in the calculations were determined on the mobile home using sulfur hexafluoride

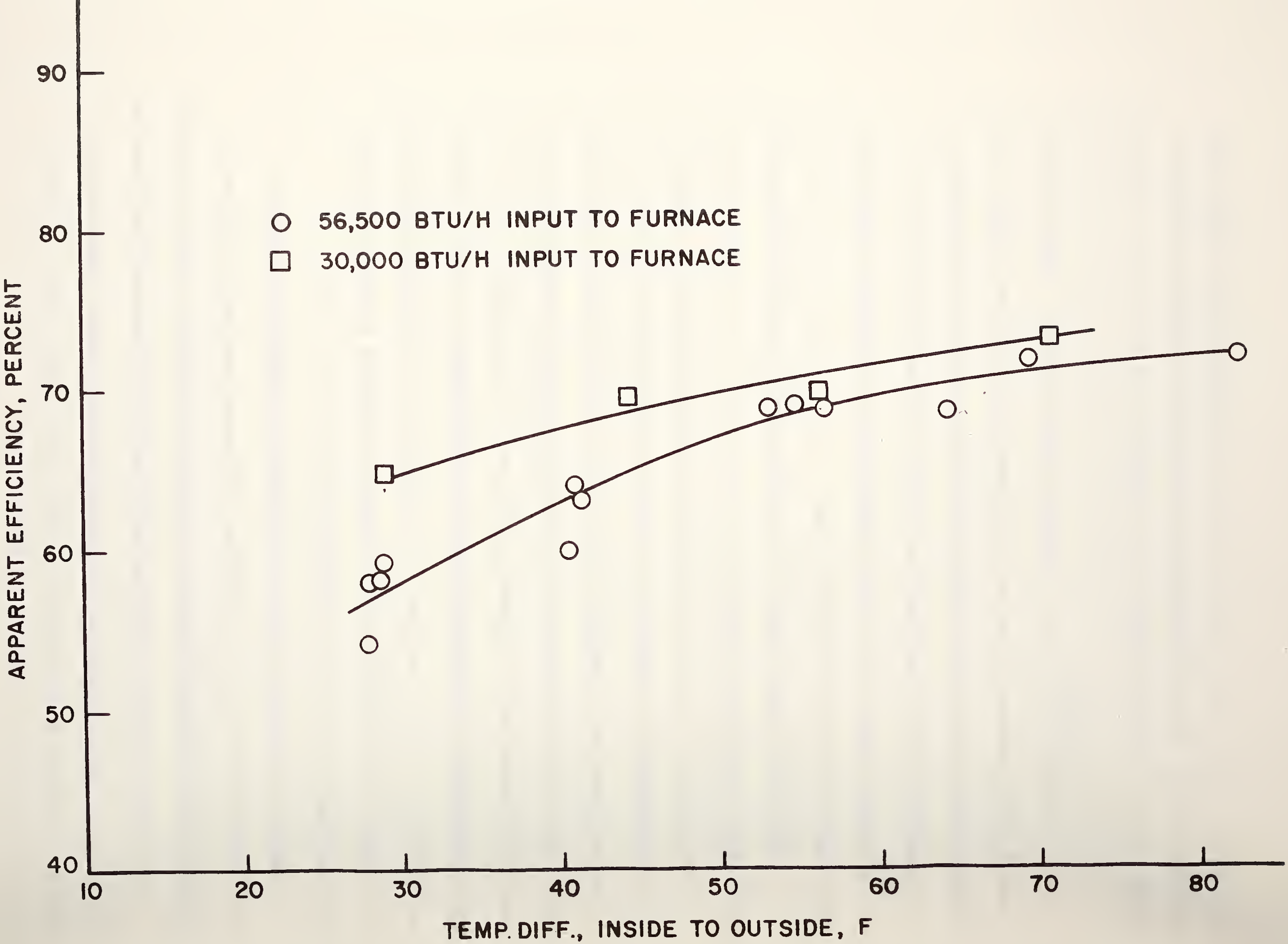

Figure 16. Apparent thermal efficiency of the original and modified furnace vs. inside-to outside temperature difference.

Table 1

Mobile Home Energy Consumption

Test Conditions		Energy Input, Btu/h			Temp. Diff. F.	Total Energy Supplied per Unit Envelope Area and per unit Temp. Difference Btu/h-ft²-F
		Furnace Input	Electric	Total		
56,500 Btu/h Input with Storm Windows						
	-15 F	25,122.1	1929.6	27,051.7	62.2	.1718
	0 F	20,553.3	1810.0	22,363.3	69.3	.1684
	0 F	18,485.0	1782.2	20,268.2	64.0	.1653
	15 F	15,698.0	1716.0	17,414.0	56.8	.1601
	15 F	14,524.7	1409.2	15,933.9	52.9	.1572
	30 F	11,297.0	1139.6	12,436.6	40.8	.1591
	30 F	11,150.2	1588.0	12,738.2	40.5	.1641
	45 F	7,335.7	1356.0	8,691.7	28.6	.1586
	45 F	7,042.1	1396.1	8,438.2	27.9	.1578
without Storms						
	15 F	17,063.6	1275.5	18,339.1	54.7	.1750
	30 F	12,674.1	1222.5	13,896.6	41.1	.1765
	45 F	8,509.7	1060.6	9,570.3	28.7	.1740
30,000 Btu/h Input with Storms						
	0 F	19,659.7	1972.9	21,632.6	70.5	.1601
	15 F	15,062.7	1750.1	16,812.8	55.9	.1570
	30 F	10,783.5	1667.3	12,450.8	44.2	.1470
	45 F	6,333.2	1525.2	7,858.4	28.7	.1429

* Based on a thermal envelope area of 1916 ft^2.

(SF_6) as a tracer gas. Section 4.3 of this report discusses the infiltration rate of this mobile home as a function of inside-to-outside temperature differences. Infiltration rates were determined both with the furnace blower running continuously and the blower off. In the steady-state heating tests, however, the furnace and blower cycled on and off by thermostat demand. Therefore, the infiltration rate used in the calculations was estimated to be between the observed rate with and without fan operation based on the percent on-time of the blower for each test condition. The percent furnace on-time for the tests with the gas-fire furnace operation is shown in figure 17. The estimated infiltration rate as a function of inside-to-outside temperature with cyclical furnace operation is shown in figure 18. These infiltration rates were used in the calculations.

Using the method outlined in the calculation form of Appendix A, the predicted overall thermal transmittance is determined by dividing the heat-loss rate by the actual temperature difference and the thermal envelope area of 1916 square feet. The measured heat-loss rate is determined in a like manner, and table 2 gives the measured and predicted thermal transmittance values. Generally, at the lower temperature differences there is good agreement between the measured and predicted values, but with increase in temperature difference, the measured values become greater than the predicted values. This seems to indicate a process taking place that is dependent upon increase in temperature difference, such as the increased buoyant effect on air. In section 4.2, we note that there is thermosiphoning of air in passageways between the insulation and wall paneling due to loose insulation fits at the top and bottom of the stud spaces. These effects are difficult to determine from a predictive analysis because they are indeterminate and depend upon the workmanship and methods used to install the insulation and the magnitude of the inside-to-outside temperature difference.

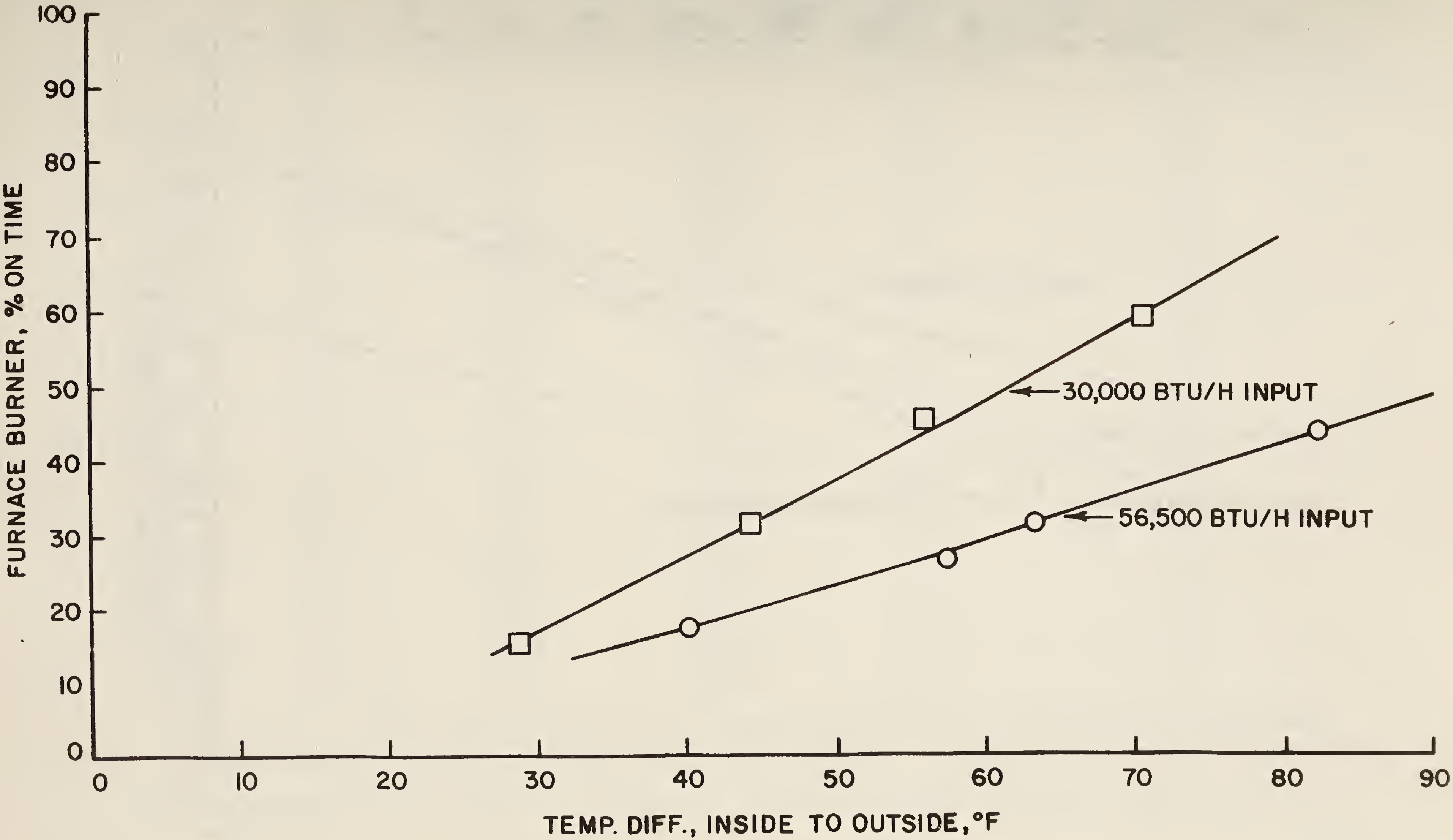

Figure 17. Percent furnace on-time vs. inside-to-outside temperature difference, F. for the original and modified furnace.

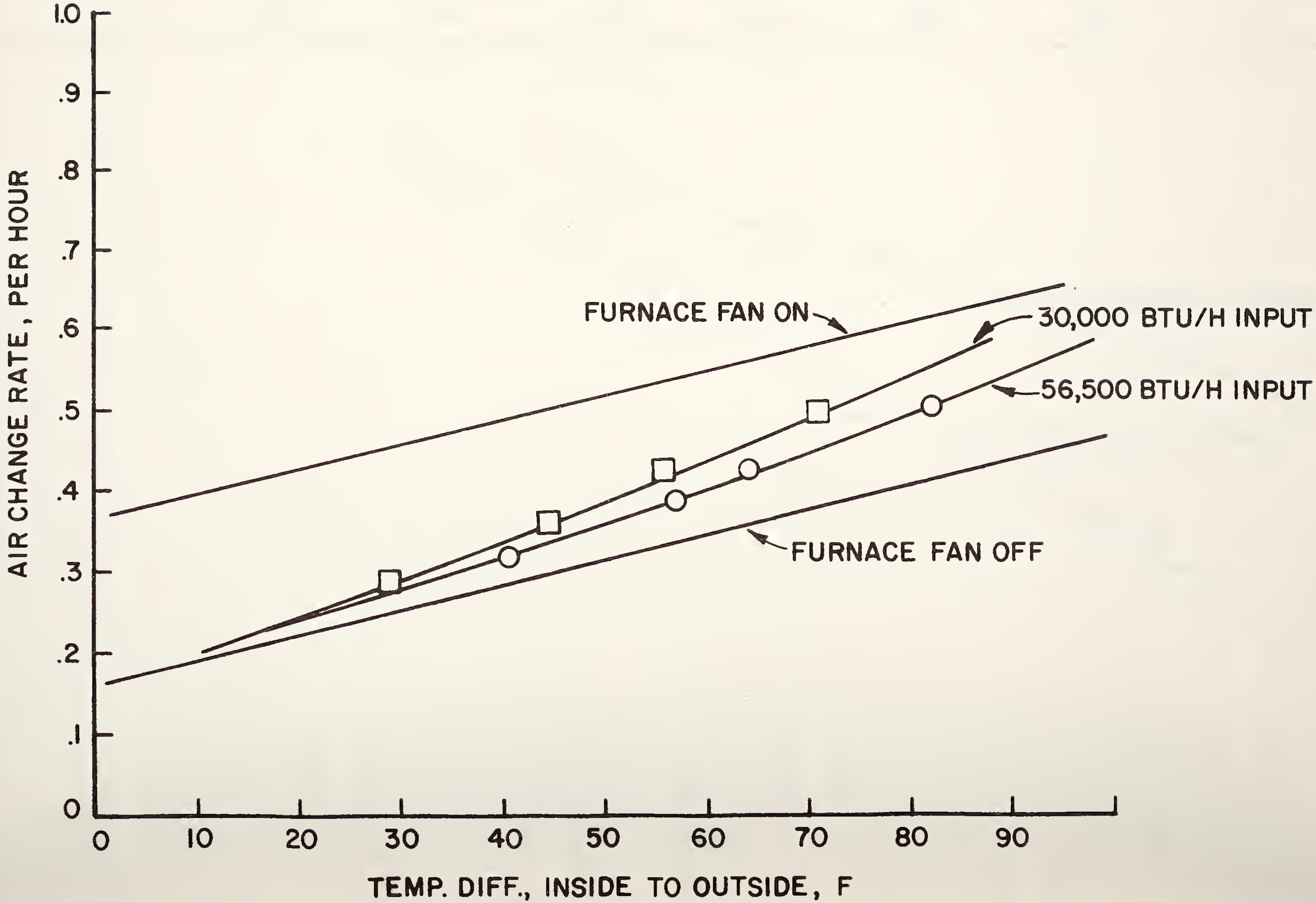

Figure 18. Estimated infiltration rate for cyclical furnace operation vs. inside-to-outside temperature difference.

Table 2

Table 2

Comparison of measured and predicted heat loss

Test Type*	Temp. Diff. F	Efficiency %**	Measured Values: Heating Rate Btu/hr	Measured Values: Overall Thermal Transmittance Btu/hr ft^2 F	Predicted Overall Thermal Transmittance Btu/hr ft^2 F
WE+0	69.5	100.0	16052.2	.121	.105
WE+15	56.3	100.0	12228.6	.113	.104
WE+30	41.5	100.0	8567.8	.108	.102
WE+45	28.7	100.0	5622.0	.103	.101
WG-15	82.2	71.7	20001.6	.127	.107
WG+0	69.3	70.8	16549.1	.124	.105
WG+0	64.0	68.4	14426.4	.118	.104
WG+15	56.8	68.2	12422.0	.114	.102
WG+15	52.9	68.8	11391.9	.112	.104
WG+30	40.8	63.9	8358.8	.107	.104
WG+30	40.5	59.9	8266.9	.106	.101
WG+45	28.6	57.9	5615.7	.102	.104
WG+45	27.9	57.7	5476.7	.102	.104
WG+45	27.8	54.0	5450.0	.102	.103
WGM+0	70.5	72.8	16343.7	.121	.105
WGM+15	56.1	68.5	12226.6	.114	.102
WGM+30	44.2	68.3	9172.7	.108	.101
WGM+45	28.7	63.7	5640.4	.102	.100
NE+15	56.1	100.0	13459.0	.125	.111
NE+30	41.4	100.0	9305.7	.117	.110
NE+45	28.3	100.0	5998.3	.111	.110
NG+15	54.7	68.6	13049.2	.124	.110
NG+30	41.1	63.4	9225.8	.117	.111
NG+45	28.7	59.0	6093.8	.111	.113

* For test type W-with storm windows, N-no storm windows, E-electric resistance heating, G gas fired furnace, M-modified gas furnace and remaining numbers denote approximate outdoor temperature.

