

Article

Method of Quality Control of Nuclear Reactor Element Tightness to Improve Environmental Safety

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Abstract: Low carbon dioxide (CO₂) emissions make nuclear energy crucial in decarbonizing the economy. In this context, nuclear safety, and especially the operation of nuclear power plants, remains a critical issue. This article presents a new fractal cluster method of control that improves the quality of assessing fuel element cladding integrity, which is critical for nuclear and environmental safety. The proposed non-destructive testing method allows for detecting defects on the inner and outer cladding surfaces without removing the elements from the nuclear reactor, which ensures prompt response and prevention of radiation leakage. Studies have shown that the fractal dimension of the cladding surface, which varies from 2.1 to 2.5, indicates significant heterogeneity caused by mechanical damage or corrosion, which can affect its integrity. The density analysis of defect clusters allows quantifying their concentration per unit area, which is an important indicator for assessing the risks associated with the operation of nuclear facilities. The data obtained are used to assess the impact of defects on the vessel’s integrity and, in turn, on nuclear safety. The monitoring results are transmitted in real time to the operator’s automated workstation, allowing for timely decision making to prevent radioactive releases and improve environmental safety. The proposed method is a promising tool for ensuring reliable quality control of the fuel element cladding condition and improving nuclear and environmental safety. While the study is based on VVER-1000 reactor data, the flexibility of the proposed methodology suggests its potential applicability to other reactor types, opening avenues for broader implementation in diverse nuclear systems.

Keywords: nuclear safety; environmental safety; quality control; fuel element; radiation release prevention; nuclear reactor elements; non-destructive testing



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1. Introduction

Low carbon dioxide emissions make nuclear energy vital for decarbonizing the economy, significantly contributing to global climate goals [1,2]. However, nuclear safety, particularly in nuclear power plant operations, remains a critical challenge. The integrity of fuel element (FE) cladding is essential, as defects can lead to radioactive material leaks, endangering personnel and the environment. Kupriyanov et al. [3] developed a tolerance control approach

for cladding quality, while Trishch et al. [4] assessed safety risks using qualimetric methods. Cherniak et al. [5,6] proposed methodologies for occupational safety in nuclear systems, and Kupriyanov et al. [7] modeled tolerance impacts on cladding integrity. Ginevicius et al. [8] evaluated negative variations in municipal nuclear safety contexts. Recent studies highlight the importance of advanced, non-destructive methods for assessing cladding tightness, moving beyond traditional techniques that often lack precision or timeliness. Qian and Liu [9] introduced a fault diagnosis method using neural networks, while Fiorina et al. [10] developed multi-physics tools for reactor analysis. Ding et al. [11] proposed real-time reliability analysis for micro-milling, Wang et al. [12] advanced multisensor fault diagnosis, and Belles [13] detailed key components in small modular reactors.

The fractal cluster method employs fractal geometry and cluster analysis to evaluate fuel element cladding integrity, enhancing nuclear safety through real-time defect detection. The fractal dimension measures surface complexity, indicating damage or corrosion, while the cluster density quantifies defect concentration, both critical for preventing radioactive leaks. This approach builds on established fractal and clustering concepts from materials science and fault detection, adapting them innovatively for nuclear applications. It enables non-destructive monitoring without removing the cladding, offering a significant advancement in operational and environmental safety.

The current methods struggle with real-time defect detection and automated monitoring; therefore, innovative approaches are required for the distribution of quality indicators and their impact on safety [14–16]. This paper introduces a fractal cluster method for enhancing the FE cladding integrity assessment, aiming to improve nuclear and environmental safety through timely, automated defect detection [17–21].

This paper aims to present a fractal cluster method for monitoring the fuel element cladding tightness, which allows for automated defect detection in real time. This method provides a qualitative analysis of the cladding condition and can significantly increase the nuclear safety level by timely detection of threats to the cladding integrity. The study results show that the implementation of the method can be an important step in the quality improvement of the monitoring system for the tightness of a nuclear reactor's fuel element cladding at a nuclear power plant.

2. Materials and Methods

The VVER-1000 nuclear reactor contains 163 fuel assemblies. Each fuel assembly contains up to 300 FEs (Figure 1), and each FE can be depressurized, leading to contact of nuclear fuel with the coolant, which is an emergency situation [22–26].

