APPLICATION OF THERMOGRAPHY FOR EVALUATING EFFECTIVENESS OF RETROFIT MEASURES

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ABSTRACT

Retrofit measures in single family dwellings are considered an important part of the overall U.S. energy conservation program. Thermography was used to evaluate the effectiveness of a number of different retrofit measures normally available to the resident-owner. In this study, a group of townhouses was selected which, it was suspected, could benefit by commonly available retrofit measures. These houses were thermographically inspected before and after various retrofit measures were performed. Thermography was found to be an effective tool for evaluating these retrofit measures which decreased the energy consumption by about 25%.

INTRODUCTION

During the winter of 1975-76 the National Bureau of Standards participated with the Center for Environmental Studies of Princeton University in a field demonstration of the effectiveness of various low cost retrofit measures in reducing the energy consumption of a preselected group of nineteen townhouses in the community of Twin Rivers, New Jersey.

The goal of this experiment was to affect a 30 to 40 percent reduction in the energy usage for space heating and cooling by applying a series of retrofit measures whose total cost including labor would not exceed $400 per dwelling. The community of Twin Rivers has been the object of an intensive study on energy usage and a determination of those parameters that affect energy usage by the Center of Environmental Studies of Princeton University since 1972.[1, 2] Initial phases of this study consisted of: analysis of the gas and electric bills of the dwellings at Twin Rivers; collecting and analyzing data from three highly instrumented homes (66 measurement points per dwelling, collected at twenty minute intervals); measuring air infiltration rates in specific homes using specifically designed measuring equipment;[3] performing thermographic surveys of selected dwellings; and designing and implementing an

Initial funding for this project came from the RANN Division of the National Science Foundation. The retrofit phase of the project was funded by ERDA.

experimental method for collecting a limited amount of data (10 data points) from a sample of 32 nearly identical townhouses.[4, 5]

Those initial efforts lead to the following findings: identical dwellings used different amounts of energy for performing the same task, for example an analysis of gas bills showed a factor of two differences between the amount of gas used for heating similar three bedroom townhouses;[1] that this large variation could not be adequately explained in terms of known parameters such as dwelling orientation, family size, family income or even the amount of energy used for other tasks (i.e. electricity); that air infiltration accounted for approximately 30% of the heating load of the dwellings and 7% of the air conditioning load; thermography showed that the party wall (or firewall) between dwellings, though in theory adiabatic, in practice was colder than the exterior walls and an added source of heat loss which was not normally taken in consideration for townhouses; attic temperatures were measured to be considerably higher than what one would expect from the level of attic insulation (R-11) and this was attributed to the existence of communication paths between the attic, the living space and the basement which allowed heat to bypass the insulation; that the home's warm air duct distribution only delivered approximately 50% of the heat supplied by the furnace to the dwelling through the registers, and a good 30% of this heat ended up in the basement, often making the basement the warmest part of the house and leaving the upstairs rooms cool.

The above results lead to the selection of a set of retrofit measures: a) increase attic insulation to the level of R-30 and seal the interface of the second floor ceiling and the masonry firewall, b) tighten the basic living area against air infiltration through caulking and adding seals to doors and windows, c) insulate the duct system in the basement, where accessible, seal basement ceiling-firewall interfaces and wrap the water heater with R-7 insulation and d) seal the opening around the flue to eliminate the channel between the basement and the attic through which air could pass.

An example consisting of 16 townhouses, plus the three highly instrumented townhouses was chosen to be used in the demonstration of these retrofit measures. This sample was chosen such that it included both low and high energy users. The above retrofit measures were applied in stages – some townhouses receiving one measure first and initially 8 townhouses received no retrofits. This experimental design allowed for both a before and after analysis of the effectiveness of the retrofits, cross analysis with the control group which initially received no retrofits and an evaluation of the effectiveness of individual retrofits. Ultimately all townhouses received the full retrofit package of a), b), c) and d) described above.

Besides using a statistical analysis of the energy consumption as a means of evaluating the consequences of the retrofit measures, air infiltration tests and thermographic analysis of some of the dwellings were made in order to obtain a more detailed insight into the effectiveness of certain retrofits. The object of this article is to assess the usefulness of thermography in evaluating the effectiveness of retrofits to dwellings (see references 7, 8, 9).

