**Reactor Power Monitoring using Cherenkov Radiation   
with a Commercial Camera System**

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ABSTRACT

Ensuring safety in nuclear installations critically relies on robust and diverse power measurement systems. Conventional in-core detectors, such as ionization and fission chambers, often face limitations in harsh radiation environments, particularly during fast transients or due to their size for in-core applications, and optical fibers can suffer from radiation-induced darkening. This paper explores the development and validation of an innovative, alternative method for nuclear reactor power monitoring and spatial power profile reconstruction using Cherenkov radiation.

Cherenkov radiation, characterized by a distinctive bluish glow, is emitted when charged particles, primarily electrons generated from gamma-ray interactions (Compton scattering, photoelectric effect, and pair production), travel through a dielectric medium (like water in research reactors) faster than the phase velocity of light in that medium. The intensity of this radiation is linearly proportional to the reactor's fission power in operating conditions, making it a reliable indicator of reactor output.

Various methodologies are discussed and developed, including:

• Direct detection of Cherenkov light from the reactor core using photodiode arrays or microcontrollers with brightness/color sensors.

• Transmission of Cherenkov light through highly reflective metallic tubes to remote photon detectors, overcoming the degradation issues of optical fibers in high-radiation fields.

• Computational modeling using MCNP to generate response functions that correlate electron flux within coolant channels to the observable Cherenkov light above the core. This enables the reconstruction of 2D and 3D spatial power profiles.

Experimental results from various research reactors (IPR-R1 Triga, CABRI, JSI TRIGA, SLOWPOKE-2, and Tehran Research Reactor) demonstrate that Cherenkov-based systems offer fast response, high fidelity, and reliable measurements of reactor power, even during transients. Furthermore, the MCNP-based approach facilitates the detection and identification of physical anomalies, such as coolant channel blockages, and the determination of axial flux tilts within the reactor core by comparing signals from multiple viewpoints.

This research highlights the significant potential of Cherenkov radiation detection as a non-invasive, cost-effective, and highly reliable auxiliary tool for reactor power measurement, enhancing redundancy and diversity in nuclear instrumentation and control systems, thereby improving operational safety and efficiency in various reactor types with optically transparent coolants.

Keywords: Cherenkov radiation, TRIGA reactor, Nuclear reactor power monitoring, Reactor safety, Transient

# **Introduction**

Ensuring safety is the paramount concern in any nuclear installation, especially within nuclear reactors. The International Atomic Energy Agency (IAEA) emphasizes that the fundamental objective of safety is to protect people and the environment from the harmful effects of ionizing radiation. To achieve this, the IAEA recommends adhering to several safety principles, including redundancy, diversity, and independence in safety systems. This means that multiple devices, operating on different principles, should independently perform the same critical functions, such as reactor power measurement. Accurate and reliable power monitoring is a cornerstone of maintaining safe and stable operation in both nuclear power plants and research reactors.

TRIGA 리엑터에 관해. 왜 이 리엑터가 좋은지

Conventional reactor power monitoring systems typically rely on in-core gamma or neutron detectors, fission chambers, and ionization chambers. While these systems are well-established, there is a continuous drive to enhance their capabilities, particularly in terms of providing diverse, redundant, and robust measurement channels. Cherenkov radiation, the characteristic blue glow observed in water-cooled reactors, offers a promising alternative or complementary method for power monitoring. Its intensity is directly proportional to the reactor's fission power during operation, making it a viable indicator of core activity.

This study proposes an innovative approach to reactor power monitoring by utilizing a commercial-grade camera, specifically a GoPro HERO13, to measure Cherenkov radiation. This method aims to contribute to reactor safety and operational efficiency by offering several key advantages:

• Enhanced Redundancy, Diversity, and Independence: By employing a measurement principle distinct from traditional neutron or gamma flux detectors, this Cherenkov-based system provides an additional, independent channel for power monitoring, directly addressing IAEA recommendations for increased safety margins.

• Non-Invasive and Remote Monitoring: The system allows for detectors to be placed a significant distance from the reactor core, typically above the cooling pool, thereby avoiding the harsh radiation environments that can degrade in-core sensors and simplifying maintenance and adjustment procedures.

• Fast Response Time: Cherenkov-based instruments have demonstrated fast response capabilities, able to track rapid changes in reactor power, including during pulse operations that occur on millisecond timescales.

• High Data Quality and Reliability: Previous research has shown that Cherenkov power meters can provide highly accurate and reliable data, even outperforming conventional nuclear instrumentation in precisely recording low peak power pulses and demonstrating excellent fidelity during power changes. This suggests the potential for obtaining clearer and more consistent signals compared to some conventional detectors, which may struggle with signal-to-noise ratios at very low power ranges or experience issues like radiation-induced darkening in optical fibers.

• Cost-Effectiveness: The development of Cherenkov power meters has been noted for being significantly more economical than some implemented conventional instrumentation while delivering comparable, or in some cases, superior performance.

The objective of the present project is to develop and validate an innovative and alternative method to monitor the power of nuclear research reactors by analyzing and monitoring the intensity of luminosity generated by the Cherenkov radiation in the reactor core, specifically using a GoPro HERO13 camera. This method will then be compared against established detector outputs to assess its efficacy and potential for integration into existing monitoring frameworks.

# **Background / Theory**

Cherenkov radiation is a fascinating electromagnetic phenomenon that provides a visible indicator of nuclear activity in transparent media. It is defined as the electromagnetic radiation emitted when a charged particle moves through a dielectric (insulating) medium at a speed greater than the phase velocity of light in that medium. This effect was first characterized by Pavel Cherenkov, who later received the Nobel Prize in Physics for his discovery in 1958.