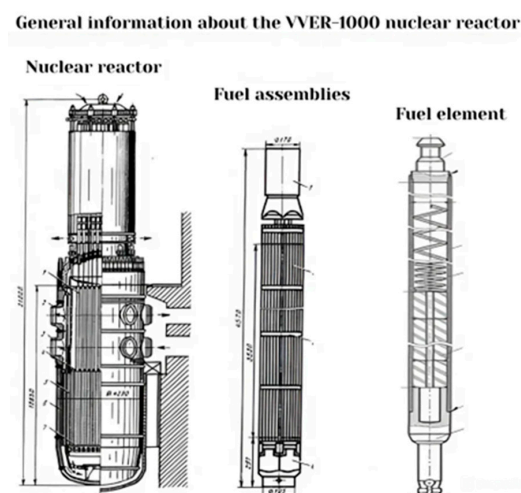


Figure 1. VVER-1000 nuclear reactor, fuel assembly, and FE. Source: elaborated by the authors.

It should be clarified that the experimental studies were not conducted on a working reactor or with spent fuel. Instead, specially prepared samples of fuel element cladding, i.e., metal hollow cylindrical tubes that were not in operation, were used. These cladding samples, designed to replicate TVEL fuel element cladding, were manufactured by the National Aerospace University “Kharkiv Aviation Institute” in Kharkiv, Ukraine.

These samples were pre-analyzed for mechanical damage and cleaned of contaminants to ensure measurement accuracy. This approach allowed for the simulation of leakage control in a controlled laboratory environment.

Depressurization can occur due to basic physical processes in the structure of the FE cladding material, such as radiation hardening of the material, reduction of material plasticity, radiation creep of the material, radiation growth, and thermomechanical interaction between the cladding and fuel [15,27–32].

The following **mechanisms cause damage to the FE cladding**: primary hydrogenation of the cladding, fretting corrosion of the cladding, debris damage to the cladding, interaction of nuclear fuel with the cladding, debris in the coolant, and unknown causes (20%) [23,33–37].

To date, the following methods are used to control the tightness of the FE cladding:

Acoustic emission—a method based on detecting and analyzing sound waves generated by crack formation or other defects in a material. It allows for continuous FE monitoring during reactor operation.

Although the acoustic emission method provides continuous monitoring, it has drawbacks. First, it is sensitive to external noise, which can distort the results. Second, this method cannot accurately localize the source of defects at all times, as sound waves can reflect from other structures, complicating the analysis [38–42].

Ultrasonic tomography—the use of ultrasonic waves to obtain three-dimensional images of the internal FE structure. It makes detecting defects, such as cracks, pores, or material inhomogeneities, possible.

Ultrasonography is an effective method for detecting defects but has limited penetration depth of ultrasonic waves into the material, which can lead to missed detection of small cracks or inhomogeneities that are deeper in the structure. In addition, ultrasound requires good surface contact, which can be problematic in the case of worn or contaminated claddings.

Fiber-optic sensors use fiber-optic technology to measure FE temperature, deflections, and vibrations. Fiber-optic sensors are resistant to radiation and allow for real-time monitoring.

Fiber-optic sensors are highly resistant to radiation and can be monitored in real time; however, their installation can be complex and costly, and they can be sensitive to mechanical tension, leading to false readings [43–49].

X-ray computed tomography—a method based on using X-rays to obtain three-dimensional images of the FE’s internal structure. It allows for detecting defects and assessing changes in the cladding geometry.

X-ray computed tomography provides detailed images of the internal structure but has safety limitations due to the use of ionizing radiation. It can be dangerous to personnel and the environment if used frequently. In addition, the high equipment and operation costs can hinder this method’s implementation [50–54].

Magnetic tomography—the use of a magnetic field to obtain images of the internal structure of a cladding. It allows for detecting defects and assessing changes in the material’s magnetic properties, which may indicate mechanical damage.

Magnetic tomography is a powerful tool for detecting defects, but its use is limited in conditions of high background radiation levels, as magnetic fields can be distorted. The method also requires significant time for image acquisition and data analysis [55–59].

The hydrostatic method involves immersing the fuel assembly in water, where a certain pressure is created. If the cladding has defects, air or gases inside the FE escape, forming bubbles on the water surface, indicating the presence of damage and allowing for the assessment of the cladding integrity.

