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FIELD INSPECTION OF BUILDING COMPONENTS—A TOOL FOR COST-EFFECTIVE MEASURES IN RETROFITTING BUILDINGS

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ABSTRACT

When retrofitting or implementing energy conservation measures in buildings, the most cost-effective measures must be identified. This requires the collection of relevant technical and economical data. Field inspections provide data for setting priorities among different possible measures.

Thermographic methods have a good accuracy in indicating damages and energy-related conditions of building envelopes. Radiative temperature patterns indicate the extent and character of building anomalies, while temperature differences indicate the degree. Inspection, using fiber optics, of the building envelope interior confirms the indication of damages such as wet, faulty, or missing insulation, thermal bridges, and air leak paths. The influence of air leaks may be quantified by measuring the air change rate. The energy losses for various building components can be computed using building design data and field inspection data as input. A check for consistency is provided by the metered total energy consumption of the building.

This paper presents results from a detailed study of one building that was to be retrofitted. The energy consumption had previously been reduced by adjustments of the control system. Before the retrofit, we analyzed the probable reduction in energy consumption for different measures proposed. Also, the highest investment cost compatible with payoff criteria applied was calculated for each measure. This information was presented in the form of a priority list to the building manager and the contractor. Some of the measures proposed were selected for implementation. After the retrofit was evaluated, the cost benefit of the selected measure was compared to the optimal choice according to the priority list.

INTRODUCTION

Buildings require continuous control and maintenance. The service life of buildings may vary from 20 to 100 years depending on building function and design and on maintenance frequency. Cheap energy and the lack of reliable operational methods has led to a reduction in the frequency and extent of maintenance. In some cases, the maintenance of buildings has never had a high priority due to lack of interest or economic resources. However, neglect of control and maintenance of buildings sooner or later leads to severe building damages, increasing energy cost and downgrading building performance.

Before upgrading or retrofitting building envelopes, one has to assess the condition and performance of the envelope. This requires an inspection of the envelope with regard to

- energy and air leaks at joints, windows, and doors;
- damage to the envelope coating;
- missing or defective insulation;
- damage to the envelope interior, for example, moisture damage.

The surveillance of building attics is usually carried out by airborne thermographic equipment (Ljungberg and Rosengren 1987; Tobiasson 1988). The surveillance of basements must be done from the building interior. For external walls, thermographic examination can be carried out from the inside or from the outside (Allen 1987; Ljungberg and Lyberg 1990). If applied to a single building, it is often combined with pressurization or depressurization of the building interior to detect paths of air infiltration or exfiltration.

Traditional indoor thermography normally encompasses a very detailed survey of damage and air leaks. The method is accurate but is very time consuming and labor intensive. It is mostly applied to single buildings, and a trained operator may survey two or three houses in a day. Most of the analysis of thermal data is carried out at the site.

Outdoor thermography permits a survey of radiative temperatures and patterns of large surfaces and gives an overall picture of the status of the building envelope. However, if one has to carry the equipment, it is rather time consuming and is mostly applied to single buildings.

Visual inspection using fiber optic equipment and a camera for photographic documentation can be used to survey and detect the causes of the deviating radiative

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temperatures and patterns indicated in the thermograms. The alternative is to remove the wall cladding or panel to inspect an external wall or attic to clarify the type and extent of damage or an energy-related condition. This method is often destructive, time consuming, and costly. Using fiber optics, it suffices to drill a small hole to get a clear picture of the conditions prevailing in the interior of the building envelope. This is a cheap, efficient, and easy method.

The air change rate can be measured applying tracer gas techniques. The air change rate is often expressed in terms of air changes per hour for the volume considered.

Air infiltration or exfiltration paths through the building envelope are often easily detected by thermographic methods, especially if combined with pressurization or depressurization of the building interior. The leakiness of a building is often expressed by the number of air changes per hour at a pressure difference of 50 Pa. However, this measure does not tell the magnitude of the rate of air exchange under normal conditions.

