

AERIAL AND MOBILE THERMOGRAPHY TO ASSESS DAMAGES AND ENERGY
LOSSES FROM BUILDINGS AND DISTRICT HEATING NETWORKS - OPERATIONAL
ADVANTAGES AND LIMITATIONS

Abstract

The building stock and the energy distribution networks of most countries in cold regions require continuous control and maintenance. The service life of buildings vary from 40 to 50 years depending on constructions and frequencies of maintenance. The service life of a heat culvert system has been estimated to exceed 30 years. In order to evaluate the conditions of buildings and district heating networks it is necessary to supply the planners and the maintenance with both detailed and overview information of technical and energy-related conditions of the building stock and the energy distribution network. Thermography gives radiative information related to the condition of the object studied. Results from different studies (Goldstein 1978, Schott and Biegel 1982, Mackay 1984, Ljungberg and Rosengren 1987) shows that thermography in general has good accuracy and stability, and gives detailed and overview information on heat losses and damages of roofs and district heating networks.

In this paper, the conditions for applying aerial or groundbased mobile thermography for building and district heating network applications is discussed. The information content of thermograms, and the operational advantages and limitations of different infrared systems are evaluated. Analysis methods and interpretation routines are described and evaluated. The implementation of thermographic methods in regular control and maintenance programs are discussed.

Introduction

Authorities in many countries are supporting the development of supervisory methods and energy maintenance programmes. Technicians and planning authorities are struggling to find out the best solutions of constructions of buildings and district heating networks, to improve function and to decrease cost. However, there will always be both known and hidden factors impacting on technical lifelength, function and economical lifelength of buildings and district heating networks. Aerial and mobile thermography has been proved to be a useful tool to survey the conditions of buildings and district heating networks. Thermography has however also been looked upon as a "magic tool", too sophisticated and with too many severe limitations to be used in practice.

In order to find the technical and operational advantages and limitations of thermography to detect and quantify energy losses and damages from buildings and district heating networks, apparent temperature and surface radiation patterns in thermographic

data from several night and daytime registrations have been analyzed. The registrations were carried out during the period of 1978 - 1987, with an infrared line scanner (Daedalus DS 1210, 8 - 14 μm), mounted in a fixedwing aircraft, and with Thermovision cameras (AGEMA Thermovision 780, 8 - 14 μm), mounted in a helicopter and a minibus.

One study, performed 1978 - 1985, comprehends a detailed field investigation of roof structure and insulation condition of 60 buildings. The other study, performed in 1986 to 1987, comprehends detailed analysis and field investigation of 395 km district heating network.

Airborne and mobile infrared registrations were performed during strictly defined weather conditions. In order to find the best composition of weather conditions for thermographic registration, repeated mobile registrations and field measurements were performed during a six months period, from November 1986 to June 1987.

Conditions of thermography

Thermography for building and district heating networks applications can be performed at different levels of ambitions, with different demands of conditions. We here deal with three different levels of ambitions corresponding to the following methods:

- The indicating method, which is the simple way to use thermal image to locate and estimate the general condition of an object for quick measures. In this case no absolute measurement of the radiative temperature is needed. Eventually interfering objects of importance are mainly obstacles that prevent the radiative surface temperature, or the surface temperature pattern to be seen by the infrared instrument.
- The analytic method, is a more qualified way to use thermography to locate potential problem areas, to quantify the condition of buildings or district heating networks. The thermal information is used to give priorities within a regular control and maintenance program. For this purpose the radiative temperature measured is used as an indirect measure of the condition of the object.
- The research method, is the most ambitious way of using thermography. Thermal information is here used within a physical, mathematical model, quantifying heat losses and damage extent of the object. The results from this kind of approach can give valuable knowledge to improve the construction of the building or the heat culvert, or to improve the knowledge about the interaction between instrumental, weather or object oriented conditions influencing the thermal information. However, this require relevant data of different weather parameters of the environment close to the object and methods to compensate for different sources of disturbances, influencing the thermal image.

