

# INFRARED THERMOGRAPHY FOR DETECTING DEFECTS IN CONCRETE STRUCTURES

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# Infrared Thermography for Detecting Defects In Concrete Structures

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## Foreword

**Condition monitoring of cooling waterways is important to keep track of cracks and risk of rebar corrosion. There are several methods for condition monitoring, mostly involving non-automated and time-consuming methods like impact testing and visual inspection.**

The feasibility of using IR thermography as a global non-destructive condition monitoring method was investigated in this project. The basic idea was that immediately after emptying the cooling water channel, damaged areas of the cooling water way walls would change temperature in a different manner compared to undamaged. The analysis however showed that the temperature differences are most probably too small to facilitate using IR thermography as a successful method for the cooling waterway application. Senior RISE researchers Dimitrios Boubitsas, Lars Olsson and Fredrik Ståhl carried out the analysis.

This project was carried out in the Energiforsk Nuclear Concrete Research Program, with stakeholders Vattenfall, Uniper/Sydkraft Nuclear, Fortum, Teollisuuden Voima Oy (TVO), Skellefteå Kraft, Karlstads Energi and the Swedish Radiation Safety Authority (SSM).

These are the results and conclusions of a project, which is part of a research programme run by Energiforsk. The author/authors are responsible for the content.

## Sammanfattning

**Följande arbete är en förstudie vars syfte är att bedöma möjligheten till att använd IR-teknik för att detektera sprickbildning i de kylvattenvägar av betong som återfinns i kärnkraftverk.**

För att kunna inspekteras töms dessa kylvattenvägar på vatten och man söker nya snabba metoder för att hitta defekter i konstruktionen och därmed minska tiden verket är satt ur drift.

Det här arbetet är främst koncentrerat på IR-teknikens möjligheter och består av en mindre litteraturstudie av användning av termografi för att hitta skador i betongkonstruktioner. Arbetet redovisar också ett urval av kommersiell utrustning för termografering och pekar på egenskaper hos dessa produkter som är viktiga i samband med termografering i en tunnel. Arbetet avslutas med en numerisk simulering av temperaturfördelningen på ytan av en betongvägg med olika typer av sprickor i samband med att tunneln töms på vatten.

Slutsatsen av simuleringarna är att under extrema förhållanden går det att påvisa en temperaturskillnad mellan betongytor med och utan sprickor som teoretiskt bör kunna detekteras av en avancerad värmekamera. Under mer realistiska förhållanden blir den här temperaturvariationen förmodligen mindre och mer svår-detekterad. Även med extrema ingångsvärden avklingar dessutom temperaturvariationer på några få timmar vilket ytterligare försvårar detektering av sprickbildning i dessa tunnlar.

## Summary

**The following work is a feasibility study whose purpose is to assess the possibility of using IR technology to detect crack formation in the concrete tunnel for cooling water found in nuclear power plants.**

In order to be inspected, these concrete tunnels are emptied of water and new fast methods are sought to find defects in the structure and thereby reduce the time the plant is put out of operation.

This work is mainly concentrated on the possibilities of IR technology and consists of a literature study of the use of thermography to find defects in concrete structures. The work also presents a selection of commercial equipment for thermography and points to properties of these products that are important in connection with thermography in a concrete tunnel. The final part of the work is a numerical simulation of the temperature distribution on the surface of a concrete wall with different types of cracks and this in connection with the tunnel being emptied of water.

The conclusion of the simulations is that under extreme conditions it is possible to demonstrate a temperature difference between concrete surfaces with and without cracks that should, theoretically, be detectable by an advanced thermal camera. Under more realistic conditions, this temperature variation probably becomes smaller and more difficult to detect. Even with extreme input values, temperature variations also subside in a few hours, which further complicates the detection of crack formation in these tunnels.

## List of content

<b>1</b>	<b>Introduction</b>	<b>7</b>
<b>2</b>	<b>Background</b>	<b>8</b>
<b>3</b>	<b>Literature study</b>	<b>9</b>
	3.1 Applications	9
	3.2 Laboratory investigations	10
	3.3 Real concrete structures	11
<b>4</b>	<b>Equipment for infrared thermography</b>	<b>15</b>
<b>5</b>	<b>Numerical analysis of the surface temperature in the proximity of deep cracks in a concrete wall</b>	<b>16</b>
	5.1 Calculation conditions	18
	5.2 Results	19
	5.3 Comments	21
	5.3.1 Air-filled crack in concrete wall	21
	5.3.2 Water-filled crack in concrete wall	21
	5.3.3 Air-filled delamination in concrete wall	21
	5.4 Further comments	21
<b>6</b>	<b>Concluding remarks</b>	<b>23</b>
<b>7</b>	<b>Refereces</b>	<b>24</b>



# 1 Introduction

The following work is a feasibility study whose purpose is to assess the possibility of using infrared technology to detect cracking in the concrete tunnels for cooling water found in nuclear power plants. In order to be inspected, these tunnels are emptied of water and new fast methods are being sought to inspect the construction to reduce the time the plant is put out of operation. This work is mainly concentrated on the possibilities of infrared thermography.