The hydrostatic method is simple and effective for detecting fuel cladding leaks but has its drawbacks: it does not allow for determining the exact nature of the defect and is not suitable for assessing internal damage. In addition, this method may not be suitable for cladding with large dimensions or complex shapes [60–64].

Eddy current detection involves detecting changes in electric currents that pass through a material under the influence of an alternating magnetic field. When an alternating current passes through the FE cladding, it generates eddy currents that can be distorted by defects such as cracks or pores. Special sensors measure these changes, allowing defects to be detected and their characteristics to be evaluated without destroying the material.

Eddy current detection of flaws is an effective method for monitoring the tightness of the FE cladding, as it provides high accuracy and real-time monitoring. However, the method has its drawbacks: its measurement effectiveness is reduced under contamination or corrosion on the surface. In addition, eddy current detection cannot always detect defects located deep in the material, as the signal can be attenuated or distorted [65–70]. Figure 2 depicts the principle of eddy current detection.

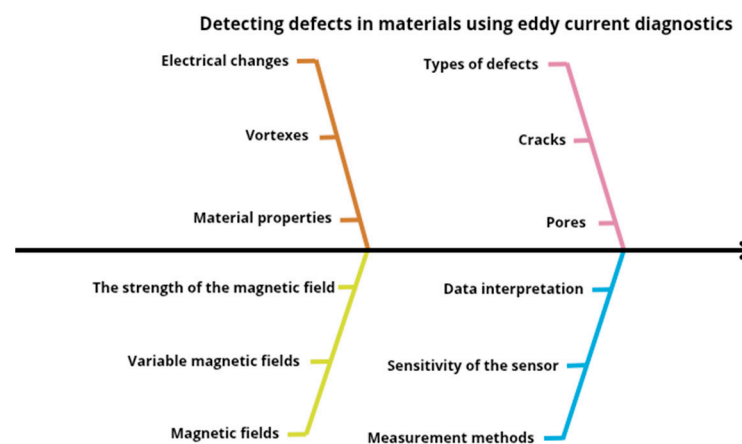


Figure 2. Detecting defects in materials using eddy current diagnostics. Source: elaborated by the authors.

However, all these methods have common disadvantages:

Many control methods, such as acoustic emission and eddy current detection, are sensitive to external noise and contamination, which can distort the measurement results. Ultrasonic imaging has limitations in depth penetration, which can lead to missed defects located deep in the material. Many of these methods cannot accurately determine the nature of the defects or their impact on the integrity of the cladding, which complicates subsequent repair decisions. Some of them require considerable time for analysis, which slows down the monitoring of the FE condition.

The detection of depressurized FEs occurs only after depressurization, and fission products are detected in the gas collector or coolant, indicating that fission products have already leaked. At the same time, no clear criteria for the tightness of the cladding are established, and control is limited to the outer surface. Most methods require the removal of

the fuel assembly to inspect each element. All these methods do not work in an automated mode and do not transmit information to an automated operator's workstation about the state of the cladding's tightness.

These shortcomings emphasize the need to develop a new method for monitoring the tightness of FE cladding, which will eliminate existing problems and provide more effective control.

3. Experiment

3.1. Research Conducted

The fractal dimension is an important parameter for assessing the complexity and heterogeneity of the fuel cladding surface. This study used fractal analysis to determine the condition of the inner and outer cladding surfaces to detect damage that may affect the safety of nuclear power plants.

The fractal dimension D can be calculated using the box-counting method. According to this method, the fractal dimension is determined by the formula:

$$D = \lim_{e \rightarrow 0} \frac{\log(N(e))}{\log\left(\frac{1}{e}\right)}, \quad (1)$$

where D —fractal dimension; $N(e)$ —the number of boxes (or clusters) with the size that cover the surface; and e —box size.