The optimal conditions for thermography are slightly different for buildings and district heating networks. Experiences from repeated thermographic registrations, field and weather observations give some general guide-lines:

- Thermography should be carried out with an infrared system adequate for the application, and during stable weather conditions.
- The infrared instrument should give a stable signal throughout the whole registration.
- Thermographic registrations can be performed during cloudy days and nights with equalized temperature conditions, and during nights with clear sky.
- Ground temperature should be over 3°C (37°F), to avoid frosty surfaces when registration during nights with clear sky.
- Wind speed should not exceed 3 m/s at ground level.
- Surfaces should be free from rain, snow and dampness.
- Relative humidity should be low, especially when recording during a clear night.
- Thermography for building applications is preferably performed at an air temperature of $0^{\circ} - 5^{\circ}\text{C}$ ($32^{\circ} - 23^{\circ}\text{F}$)
- Thermography for district heating network applications could be performed even at high air temperature, for instance during late spring or early summer, up to a temperature of $10 - 15^{\circ}\text{C}$ ($50 - 59^{\circ}\text{F}$).
- Variations in emissivity greatly influence the thermal image.
- Different wear of surface materials, even of the same kind, influence the emissivity factors.
- Oblique view angles and damp wet surfaces influence the thermal image and give false information about the condition of the culvert. This should be considered especially for groundbased mobile thermography.

Information contents of thermograms

Thermographic systems measures the local apparent surface temperature of every single picture element of the surface imaged. The apparant surface temperature is a function of the temperature from the object studied, and the temperature of reflected objects and clouds or clear sky. Knowing the emissivity of the surface studied and the sky temperature the apparant surface temperature can be converted into "real", or close to real surface temperature. The thermogram also gives a surface temperature pattern, which gives information of the damage extension of the roof insulation or culvert leakage.

Analysis and interpretation routines

The analysis and interpretation of the thermal data has been done visually, and by using an interactive image processing system.

- **Visual interpretation** was carried out to get a quick-look information, and an overview of the apparent surface temperature of the examined object. This could be done on a hard copy or presented as a thermal image on a monitor. Visual interpretation was mainly used for the indicating method.
- Using an **interactive image analysis processing system** made it possible to correct apparent temperature into "real" surface temperature. Interpretation of thermograms were made for roof surfaces, on the ground above district heating pipes, and on reference surfaces with surface materials similar to those of the object studied. Corrected temperature measurements were made for each picture element in the thermogram, across and parallel to the surface above district heating pipes and across the surface of roofs. This to create temperature profiles in order to assess the radiation pattern of the surfaces and to estimate temperature values within the surfaces for statistic analysis. Interpretation using an interactive image analysis system was mainly used within the analysis method.

Building applications

The building study included apartment buildings, industrial, commercial and office buildings, and single family houses. Thermography for building applications were found to give a correlation of about 90 % when tested against ground level information. Following examples illustrates the information contents of thermograms for building applications:

The first case concerns a 3-storey industrial building, the Marabou chocolate factory, at Upplands Väsby, 25 km north of Stockholm. The building is built in two sections, during the period of 1970 - 1975. The roof area is 154 m x 142 m (462 ft x 426 ft). The roof construction and the insulation design is different for the two sections. Section 1 is used for storage of the chocolate products and has the better insulation (K-value $0.33 \text{ Wm}^{-2} \text{ }^{\circ}\text{C}$), with a steady low temperature of 15°C (59°F). Section 2 (K-value $0.58 \text{ Wm}^{-2} \text{ }^{\circ}\text{C}$) is mainly used for production, and packing of products, and here the temperature vary for different activity areas, from $15^{\circ} - 27^{\circ}\text{C}$ ($59^{\circ} - 81^{\circ}\text{F}$). On top of the building are two parallel, 9.5 m (29 ft) wide and 5 m (15 ft) high sections for supporting activities such as airconditioning, refrigerating equipments and heat and water recovery plants. Within the production and packing areas a number of machinery emitting heat are placed.

In the thermogram, figure 1, a surface temperature pattern dividing the building in two parts can be distinguished. The northern half of the roof has a brighter grey tone due to higher radiative surface temperature originating from the heat losses within the production areas of the building. The southern half has a darker grey tone, due to a lower radiative temperature for the roof over the storage areas. The surface temperature pattern also indicates

that there are several sub patterns with different temperature, and "glowing" white spots on the roof. On site investigation of the building including measurements of indoor air temperature, and actual surface temperatures of the roof surface confirms that the indication of the thermogram is correct. Differences in building construction, insulation performance and different energy related activities within the building give rise to the temperature pattern of the roof surface, indicated in the thermogram. The glowing white spots are due to heat from vents. Using pseudo colour printout, figure 2, it is easy to separate the surface temperature pattern indicated in figure 1.

