SECTION 4
IRRADIATION INSTALLATIONS, DIAGNOSTIC AND RESEARCH METHODS

https://doi.org/10.46813/2024-152-136

THE DATA PROCESSING METHODS FOR THE THERMOGRAPHY MONITORING OF WATER COOLING SYSTEMS IN NPP

M.I. Bazaleev, S.E. Donets, V.V. Lytvynenko, E.M. Prokhorenko, O.A. Startsev, V.V. Shatov
Institute of Electrophysics and Radiation Technologies NAS of Ukraine, Kharkiv, Ukraine
E-mail: startsev-alex@ukr.net

The article discusses approaches to the analysis of data from thermographic measurements conducted at the ZNPP in order to assess the condition of above-ground and underground communications of cooling water. Methods of analyzing the surface topology of radiation temperature distribution on the welding seam of an overhead pipeline were proposed in order to identify potentially dangerous areas. An approach to the assessment of external loads on the surface of the soil in order to determine the areas with excessive external influences.

PACS: 28.41.Te, 65.90.+I, 87.63.Hg

INTRODUCTION

Rechecking the state of the technical water supply system for responsible consumers of group A at the Nuclear Power Plant (NPP) is the key to avoiding cases of emergency vacuum reduction in the turbine condenser, improper cooling of the spent nuclear fuel storage pool, etc. Taking into account that under the conditions of occupation, the ZNPP is not under proper control of the state of the cooling water supply system to the final heat absorber (in the case of the ZNPP, it is a cooling pond), it is necessary to focus on the development of additional measures to fulfill the order of the State Nuclear Regulation Inspection of Ukraine from 24.12.2015 No. 233 “On approval of Requirements for emergency cooling systems of nuclear fuel and heat removal to the final absorber”. Namely, the provisions of clause 9.: “9. When designing underground pipelines that are part of heat removal systems to the final absorber, the following are assumed:

- measures for their increased protection against corrosion;
- means for assessing their technical condition, which do not require direct access to these pipelines;
- organizational measures and technical means to reduce external loads on these pipelines”.

Water cooling pipelines, particularly those in critical infrastructure such as NPPs, are essential for maintaining operational efficiency and safety [1]. However, these pipelines are vulnerable to degradation over time due to factors like corrosion, mechanical stresses, and environmental conditions. The integrity of welds, crucial junctions within these pipelines, plays a pivotal role in ensuring their reliability and minimizing the risk of catastrophic failures.

The challenge of monitoring and maintaining the integrity of welds in water cooling pipelines necessitates advanced inspection techniques capable of detecting defects and anomalies that may develop over time [2]. Techniques must capture underlying issues such as microstructural changes or thermal irregularities that can precede more significant failures.

Thermography has emerged as a powerful tool in non-destructive testing (NDT) for assessing the condition of industrial assets, including welds in pipelines [3]. Thermography offers rapid detection of discrepancies in metal condition, incl. during regular operational periods. It serves as an express diagnostic tool, identifying areas of interest based on temperature anomalies at considerably low cost. This approach not only saves time but also enhances the quality and immediacy of inspections. Implementing thermographic methods facilitates prioritized NDT, scaling inspection volumes at flexible schedules. Utilizing infrared imaging technology, it enables the visualization and quantification of surface temperature variations along welds. These variations can indicate potential defects such as cracks, porosity, or improper fusion, which are critical indicators of structural integrity and operational reliability. It is of a major importance to find the defects prior them causing water leakages. Because of the temperature gradients between the ambient environment and the internal heat source, the heat transfer conditions are affected by the flow conditions in the pipe, the structural conditions and material properties of the pipe’s wall, thus making possible to detect defects in the thermal spectrum. The size of the concealed defects that can be potentially detected depends on the heat transfer conditions, however, propagation of the heat is not enough and external energy sources are required in some cases. Considering thin walls in the pipes, a multi-coil eddy current testing is one of the primary choices of NDT technologies, while ultrasonic inspection is a better fit for thicker walls [4].