Neglecting wind effects and solar radiation, the surface temperature of a building envelope is mainly determined by the thermal conductance of the wall, that is, the U-value, and the surface emissivity. Surface temperature differences between two parts of a wall, or between two similar walls, can be translated into differences in U-value. To analyze thermographic data, it is important to know the U-value and the emissivity. This information may sometimes be obtained from design drawings or may be collected by an inspection at the site.

Using information on the air change rate and the U-value of different building components, one can establish the building heat balance, that is, estimate the heat losses through the various building components. The sum of these heat losses must equal the amount of energy supplied to the building. The heat losses may, for example, be divided into heat losses through external walls, ceilings, windows and doors, heat losses to the ground, and heat losses by ventilation and air infiltration.

Information on a building's heat balance is relevant when selecting energy conservation measures. The reduction in energy consumption has to be compared to the investment cost and payback time of different measures and to the expected lifetime of the measure and the building component.

New IR measurement techniques, combined with modern video techniques, permit the development of building thermography into more operational and cost-effective methods. Using new techniques, one can carry out thermography from the building exterior using portable, mobile, or airborne equipment. A large part of the building envelope can be surveyed in a short time.

Modern, computer-based systems of interactive image analysis permit a more complete use of thermographic data. A quantitative or qualitative analysis can be performed at a level of detail down to separate picture elements.

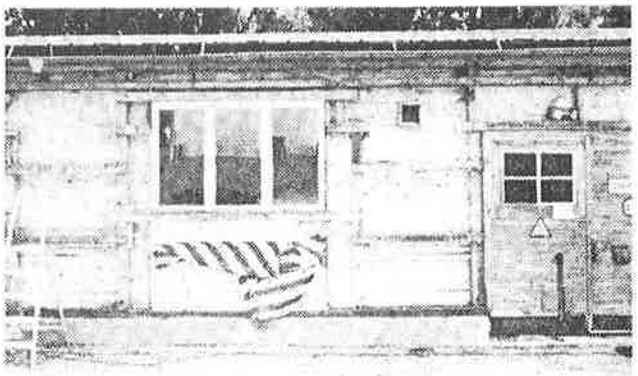

Figure 1 *One of the facades of the selected building during the replacement of the insulation in the exterior walls.*

The above circumstances have led to a renewed interest in developing efficient and cost-effective methods for the inspection and energy auditing of buildings (Tobiasson 1988; Ljungberg and Lyberg 1990; Kittsson 1990). For the Swedish Army, we have evaluated the advantages and limitations of combining aerial and ground-based thermography for building applications, as well as developing simplified working routines to be used by the maintenance staff at military bases. In this paper, we will describe a case study of how these methods have been applied to a building to select cost-effective retrofit measures.

THE BUILDING

The building selected is an 80-year-old one-story office and storage building with a floor area of 730 m^2 (7,200 ft^2) and a volume of 2,700 m^3 (87,000 ft^3). It has wood-frame construction on a concrete slab (Figure 1). The insulation level of the building was poor. The insulation of the attic consists of 30 mm (1.2 in.) mineral wool blankets. It can be seen in Figure 2 that indoor thermography reveals many spots with faulty insulation or moisture damage.

The external walls had insulation consisting of 50 mm (2 in.) of mineral wool. The insulation did not completely fill the space between the external wood panel and the internal panel, resulting in voids and crumbled insulation, as indicated in Figure 3. Figure 4 shows that this could be verified by an inspection using fiber optics equipment. The voids constituted excellent air paths. Outdoor thermography revealed many places where heated air was streaming out, especially in the joint between the attic and external walls, as can be noted in Figure 3.

The concrete slab on the ground was uninsulated as well as the concrete base of the external wall. Figure 5 shows a thermographic inspection from the outside that indicated large heat losses through the concrete base, and

