Л.Н. Гумилев атындағы Еуразия ұлттық университетінің ХАБАРШЫСЫ.
ISSN: 2616-6836. eISSN: 2663-1296

ФИЗИКА СЕРИЯСЫ/ PHYSICS SERIES / СЕРИЯ ФИЗИКА

IRSTI 29.31.29, 44.31.39
Article

https://doi.org/10.32523/2616-6836-2025-151-2-77-96

Quality Assurance Methods for Hydrogen Energy, Fuel Cells Using "Delta^4 Phantom+" Diode Matrix

A.M. Dossanbek[1], A.A. Baratova*[1], A.M. Kabyshev[1], K.Zh. Bekmyrza[1], M.M. Kubenova[1]

[1] *Institute of Physical and Technical Sciences, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan*

(E-mail: baratova_aa@enu.kz, aa.baratova@yandex.kz)

Abstract. Hydrogen energy systems require precise verification methods to ensure the efficiency and stability of fuel cells, similar to the high-precision techniques used in tomotherapy. A key stage in ensuring accuracy in radiation therapy is the verification of dosimetric plans, confirming that the delivered dose matches the planned values. Various physical and technical methods assess dose distribution accuracy.

The principles of precision verification in tomotherapy share striking similarities with diagnostic and quality assurance techniques in hydrogen energy. Fuel cells require meticulous monitoring of ion transport, energy distribution, and material stability to optimize performance. The methodologies developed for tomotherapy, particularly those utilizing the Delta^4 solid-state phantom, can be adapted for assessing spatial energy variations and charge transport efficiency in hydrogen fuel cells.

This study explores the capabilities of the Delta4 solid-state phantom, equipped with a two-dimensional diode detector matrix, for verifying tomotherapy plans delivered with the «Tomotherapy HD» linear accelerator. Dosimetric plan quality was assessed using gamma analysis based on international 3%/3 mm criteria, the standard in intensity-modulated radiation therapy. The operational advantages and limitations of the Delta^4 phantom were analyzed, including the impact of geometric and dosimetric parameters on measurement accuracy.

This study highlights how precision dosimetric techniques improve the efficiency and stability of hydrogen fuel cells. Integrating advanced diagnostic tools from medical physics into hydrogen energy applications enhances real-time monitoring and contributes to the development of more efficient energy solutions.

Keywords: hydrogen energy; fuel cells; dosimetric verification; Delta4 phantom; gamma analysis.

Received 3.02.2025. Revised 25.02.2025. Accepted 28.02.2025. Available online 25.06.2025

[1] *the corresponding author

Introduction

Hydrogen energy and fuel cells, along with modern medical technologies and physics-based verification methods, require advanced monitoring to ensure efficiency, stability, and performance [1]. As of now, over 37.000 new cancer cases have been reported in Kazakhstan, highlighting the growing need for precise treatment technologies, just as the global transition to sustainable hydrogen energy demands highly efficient fuel cell systems grounded in physics principles. Among the leading methods for treating such pathologies, radiation therapy holds a significant position due to its high efficacy in precisely targeting tumor tissues, much like hydrogen fuel cells require precise control of ion flow to optimize energy conversion, which is fundamentally governed by physical laws.

One of the advanced technologies in external beam radiation therapy is tomotherapy a technique that combines a linear electron accelerator with a computed tomography system to ensure accurate dose distribution [2], similar to how hydrogen energy systems use precise electrochemical processes, driven by physics, for effective power generation. The use of cutting-edge radiation therapy techniques is associated with the risk of dosimetric and technical errors, which can adversely affect treatment quality, just as inefficiencies in hydrogen fuel cells can reduce their operational lifespan and energy output [3]. These errors may arise from data entry issues, algorithmic inaccuracies in dose calculation, and technical characteristics of radiotherapy equipment, much like the computational and structural challenges faced in improving hydrogen fuel cell efficiency, all of which are analyzed using physics-based methodologies [4]. Ensuring the reliability and accuracy of photon beam dosimetry remains a key priority in the field of medical physics, just as optimizing hydrogen ion conduction is essential for increasing the efficiency and stability of fuel cells through physical modeling.

Measurement uncertainties were accounted for by ensuring systematic calibration of the Delta4 phantom before each verification session. Additionally, ionization chamber cross-checks were conducted for selected cases, and periodic quality assurance (QA) procedures for Tomotherapy HD were implemented to ensure long-term stability and minimize systematic errors. These steps enhance the reliability of the verification process.

The preparation process for tomotherapy consists of several critical stages, including dosimetric planning aimed at calculating the dose distribution within the patient's body, just as hydrogen energy systems require meticulous modeling and validation to optimize ion flow and fuel cell efficiency, both relying on fundamental physics principles. Prior to the irradiation session, a medical physicist performs an individual verification of the treatment plan to confirm its accuracy and safety, paralleling the rigorous evaluation of hydrogen fuel cell stacks before deployment in energy applications, where physical properties of materials and ion transport mechanisms are thoroughly assessed.

Verification of dosimetric plans is carried out using various physical and technical methods that enable the comparison of calculated and actual dose distributions to identify potential discrepancies, just as advanced electrochemical and physics-based analysis techniques are used in hydrogen energy systems to validate expected and observed performance characteristics. The continuous improvement of verification techniques remains a relevant objective in radiotherapy, aimed at enhancing treatment precision, just as ongoing research in hydrogen fuel cell technology seeks to improve power density, fuel utilization, and system longevity through advanced physical modeling.

Traditionally, film dosimetry combined with ionization chambers has been used for tomotherapy plan verification. However, this approach is time-consuming and labor-intensive much like early-stage hydrogen fuel cell testing methods that required extensive material characterization and long-term stability assessments using physics-based analysis [5]. Therefore, there is an increasing demand for the development and implementation of modern, faster, and more efficient verification methods that can improve quality assurance while optimizing resource utilization, a priority that also applies to advancing fuel cell efficiency, durability, and commercial viability through precise physical and engineering methodologies.

Methods

In this study, we propose an advanced method for verifying tomotherapy dosimetric plans using the «Delta^4 Phantom+» detector matrix (hereinafter referred to as Delta^4), developed by Scandidos (Uppsala, Sweden). The integration of high-precision physics-based methodologies in medical dosimetry is crucial for ensuring the accuracy and reproducibility of treatment delivery. Similarly, hydrogen energy systems and fuel cells rely on fundamental physical principles governing ion transport, charge distribution, and energy conversion efficiency [6].

The integrated Delta^4 software seamlessly connects with treatment planning systems (TPS) using the DICOM-RT standard, an approach analogous to computational simulations used in hydrogen fuel cell design, where accurate modeling of ion conductivity and electrochemical reactions is necessary for optimizing fuel efficiency and durability. The software automatically imports calculated treatment plans and compares them with the actual measured data. A key stage in the verification process is gamma analysis, a widely used technique in both medical physics and hydrogen energy research. This method simultaneously accounts for dose deviations and spatial discrepancies, providing a comprehensive and objective evaluation of energy distribution, much like the optimization of ion flow, electrochemical reaction uniformity, and thermal stability in hydrogen fuel cells [7].