Traditional methods such as acoustics for diagnostics of defects may appear impractical due to their time-intensive and labor nature compared to alternative detection techniques [5]. Therefore, the detection of thermal signatures associated with defects represents a significant breakthrough, but still, it should be combined with subsequent detailed examination using more precise methods that offer higher detection accuracy.

The application of thermography to assess welds in technical cooling water pipes at NPPs aligns with scientific findings that underscore the method's effectiveness in identifying defects [6]. Welds are particularly prone to property degradations compared to base metal and they may contain erosion defects, lack of fusion weld, etc. Also, as the scientific community works on fusion engineering, pipe NDT and inspection methods are being addressed and improved [7].

Additionally, thermographic methods are especially well-suited for the monitoring of the underground facilities where other express methods are of limited application.

Furthermore, complementing thermography with fractal analysis enhances the diagnostic capabilities by evaluating the spatial complexity of temperature distributions along welds or pipe’s surface. Fractal dimensions derived from thermal data offer a quantitative measure of irregularities that may indicate areas of material degradation, providing engineers and maintenance personnel with a supplementary assessment metric of structural state.

This study is focused on the research of thermographic data processing methods for evaluation of the conditions of the underground and above-ground water cooling systems at the NPP.

MATERIALS AND METHODS

The measurements were carried out at the site of the Zaporizhzhya NPP before the occupation, in order to avoid a period of the day with high solar activity, as this would lead to a temporary redistribution of the radiation temperature field caused solely by external heating. Thermograms were obtained in a panoramic way. As an example of the most large-scale object, there is a panoramic shot of the power unit in Fig. 1.

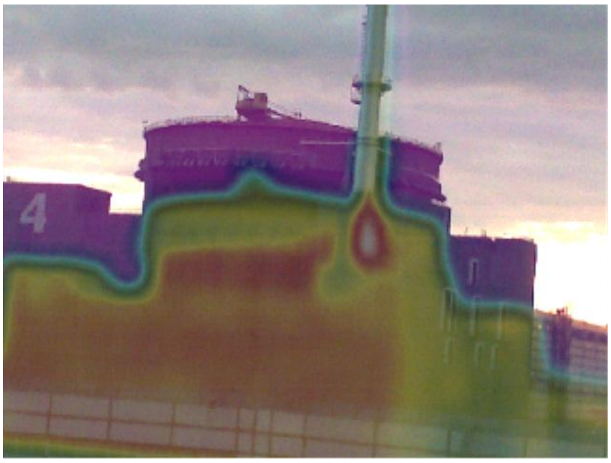


Fig. 1. Panoramic thermogram of the nuclear power unit

As a part of this study, the technical cooling water pipeline was also examined. A weld in the pipe was selected as an area of interest. The diameter of the pipe was ~70 cm. The wall thickness was ~1.5 cm.

The infra-red inspection was performed using the Fluke ^{32}Ti thermographic camera with a temperature sensitivity of 0.05 K and a matrix size of 240x320 pixels. The vendor’s default software “Fluke SmartView” was used to pick the best quality images and for the initial processing of thermograms.

Ambient temperature during inspection was around 17 °C. Internal water had a temperature ~ 28 °C. The increasingly active use of thermographic monitoring poses the task of its automation, which is discussed in particular in the paper [8]. Thus, the task of developing approaches to automating the processing of thermographic data arises.

FRACTAL ANALYSIS OF THERMOGRAMS FOR MONITORING OF WELDS

When analyzing the field of radiation temperature intensities, the task of estimating the degree of local curvature of the relief surface arises, since thermal anomalies caused by the features of the internal structure of the material will differ from thermal anomalies caused by the radiation coefficient. Fractals, characterized by self-similarity and intricate detail at every scale, are prevalent in numerous natural and artificial structures. Understanding and calculating the fractal dimension of these structures provide insights into their complexity and underlying patterns.