** The efficiency of 100 percent is assumed for electric resistance heating as delivered to the mobile home.

Gross energy (not adjusted for efficiency) input versus inside-to-outside temperature difference is shown in figure 19. Throughout the tests, it was observed that the inclusion of storm windows caused an approximate 10-percent reduction in energy consumption under each test condition. This reduction was close to the predictions from the heat flow calculations. Previous infiltration studies on this mobile home (refer to section 4.3) show that the storm windows had only a small effect on infiltration rates. Therefore, it is assumed that the difference in energy input with and without storm windows is due to heat transfer through the windows by conduction and convection.

Throughout the tests the furnace was observed to be greatly oversized for the test conditions. The original furnace configuration was rated at 56,500 Btu/h input and the mobile home was certified to maintain a 70 F interior temperature with an outside temperature of -50 F, assuming a maximum 15-mile-per-hour wind. This mobile home can be considered to be equipped with a furnace oversized for the New York State marketing area for which it was produced. The degree of oversizing of the original furnace can be seen in figures 17 and 19. When the mobile home was tested in the environmental chamber at -15 F with the original furnace configuration, the furnace burner was operating only 43 percent of the time. Energy input to this furnace was 20,5000 Btu/h or 36 percent of furnace rating when the environmental chamber was maintained at approximately 0 F.

In order to evaluate the effect of this oversizing, measured energy consumption was compared between tests run with the original 56,500 Btu/h input furnace and the modified 30,000 Btu/h input. The energy input with the two sized furnaces is shown in table 1. The actual gas and electrical energy inputs (not adjusted for furnace

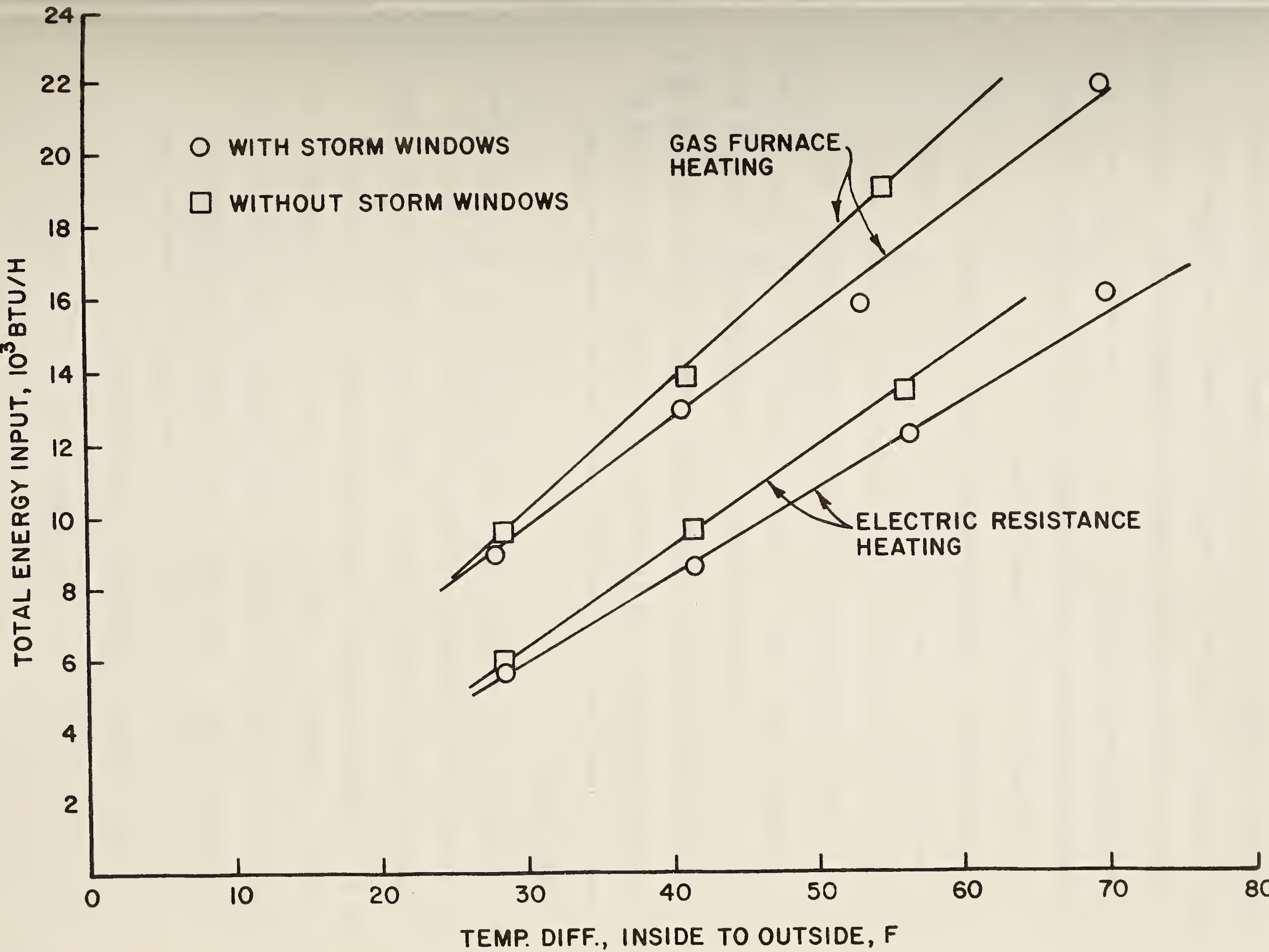

Figure 19. Total energy input to mobile home vs. inside-to-outside temperature difference.

efficiency) are shown for each of the steady-state tests. It can be seen that the energy consumption rate was significantly lower for the modified furnace than for the original-equipment furnace, especially at the lower inside-to-outside temperature differences where the effect of oversizing is more pronounced. This is true even though infiltration rates are assumed to be slightly higher with the smaller furnace because of the increased furnace blower on-time.

The reduction in energy consumption can be attributed to the increased percent on-time shown in figure 17, resulting in decreased time for off-cycle stack losses. The apparent efficiencies shown in figure 16 were determined by comparing the gross gas furnace input to the electrical input under the same test conditions, assuming the electric furnace to be 100 percent efficient. At a temperature difference of 70 F, both gas furnaces approach their continuous running efficiencies. At 30 F temperature difference, the difference in efficiency is greater than 10 percent. These low-load operating conditions are common during the heating season.

The floor-to-ceiling temperature gradients within the mobile home with each of the furnaces were checked to determine the effect of furnace sizing on occupant comfort. Table 3 shows these results. These results indicate that the floor-to-ceiling temperature differences were not significantly different between the two sizes of gas furnaces. However, the temperature gradient experienced with the electric furnace was obviously lower. This could be due to longer running time with the electric furnace, but this is not known because percent on-times were not recorded for the electric furnace tests.

Table 3

Average Floor-to-Ceiling Air Temperature Differences (F) as Affected by Furnace Size

Approximate Chamber Temp. F	56,500 Btu/h Furnace, 1st Series	56,500 Btu/h Furnace, 2nd Series	30,000 Btu/h Furnace	Electric Furnace
-15		14.0		
0	10.4	13.1	12.9	9.8
15	11.9	11.2	11.3	7.5
30	9.2	10.0	9.7	5.9
45	8.5	9.7	7.8	5.3

The lack of significant effect of furnace oversizing on occupant comfort may be specific to this mobile home design. Floor-to-ceiling temperature gradients in typical residential construction range from 5 to 20 F, depending upon the type of air distribution system used. It is possible that the temperature gradients would be affected to a greater degree if the ducts and registers were designed for better air mixing within the mobile home.

4.2 Thermal Performance by Thermographic Technique

A method for determining the thermal performance of the components of buildings is use of a thermographic system which detects infrared radiation emitted from surfaces. The surface temperature in a relatively narrow temperature range is proportional to the infrared radiation and relatively warm or cold spots can be quantified and displayed in a scan of surface temperatures if the surface emittances are known. Such warm and cold spots can help to identify areas of varying thermal transmittance due to thermal bridges and internal air movement.

The thermographic technique was also successful in identifying locations of air infiltration and air movement. The relation of warm and cold areas of walls to thermal performance of walls was investigated.

Refer to figures 20 and 21 and to section 2 of this report for a description of the wall construction.

4.2.1 Description of thermographic system

A photograph of the thermographic system used for this study is shown in figure 22. The equipment from right to left consists of an infrared camera, black-and-white television monitor, a color television display and a temperature profile adapter. The long-wave radiation that is emitted and reflected from a surface is sensed by the infrared