The second case gives information about the insulation conditions of a two storey office building before and after retrofitting the attic floor insulation. In figure 3 the thermogram indicates varying temperature and insulation defects in the roof construction. The attic floor insulation consists of pre-cast concrete panels. Before retrofitting, the building was in bad condition. There were deficiencies in the construction of the joints of the concrete panels and between the walls and the attic floor insulation. The construction of the ventilation systems was defective and energy leaked out into the attic. The southern half of the attic floor had no insulation, while the northern had 20 mm mineral wool, partly defective. The attic floor insulation was retrofitted by adding 170 mm mineral wool on the top of the old insulation. The old insulation cover were replaced with a new roof paper, and a modern ventilation system replaced the old one. The walls were retrofitted by adding an extra 120 mm mineral wool plate to the original walls consisting of 150 mm lightweight concrete panels. The thermogram, figure 4, indicates that the retrofitting has been successful. The irregular temperature pattern shown in figure 3 has disappeared. However, there are still a few areas indicated as high temperature areas. Three of those are due to heat losses from a sauna and from the ventilation system. The higher temperature radiation indicated along the roof (figure 4) is due to bad insulation in the connection between the attic floor insulation and the walls. Comparisons were made of radiative temperature of roof surfaces of the actual building and of reference buildings, before and after retrofitting. The effect of the retrofitting was found to correspond to an average improvement of the insulation conditions of 3°C (5.4°F) of the retrofitted roof.

District heating network applications

The district heating network studies covers two investigation areas, including 395 km (220 miles), the entire network of the city of Västerås, 100 km west of Stockholm, and 20 km (36 miles) primary heating culvert at the municipal of Upplands Väsby, 25 km north of Stockholm. Like in the building study thermography proved to have good accuracy in indicating the condition of the networks. The information contents of thermogram for district heating network applications are illustrated by the following case:

The aerial thermogram in figure 5 illustrates the combination of good overview and detailed information in the same thermal image. Figure 5 indicates damages along the culvert, where some sections

have quite a high radiative surface temperature. Field investigations, including digging up and investigating the condition of the culvert, gives at hand that high radiative surface temperatures are due to severe damage of pipe, leakage, or wet insulation. While low radiative surface temperature corresponds to nonproblem culvert. Measuring the radiative temperature for each pixel across or along the culvert and for reference surfaces (figure 6 and 7) makes it possible to create temperature profiles in order to localize the position of damages and to classify damages for priority purpose. This is extremely useful when having a large network, using thermography within an regular control and maintenance program. Such an methodologic approach gives quantitative data which can be used for relative comparisons for sub parts or entire district heating networks. The damage classification results can then be presented on culvert maps.

In figure 8 the final results of the district heating network study of the city of Västerås is presented. The thermograms indicated 256 sites with abnormal or increased radiative surface temperature above culvert. 207 of those objects were shown by inspection of the site to process an abnormally high temperature. By May 1987, 47 of those 207 culvert sites had been dug up. 36 of those were classified as leaking pipes and 11 were found to have wet insulation. The average damage indication density was found to be one site for every 1.9 km (1.2 miles) of culvert for the 395 km (220 miles) network studied.

Operational advantages and limitations of thermography for building and district heating networks applications

The results from the studies presented confirms that thermography performed during stable weather conditions, with low wind speed gives good accuracy and stability in assessing damages and heat losses of buildings and district heating networks. However, there still remains to validate the operational advantages and limitations of thermography in general, particular operated during different weather conditions, and with different infrared systems.

Concerning the level of ambition one can limit the approach to those of the indicating, analysis and the research method, mentioned above. Here we just deal with the indicating and analysis method. Factors influencing the thermal image can be divided into three groups; instrumental factors, weather oriented, and those specific of the object and its close surroundings.