Infrared thermography (IRT) is based on the measurement of invisible infrared radiation emitted by bodies converted into temperature and displayed as thermal images (thermographs) [1]. Because IRT is a timesaving non-destructive test (NDT) method it has gained a lot of popularity in recent years and has a wide application area [1][2][3]. Furthermore, the equipment is often small and practical to use. However, the technique is somewhat new to civil engineering as an NDT method for detecting damage or defects in concrete structures [3].

## 2 Background

IRT is a technology to detect thermal radiation emitted from materials. It creates an image of surface temperatures based on the emitted radiation. Thermal IR radiant energy is emitted from all objects that have a temperature greater than absolute zero. The rate at which this energy is emitted is a function of the temperature of the material and its emissivity. A material's emissivity is the ability of its surface to emit energy by radiation relative to a black body and has a value between 0 and 1. This value is typically greater than 0.9 for concrete.

Steel elements have uniform temperatures because of high conductivity, while temperatures on a concrete element are likely to vary over its surface [1]. The infrared camera senses the exitant thermal energy from the material, converts into temperature and display thermal images. The different colors of the image correspond to the temperature distribution of the targeted surface.

The energy emitted by a surface is as previous mentioned affected by the properties of the material. The changes of the quality of the concrete due to local deficiencies such as poor compaction, seepage of water and deterioration, results in small changes in the surface temperature. In the thermal images it will display as different colours and enable damage assessment of structures.

The quality of thermal image depends on the variation in surface temperatures, the greater the contrast in temperatures, the better will be the images. There are two approaches for thermography inspections, passive and active [2]. The passive approach measures the temperature differences of a structure that occur under normal conditions. While the active approach generates the temperature differences of the structure using an external source. External heat source can be lamps, ovens, and hot packs. The nature of the external heat source can further distinguish active thermography into pulsed thermography and lock-in thermography [2]. Passive thermography is adopted while assessing large structures, while active thermography is general adopted in laboratory investigations.

## 3 Literature study

### 3.1 APPLICATIONS

The nature of IRT enables a broad range of applicability. The main IRT applications are summarized in [2]. In civil engineering IRT is widely employed for quantitative evaluations for building diagnostics, such as the evaluation of the thermal characteristics of the building envelope, the detection of thermal bridging or excessive heat loss areas, air leakages, missing or damaged thermal insulation in the building's elements, sources of moisture, the location of building components, as well as the monitoring for the preservation of historical buildings and monuments [2].

The focus in this report is on the IRT application for detecting defect in concrete structures. In their review Sirca and Adeli [3] pointed out that there is a limited performed research in IRT for detecting defects in concrete structures. In the following some selected references dealing with IRT for concrete defect detection in a laboratory setting will be shortly presented. Further, research on IRT in real concrete structures will be discussed. In this section two works [8][9] have been chosen to be presented more thoroughly to give the reader an insight of IRTs broad range of applicability.

### 3.2 LABORATORY INVESTIGATIONS

Maierhofer et al. [4] studied how material properties (concrete age, pore content, aggregate type, and reinforcement density) affect thermal images for damage (voids) detection of plain and reinforced concrete specimens in the form of slab structures. A thermal heating unit set up with three infrared radiators (each with 2400 W) was used. After the heating process, the radiator was switched off and the cooling down process of the surface was observed with the infrared camera. The results showed that voids could be detected with best resolution soon after concreting. Further, the pore content of the matrix and the porosity of the aggregates showed a clear influence on the thermal properties. The authors conclude that the more porous mixes provide a better chance that defects in the concrete will be detected. The density of reinforcement showed only a slight influence on the detectability of voids.

Aggelis et al. [5] applied IRT and ultrasonic measurements (Rayleigh waves) for the investigation of subsurface cracking initiated by rebar corrosion. The results indicated that the location of the large cracks was easily detected from the IRT characterization of the structure, while more detail of the depth of the crack was given by one-sided ultrasonic measurements. The test in this work was performed at higher than realistic temperatures (specimens were heated in an oven for 3 h at 90° C), thus it was concluded that crack detection can be proven a difficult task in realistic conditions.

Yehia et al. [6] apply IRT and other NDT methods, such as ground penetrating radar (GPR), for detecting defects to lab samples of representative bridge deck slabs. For the IRT testing, the specimens were subjected to solar heating as would be the case in a realistic condition. The authors conclude that IRT is the fastest method for detecting defects in concrete structures such as bridge slabs compared to GPR. They concluded that determining the depth of the defect depends on environmental conditions such as the amount of solar heating and the time it takes for the structure to heat or cool.

### 3.3 REAL CONCRETE STRUCTURES

Most of the reported real concrete structure applications of IRT are about evaluating the condition of concrete bridge decks to detect delamination and cracks or other defects in the concrete [3][7][8]. The reason for this may be that there is a standard (ASTM D4788-03) that describes the procedure and equipment necessary for conducting IRT testing for detecting delamination in bridge decks.

