SiLiF Neutron Counters to Monitor Nuclear Materials

A comprehensive set of 32 solid-state thermal neutron detectors, known as Silicon-Lithium-Fluoride (SiLiF), has been successfully developed and characterized.
Key features for industrial application: The SiLiF detectors are suitable for the monitoring of nuclear materials and can be deployed around radioactive waste drums potentially containing small quantities of actinides, as well as around spent fuel casks during interim storage or transport. Appropriate polyethylene moderators can be employed to optimize the detector response to the expected neutron energy spectrum, as determined through Monte Carlo simulations. These detectors were extensively tested using an AmBe neutron source, and the results demonstrate highly uniform and reproducible performance.

"Radioactive Waste Monitoring"

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Keyword	neutron detectors, radwaste monitoring, Monte Carlo simulation

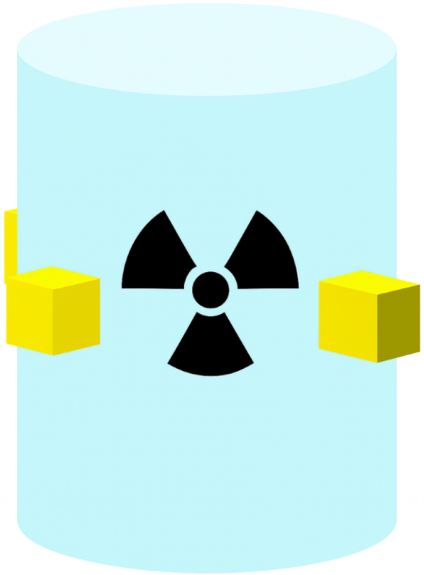


Fig. 1: The light blue cylinder represents a radioactive waste storage cask, as indicated by radiation symbol on its surface. The yellow cubes depict SiLiF thermal neutron detectors positioned around the cask

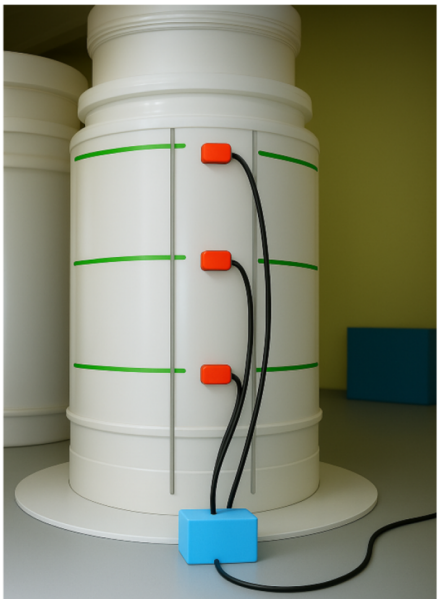


Fig. 2: Radiwaste storage cask equipped with radiation detection systems: red elements = SiLiF neutron detectors, green markers = gamma detectors, black lines = data cables, blue component = data acquisition

Description

Historically, the most widely used technology for detecting thermal neutrons has relied on Helium-3 (^{3}He) nucleus, where the absorbed neutron causes the nucleus to break apart and release a measurable energy. The primary source of ^{3}He is the nuclear weapons programs of United States and Russia, where it is produced as a byproduct of tritium decay. In recent decades, a significant shortage of ^{3}He, coupled with a substantial rise in its cost, has driven extensive research into alternative technologies. A promising alternative is the SiLiF neutron detector. It works by using ⁶Li, which captures incoming neutrons and breaks apart into energetic charged particles which is measured by the detector. Semiconductor devices such as silicon diodes are employed in combination with a neutron-reactive film (composed of ⁶Li or ^{10}B) known as a neutron converter. This film converts thermal neutrons into charged particles, which are subsequently detected by the silicon diode. In this configuration, fast neutrons can be detected by enclosing the detector in a suitable moderator, commonly made of polyethylene, which slows neutrons to thermal energies. The use of ⁶Li is preferred over ^{10}B because, upon neutron capture, it undergoes a single decay channel without gamma emission, provides higher kinetic energy release, and produces lighter charged particles that are easier to detect. A valid neutron event is recorded when the signal generated by the SiLiF detector exceeds a predefined threshold.