Instrument related factors

Using thermography according to the indicating method, investigating smaller areas, single blocks of buildings or limited parts of a district heating network, one can use a Thermovision camera, or a FLIR-system (8 - 14 μm), mounted in a helicopter or a specially equipped bus. Surveying larger areas, investigating the condition of roofs or heat culvert for an entire city area, an aircraft with an infrared line scanner is preferable from both operational and economic point of view. This system is especially

suited for the analysis method. Provided the line-scanner detector is equipped with blackbody references, it is possible to quantify the thermal information.

An advantages of **airborne infrared line-scanner systems**, besides that it gives thermograms with high information potential, is that collected data is easy to convert into digital data for analysis in an interactive computerbased image analysis system. Line-scanner registration makes it possible to cover a large investigation area in a short time during "constant" physical conditions. This could be useful when classifying thermal data for identifications of roofs or sites to be repaired, and for comparisons of data from different registration occasion within a long run control and maintenance program. The greatest limitations with this system is the cost of data collection.

Helicopterborne thermography should not be used for "strip-registration", but be operated within the indicator method, surveying well known objects, restricted to smaller investigation areas. The advantages of the helicopter system is good accessability, extremely good manoeuvrability, low wind sensitivity, and possibility to quick changes in altitude and to stand still focusing an object. The most important limitations with the combination helicopter and Thermovision is too small a field of view of the infrared instrument, gathering a large amount of data, difficulties to orient onself in the data material, hard to operate when recording a more complicated investigation area.

Groundbased mobile thermography is mainly to be used for district heating networks applications. The system is easy to operate, and gives quick detailed information about damages and weaknesses of the culvert. Interpretation can be done at the spot, marking out the area of a damaged culvert directly on ground. Data are stored on a magnetic tape and a more thorough analysis can be made later and presented as quantified and classified data for identification of sites to be repaired. Groundbased mobile thermography is not be used for survey of larger investigation areas, because it is time consuming and there are restrictions related to the effective working time of the operator. Limitations are mainly obstacles on the driving way, such as fenced areas, traffic problems, parked cars, blocked roads and pathways. Groundbased mobile thermography is a cost efficient method, it is less weather dependent and has a greater potential registration season than for example the airborne infrared systems. Using groundbased mobile thermography for building applications is an interesting approach which should be the subject of further research.

Weather oriented factors

The temperature difference between the ground surface and the surrounding air temperature is influenced by many factors. The heat transfer coefficient decreases when wind speed increase, which gives lower temperature differences between the air and the ground. The heat transfer coefficient also decreases at low sky temperatures, which also gives lower temperature differences between the air and the ground. Finally, a decrease in the heat transfer coefficient leads to decreasing differences in radiative surface temperature from roofs and from heat culvert, as the

resistans decreases. Other factors as frost, and dampness also influence the surface temperature, and the information content of the thermogram.

Object related factors

The most important factor related to the object is that of emissivity. An error analysis of the emissivity factors indicates that a change in the emissivity factor of 0.01 affects the apparent surface temperature measured in thermograms by 0.2°C when sky temperature, $T_s = -25^\circ\text{C}$, and 0.4°C when $T_s = -50^\circ\text{C}$. The roughness of the surface, dampness and the instrument view angle greatly influence the information content of the thermogram due to variations in the emissivity factors. One conclusion drawn from this is that thermal registrations should be performed during "dry" weather conditions with the instrument pointing at almost vertical angle. The analysis and interpretation should be restricted to surfaces with same or similar surface material and emissivity.

Other important factors related to the object are the technical construction of the object; type of ventilation, changes in functions, and background radiation. Those factors are specially important when using airborne thermography for building applications. Analysing the roof condition, indicated in a thermogram can sometimes be rather difficult, not being able to see the geometric construction from the right angle or missing important information of reflected radiation from objects in the surrounding. This however can be solved by using the information from an actual aerial photography of the investigation area.