THERMOGRAPHY AS A TOOL FOR DETECTING HEAT LOSSES IN DWELLINGS

The usefulness of thermography in determining heat losses in buildings can, in the authors' opinion, best be put into perspective by answering the following question: if one knows the temperature at every point on the surface of the building, how much does one know about the heat losses of that building? Thermography can give a practical means of quickly obtaining that temperature field and presents the temperature field visually so that it can be readily analyzed and interpreted. But at temperatures of interest to those who wish to determine heat losses in residential dwellings, thermography itself can give one no more than that temperature field. It does not allow one to calculate the amount of heat being lost; though with a few assumptions it can indicate the present of heat losses in a semi-quantitative manner and in most situations aid in determining if remedial action should be undertaken. However, to accomplish this, a physical undertaking of what one is observing is necessary – that is, one must have some idea as to what the possible heat loss mechanisms are in the building to which one is applying thermography.

Thermography provides a useful tool for detecting heat losses in buildings because most heat losses lead to differences in temperature on the surfaces, both interior and exterior, of the building. Thus in observing a thermogram of an exterior surface of a building, heat losses will usually show up as hot spots; on an interior surface heat losses will appear as cold regions.

Certain care should be undertaken in applying thermography to buildings and in the interpretation of the thermograms. If outside inspection of a build-

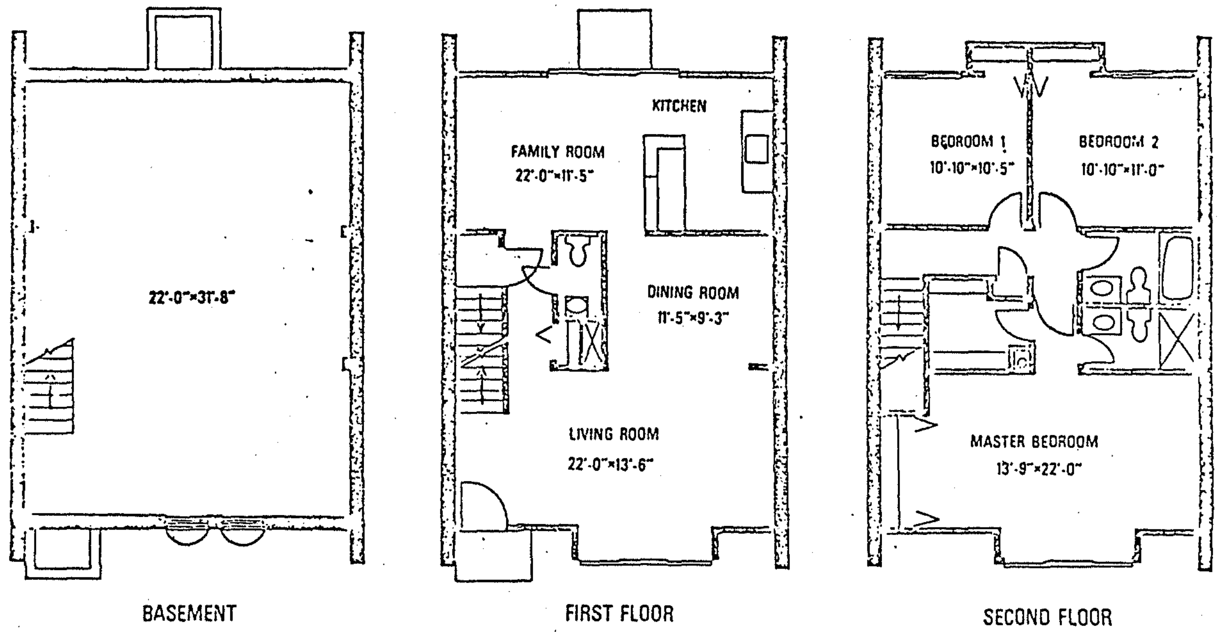

Fig. 11: Floor Plan of Twin Rivers Townhouse

fiber-glass batts; see Figure 4).

All the townhouses experienced heat losses in the same areas prior to the retrofit. A primary source of heat loss was the lack of adequate insulation in the attic. Blowing in additional insulation and stuffing openings that existed between the outer attic floor joists and the masonry firewall were the major retrofit measures in the attic. The insulation was increased from an initial thermal resistance value of R-11 to R-30 which is an increase of about 5.5 inches. Rolled unbacked fiberglass was used to fill the openings between the floor joists and the firewall.

Air infiltration was another major source of heat loss in the Twin Rivers townhouses. The two areas where air leakage was most severe were around windows and doors and along the seam between the frame structure and the masonry firewall. The heat losses around the windows result from the lack of squareness of the window frames, the seal between the glass and aluminum frame, and/or leakage past the moulding surrounding the window. Patio doors were found to have similar sealing problems. The threshold alignment and the condition of the magnetic seal strips caused sealing problems around the front door. The retrofit measures used to improve these conditions were weatherstripping with closed cell vinyl strips and caulking with silicone rubber.