The fractal nature of the thermograms was analyzed following the methodology outlined in [9, 10]. We conducted fractal dimension analyses using our custom-developed software, which employs Clarke’s triangular prism surface area method (TPSAM). The main fractal descriptor we’ve used is the fractal dimension D in terms of Hausdorff-Besicovitch dimension. Since thermographic data is 3D array, and we use Clark triangular prism method to calculate fractal dimension, its value varies in range 2.00–3.00. The Clarke's work builds upon the foundational principles established by Mandelbrot, extending these concepts to an area grid [11, 12]. This method, known as TPSAM, facilitates the calculation of the fractal dimension of a digital surface by employing virtual prisms over pixel gray-level values.

In TPSAM, the surface area A is systematically covered with triangular prisms within a square window, utilizing a specific step size δ, (1). The process involves plotting a least squares regression of $A-\delta$ against various δ on a *log-log* scale (2). This approach enables the derivation of the fractal dimension D through the following mathematical relationships [11, 12]:

$$A(\delta) = N(\delta)\,\delta^2 = K\,\delta^2 = K\,\delta^{2-D}; \quad (1)$$

$$\log(A) = K + (2-D)\log(\delta); \quad (2)$$

$$D = 2 - \beta. \quad (3)$$

Here $N(\delta)$ represents the number of steps performed, K is a constant, D denotes the fractal dimension, and β signifies the slope of the regression line. When the slope of the $\log(D)-\log(\delta)$ line approaches zero (3), the fractal dimension D approximates the theoretical value of 2, indicating a self-similar structure without additional complexity. Important, the direction of sliding (computation) on $\{x,y\}$ is bi-directional, the box travels in both x and y directions to calculate the spatial dimensionality.

The application of fractal analysis in digital imagery, particularly in grayscale images which became popular in processing the satellite images, involves interpreting the image as a matrix of pixels with dimensions x×y, where the grayscale intensity, ranging from 1 to 256, is treated as a height measure. In our case, we directly work with the temperature values as the measure of virtual height. Also, the temperature values are normalized in the range of min(T) and max(T) transforming to values 0 to 1 accordingly, before calculating the fractal dimensions. This conceptualization allows the overlay of virtual prisms on the image, facilitating the calculation of a fractal dimension map. In this study, the beforementioned method was applied to squared windows of up to 5x5 pixels with a sliding step of 1 pixel as the $\{x,y\}$ space is decomposed into squares of δ-δ size. Calculations were directly on the data exported from SmartView.

Calculations were performed on the data exported from SmartView. The relative error in this fractal dimension calculations, based on empirical tests with images, is approximately 0.025. Data visualization and post-processing were carried out using Python 3 in Jupyter notebooks. Computational-wise, the numerical complexity of the algorithm is moderate at small sizes of squares (δ < 10), making it as a potential method for live image processing at low refresh frequencies.

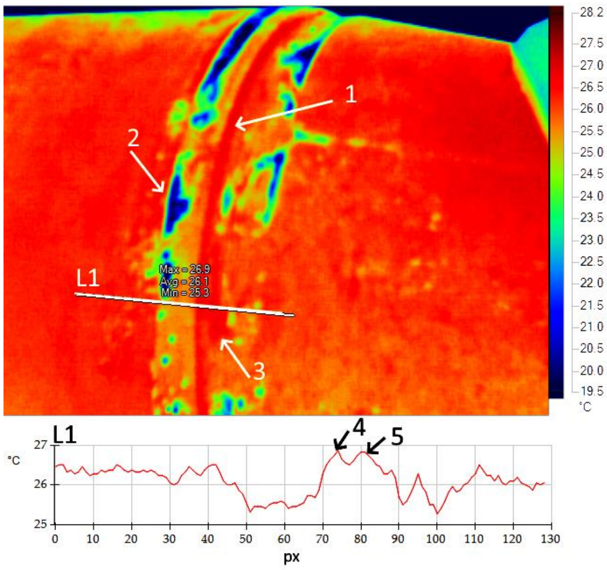
The typical examples of the thermograms of the studied pipe with the weld, were presented on Figs. 2,a and 3,a. The level of illumination from external sources varies but it was considered to be statistically negligible. The heat distribution was primarily driven by the internal water flow as a heat source. Figs. 2,a and 3,a were taken for the same pipe, but from opposite positions.