Thermographic methods in regular control and maintenance programs - the organization aspect

Lack of reliable control and investigation methods makes it hard for planners and decisionmakers to gain proper knowledge of the condition of the building stock and the district heating network. However, it doesn't matter how well proved a method is, if not fitting in to the regular control and maintenance organisation it is normally shut out. Thermographic methods are no exceptions in this aspect. The first reaction of the planner and decisionmaker, getting aware of the information potential of thermography, is positive surprise, and a wish to try the appealing methods. However, if the thermal information is delivered or presented as a lump of qualitative data, photographic or recorded on a tape, it is often useless for the client. This because he usually doesn't know how to handle this kind of information, nor how to analyse or interpret the thermal image. Even delivering quantitative and classified data can meet the same end, namely not fit in to the established organization. There is no easy way to get out of this, but it can be done, and it should be the responsibility of those offering thermal products to investigate the organization in which the method should be implemented, and suggest a solution. Experiences from those two studies presented gives at hand that all large scale operations with thermography should result in a data output, developing a database fitting in to the regular organisation. This database should have an identification code should be connected to a key-object, where the thermal

information is one dimension of information, together with for example technical data of the object, information of energy consumption, diversity of functions etc. The thermal data can then also be put into coordinates and presented on energy-related maps. Such an construction makes it possible to fit thermal methods in to any organization. Besides the organization of information there is also the problems implementing new methods into the field control organisation of for example a district heating plant. This problem is often due to inflexibility of the established organization in terms of too busy to change methods, general scepticism against introducing new methods, or problems with the staff. Those kind of organization problems are often only to be solved in the long run.

Conclusions

The main advantages of thermography for building and district heating applications are that it demonstrates high accuracy in detecting damages and heat losses from roofs and heating culverts. Repeated thermography during similar weather conditions demonstrates high stability of the methods. The best operational conditions are slightly different for different infrared systems. An airborne line-scanner is the most weather dependent system, used mainly for large scale registrations. Helicopterborne Thermovision is preferable used to detect energy related conditions of well known objects for a limited area. Its movability and ability to stand still focusing an object, makes it superior to most other systems in this case. The groundbased mobile thermography is so far mainly used for district heating network applications. It is less weather dependent then other systems, easy to operate, cost effective and interpretation can be made on the spot, marking out area of damage culvert directly on the ground.

To carry out a successful investigation for building and district heating applications, thermography should be performed during stable weather conditions, with low wind speed. In order to aquire thermal information for quantifying the conditions of an object, it is necessary to have blackbody references within the infrared instrument. Analysis and interpretation is preferably carried out with a computerbased image analysis system, to correct for variations of emissivities, to measure temperature profiles in thermograms and to convert apparent temperature into "real " temperature. The final product of thermal information should be presented in such a way that it easily fits into the established information organization of the client.

Taken into consideration the information potential of thermography, the operational advantages and limitations of different systems, and development of still better methods, we are convinced that thermography is a cost efficient way to aquire adequate information about energy related conditions of buildings and district heating networks.

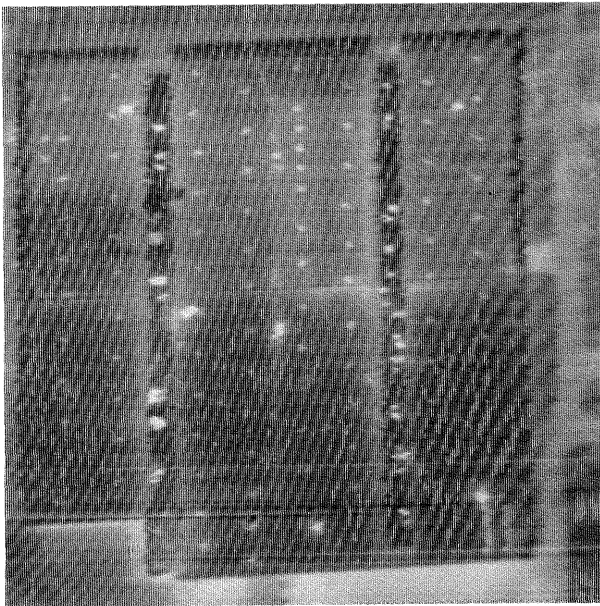


Figure 1. Aerial thermogram showing surface temperature pattern of the roof of an industrial building.