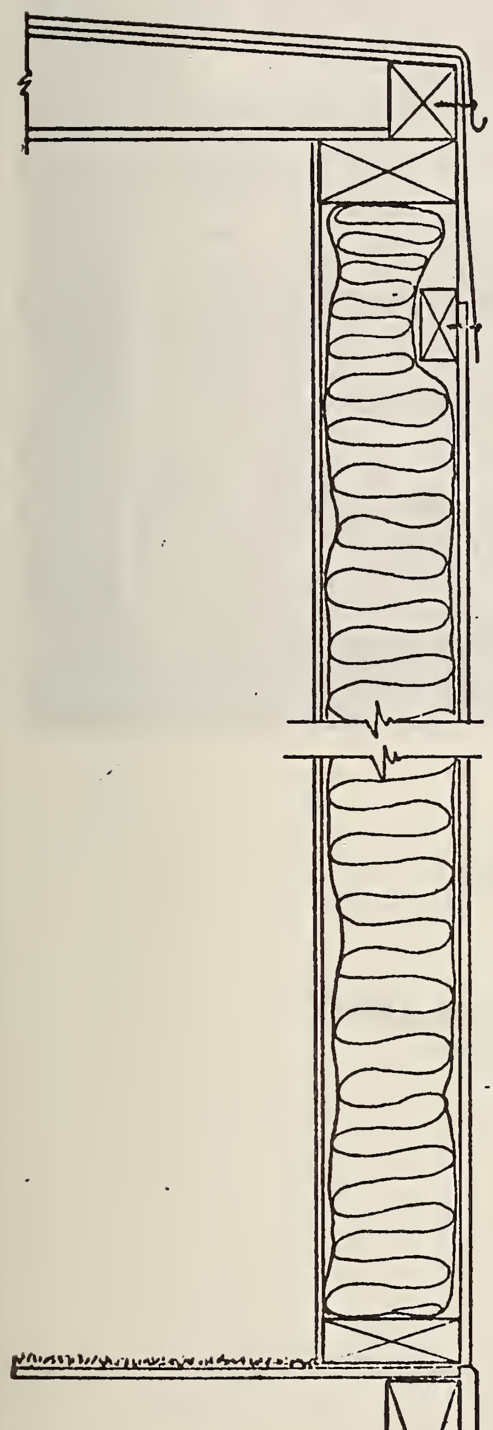

Figure 20. Elevation View of Mobile Home Wall

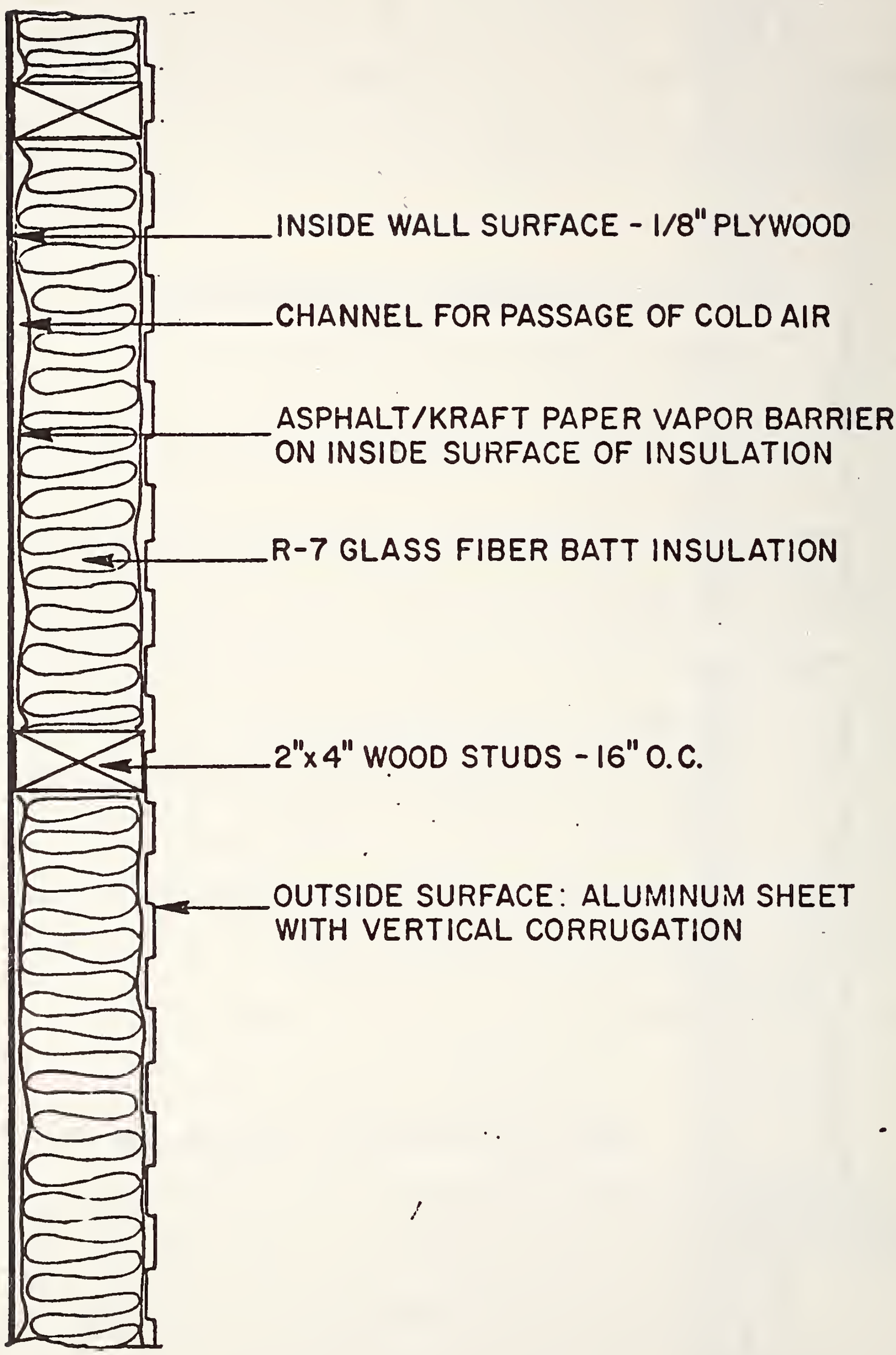

Figure 21. Plan View of Insulated Mobile Home Wall

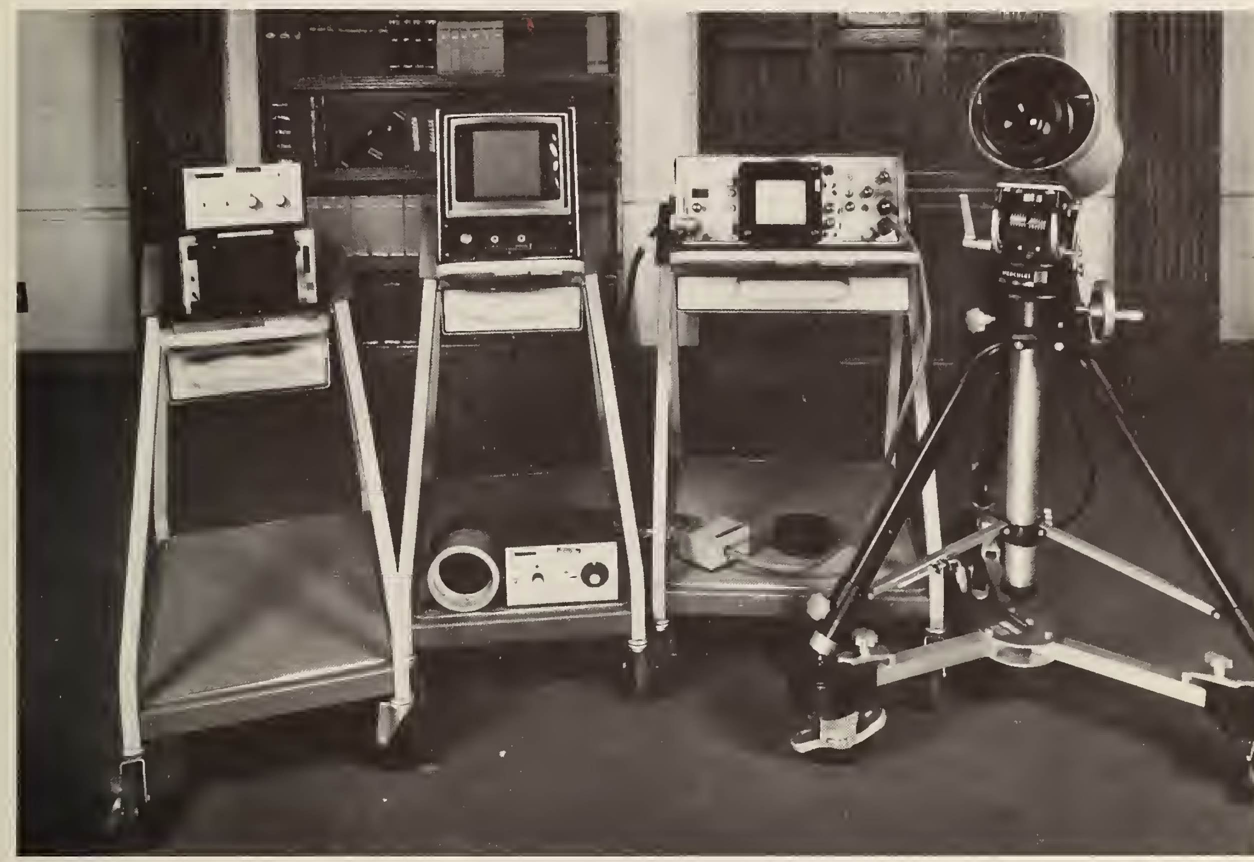

Figure 22. Thermographic System

camera and converted into a video signal. The camera consists of an optical scanning system with liquid-nitrogen-cooled indium-antimonide photovoltaic detector having a high sensitivity in the spectral range from 2.0 to 5.6 microns.

The video signal from the camera is processed in the black and white monitor and converted into a thermal picture in which the black, gray tones and the white approximately correspond to surface temperatures from cool to warm, respectively. The image is displayed on the screen of an oscilloscope for display and can be photographed with a conventional camera. The video signal is also fed into the color television display where ten individually color-coded isotherms each represent a step in the temperature gradient. The temperature profile adapter was not used in this study.

4.2.2 Observations with thermographic equipment

General thermographic observations were made of the inside and outside of the mobile home. During all of the following thermographic observations, the outside temperature was 0 F and the inside temperature was 72 F. On the outside, it was observed that the skirting around the base was warmer than the wall surface above, (fig. 23).

Most observations were made of the inside surfaces including several general observations. The location of wood studs was observable because the inside surface was slightly colder over the studded areas. Wall surfaces were observed to be colder toward the bottom as compared to the top of the wall (fig. 25). The warm heating ducts created an obvious pattern on the floor. Figure 26 shows an obviously warm floor register with a resulting warm wall area caused by the heater air

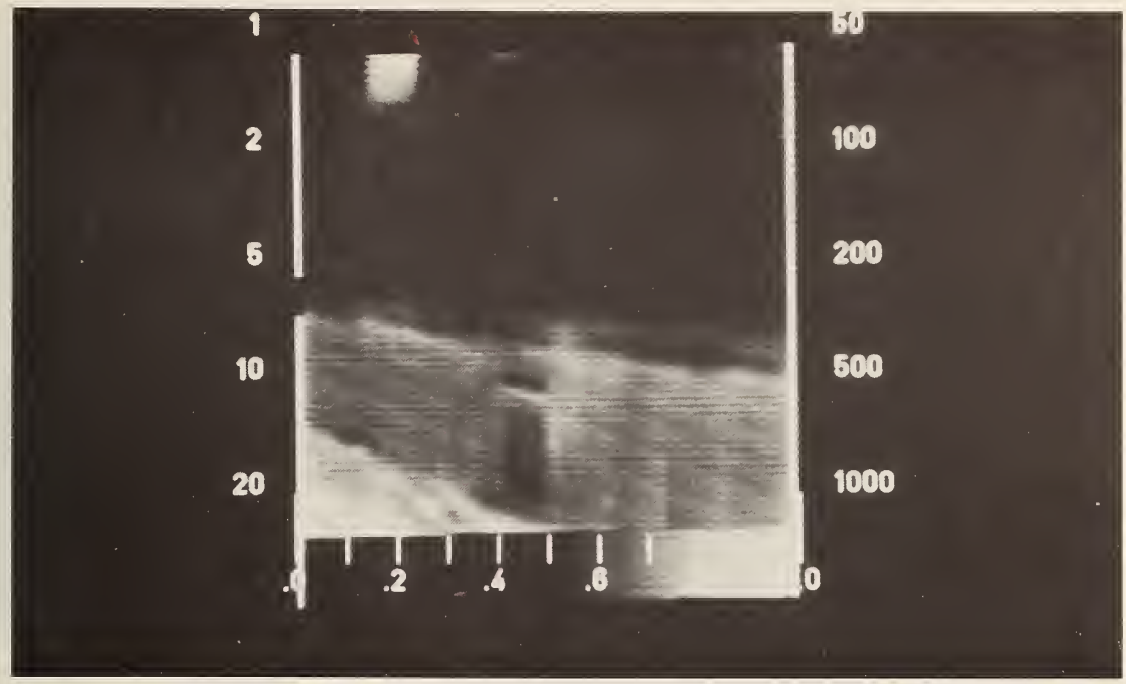

Figure 23. Angular thermograph of exterior sidewall of mobile home. Dark area (colder) is the aluminum wall surface. Lighter area (warmer) below is the skirting at base of mobile home , and white area in lower left is ground surface. Dark area found in skirting is an air vent (refer to figure 14).

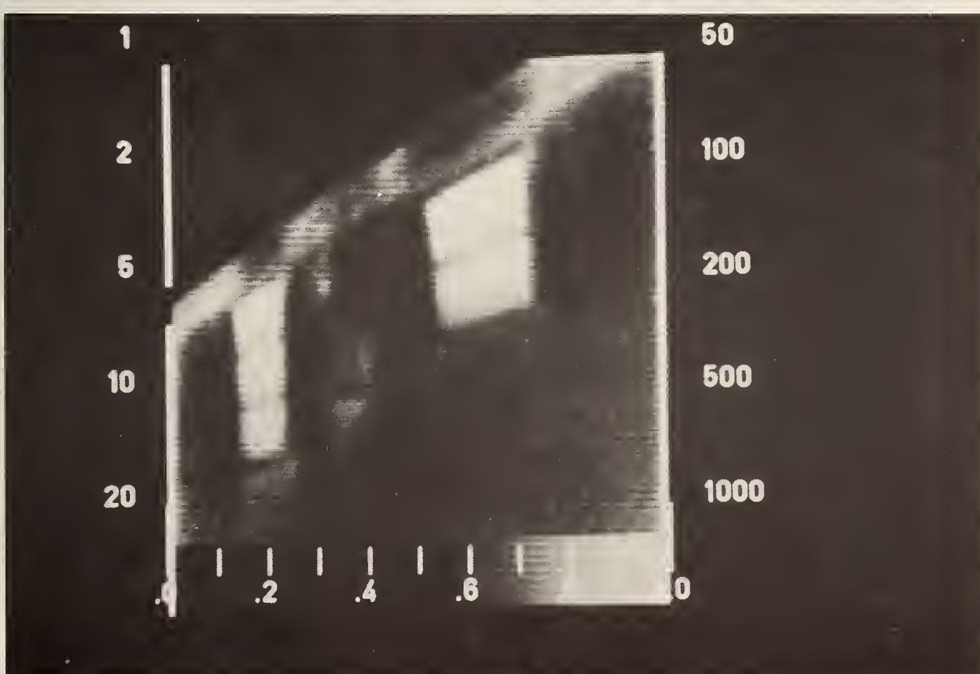

Figure 24. Warmer horizontal aluminum trim at wall roof juncture.

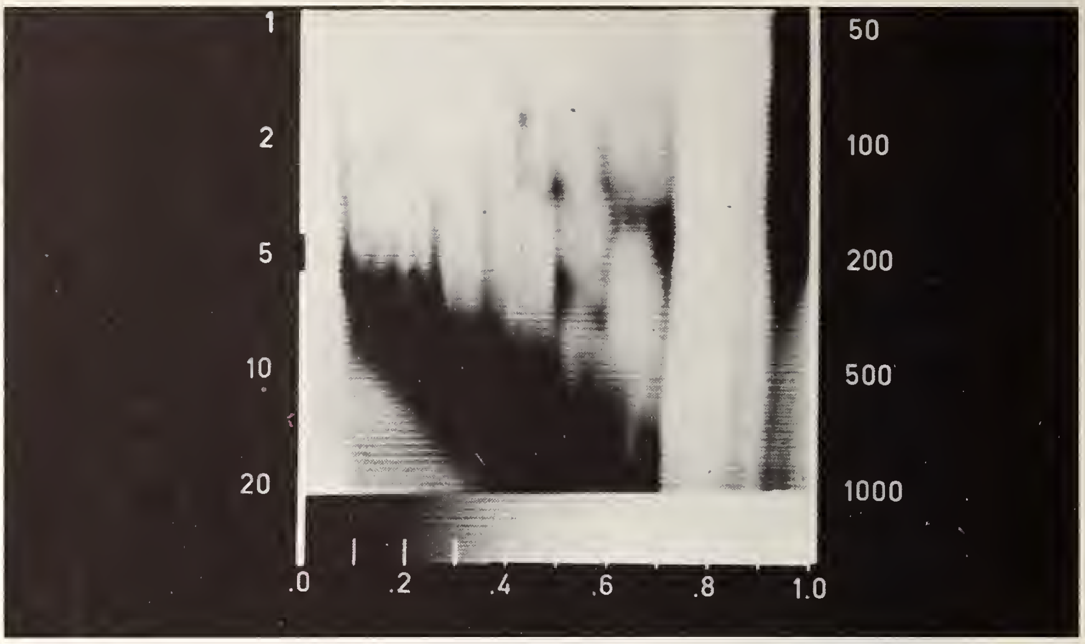

Figure 25. Wall along hallway looking from kitchen area. Walls are colder at the base of the wall. Cold streaks occur randomly along wall.

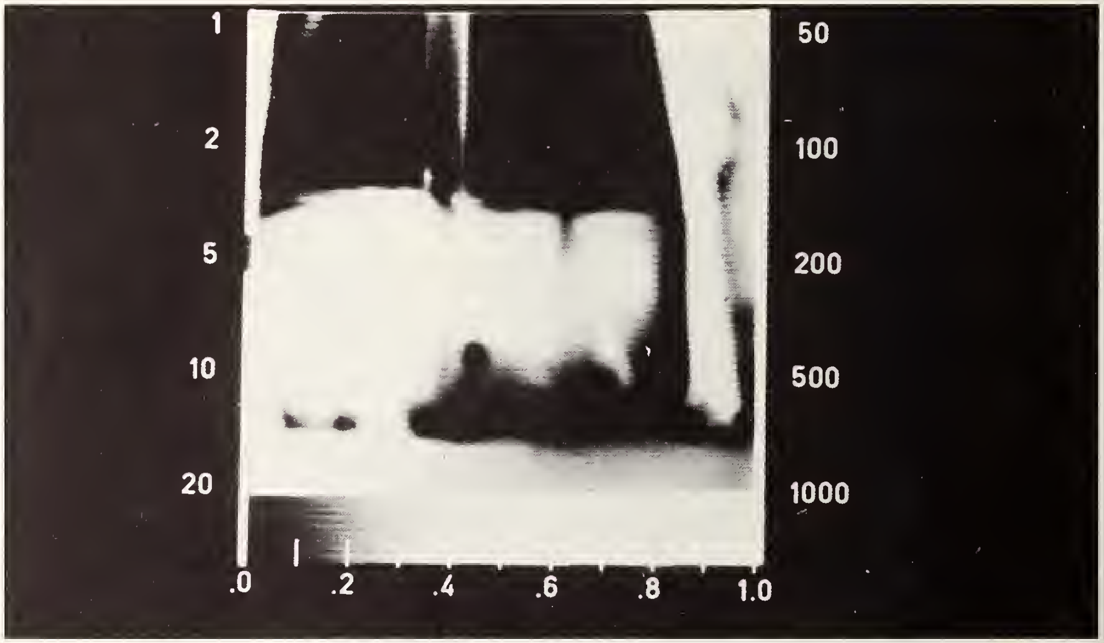

Figure 26. Wall at base of double living room window. Warm air register at lower left is warming the wall surface under left window.

warming the wall surface. The general thermographic observations also revealed some air infiltration locations. Figure 27 shows a cold (dark) area under a window where outside air is leaking in around the window framing. The wall/floor corner shown in figure 28 is obviously very cold. Closer observations at this location revealed an air leak at the wall/floor junction resulting in an interior surface temperature of 29 F in the corner (inside 72 F, outside 0 F).

One thermal characteristic was so dramatic that it created a dominant thermal pattern on the wall. Cold "streaks" (dark area of figure 29) occurred along the inside of the wall starting at the base of the wall and extending up into the upper half. Surface temperature measurements showed these streaks were about 5.5 to 6 degrees F colder than the warmer areas. The colder area covered about 25 percent of the surface area between studs.

From these observations, it was hypothesized that cold air must be in contact with the interior wood paneling. This early hypothesis was later supported when it was observed that the cold patterns on the wall correspond directly with locations where the insulation was not in contact with the wood paneling, leaving an air channel between the insulation and the paneling.

To test this hypothesis and evaluate various corrective techniques, a series of changes were made in the wall construction and the resulting thermal profiles were observed. All of these changes were made in one location as identified in figure 30.

Since gaps were observed at the top and bottom of the insulation (fig. 31), it was considered possible that cold air could enter the

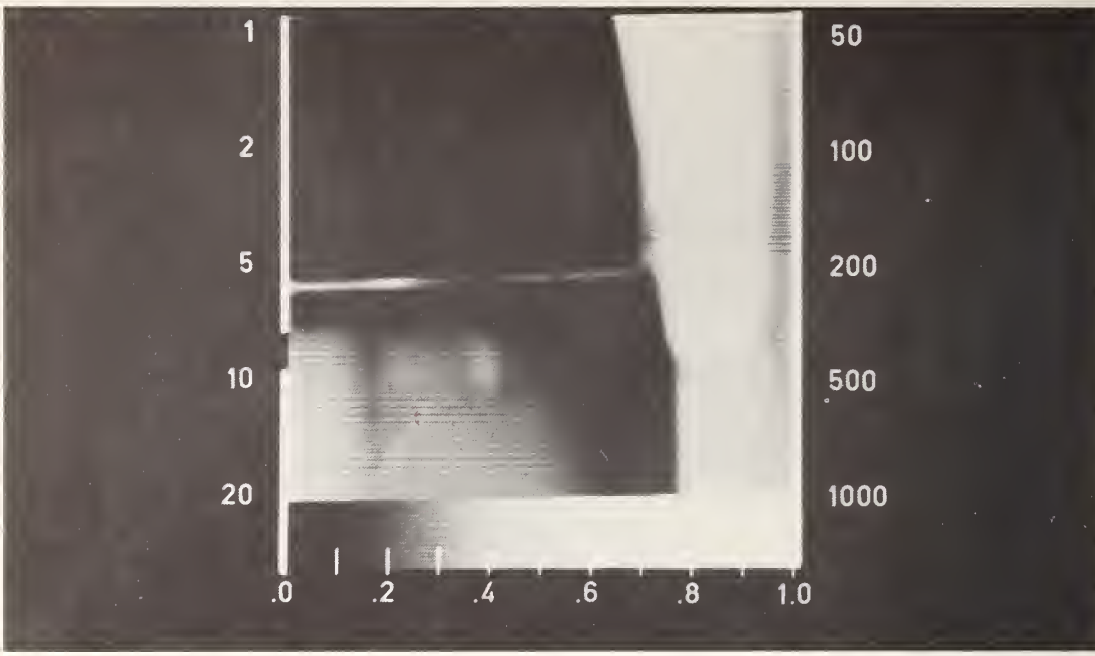

Figure 27. Window with warm curtain (light area) on right side. Dark (cold) area on wall under window is due to perceptible cold air leaking into mobile home.

