
Introduction of possible inspection methods for evaluating thermal aging status of existing pre-insulated district heating systems

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Gothenburg, Sweden 2015



Abstract

The development of district heating (DH) systems with the intention of supplying high efficiency thermal energy to the buildings has become increasingly popular over the past few decades. The thermal energy in this system is mostly hot water or steam, which is transported by heat-insulated pipelines from heat generation units to various places of consumption. The insulation performance of pipelines decreases gradually during time due to degradation of polyurethane (PUR) foam. Consequently, the requirements for detecting and monitoring the location of potential 'hot spots' in DH network are significantly favorable issue for energy companies. A literature study from several reports and scientific articles conducted to find out possible methods for remote detection of chemical, electrical and thermal properties of PUR after natural thermal degradation. Along with this aspect, 17 methods for different approaches took into consideration to weigh up whether they can be applied for this aim.

Keywords: District heating, degradation, inspection, pipeline, method, PUR

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ACKNOWLEDGMENTS

Behind each research study, is the work of a whole team, and now I would like to thank all people who supported me in the past few months with their guidance and advice to prepare this work.

Hereby I would like to thank and express my gratitude to Professor Bijan Adl-Zarrabi for sharing his knowledge with me and helping me every time I've been slowed down by a problem! Without the continuous thematic support of him, it might not possible to achieve a high level of understanding with this work.

ABBREVIATIONS

DH.....District Heating
FDR.....Frequency Domain Reflectometry
FFT.....Fast Fourier Transformer
FTIR.....Fourier Transform Infrared Spectrometry
GPR..... Ground Penetrating Radar
GWUT.....Guided Wave Ultrasonic testing
LIRA.....Line Resonance Analysis
MFL.....Magnetic Flux Leakage testing
NDT.....Nondestructive testing
PAU.....Phased Array Ultrasonic
PUR.....Polyurethane
SDD.....Silicon drift detectors
TDR.....Time domain reflectometry
UPE.....Ultrasonic Pulse Echo
UPV.....Ultrasonic Pulse Velocity
UTG.....Ultrasonic Thickness Gage
UWB.....Ultra-wideband
VLF.....very low frequency
XRF.....X-ray Fluorescence Spectroscopy

1 INTRODUCTION

1.1 Background

To decrease the primary energy supply in DH system and provide a cost effective heat distribution network, it is significant to identify parameters that affect energy loss along the pipelines. Examples of such parameters might be corrosion of steel pipes, leakage, aging of insulation and ground motion (*Friman et al, 2014*). The greatest thermal loss in DH system occurs when hot water is channeled over long distance from heat generation units to the consumption buildings. According to Technical Research Institute of Sweden (SP), total annual heat loss in Swedish DH pipelines is approximately one tenth of produced heat which is mainly related to DH pipe insulation capacity. Therefore it is favorable for many energy companies to estimate the remaining service life of pre insulated district heating pipes. The European Standard EN 253:2009 specifies that pre insulated pipes should survive at least 30 years at a constant operating temperature of 120°C.

Thermal properties of pre insulated pipes, which are normally made of polyurethane (PUR), deteriorate during the real operation conditions. The degradation of PUR occurs due to diffusion of gas molecules between the foam and surrounding air. In this process oxygen and nitrogen molecules penetrate from air to the foam bubbles and replace with blowing agent gases, which are mainly cyclopentane and carbon dioxide (CO_2) (*Persson, 2015*). In figure 1 the aging of an insulated district pipe with polyurethane thermal insulation after approximately 16 years of operation is illustrated.

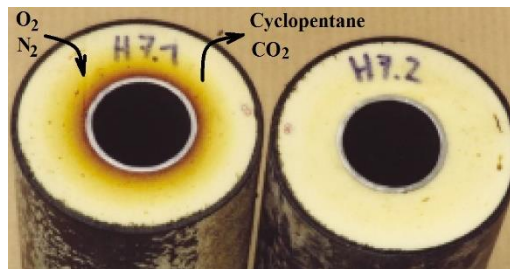


Figure 1 Diffusion of gases due to aging of a district heating pipe

The most significant factor that accelerates the natural aging process of insulation is directly proportional to the steel fluid pipes temperature (*Kręcielewska and Menard, 2014*). Thus, when insulation panels are exposed to high temperature, insulation thermal conductivity coefficient λ increases subsequently and grater heat flow (loss) is expected based on Fourier's law.

$$q = -\lambda \cdot \nabla T \quad [W \cdot m^{-2}] \quad eq. 1$$

Where, $q [W \cdot m^{-2}]$ represents the rate of heat transfer through the material, $\lambda [W \cdot m^{-1} \cdot K^{-1}]$ is the thermal conductivity coefficient and $\nabla T [K]$ stand for the temperature differences.

To detect thermal bridges in existing DH networks, the basic and customary method referred to the normal operation by digging up the pipes and inspecting the insulation status. Additionally, taking the DH pipes out and renovating the foam insulation is extremely expensive and time-consuming process. Therefore, it is largely favorable for energy companies to localize the accurate damage area and heat loss in the pipeline networks before any excavation and demolition. It should be mentioned that due to lack of objective information about the capability of non-destructive scanning techniques in this field, there are still no particular methods to detect the performance of existing pre-insulated DH system during its life cycle.

1.2 Purpose

The objective of this work has been restricted to provide an overview of different possible screening methods for estimating the status performance of existing pre-insulated DH pipes. This includes:

- Establish a general database of nondestructive (ND) testing methods with respect to the requirements of this work
- Evaluate the methods based on obtained criteria

1.3 Methodology

A literature study from several reports and scientific articles carried out to estimate the consistency of different ND inspection methods with respect to the aim of this study. The capable methods collected based on their suitability for detecting thermal, chemical and electrical changes in degraded materials.