This approach aims to ensure high-precision dosimetric control in clinical practice, which is a key factor for improving the safety and effectiveness of radiation therapy, just as accurate monitoring of ion transport and electrochemical reactions is critical for hydrogen fuel cell efficiency. The Delta^4 detector matrix is a solid-state phantom equipped with 1069 high-sensitivity p-type silicon diodes (Figure 1), similar to sensor arrays used in hydrogen energy applications for evaluating charge distribution and reaction kinetics. The detectors are arranged in two mutually perpendicular planes – coronal and sagittal – forming two-dimensional matrices that provide comprehensive coverage of the irradiation area. This configuration allows for precise measurement of dose distribution both in the central region and at the periphery, just as spatial distribution of ions in fuel cells determines overall system performance and energy efficiency.

Figure 1 – Delta[4] Phantom

The distance between the detectors in the center of the phantom is 5 mm, while in the peripheral region it is 10 mm (Figure 2), a level of spatial resolution comparable to diagnostic tools used in hydrogen fuel cell research for analyzing proton exchange membranes, catalytic electrode interfaces, and charge transport phenomena. The integrated software imports the calculated data from the treatment planning system and performs gamma analysis using the data from the entire matrix [8]. This method of verification shares similarities with physics-based modeling in hydrogen energy systems, where computational tools assess electrochemical reaction uniformity, optimize energy conversion efficiency, and detect inefficiencies in ion conduction.

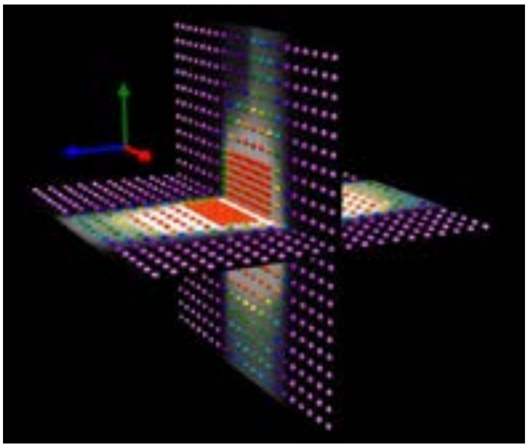

Figure 2 – Detector Arrangement in the Phantom

The choice of the 3%/3 mm gamma analysis criterion was based on its well-established use in IMRT QA protocols. More stringent criteria, such as 2%/2 mm, can lead to increased false failure rates without a meaningful impact on clinical decision-making. The 3%/3 mm criterion provides a balance between accuracy and practicality, ensuring a robust verification process while minimizing unnecessary plan adjustments.

Regular calibration and maintenance of both the Tomotherapy HD system and the Delta^4 phantom were conducted according to manufacturer recommendations. This includes pre-session recalibrations of Delta^4, software updates, and periodic beam profile and output stability checks to maintain precision in dose delivery.

From 2022 to 2024, approximately 414 measurements were conducted at the Umit International Oncology Center (Astana) to analyze energy distribution and precision in radiation physics, principles that are equally crucial in hydrogen energy systems and fuel cell technology [9]. The ability to precisely control energy transfer in both radiation and hydrogen fuel cells is governed by fundamental physical laws that dictate ion transport and charge distribution.

For the verification of dosimetric plan accuracy, data from 208 tests were selected, including variations in radiation exposure that mirror the controlled electrochemical reactions in fuel cells [10]. Ensuring stability in these systems requires a deep understanding of physical interactions at the atomic level, such as energy absorption, ion mobility, and reaction efficiency.

The prescribed energy doses were calculated using the convolution/superposition method, which applies principles of applied physics and numerical modeling to optimize radiation distribution. Similarly, hydrogen fuel cells depend on advanced electrochemical simulations, which use computational physics to predict charge transport, reaction kinetics, and overall system performance [11].

Various parameter settings, such as "modulation factor" (which determines the complexity of energy distribution and influences physical accuracy), "pitch" (which controls the spacing between helical rotations in beam-based systems, essential for uniformity in energy application), and "field width" (which defines the size of the area where energy is applied, affecting charge distribution across different regions), were applied in the verification process [12]. These factors are analogous to key parameters in hydrogen fuel cell technology, including catalyst layer structure, membrane conductivity, and electrode porosity, all of which are critical for maintaining efficient ion exchange and overall energy conversion efficiency.

Results

The verification of energy distribution and precision control was conducted for 208 experimental cases using the Delta^4 phantom on the "Tomotherapy HD" system, a process rooted in advanced physical principles that also apply to hydrogen energy systems and fuel cell technology. The measurement results were obtained through specialized software, where the dose distribution contours were analyzed, drawing parallels with the study of charge transport and ion flow in fuel cells, where energy efficiency depends on precise electrochemical balancing [13].

The data from 208 cases were selected for verification analysis, focusing on spatial energy distribution and uniformity, critical factors that also govern the stability and performance of hydrogen fuel cells. Ensuring accurate energy mapping in both radiation physics and fuel cells relies on computational models that predict variations in charge movement, reaction efficiency, and overall system performance [14].

The measurement approach involves overlaying calculated and experimental data, identifying deviations in energy absorption and distribution, much like real-time monitoring of hydrogen ion flux in electrochemical cells. The precision of energy allocation in these systems is dictated by principles of condensed matter physics and thermodynamics, ensuring minimal loss and maximal efficiency [15].

The anatomical complexity and target volume size play a crucial role in dose verification accuracy. Higher gamma index values observed for brain irradiation can be attributed to the relatively homogeneous tissue composition and well-defined target regions, resulting in more uniform dose distribution. Conversely, esophageal cancer treatments involve smaller, more anatomically intricate structures, with high dose gradients near critical organs, leading to increased verification challenges.

Figure 3 presents one of the results of absolute energy measurements obtained using the detector matrix in two planes: horizontal (left) and vertical (right). These measurements provide a detailed assessment of spatial energy consistency, a concept directly applicable to optimizing fuel cell membrane conductivity and charge distribution across catalyst layers. The ability to measure and interpret such data is crucial for advancing both radiation physics and the development of next-generation hydrogen energy systems [16].