The weld was clearly visible as a circular feature on Fig. 2,a, indicated with the arrows 1 and 4. In the area of the weld, the temperature was around ~ 26.6…26.9 °C, according to the line plot L1. The main wall of the pipe did not have noticeable defects, its average temperature was around 26.1 °C. Subtle variations were caused by the quality of the surface (coating, dust). The thermal irregularities of colder temperature near the weld (see Fig. 2,a, arrow 2) are actually a technological thickening of wall, formed connections of pipes, and they are not considered as the defects.

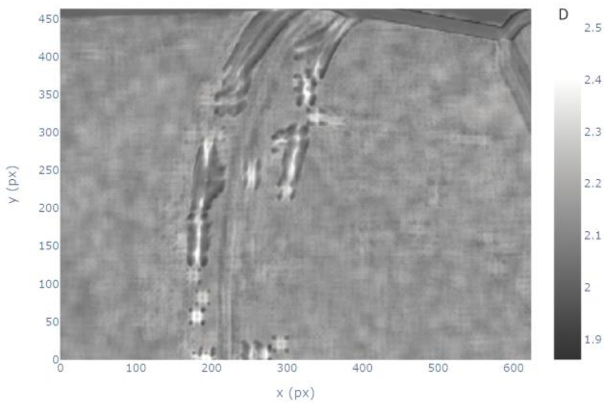
During the inspection, no clear defects were noticed that could be attributed to thinning of the wall. In case of presence of major wall thinned defects, the local areas tend to have a higher temperature and it was not observed clearly. Some possible defect was noticed on Fig. 2,a, indicated with the arrows 3 and 5. It is believed, this defect is an artifact of the welding or manufacturing of the pipe, and it does not constitute an immediate danger because the peak temperature (arrow 5) is lower than of the reference weld area (arrow 4). However, this area is of an elevated risk and it should be inspected periodically.

Fig. 3,a also did not reveal potential areas of defects. In the overall, the pipe's state looked similarly according the previous description. Thermal irregularities were attributed to the surface heterogeneities with no risk. When solving the practical problems of thermographic defectoscopy, physical and mathematical modeling of the structure, individual properties and processes occurring in the object under study is used, while preserving their physical nature.

Mathematical modeling makes it possible to unify the solutions of a wide class of problems based on the use of analytical and numerical methods, when it is possible to establish in an explicit form the dependencies connecting the determined values with the parameters of the object under given boundary conditions. For complex objects of thermal control, characterized by the presence of interdependent physical processes and their structural elements, in order to simplify the calculation schemes, it is necessary to carry out a deep system analysis of both the physics of the processes and the physical connections of the structural elements, boundary conditions, etc., which makes it much more difficult.