Warping of the batten siding along the vertical joint between the masonry firewall and the frame structure was another source of air infiltration in the battenboard townhouses. A caulking joint for this area was made using a widely-available silicon rubber sealant.

Improving the performance of the heating and cooling systems was done by insulating the furnace warm air distribution ducts, and wrapping the water heater with R-7 insulation which is backed with aluminum foil. The two retrofit measures that are best tested for effectiveness with thermography are the increased attic insulation and the caulked joint between the firewall and masonry frame.

THERMOGRAPHIC ANALYSIS OF RETROFIT MEASURES

A thermographic survey was conducted prior to any retrofit for the purpose of identifying specific heat leaks which could hopefully be eliminated by some retrofit measure. In most houses, a second survey was carried out after the attic insulation was increased, and a third performed after caulking with butyl rubber. In the case of House B, there is only one set of post retrofit thermographs which were taken after both the insulation was increased and the caulking was performed. Three or four photographs are presented in each instance. The first is a conventional one in the visible spectrum of the object; the second is a thermogram in the IR spectrum of the test house before retrofit; the third is a thermo-

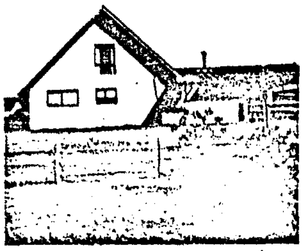
Fig. 1a

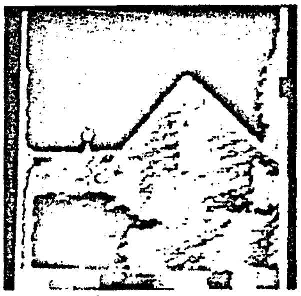
Fig. 1b


Fig. 1c

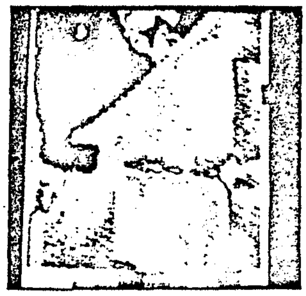
Fig. 1d


Fig. 2

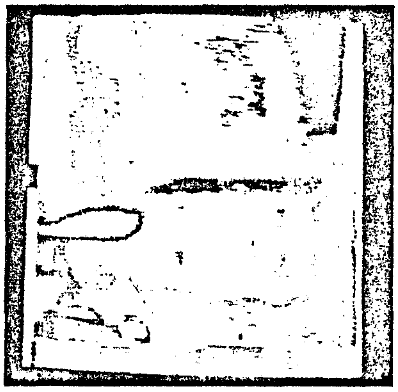
Fig. 3


Fig. 4a

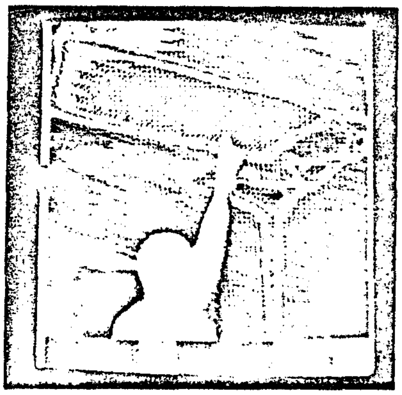
Fig. 4b

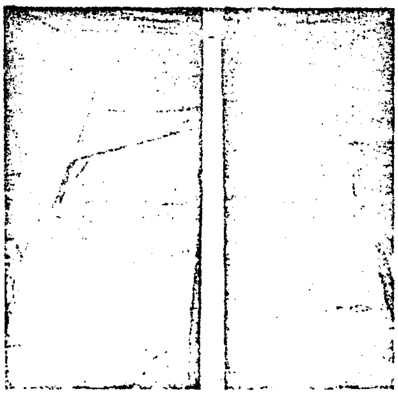
Fig. 4c

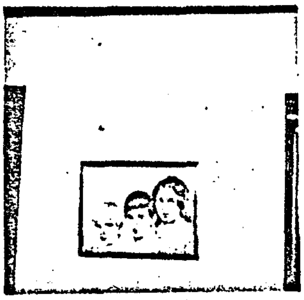
Fig. 5a

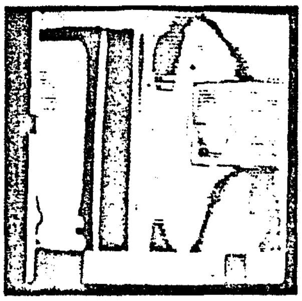
Fig. 5b

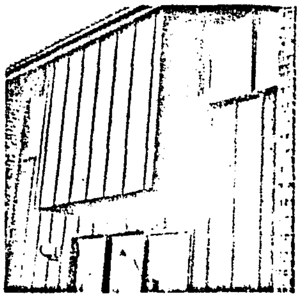
Fig. 6a


Fig. 6b

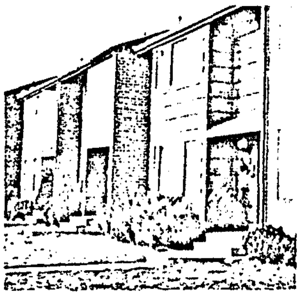
Fig. 7a

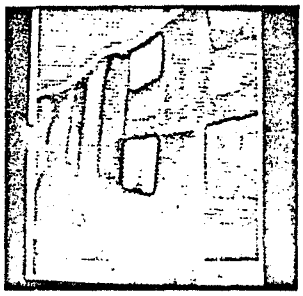
Fig. 7b

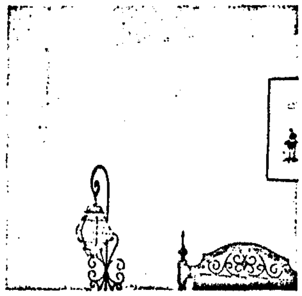
Fig. 8a


Fig. 8b

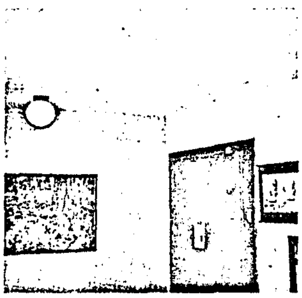
Fig. 9a


Fig. 9b

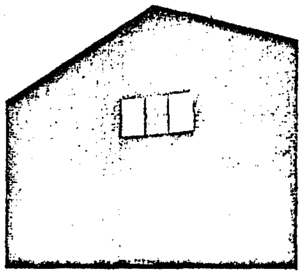
Fig. 10a

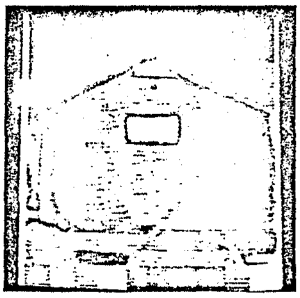
Fig. 10b

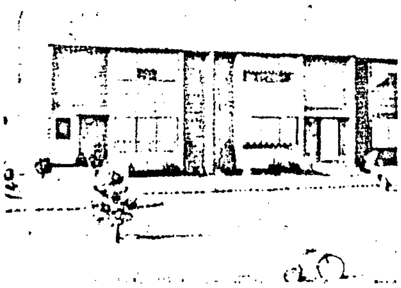
Fig. 12a

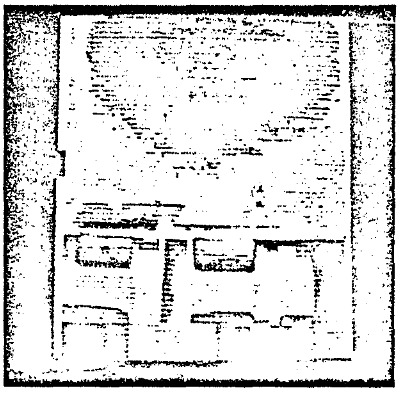
Fig. 12b

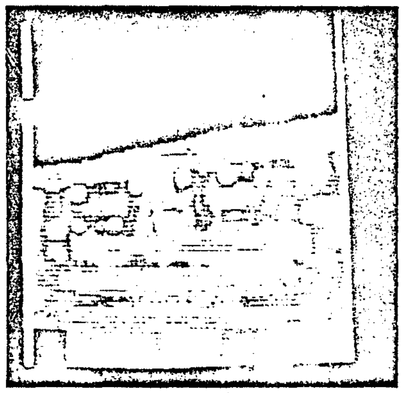
Fig. 12c


Fig. 13a

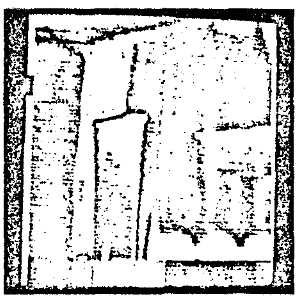
Fig. 13b


Fig. 13c


Fig. 13d

gram of the same part of the house after attic insulation; and the fourth is a thermogram of the same area after caulking.