The following stages were used to conduct the research:

1. Sample preparation: Several hollow metal tubes of cylindrical shape were selected and subjected to a preliminary analysis of mechanical damage. The samples were cleaned of contaminants to ensure the accuracy of the measurements.
2. Data collection: The box-counting method measures the fractal dimension by analyzing the inner and outer surfaces of the fuel element cladding separately. A digital microscope (0.1 μm resolution) images the outer surface, and an endoscopic attachment images the inner surface, producing distinct datasets. These independent images ensure that defect clusters are clearly attributed to their respective surfaces, preventing confusion. This dual-surface approach improves defect detection accuracy compared to single-surface methods like eddy current testing. The imaging resolution for both the digital microscope and endoscopic attachment is 0.1 μm , enabling precise defect detection, with each 50 cm^2 sample analyzed in approximately 10 min, including imaging and processing. As experiments used fuel-free cladding samples, radiation effects were not a concern.
3. Image analysis: the images were processed using image analysis software that automatically determined the number of boxes of $N(e)$ for each scale.
4. Calculating the fractal dimension: the fractal dimension was calculated using the above formulation based on the obtained data on $N(e)$.
5. Statistical analysis: to ensure the reliability of the results, a statistical analysis of the obtained values of the fractal dimension was performed, including the calculation of the mean and standard deviation.

The method's accuracy was assessed with a standard deviation of ± 0.05 for fractal dimension measurements across five 50 cm^2 samples, indicating high reliability but sensitivity to surface contamination, which may introduce minor errors if not fully removed during preparation. Calibration of imaging equipment was critical to minimize variability, though small defects ($< 0.1 \mu\text{m}$) could be missed due to resolution limits.

3.2. Fractal Dimension Measurement Results

To clarify the fractal cluster method's application, experiments involved mechanically stressing cylindrical metal tube samples simulating FE cladding, followed by high-resolution imaging to capture surface defects. The fractal dimension (D) was calculated using the box-counting method, where images were processed with software to count defect-covering boxes across multiple scales, yielding average D values from five sample sets (50 cm² each). Table 1 presents these results (internal: 2.5, external: 2.1), reflecting the defect complexity after 48 h of stress exposure. This approach ensures repeatable, statistically reliable detection of cladding damage.

Table 1. Detection of fractal dimensionality on cladding surfaces.

Surface	Fractal Dimensionality D
Internal	2.5
External	2.1

Source: elaborated by the authors.

The studies have shown that the fractal dimension for the inner and outer surfaces of the FE cladding varies from 2.1 to 2.5 (Table 1). This indicates significant heterogeneity on the surface, which may result from mechanical damage or corrosion.

The fractal dimension values indicate that mechanical damage can seriously impact the integrity of the fuel cladding. An increase in fractal dimensionality indicates an increase in the number of clusters and their complexity, which can lead to a decrease in heat transfer efficiency and an increased risk of radioactive material leakage.

Cluster density is a critical indicator for assessing the condition of the fuel cladding. It reflects the amount of mechanical damage per unit surface area, which can significantly affect the safety and efficiency of nuclear power plants.

3.3. Determining the Density of Clusters

The cluster density can be calculated by the formula:

$$\rho = \frac{N}{A}, \quad (2)$$

where ρ —cluster density (number of clusters per unit area); N —total number of detected clusters; and A —surface area (internal or external).

This formula allows for assessing the extent to which the surface of the cladding is exposed to damage and is an important indicator for further analysis.

The following steps were performed to determine the density of clusters in the studied FEs:

1. Data collection: The preliminary analysis of the FE samples was followed by measurements using imaging techniques, such as X-ray computed tomography and ultrasonic scanning. These methods allowed for the detection of cracks, pores, and other clusters on the surface.
2. Image processing: the acquired images were processed using image analysis software that automatically determined the number of clusters N in area A .
3. Density calculation: the cluster density was calculated using the above formula based on the data regarding the number of clusters N and the area A .

3.4. Cluster Density Measurement Results

The measurement results showed that the cluster density on the inner and outer surfaces of the fuel cladding varies depending on the operating conditions and operating time (Table 2).

Table 2. Density of clusters in the cladding.

Surface	Number of Clusters N	Area A (cm ²)	Clusters Density ρ (Clusters/cm ²)
Internal	150	50	30
External	80	50	1.6

Source: elaborated by the authors.

An example of processing one sample is provided to illustrate the correctness of data acquisition. A 50 cm² shell surface was analyzed using the software for analyzing X-ray tomography images. As a result, 120 clusters (defects) were detected, which yielded a density of 2.4 clusters/cm². This example confirms that it is possible to accurately determine the density of clusters without disclosing the full primary data, which are restricted for commercial and confidentiality reasons.