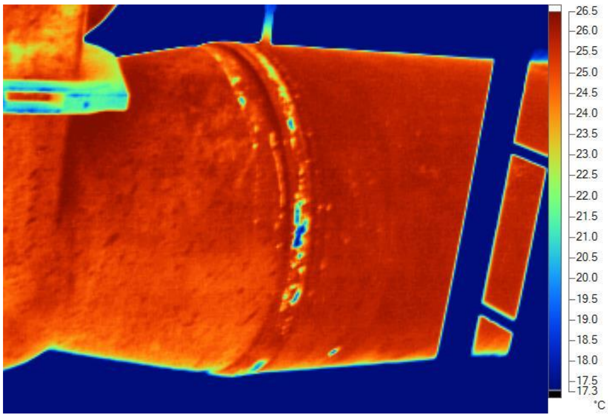
a



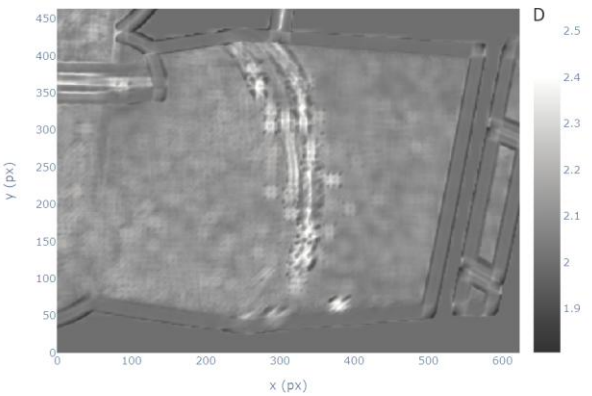
b

Fig. 2. Thermogram of the pipe in the vicinity of the weld seam (a); calculated fractal dimensions map of the thermogram (b)

Fractional-order calculus on thermographic data gives an additional analytic measure compared to traditional methods and techniques. By considering the thermal image in these three dimensions, fractal dimension maps were computed and presented on Fig. 2,b and Fig. 3,b. The fractal dimension (D) map is notably sensitive to temperature fluctuations, but also it also statistically smooths the distribution and it highlights edge features. In our case, *D* values were observed around 2.0 to 2.2. Worth noting, when $D \to 2$ it indicates a completely flat surface without any variations, which contributes to a sharp peak on Fig. 4. It is explained by the presence of cold background objects (in blue) on Fig. 3,a. In our study, we identified areas of variation that suggest the presence of local structural defects in the pipe and they were areas of high contract of *D* values on fractal maps.



a



b

Fig. 3. Thermogram of the pipe in the vicinity of the weld seam (a); calculated fractal dimensions map of the thermogram (b)

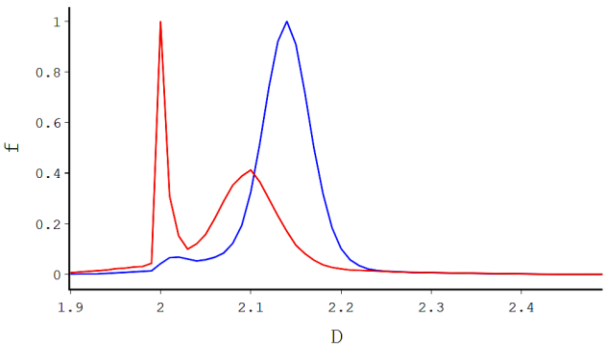


Fig. 4. Normalized plot of frequency distribution of calculated fractal dimensions of thermograms: blue – Fig. 2,a, red – Fig. 3,a

Lower *D* (~2) with a rapid transition to higher *D* (~2.15) were more prevalent in regions with heterogeneities and higher temperature gradients. Predominantly, the pipe's surface had D ~2.05-2.15, corresponding to subtle variations of temperature in small areas. Worth noting, area 3 from Fig. 2,a did not contribute to very high fractal dimension contract as the "cold" technological areas near the connection. It is explained by relatively small temperature gradients. The found results correlate with the literature findings in [1, 14]. To point out in general, the fractal dimension mapping is not a primary metric, as *D* is derived from temperature distributions. Therefore, it serves as a supplementary tool for analysis.