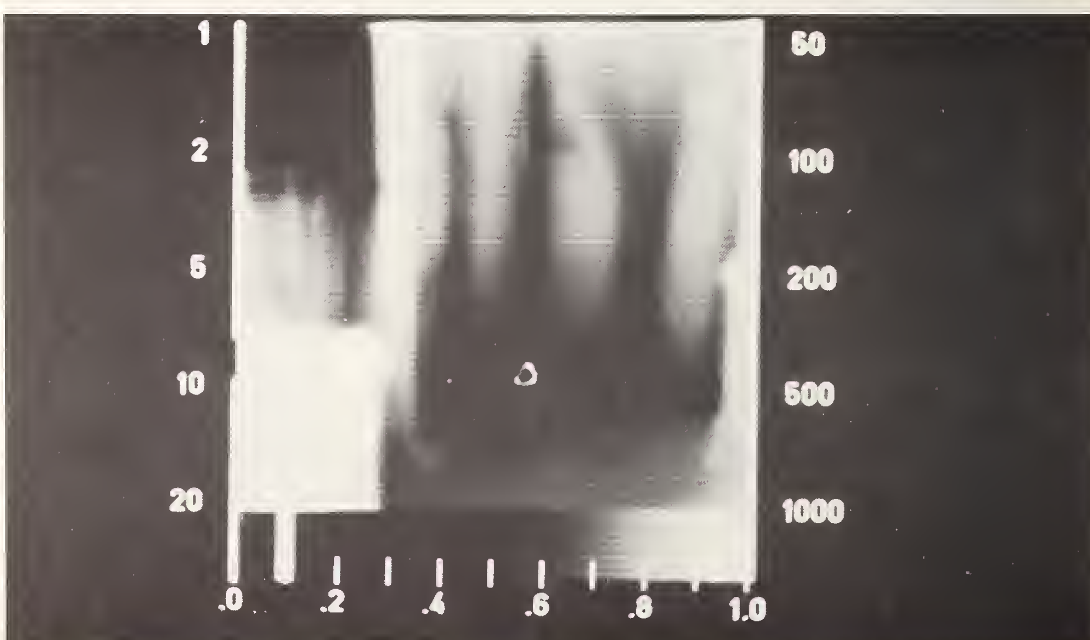

Figure 28. Living room wall/wall/floor corner. Perceptible air leak in corner created very cold spot, out of camera range. Light area in lower left is couch.

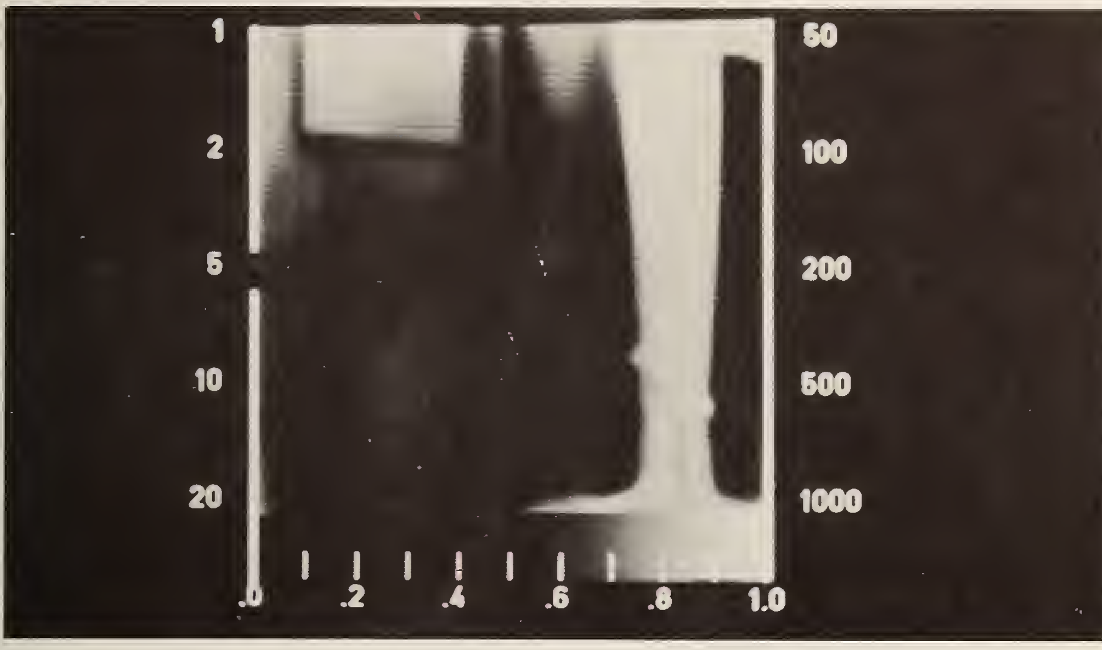

Figure 29. Wall area to left of living-room side-wall window. Picture on wall at upper left, draperies along window on right side of picture. Dark areas are cold. Note wall studs showing through in upper center. Location as shown on figure 30.

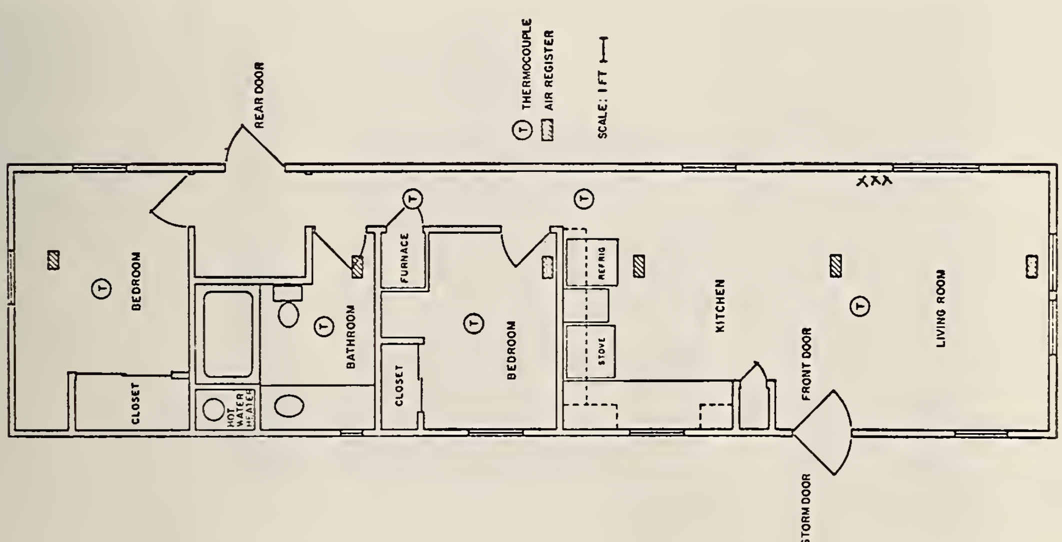

Figure 30. Location of thermographic investigation of wall performance denoted by X.

Figure 31. Gap between sill plate and bottom of insulation which could allow outside air in contact with back of inside paneling.

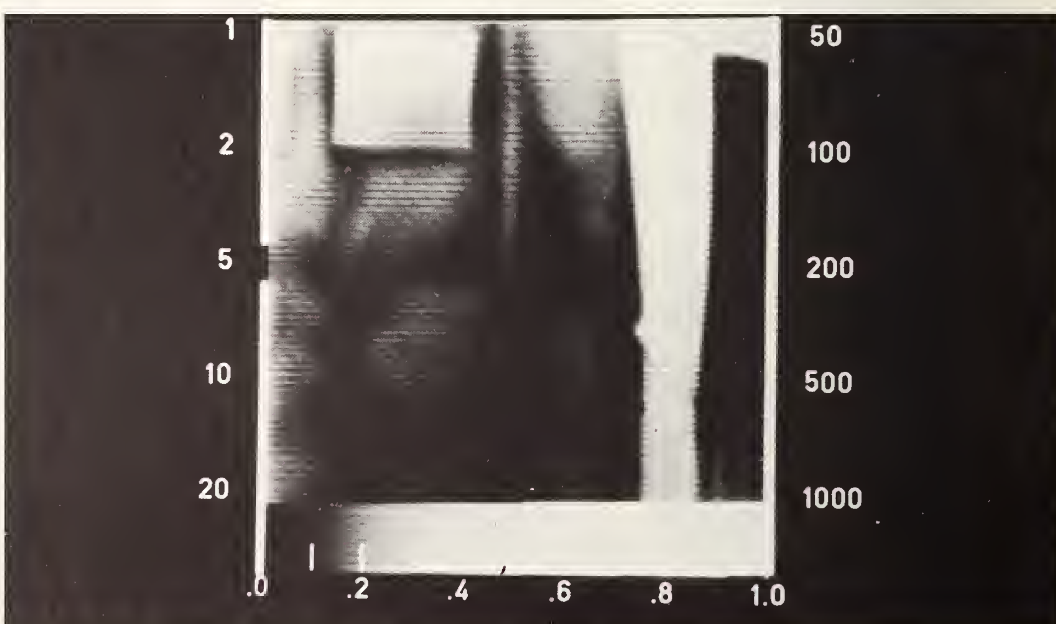

Figure 32. Thermograph of wall test area after sealing outside of insulation cavity with polyethylene film.

cavity, pass under the insulation, rise between the insulation and interior paneling and then pass to the outside over the insulation at the top. The exterior aluminum paneling allows more or less free passage of outdoor air into and out of the wall cavity outside of the insulation.

Six-mil ployethylene film was then attached to the outside surface of the studs at the test location to prevent cold air from penetrating directly into the insulation cavity (see fig.33). After the outside surface was sealed, the resulting thermographs (see fig.32) revealed that the cold pattern still remained with the same configuration as received from the factory. The surface temperatures were slightly warmer and the intensity of the cold/warm pattern was not quite as sharp as shown in fig.29. See table 4 for surface temperatures at locations A and B of fig.39. Location A is a spot where temperatures were lowest, and location B is the warmest temperature.

After it was determined that sealing the outside surface of the wall would not prevent the occurrence of cold patterns on the inside surface, it was reasoned that cold air could be circulating in a closed loop around the insulation within the stud cavity, without direct air leakage to the outside, effectively siphoning heat to the outside. This theory was tested by taping the inside vapor barrier of the insulation to the adjacent wood studs (see fig. 34). This figure also shows the taped lines outlining areas of the insulation which were in contact with the back surface of the wood paneling. Those areas in contact had warmer inside surface temperatures, supporting the theory that air movement within the stud space was causing the cold streaking on the inside wall surface.

After taping the vapor barrier to adjacent studs, more thermographs were taken. The resulting thermal profiles showed that the inside sealing process had a greater effect on reducing the cold streaks than did sealing the outside of the study cavity. Observations were made

Figure 34. Inside of mobile home wall with paneling removed. Insulation vapor barrier has been sealed to stud with duct tape. White tape outline on surface of insulation outlines areas in contact with back of paneling.

Figure 33. Six mil. polyethylene film used to seal insulation cavity from penetration of outside air.

both with and without sealing the outside of the stud cavity with polyethylene film. Although the film did have an observable effect of reducing the cold streaking on the inside surface, sealing the inside surface to prevent siphoning was obviously more effective (see table 4).

An alternative way to stop air movement within wall cavities and subsequent siphoning of heat to the outside would logically be to fill the cavity with insulation to remove locations where air could move. This theory was tested by removing the original insulation (R-7) and replacing with an R-11 full thick batt. This technique was evaluated with insulation installed by friction fit (figure 35) and with the insulation stapled neatly to the faced of the wood studs (figure 36).

In both cases, thermographic and thermocouple observations revealed that the cold streaks were substantially eliminated with full batts. Without neat, mechanically-attached placement, some streaks did occur along the studs where the insulation was wrinkled due to stuffing the stapleing flanges of the vapor barrier into the stud space, allowing air passage (see figure 37). With neat attachment, cold streaking was eliminated and surface temperatures were very even, as shown in figure 38 . As changes were made in the insulating system, inside-surface temperatures were recorded with the thermocouples located at A and B as shown in figure 39 . These temperatures are shown in table 4.

Some conclusions can be drawn. As currently installed, a portion of the R-7 insulation in the walls is made ineffective by the passage of cold air through the insulated cavity, siphoning air around the insulation. Although the surface temperature depression of 5.5-6.0 degrees F seems rather small, calculations indicate that this effectively means a reduction in insulation effectiveness in the cold spot

Figure 36. Same as Figure 35 but with R-11 batt stapled neatly in place.

Figure 35. Inside of mobile home wall with paneling removed. Original R-7 batt insulation has been replaced with R-11 batt. Insulation friction fit.

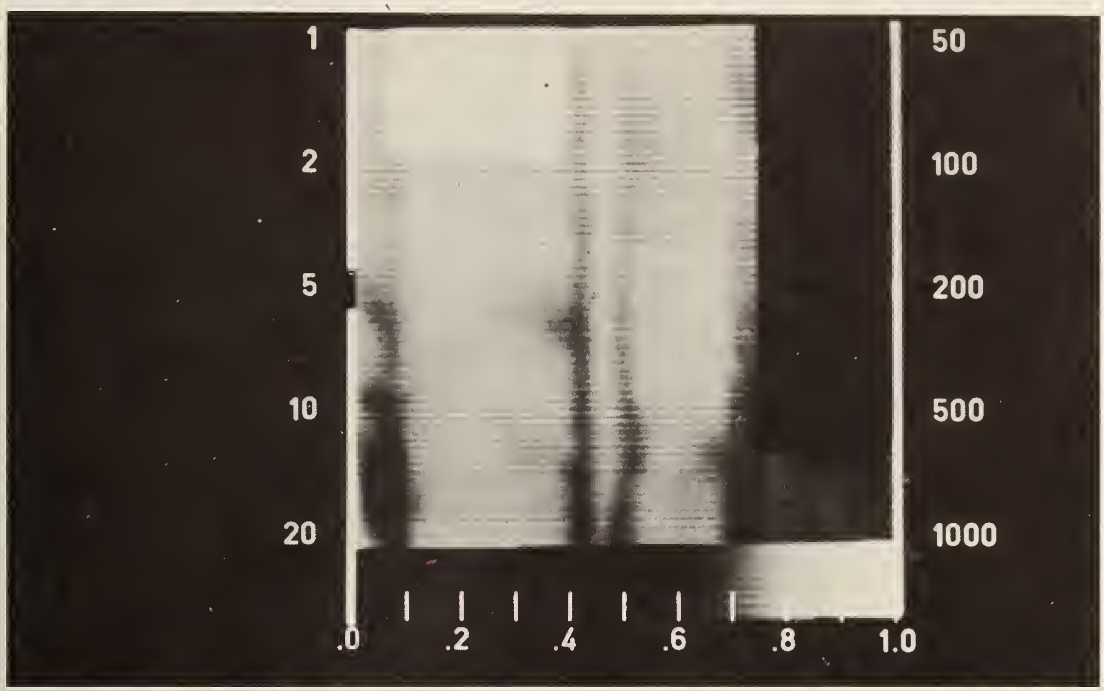

Figure 37. Interior thermograph after installing R-11 batt with friction fit. Note studs and cold streak caused by wrinkle in friction fit batt in narrow cavity.