Pla-Rucki and Eberhard [7] evaluate different imaging techniques in their State-of-the-art review for assessment of concrete bridge decks. The authors report that IRT provides large scale condition assessment better than the other methods but is not able to provide much detail on the nature of the defects. And other traditional techniques such as hammer testing or chain dragging are needed to provide confirmation of the nature of the defects.

Omar and Nehdi [8] evaluate the capability and reliability of using passive IRT and ground penetrating radar (GPR) technologies as bridge inspection tools to detect the subsurface defects in reinforced concrete bridge decks. They conduct passive (solar radiation) IRT testing on a deteriorated full-scale concrete bridge deck. A thermal IR camera was mounted on a vehicle at a height of 2.6 m oriented facing straight-down to the concrete deck surface.

The vehicle was driven at low speed over the centre of the bridge deck, and a total of 392 thermal and digital images were collected, which covered the entire bridge deck. The total time of data collection was about two hours. Multiple software tools were used to enhance the captured IRT images and making it possible to differentiate delaminated areas from other surface features (discoloration, oil stains, sand and rust deposits, etc.). The max thermal contrast of the recorded data was  $7.7^{\circ}\text{C}$ . The selected threshold value for the calculated thermal contrasts that could indicate where delamination was likely to be detectable was chosen to  $1^{\circ}\text{C}$ . The pixels with a higher temperature than this threshold value were highlighted because delamination appear with a higher temperature. Figure 1 illustrates the created map from the IRT measurements of the surveyed bridge deck.

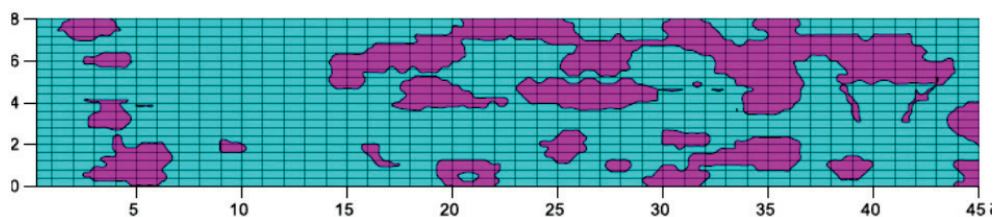
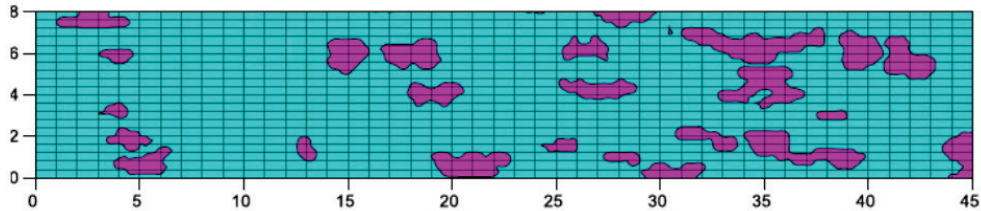


Figure 1. IRT condition map indicating delaminated areas in the surveyed bridge deck [8].

As a comparison Figure 2 illustrates the corresponding GPR condition map indicating location of corrosion in the surveyed bridge deck.



**Figure 2. GPR condition map indicates location of corrosion in the surveyed bridge deck [8].**

As can be seen in Figures 1 and 2, despite the different mechanisms of both techniques and their capabilities of detecting different deterioration types, the condition maps in both figures are comparable. It must be noted that both methods require extensive post-processing analysis of the acquired data to reveal subsurface anomalies.

The authors concluded that IRT testing produces visual delamination images with good location accuracy. However, as a surface temperature method, its detection capability is depth limited and that its effectiveness can be reduced in the presence of overlays. Also, IRT testing requires adequate solar radiation and weather conditions to produce the required temperature differentials.

Sirieix et al. [9] examine a precast concrete culvert (Figure 3) for defect identification using different NDT methods, one of which was passive IRT. The other methods evaluated include electrical resistivity and capacity methods.



**Figure 3. Entrance of the concrete culvert [9].**



The concrete culvert consisted of 55 precast pipe segment each 3 m long, and the total structure is 165 m. The pipe segment shape was ovoid with a height of 1.7 m and a width of 1.8 m and the concrete thickness was about 20 cm. Only the internal surface of the duct could be inspected and showed some damage, such as cracks, which sometimes contained calcite and, in some cases, visible corroded rebars (Figure 4).



**Figure 4. Calcite in cracks and visible corroded rebars [9].**

Based on a visual inspection, the damage pattern of the pipe segments was previous recorded, and the overall dimensions of the cracks had been evaluated for each 3-m-length segment. The cracks were mainly concentrated to the upper part of the culvert. Figure 5 shows the total crack length for each segment. Three segments, between 60 and 69 m had been repaired previous, so these segments were excluded from the investigation.