Some of these methods are utilized for a specific condition and the presence of them is to consider their relative strengths and weaknesses for developments of new methods. Examples include ultrasonic methods which are basically applied to metallic materials and perhaps they can be developed for monitoring the status of PUR insulation from internal steel pipes. There is still a lack of laboratory tests and theoretical calculations to determine the effects of aged polyurethane foam to steel pipe properties.

Afterwards, to sort out and evaluate the possible inspection capabilities of gathered methods, 11 criteria identified and registered in a weighted decision table with reference to limitations and requirements. Finally, a decision matrix table developed by using the criteria weight factors to bring out the most possible and capable methods.

1.4 Limitation and requirements

The scope of this work has been limited to investigate the non-destructive (ND) inspection methods for evaluating thermal resistance status of existing pre-insulated pipes. The ability of methods should also be restricted for field operation. The methods collected based on their capability for detecting thermal, chemical and electrical changes in degraded materials. Due to lack of ND testing information for status monitoring of PUR, different approaches with different inspection probability are considered. However, some methods with similar concepts aren't observed in this study.

2 REVIEW OF STATUS MONITORING METHODS

2.1 Ultrasonic methods

2.1.1 Ultrasonic Thickness Gage (UTG)

This nondestructive (ND) technique measures the propagation velocity of longitudinal ultrasonic waves in materials and converts the values to the thickness according to mathematical equations. In this method the probe's transmitter sends a short ultrasonic pulse into tested element. The reflection of the pulse returns to the probe's receiver and then converts into a high frequency electrical signal. This signal is analyzed to determine the thickness of sample. The method is basically used where there is only one side access to the surface of sample such as pipes, containers, tanks and large sheets of metal and plastic. All ultrasonic thickness gauges are operated based on very precise measurement of the required time that the sound pulse passes through the test sample. In this method one side of material surface is needed for placing the probe therefore it is not suitable for underground investigation because the accuracy of testing is highly depends to uniformity of coating surface and the surface condition between transducer face and material. (Trade name: Magna-Mike 8600)

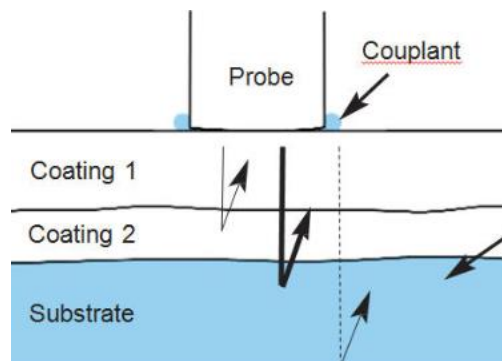


Figure 2. Thickness measurement in a multilayer system

Dependences:

- Density
- Grain Structure

Applications:

- Metals
- Plastics
- Rubber
- Corroded materials

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM D6132 – 13 (2013) *Nondestructive Measurement of Dry Film Thickness of Applied Organic Coatings Using an Ultrasonic Coating Thickness Gage*
- Meier, J.H. (1969) *Ultrasonic Thickness Gage*

2.1.2 Ultrasonic Pulse Velocity (UPV)

The propagation velocity of ultrasonic waves inside a solid body depends on the density and elastic constant. Furthermore, both density and elastic constant vary from one point to another inside materials due to different parameters, such as structural inhomogeneity, quality changes and production methods (for instance blowing agent for manufacturing polyurethane foam). In this method the strength and quality of materials are evaluated by sending ultrasonic pulses from a pulse generation circuit. The electronic sounds are then transformed to mechanical pulses by a transducer. Deviations from the average speed, and perceived wave amplitude variations, indicate inhomogeneity and air intrusions into

materials. Ultrasonic pulse velocity is a nondestructive method and is basically used for analyzing the strength and quality of concrete in the field.

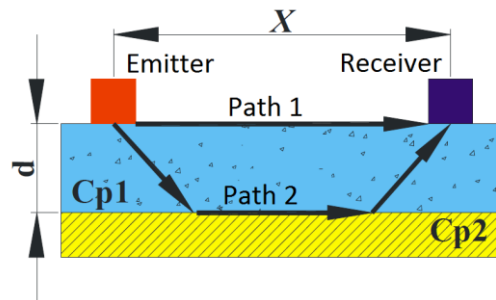


Figure 3. Ultrasonic Pulse Velocity – Indirect Transmission

The accuracy of this method is related to the distance between receiver signal equipment and the transducer, therefore it is not applicable for underground inspection through probe testing. (Trade name: Pundit Lab)

Dependences:

- Density
- Elastic properties
- Crystal orientation
- Grain Structure

Applications:

- Concrete
- Wood
- Ceramics
- Metal materials

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM C597 – 9 (2009) *Pulse Velocity Through Concrete*
- Guidebook on non-destructive testing of concrete structures (2002) *International Atomic Energy Agency, Vienna*

2.1.3 Ultrasonic Pulse Echo (UPE)

When acoustic waves propagate into a material the attenuation and velocity of sound waves depends on the density, elastic modulus and void formation of that material. These factors might be transformed due to other chemical rearrangement in a molecule. In this condition the reflection of ultrasonic waves would be helpful for analyzing the properties of tested material. High frequency sound waves are transmitted by a straight beam transducer which is vertically set on the tested material. A liquid (or semi-liquid) substance is also required between the searching units and the material surface during inspection process. The reflection of signals from material surface are visualized through a digital oscilloscope for inspection analysis. The inspection efficiency of this method is decreased at locations with limited access. (Underground inspection)

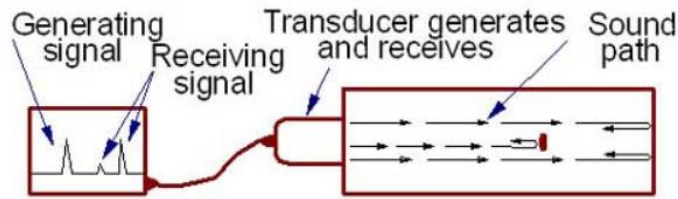


Figure 4. Typical ultrasonic pulse echo testing

Dependences:

- Density
- Elastic modulus
- Void formation

Applications:

- Concrete
- Insulated materials

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E114 – 10 (2010) *Ultrasonic Pulse-Echo Straight-Beam Contact Testing*
- Guoli Wang, Y.H., Jia, Z. and Xie, H. (2005) *Application of Ultrasonic Pulse-echo Method to Insulation Condition Diagnosis for Large Generators*

2.1.4 Phased Array Ultrasonic (PAU)

The phased array ultrasonic technology can be utilized in different sectors, from power generating station to construction industry. PAU is involved with ultrasound technology in the field of nondestructive testing. The method can be effectively used for measuring the wall thickness of elements as corrosion test. In this technique the array is referred to a single large probe which is combined with several piezoelectric crystals. These piezoelectric crystals are divided in very narrow segments and they pulse and receive the ultrasonic waves separately. The width of these segments can typically vary from 0.5mm to 2.5mm. Since different beam angles and focal depths can be combined with only one probe, it is possible to perform several different test separately without changing the transducer. The results of inspection are clearly stored and available for evaluation.

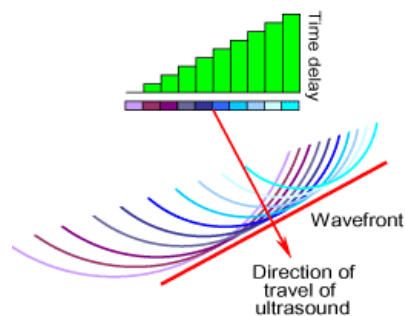


Figure 5. Flat probe in PAU – beam angles

Dependences:

- Crack size
- Orientation of discontinuities
- Probe size

Applications:

- Weld inspection

- Corrosion mapping
- Composite testing

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E2491 – 13 (2013) *Evaluating Performance Characteristics of Phased-Array Ultrasonic Testing Instruments and Systems*
- Ciorau, P. and Pullia, L. (2007) *How Reliable is Your Call? OPG Phased Array Ultrasonic Inspection Experience on Siemens- Parson Turbine Blade Roots 2001-2007*

2.1.5 Guided Wave Ultrasonic testing (GWUT)

This ND inspection method is widely utilized for assessing corrosion and structural integrity in long-distance in-service network from a single remote point, for instance above ground metallic pipelines and rail tracks. During the testing process three different guided wave modes, torsional, longitudinal and flexural, can be applied into the material body. Each of these guided waves is selected based on the geometry of element and applied frequency. The system uses low frequency ultrasonic waves (10-100 kHz), which are transmitted along the pipelines in both forward and backward directions. In this technique an array of transducers, which are equipped by ultrasonic piezoelectric sensors is employed to produce guided waves (torsional or longitudinal) along the pipe segment. If any discontinuities are recognized along the pipelines the waves are reflected back to the original location for evaluating the form and location of damages. The main advantage of this method is related to its ability for inspecting limited access areas of a system.

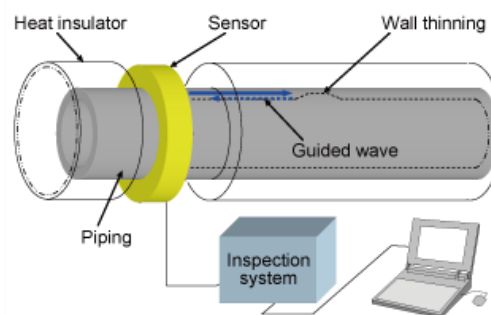


Figure 6. Ultrasonic guided wave pipe inspection

Dependences:

- Pipe content
- Pipe diameter
- Surface condition

Applications:

- Detecting pipe corrosion
- Monitoring changes in cross-section of pipes
- Detecting pipe stiffness

In-situ screening ability: yes (efficient method for long distance testing)

Non-destructive testing: yes

References:

- ASTM E2775 – 11 (2011) *Guided Wave Testing of Above Ground Steel Pipework Using Piezoelectric Effect Transduction*
- Zhang, L. (2014) *A Multi-channel Transmitter System for NDT Pipeline Testing using Guided Waves Ultrasound*
- Sonia, D. (2010) *Propagation of guided waves in a hollow circular cylinder application to nondestructive testing*

2.2 Chemical analysis

2.2.1 Fourier Transform Infrared Spectrometry (FTIR)

The objective of Fourier-transform spectroscopy is to measure infrared spectrum of a particular substance. FTIR is based on the absorption of light from the spectrum of a light source. In this technique a monochromatic light beam is emitted into material at different frequency. Some light is absorbed by tested material and other is transmitted. Consequently, by measuring the amount of molecular absorption and transmission in the sample, it will be possible to determine the quality and the amount of components of sample. The possibility of achieving accurate information across the entire infrared frequency at the same time is the main advantage of this method.



Figure 7. Portable FTIR Spectrometer

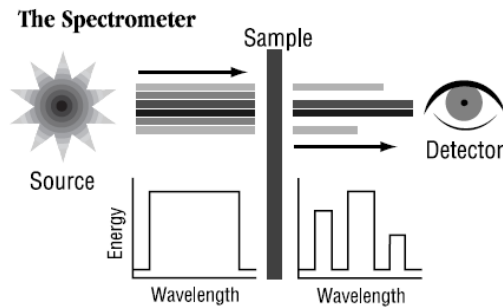


Figure 8. Schematic diagram of FTIR

<http://www.labo.de/spektroskopie/das-tragbare-ftir-spektrometer-ermoeglicht-eine-direkte-analyse-vor-ort.htm>

Dependences:

- Molecular bond between atoms
- Density

Applications:

- Polymer and polymer blend
- Rubbers
- Organic material
- Analysis of gaseous compounds