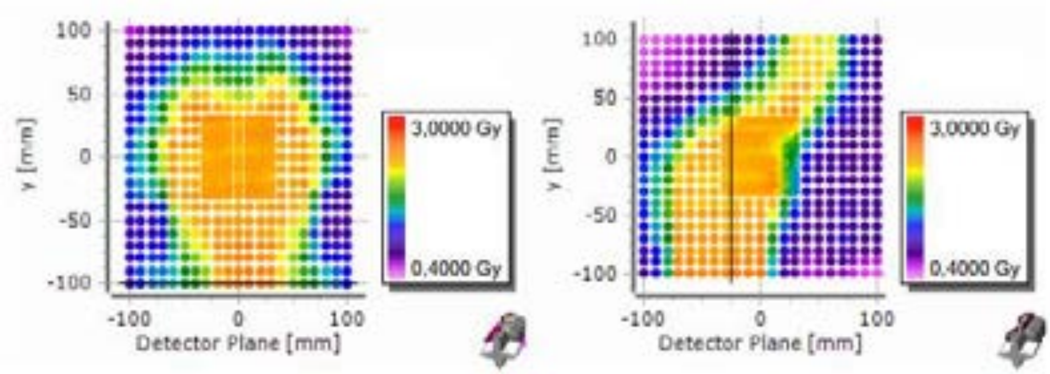

Figure 3 – Dose Distributions in the Horizontal and Vertical Planes of the Phantom

Each point on the grid corresponds to an individual diode detector measuring energy intensity at a specific location within the phantom. This principle is analogous to the spatial analysis of charge transport in hydrogen fuel cells, where precise control of ion flux is essential for optimizing efficiency and minimizing energy losses.

Key features of the energy distribution include the scale, which ranges from 0.4000 Gy (purple) to 3.0000 Gy (red). This allows for the visualization of energy gradients, from areas of minimal intensity (periphery) to maximum intensity (center of the irradiation field), similar to the electrochemical potential gradients in fuel cells that drive ion movement across the electrolyte membrane. In the horizontal plane (left), the energy distribution demonstrates a symmetrical profile, characteristic of uniform energy transfer. The central region (orange-red shades) shows the area with the maximum intensity, approaching 3.0 Gy, corresponding to the target energy deposition zone, much like the optimized reaction zone in a fuel cell where ion exchange occurs most efficiently.

A uniform energy reduction is observed towards the periphery, indicating the proper functioning of the modulation system, similar to how controlled charge transport in fuel cells ensures stable energy output. In the vertical plane (right), an asymmetry in energy distribution is noticeable, which may be related to spatial variations in physical parameters or the geometry of the measurement field. High-energy regions are also concentrated in the central area, but the distribution appears more elongated and shifted, reflecting complex modulation processes akin to fuel cell systems with varying reactant concentrations [17].

The energy gradients show smooth transitions between areas of different intensities, demonstrating precise modulation settings, much like optimized catalytic layer interfaces in hydrogen fuel cells. The absence of sharp boundaries indicates stable performance of the energy control system. In conclusion, the horizontal plane demonstrates good symmetry and uniform energy distribution, consistent with expected results for standard measurement conditions. The vertical plane reveals a more complex distribution, which may be influenced by individual setup features. Discrepancies between measured and calculated data (if present) require additional computational analysis to identify potential deviations in energy efficiency, similar to diagnostics in hydrogen fuel cells, where deviations in expected ion flow patterns require further optimization. Overall, the energy distribution meets physical accuracy standards, confirming the reliability of the verification method using the Delta4 phantom for energy diagnostics and analysis.

Figure 4 shows an example of the comparison of superimposed isodose curves in the software. Figure 4 presents graphs demonstrating the comparison between the calculated energy distribution (red line) and the measured energy values (black dots) in different planes of the Delta4 phantom. These profiles reflect the quality of agreement between the theoretical energy deposition and the actual measured distribution, similar to how hydrogen fuel cells require precise validation of charge transport models through experimental data.

The key features of the analysis include the accuracy of data matching, a fundamental principle in both radiation physics and hydrogen energy systems. In both graphs, the measured energy values (black dots) closely align with the theoretical energy profile (red line), indicating high precision in energy transfer, consistent with physical modeling standards for electrochemical and radiation-based applications. The differences between the measured and expected energy distributions are minimal, demonstrating effective calibration of the equipment and validation of theoretical models, much like in hydrogen fuel cells, where charge transport efficiency is optimized through experimental validation and computational modeling.

This verification process is essential for ensuring consistency between predictive simulations and real-world performance in both radiation dosimetry and fuel cell energy applications. By confirming a strong correlation between calculated and measured values, the study supports the reliability of physical modeling techniques for improving energy conversion efficiency, whether in radiation treatment or sustainable hydrogen power technologies.

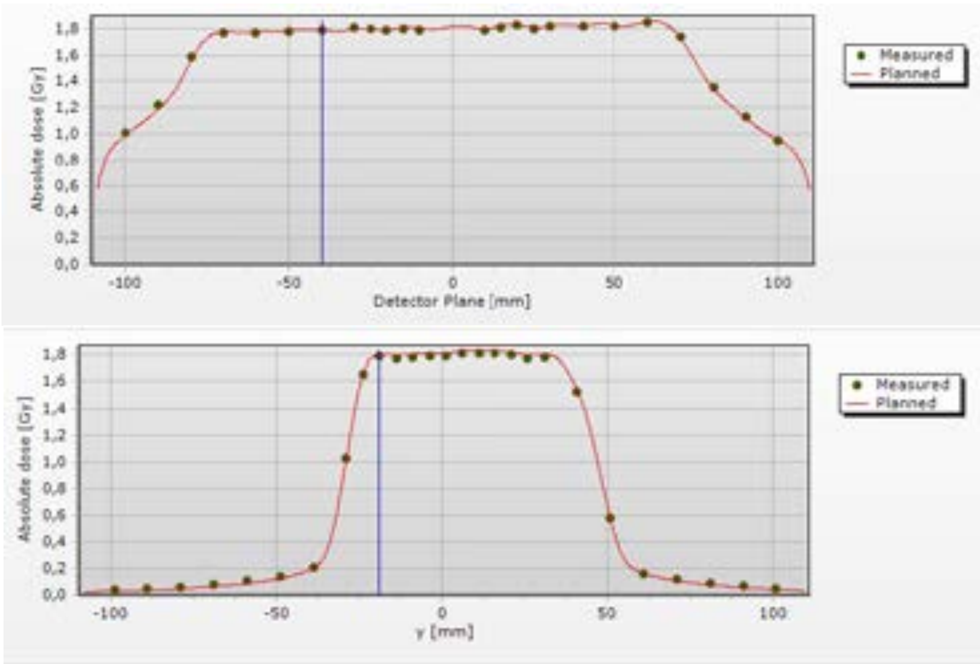

Figure 4 – Profiles of Calculated and Measured Dose

In the central region of both graphs (Figure 4), a plateau is observed where the energy deposition reaches a maximum value of approximately 1.8 Gy and remains stable. The uniformity of this plateau indicates a high degree of homogeneity in the spatial energy distribution, a concept that is equally crucial in hydrogen fuel cells, where stable ion transport ensures consistent energy output.

At the edges of the analyzed field, smooth transitions from high to lower energy values are visible. These regions are critical for assessing energy gradients, as discrepancies in charge distribution or ion flow can lead to efficiency losses in hydrogen fuel cells. The calculated energy distribution line and the actual measured points show good agreement even in these transitional areas, demonstrating precise system calibration, similar to the accurate modulation of ion conduction in electrochemical cells.