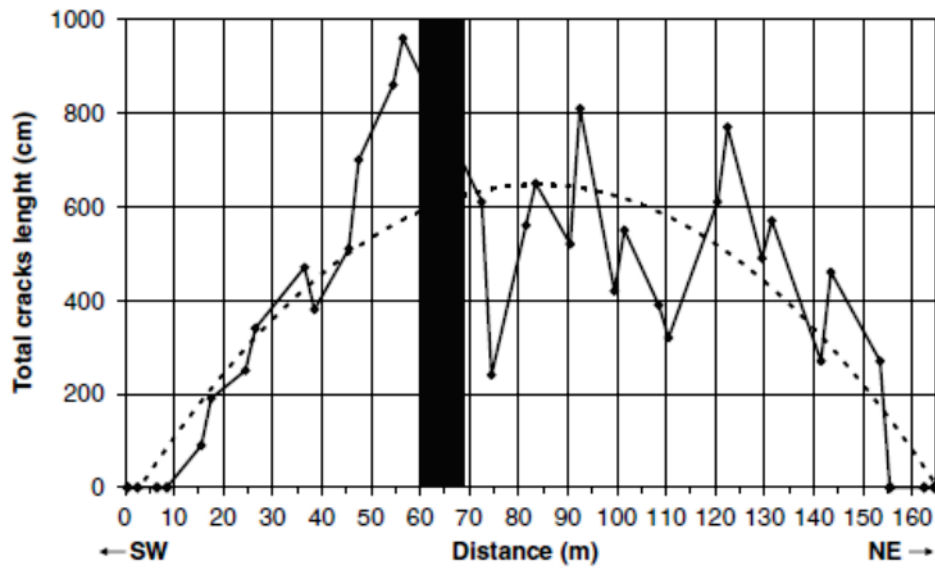


Figure 5. Profile of total cracks length for each segment [9].

Because the investigated structure in this work was a culvert, there is no reflection, no solar radiation nor any artificial source of heat, and the emissivity will be constant and high (more than 0.93). Therefore, in this case it was concluded that, a variation of surface temperature would be dependent on thermal diffusivity or evaporation. The results from the IRT measurement are shown in Figure 6, as the average surface temperature of the keystone (upper part of the culvert) for each pipe segment.

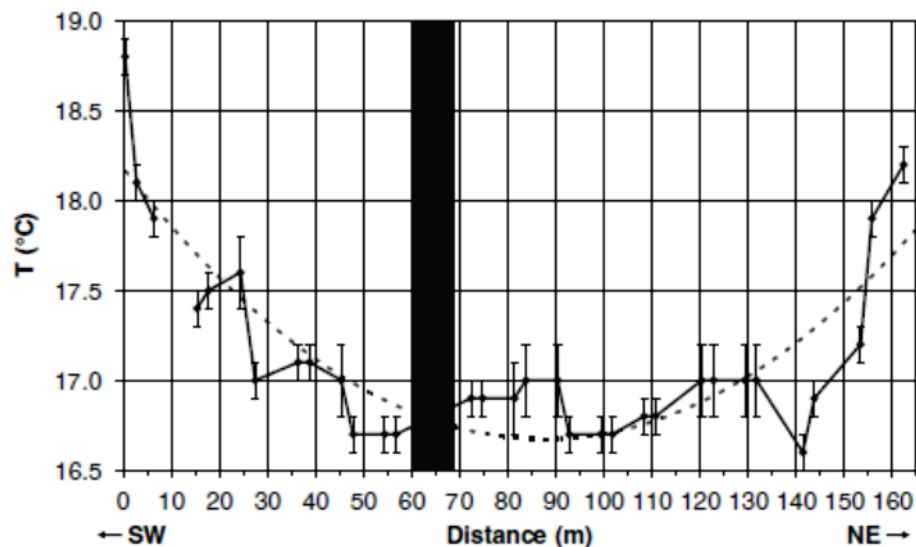


Figure 6. Average surface temperature of the keystone for each pipe segment as measured by IRT [9].

The results in Figures 5 and 6 suggest a correlation between the measured total crack length and the surface temperature of the upper part of the culvert.

The authors [9] conclude that IRT is best suited for preliminary investigation to identify general areas of defects to be followed by other more labor-intensive methods for verifying the locations of the defects and determining the extent of the defects.



## 4 Equipment for infrared thermography

A compilation of some of the available IR equipment on the market is presented in Table 1. Many of the cameras comes with different lens option, hence the different choice in the field of view column. A wide angle, around 45 degrees, is probably best suited for the application in a tunnel. A higher IR resolution gives better image detail. The thermal sensitivity is the smallest temperature difference the thermal imaging camera can detect.