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM D5477 – 11 (2011) *Identification of Polymer Layers or Inclusions by Fourier Transform Infrared Microspectroscopy (FT-IR)*
- Seguchi, T., Tamura, K., Ohshima, T., Shimada, A. and Kudoh, H (2010) *Degradation mechanisms of cable insulation materials during radiation– thermal ageing in radiation environment*
- Rogovin, D. and Lofaro, R. (2005) *Evaluation of the Broadband Impedance Spectroscopy Prognostic/Diagnostic Technique for Electric Cables Used in Nuclear Power Plants*

2.2.2 Raman Spectrometry

Raman spectroscopy is a nondestructive analytical technique and gives information about different chemical components and their molecular rotation and vibration modes. In this technique a monochromatic light source, such as laser, near ultraviolet and near infrared, is transmitted into material at specific wave length to excite the vibro-rotational energy level of molecules. The material molecular composition characteristics will be changed by sending different monochromatic light. A very small part of reflected light is shifted into energy form which provides valuable data regarding to the vibrational mode of molecules chemical bounds. It should be noted that monochromator is referred to filter out the unwanted wavelength of light which are emitted from a light source.

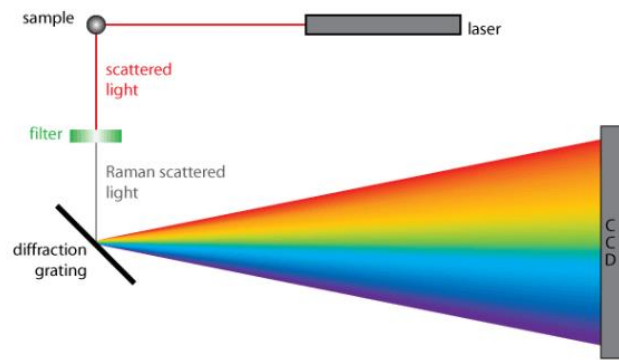


Figure 9. Simplified diagram of Raman Spectrometer's operation

Dependences:

- Chemical components
- Chemical bounds

Applications:

- Identification and characterization of polymers
- Characterization of minerals and soils

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E1840 – 96 (2014) *Raman Shift Standards for Spectrometer Calibration*
- Peike, C., Kaltenbach, T., Weis, K.A. and Koehl, M. (2011) *Non-destructive degradation analysis of encapsulants in PV modules by Raman Spectroscopy*
- Veitmann, M., Jumeau, R., Bourson, P., Ferriol, M. and Lahure, F. (2014) *Understanding and Control of High Temperature Oxidation Flaws of Low-Density Poly (ethylene) with Raman Spectroscopy*

2.2.3 X-ray Fluorescence (XRF) Spectroscopy

This method is based on the analysis of X-ray emission energy spectrum for characterizing the chemical properties of materials. It examines the interaction between excitation of X-ray source and electron beams with in the sample. The main feature of this method is based on the general principle that each material has a unique atomic structure which shows a unique collection of peaks in the X-ray spectrum analysis. Investigating the energy spectrum of such radiation can determine the qualitative and quantitative composition of the material. The measurement procedure of the material composition can be considered as below:

- Excitation the atoms in a sample by X-ray radiation – generation of fluorescent radiation from the material
- Recording of the fluorescence radiation by the Silicon drift detectors (SDD)
- Transmission of signal from the SDD
- The pulses are processed by the measuring logic
- Trapezoidal filters prevent undesired effects that occur during signal processing due to different times and energies.

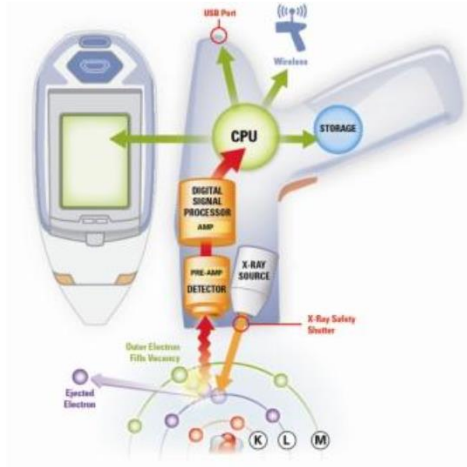


Figure 10. Scheme of X-ray Fluorescence spectrometry

Dependencies:

- Atomic properties of tested elements

Applications:

- Soil surveying and Mining
- Bulk chemical analysis for different elements
- Petroleum analysis

In-situ screening ability: yes

Non-destructive testing: yes

References:

- Verma, H.R. (2007) *Atomic and Nuclear Analytical methods - X-ray Fluorescence (XRF) and Particle-Induced X-ray Emission (PIXE)*
- Cobb, D. (2009) *Study on the Effectiveness, Precision, and Reliability of X-ray Fluorescence Spectrometry and Other Alternative Methods for Measuring Lead in Paint*

2.3 Electromagnetic methods

2.3.1 Eddy current testing

This technique is one of the nondestructive electromagnetic testing methods which is utilized for identifying discontinuities and flaws in surface of conductive materials. For investigating the inner layer of material an alternating magnetic field is generated through a wire coil at a chosen frequency into the conductor. Basically eddy current is referred to a circular flow of electrons which are produced by placing the wire coil close to the metal surface. Since discontinuities and flaws in conductive materials cause disturbance in circulation of electrons, the material impurities and defects are recognized by applying eddy current. Low cost, portability, great accuracy, time efficiency and receiving real time result are the main advantages of this method.