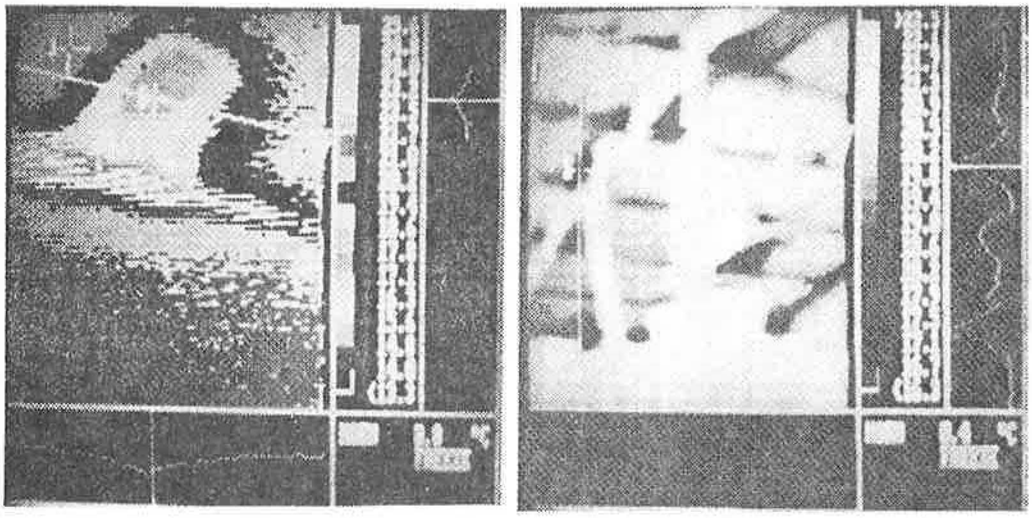

Figure 2 *The attic as seen from the inside. Thermographic pictures reveal moisture damage (detail left) and many spots with default insulation in the 30 mm (1.2 in.) mineral wool insulation (right).*

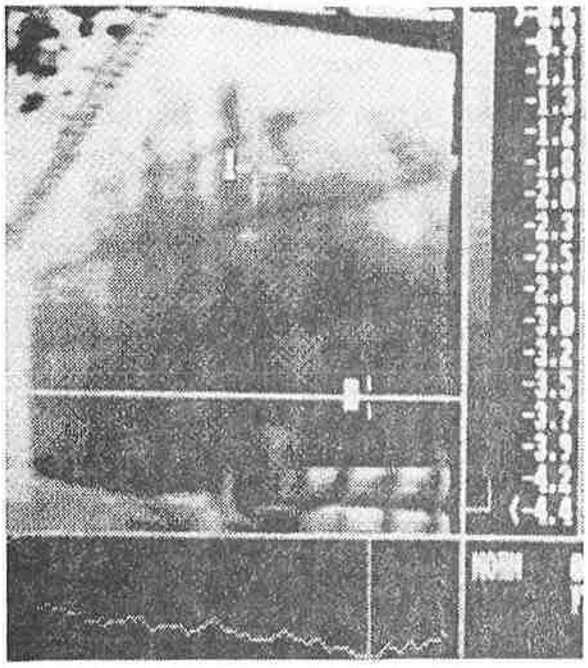

Figure 3 *Part of the external wall as seen from the outside. The 50 mm (2 in.) mineral wool insulation did not fill the space between the interior and exterior panel. This resulted in voids, degraded insulation, and air leak paths, resulting in heated air leaving the building in the joint between the attic and exterior walls.*

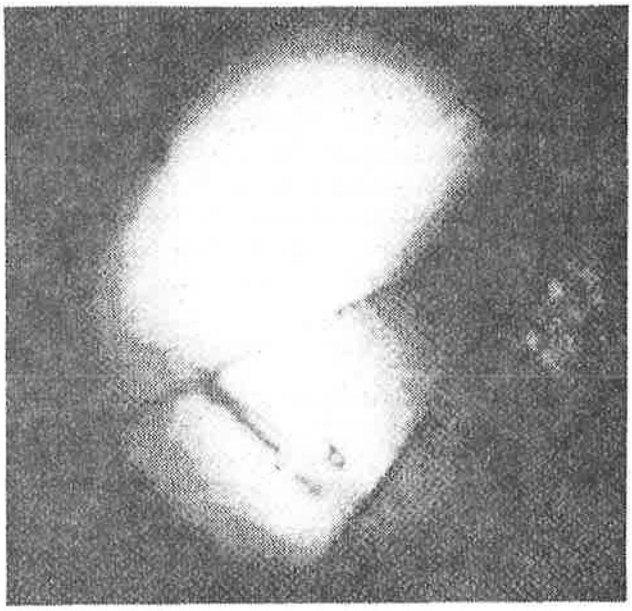

Figure 4 *Inspection of the interior of the external wall using fiber optics revealed voids in the insulation.*