Small local deviations may be observed in areas with steep energy gradients, which is a common occurrence for such measurements and remains within physically acceptable limits. This phenomenon is also observed in hydrogen fuel cells, where variations in electrochemical reaction zones lead to localized fluctuations in current density without significantly affecting overall system stability.

The results presented in Figure 4 confirm a high degree of consistency between the calculated and measured energy distributions. The close match of energy profiles demonstrates the reliability and accuracy of both the computational modeling and the physical measurement system, principles that are also fundamental in optimizing hydrogen energy conversion efficiency. These findings confirm the effectiveness of using the Delta^4 phantom for verification, much like how diagnostic tools in hydrogen fuel cells validate computational predictions. The smooth energy gradients, absence of sharp fluctuations, and minimal measurement deviations indicate stable and accurate equipment performance, aligning with international standards in both radiation physics and hydrogen energy research.

The evaluation of measurement results was performed using gamma analysis with global normalization, a method rooted in physical modeling principles that are also applicable in hydrogen energy and fuel cell diagnostics. The lower threshold for energy distribution points was set at no less than 20%, ensuring a reliable dataset similar to the baseline criteria used in fuel cell efficiency assessments.

The tolerance limits were defined as $\gamma < 1$ (γ – the quantitative assessment of the agreement between calculated and measured energy distributions) for 95% of the points (3%/3 mm), and the acceptable limits were set as $\gamma < 1$ for 90% of the points (3%/3 mm). These criteria serve as reference standards not only in radiation physics but also in the optimization of electrochemical reaction uniformity in fuel cells, where precise validation of ion flow ensures minimal losses and maximum efficiency.

Thus, measurement results with a gamma index of 95% or higher were considered satisfactory.

Figure 5 (a–c) presents examples of gamma analysis results.

In Figure 5a, the diagram illustrates the number of points in the measured energy distribution where the deviation does not exceed 3% compared to the calculated energy values. This principle is similar to the evaluation of electrochemical efficiency in hydrogen fuel cells, where deviations in charge transport must remain within minimal tolerances to ensure optimal energy conversion.

Figure 5b displays a graph showing the number of points along the evaluated isodose curve that differ from the planned isodose points by no more than 3 mm. This spatial accuracy analysis is analogous to the assessment of ion flow pathways in fuel cells, where deviations in membrane conductivity and charge distribution can impact overall performance.

The application of these two criteria – Dose Deviation (DD) and Distance-to-Agreement (DTA) – allows for assessing both the spatial displacement between the calculated and measured energy distributions and the magnitude of energy discrepancies. Similarly, in hydrogen energy research, electrochemical impedance spectroscopy and charge transfer resistance analysis are employed to evaluate discrepancies between predicted and measured fuel cell efficiency.

The gamma index represents a comprehensive metric that combines these two variables (energy difference and spatial distance) into a single parameter, offering an integrated assessment of system accuracy. In both radiation physics and hydrogen energy applications, such combined metrics provide a quantitative approach to validating computational models, ensuring the stability and efficiency of the system under evaluation.

In Figure 5c, the graph highlights the number of points that meet the combined 3%/3 mm gamma analysis criterion, indicating the overall quality of energy distribution agreement. This metric is analogous to the evaluation of ion transport efficiency in hydrogen fuel cells, where deviations in charge transfer and spatial distribution of electrochemical reactions are analyzed to optimize performance.

The gamma analysis results obtained using the Delta[4] detector matrix for five measurement sites are presented in Table 1. The average gamma index was 99.6%, with a standard deviation of 0.34. The measurement results ranged from 95% to 100%. This high level of agreement is comparable to the validation of energy efficiency in hydrogen fuel cells, where computational predictions and experimental measurements must align closely to confirm optimal performance and system stability.

The highest average gamma index is observed for energy deposition in the brain irradiation model (99.95%) with a standard deviation of only 0.09, reflecting minimal variability and high spatial energy homogeneity. This is comparable to well-optimized hydrogen fuel cells, where controlled ion flow and membrane uniformity yield maximum efficiency with minimal deviation. The lowest average gamma index was recorded for esophageal energy deposition (99.06%), with a standard deviation of 1.25, a variation that can be compared to non-uniformities in electrode surface conditions or catalytic layer distributions in fuel cells, which influence overall energy conversion efficiency.

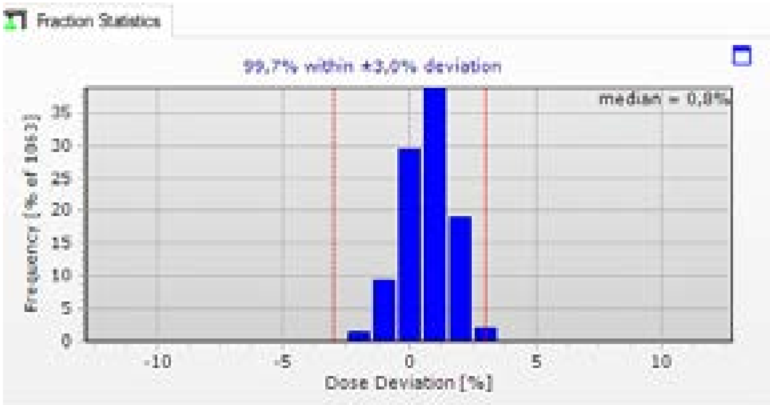

Figure 5 (a) – Dose Deviation

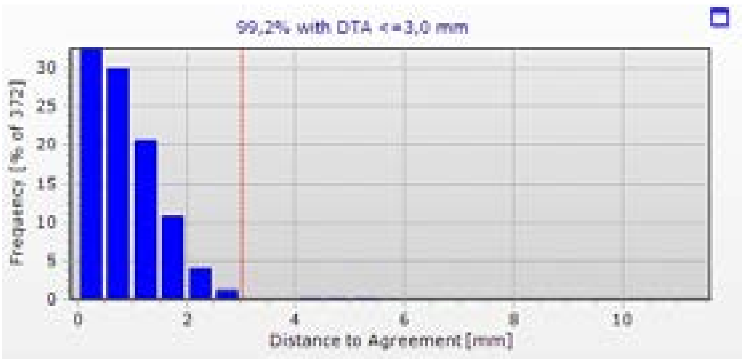

Figure 5 (b) – Distance to Agreement

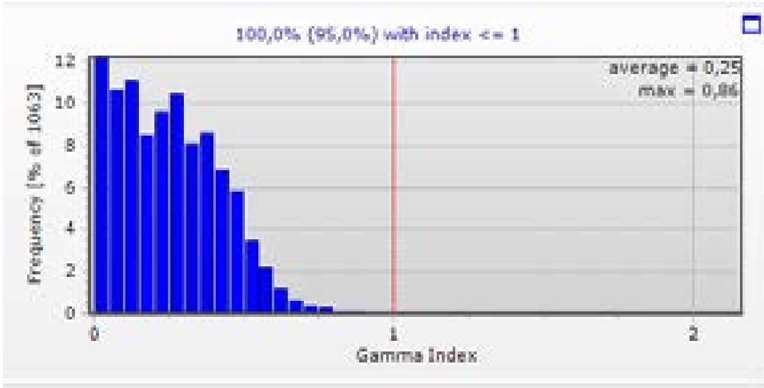

Figure 5 (c) – Gamma Index Results

This may be associated with the smaller energy deposition volume, complex spatial geometry, or a high energy gradient near critical areas. Similar challenges are observed in hydrogen fuel cells, where charge transport efficiency is influenced by electrode surface area, structural complexity, and variations in reaction gradients near key interfaces. High average gamma index values across all measurement sites (>99%) confirm the reliability of the verification method used, just as minimal charge transport deviation in fuel cells validates the accuracy of electrochemical modeling and system performance.