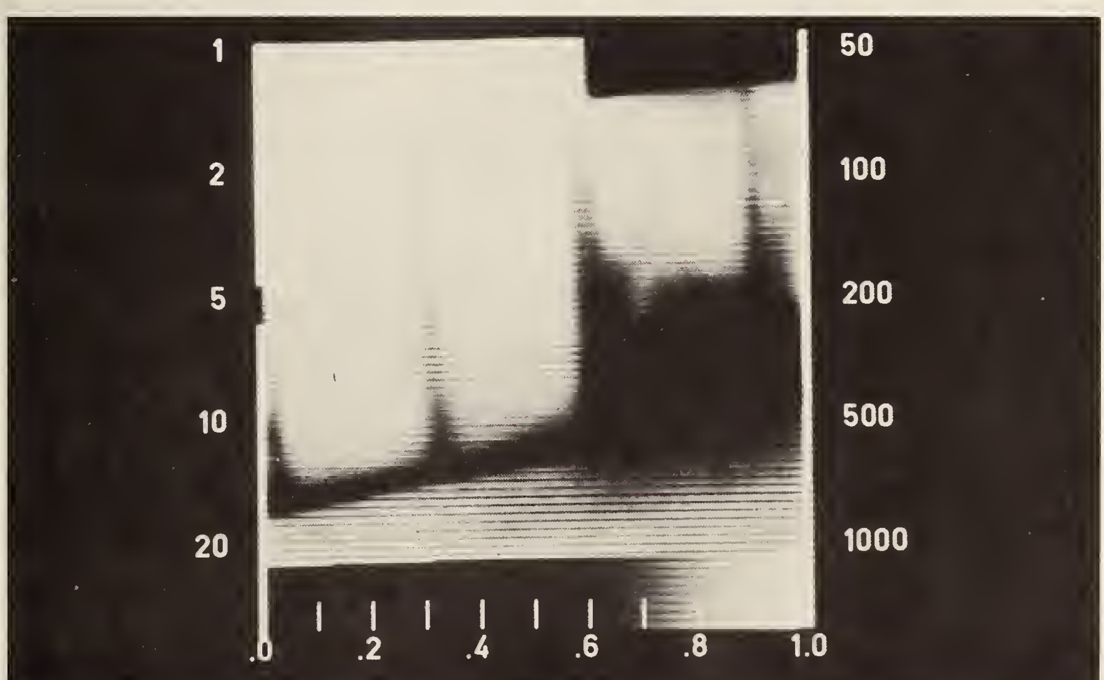

Figure 38. Interior thermograph with R-11 batts installed as shown in figure 36.

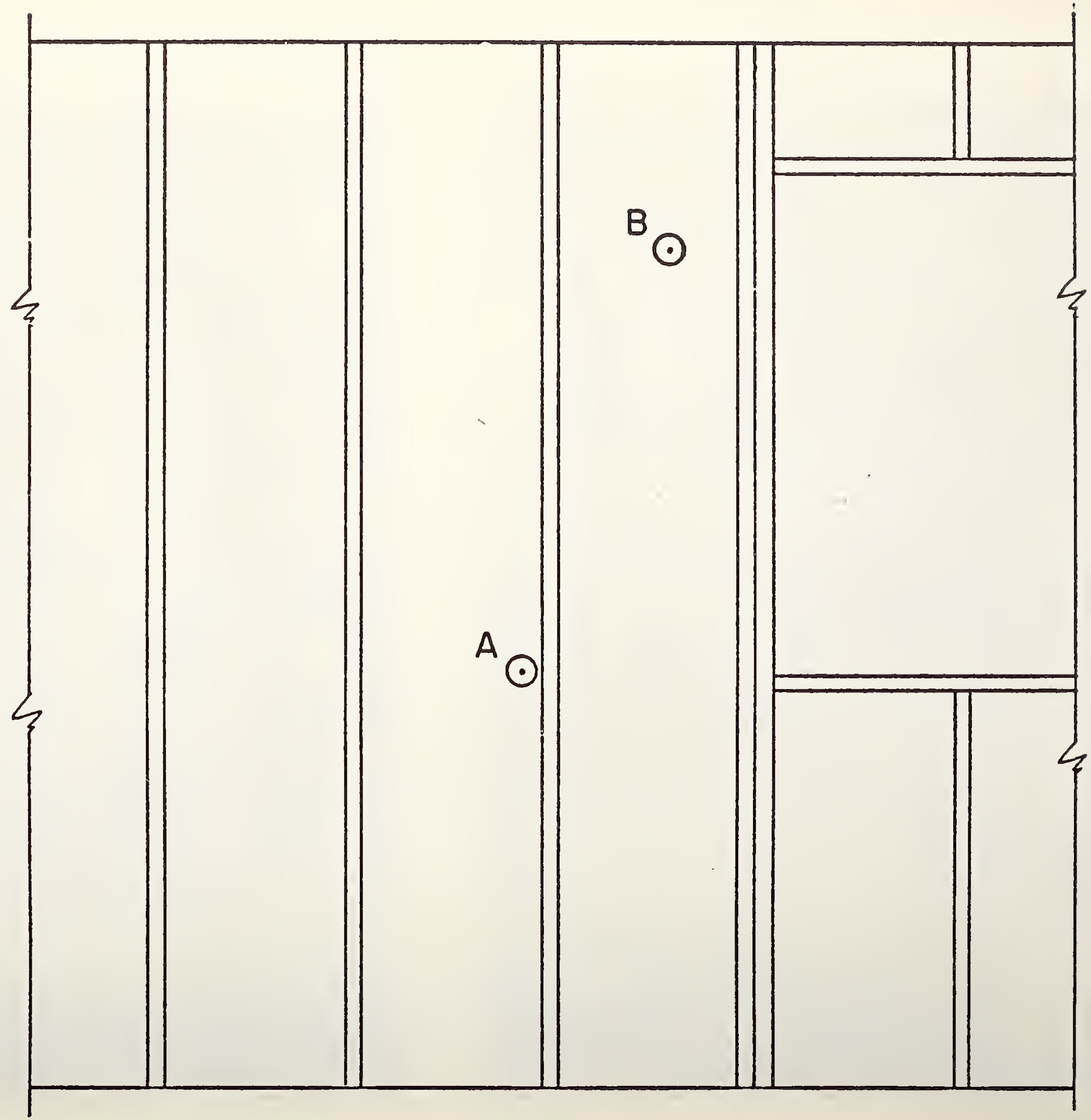

Figure 39 . Thermocouple locations on inside of wall paneling. Temperature readings shown on Table 4.

Table 4

Thermocouple readings on the wall surface at locations A and B of the **wall test element**

Condition	Location A	Location B	Observations
1. As received from factory	57.8	63.3	Thermographic observations showed rather sharp contrast between cold and warm areas.
2. After sealing outside surface of stud cavity	59.7	64.0	Intensity of pattern not quite as great Overall temp. of wall slightly warmer. Same pattern still exists.
3. After sealing inside surface of insulation to studs to prevent thermal siphoning	61.0	62.2	More significant effect than condition No.2 Wall warmer and temp. gradient reduced.
4. Inside surface of insulation sealed but outside stud cavity unsealed	60.0	62.0	Wall slightly colder than condition No.3 but temp. gradient still smoother than condition No. 2.
5. Carefully installed full thick insulation	61.8	62.8	Surface temperature very uniform. Dramatic effect.

NOTE: For all temperature recordings, outside temperature was 0°F and inside temperature was 72°F.

areas of over 50 percent. Since cold areas appear to constitute approximately 25 percent of the wall area, movement of cold air within the wall could result in a 9-percent reduction of overall wall resistance. Further, since wall losses constitute about 40 percent of the total energy loss of the mobile home, thermal siphoning could account for 4 percent of all energy loss at a temperature difference of 70 F. It appears that full, thick, properly installed insulation substantially reduces or eliminates air movement in insulated cavities. The presence of non-insulating sheathing such as the polyethylene film did not effectively stop air movement and thermal siphoning. Placement of a vapor barrier such as polyethylene film on the outside surface is not a recommended practice, but was used as an expedient for excluding outside air from entering into the stud walls, for the purposes of this test.

4.3 Air Leakage Analysis

4.3.1 Natural air infiltration as a function of stack effect

A separate NBS study was conducted on the air infiltration characteristics of this mobile home. This work is described in detail in a report entitled, "Air Leakage Measurement in a Mobile Home" [2].* For purpose of reference to calculations and observations in this report, some results from that study are included in this report.

a. Test method

Infiltration tests were made with sulfur hexafloride (SF_6) gas introduced into the furnace fan and distributed throughout the house. Tracer concentrations were measured with a gas chromatograph equipped with an electron capture detector. Samples were introduced into the

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* Figures in brackets indicate the literature references at the end of this paper.

chromatograph by means of an automated sampling system. Replicate samples were collected every 10 minutes from various locations inside and outside of the mobile home. The infiltration rate of the mobile home was calculated from the decay of tracer gas concentration as a function of time. (See above-referenced report for further test method details.)

b. Observed infiltration rates

The NBS environmental chamber provided the ideal laboratory for determining infiltration as a function of inside-to-outside temperature difference. It is generally recognized that this stack effect is one of the driving forces. Another driving force is the outside wind pressure.

The initial series of infiltration tests were run with the furnace blower running continuously. Later tests showed that the furnace blower had a considerable effect on the infiltration rate. Comparison tests were made between continuous-fan and no-furnace-fan operation. Without operation of the furnace fan, air infiltration rates were reduced by about 0.2 air changes per hour (figure 17). In this test, the air within the mobile home was circulated by means of fans located within the rooms.

The reason for the large effect of furnace blower operation on infiltration rate was observed to be an annular gap around the furnace flue where it penetrated through the ceiling (see figure 40), allowing the furnace room to communicate almost unobstructed with the vented attic space. When the fan was operated, the furnace room was under a slight negative pressure which induced outside air from the attic space.

Figure 40. Ceiling of furnace room showing air gap to attic space at the furnace air intake flue annulus.

Another suspected source of air leakage was through the joints in the furnace duct under the floor. This was checked by drawing air samples out from the crawl space under the mobile home during infiltration measurements. These air samples were monitored regularly for SF_6 traces, but none were found. This would suggest that the combination of duct and bottom board provided an effective seal.

Infiltration rate tests were also run with and without storm windows on the inside. The effect was found to be quite small. This was because window frames are not usually sealed to the interior paneling, and infiltration can occur through the resulting gaps; and because the mounting frame for the storm window is not tightly sealed to the inside wall paneling. Air leaking through or around the primary window is relatively free to pass around the inside mounted storm sash.

4.3.2 Pressurized leakage tests

Although actual infiltration rates were determined through the SF_6 tracer-gas technique, this study did little to identify the paths of air infiltration. Some of the infiltration paths were observed with the infrared camera, such as the previously mentioned air leakage under a window and in the living room corner. This section discusses another attempt to locate leakage paths by pressurizing the mobile home interior, and measuring air flow rates through the mobile home as various suspected leakage paths were blocked and unblocked.

a. Test method

Refer to figure 41 for a diagram of the test equipment. An interior-mounted axial fan (figure 42) was used to pressurize the mobile home and the total air flow was measured by means of a pitot static-air velocity measuring device located upstream of the fan (figure 43). The differential pressure was maintained at a constant 0.20-inch water

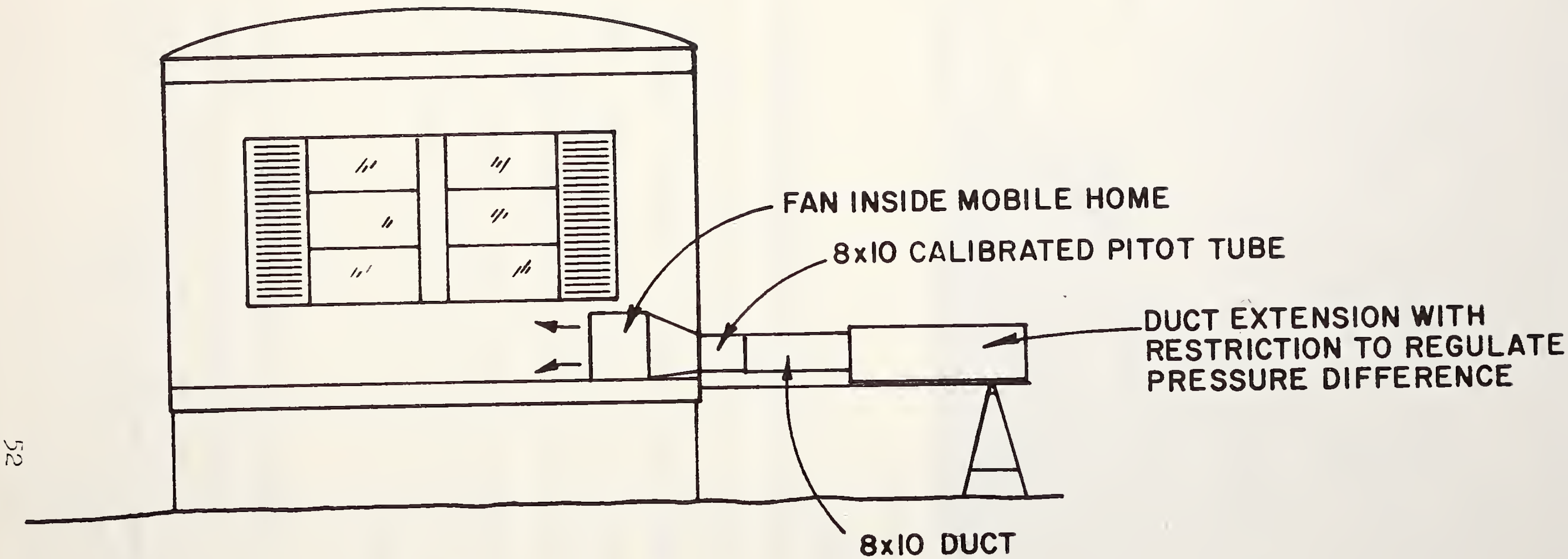


Figure 41. Equipment configuration for air leakage tests.

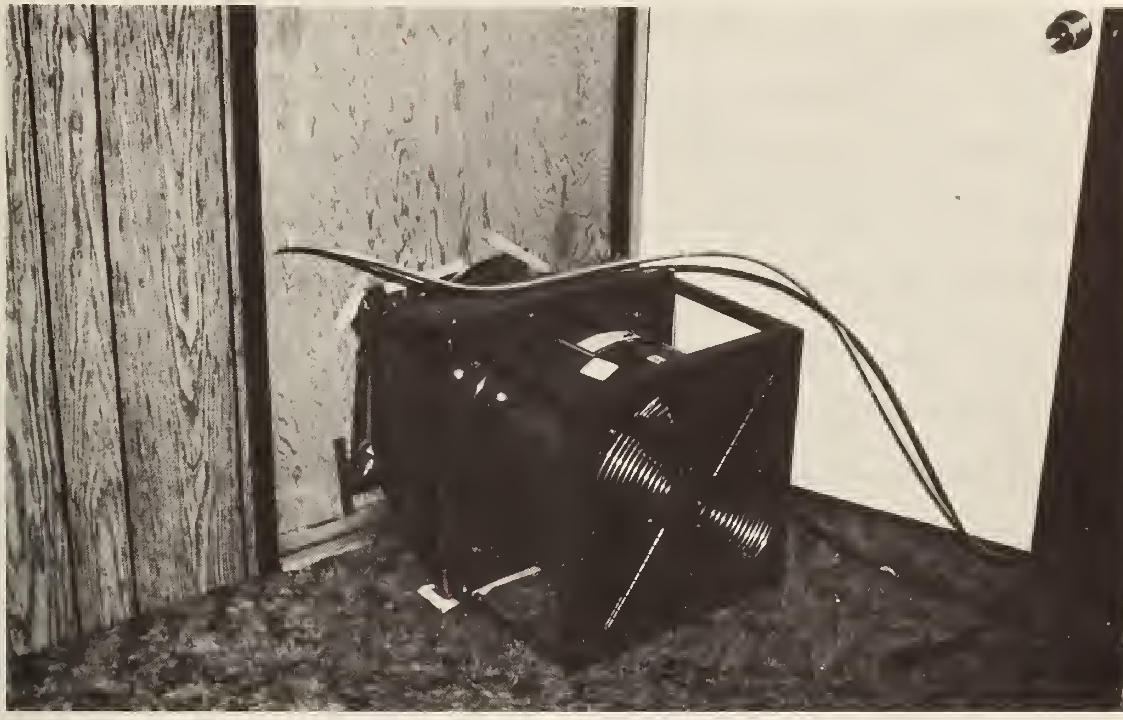


Figure 42. Vane axial fan mounted through sealed plywood partition at front entrance door opening.