inspection from the inside revealed moisture damage to the fiberboard. Most windows and doors were very leaky, as indicated by thermogram (Figure 5). No pressurization was necessary to detect this phenomenon. The air change rate was measured by the decay method using dinitrooxide (N_2O) as the tracer gas. This gave an air change rate of 0.65 air changes per hour (ach) at a temperature difference of 20°C (36°F), indicating a very leaky building. The lasting impression of the building audit before any measures were taken was that a retrofit of most building components could be justified from a maintenance or energy conservation point of view.

The building is heated by electric resistance heaters. There is a mechanical exhaust air ventilation system. There are no other major energy-consuming systems apart from the lighting. Thus, the only energy source is electricity. The heat output is determined by an indoor thermostat. The electricity consumption has not been monitored, but it has been metered monthly. The building is occupied during office hours, that is, about 25% or 30% of the time.

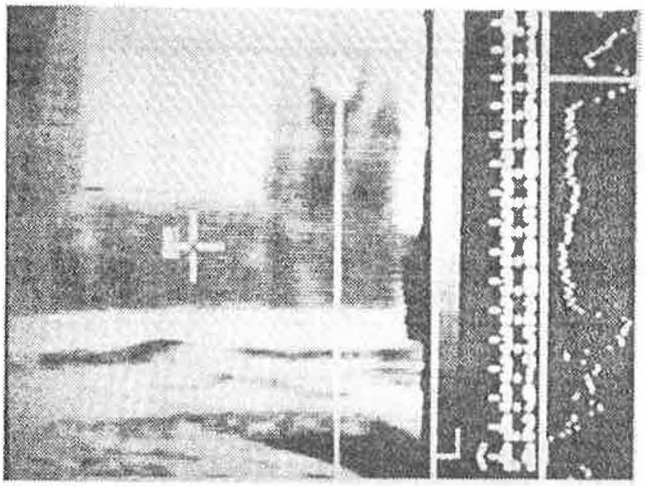

Figure 5 *Thermographic picture of the building exterior indicating heat losses through the concrete base of the external wall and also showing a leaky window.*

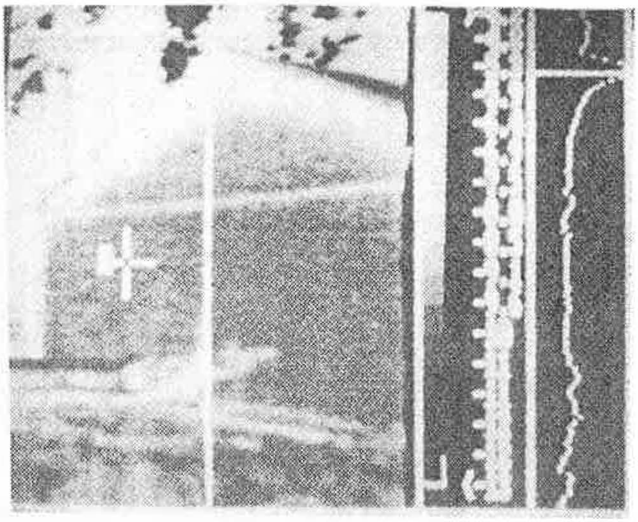

Figure 6 *A section of the external wall after the retrofit showing a successful replacement of the insulation of the external wall, but a remaining air leak path in the joint between the external wall and the attic (compare with Figure 3).*

Four years ago, the building consumed 151 MWh a year. Figure 9 shows the energy consumption for some months during this period. There is a rather good linear relation between electric power and external temperature even for the summer months. One gets the impression that heating, ventilating, and lighting systems have been on all year round. Making this assumption, the energy consumption as computed from the building design and the measured rate of air exchange amounts to 159 MWh a year. Considering that it is hard to make an estimate of this kind without an error of less than 10%, the proximity to the metered consumption of 151 MWh is striking. Energy losses through various building components as estimated from design data are given in Table 1.