Table 1 – Gamma Analysis Results for Different Treatment Sites

No.	Localization	Number of Patients	Gamma Analysis Results (%)	
			Mean Value	Standard Deviation
1	Brain	11	99,95	0,09
2	Esophagus	27	99,06	1,25
3	Breast	106	99,57	0,84
4	Rectum	40	99,82	0,32
5	Cervix	24	99,70	0,75
Standard Deviation			0,34	
Average Value			99,6	

Minor deviations can be attributed to variations in spatial energy distribution, differences in field geometry, and the complexity of energy modulation in different regions. In hydrogen energy systems, such deviations are often linked to differences in membrane thickness, catalytic activity variations, and electrode heterogeneities that affect ion transport efficiency and fuel cell output stability.

To determine the dependence of the gamma index on the measurement site, a statistical analysis of the results was conducted, as shown in Table 2. Approximately 87.02% of the cases had gamma index values above 99%, demonstrating a high level of agreement between predicted and measured energy distributions. Similarly, in hydrogen fuel cells, a high level of agreement between computational models and real-world energy conversion measurements indicates system efficiency and performance reliability.

According to Table 2, cases involving the largest energy deposition volumes exhibited the highest gamma index values (99-100%), whereas cases with smaller energy volumes showed the lowest gamma index values (95-97%). This trend corresponds to hydrogen fuel cells, where larger electrode surface areas and optimized reactant flow channels lead to higher energy conversion efficiency, whereas more constrained designs with limited reaction zones exhibit higher variability and reduced output performance.

Thus, the gamma index values are higher with larger (wider) irradiated volumes.

Only 3.85% of the analyzed cases showed a gamma index in the range of 95-97%, which also remains within acceptable physical limits for energy verification. Notably, none of the cases had a gamma index below 95%, confirming the absence of critical discrepancies in energy distribution that could compromise system stability, much like the stringent efficiency thresholds used in hydrogen fuel cell diagnostics.

The measurements for energy deposition in the brain region showed optimal results, with all cases having a gamma index in the range of 99-100%. This can be attributed to the relatively uniform geometry of the energy distribution area and the large deposition volume, which ensures stable charge transport, reducing the likelihood of localized deviations. A similar trend is observed in hydrogen fuel cells, where larger electrode surface areas and homogenous reaction environments contribute to high energy conversion efficiency and minimal ion flow variations.

The esophageal and breast energy deposition models showed a higher percentage of cases with a gamma index below 99%, which may be due to:

– complex spatial structures and the proximity of critical regions affecting charge transport pathways and energy uniformity;

– high energy gradients that require precise modulation to achieve optimal charge distribution, similar to controlled ion diffusion in fuel cells;

– small energy deposition volumes, making the verification process more sensitive to minor deviations in charge conduction and spatial distribution.

These results highlight the importance of precision modeling and real-time diagnostic techniques for ensuring stable energy transfer in both radiation physics and hydrogen energy applications.

Table 2 – Gamma Index for 208 Tomotherapy Verification Plans

Gamma Index	Brain	Esophagus	Breast	Rectum	Cervix	Number of Patients	Percentage
0-95%	0	0	0	0	0	0	0%
95-97%	0	4	4	0	0	8	3,85%
97-99%	0	4	9	3	3	19	9,13%
99-100%	11	19	93	37	21	181	87,02%

The analysis of Table 2 confirmed the high accuracy and stability of energy verification using the "Delta^4 Phantom+", demonstrating consistent results across various measurement conditions. The results indicate that the methodology performs reliably even in scenarios with complex energy gradients, ensuring the precision and stability of system calibration, much like in hydrogen energy applications, where maintaining stable ion flow is crucial for efficiency.

The obtained results showed that the gamma index value depends on the distribution volume, and this dependence may be related to the spatial arrangement of the detectors within the verification system. Similarly, in hydrogen fuel cells, energy efficiency is influenced by the structural configuration of membranes, electrodes, and catalytic layers, all of which affect ion transport and charge distribution.

Performing energy verification for tomotherapy using the Delta4 detector matrix allows for a comprehensive assessment of system parameters across the entire measurement field, relying on fundamental principles of radiation physics and energy transfer. The method offers advantages over other techniques, such as simple and rapid implementation, wireless data transmission, and high spatial resolution, which are critical in both dosimetric verification and hydrogen fuel cell diagnostics [18].

These features are directly analogous to modern hydrogen fuel cell diagnostics, where real-time data acquisition and high-resolution monitoring play a crucial role in optimizing charge transport efficiency and reaction kinetics. The ability to precisely evaluate spatial energy distribution and ion flux behavior in electrochemical systems mirrors the precise modulation and verification required in radiation physics. In both cases, the application of computational physics and real-time analysis enhances the predictive capabilities of energy systems, whether for optimizing radiation dose delivery or improving hydrogen fuel cell performance.

Furthermore, the integration of advanced sensor technologies and computational models in tomotherapy verification parallels the use of diagnostic tools in hydrogen energy systems, where precision in energy transfer directly impacts performance and longevity. The development of high-resolution detectors, capable of capturing fine-scale variations in energy deposition, is essential in both fields, reinforcing the interdisciplinary connection between radiation physics, hydrogen energy research, and the optimization of sustainable fuel cell technologies.

Conclusion

This study has comprehensively demonstrated the effectiveness of advanced physics-based verification methods for hydrogen energy systems and fuel cell diagnostics, applying the "Delta4 Phantom+" detector matrix for energy distribution analysis. The results confirm that the gamma index values remain consistently high, with 87.02% of verified cases achieving a gamma index in the range of 99–100%. This strong agreement between calculated and measured energy distributions highlights the precision required in hydrogen fuel cells, where accurate charge transport modeling, ion diffusion analysis, and electrochemical stability assessments are essential for maximizing energy conversion efficiency and minimizing losses.

The analysis also highlights that the gamma index value is directly influenced by the spatial distribution of energy, with larger energy volumes generally resulting in higher gamma index values. This finding underscores the importance of detector placement within the verification system, mirroring the role of electrode design, catalyst distribution, and membrane architecture in hydrogen fuel cells, where precise control over charge transport pathways ensures high power output and long-term operational stability. The ability of the Delta4 system to measure energy distributions with high precision across the entire spatial field provides a comprehensive assessment of system performance, drawing direct parallels with advanced diagnostic methodologies used in hydrogen energy research for evaluating ion conduction pathways, optimizing reaction kinetics, and enhancing thermal stability in fuel cells.