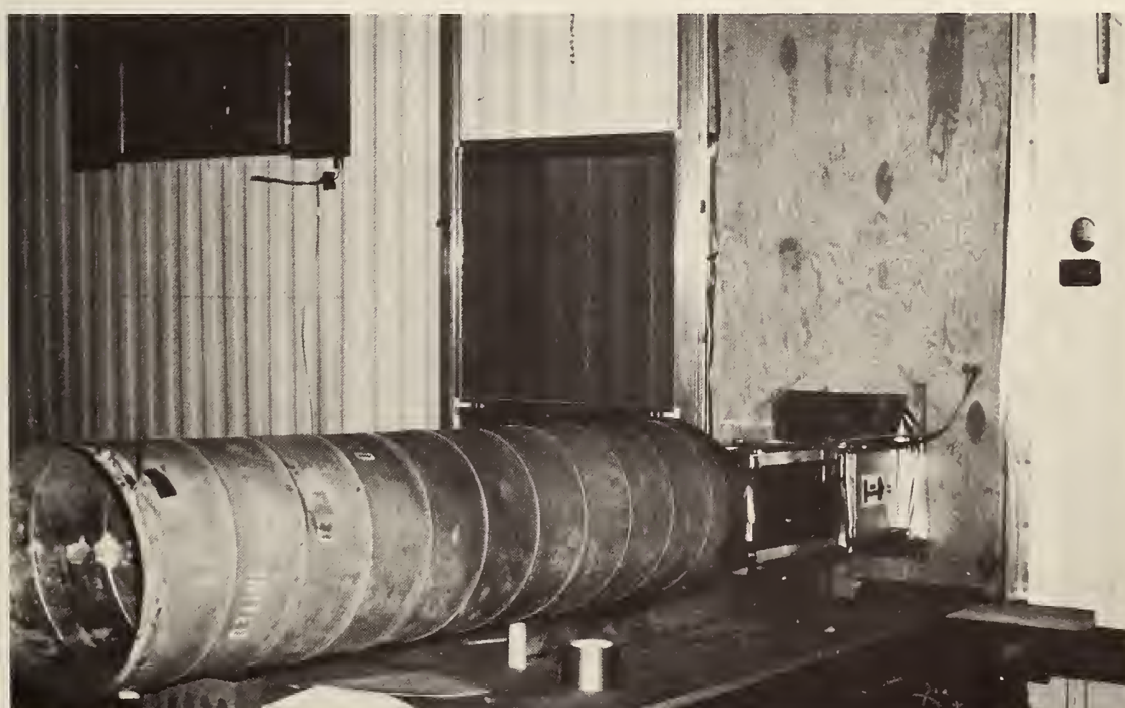


Figure 43. Pitot static air velocity measuring device located at plywood barrier. Duct leading to velocity measuring device was used to provide laminar flow of air over pitot static tubes.

gage by restricting the size of the open end of the duct extension as more and more leakage paths were blocked.

Potential air leaks within the mobile home were blocked from the inside with the use of duct tape. As each air leak was blocked the reduction in air flow was noted. Because the weather outside the environmental test chamber changed rather dramatically during the test, the temperature and barometric pressure within the test chamber were recorded at least two times per day and these variables were used in the calculation of air flow. The air density was calculated using the equation:

$$\rho = 1.325 \frac{P_B}{T}$$

where ρ = air density in pounds per cubic foot

P_B = barometric pressure in inches of mercury

T = absolute temperature (F + 460)

The air flow rate, Q, in cubic feet per minute, moving through the duct containing the calibrated pitot tube was calculated using the equation:

$$Q = 1096.7A \sqrt{\frac{h}{\rho}}$$

where A = duct area, .555 ft^2

h = pitot tube pressure difference in inches of water

There was a question whether to use a pressure or vacuum on the interior in order to create forced leakage. Previous forced-leakage studies on conventional homes by G. T. Tamura of the National Research Council of Canada (NRC) utilized a negative interior pressure and leakage paths which were blocked from the outside with polyethylene film and tape. This is a logical way to test conventional homes because it appears that the pressure envelope is on the exterior surface and it is easier to seal areas with the sealing medium drawn toward the surface rather than pushed away. Because of the vented exterior wall design used with this mobile home, the pressure envelope was known to exist at the inside wall surface. Therefore, the leakage paths were blocked from the inside and an interior positive pressure was more logical. In addition, equilibrium values were slower in developing and were more erratic when negative pressure was applied to the mobile home.

Previous studies by NRC were conducted with a constant inside-to-outside pressure difference of 0.300 inches water gage while these tests at NBS were run at 0.200 inches water gage. The 0.200-in water gage pressure was used because it was found that the vane axial fan was capable of maintaining approximately 0.204 inches wg pressure difference without any leakage paths blocked. With this capacity, it was decided to run all tests at 0.200-in wg pressure.

The decision to test at 0.200-in water gage was accompanied by a determination of the relationship between pressure and flow rates. Figure 44 shows that this relationship is apparently linear down to about 0.02 inches wg pressure difference. As the graph indicated, this relationship was checked with approximately one half the leakage paths blocked as well as with the mobile home in its original condition.

The inside-to-outside and pitot-static pressure measurements were made with a micro-manometer and a standard Hooke gage with micrometer scale.

b. Results and Discussion

The sequence of leak blockage and unblockage as well as their effects are shown in table 5. In general, the consistency of the effect of blocking and unblocking leakage locations was very good, with the exception of two cases; namely, the effect of sealing the wall-ceiling

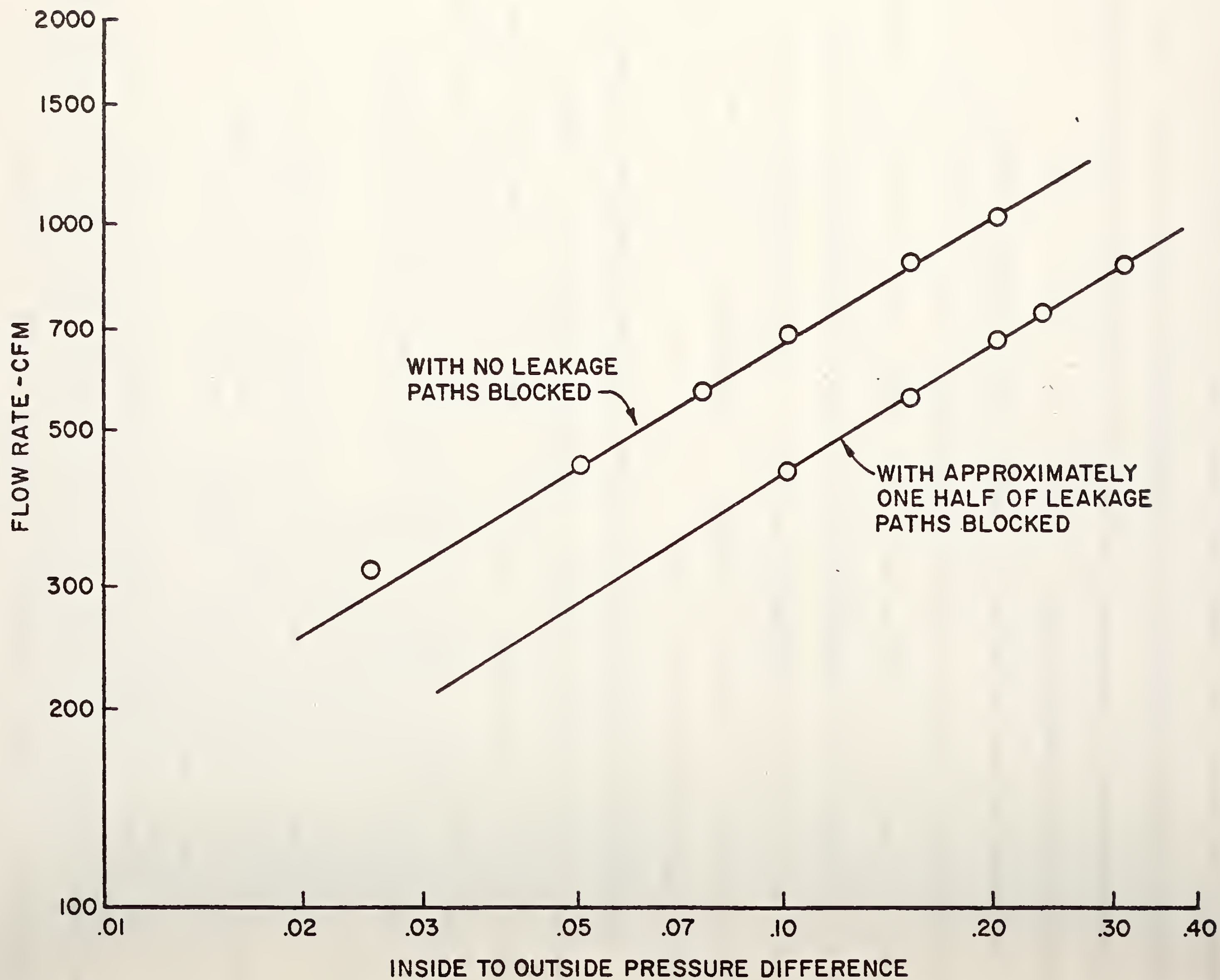


Figure 44. Air flow rate vs. inside-to-outside pressure difference showing effect of partial blockage of leakage paths.

Table 5

Mobile-home forced air leakage characteristics, ft^3/min

Sequence of Sealing	Potential Leak Location Sealed or Unsealed	Residual Air Leakage	Reduction in air Flow Due To Sealing of Leak		Sequence of Seal Removal	Increase in air flow due to removal of Seal
1	Original condition	1020			13	1039
2	Bathroom ventilation fan	869	151	(14%)	11	156
3	Between ceiling and flue vent	789	80	(8%)	9	88
4	Lower hinge side of rear entrance door	783	6	(<1%)	2	4
5	Two plumbing holes through floor	744	39	(4%)	8	38
6	Duct system (register opening and blower return opening)	744	-		10	6
7	Wall heater	716	28	(3%)	7	36
8	All exterior outlets and switches	699	17	(<2%)	5	19
9	Windows sealed to inside surface of wall paneling	511	188	(18%)	1	240
10	Front base of furnace	497	14	(1%)	12	-
11	Paneling side joints	420	77	(8%)	4	76
12	Joint between wall and ceiling	282	138	(14%)	3	90
13	Furnace room door	275	7	(<1%)	6	-

All leakage rates were taken with inside-to-outside pressure difference of 0.200 inches water gage.

juncture and the windows. However, if these two leakage locations are recognized as being parallel leakage paths through one element (the wall), it is logical that the sequence of blockage of these parallel paths may have an effect on the reduction or increase of air flow. It can be seen from the figures below that the total leakage through the wall was virtually the same in both directions.

Variable	Decrease in air flow upon sealing	Increase in air flow upon unblocking
1. Sealing exterior switches and outlets	17	19
2. Sealing windows and rear door	188	240
3. Sealing plywood butt joints	77	76
4. Sealing wall/ceiling juncture	138	90
Total Effect	420 cfm	425 cfm

The sealing process was accomplished with aluminized duct tape. Figures 45 through 47 show examples of sealing of suspected air leaks.

After all the obvious and sealable leaks were taped shut, only approximately 30 percent of the initial leakage remained. At this point, some air was still observed to be leaking at penetrations through the asphalt-impregnated underlayment, through the roof vents and through the exterior-wall-vent openings. This residual leakage is presumed to be occurring by such means as:

1. permeability through the building materials.
2. inaccessible holes through the ceiling such as electrical penetrations within partitions and under light fixtures.

Figure 45. Panel side joints, wall corner joint, ceiling wall joints and window sealed with duct tape.

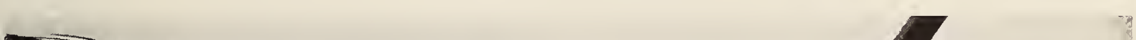


Figure 46. Bathroom exhaust fan sealed shut with duct tape.

Figure 47. Plumbing hole through floor under bathtub sealed with duct tape. Access gained through hole cut in end bedroom wall.

Figure 48. Bathroom exhaust fan with foam plastic backflow sealing flaps.

3. non-sealable leaks through the floor at the base of the furnace.

4. other miscellaneous locations.

The wall leakage was found to be greater than 40 percent of the total forced leakage. This is a combination of leakage through the window construction (the largest portion), through the exterior electrical switches and outlets, through the wall/ceiling juncture, and through the joints between plywood panels. Observation of the window construction leads to the conclusion that much of the total window loss was caused by sealing the primary window to the exterior surface, which is not the pressure envelope. It appears that air was leaking between the inside-mounted storm windows and the exterior mounted primary window, allowing air flow into the vented wall cavity. This observation was supported by the fact that air leakage out of the exterior wall base and top vents was reduced substantially when the total window construction was sealed. Yet, significant leakage through the outside prime window could not be felt while the window was unsealed on the inside and the house was under pressure.

The leakage through wall switches and outlets was small, considerably less than anticipated. This tightness is attributed to the close fit between the electrical box and the paneling and to the air resistance of the switch or outlet and cover assembly.

The pressurized leakage of the bath exhaust vent may not be indicative of air leakage through this path under normal infiltration pressure differences. However, this unit could be designed to provide a more effective seal. As constructed (figure 48), the circular duct is dampered with two semi-circular, 1/4-inch-thick sheets of open-cell polyurethane foam glued to the fan housing at only one point. The fan blows these flaps up, effectively opening the damper. Unfortunately, the flaps overlap and do not fit well, allowing some unrestricted air flow. It was noted that warm air was escaping from the fan vent due to stack effect only, with the interior at 70 F and the chamber at 0 F.

Pressurization tests were used to identify air-flow paths as sources for potential air leakage. Results of these tests should not be extrapolated to quantify air infiltration and exfiltration rates. The complex natural convection forces due to wind and temperature differences are not expected to behave in the same manner as that for the constant internal pressure.

4.4 Condensation Potential

a. Instrumentation

Condensation tests on this mobile home were conducted in the environmental chamber. Humidification was achieved with a portable power type wetted element humidifier located in the kitchen area of the mobile home. The built-in humidistat was by-passed by setting the humidifier control to continuous operation. The on-off cycling was controlled using a humidistat with a hair-type sensing element.

Two full-range humidity transducers were utilized to read the relative humidity in the living space of the mobile home and the attic space. Four narrow-range (89% to 99%) lithium-chloride moisture sensors were installed in the insulated wall cavity. Two of the sensors were installed between the interior paneling and the insulation vapor barrier. The remaining two were installed between the wall-cavity insulation and the outside aluminum sheathing.

b. Test methods and conditions.

The condensation-potential tests were conducted with the environmental chamber maintained at approximately 0 F and the the interior of the mobile home maintained at 72 F by means of the mobile-home thermostat-controlled furnace. Mixing of the humidified air was accomplished with a flexible duct and small fan moving humidified air from the living room to the rear bedroom and through the mixing action of the furnace blower. The furnace blower was allowed to cycle on demand.

These tests were conducted with the interior relative humidity maintained at approximately 42 percent RH (±1%). It is recognized that a 42 percent interior RH is unusual under 0 F weather conditions, but it is possible with either a portable humidifier (as used in this test) or a furnace-mounted humidifier. It is also possible to achieve relatively high humidities with unvented driers, hanging clothes to dry indoors, showers, cooking, or other high moisture-producing activities within the mobile home. Therefore, it was decided to test under conditions severe enough to reveal condensation potential.

At the beginning of the test, two full-range humidity transducers were used to determine consistency of relative humidity throughout the mobile home. One of the transducers was located in the center of the living room area and the other transducer was installed in various locations such as the rear bedroom, bathroom and hallway. After it was determined that the interior fan mixing systems produced even humidities throughout the mobile home, the second humidity transducer was installed in the attic space near the center of the mobile home. The transducer was mounted in the free air space of the attic and the lead-in wire was inserted through a ceiling light fixture to the mobile home interior.

The condensation-potential tests were conducted over a continuous two-week period. During this time, the full- and narrow-range sensors were read at least four times daily to ensure that the interior relative humidity was being maintained at the set point and to observe whether condensation was occurring in the attic or wall spaces. The full-range transducers were also observed closely for variations caused by furnace on-off cycles by taking readings every minute over two 2-hour periods.