About four years ago, a meter was installed and the

TABLE 1
Energy Consumption of Building Components

All the estimates in this table for energy losses through various building components are based on design data, with the exception of air infiltration and ventilation losses, which are based on measurements of the air change rate of the building.

Building Component	Area (m^2)	U-Value ($W/K \cdot m^2$)	UA-Value (W/K)	Energy (MWh/yr)	Energy (%)
Before Energy Conservation Measures:					
Attic	730	0.57	415	43	27
Walls	340	0.62	210	22	14
Windows	40	2.5	100	10	6
Doors	32	0.8	25	3	2
Ventilation			600	63	40
Ground heat losses	680		175	18	11
Total			1525	159	100
After Energy Conservation Measures:					
Attic	730	0.57	415	43	45
Walls	340	0.21	70	7	7
Windows	40	2.5	100	10	11
Doors	32	0.5	16	2	2
Ventilation			220	23	24
Ground Heat Losses	680		100	10	11
Total			921	95	100

excess energy consumption was noted. A time control was installed that shut off the ventilation and lighting and set back the heating outside of office hours. It also shut off the heating system in the summer. During the next two years, this reduced the energy consumption to 135 MWh a year, a reduction of about 10%.

THE EVALUATION PROCESS

The evaluation of the building as carried out in this study can be divided into six stages—the detection, verification, classification, and analysis of building anomalies, the selection of measures and economic evaluation, and, finally, the report to the building manager.

Detection of Suspected Building Anomalies

Information was collected from the building management and maintenance staff regarding observed and suspected building anomalies. A recording of the thermal image of the building exterior was made using vehicle-borne equipment for exterior walls and aerial thermography for roofs. The thermal image may indicate the presence of moisture damage, degraded insulation, missing insulation, and air leaks.

Verification of Building Anomalies

Possible major building anomalies observed by the maintenance staff or indicated by the thermal images have been subjected to a closer examination.

Areas of anomalies have been analyzed regarding radiative temperatures and temperature radiation patterns. The presence of moisture damage has been verified by measurements of the moisture content of building components. Missing insulation or the presence of insulation that is degraded or not properly functioning has been verified by indoor thermography and the use of fiber optic techniques to visually inspect the interior of the building envelope. The presence of air leaks has been confirmed by inspection or by indoor thermography. The level of indoor comfort has been estimated by air temperature measurements, measurements of surface temperatures using IR techniques, and measurements of the air change rate.

Classification of Building Anomalies

Verified anomalies have been classified with regard to what factors they influence, that is, factors such as building performance, building operation, energy consumption, etc. This stage has been carried out using existing data, such as information on building design, including insulation levels and HVAC systems, past retrofits, present building function and operation, and present energy consumption. These data as well as drawings have been provided by the maintenance staff. The information also includes thermographic data such as temperature patterns and building anomalies detected as well as other data from field inspections.

Analysis of Building Anomalies

The data collected have been used to create a data base for the analysis, including numerical data on building design and energy consumption, and other data consisting of photographic recordings from inspections and the use of fiber optics. All thermographic inspections have been recorded on a digital video. This kind of information may be used in future periodic inspections. For example, by comparing thermographic videos a few years apart, one may assess the development of moisture damage. This information can be used to predict the time when it will be necessary to take measures against the damage to prevent serious damage to the building structure.

Building anomalies have been divided into

- severe anomalies that may constitute an immediate threat to the building function and require immediate attention;
- anomalies that degrade building performance but do not jeopardize function, for example, damage that should be repaired but can be included in the ordinary building maintenance plan or damage that causes excessive energy loss but requires an economic evaluation before any measures are taken; and
- anomalies that do not require any measures but should be observed for future development.

An example of the kind of analysis that has been carried out is the following. For anomalies causing conductive energy losses, the area of the anomaly has been estimated using photographs and drawings, and the effective U-value of the area has been estimated from the surface temperature by a comparison to the surface temperature of undamaged parts of the envelope. It has then been assumed that the U-value of the undamaged surface equals the design U-value. The effective U-value of the damaged parts has been used to estimate the resulting excess energy losses. For an analysis of this kind, the thermographic recordings must be carried out under suitable climatic conditions.