MONITORING OF THE SOIL SURFACE ABOVE UNDERGROUND COMMUNICATIONS

The above-mentioned requirements are becoming more relevant. Namely, it is necessary to develop means of operational remote monitoring of the state of the thermal energy transmission system to the final absorber. Moreover, this system should be able to identify places of excessive loads on the ground, caused by the presence of heavy military equipment, as well as the places of arrival of projectiles, even after the elimination of external signs. The methods of IR – radiometric control with their appropriate adaptation allow such monitoring. The software with which the devices are equipped does not contain a complete set of computing tools, but the data conversion function in various formats allows them to be used in the author's software.

There is a need to formulate a set of features, both by belonging to the interval of intensity characteristic of a potentially dangerous area, and by a weighting factor that depends on the number of pixels *k* occupied by the image and its specific weight in the area of a homogeneous field, which belongs to the image formed by object of a similar structure (pipeline, asphalt surface, plant surface, water surface, etc.). To do this, it is necessary to perform a preliminary breakdown of the image into temperature intervals ΔT_{n1-n2}. The method of solving this problem is the clustering of the radiation temperature field *T(x,y,z)*, by grading their components according to the signs of belonging to certain structural and radiative intensity classes. The primary step is the segmentation of the obtained image by temperature intervals, then each cluster will be subjected to a criterion evaluation according to belonging to a structural class. For this purpose, an observation channel in the infrared range with fixation of intensity values $I(x,y,t)$ will be used. By dividing the observed radiation temperature field into l intensity intervals, we obtain a vector of classification features

$$K = (T, I,\ k_1,\ ...,\ k_n). \quad (4)$$

If the set of thermographic data contains matrices with a set of intensity fields $\sum_1^N I = \{k_1,\ r_2,\ ...,\ k_N\}$. Each component k_I is the number of pixels with intensity. One of the approaches to detecting signs of a disturbed soil heat exchange regime is the entropy analysis of the radiation temperature field using the Shannon entropy calculation.

$$H_k = -\sum_{i=0}^{I} \frac{n_i}{N} \ln \frac{n_i}{N}, \quad (5)$$

where n the number of pixels with radiation temperature values I (in the case of segmentation, the temperature intervals correspond to them) N is the total number of pixels. This approach to thermographic data processing was applied in the work [13, 14]. Observing the dynamics of changes in the temperature field, we expect that the areas of the soil that experienced excessive loads will have excellent thermophysical characteristics [15, 16].

At the same time, during the daily cycle of temperature changes at a certain time of the day, the transient processes on these areas of the soil will manifest themselves most clearly. It is proposed to establish this time by entropy analysis of the radiation temperature field, namely by searching for the time when the entropy will be minimal. (we consider that the case of maximum entropy is a marginally balanced distribution of values, and the minimum is characterized by temperature manifestations due to the presence of areas with excellent values of thermal conductivity and heat capacity). In Fig. 5 graphs of the distribution of information entropy values (according to (5)) for cases with preliminary segmentation of the field for a certain number of intervals are given.

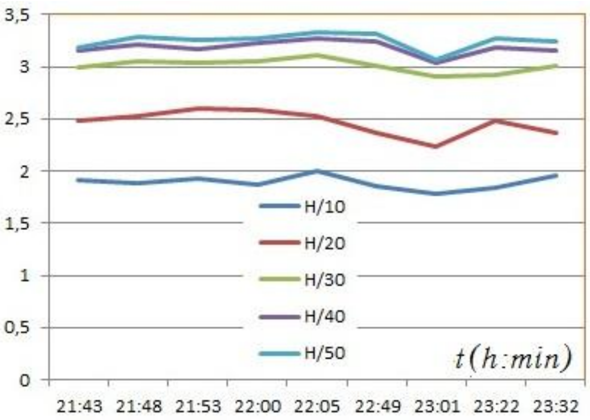


Fig. 5. Entropy distribution for different values of preliminary clustering of the temperature field (from 10 to 50 intervals)

As can be seen at the time of day at 11:01 p.m., entropy takes on a minimum value, and at this time one should expect the most visible manifestation of thermal anomalies on the ground.