The data obtained indicate that the inner surface of the cladding has a higher density of defects than the outer surface. This may be due to the influence of high temperatures and pressures during the FE operation. An increase in the density of defects on the inner surface may indicate an increased risk of radioactive material leakage; it requires special attention when monitoring the fuel cladding condition.

Thus, fractal analysis is a powerful tool for monitoring the state of the fuel cladding and can be used for the timely identification of potential threats to the safety of nuclear power plants.

4. Results

A mathematical model was developed to demonstrate the principle of the fractal cluster method.

The fractal cluster method can be used to assess the state of the inner and outer surfaces of the FE cladding and analyze their cross-section.

Formulas for calculating the fractal dimension and cluster density on the surface of the fuel cladding were provided in the previous section.

A qualitative calculation of the quality of the cladding state requires an estimate of the change in the cross-sectional geometry, which is calculated by the formula:

$$A = \pi(R_{outer}^2 - R_{inner}^2), \quad (3)$$

where R_{outer} —the radius of the outer cladding; and R_{inner} —the radius of the inner cladding.

This formula allows for estimating how mechanical damage can affect the cross-sectional area, which, in turn, will affect heat dissipation and cladding integrity.

The equation for the radial tension σ_r is used to estimate the mechanical tensions on the cross-section of the cladding:

$$\sigma_r = \frac{P \cdot R_{inner}}{t^2}, \quad (4)$$

where P —internal pressure; R_{inner} —radius of the inner cladding; and t —cladding thickness.

This formula allows for estimating how the internal pressure affects the mechanical tensions in the cladding.

The corrosion rate equation to analyze corrosion damage on the surface of the cladding:

$$v = k \cdot C^n, \quad (5)$$

where v —corrosion rate; k —corrosion rate constant; C —concentration of corrosion agent; and n —reaction order.

This formula allows for the assessment of how corrosion processes affect the cladding integrity. The use of these mathematical formulas in the fractal cluster method allows for a detailed assessment of the condition of the fuel cladding's inner and outer surfaces and their cross-sections.

The general formula for the fractal cluster method of FE cladding leakage integrates various aspects, such as the fractal dimension, defect density, changes in cross-sectional geometry, mechanical tensions, and corrosion processes:

$$F = k_1 \cdot D + k_2 \cdot \rho + k_3 \cdot A + k_4 \cdot \sigma + k_5 \cdot v, \quad (6)$$

where F —a general indicator of the state of the FE cladding; D —fractal dimension of the surface (determines complexity and heterogeneity); ρ —defect density (number of defects per unit area); A —cross-sectional area (affects heat dissipation and integrity); σ —mechanical tensions (assessing the impact of internal pressure); v —corrosion rate (affects the integrity of the cladding); and k_1, k_2, k_3, k_4, k_5 —weighting factors that reflect the importance of each parameter in the overall cladding condition indicator.

These formulas allow for integrating various aspects of the fractal cluster method to assess the condition of the fuel cladding. They can be used to monitor and assess risks associated with mechanical damage, corrosion, and other factors that affect the fuel cladding tightness and nuclear power plant safety.

The fractal cluster method's parameters, such as fractal dimension (D) and defect density (ρ), are tailored to assess cladding conditions typical of VVER-1000 reactors, ensuring relevance to their 163-fuel assembly design.

Figure 3 is a block diagram of the computational module of the fractal cluster method operation principle, where “No” denotes the “Number of defects” in English (Source: developed based on [71]). The FE cladding is divided into eight axial segments: scanning for defects on the inner and outer surfaces of the cladding is performed first. Then, the coordinates of the defect are stored, and the type and size of the defect are detected. It is determined whether the cladding is currently leaking, and information is transmitted to the operator's automated workstation for making an operational decision. All this occurs in real time without removing the fuel assembly from the nuclear reactor.

The fractal cluster method of controlling the tightness of the fuel cladding allows the analysis to be performed without removing the cladding from the fuel assembly.

In contrast to the known methods, the fractal cluster method allows for determining whether the cladding is tight or damaged and tight, or whether it is depressurized according to the developed criterion of the FE cladding tightness. This, in turn, will reduce the downtime of the nuclear reactor and accelerate the process of scheduled inspection [43].