In addition to the instrumentation observations, visual observations were made throughout the testing, including checks for surface condensation and condensation within structural elements. The visual observation of condensation within the structural elements was accomplished by opening sections of the wall and roof at the conclusion of the test.

c. Results and discussion

1. Results obtained through instrumentation.

The narrow-range wall-cavity moisture sensors were used solely for purposes of determining when relative humidities approached condensation-potential levels. The sensors located on the inside or the outside of the insulation showed no reading throughout the test. This would indicate that relative humidities never exceeded the bottom of the range (89 percent) for the sensor. This was also true for the sensor between the paneling and the insulation; however, it was later found that frost had accumulated in the entire area surrounding the sensor between the insulation and the exterior siding. It is assumed that the narrow-range sensor was not operative at the low temperature on the outside of the insulation. The results obtained with the wall-mounted narrow-range sensors were not considered meaningful and no conclusions were based on these results.

The full-range RH transducers located in the attic and living room areas did provide useful information.

It was observed that the interior relative humidity was maintained at an approximately constant level as the humidifier cycled on and off once each 25 minutes. The attic relative humidity cycled considerably as a direct function of the furnace-blower operation. It was concluded that when the furnace blower was on, outside dry air was being drawn through the attic space into the mobile home. This was caused by the annular gap around the chimney as shown in figure 40. This conclusion was later verified by closing the gap with duct tape and virtually eliminating any effect on attic relative humidity by the on-off cycles of the furnace blower. At the location of the RH transducer, the attic space relative humidities ranged from a low of 80 percent to a high of 94 percent over the entire two-week period. With the gap sealed at the chimney, the attic space RH levels were also within this range but were held more nearly constant.

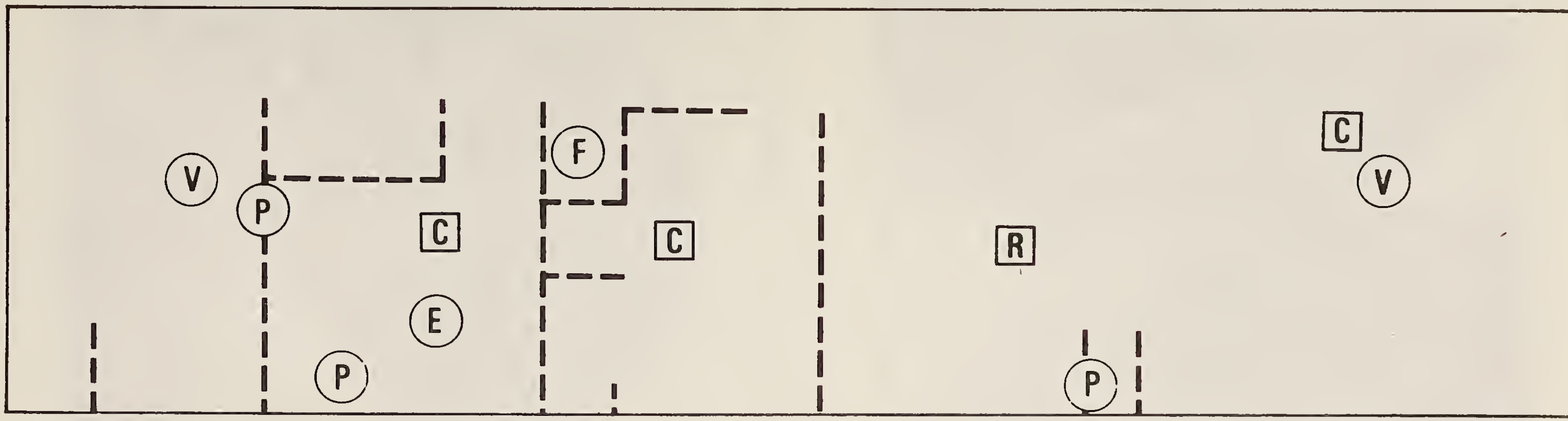
2. Results from visual observations

Observations of interior structural condensation were made by cutting holes through the metal roof to observe attic condensation. Refer to figure 49 for location of roof cuts. These test cuts were made at the end of the second week of condensation testing while the chamber was still at 0 F and the interior temperature and relative humidity were still maintained at 72 F and 42 percent RH.

Roof test cut No. 1 was made near the furnace flue. Observers walking on the roof in the general area of the test cuts heard cracking noises which were interpreted as indicating possible frost attachment between the metal roof membrane and the foam-core sheathing. Considerable frost was observed on the underside of the sheathing and a single droplet of water was observed on top of the fiberglass roof insulation.

Roof test cut No. 2 was made far removed from the furnace flue, in an area where the cracking noise created by roof-top traffic was not predominant. At this location, very little frost appeared between the metal roof and the sheathing. This frost consisted of fine frost lines on the under surface of the metal with no observable frost on the top side of the sheathing. A thin film of frost was observed on the underside of the sheathing (more than on the underside of the metal roofing). The glass-fiber-batt roof insulation appeared dry at this location.

Roof test cut No. 3 was made near the bathroom exhaust vent stack. The previously discussed cracking noises were very predominant in this general area. Frost was observed between the metal and the sheathing (more frost at this



C – TEST CUTS

R – RH SENSOR

V – ATTIC VENTS

F – FURNACE FLUE

E – BATH ROOM EXHAUST

P – PLUMBING VENTS

Figure 49.. **PLAN VIEW OF ROOF**

location than at either test cut No. 1 or 2). Considerable ice and water were observed on the underside of the sheathing and water droplets covered the surface of the batt insulation. See figure 50.

These roof test cut observations indicated that attic-space condensation was heavily influenced by air leakage through the penetrations in the ceiling of the mobile home rather than general diffusion through the ceiling construction (which contained a plastic film vapor barrier). Moisture accumulations were obviously heavier near the penetrations (bath exhaust and furnace flue) as observed by both the test cuts and by noises created by cracking frost and ice observed while walking over the roof surface.

The bathroom exhaust vent constituted a penetration into the attic space because the two sections of the exhaust stack were not properly joined, allowing interior air to go into the attic space as well as to the outside of the mobile home. It appeared that the stack effect alone was sufficient to force interior air up through the foam flap "sealed" vent. This deduction was made because of the attic space moisture found near the vent and because of the frost accumulation within the outside bonnet covering the vent. This moisture was observed even though the exhaust fan was never turned on. It was also observed that moisture was condensing on the inside walls of the vent stack and running back onto the surface of the ceiling vapor barrier. Figure 51 shows

Figure 50 Roof test cut number 3 showing water and ice on bottom surface of sheathing and water droplets on top surface of roof insulation.

Figure 51 Location of water found on top of plastic film vapor barrier of bathroom exhaust.

the point where water was observed on top of the vapor barrier at the base of the exhaust vent.

Interior wall observations - The walls were inspected for condensation by peeling back the aluminum siding. Since exterior sheathing was not installed under the aluminum, this revealed the outside surface of the wall insulation. See figure 52 It was observed that considerable frost had accumulated between the outside surface of the wall insulation and the metal siding and on the inside surface of the top fascia. This frost accumulation was very pronounced on the upper half of the wall but not on the lower half.

These observations indicated that interior moisture was getting into the wall cavity either through a diffusion process, or through leaks. The location of the frost further supports previous observations concerning convective air currents within the insulated walls. It appears that air is moving up within the cavity carrying moisture to the upper half of the wall and allowing it to escape under the vented fascia. On this basis, it appears that the vented design of the wall is functioning to remove moisture from the wall cavity.

Surface condensation - Moisture was also observed to be accumulating on the inside surface of the walls. This condensation occurred only at the base of the walls both in open areas and within enclosed cupboard and closet areas. Figure 53 shows a close-up photograph of this condensation

Figure 52. Frost accumulation at top of wall and under fascia.

Figure 53. Surface moisture condensation at base of wall.

at the base of a wall. Note that the condensation pattern was very distinct. Figure 55 is a picture taken of the hallway looking from the kitchen area. The surface condensation locations were outlined with white tape to make them visible in the photograph. Note that the condensation did not occur in a uniform manner along the wall but at specific areas only. By comparing the thermographs of the same area (fig. 25) it was noted that condensation had occurred at those locations where pronounced cold streaking had previously been observed. It was concluded that cold outside air which was convectively looping within the wall cavity was lowering the temperature of the wall paneling below the dew point (48 F) of the inside air (72 F, 42 percent RH), resulting in this surface condensation.

Surface condensation also occurred at locations having obvious thermal shorts. This was true especially for the aluminum frame around the rear entrance door, which showed heavy condensation and frost and ice buildup.

Window condensation - Surface condensation was also observed on the windows. This condensation appeared to be excessive due to the design of the exterior primary window and interior storm window. Figure 55 shows a typical window with surface condensation. It is important to note that almost all of this condensation occurred on the inside surface of the outside window, not on the inside surface of the storm window. It was concluded that the lack of seal between the storm

Figure 54. Pattern of surface condensation at base of wall.

Figure 55. Typical window condensation.

window and the interior wall surface allowed moisture to move freely to the outside, primary window.

It was hypothesized that if the inside window were well sealed and the outside window sealed to a lesser extent (as in typical residential site-built construction where the storm window is on the outside), the window condénsation would not have been severe. To test this theory, the inside storm window was sealed to the wall surface using duct tape as shown in figure 56, and the outside window was cracked open approximately 1/16 inch. Under these conditions, condensation did not occur on the inside surface of the outside window.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions.

A. For laboratory tests without wind effects, it was found that the original-equipment furnace was considerably oversized. Using this original-equipment furnace, the total energy supplied per unit temperature difference based on a thermal envelope area of 1916 ft^2 ranged from 0.172 to 0.158 Btu/h·ft^2 F at inside-to-outside temperature differences of 82.2 and 27.9 F, respectively. Under these same inside-to-outside temperature differences, the apparent cyclical efficiency (determined by comparison with assumed 100-percent-efficient electric resistance furnace) of the original-equipment gas furnace ranged from 71.7 to 57.7 percent, respectively. After modifying the furnace to reduce its input capacity by 47 percent, the values ranged from 0.160 to 0.143 Btu/h ft^2 F at inside-to-outside temperature differences of 70.5 and 28.7 F, respectively.

Figure 56 . Inside storm window sealed to wall surface.

Under these same inside-to-outside temperature differences, the apparent cyclical efficiency of the smaller capacity furnace ranged from 72.8 to 63.7 percent, respectively. It is concluded that a greatly oversized furnace will cause a significant increase in seasonal energy consumption.

From the calculation procedure in Appendix A, the modified gas furnace configuration is estimated to meet the heating load at -22 F with a 15-mile per hour wind; and so is somewhat oversized for most areas of New York State. Generally, a certain amount of oversizing is required for recovery due to nighttime setback of the thermostat, reduction of furnace capacity for mobile homes located in high altitude areas, and a possible reduction with time of the thermal insulating effect of the mobile home.

B. The comparison between measured and predicted heat loss was very close, especially under conditions where the outside temperature was relatively high (45 and 30 F). It should be noted, however, that predicted heat-flow calculations included allowances for effect of cupboard and closet areas, furnishings, draperies, and modified surface air films (refer to Appendices A and B). If the standard ASHRAE calculations were made ignoring these aspects, the heat-flow predictions would have been higher than measured. Thus, standard heat flow calculations would normally result in some degree of furnace oversizing.

C. Although the comparison between predicted and measured heat loss using the calculation procedure referred to in item B. was close where the approximate outdoor temperatures were 30 and 45 F, for lower outdoor temperatures the measured values were from 5 to 17 percent greater than the predicted values. It should be noted that the predicted heat losses included increased infiltration rates caused by stack effect and longer furnace percent on-time. It is concluded that this apparent loss of insulating efficiency at lower temperatures (higher inside-to-outside temperature differences) is due at least in part to thermosyphoning of air in and around the insulation within wall stud spaces.

D. A thermographic survey using an infrared television camera was useful in identifying locations of air leakage, thermal bridges and temperature differences on wall surfaces. Through this analysis, it was determined that, under low outside temperature conditions, convective air currents were found to exist within the insulated walls, reducing their efficiency. The thermographic analysis indicated that this thermosiphoning was caused in part by the vented wall construction which was used, and by the method of installing the insulation. To reduce this thermosiphoning action, it is recommended that carefully fitted, full-thickness insulation be used, or some other mechanism be employed to reduce the driving force, or to eliminate locations where convective air currents can occur through gaps around the edges of the insulation.

E. Pressurization tests were used to identify air-flow paths as sources for potential air leakage. These tests showed that 40 percent of the total pressurized leakage occurred through the walls. The largest portion of the wall loss was due to the specific wall-window construction used on this mobile home. Air leakage at this location was caused by sealing the primary window to the vented outside siding. The interior storm windows are attached to the inside paneling (the pressure envelope) but are not sealed in any fashion. Other envelope penetrations such as furnace flue and bathroom exhaust vents were found to be poorly sealed, resulting in excess leakage.

F. In this study, it appeared that the combination of a vapor barrier and the attic space vents would prevent excessive moisture build-up or condensation in the attic space. However, unsealed penetrations through the ceiling of the mobile home will allow moisture-laden interior air to rise into the attic space, resulting in excessive condensation under high interior-moisture conditions.

G. Convective looping of cold air within the wall cavities will cause interior surface wall condensation under high interior-moisture conditions.

H. Excessive surface window condensation was observed and was found to be the result of putting a non-sealed storm window on the inside surface with a well-sealed window on the exterior.

5.2 Recommendations

A. It is recommended that this study be continued to provide further information in some areas which have been investigated and to allow work in some new energy-related areas. The continued work should involve:

1) An analysis of energy consumption characteristics of this mobile home under heat-gain (cooling) conditions;
2) A heat-loss analysis of a similar mobile home constructed to eliminate thermosiphoning within walls--to assess the magnitude of this heat loss;
3) An analysis of alternative wall constructions such as full-thickness insulation, insulating sheathing, and others, to clarify their heat transfer and condensation characteristics.

4) An analysis of the relationship between pressurized leakage and natural air infiltration. A standardized pressurized leakage test should be developed and a maximum pressurized leakage should be recommended for future construction standards.

B. It is recommended that the following findings from this study be utilized in future modifications of construction and safety standards for mobile homes; specifically, these standards should be modified in the following areas:

1) Construction standards should limit furnace oversizing in order to increase seasonal efficiency. This could be done by providing furnaces adequate for the coldest areas within the applicable market, along with a dealer-installed kit designed to reduce the excessive capacity of the furnace in warmer climates;

2) Also, in order to reduce oversizing of furnaces, calculations to predict heat loss or gain under design conditions should include the insulating effect of draperies, cupboards, closets, and similar items which add to the thermal resistance of the exterior envelope of the mobile home. The resistance of the interior air films used in the calculations should recognize that each exterior wall of a mobile home typically "sees" more cold wall surfaces than for conventional residences, thus reducing the radiation component of the film heat transfer coefficient. It is recommended that these factors be included in standard calculation procedures.

3) Installation methods for insulation should be specified to reduce potential for thermosiphoning by convective air currents. This should include full-thickness insulation in walls, smooth installation of mechanically attached wall insulation, and careful installation of insulation at all locations to eliminate locations for convective air movement.

4) Mobile home construction standards should include methods to reduce air leakage paths and to reduce the potential for condensation within attic and other structural cavities.

   First of all, the primary window should be sealed continuously to the pressure envelope of the mobile home.

   Secondly, penetrations through the pressure envelope should be made airtight with respect to the envelope, especially those penetrations through the ceiling, such as plumbing, vent stacks, ceiling exhaust vents, and furnace stacks.

   Thirdly, connections between wall and floor and between floor and ceiling should be specifically designed to eliminate air leakage at these locations.

   It is recommended that future construction standards include these methods and enforce them through pressure-leakage tests of completed mobile homes.

6. REFERENCES

1. G. T. Tamura, "Measurement of Air Leakage Characteristics of House Enclosures," ASHRAE Transactions, Vol. 82, Part II, 1975.

2. C. M. Hunt, S. J. Treado, and B. A. Peavy, "Air Leakage Measurements in a Mobile Home," Natl. Bureau of Standards report NBSIR 76-1063 (July 1976).