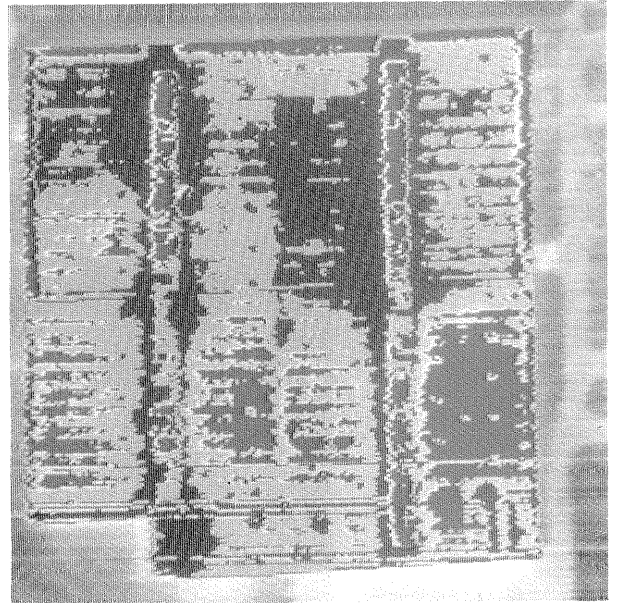


Figure 2. Colour-coded aerial thermogram separating areas with different surface temperature.

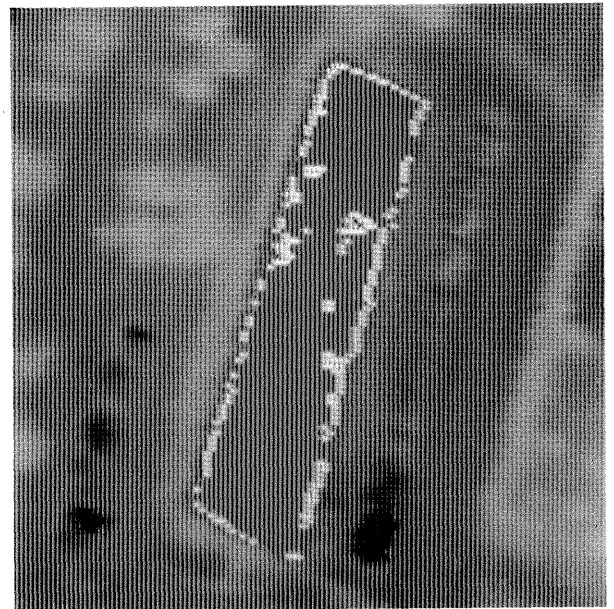
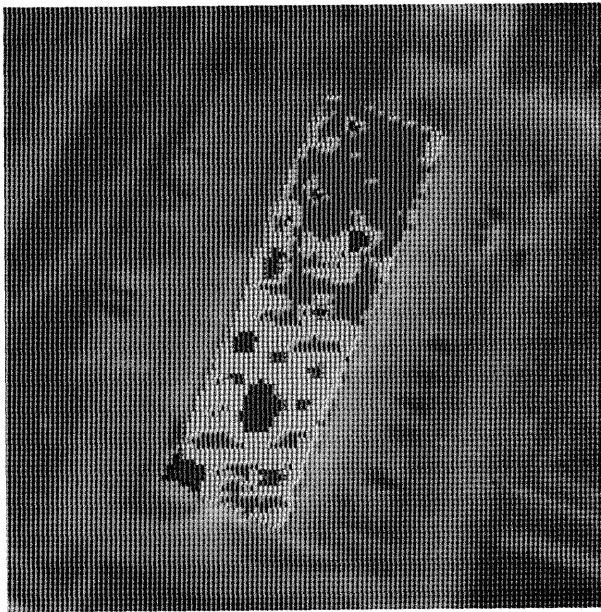


Figure 3 and 4. Thermogram showing surface temperature of the roof of an office building, before and after retrofitting the attic floor insulation.