In Fig. 6, on the thermogram of a soil plot, there is a clear trace of construction equipment. The thermogram was obtained at the specified time of the minimum entropy value. Thus, it is possible to track the places of hot loads on the soil, as well as the traces caused, for example, by the destruction of the support on which the pipeline is laid. This gives reason to develop such a method of monitoring within the framework of the requirements of the document "On Approval of Requirements for Systems of Emergency Cooling of Nuclear Fuel and Heat Removal to the Final Absorber" and actual modern problems [17].

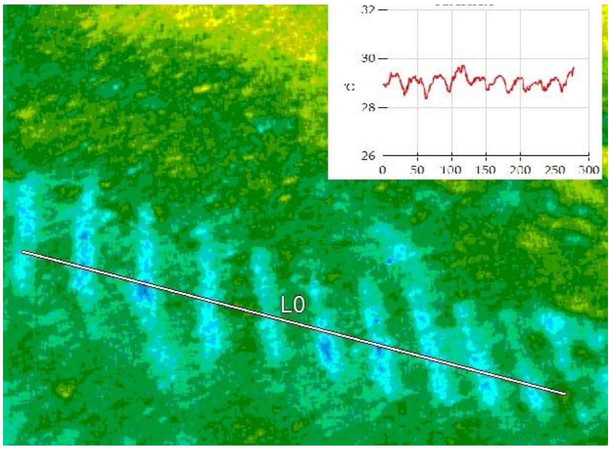


Fig. 6. Thermogram of a plot of soil with traces of construction equipment (above radiation temperature distribution along the line L0)

CONCLUSIONS

The application of thermographic monitoring of the state of the technical water supply system at the NPP becomes effective under the condition of maintaining a database of measurements linked to the time coordinate. To assess the potential emergency of the detected thermal anomaly on objects with high thermal conductivity (for example, open pipelines), it is advisable to use a fractal analysis device for quantitative assessment of the gradient of the thermal field. To assess the loads on the soil in the places where underground pipelines are laid, it is advisable to carry out an entropy analysis of the radiation temperature field, in order to establish the time of the most likely manifestation of areas with anomalous heat exchange with minimal entropy. Thermographic analysis revealed a good state of the pipe, and identified an area of a potential defect. Fractal mapping was also performed using thermograms as a source of data. Fractal dimensional mapping is a tool to evaluate the geometrical parameters of objects such as separate contours and areas of inhomogeneities etc. in statistical sense.

ACKNOWLEDGEMENTS

The research presented in this article was performed by financial support of the Ukrainian state budget program "Support for the development the priority areas of scientific researches" (Budget Financial Code 6541230).

REFERENCES

1. S.E. Donets, V.V. Lytvynenko, E.M. Prokhorenko, O.A. Startsev, V.V. Shatov. Thermographic Analysis of Damaged and Polluted Water Pipe Enhanced with Fractal Methods // *Procedia Structural Integrity*. 2024, v. 59, p. 367-371.

2. V. Vasagar, M.K. Hassan, A.M. Abdullah, A.V. Karre, B. Chen, K. Kim, N. Al-Qahtani, T. Cai. Non-destructive techniques for corrosion detection: A review // *Corrosion Engineering, Science and Technology*. 2024, v. 59(1), p. 56-85

3. N.I. Bazaleev, V.V. Lytvynenko. Thermo-graphic defectoscopy of materials in nuclear power engineering based on the analysis of the dynamics of

thermoproduction of defects at induction activation // *Problems of Atomic Science and Technology*. 2018, N 5(117), p. 154-161.

4. J. Latif et al. Review on condition monitoring techniques for water pipelines // *Measurement*. 2022. v. 193, p. 110895.

5. S.N. Meshkov, R.P. Orel. Application of tomography to determine the state of pipeline metal // *Tehnicheskaya diagnostika i nerazrushayushchij control.* 2015, N 2, p. 30-33 (in Russian).