7. CONVERSION FACTORS TO METRIC (SI) UNITS

Physical Quantity	Symbol	To convert from	To	Multiply by
Length		foot	meter	3.048×10^{-1}
		inch	meter	2.540×10^{-2}
Area	A	ft^2	m^2	9.290×10^{-2}
Volume		ft^3	m^3	2.832×10^{-2}
Temperature	t	F	C	$t_c = (t_F - 32)/1.8$
Flow	Q	ft^3/min	m^3/S	4.719×10^{-4}
Density	ρ	lbm/ft^3	kg/m^3	1.602×10
Pressure	P	inch mercury (60F)	Pa	3.377×10^3
	h	inch water (60F)	Pa	2.488×10^2
Power		Btu/h	W	2.931×10^{-1}
Heat Flux		Btu/h ft^2	W/m^2	3.154
Thermal Transmittance	U	Btu/h ft^2 F	W/m^2 K	5.678
Thermal Resistance	R	h ft^2F/Btu	Km^2/W	1.761×10^{-1}

APPENDIX A

Calculations for Thermal Transmittance

The following calculations for thermal transmittance, U in Btu/h ft^2 F, are made for the calculation form (table A-1) from the numbered items using the resistances in h ft^2/Btu of individual components and weighted area, A in ft^2.

1.a) Unobstructed roof area

	At Insulation	At Framing
Inside Air Film	0.99	0.99
3/4" Fiberboard	1.89	1.89
2" x 2" Wood Truss	--	1.88
R-14 Insulation (thickness constructed near edges)	14.00	--
Partial Air Space	--	.89
2" x 2" Wood Truss	--	1.88
Foam Sheathing, 1/4"	1.04	--
Metal Roofing	.00	.00
Outside Air Film	.61	.61
	18.43	9.18

$$\text{Weighted UA} = \frac{446.39}{18.43} + \frac{48.7}{9.18} = 29.52$$

$$U = 29.52/495.09 = .0596$$

1. b) Partition contact area - Additional thermal resistance occurs at partition contact areas.

Resistance of unobstructed roof area	=	16.41
Wood partition resistance	=	.94
Air film obstruction	=	.50
		17.85

$$U = .056$$

1. c) Bathroom vent - The bathroom vent pipe forms a thermal bridge from the inside to the outside through the metal of the duct pipe. From considerations of air films, the thermal transmittance is estimated to be U = 0.5.

2. a) Unobstructed wall area

	At Insulation	At Framing
Inside Air Film	1.07	1.07
Wood Paneling, 1/8"	.16	.16
Wood Framing, 3 1/2"	--	4.38
Insulation, R-7	7.00	--
Air Space, 3/4"	1.01	--
Siding, Aluminum	.00	.00
Outside Air Film	.68	.68
	9.89	6.29

$$\text{Weighted UA} = \frac{467.3}{9.89} + \frac{77.10}{6.29} = 59.51$$

$$U = \frac{59.51}{544.37} = .1093$$

2. b) Wall area covered by draperies and valance - the heavy drapery material reduces the radiant and convective components of the inside air film resistance in addition to heat transfer through the drapery material. R = 0.99 + 9.15 = 10.14 or U = .099

2. c) Partition contact area - Refer discussion of 1. b).

Resistance of unobstructed wall area	=	9.15
Wood partition resistance	=	.94
Air film obstruction	=	.50
		10.59

U = .094

2. d) Window area - Considerations for the window area include exposed glass, drapery, and opaque and sheer curtains calculated on a weighted area average basis. The thermal transmittance of the exposed glass area is based on inside and outside air film resistances of 1.46.

	Area	Storm Windows	No Storm Windows
Exposed glass	5.22	.44	.73
Sheer curtains	24.26	.40	.64
Opaque curtains	4.69	.37	.56
Draperies plus curtains	39.34	.31	.44
	73.51		
Totals UA =		25.93	39.27
Weighted U =		.353	.534

The sheer curtains have patterned holes and add a thermal resistance to the window area by a decrease in the radiative transfer and a decrease in the convective air flow. Assuming that the opaque area of the sheer curtain reduces the radiative transfer by 1/3 and the curtain reduces convective transfer by 10 percent, the inside surface resistance is then 0.86 or an incremented resistance of 0.18. This gives U = 0.4.

The opaque curtains are assumed to reduce radiative transfer by 50 percent and the convective transfer by 25 percent, giving an inside surface resistance of 1.09 or an increase of 0.41. This gives U = 0.37.

The combination of draperies and curtains are assumed to give an incremented resistance of 0.481, due to the thermal resistance of the drapery material (k = 0.26, 1/8" thickness).

This gives U = 0.31.

The above calculations are for storm windows. A similar procedure is followed for windows without storm windows assuming U = 0.73 for exposed glass.

2. e) Front door with storm door

Inside surface	1.07
Door with storm door	2.18
Outside surface	0.68
	3.93

or U = 0.25

2. f) Rear door

Inside surface	1.07
Door	1.19
Outside surface	0.68
	2.94

or U = .34

3. a) Unobstructed floor area

	At Insulation	At Framing
inside air film	3.83	3.83
carpet/vinyl flooring (see note)	1.20	1.20
subfloor, 3/4"	.98	.98
joist, 5 1/2"	--	6.88
air space, 4"	1.23	--
insulation R-4	4.00	2.00
simplex Board	.10	.10
outside air film	.92	.92
	12.26	15.91

$$\text{Weighted UA} \doteq \frac{307.76}{12.26} + \frac{33.57}{15.91} = 27.21$$

$$U = 27.21/341.34 = .0797$$

Note: Averaging individual resistance for carpeting ($192.88\ ft^2$ and vinyl flooring ($148.46\ ft^2$) is

$$R = \frac{2.08 \times 192.88 + .05 \times 148.46}{341.34} = 1.20$$

3. b) Floor area obstructed by bed - The area under beds is considered to have increased thermal resistance because of the air space trapped by hanging bedspreads, and the resistance of the mattress. For the series and parallel heat-flow paths, analysis shows that the equivalent U - value is

$$U' = \frac{(U_m a_m + U_h a_h)\ U}{U + U_m a_m + U_b a_b}$$

where

U_m = U - value for mattress .05

U_b = U - value for bedspread = .685

U = U - value for unobstructed floor = .0797

a = ratio of area of component to area of floor under beds

$$U' = \frac{(.05 \times 1.0 + .685 \times .43)\ \ .0797}{.0797 + .05 + .685 \times .43} = .0647$$

3. c) Floor area under stove - The stove area is considered to have increased thermal resistance, using the rationale of 3.b, U = .072

3. d) Floor area under couch and stuffed chairs - using the rationale of 3.b, U = .068.

3. e) Partition contact areas - using the rationale of 1.b, U = 0.071.

4. Heating ductwork in floor - Heat loss from duct work occurs through insulation (R-4) and bottom board downward into the crawl space.

Insulation R-4	= 4.00
Simplex board	= 0.10

or U = 0.20

5. Closets and cupboards - Heat flow through closets and cupboards eventually flows through the walls, ceiling, and/or floor. These areas are not equal to areas of closets and cupboards exposed to interior environment of the mobile home. In order to calculate the heat flow through these areas, it was necessary to develop an equation based on a heat balance into and out of the closet and cupboard areas such that

$$Q = \frac{(t_i - t_o) + C\,(t_o - t_c)}{D}$$

where

$$D = \frac{A_1U_1 + A_2U_2 + A_3U_3 + A_4U_4 + A_5U_5 + A_6U_6 + A_7U_7 + A_8U_8}{(A_1U_1 + A_2U_2 + A_3U_3)\,(A_4U_4 + A_5U_5 + A_6U_6 + A_7U_7 + A_8U_8)}$$

and

$$C = \frac{A_3 + U_3}{A_1U_1 + A_2U_2 + A_3U_3}$$

Subscripts 1, 2, and 3 refer to properties of the walls, ceiling and floor, respectively. Subscripts 4, 5, 6, 7, and 8 refer to the five possible sides of the enclosure (closet or cupboard) exposed to the interior temperature, and

t_i = interior temperature

t_o = outside temperature

t_c = crawl space temperature

For the 16 enclosures in the mobile home, values of D and C were calculated. The sums are

$$\frac{1}{D} = 20.2, \quad \frac{C}{D} = 7.09$$

Table A-1

Calculation form for area thermal transmittance

		U Btu/h ft^2 F	Area ft^2	UA Btu/h F
1.	Roof Areas (552 ft^2)			
	a. Net roof area	.060	495.09	29.70
	b. Partition contact area	.056	13.72	.77
	c. Bathroom vent	.5	3.00	1.50
	Total			31.97
2.	Wall Areas (812 ft^2)			
	a. Net wall area	.109	544.37	59.88
	b. Wall with drape and valance	.099	20.17	2.02
	c. Partition contact area	.094	9.33	.89
	d. Window area (storm windows)	.353	73.51	25.95
	e. Front door with storm door	.25	16.55	3.97
	f. Rear door - no storm door	.34	13.71	4.32
	Total			96.96
3.	Floor Areas (522 ft^2)			
	a. Net floor area	.079	341.34	25.60
	b. Under bath tub	.070	10.22	.72
	c. Under beds	.065	50.25	3.12
	d. Under stove	.072	5.00	.35
	e. Under couch & stuffed chairs	.068	22.20	1.46
	f. Partition contact area	.071	13.72	.93
	Total			33.79
4.	Heating Duct Work In Floor	.20	55.00	11.00
5.	Closets & Cupboards			
	$(t_i - t_o)$			20.20
	$(t_o - t_c)$			7.09

Conduction Heat Loss - Q_c = Sum of lines 1-6.

1. 31.97 $(t_{ic} - t_o)$
2. 96.96 $(t_{iw} - t_o)$ 110.36 $(t_{iw} - t_o)$ (no storm windows)
3. 33.79 $(t_{if} - t_c)$
4. 11.0 $(t_d - t_c)$
5. 20.2 $(t_{iw} - t_o)$
6. 7.09 $(t_o - t_c)$

Table A-1

Calculation form for area thermal transmittance (continued)

where t_{ic} = interior air temp near ceiling
t_{iw} = interior air temp near mid-height
t_{if} = interior air temp near floor
t_d = average heating duct air temp
t_c = air temperature in crawl space
t_o = outside air temp

Infiltration Heat Loss - See section 4.1.

$$Q_1 = 55.8\ I\ (t_i - t_o)$$

I = infiltration rate, air changes per hour

APPENDIX B

APPENDIX B

Rationale for Determining Thermal Resistance of Interior Surfaces

Initial thermal analyses of the mobile home indicated that the resistance of the interior air film was greater than design values published in the ASHRAE Handbook of Fundamentals. This is logical because large portions of the interior wall, ceiling, and floor surfaces face other surfaces that are nearly identical to the temperature of the surface in question. Since conductance across a surface air film is composed of both convective and radiative heat transfer, and since radiative transfer does not occur between surfaces of equal temperature and emittance, the interior surface conductance is decreased under these conditions.

The ASHRAE design surface conductance value for vertical surfaces* is listed as 1.46 Btu/h ft^2 F, and consists of 0.54 transferred by convection and conduction, and the remainder, 0.92, transferred by radiation. Obviously, this is a conservative value for mobile homes where surfaces of exterior walls, floor and ceiling face many similar surfaces of nearly equal temperature. For example, the living room and kitchen and the rear bedroom have five sides with surfaces of exterior walls, floor and ceiling. Each of these five surfaces faces four surfaces with nearly the same temperature, with only one warmer surface, an interior partition wall. The radiative transfer component of the film conductance is small under these conditions.

A paper by F.W. Hutchinson, "A Rational Reevaluation of Surface Conductances for Still Air," (ASHRAE Transactions,Vol.70, 1964, p.105) deals with this subject. In this reference, the following surface conductances are proposed based on the number of room surfaces where outside surfaces are exposed to outdoor temperatures.

*ASHRAE Handbook of Fundamentals, p. 357 (1972).

Position of Surface	Direction of Heat flow	Number of room surfaces exposed 1	2	3	4	5	6
Horizontal	Upward	1.43	1.17	1.01	.88	.78	.71
Vertical	Horizontal	1.21	.96	.80	.68	.60	.59
Horizontal	Downward	.57	.37	.28	.22	.19	.16

These values were used as a guide in estimating the surface conductance for different areas of the mobile home. Obviously, in a furnished mobile home, some adjustments must be made for furnishings which are considered to be at or near room temperature, and for the heating effect on floor surfaces of the heating duct. The following surface conductances were used to calculate predicted heat losses for the mobile home:

A. Walls (vertical surfaces, heat flow horizontal)

1. Living Room and Kitchen.

   Five room surfaces are exposed to the outside. Adjustment was made for cupboards, furniture, heated floor duct areas. Conductance estimated to be 0.90 Btu/h ft^2 F.

2. Hallway.

   Three sides exposed, but interior nonexposed wall is large compared to exposed floor and ceiling areas. Conductance estimated to be .96.

3. Rear Bedroom.

   Five sides exposed. Adjustment was made for bed, closet and heated floor duct areas. Conductance estimated to be 0.90.

4. Bathroom.

Three sides exposed. Adjustment was made for tub alcove, lavatory cabinet and furnishings. Conductance estimated to be 1.08.

5. Center Bedroom.

Three sides exposed. Adjustment was made because of bed area. Conductance estimated to be 1.08.

In order to calculate total heat loss for the mobile home, it was decided to average the surface resistances based on areas involved so that one interior surface resistance could be used for all walls. This was done as follows:

Location	% of Total Wall Area	Surface Conductance	
1. Living room and Kitchen	46	0.90	.41
2. Hallway	19	.96	.18
3. Rear Bedroom	24	0.90	.22
4. Bathroom	4	1.08	.04
5. Center Bedroom	7	1.08	.08
		Weighted average =	.93
			R = 1.07

B. Ceilings (horizontal, heat flow up)

1. Living Room and Kitchen.

Five surfaces exposed. Adjustment made for cupboard and furniture area. Conductance estimated to be .95 Btu/h ft^2 F.

2. Hallway.

Three surfaces exposed. No adjustments. Conductance estimated to be 1.01.

3. Rear Bedroom.

Five surfaces exposes. Conductance estimated to be .95.

4. Bathroom.

Three surfaces exposed. Adjustments made for limited exterior wall area and for furnishings. Conductance estimated to be 1.17.

5. Center Bedroom.

Three sides exposed. Adjustment made for bed area. Conductance estimated to be 1.17.

Average resistance of ceiling surface was calculated as follows:

Location	% of Total Ceiling Area	Surface Conductance	
1. Living room and kitchen	49	.95	.466
2. Hallway	9	1.01	.091
3. Rear bedroom	17	.95	.162
4. Bathroom	12	1.17	.140
5. Center bedroom	13	1.17	.152
		Weighted average conductance =	1.011
		R =	.99

C. Floors (horizontal, heat flow down)

1. Living Room and Kitchen.

Five surfaces exposed. Adjustment made for furnishings covering floor and for cupboard areas. Conductance estimated to be .22 Btu/h ft^2 F.

2. Hallway.

Three surfaces exposed. No adjustment made. Conductance estimated to be .28

3. Rear Bedroom.

Five surfaces exposed. Adjustment made for closet area on one exterior wall. Conductance estimated to be .22

4. Bathroom.

Three surfaces exposed. Adjustments made for cupboard area furnishings. Conductance estimated to be .37

5. Center Bedroom.

Three surfaces. Adjustments made for closet area on one exterior wall. Conductance estimated to be .37

Average resistance of floor surface . was calculated as follows:

Location	% of Total Floor Area	Surface Conductance	
1. Living room and kitchen	53	.22	.117
	11	.28	.031
	14	.22	.031
	14	.37	.052
	8	.37	.030
			.261
		R =	3.83

Based on the above calculations, the surface resistances used to calculate wall, ceiling and floor 'U' factors were as follows:

1. Wall area R = 1.07 h ft^2 F/Btu
2. Ceiling area R = .99
3. Floor area R = 3.83

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant*

Tests were conducted on a mobile home located in an Environmental Climatic Laboratory for the purpose of evaluating its thermal performance. The heating demand greatly affected the part-load efficiency of a gas-fired, forced-air, sealed-combustion furnace system. The practice of installing oversized heating plants was shown to result in low seasonal operating efficiencies. Air leakage measurements were performed using a pressurization technique to quantify the amount of air leakage through the various parts of the mobile home. Separate air infiltration tests using the SF_6 tracer-gas technique showed that somewhat higher air infiltration rates were induced by operation of the mobile home heating plant. A thermographic survey of interior surfaces showed that the technique used to install the wall insulation may allow wrinkles formed in the surface of the insulation to form air paths running the height of the wall cavity. Convective air flow through these paths may create heat leaks on the building surface which can have an impact on the overall heat-loss rate. Separate tests were also conducted to identify places in the mobile home envelope having high condensation potential.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*
Air infiltration; energy conservation; mobile home; part-load efficiency; thermography.

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