Table 1 gives weather data for selected times when thermograms were taken. Except for January 13 when the temperature was somewhat higher, the conditions are similar, which is desirable when comparing thermographs. The discussion of the weather data is included with the discussion of the selected thermograms. Figure 12B shows the effect of increased attic insulation. The house on the left has had the attic retrofitted, increasing the insulation from R-11 to R-30. The attic insulation in the house on the right has not been increased. The left roof is darker in color, and is therefore, colder because less heat is escaping through the ceiling than in the house on the right. Using dark blue as the base color for the left roof and light green for the right roof, the left roof is three isotherm units colder than the right roof. Figure 12A is an exterior view of these townhouses. Figure 12C shows another row of townhouses. The dark roof is a retrofitted townhouse attic.

The next thermograms are of the front left corner of the master bedroom in House A. Figure 13A is the visual picture of the bedroom. The thermograph was taken January 13 when the outside temperature was 47°F and the wind velocity was 10 mph from the south. The inside temperature was approximately 70°F, giving an approximate temperature difference of 23°F. The pre-retrofit thermograph, 13B, shows a large cold area in the corner of the room, which runs from the ceiling to the floor. Figure 13C was taken on January 21 after the attic insulation was increased. The outside temperature at the time of this thermograph was 31°F with a 13 mph wind from the west. The outside to inside temperature difference is approximately 39°F, somewhat larger than at the time of the pre-retrofit thermograph. Although this thermograph was taken from a slightly different angle and at a different sensitivity, it is obvious that the shape of the cold area has changed. It is now triangular shaped with the area closest to the ceiling being warmer. This indicates that the added attic insulation helped reduce the heat loss near the ceiling. It can also be assumed that the remaining cold area is due to air infiltration along the firewall and masonry wall seam. Figure 13D shows the corner after caulking. This thermograph was taken March 17, with an outside temperature of 30°F with a 10 mph wind from the NW. These conditions, giving a 40°F temperature difference, are very similar to those on January 21. The cold area is now confined to one thin line along the corner seam. The remaining cold strip may be due to the fact that although caulking stops the cold air flow from the outside, it does not provide any insulation so the temperature along this area is slightly colder than across the rest of the wall. From these thermographs, it can be concluded that the retrofit measures were successful in stopping heat leaks in this corner of House A.

TABLE 1

WEATHER DATA FOR DAYS WHEN THERMOGRAPHY WAS PERFORMED

DATE	TEMP. °F	WIND DIRECTION	WIND VELOCITY mph
January 12	30	N	2
January 13	47	S	10
January 21	31	W	13
February 4	38	NW	5
March 17(a)	30	NW	10
March 17(b)	32	NW	12

In Bedroom #2 of House A, shown in Figure 14A, post retrofit thermographs were taken after increasing the attic insulation only. Figure 14B shows the room before the insulation has been added. The walls are streaky with cold areas especially along the corner seam. Figure 14C shows the room after the insulation has been increased, and it can be seen that the wall is now an even color with no cold streaks. The corner area is still somewhat colder as indicated by the spot of green and lighter shades of red, but the cold spots seen earlier near the ceiling are now virtually gone. These thermographs were taken in the same sequence of dates as those just discussed with the pre-retrofit shot on January 13 when the temperature difference was 23°F and the post retrofit shot on January 21 when the temperature difference was 39°F.

The next group of thermographs are of House B, which was the highest energy user of all the test homes. The thermographs were taken on February 4 before any retrofits were performed and on March 17 after both the attic insulation was increased and the seam between the firewall and the house frame had been caulked. At the time of the pre-retrofit thermographs, the inside temperature of House B was approximately 75°F. The outside temperature was 38°F, giving a temperature difference of 37°F. The wind that night was from the northwest with a velocity of 5 mph. Environmental conditions at the time of the post-retrofit thermographs on March 17 were an inside temperature of 70°F, an outside temperature of 32°F, and northwesterly wind with a 12 mph velocity. These conditions give a temperature difference of 38°F.

The first thermograms are of the front door area of House B shown in Figure 15A. Figure 15B shows a large cold area along the corner seam from the ceiling down. The black line outlining the door is due to the cold air which leaks through the cracks between the door and the frame. The warm pink spot in the middle of the door is the doorbell. Figure 15C, taken after both retrofits were performed, no longer has the large cold area from ceiling to floor seen in Figure 15B, and the ceiling and wall are both warmer. It is hard to tell which retrofit measure has been the most effective in this case, but there has definitely been an improvement.

Figure 16A shows the left front corner of House B's living room. Figure 16B was taken prior to any retrofit. A cold area that runs from the ceiling to the floor is seen along the corner seam. The triangular shape near the ceiling indicates cold leaking from the attic. In Figure 16C the cold area has been reduced to a thin strip. The large pink area is still present, but the right wall has warmed up and seems to have a more uniform temperature distribution than before. In both thermographs the dark outlines to the right of the cold area are pictures that are hanging on the wall, as seen in Figure 14A.