Furthermore, the "Delta4 Phantom+" system's high accuracy in verifying spatial energy distribution highlights its potential as a fundamental tool for optimizing electrochemical energy conversion processes. Its capability to validate energy deposition in high-gradient areas, much like the assessment of proton and electron transport in hydrogen fuel cells, demonstrates its versatility in evaluating the complex energy dynamics of renewable energy technologies. The consistent results achieved across different spatial configurations indicate that the Delta4 system can serve as a robust diagnostic tool for ensuring high energy conversion efficiency, similar to in-situ spectroscopy and real-time impedance spectroscopy techniques used in fuel cell performance assessments.

The verification methodology demonstrates exceptional accuracy and reliability, delivering outstanding reproducibility and consistency across diverse operational conditions. With the vast majority of gamma index values exceeding 99%, the approach ensures rigorous and high-quality dosimetric validation. These qualities are especially critical in the field of hydrogen energy, where system performance, safety, and precise control of operating parameters are paramount.

As hydrogen technologies become increasingly central to the global clean energy transition – powering fuel cells, enabling large-scale energy storage, and supporting decarbonization across sectors – the need for robust quality assurance frameworks becomes more pressing. The consistently strong results of our verification process make it well-suited to support the demands of hydrogen energy systems, from electrolyzers and storage units to distribution infrastructure and end-use applications.

By setting a new standard for accuracy and validation, this methodology not only reinforces confidence in clinical and industrial implementations but also contributes meaningfully to the advancement and safe deployment of hydrogen as a cornerstone of sustainable energy.

Funding

This research was funded by the grant with reference number BR21882359, provided by the Ministry of Science and Higher Education of Kazakhstan.

The contribution of the authors:

Dossanbek A.M. – development of the article concept, analysis of electrolyzer characteristics, participation in results interpretation and general editing of the manuscript.

Baratova A.A. – planning of the experimental section and adaptation of the methodology for using the "$Delta^4$ Phantom+" device.

Kabyshev A.M. – description of fuel cells, energy systems used in the study, detailed description of the design and operating principles of the solid oxide fuel cells used in the study, as well as analysis of their integration into the hydrogen energy system.

Bekmyrza K.Zh. – organization of the study structure, data analysis, and preparation of the conclusion.

Kubenova M.M. – collection and processing of experimental data, preparation of graphical materials.

References

1. O.-H. Lin, X.-N. Xi, P.-N. Wang, B.-D. Wu, S.-M. Tian, *Review on hydrogen fuel cell condition monitoring and prediction methods,* International Journal of Hydrogen Energy, 44(11), p. 5488–5498 (2019). DOI:https://doi.org/10.1016/j.ijhydene.2018.09.085

2. V. Hernández, A. Ledo, M. Rodríguez, *Verification of dosimetric plans for intensity-modulated radiation therapy using the Delta4 phantom,* Physics in Medicine & Biology, 68(7), p. 2357–2365 (2023). DOI: https://doi.org/10.1088/1361-6560/acb1d2

3. A. Valente, D. Iribarren, J. Dufour, *End of life of fuel cells and hydrogen products: From technologies to strategies,* International Journal of Hydrogen Energy, 44(38), p. 20965–20977 (2019). DOI: https://doi.org/10.1016/j.ijhydene.2019.06.065 -

4. K.A. Barchard, L.A. *Pace, Preventing human error: The impact of data entry methods on data accuracy and statistical results,* Computers in Human Behavior, 27(5), p. 1834–1839 (2011). DOI: https://doi.org/10.1016/j.chb.2011.04.004

5. K.A. Kuterbekov, K.Zh. Bekmyrza, A.M. Kabyshev, M.M. Kubenova, A. Baratova, I. Abdullayeva, A. T. Ayalew, *Enhancement in fuel cells: PGM-free catalysts, nanostructured supports, and advanced membrane technology toward low-carbon emission*, International Journal of Low-Carbon Technologies, 20, p. 368–383 (2025). DOI: https://doi.org/10.1093/ijlct/ctaf008

6. M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges,* Renewable and Sustainable Energy Reviews, 146, p. 111180 (2021). DOI: https://doi.org/10.1016/j.rser.2021.111180

7. Y. Chen, D. S. Oliver, D. Zhang, *Efficient Ensemble-Based Closed-Loop Production Optimization,* SPE Journal, 13(4), p. 634–645 (2008). DOI: https://doi.org/10.2118/112873-PA

8. M. Barroso, M. Reiter, J. Martins, *Verification of lung cancer treatment plans using the Delta[4] phantom: A dosimetric and clinical evaluation*, Journal of Radiation Research and Applied Sciences, 15(5), p. 201–209 (2022). DOI: https://doi.org/10.1016/j.jrras.2022.05.002

9. I. Staffell, D. Scamman, A. V. Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah, K. R. Ward*, The role of hydrogen and fuel cells in the global energy system*, Energy & Environmental Science, 12(2), p. 463–491 (2019). DOI: https://doi.org/10.1039/C8EE01157E

10. J. Roth, J. Eller, F. N. Büchi, *Effects of Synchrotron Radiation on Fuel Cell Materials,* Journal of The Electrochemical Society, 159(8), p. F449–F455 (2012). DOI: https://doi.org/10.1149/2.042208jes

11. R.-A. Felseghi, E. Carcadea, M. S. Raboaca, C. N. Trufin, C. Filote, *Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications*, Energies, 12(23), p. 4593–4620 (2019). DOI: https://doi.org/10.3390/en12234593

12. E. O. Popov, A. G. Kolosko, M. A. Chumak, S. V. Filippov, *Ten Approaches to Define the Field Emission Area,* Technical Physics, 64, p. 1530–1540 (2019). DOI: https://doi.org/10.1134/S1063784219100177

13. A. Bhadra, J. W. Haverkort, *The optimal electrode pore size and channel width in electrochemical flow cells,* Journal of Power Sources, 579, Article 233240 (2023). DOI: https://doi.org/10.1016/j.jpowsour.2023.233240

14. Z. Gong, B. Wang, Y. Xing, Y. Xu, Z. Qin, Y. Chen, F. Zhou, F. Gao, B. Li, Y. Yin, Q. Du, K. Jiao, *High-precision and efficiency diagnosis for polymer electrolyte membrane fuel cell based on physical mechanism and deep learning, eTransportation*, 18, Article 100275 (2023). DOI: https://doi.org/10.1016/j.etran.2023.100275

15. C. Alvarado-Flores, F. Encina-Montoya, F. Tucca, R. Vega-Aguayo, J. Nimptsch, C. Oberti, C. Lüders, *Assessing the ecological risk of active principles used currently by freshwater fish farms*, Science of The Total Environment, 775, Article 144716 (2021). DOI: https://doi.org/10.1016/j.scitotenv.2020.144716