**Table 1. Handheld IR equipment in different price ranges.**

Product	IR resolution	Thermal Sensitivity	Field of view	Cost (excl. VAT)
FLIR T1020	1024x768	<0,02°C	45°, 28°, 12°	370 000 SEK
FLIR E8-XT	320x240	0,05°C	45° x 34°	25 000 SEK
FLIR T840	464x348	<0,04°C	42°x32°, 24°x18°, 14°x10°	165 000 SEK
Testo 890-2	640 x 480	<0.04°C	42° x 32°, 15° x 9°	127 000 SEK
Sonel KT-670	640x480	<0.03°C	11°, 45°	251 000 SEK
Sonel KT-650	640x480	<0.04°C	11°, 45°	197 000 SEK

The tunnel for the cooling water is approximately 5 meters wide and 7 meters in height. The greatest possible distance to the object, in this case the tunnel wall, is assumed to be 5 meters. Being as far as possible from the object means a greater part is covered with each thermal image but the level of detail is low. A shorter distance from the object means greater detailed images but it covers a smaller part of the object and it will be more time consuming to cover the whole object with images, see Table 2.

**Table 2. Possible resolution of handheld IR equipment in concrete tunnel.**

Field of view	Distance to object (m)	Projected length (m)	Resolution	Projected length for each pixel (mm)
45°	1	0.83	1024	0.8
45°	5	4.14	1024	4.0
12°	1	0.25	1024	0.24
12°	5	1.26	1024	1.2
42°	1	0.77	464	1.66
32°	1	0.57	348	1.65

At maximum distance to the tunnel wall, each picture covering approximately 4 m of the tunnel wall. Each pixel of the thermal image gives the average temperature of 4x4 mm of the concrete wall. At close distance (1 m from the wall) each pixel is covering 1x1 mm.

## 5 Numerical analysis of the surface temperature in the proximity of deep cracks in a concrete wall

The purpose of the analysis is to estimate the surface temperature at the wall of a concrete tunnel immediately after the tunnel is emptied of water. The surface temperature at the concrete wall with or without cracks is compared. If the temperature difference between damage and non-damage concrete is large enough, it is assumed that it will be possible to detect these cracks using IR technology.

A numerical analysis of the surface temperature of the wall in a concrete tunnel has been performed. The purpose of the analysis is to estimate the temperature difference at the surface of a concrete wall with or without cracks.

Two different types of cracks in the concrete wall are analysed:

- A crack (width 0.5 mm and depth 45 mm) perpendicular to the wall, see Figure 7.
- Delamination (500 mm wide and 45 mm thick delamination with a crack width of 0.5 mm) of wall, see Figure 9

A 2-dimensional cross section of the wall is analysed. The wall with its crack or delamination are assumed to be infinitely long or high.

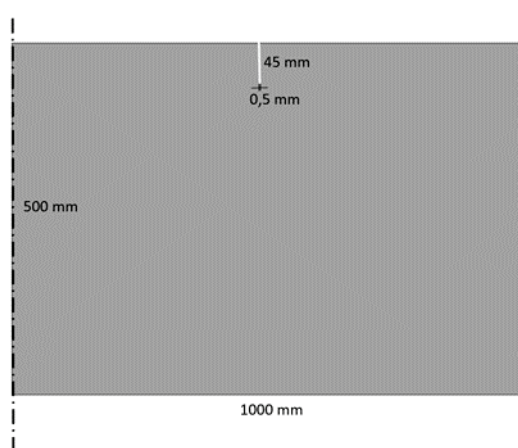


Figure 7. A crack in a concrete wall. Simulated section (not to scale).

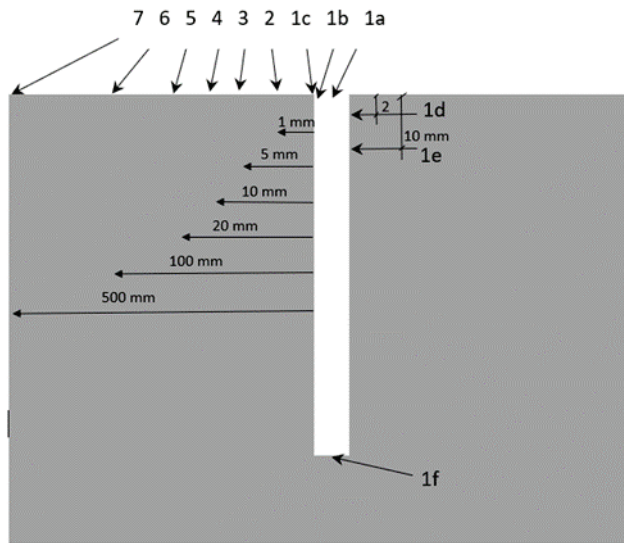


Figure 8. A crack in a concrete wall. Position of calculation points in relation to the crack (not to scale). Calculation points 1a and 1b are either in the air or at the water surface. The other points are on the concrete surface.