The developed method detects defects on the outer and inner surfaces and then determines their location on the axial segments and the type and size of defects. The obtained data are compared with the codes in the database of the nuclear reactor's pressure vessel leakage system and transferred to the automated operator workstation in real time [72].

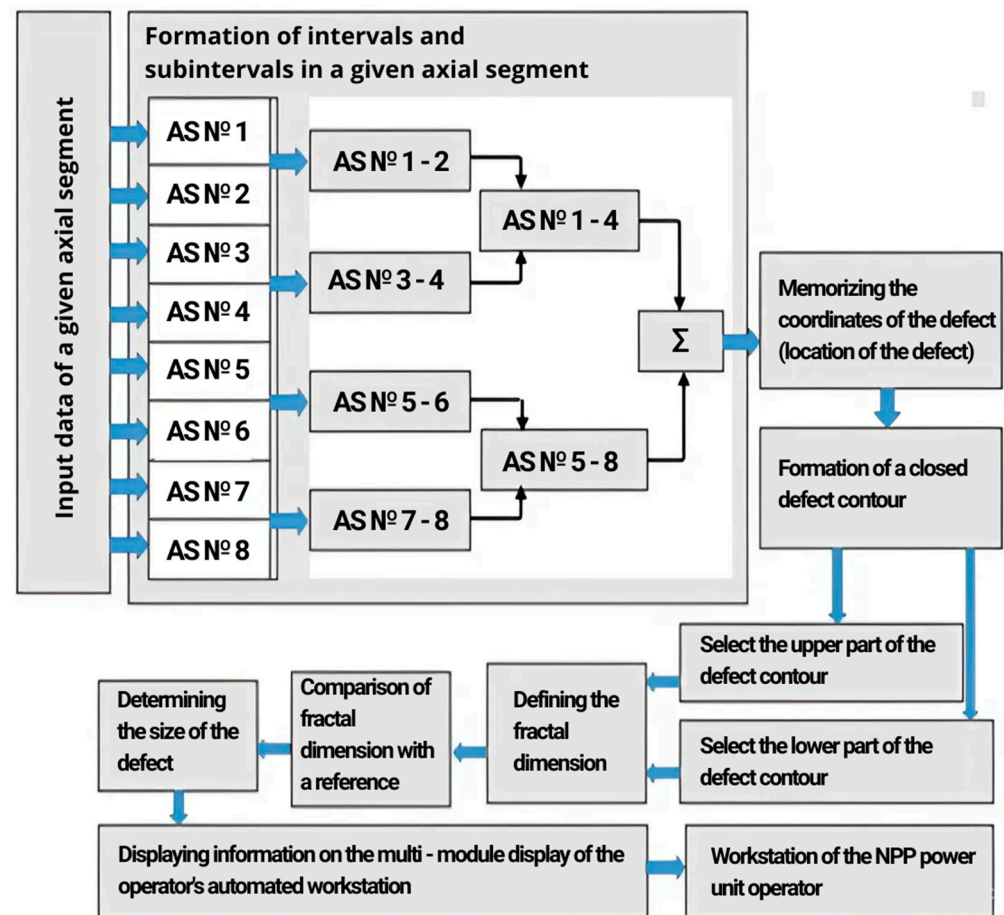


Figure 3. Block diagram of the computational module of the fractal cluster method's operation principle. Source: developed based on [71].

The method involves measuring several key parameters: fractal dimensionality (D), reflecting the complexity of the surface; density of defects (ρ), which assesses the degree of damage; cluster density (C), measuring the density of defects; and cluster size (R_c), which determines the average size of defects. All these parameters are measured using specialized imaging equipment that detects defects and evaluates their characteristics without destroying the cladding. Thus, the method provides comprehensive monitoring of the fuel cladding condition and timely detection of threats to the safety of nuclear power plants.

5. Discussion

The proposed fractal cluster method for monitoring the tightness of the fuel element cladding presents significant advantages compared to traditional control techniques. One of the most notable benefits of this method is its capability to continuously analyze the condition of the cladding without its removal from the fuel assembly. This continuous monitoring significantly enhances the quality of control processes and minimizes the risks associated with reactor operations, which is crucial for maintaining safety standards in nuclear facilities. Compared to traditional techniques like eddy current or hydrostatic methods, which often detect defects post-depressurization or require disassembly, the fractal cluster method's real-time analysis—evidenced by fractal dimension shifts from 2.1 to 2.5 (Table 1)—enables earlier intervention, reducing downtime and enhancing safety.