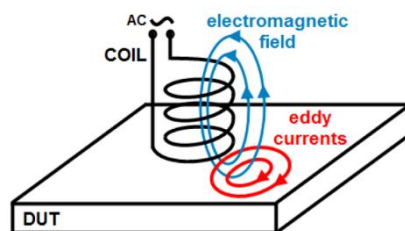


Figure 11. Producing of eddy currents in the tested specimen

Dependencies:

- Surface conditions

Applications:

- Thickness measurement of steel coating layers
- Crack detection
- Electrical resistivity

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E309 – 11 (2011) Eddy-Current Examination of Steel Tubular Products Using Magnetic Saturation
- IAEA - Eddy Current Testing at Level 2: Manual for the Syllabi Contained IAEA-TECDOC-628/Rev. 2 'Training Guidelines for Non-Destructive Testing Techniques'

2.3.2 Remote Field testing

This nondestructive inspection technique is based on low frequency alternating current for inspecting the inside and outside defects of steel pipes. The probe in this method is made up of two different coils, one is exciter and the other one is detector. When the probe is driven inside the pipe, the exciter coil which is supplied by a low frequency alternating current sine wave generates an electromagnetic field. The electromagnetic field is released in axial direction inside the pipe and produced a secondary field for monitoring the outside condition of pipe wall. The detector coil detects and analyses the magnetic field which is transmitted from outside of the pipe wall. Fast inspection and monitoring complex joints such as U-bend and elbow connections are advantages of this method.

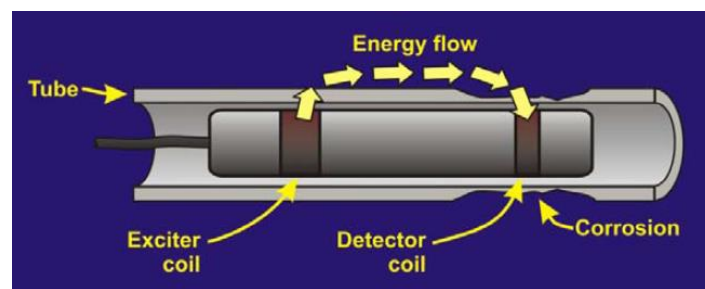


Figure 12. Basic principle of Remote Field Eddy Current probe

Dependences:

- Type of material
- Wall thickness
- Residual stress
- Ambient temperature

Applications:

- In-line corrosion inspection of steel pipelines
- Ferromagnetic tubes

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E2096/E2096M – 10 (2010) *In Situ Examination of Ferromagnetic Heat-Exchanger Tubes Using Remote Field Testing*
- RUSSELL, D. and Shen, V. (2008) *Increased Use of Remote Field Technology for In-Line Inspection of Pipelines Proves the Value of the Technology for this application*
- Sadek, H.M. (2006) *NDE technologies for the examination of heat exchangers and boiler tubes – principles, advantages and limitations*

2.3.3 Magnetic Flux Leakage testing (MFL)

MFL is a magnetic nondestructive method for detecting and evaluating magnetic properties of metallic elements. The magnetic characteristic of materials vary due to mechanical and thermal effects such as corrosion, pitting and wall thickness losses. In this method the steel element is magnetized to saturation level by a powerful magnetic field. In case of above-mentioned defects are realized during the inspection, the magnetic flux lines leak out from the surface of material. In this condition the leakage flux can be measured by magnetic sensors. As long as the leakage magnetic field is propagated uniformly, the tested equipment is out of defects.

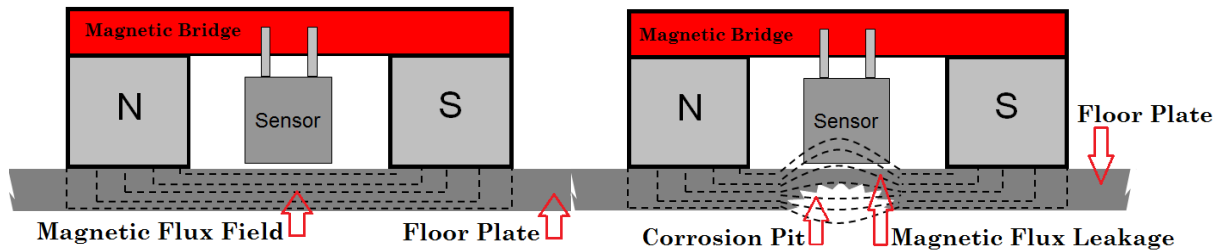


Figure 13. MFL testing for material without defects

Figure 14. MFL testing for material with flaw defects

Dependences:

- Orientation of discontinuities

Applications:

- Monitoring corrosion of underground steel pipes
- Oil storage tank
- Rail tracks
- Detecting flaws in bridge cables

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E570 – 15 (2015) *Flux Leakage Examination of Ferromagnetic Steel Tubular Product*
- Xu, J., Wu, X., Cheng, C. and Den, A. (2012) *A Magnetic Flux Leakage and Magnetostrictive Guided Wave Hybrid Transducer for Detecting Bridge Cables*
- Pearson, N. (2012) *Discrimination of top and bottom discontinuities with MFL and the Surface Topology Air-gap Reluctance System (STARS)*

2.4 Reflectometry methods

2.4.1 Time domain reflectometry (TDR)

Time domain reflectometry is an accurate NDT method for identifying and measuring dielectric properties of transmission and distribution lines. In this method a pulse generator generates incident electrical direct current (DC) signal over a conductor such as alarm wire in district heating system. The measurement probe registers the reflected voltage if impedance mismatches are detected on the conductor. Impedance mismatches will cause all or some of the transmitted signal to be sent back towards the oscilloscope. The oscilloscope monitors the pulses that are generated from TDR. The distance of discontinuity can also be determined by measuring the reflection time between reflected impulse and pulse generator.