We next consider the ceiling above the patio door (Figure 17A). The pre-retrofit thermogram (Figure 17B) shows cold streaks along the seam between the wall and ceiling. The post-retrofit thermogram (Figure 17C) shows a decrease in the size of the cold area. The remaining cold spots may be attributed to the lack of insulating value of the butyl rubber. It should be mentioned that this heat loss mechanism is the same as that demonstrated earlier in Figures 2 and 4. We have taken thermograms of ceilings at Twin Rivers which show cold streaks penetrating ten or more feet into a room.

In the House B family room there was a large cold area that extended from the ceiling to the floor along the corner (Figure 18A). Figure 18B shows the pre-retrofit temperature variations. The white streak in the ceiling is an uninsulated heat duct. The coldest part of this corner is near the bottom, which would indicate that the cold is not all streaming down from the ceiling. Figure 18C shows the corner after the two retrofit measures have been performed. The cold area has been reduced somewhat with the coldest area along the corner seam. There is still a spreading out of the cold area towards the bottom. This may indicate a lack of insulation in this section of the wall. It may also be that since the firewall extends past the exterior of the townhouse that it could be acting like a fin and thus it could be a conduction path to the exterior. If such is the case, only insulation would effectively reduce this component of the heat loss.

Considering that House B was an extremely leaky one in comparison to the other houses surveyed, and that from the thermograms it appears that the cold areas were significantly decreased in size, it can be assumed that the two retrofit measures were at least partially effective.

House C, which is the third home to be considered here, presents another side to the effectiveness of the retrofits. The thermographs of this house were taken in three steps as described earlier. The pre-retrofit thermographs were taken on January 12 when the outside temperature was 30°F with a 2 mph wind blowing from the north. The inside temperature was approximately 75°F, giving a temperature difference of 45°F. The thermographs taken after the attic insulation was increased were taken January 21 with an outside temperature of 31°F and a westerly wind with a 13 mph velocity. The inside-to-outside temperature difference was 44°F. The last set of thermographs were taken March 17 when the outside temperature was 30°F and the wind had a 10 mph velocity from the northwest. Once again the temperature difference was 45°F.

Figure 19A shows the family room of House C. Figure 19B is the pre-retrofit thermogram. Figure 19C shows the corner after caulking with butyl rubber and there appears to be little improvement. Although the size of the cold area as a whole does not seem to have decreased, the colors are lighter and the saturated blue area is smaller.

The retrofit measures in this home do not seem to have been as effective as in the other two. At this point there are no apparent reasons why the retrofit measures appear effective in some homes but not in others.