The fractal cluster method, initially designed for the VVER-1000 reactor, exhibits characteristics that may allow its application across various reactor types. For instance,

its adaptability could facilitate deployment in PWR (Pressurized Water Reactor) or BWR (Boiling Water Reactor) systems, thereby extending its utility beyond the current scope. Future research should aim to validate the method's effectiveness in these contexts.

Despite its effectiveness, the fractal cluster method is not without limitations. For instance, the accuracy of measurements can be adversely affected by factors such as contamination or corrosion on the surface of the cladding. Additionally, it is essential to consider that the fractal dimension, which ranges from 2.1 to 2.5, serves as an indicator of surface heterogeneity. This heterogeneity may arise from mechanical damage or ongoing corrosion processes that compromise the integrity of the cladding. Furthermore, a high cluster density on the inner surface of the cladding suggests an elevated risk of radioactive material leakage, which poses a serious concern for operational safety and environmental protection.

Research conducted in this area supports the assertion that the fractal cluster method is a powerful tool for assessing and controlling the tightness of fuel claddings. However, to maximize its effectiveness, it is crucial to account for external factors that could influence the analysis results. Future research should focus on enhancing data processing algorithms and integrating this innovative method into existing control systems to ensure a seamless transition and improved monitoring capabilities.

In conclusion, the fractal cluster method represents a significant advancement in ensuring nuclear safety and enhancing the quality of leakage control for fuel element claddings. Once the method's limitations can be addressed and its application can be refined, it could play a pivotal role in safeguarding nuclear operations and protecting public health and safety from potential hazards associated with radioactive materials.

6. Conclusions

The fractal cluster method for controlling the tightness of fuel element cladding has demonstrated its effectiveness in ensuring high-quality control of the cladding's integrity. This innovative method enables the detection of defects on the cladding's inner and outer surfaces without requiring its removal from the fuel assembly, allowing for direct application within the nuclear reactor. This capability significantly enhances the efficiency of response measures to potential nuclear safety threats, streamlining the inspection process and reducing downtime.

The method facilitates a comprehensive analysis of the cladding's structure, establishing a clear and reliable criterion for assessing the tightness of the FE cladding. By employing fractal geometry, the method can study the structure of the cladding material with damaging defects (macropores and microcracks), which is a porous heterogeneous structure with fractal properties of self-similarity and scalability. The necessary information is transmitted in real time to the operator's automated workstation, enabling informed and prompt decisions regarding the fuel cladding's integrity and overall safety status.

Research has indicated that the fractal dimension typically varies from 2.1 to 2.5, which suggests a notable surface heterogeneity potentially resulting from mechanical damage or other degradation processes. These factors can adversely affect the containment integrity and, by extension, the operational safety of nuclear power plants. An improved model of damage to the FE cladding considers fractal increases in the geometric parameters of the FE for established values of fractal dimensionality. Experimental studies of the FE cladding, using the skin effect, confirmed the theoretical results and showed the validity of choosing the practical use of the fractal dimensionality parameter as an effective criterion for assessing the hermeticity degree of an FE cladding. It has been experimentally established that a fractal dimensionality value of 2.68 corresponds to the maximum degree of damage to the cladding for a leaky FE.

Designed with VVER-1000 reactors in mind, this method addresses the specific cladding integrity challenges of their fuel assemblies, enhancing safety in such nuclear systems. Moreover, extending the validation of the method to other reactor types could significantly enhance its relevance and impact, ensuring wider applicability in the field of nuclear safety.

The effectiveness of this advanced method can be maximized by regular training of personnel on its proper utilization. The fractal cluster method holds substantial potential as an important tool for improving the quality control of fuel cladding leakage, which will help to strengthen nuclear and environmental safety and reduce risks associated with the operation of nuclear facilities. The method can be used to improve the model of damage to an FE cladding, considering structural and phase changes in the material of the cladding with damaging defects on the outer and inner surfaces to establish the actual criterion for assessing the FE hermeticity degree.

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Conflicts of Interest: The authors declare no conflicts of interest.

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