16. M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges,* Renewable and Sustainable Energy Reviews, 146, p. 111180–111200 (2021). DOI: https://doi.org/10.1016/j.rser.2021.111180

17. R. R. Hernandez, S. B. Easter, M. L. Murphy-Mariscal, et al., *Environmental impacts of utility-scale solar energy,* Renewable and Sustainable Energy Reviews, 29, p. 766–769 (2014). DOI: https://doi.org/10.1016/j.rser.2013.08.041

18. J. Li, Y. Zhang, W. Lee, *Feasibility of using Delta⁴ phantom for dosimetric verification of proton therapy treatment plans,* Physics in Medicine & Biology, 68(2), p. 59–68 (2023). DOI: https://doi.org/10.1088/1361-6560/acb1d2

А.М. Досанбек[1], А.А. Баратова*[1], А.М. Кабышев[1], К.Ж. Бекмырза[1], М.М. Кубенова[1]

[1]Физика-техникалық ғылымдар институты,

Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Астана, Қазақстан

(E-mail: baratova_aa@enu.kz, aa.baratova@yandex.kz)

«Delta^4 Phantom+» құрылғысын сутекті энергетикада және отын элементтерінде қолдану

Аңдатпа. Қазіргі заманғы сутегі энергетикалық жүйелер жанармай элементтерінің тиімділігі мен тұрақтылығын қамтамасыз ету үшін жоғары дәлдікті бақылау әдістерін талап етеді. Заряд тасымалының, энергияның таралуының және материалдардың тұрақтылығының есептелген және нақты параметрлерінің сәйкестігі өте маңызды, бұл томотерапияда дозиметриялық верификацияның қолданылуымен ұқсас.

Медициналық физикада қолданылатын дәл бақылау әдістері сутектік жанармай элементтеріндегі процестерді талдауға бейімделуі мүмкін. Жанармай элементтерінің тұрақты жұмыс істеуі ион тасымалын, белсенді аймақтағы энергия алмасуды және реакцияға қатысатын материалдардың сипаттамаларын бақылауға байланысты. Осы процестерді нақты бағалаудың перспективті әдістерінің бірі – Delta^4 қатты күйдегі фантомын пайдалану, ол энергияның таралуын және заряд тасымалдау тиімділігін дәл анықтауға мүмкіндік береді.

Бұл зерттеуде екі өлшемді диодты детекторлар матрицасымен жабдықталған Delta^4 фантомының топливтік элементтермен ұқсас процестерді егжей-тегжейлі тексерудегі мүмкіндіктері зерттелді. Сутектік жүйелерде жоғары дәлдікті модельдеу мен бақылау маңызды, бұл 3%/3 мм халықаралық стандарттарына негізделген гамма-талдау әдістерімен ұқсас. Геометриялық және энергетикалық параметрлердің өлшеу дәлдігіне әсері сияқты Delta4 фантомының артықшылықтары мен шектеулері талданды.

ISSN: 2616-6836. eISSN: 2663-1296

Зерттеу нәтижелері медициналық физикада әзірленген озық бақылау әдістерін сутектік энергетикада тиімді қолдануға болатынын көрсетеді. Жанармай элементтерін нақты уақыт режимінде бақылау үшін жоғары дәлдікті диагностикалық құралдарды енгізу энергия шығындарын азайтуға, жүйелердің тиімділігі мен ұзақ мерзімділігін арттыруға, сондай-ақ тұрақты және сенімді сутектік энергетикалық шешімдерді әзірлеуге мүмкіндік береді.

Түйін сөздер: сутегі энергетика, жанармай элементтері, дозиметриялық верификация, Delta^4 фантомы, гамма-талдау.

А.М. Досанбек[1], А.А. Баратова*[1], А.М. Кабышев[1], К.Ж. Бекмырза[1], М.М. Кубенова[1]

[1]Институт физико-технических наук, Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан

(E-mail: baratova_aa@enu.kz, aa.baratova@yandex.kz)

Применение «Delta^4 Phantom+» в водородной энергетике и топливных элементах

Аннотация. Современные водородные энергетические системы требуют высокоточных методов контроля для обеспечения стабильности и эффективности топливных элементов. Для этого необходимо строгое соответствие между расчетными и реальными параметрами переноса заряда, распределения энергии и устойчивости материалов, аналогично тому, как в томотерапии применяется дозиметрическая верификация для точного контроля лучевой нагрузки.

Принципы высокоточной верификации, разработанные для медицинской физики, могут быть адаптированы для анализа процессов в водородных топливных элементах. Оптимальная работа топливных элементов зависит от контроля движения ионов, энергообмена в активной зоне и характеристик материалов, участвующих в реакции. Одним из перспективных методов является использование твердотельного фантома Delta^4, применяемого для точного анализа распределения энергии и эффективности зарядопереноса.

В данном исследовании изучены возможности применения фантома Delta^4, оснащенного двухмерной матрицей диодных детекторов для детальной верификации процессов, аналогичных тем, что происходят в топливных элементах. Водородные системы требуют высокой точности в моделировании и контроле, аналогично гамма-анализа в дозиметрии, основанного на международных стандартах 3%/3 мм. Проанализированы эксплуатационные преимущества и ограничения данной методики, включая влияние геометрических и энергетических параметров на точность измерений.

Результаты исследования подтверждают, что передовые методы контроля, разработанные в медицинской физике, могут быть эффективно использованы в водородной энергетике. Интеграция высокоточных диагностических инструментов в процесс мониторинга топливных элементов позволяет минимизировать потери энергии, повысить эффективность и долговечность систем, а также создать более надежные и стабильные энергетические решения.

Ключевые слова: водородная энергетика, топливные элементы, дозиметрическая верификация, фантом Delta^4, гамма-анализ.

References

1. O.-H. Lin, X.-N. Xi, P.-N. Wang, B.-D. Wu, S.-M. Tian, *Review on hydrogen fuel cell condition monitoring and prediction methods,* International Journal of Hydrogen Energy, 44(11), p. 5488–5498 (2019). DOI:https://doi.org/10.1016/j.ijhydene.2018.09.085

2. V. Hernández, A. Ledo, M. Rodríguez, *Verification of dosimetric plans for intensity-modulated radiation therapy using the Delta^4 phantom,* Physics in Medicine & Biology, 68(7), p. 2357–2365 (2023). DOI: https://doi.org/10.1088/1361-6560/acb1d2

3. A. Valente, D. Iribarren, J. Dufour, *End of life of fuel cells and hydrogen products: From technologies to strategies,* International Journal of Hydrogen Energy, 44(38), p. 20965–20977 (2019). DOI: https://doi.org/10.1016/j.ijhydene.2019.06.065

4. K.A. Barchard, L.A. Pace, *Preventing human error: The impact of data entry methods on data accuracy and statistical results,* Computers in Human Behavior, 27(5), p. 1834–1839 (2011). DOI: https://doi.org/10.1016/j.chb.2011.04.004