Selection of Measures and Economic Evaluation

After the analysis of damages and the energy status of individual components, the energy balance of the building has been established as well as a list of all damage requiring attention. This information has been used to identify possible measures and combinations of measures. For each measure proposed, the reduction in energy consumption and reduction in future maintenance costs were calculated. These results were used to calculate the maximum investment compatible with the economic criteria adopted by the building manager. The idea has been that the manager should implement all measures where the actual investment cost is lower than the maximum allowed.

The economic criterion applied is that the accumulated investment cost must be lower than the accumulated reduction in energy cost during the lifetime of the energy conservation measure. The accumulated cost should be calculated assuming a real annual interest rate of 4%. The energy cost is assumed to be 6 cents/kWh.

Report to the Building Manager

All information collected, including videotapes and the data base as well as the results of the analysis, has been included in the report to the building manager. The data base will serve as a basis for the future building maintenance scheme. The procedure outlined here is illustrated below with a more detailed account of how it has been applied to a particular building.

THE BUILDING REFURBISHMENT

The selected building was subjected to a detailed study comprising the steps outlined in "Analysis of Building Anomalies." The findings from the thermographic survey and their confirmation by field inspection have been described.

The heat losses through various building components, as estimated from design data, are given in Table 1. The major losses occurred through the attic and by air infiltration, and it was concluded that, from an energy conservation point of view, the optimal measures should include an upgrading of the insulation level of the attic and an improvement of the airtightness of the building.

From a maintenance point of view, it was obvious that the attic insulation, the external wood panel, and the wall insulation should be replaced, windows and doors repaired or replaced, and the concrete base of the external walls repaired.

In the report to the building manager, a number of measures or combinations of measures were proposed (see Table 2). This report also presented an estimate of the reduction in the annual energy consumption for the measures proposed, along with the highest permissible investment for each measure compatible with the economic criterion applied. Two alternatives were presented where the lifetime of the retrofit or the remaining lifetime of the building was 10 or 30 years, respectively. The estimates presented are given in Table 3.

Results of the audits and the energy analysis have been discussed with the building manager and the contractor. All alternatives were discussed in some detail.

TABLE 2
Measures or Combinations of Measures Proposed

This table presents the different retrofit alternatives presented to the building manager after an analysis of the maintenance and energy status of the building.

I. Replacement of the attic insulation by 220 mm (11 in.) mineral wool.
II. Replacement of the attic insulation by 300 mm (12 in.) mineral wool.
III. Replacement of the wall insulation by 200 mm (8 in.) mineral wool.
IV. Replacement of the wall insulation by 250 mm (10 in.) mineral wool, also requiring additional wood framing.
V. Measures I + III combined with a vapor barrier and improved airtightness of doors and windows to reduce the air infiltration rate to 0.2 air changes per hour.
VI. Measures I + III combined with improved airtightness of windows and doors to reduce the infiltration rate to 0.35 air changes per hour.
VII. Insulation of the ground outside the building by a horizontally reinforced mineral wool slab, 100 mm (4 in.) thick and 750 mm (30 in.) wide.

The building manager decided to improve the insulation level of the external walls, according to proposed measure III, complemented by a vapor barrier; to replace the external wood panel, to implement measure VII; and to replace all doors and to repair and improve the airtightness of all windows. The need to replace the external wood panel made it cost-effective to simultaneously improve the insulation level.

The replacement of doors and repair of windows were dictated by maintenance reasons, but the simultaneous improvement of the airtightness was dictated by energy and comfort reasons. Energy reasons also dictated the introduction of the vapor barrier. There were no funds for increasing the insulation level of the attic, and the remainder of the money was spent on an improvement of

TABLE 3
Reduction in Energy Consumption and Highest Permissible Investment for Proposed Measures if Only Energy Conservation Aspects Are Considered

This table presents the estimated reduction in energy consumption for the different retrofits proposed. The estimate is based on design data. Two alternatives for the lifetime of the retrofit or the remaining lifetime of the building are given—10 and 30 years, respectively.