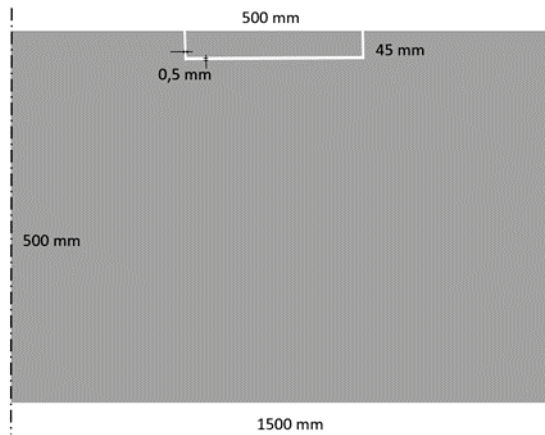
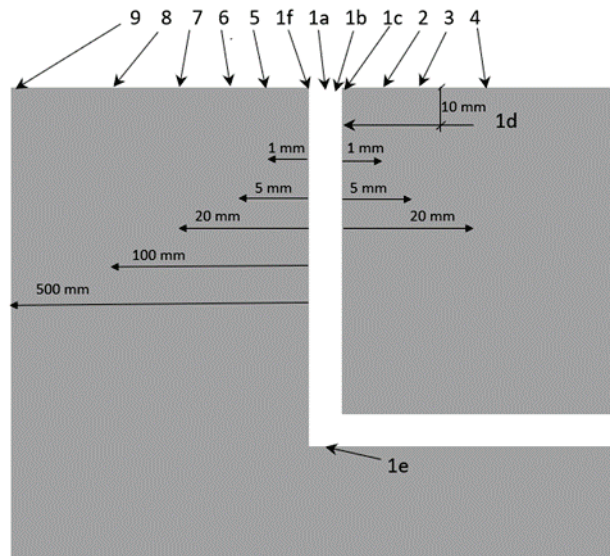


Figure 9. Delamination in concrete wall. simulated section (not to scale).



**Figure 10. Delamination in concrete wall. Location of calculation points in relation to the crack / delamination (not scaled sketch). Calculation points 1a and 1b are situated in air. The other points are situated on the concrete surface.**

## 5.1 CALCULATION CONDITIONS

The humidity and temperature simulations have been performed using WUFI 2D 4.3, a 2-dimensional heat and moisture simulation program. The result is reported for specified points, see Figure 8 and Figure 10. The simulation starts when the water (assumed temperature 35°C) in the concrete tunnel is replaced by outdoor air. The concrete tunnel is assumed to be ready for inspection immediately after the water has been removed.

Probably, a thin film of water remains on the concrete surface after the tunnel is emptied of water, but this film is assumed to evaporate instantly and has been excluded from the simulation. It has been assumed that cracks and delamination is filled with air at the start of the simulation, see material data for air gaps in Table 3.

As a comparison, an additional simulation (case 3) is performed when the crack perpendicular to the wall is filled with water at the start of the simulation, see material data in Table 3.

A fourth case with residual water in the delamination crack has not been considered. The thermal conductivity of concrete and concrete with a waterfilled delamination will be very similar and almost no temperature difference at the surface is expected.

One of the tunnel walls is assumed to adjoin a room with an indoor climate of about 30°C, the other concrete surfaces adjoin rocks and other solid parts, so the temperature is assumed to be relatively stable during the short period of time covered by this simulation. A constant temperature of 10 degrees and 75% RH has been assumed for the air temperature in the tunnel (based on the outdoor air temperature) and in adjacent rooms of 30°C and 45% RH. A heat transfer coefficient of 17 W/m<sup>2</sup>·K has been assumed on the surfaces in the tunnel. Since the

tunnel adjoins surfaces with basically the same surface temperature, the radiation exchange to opposite surfaces has been excluded from the calculation.

At the start of the calculation, the temperature in the concrete was set at 35°C and the concrete is assumed to be water-saturated and other material properties according to material data in Table 3. The calculation time was set to 24 hours with a numerical time step of 10 minutes.

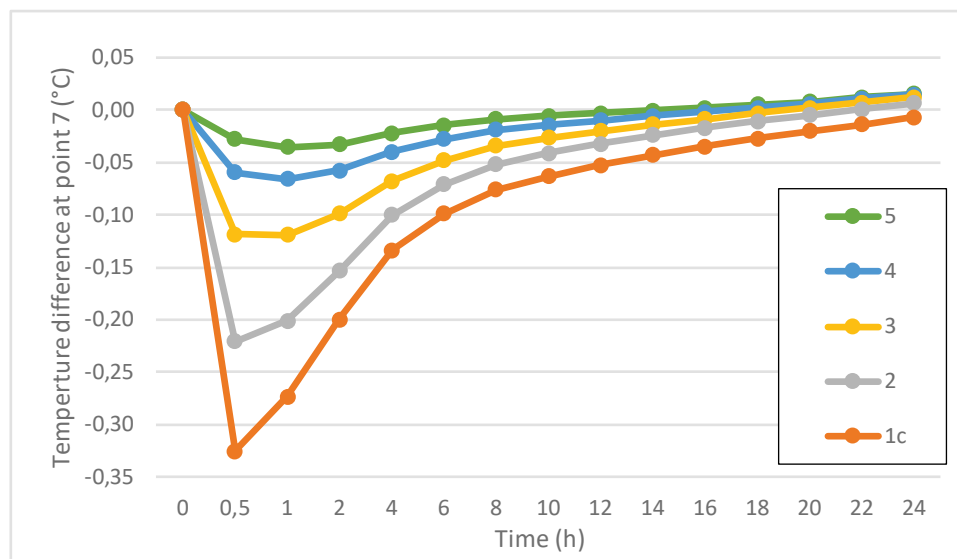
**Table 3. Material data.**

Material	$\mu$ -value [-]	Specific heat capacity [J/kg·K]	Density [kg/m <sup>3</sup> ]	Thermal conductivity [W/m·K]	In built moisture (kg/m <sup>3</sup> )
Concrete, vct=0.5	179	850	2308	1.7	160
Air gap (5 mm)	0.79	1000	1,3	0.047	0,017
Approximated water-filled gap*	0.79	4180	40	0.6	998