Innovative aspects

Cost-effective solid-state neutron detectors with excellent gamma/neutron discrimination can be produced. These detectors are well suited for long-term, real-time monitoring and represent a promising solution for enhancing safety and security in nuclear waste storage facilities. Optimal counting threshold can be selected based on the required level of gamma/neutron discrimination and the specific characteristics of the waste being monitored, including the expected neutron and gamma spectra. Compared to ^{3}He tubes, this alternative offers several advantages:

Cost and availability: ⁶LiF is less expensive and readily available than ^{3}He reducing material costs and supply chain risk

Detector flexibility: in principle, any solid-state detector can be used to detect the secondary charged particles

Low operating voltage: operates at only 30–50V, lower than ⁶1000V required for gas-filled ^{3}He detectors, simplifying power requirements

Modular design: semiconductor detector and neutron converter can be independently replaced if damaged minimizing maintenance costs and downtime

Increased efficiency: a double-sided silicon diode can be used to effectively double the neutron detection efficiency

Potential applications

SiLiF approach represents an opportunity for the industry to deliver high-performance, sustainable alternatives to traditional neutron-detection technologies, which are often reliant on scarce or hazardous materials, across several critical domains:

radioactive waste monitoring: Ideal for non-destructive characterization of low- and intermediate-level radioactive waste

nuclear safety and security: Improves safety and operational efficiency by reducing dependence on scarce materials while providing continuous, high-fidelity monitoring

interim storage and/or transport: Monitoring spent fuel casks



Fig. 3: A AmBe neutron source box (in black) with a SiLiF detector (in white) during a measurement in the front position (https://doi.org/10.3390/s21082630 for details)

Involved partners	ENEA (Bologna, Italy), INFN-LNS (Catania, Italy), CEA (Cadarache, France), Centro Siciliano di Fisica Nucleare e Struttura della Materia (Catania, Italy)
Implementation Time	Already done
Technology Readiness Level	TRL7 - System prototype demonstration in operational environment
Exploitation	The SiLiF detectors were successfully tested in a real-world operational environment, not just in the lab, within the MICADO project. Rigorous testing validated the technology as a reliable and robust solution, confirming its maturity for demanding nuclear applications. This deployment demonstrated their superior effectiveness and enhanced stability where conventional detectors often fall short.

Application example

The main application was developed for the MICADO EU project. The project aimed at the full digitalization of low- and intermediate-level radioactive waste management. The goal was to develop a robust and cost-effective solution for the non-destructive characterization of nuclear waste by implementing a digitization process that could become a standardized reference, facilitating and harmonizing the methodologies used in in-field Waste Management and Dismantling & Decommissioning operations

According to studies and findings reported in the literature, a double-sided silicon detector MSX09-300 was employed. This detector is a 3 cm × 3 cm diode, 300 µm thick, with a 0.3 µm aluminum metallization layer on both faces, manufactured by Micron Semiconductor Ltd., Lancing. The silicon diode was integreted (sandwiched) between two ⁶LiF converter layers deposited onto carbon fiber substrates. The selected areal density of the ⁶LiF layer was ptimized at 4300 µg/cm². The detector response to monoenergetic neutrons at 13 different energies (0.025 eV, 0.1 eV, 1 eV, 10 eV, 100 eV, 1 keV, 10 keV, 100 keV, 1 MeV, 2.5 MeV, 5 MeV, 7 MeV, 10 MeV) was simulated using the Geant4 Monte Carlo code under full, half, and no moderator configurations. Various tests, measurements, and simulations demonstrated the suitability of SiLiF technology for neutron detection (https://doi.org/10.3390/s21082630 for details). The set of 32 detectors that we developed exhibited a uniform response, except for an unexpected systematic shift in detection efficiency caused by the converter substrate, which was thoroughly investigated and fully understood. The study concluded that SiLiF is a highly promising candidate for future applications in the monitoring of low- and intermediate-level radioactive waste.

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Laboratorio ENEA per la TRACCIABILITA' di ALIMENTI e SICUREZZA dell'ARIA



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Settori di riferimento: industria agro-alimentare, sicurezza chimica e nucleare, radioecologia

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