6. M. Ismon, I. Zaman, N.C. Seng. Thermography analysis on welding defects and internal erosion of carbon steel pipeline // *ARPN Journal of Engineering and Applied Sciences.* 2016, v. 11, N 12, p. 7498-7502.

7. Y. Ren, R. Skilton. A review of pipe cutting, welding, and NDE technologies for use in fusion devices // *Fusion Engineering and Design.* 2024, v. 202, p. 114396.

8. P. Venegas, E. Ivorra, M. Ortega, I.S. de Ocáriz. Towards the Automation of Infrared Thermography Inspections for Industrial Maintenance Applications // *Sensors*. 2022, v. 22, p. 613; https://doi.org/10.3390/s22020613

9. S.E. Donets, V.V. Lytvynenko, O.A. Startsev, Yu.F. Lonin, A.G. Ponomarev, V.T. Uvarov. Fractal analysis of fractograms of aluminum alloys irradiated with high current electron beam // *Physics and Chemistry of Solid State*. 2023, v. 24, issue 2, p. 249-255.

10. V.F. Klepikov, V.V. Lytvynenko, Yu.F. Lonin, A.G. Ponomarev, O.A. Startsev, V.T. Uvarov. Fractality of fractures of aluminum and titanium alloys irradiated by intensive electron beam // *Journal of Nano- and Electronic Physics*. 2016, v. 8, issue 3, Article number 03009.

11. K.C. Clarke. Computation of the fractal dimension of topographic surfaces using the triangular prism surface area method // *Computers & Geosciences.* 1986, v. 12(5).

12. N. Lam et al. An evaluation of fractal methods for characterizing image complexity // *Cartography and Geographic Information Science*. 2002, v. 1(29), p. 25-35.

13. J.C. Mello Román, J.L. Vázquez Noguera, H. Legal-Ayala, et al. Entropy and Contrast Enhancement of Infrared Thermal Images Using the Multiscale Top-Hat Transform // *Entropy.* 2019, v. 21, p. 244; doi:10.3390/e21030244

14. M.I. Bazaleev, V.V. Bryukhovetsky, S.E. Donets, V.V. Lytvynenko, O.A. Melyakova, E.M. Prokhorenko, O.A. Startsev, V.V. Shatov. Thermographic monitoring of nuclear power plant's spray ponds using infra-red data processing methods // *Problems of Atomic Science and Technology.* 2023, N 2(144), p. 148-152.

15. M.P. Luong. Introducing infrared thermography in soil dynamics // *Infrared Physics and Technology.* 2007, v. 49, p. 306-311.

16. M. Fahmy, P. Eng, et al. Detecting and location leaks in underground water main using thermography // *26 Int. Symposium on Automation and Robotics in Construction*. 2009, p. 61-67.

17. V. Dolin, O. Kopylenko, Yu. Zabulonov. Global nuclear threats caused by russis's invasion od Ukraine (at the place of foreword) // *Geochemistry of Technogenesis.* 2022, p. 7-17; DOI https://doi.org/10.32782/geotech2022.35.01

Article received 26.07.2024

МЕТОДИ ОБРОБКИ ДАНИХ ТЕРМОГРАФІЧНОГО МОНІТОРИНГУ СИСТЕМ ВОДООХОЛОДЖЕННЯ АЕС

М.І. Базалєєв, С.Є. Донець, В.В. Литвиненко, Є.М. Прохоренко, О.А. Старцев, В.В. Шатов

Розглянуто підходи до аналізу даних термографічних вимірювань, що були проведені на ЗАЕС з метою оцінки стану надземних та підземних комунікацій охолоджуючої води. Були запропоновані способи аналізу топології поверхні розподілу радіаційної температури на зварювальному шві надземного трубопроводу з метою виявлення потенційно небезпечних ділянок. Запропоновано підхід до виявлення зовнішніх навантажень на поверхні грунту.