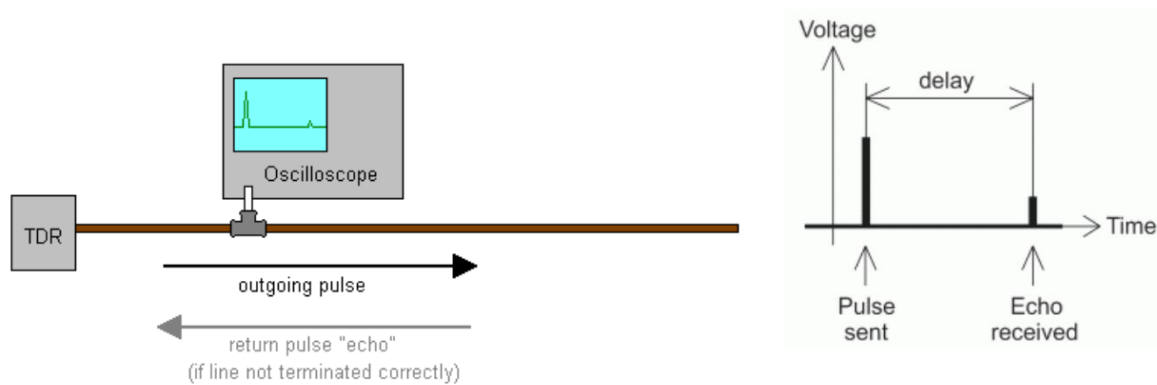


Figure 15. TDR principle

Dependences:

- Dielectric properties of material
- Micro-voids

Applications:

- Identifying insulation degradation of electrical cables
- District heating systems

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM D6565 – 00 (2005) *Determination of Water (Moisture) Content of Soil by the Time-Domain Reflectometry (TDR) Method*
- Mohd Ariffin, A., Kuan, T.M., Sulaiman, S and Illias, H.A. (2012) *Application of Time Domain Reflectometry Technique in Detecting Water Tree Degradation within Polymeric-Insulated Cable*
- Neier, T. (2009) *Cable Fault Location in LV, MV and HV Underground Cable Networks*

2.4.2 Frequency Domain Reflectometry (FDR)

Frequency domain reflectometry (FDR) is a distance to false measurement technique for monitoring the performance of cables/wires. This technique works by transmitting stepped-radiofrequency signal into conductor and measuring the amplitude of reflected sine waves over separate frequencies. The size of reflected signals are analyzed based on the measured amplitude and then will transform into time domain by Fast Fourier Transformer (FFT). In order to evaluate the distance of reflected signals location, the relative propagation velocity is required, which is the velocity of signal transmitted into medium to the velocity of light in a vacuum. This method is widely used for detecting dielectric breakdown and moisture ingress into the cables.

Dependences:

- Dielectric properties
- Sine wave velocity in wire
- Wavelength of electrical signal

Applications:

- Aging assessment of power cables

In-situ screening ability: yes

Non-destructive testing: yes

References:

- Simmons, K.L., Fifield, L.S., Westman, M.P., Ramuhalli, P., Pardini, A.F., Tedeschi, J.R. and Jones, A.M. (2013) *Determining Remaining Useful Life of Aging Cables in Nuclear Power Plants – Interim Study FY13*
- Fantoni, P.F. (2006) *Wire System Aging Assessment and Condition Monitoring Using Line Resonance Analysis*

2.5 Voltage Response

This diagnostic technique is basically used to evaluate the moisture contents and aging degrees of power transformer insulation. Degradation of insulation materials occurs due to ingress of moisture and oxygen in process of time. This method is based on the measurement of decay voltage and return voltage curves (Figure.13). To measure the return voltage curve different test cycles should be applied during the measurement procedure. Each test cycle is divided to several phases. In the first phase the insulation is charged up by a certain DC voltage for a long period of time (t_c). In this condition the molecules of insulation are excited and polarized via charging. In the second phase electrodes are discharged from insulation by disconnecting the DC voltage (t_d). Hence a decay voltage appears in the voltage curve (Figure.13). The first slope of this curve is directly related to the conductivity of insulation material. The next phase is related to return voltage measurement when no voltage is dropped across the circuit. The slope of the return voltage curve represents the intensity of polarization. In this case the position of polarized insulation is changed into free of charges state (primary state) and then a voltage originates between dielectric electrodes.

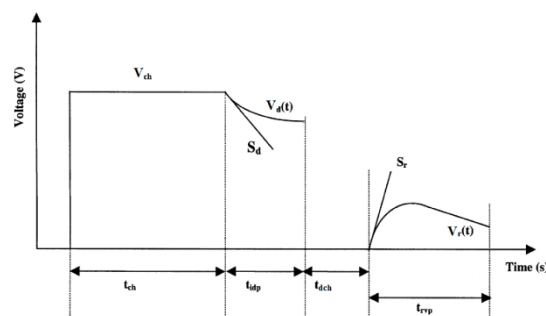


Figure 16. Timing diagram of voltage response method

Dependences:

- Dielectric strength of insulation

Applications:

- Power cable
- Oil paper insulated cables

In-situ screening ability: yes

Non-destructive testing: yes

References:

- Nemeth, E. (1999) *Measuring voltage response: a non-destructive diagnostic test method of HV insulation*
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2.6 Tan-Delta

In-service performance of insulated cables are decreased over certain period of time due to moisture and water ingress into the cables. Therefore, predicting remained service life and degradation condition of insulation would be worthwhile. Tan Delta is a diagnostic technique which is utilized to evaluate dielectric integrity and resistivity of insulated cables. In this method sinusoidal voltage with a very low frequency (VLF) is applied to the cable through a voltage source. In case that no imperfections in insulated cables are detected, the insulation behaves as a perfect capacitor. It means that the phase shift between current and voltage becomes 90 degrees, because when the current is maximum, the voltage has its minimum amount. Conversely, existence of any discontinuities in insulation case leads a shifted

phase between current and voltage which is normally less than 90 degrees. The loss angle δ indicates the level of insulation defects and it measures by tangent of the angle δ .