\* The water-filled gap is approximated during the calculations using a water-saturated mineral wool with changed characteristics.

## 5.2 RESULTS

The surface temperature of the concrete tunnel is decreasing after the tunnel has been emptied of water. The surface temperature close to a crack is decreasing faster compare to the surface temperature further away from the crack. Figure 11 shows the surface temperature difference between a point 0.5 m from the air-gap (point 7 in Figure 8) and several points (point 1c, 2, 3, 4 and 5) closer to a crack filled with air. The change of temperature difference is shown during the first 24 hours after the tunnel has been emptied of water. The surface temperature at point 7 is used as a reference and the surface temperature at this point is assumed to be unaffected by the air-filled crack. The greatest simulated temperature difference occurs between point 7 and point 1c (at the edge of the crack, see Figure 8) at the beginning (0.5h) of the process.



**Figure 11. Temperature difference at point 7, for the case with a crack filled with air.**

In a similar way, Figure 12 shows the surface temperature difference between a point 0.5 m from the air-gap (point 7 in Figure 8) and several points (point 1a, 1c, 2, 3, 4 and 5) closer to a crack that, in this case, is filled with water.

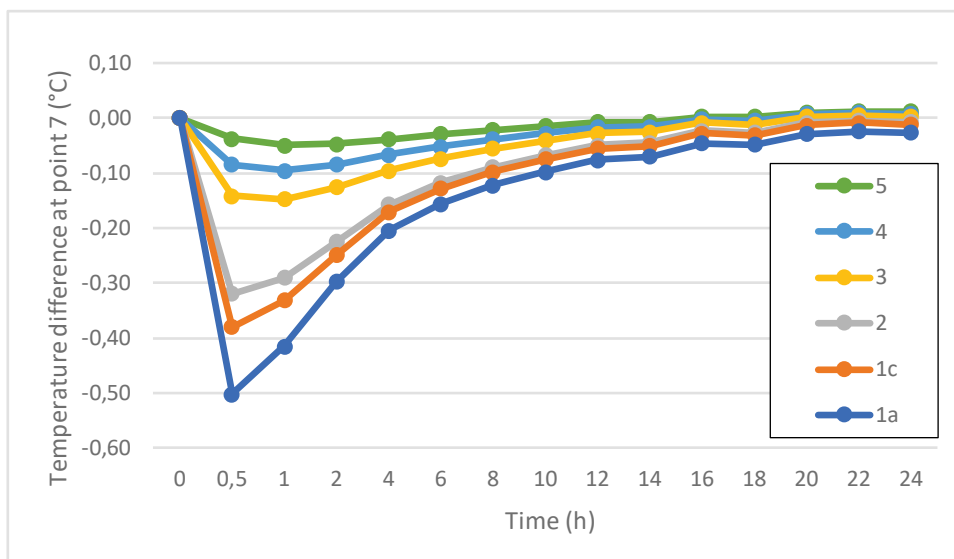


Figure 12. Temperature difference at calculation point 7, for a water-filled crack.

Figure 13 shows the surface temperature difference between a point far away from a delamination crack (point 9 in Figure 10) and several points (point 1c, 2, 3 and 4, see Figure 10) closer to the air-filled delamination crack. In this case, the surface temperature difference is greatest around 2 hours after the tunnel has been emptied of water.