Measure	Reduction in Energy Consumption (MWh/yr)	Highest Permissible Investment Compatible with the Investment Criterion (thousands of U.S. $)	
		10 years use	30 years use
I	30	10	23
II	33	10	25
III	15	18	45
IV	17	20	52
V	82	50	127
VI	72	45	110
VII	6	3	10

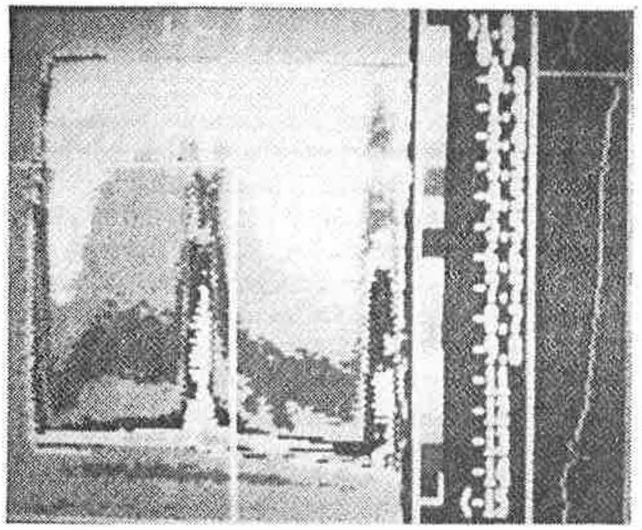

Figure 7 A thermographic picture of a window after the retrofit indicating an only partially successful improvement of the airtightness.

the ground insulation, although there was no clear justification to do so from an energy point of view.

The contractor was informed that a thermographic survey and energy audit was to take place after the retrofit. The thermographic inspection revealed that the replacement of the insulation in the external walls had been successful. However, as nothing had been done to the attic or to improve the airtightness of the joint between attic and external walls, heated air was still streaming out of the building through this joint, as can be seen from Figure 6.

The airtightness of the window casing was not satisfactory after the retrofit; the thermographic inspection indicated many instances with air leak paths between the window frame and the wall (see Figure 7). Although the doors had been replaced, there was still some air leaking through the joints between the doors and the wall.

A measurement of the air infiltration rate demonstrated that the airtightness of the building had been improved, mainly due to the introduction of the vapor barrier. A tracer gas measurement gave a rate of 0.24 ach, compared to 0.65 before the retrofit. The retrofit of the concrete base of the external wall reduced the heat losses, but there were still air leak paths present in the joint between the base and the external wall, as one can note from Figure 8. Table 1 gives the energy consumption before and after the retrofit as estimated from design data.

The predicted energy consumption after the retrofit was 95 MWh per year. The actual energy consumption during the first year turned out to be 107 MWh per year, still a reduction of more than 20% from the previous level of 135 MWh. Looking at the monthly energy consumptions in Figure 9, one can note that for external temperatures above about 0°C (32°F) there is a rather good agreement between the actual energy consumption and that predicted from design data.

Comparing this result with "Classification of Building Anomalies" above, one may conclude one result of the retrofit. The external temperature limit for an acceptable indoor climate has moved from 5°C (41°F) to 0°C (32°F). There are still some complaints about draft in the winter, but this is not surprising considering the very leaky attic.

Assuming that the attic had been retrofitted by increasing the mineral wool insulation from 30 mm (1.2 in.) to 250 mm (10 in.), the resulting energy consumption can be estimated to be 59 MWh per year, a drastic reduction from 107 MWh.

CONCLUSIONS

The combination of methods applied makes it possible to establish a data base that can be used to identify the most cost-effective measures in building maintenance and energy conservation. The building auditor should advise and propose the optimum mix of measures compatible with the investment budget of the manager. If possible, this should be carried out within the framework of a process where the different steps of the investigation and their results are discussed with the client and, if possible, with the contractor. This implies that the audit consultant team should possess expertise in inspection methods such as thermography and basic knowledge of building construction and HVAC systems.