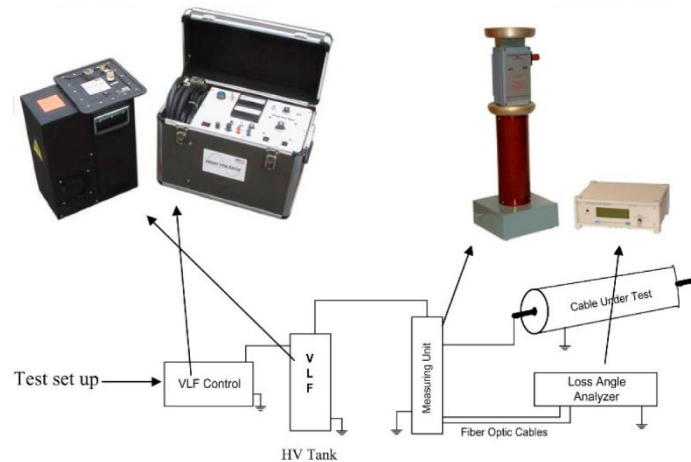


Figure 17. Basic principle of Tan Delta measurement

Dependencies:

- Dielectric properties of insulation

Applications:

- Electrical cables

In-situ screening ability: yes

Non-destructive testing: yes

References:

- Ponniran, A., Akmal Mohd. Jamail, N. and Jalaludin, N.A. (2009) *Tan Delta and Capacitance Characteristics of Underground XLPE Cables – 11 kV*

2.7 Ground Penetrating Radar (GPR)

The GPR is a non-destructive technique based on transmission of high frequency electromagnetic waves into the material under investigation. In geological engineering applications it is utilized for geophysical surveying and monitoring disturbances in upper layers of soil via reflection of electromagnetic radiation. Furthermore, in some cases it can also be applied in the field of civil engineering. For instance for estimating internal concrete inhomogeneity and defects such as localization of reinforcement bars corrosion, cracks, and voids dimensions. The GPR works by Ultra-wideband (UWB) technology and emits very short pulses into the material via an antenna. The reflection of signals are then recorded in the source of electromagnetic waves and displayed to the operator.

Dependencies:

- Electrical properties of the object such as dielectric constant and electrical conductivity
- Transmitting frequency from the antenna

Applications:

- Estimating moisture content in concrete
- Detecting reinforcement corrosion
- Geophysical surveying
- Detecting of pipelines and street surveying

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM D6432 – 11 (2011) *Using the Surface Ground Penetrating Radar Method for Subsurface Investigation*

- Hong, S. (2014) *GPR-Based Periodic Monitoring of Reinforcement Corrosion in Chloride-Contaminated Concrete*
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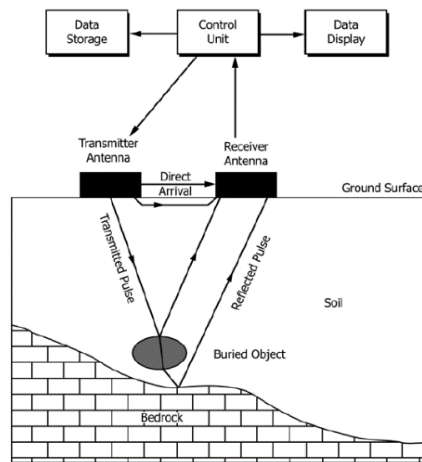


Figure 18. Schematic principle of GPR

2.8 Infrared Thermography Test

Thermography analysis is based on the study and interpretation of thermal images. According to radiation law of black body, all objects at temperature above absolute zero, emits electromagnetic radiation with a specific wavelength. The infrared radiation emits from an object varies with temperature changes. Infrared thermography can monitor this temperature changes by converting emitted radiation into electrical signal. In this method thermographic devices detect infrared radiation from the electromagnetic spectrum (wavelength between 9 -12 μm). For monitoring the thermal image in large scale conditions such as leakage detection in district heating systems, the Airborne Thermography can be utilized as an instrumental technique. The temperature profile of district heating leakages is measured by the thermal camera for this method.



Figure 19. Leakage in an aerial thermal image

Dependences:

- Depth of the pipeline
- Temperature
- Size of the leakage

Applications:

- Electrical networks
- Heat loss in the insulated building and high temperature equipment
- Power plant machinery
- Detection of leakage location in district heating pipelines

In-situ screening ability: yes

Non-destructive testing: yes

References:

- ASTM E1934 – 99a (2014) *Examining Electrical and Mechanical Equipment with Infrared Thermography*
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3 EVALUATION PHASE

In order to evaluate and prioritize the possible inspection abilities of above-suggested methods for detecting chemical, physical and electrical changes in PUR after thermal aging, three phases are taken into consideration.

3.1 Weighting of criteria

The first approach is involved to identify and present different criteria to separate the suggested methods from each other with respect to their capability for the proposed requirements of this study. To narrow down to one or more possible solutions, criteria should fulfill the requirements and demands. In this task eleven criteria are identified and registered in a weighted decision table to show the importance of one criterion in comparison to others. To this aim, criterion with higher competence and criterion with lower valuation compared to each other are presented by a positive and negative symbol respectively. The summation of positive symbols in each row indicates the overall weighted score for each criterion. Finally, the weight factor for each criterion is obtained by dividing the weighted score for that criterion to the total score.

Table 1: Weighted decision table

Criterion	Level of consistency	In-situ inspection	Chemical detection	Longitudinal inspection	Commercial availability	NDT	Portability	Thermal detection	Electrical Detection	Inspection costs	Inspection Time	Sum	Weight - Factors
Level of consistency	0	-	+	+	+	-	+	+	+	+	+	8	15%
In-situ inspection	+	0	+	+	+	-	+	+	+	+	+	9	16%
Chemical detection	-	-	0	+	-	-	+	-	+	+	+	5	9%
Longitudinal inspection	-	-	-	0	-	-	+	-	+	+	+	4	7%
Commercial availability	-	-	+	+	0	-	+	+	+	+	+	7	13%
NDT	+	+	+	+	+	0	+	+	+	+	+	10	18%
Portability	-	-	-	-	-	-	0	+	-	+	+	3	5%
Thermal detection	-	-	+	+	-	-	-	0	+	+	+	5	9%
Electrical Detection	-	-	-	-	-	-	+	-	0	+	+	3	5%
Inspection costs	-	-	-	-	-	-	-	-	-	0	-	0	0%
Inspection Time	-	-	-	-	-	-	-	-	-	+	0	1	2%
												55	100%

3.1.1 Comment on criteria

- NDT, refers to a number of test methods for evaluating the material properties without causing damage to it.