In open-pool nuclear research reactors, Cherenkov radiation is conspicuously observed as a characteristic blue glow emanating from and around the reactor core. This visible blue light is primarily produced through several mechanisms involving energetic charged particles:

• Beta Particles: Electrons (beta particles) emitted during the beta-decay of fission products can travel at speeds exceeding the speed of light in water, directly producing Cherenkov light.

• Indirect Ionization by Gamma Radiation: Gamma rays, which are not directly charged, interact with the medium (typically water in research reactors) through processes such as the photoelectric effect, Compton scattering, and pair production. These interactions generate energetic electrons, with Compton electrons being the main contributors to Cherenkov radiation production in nuclear reactors.

• Prompt Gamma Rays: In an operating nuclear reactor, prompt gamma rays—those emitted almost instantaneously from the fission process—represent the largest contribution to the intensity of Cherenkov light.

The generation of Cherenkov light has a threshold kinetic energy for electrons. For pure water at 20°C, with a refractive index of approximately 1.33, the speed of light is about 0.75 times the speed of light in a vacuum. This means that electrons must possess a kinetic energy greater than approximately 200–261 keV to produce Cherenkov radiation in water. Below this threshold, electrons will not emit Cherenkov photons. The emission rate of Cherenkov photons is approximately proportional to their frequency, resulting in a peak intensity in the upper blue and ultraviolet ranges of the spectrum.

Crucially for reactor monitoring, the intensity of Cherenkov light produced in the reactor cooling water is linearly proportional to the reactor power when fission power is dominant compared to residual power. This linear relationship allows the measured light intensity to serve as a direct indicator of instantaneous reactor power, provided proper calibration is applied. Cherenkov photons, particularly in the visible spectrum, are transported through pure water with minimal attenuation. The mean free path for scattering of visible photons in water is greater than 10 meters, indicating that the light travels in a straight line with little information loss, making it suitable for remote detection.

Previous applications of Cherenkov radiation for reactor monitoring include systems in the Tehran Research Reactor, which uses a photodiode array for power measurement, demonstrating good linearity above 100 kW and offering enhanced redundancy and diversity. The Jožef Stefan Institute (JSI) TRIGA research reactor has also developed a Cherenkov power meter that shows excellent agreement with existing nuclear instrumentation, especially for high peak power pulses, and even outperforms conventional systems for low peak power pulses. These prior efforts highlight the viability and benefits of Cherenkov-based power monitoring.

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|  |  | (1) |

In Eq. (1) and

# **Materials and Methods**

The proposed methodology focuses on developing and validating a research reactor power measurement system using Cherenkov radiation captured by a commercial-grade camera. The core of this approach involves measuring the intensity of Cherenkov luminosity from the reactor core and correlating it with the reactor's established power output.

* 1. Experimental setup and imaging device

The experimental setup will primarily involve the non-invasive placement of a camera system above an open pool-type research reactor, such as the IPR-R1 Triga reactor. The reactor's open-pool design provides direct visibility of the core and the inherent blue glow of Cherenkov radiation.

For Cherenkov radiation detection, a GoPro HERO13 camera will be utilized. This camera offers a balance of portability, robustness, and high-resolution imaging capabilities suitable for capturing the visible light emitted by Cherenkov radiation.

• Key Camera Specifications and Settings:

    ◦ Resolution: 4K (3840 x 2160 pixels)

    ◦ Frame Rate: 60 frames per second (fps)

    ◦ Further detailed camera specifications, including sensor type, lens aperture, ISO sensitivity, and white balance settings, will be determined and documented during the experimental phase to optimize image acquisition under varying reactor power levels and ambient lighting conditions.

The camera will be positioned to provide a clear line-of-sight to the reactor core, typically from an elevated point above the pool surface. This remote placement ensures that the camera remains outside the high-radiation field, simplifying operation and maintenance.

* 1. Data acquisition and analysis

The process will involve simultaneously operating the GoPro HERO13 camera to record the Cherenkov light intensity and recording the reactor power data from the reactor's existing, calibrated instrumentation (e.g., neutron-sensitive cameras, fission chambers, ionization chambers).

• GoPro Data Acquisition: Video footage of the reactor core's Cherenkov glow will be captured under various steady-state reactor power levels and potentially during power transients. Each video frame will contain visual data of the light intensity.

• Reactor Power Data: Concurrently, precise reactor power measurements (e.g., in kilowatts, kW) will be obtained from the control console's neutron measuring channels. This conventional data will serve as the reference for calibration and validation.

• Data Correlation: The captured video frames will be processed using image analysis techniques. This will involve extracting luminosity values from specific regions of interest within the images (e.g., areas directly above the coolant channels where Cherenkov radiation is most prominent). An algorithm will be developed to establish a quantitative relationship between the measured light intensity (e.g., pixel brightness values) and the corresponding reactor power levels. This will involve:

    ◦ Luminosity to Power Conversion Equations: These equations will be established by recording luminosity values from the camera for each increment of reactor power varied.

    ◦ Comparison and Validation: The Cherenkov-derived power estimates will be rigorously compared against the measurements from conventional detectors. The linearity, accuracy, reliability, and response time of the GoPro-based system will be evaluated across the operational power range of the reactor.

The aim is to demonstrate that the GoPro HERO13, as an innovative and alternative measurement device, can reliably and accurately monitor reactor power, providing high-quality data that complements existing instrumentation and enhances the overall safety and operational understanding of nuclear reactors.

# **Results**

For

* 1. Full screen averaged

Full

* 1. Best ROI

Contents

* 1. Best pixels

1. Conclusion and Future Work

This paper has explored …

Acknowledgements

Research support, data sources, and key contributors which are not mentioned in the author list

References

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