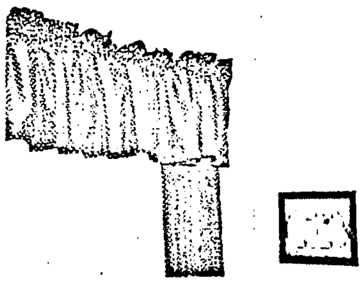

Fig. 14a

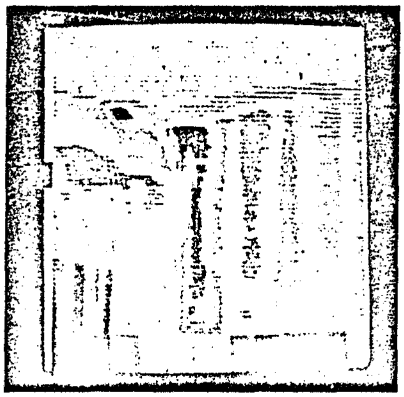

Fig. 14b

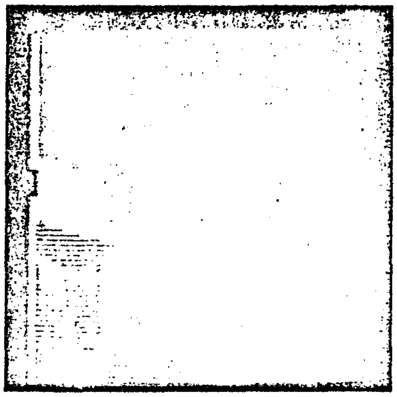

Fig. 14c

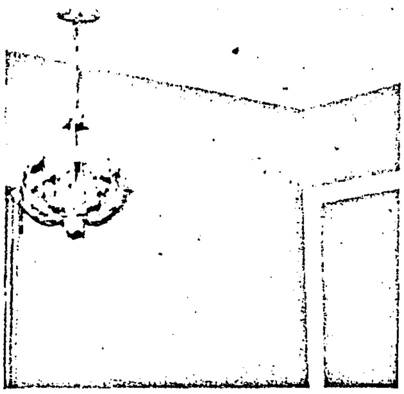

Fig. 15a

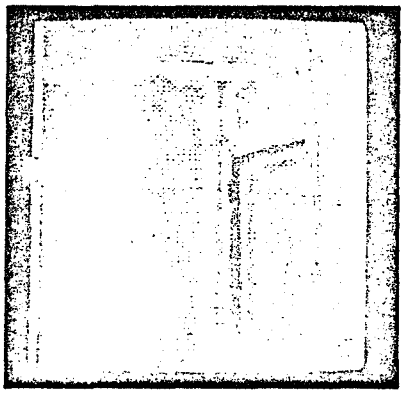

Fig. 15b

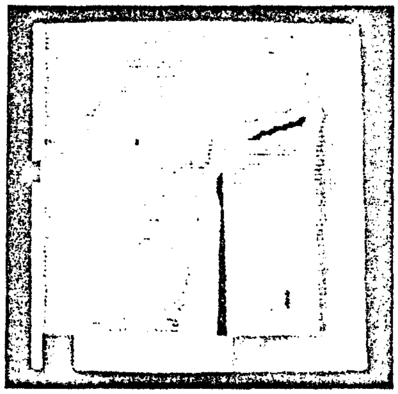

Fig. 15c

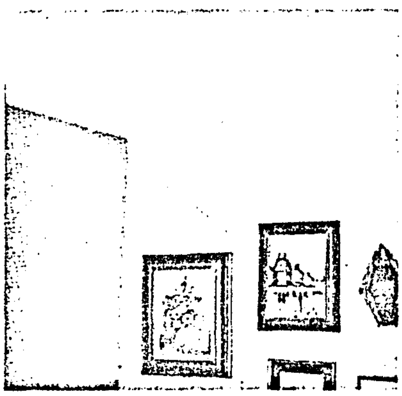

Fig. 16a

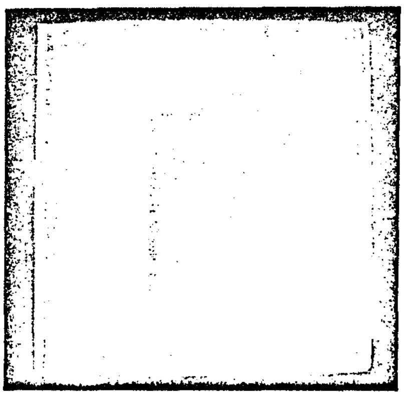

Fig. 16b

Fig. 16c

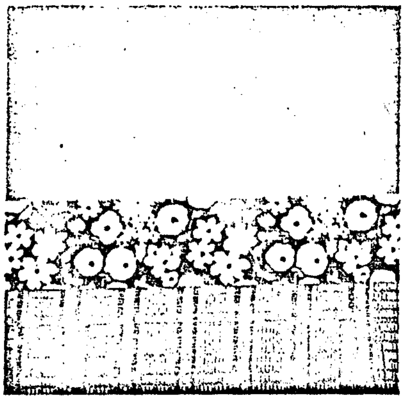

Fig. 17a

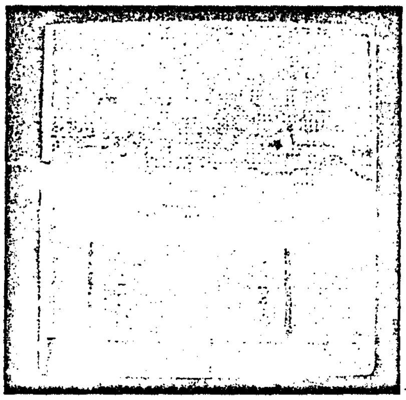

Fig. 17b

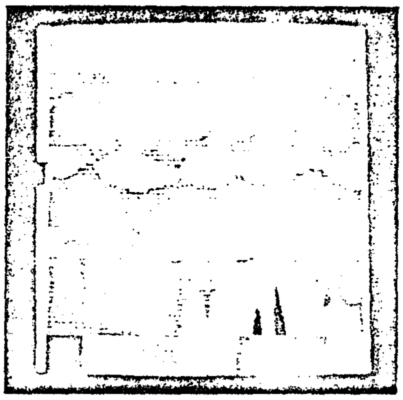

Fig. 17c

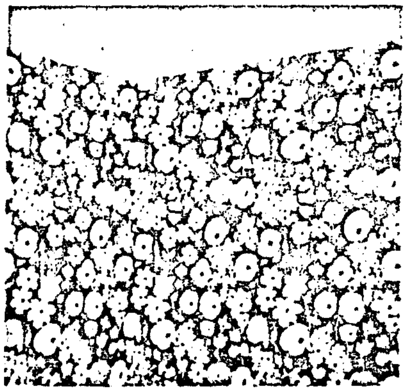

Fig. 18a

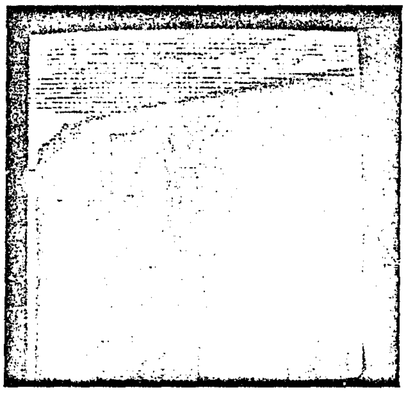

Fig. 18b

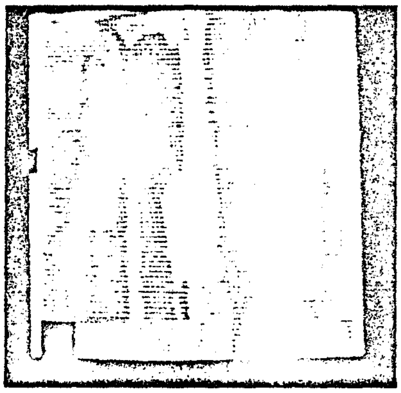

Fig. 18c

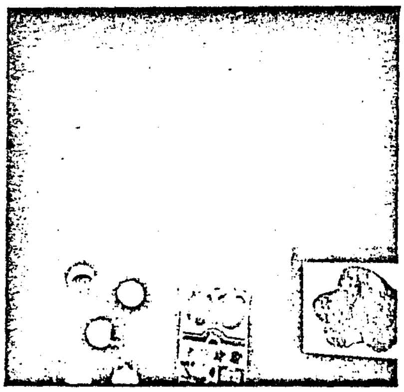

Fig. 19a

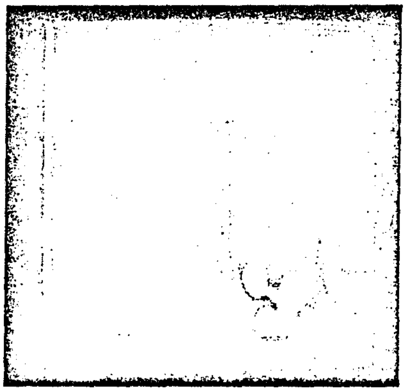

Fig. 19b

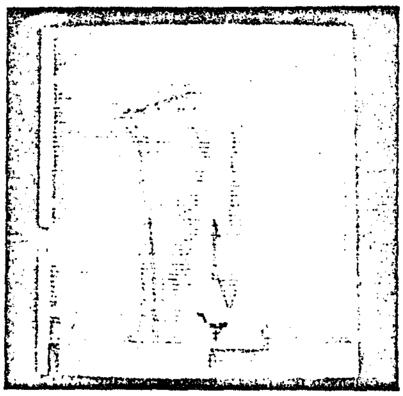

Fig. 19c

CONCLUSION

Defects in construction of residential buildings can cause a substantial increase in the consumption of energy. Because these defects are usually not detected by a visual inspection, thermography can be very useful in locating sources of heat leaks. It has been shown that in many cases, once a defect has been located with thermography, a retrofit measure can be implemented to correct it. But it cannot be assumed that because a retrofit has been performed the defect is necessarily corrected. Thermography is also useful in showing if a retrofit measure corrected the defective area.

The retrofit measures implemented on the townhouses in Twin Rivers, New Jersey are the major reason for the twenty-five percent energy consumption decrease. The use of thermography in these homes has also revealed some of the main problem areas that needed correction. Why some retrofit measures appear to be effective in one house and not in another is a puzzling matter. A better understanding of the effect of air infiltration in this area may reveal logical reasons. Possibly the defects that are seemingly not corrected are more extreme cases of the construction defect than those found in other homes.

A clear understanding of the basic construction of a building is needed when using thermography, so that heat leaks that are located can be explained. This helps in choosing a retrofit measure that will be effective.

In the future thermography may prove to be useful in gaining a quality improvement in the practices of builders and contractors either through improved construction standards and better building codes. At the present time the cost of thermography is too high for the average homeowner to have his house surveyed for heat leaks. As the usefulness of thermography is realized, it will become a more widely used tool in the field of energy conservation either by specialized groups of investigators, but inspectors as part of a building regulatory evaluation method or by homeowners desiring to assess the quality of their dwelling both before and after improvements have been made.[7]

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