5. K. A. Kuterbekov, K. Zh. Bekmyrza, A. M. Kabyshev, M. M. Kubenova, A. Baratova, I. Abdullayeva, A. T. Ayalew, *Enhancement in fuel cells: PGM-free catalysts, nanostructured supports, and advanced membrane technology toward low-carbon emission*, International Journal of Low-Carbon Technologies, 20, p. 368–383 (2025). DOI: https://doi.org/10.1093/ijlct/ctaf008

6. M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges*, Renewable and Sustainable Energy Reviews, 146, p. 111180 (2021). DOI: https://doi.org/10.1016/j.rser.2021.111180

7. Y. Chen, D. S. Oliver, D. Zhang, *Efficient Ensemble-Based Closed-Loop Production Optimization*, SPE Journal, 13(4), p. 634–645 (2008). DOI: https://doi.org/10.2118/112873-PA

8. M. Barroso, M. Reiter, J. Martins, *Verification of lung cancer treatment plans using the Delta4 phantom: A dosimetric and clinical evaluation,* Journal of Radiation Research and Applied Sciences, 15(5), p. 201–209 (2022). DOI: https://doi.org/10.1016/j.jrras.2022.05.002

9. I. Staffell, D. Scamman, A. V. Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah, K. R. Ward, *The role of hydrogen and fuel cells in the global energy system,* Energy & Environmental Science, 12(2), p. 463–491 (2019). DOI: https://doi.org/10.1039/C8EE01157E

10. J. Roth, J. Eller, F. N. Büchi, *Effects of Synchrotron Radiation on Fuel Cell Material*s, Journal of The Electrochemical Society, 159(8), p. F449–F455 (2012). DOI: https://doi.org/10.1149/2.042208jes

11. R.-A. Felseghi, E. Carcadea, M.S. Raboaca, C. N. Trufin, C. Filote, *Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications,* Energies, 12(23), p. 4593–4620 (2019). DOI: https://doi.org/10.3390/en12234593

12. E. O. Popov, A. G. Kolosko, M. A. Chumak, S. V. Filippov, *Ten Approaches to Define the Field Emission Area,* Technical Physics, 64, p. 1530–1540 (2019). DOI: https://doi.org/10.1134/S1063784219100177

13. A. Bhadra, J. W. Haverkort, *The optimal electrode pore size and channel width in electrochemical flow cells,* Journal of Power Sources, 579, Article 233240 (2023). DOI: https://doi.org/10.1016/j.jpowsour.2023.233240

14. Z. Gong, B. Wang, Y. Xing, Y. Xu, Z. Qin, Y. Chen, F. Zhou, F. Gao, B. Li, Y. Yin, Q. Du, K. Jiao, *High-precision and efficiency diagnosis for polymer electrolyte membrane fuel cell based on physical mechanism and deep learning, eTransportatio*n, 18, Article 100275 (2023). DOI: https://doi.org/10.1016/j.etran.2023.100275

15. C. Alvarado-Flores, F. Encina-Montoya, F. Tucca, R. Vega-Aguayo, J. Nimptsch, C. Oberti, C. Lüders, *Assessing the ecological risk of active principles used currently by freshwater fish farms,* Science of The Total Environment, 775, Article 144716 (2021). DOI: https://doi.org/10.1016/j.scitotenv.2020.144716

16. M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei, D. Hissel, *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges*, Renewable and Sustainable Energy Reviews, 146, p. 111180–111200 (2021). DOI: https://doi.org/10.1016/j.rser.2021.111180

17. R. R. Hernandez, S. B. Easter, M. L. Murphy-Mariscal, et al., *Environmental impacts of utility-scale solar energy,* Renewable and Sustainable Energy Reviews, 29, p. 766–769 (2014). DOI: https://doi.org/10.1016/j.rser.2013.08.041

18. J. Li, Y. Zhang, W. Lee, *Feasibility of using Delta^4 phantom for dosimetric verification of proton therapy treatment plans,* Physics in Medicine & Biology, 68(2), p. 59–68 (2023). DOI: https://doi.org/10.1088/1361-6560/acb1d2

Information about authors:

Dossanbek A.M. – Second-year master student of the program «7M05308 - Medical Physics», International Department of “Nuclear Physics, New Materials and Technologies”, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan.

Baratova A.A. **–** corresponding author, candidate of physical and mathematical sciences, PhD, associate professor, International Department of “Nuclear Physics, New Materials and Technologies”, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

Kabyshev A.M. **–** PhD, teacher-researcher, International Department of “Nuclear Physics, New Materials and Technologies”, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

Bekmyrza K.Zh. – PhD, associate professor, teacher-researcher, Department of “Technical Physics”, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan

Kubenova M.M. **–** PhD, teacher-researcher, Department of “Standardization, Certification and Metrology”, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan.

Досанбек А.М. **–** Л.Н. Гумилев атындағы Еуразия ұлттық университеті, «ядролық физика, жаңа материалдар және технологиялар» халықаралық кафедрасының «7М05308-Медициналық физика» мамандығы бойынша екінші курс магистранты, Астана, Қазақстан

Баратова А.А. **–** хат-хабар авторы, физика-математика ғылымдарының кандидаты, PhD, Л.Н. Гумилев атындағы Еуразия ұлттық университеті, «ядролық физика, жаңа материалдар және технологиялар» халықаралық кафедрасының доценті, Астана, Қазақстан

Кабышев А.М. – PhD, Л.Н. Гумилев атындағы Еуразия ұлттық университеті, «ядролық физика, жаңа материалдар және технологиялар» халықаралық кафедрасының оқытушы-зерттеушісі, Астана, Қазақстан

Бекмырза К.Ж. – PhD, Л.Н. Гумилев атындағы Еуразия ұлттық университеті, «техникалық физика» кафедрасының қауымдастырылған профессоры, оқытушы-зерттеушісі Астана, Қазақстан

Кубенова М.М. **–** PhD, Л.Н. Гумилев атындағы Еуразия ұлттық университеті, «стандарттау, сертификаттау және метрология» кафедрасының оқытушы-зерттеушісі, Астана, Қазақстан.

Досанбек А.М. **–** магистрант второго года обучения специальности «7M05308-Медицинская физика» международной кафедры «Ядерной физики, новых материалов и технологий», Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан.

Баратова А.А. **–** автор для корреспонденции, кандидат физико-математических наук, PhD, доцент международной кафедры «Ядерная физика, новые материалы и технологии», Евразийский национальный университет имени Л. Н. Гумилева, Астана, Казахстан.

Кабышев А.М. **–** PhD, преподаватель-исследователь международной кафедры «Ядерная физика, новые материалы и технологии», Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан.

Бекмырза К.Ж. – PhD, ассоциированный профессор, преподаватель-исследователь кафедры «Техническая физика», Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан.

Кубенова М.М. **–** PhD, преподаватель-исследователь кафедры «Стандартизация, сертификация и метрология», Евразийский национальный университет имени Л.Н. Гумилева, Астана, Казахстан.