From an energy point of view, the decision by the building manager to retrofit the walls instead of the attic was a suboptimization. The energy consumption had been reduced from 151 MWh per year to 135 MWh by simple control measures, and was now further reduced to 107 MWh by the wall retrofit. Before the retrofit, the indoor

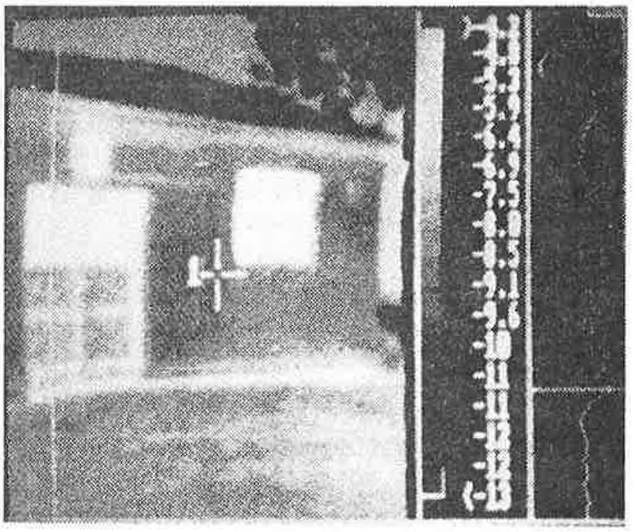

Figure 8 A thermogram after the retrofit showing air leaks at a door and heat losses to the ground, partly due to air leak paths present in the joint between the base and the external wall.

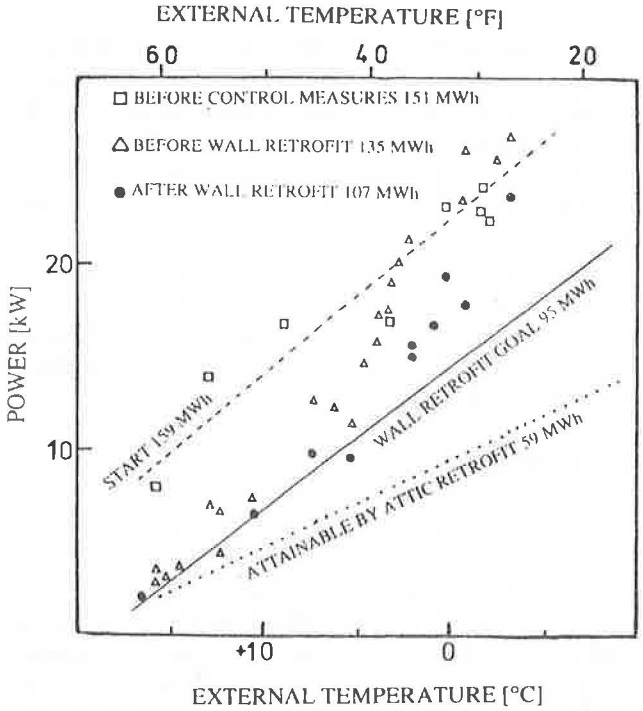

Figure 9 *Metered monthly energy consumption of the building. The annual energy consumption was 151 MWh a year (squares), which agrees well with the value estimated from design data, 159 MWh. Some simple control measures brought the consumption down to 137 MWh (triangles). The nonlinearity of the power dependence on external temperature probably indicates a lack of indoor comfort for external temperatures below 5 °C (41 °F). A wall retrofit brings the consumption down to 107 MWh, but not down to 95 MWh as design data would predict. There is still a nonlinearity in the power dependence of the external temperature, indicating a lack of indoor comfort for external temperatures below 0 °C (32 °F). This lack of comfort is probably due to the leaky attic. An attic retrofit would give a predicted energy consumption of 59 MWh a year.*

climate was not acceptable at outdoor temperatures below 5°C (41°F); the retrofit brought this limit down to 0°C (32°F). An attic retrofit would bring energy consumption down to 59 MWh a year and bring an acceptable indoor comfort for all external temperatures. However, the funding for this was not available. Building maintenance dictated what retrofits were most urgent.

The contractor was informed about all inspections made before and after the retrofit. The upgrading of the insulation level was carried out in an acceptable manner, but this was not the case for the replacement of the doors and the airtightening of the windows. Thermography revealed that there were almost as many air leaks at windows and doors after the retrofit as before. This indicates a need by the contractor to increase the level of craftsmanship of his staff.

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