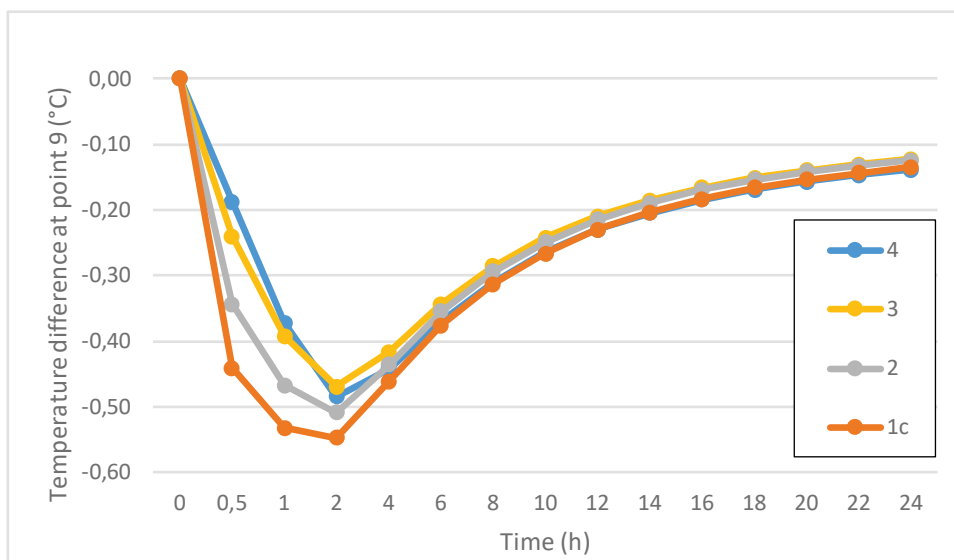


Figure 13. Temperature difference at calculation point 9, for delaminated concrete.

## 5.3 COMMENTS

### 5.3.1 Air-filled crack in concrete wall

The lowest simulated temperature on the wall surface occurred at the crack and the highest temperature occurred furthest from the crack. The temperature difference decreased over time. After 30 minutes, 1 hour, and 4 hours, the temperature difference was 0.32, 0.27 and 0.13°C, respectively, for the wall surface (between points 1c and 7). After 24 hours, the difference was only 0.02°C for the wall surface.

### 5.3.2 Water-filled crack in concrete wall

The lowest simulated temperature on the wall surface occurred at the crack and the highest temperature occurred furthest from the crack. The temperature difference decreased over time. After 30 minutes, 1 hour, and 4 hours, the temperature difference was 0.38, 0.33 and 0.18°C, respectively, for the wall surface (between points 1c and 7). In addition, during the first two hours, the difference was another tenth of a degree greater between the water-filled crack, 1a, and calculation point 7. After 24 hours, the difference was only about 0.01°C for the wall surface.

### 5.3.3 Air-filled delamination in concrete wall

The lowest simulated temperature on the wall surface occurred at the crack and the highest temperature occurred furthest from the crack. The delaminated part also showed lower temperatures compared to the wall surface further away from the crack. The temperature difference decreased over time. After 30 minutes, 1 hour, and 4 hours, the temperature difference was 0.44, 0.53 and 0.46°C, respectively, for the wall surface (between points 1c and 9). After 24 hours, the difference was at most 0.14°C for the wall surface calculation points.

## 5.4 FURTHER COMMENTS

The concrete wall has been divided into thin material layers and the distribution differs somewhat between the two simulated cases. Furthermore, the simulation started with the same temperature in the entire wall and then gradually adapted to the surrounding climate. This, together with a relatively short time period and the division into time steps, is a possible explanation for why the temperature differences differ or vary somewhat within the respective simulated case and between the simulation cases.

Calculation applies to the respective calculation section under given conditions regarding material properties and input data. In addition, the concrete has been assumed to be homogeneous, but in fact there may be larger particles of stone that increase the heat flow locally. Reinforcing bars in the concrete have also not been considered. There is no information for how long the cracks are filled with water after the tunnel has been emptied of water, so it is unclear which alternative (air or water) is most representative.

The uncertainties in the simulations and material data has not been included in the reported result. Remaining water, water film and water droplets on the concrete surfaces after the tunnel has been emptied have also not been considered. In addition, several significant assumptions have been made about the climate. As there are uncertainties that are difficult to assess, temperatures should be followed up with measurements suggested in a test set-up and with supplementary measurements on site to check temperature differences.



## 6 Concluding remarks

Under the simulated conditions, there is a small but detectable difference in temperature between a concrete surface with and without cracks. The greatest simulated temperature difference is at least 0.2°C close to the crack. The area 5 to 10 mm from the crack is the most affected. The Thermal Sensitivity of the best available Infrared equipment is around 0.02°C and the high resolution enable the camera to read the average temperature on a surface area the size of a few square millimetres so, according to these simulations, it should be possible to detect cracks in the concrete surface. This temperature difference occurs during a very short time period, a few hours, after the tunnel has been emptied of water.

However, in this study the input values are exaggerated to emphasize the possibility with the IR technology. In reality, the temperature difference between the water in the tunnel and the air that replaces the water during the emptying process is much lower in most cases. Thus, the temperature difference between concrete with and without cracks becomes smaller and more difficult to detect. Furthermore, the influence of water remaining on the concrete surface after the emptying of the tunnel is neglected in the simulations. Finally, the uncertainties of the material data and the simulations themselves has not been considered but might well shadow the estimated temperature differences.

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## Keywords

*infrared thermography, crack formation, detection of defects in concrete*



# INFRARED THERMOGRAPHY FOR DETECTING DEFECTS IN CONCRETE STRUCTURES

Infrared thermography is a timesaving non-destructive test method. It has gained a lot of popularity in recent years and has a wide application area. This work assesses the possibility of using infrared thermography to detect cracking in concrete tunnels for cooling water found in nuclear power plants. This study concludes that the possibility to detect temperature differences caused by cracks in the concrete wall of a nuclear powerplant cooling waterway probably is small under realistic conditions.

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