- In-situ inspection, related to ability of methods to survive and work under different level of outdoor environment.
- Level of consistency, is the inspection method compatibility to monitor degradation changes in polyurethane.
- Longitudinal inspection, is the ability of methods to inspect the status along tested element from a single access point.
- Inspection costs, is defined by all costs related to the inspection process, such as work cost, transports, etc.
- Thermal detection, is related to the methods which are capable for scanning thermal properties of tested element.
- Chemical detection, is related to the methods which are capable for scanning chemical properties of the tested element.
- Electrical detection, is related to the methods which are capable for scanning electrical properties of the tested element.
- Commercial availability, means the equipment availability of methods in market.
- Inspection time, refers to scanning duration time needed for material testing.

3.1.2 Description of weighted decision table

As observed in table 1 prioritized criterion is nondestructive testing, meaning that during the inspection process the suggested methods shouldn't damage the casing layer of insulated pipes. It is also significant to determine whether the detecting methods are capable for field inspection. A laboratory testing method would be worthless in this task. Moreover, in order to evaluate the degree of compatibility, the methods should provide sufficient level of consistency to monitor thermal aging changes in polyurethane. As it is shown in the table some of the criteria have equal weight-factor which means that there is a room for further development of the final suggested method concept. The inspection cost is placed in the lowest rank at this level of investigation.

3.2 Weighting of methods

In this section to grade and rank the methods a decision matrix table is developed by means of presented weight factors at part 3.1. The methods are given a rating scale from 1 to 3 according to their relative compatibility with criteria. Thus, rating scale 1 indicates lowest relative compatibility level, rating scale 2 indicates medium relative compatibility level and rating scale 3 shows the highest level. The rank of each method is obtained by multiplying the rating to weight factors for that criterion and summing up scores across each column. Consequently, methods with highest score are expected to be more capable for the purpose of this study. In some methods, due to lack of adequate testing information on polymeric materials, only one point is assigned during the evaluation.

Table 2 – Decision matrix table

Criteria	Ultrasonic Thickness Gage	Ultrasonic Pulse Velocity	Ultrasonic Pulse Echo	Phased Array Ultrasonic	Guided Wave Ultrasonic testing	Fourier Transform Infrared Spectrometry	Raman Spectrometry	X-ray Fluorescence (XRF) spectroscopy	Eddy current testing	Remote Field testing	Magnetic flux leakage testing	Time domain reflectometry	Frequency domain reflectometry	Voltage response	Tan-Delta	Ground penetrating radar	Infrared thermography test
Level of consistency	1*15	1*15	1*15	1*15	1*15	3*15	3*15	2*15	1*15	1*15	1*15	2*15	3*15	2*15	2*15	1*15	1*15
	0,15	0,15	0,15	0,15	0,15	0,45	0,45	0,30	0,15	0,15	0,15	0,30	0,45	0,30	0,30	0,15	0,15
In-situ inspection	3*16	3*16	3*16	3*16	3*16	2*16	3*16	3*16	3*16	3*16	3*16	3*16	3*16	3*16	3*16	3*16	2*16
	0,48	0,48	0,48	0,48	0,48	0,32	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,48	0,32
Chemical detection	1*9	1*9	1*9	1*9	1*9	3*9	3*9	3*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9
	0,09	0,09	0,09	0,09	0,09	0,27	0,27	0,27	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09
Longitudinal inspection	1*7	1*7	1*7	1*7	3*7	1*7	1*7	1*7	1*7	2*7	1*7	3*7	3*7	3*7	3*7	1*7	1*7
	0,07	0,07	0,07	0,07	0,21	0,07	0,07	0,07	0,07	0,14	0,07	0,21	0,21	0,21	0,21	0,07	0,07
Commercial availability	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13	3*13
	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39	0,39
NDT	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18	3*18
	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54	0,54
Portability	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5	3*5
	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
Thermal detection	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	1*9	3*9
	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,09	0,27
Electrical Detection	1*5	1*5	1*5	1*5	1*5	1*5	1*5	1*5	1*5	1*5	1*5	3*5	3*5	3*5	3*5	3*5	1*5
	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,05	0,15	0,15	0,15	0,15	0,15	0,05
Inspection costs	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Inspection Time	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2	1*2
	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02	0,02
Grades	2,03	2,03	2,03	2,03	2,17	2,35	2,51	2,36	2,03	2,10	2,03	2,42	2,57	2,42	2,42	2,13	2,05

Grade Scales	2,45 - 2,60	2,30 - 2,45	2,15 - 2,30	2,00 - 2,15
Rank	1	2	3	4

3.3 Argumentation and results

The outcome of the decision matrix table reveals that the most possible solutions for this task are Frequency domain Reflectometry and Raman Spectrometry method respectively. In this table some methods gain equal scores due to their characteristic similarity with presented criteria. Therefore, to distinguish these methods from each other further investigation and laboratory testing is required. It is also needed to mention that the best and suitable NDT inspection method is far from fully developed at this investigation level. Although the results from the evaluation phase give a general indication of how these methods differentiate. In order to extend Frequency domain Reflectometry to a most appropriate technique for pre insulated pipe system the inspection capabilities and limitations of this method should be recognized in greater specifications.

4 CONCLUSION

To find out an appropriate method for remote detection of chemical, electrical and thermal properties of PUR after thermal degradation, different NDT methods for different approaches are studied briefly. From the evaluation phase, Frequency domain Reflectometry and Raman Spectrometry methods have highest inspection capabilities regarding to proposed requirements. However, the test data concerning the accuracy of these methods for PUR inspection is inadequate. Therefore, further research and laboratory test are required both on aged and unaged polyurethane foam to realize the critical destructive aging factors. For instance thermal conductivity could be introduced as a destructive factor of the PUR because it increases significantly during the aging process. Nevertheless, no well-defined NDT thermography methods are capable for this aim.

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