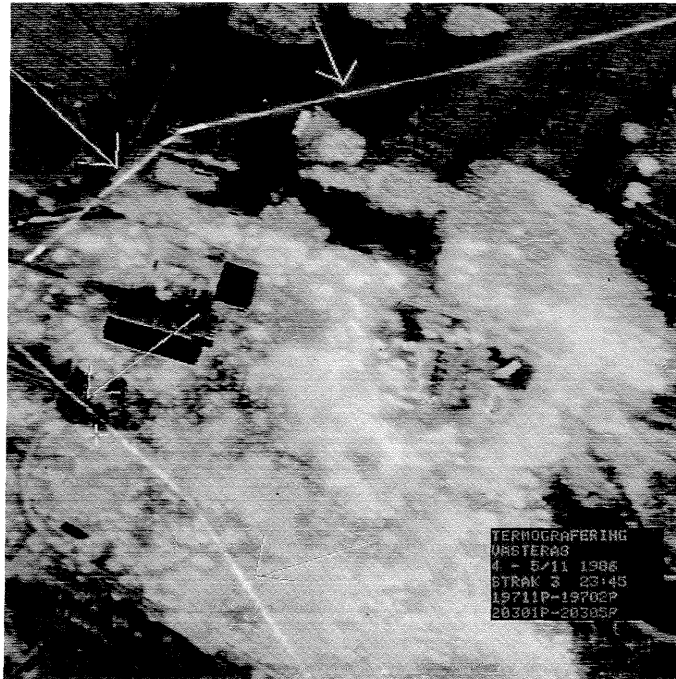


Figure 5. Aerial thermogram gives both a good overview and detailed information of the culvert condition in the same image. Intensive bright grey tone = high excess surface temperature indicates damage of culvert, dark grey tone nonproblem culvert. Registration performed 1986-11-04/05. Flight altitude 600 m (1800 ft).

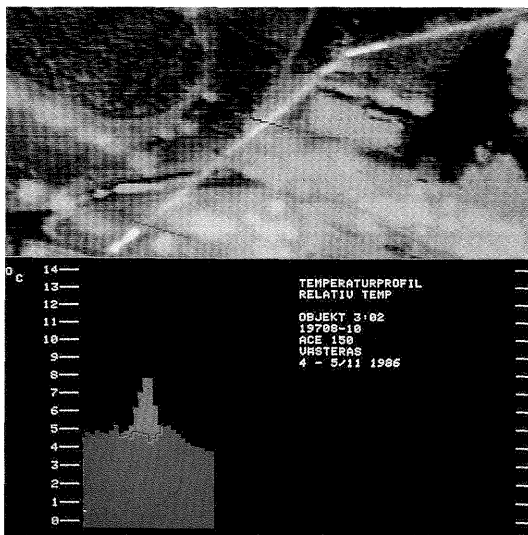


Figure 6. Thermogram = part of fig 5. Measuring excess temperature across culvert relatively a reference surface.

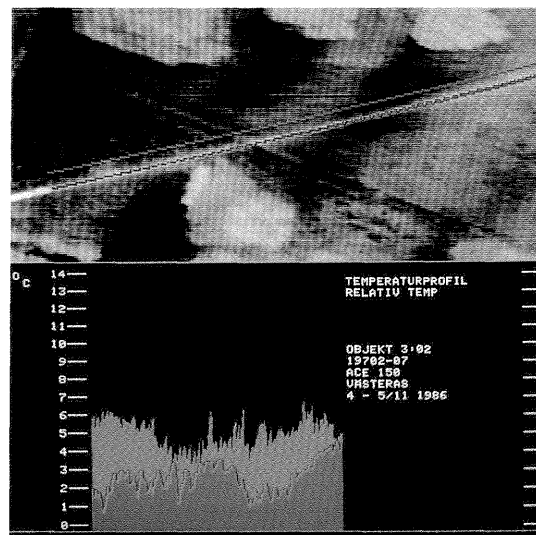


Figure 7. Thermogram = part of fig 5, illustrating how to use temperatureprofiles to excess temperature along a surface above culvert relative a reference surface.

	Number of object	km/indication
Damages repaired		
- Culvert damage	36	10.9/object
- Wet insulation	11	35.9/object
Abnormal heat loss	160	2.5/object
Misinterpretation	6	2.3%
Open cave	10	3.9%
Culvert without damage	33	12.9%
Total object indicated	256	100%
With damage	207	80,9%
Total network which could be reached with aerial thermography	-	395 km
Average damage indication for the entire network 1.9 km/1 object		

Figure 8. Table showing total number of culverts with damages confirmed (culvert leakages, and wet insulation), indicated in thermograms, for the district heating networks of Västerås, including 395 km (220 miles) culvert within reach of aerial thermography.

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