DOI: 10.24425/academiaPAS.2024.152928

All-Penetrating Neutrons

An artistic depiction of a remotely operated underwater vehicle conducting a non-invasive inspection of suspicious objects on the sea floor using the SABAT sensor, which utilizes neutron technology

Devices utilizing neutron activation techniques for the rapid identification of hazardous substances could play a vital role in detecting toxic materials submerged in the ocean depths.

Michał Silarski

Faculty of Physics, Astronomy, and Applied Computer Science
Jagiellonian University, Kraków

In late June 2023, a storm washed a barrel containing an unknown substance ashore in the Polish seaside town of Gąski. Tourists in the area were swiftly evacuated out of concern that it might contain hazardous materials. Fortunately, the container was sealed and posed no environmental threat. However, the fear sparked by such discoveries is well-founded. Similar incidents have occurred multiple times along the Baltic coast, often with tragic consequences. In 1955, waves in another seaside town, Darłówko, carried in a damaged container holding a dark, oily liquid that turned out to be mustard gas, causing severe burns to children playing on the beach. A similar event happened in the Russian city of Kaliningrad in 1990, when chunks of mustard gas injured several people who mistook them for amber. Even today, fishermen sometimes pull corroded munitions containing explosives or chemical agents – or even chunks of mustard gas resembling clay – out of their nets.

Numerous hazardous substances are present on the Baltic Sea floor, primarily chemical warfare agents like adamsite, Clark 1, Clark 2, tabun, mustard gas, and phosgene. These materials were dumped into the sea after World War II as part of international agreements to neutralize chemical weapons found in Germany. At the time, submerging this arsenal in 1945 seemed like the best solution, but in hindsight, it may have catastrophic consequences.

The most conventional and chemical munitions were dumped in the Gotland Deep, Bornholm Deep, and other deep areas of the Baltic Sea. These are officially recognized dumping sites, with well-documented quantities and types of ammunition. However, during the Cold War, chemical weapons were also discarded in the Gdańsk Deep region, and much of Germany's arsenal ended up in shallower waters. This happened due to shipwrecks or uncontrolled dumping carried out along the way to designated sites. As a result, the exact locations and quantities of post-war munitions in the Baltic remain uncertain.

This uncertainty poses significant threats – not only to those working at sea or on its shores, such as tourists and underwater explorers, but also to the environment. Studies have revealed traces of TNT and its derivatives, as well as arsenic – a component of Clark 1 and Clark 2 gases – in Baltic fish. An even greater ecological threat comes from heavy fuel oil trapped in wrecks, which, if released, could contaminate vast stretches of coastline. The contamination of the Baltic Sea also increases the cost of engineering projects, such as the construction of wind farms, which require extensive seabed surveys and clearance operations. These projects are expensive due to the advanced detection and identification methods needed for submerged objects.

Unfortunately, the Baltic is not unique in this respect. Sunken ammunition and fuel can be found in nearly every region that experienced intense naval battles. For instance, large quantities of mustard gas were sunk in the port of Bari, Italy, in 1943 by the Luftwaffe. This weaponry, shipped there from the United States, was intended for potential use by Allied forces against German troops.

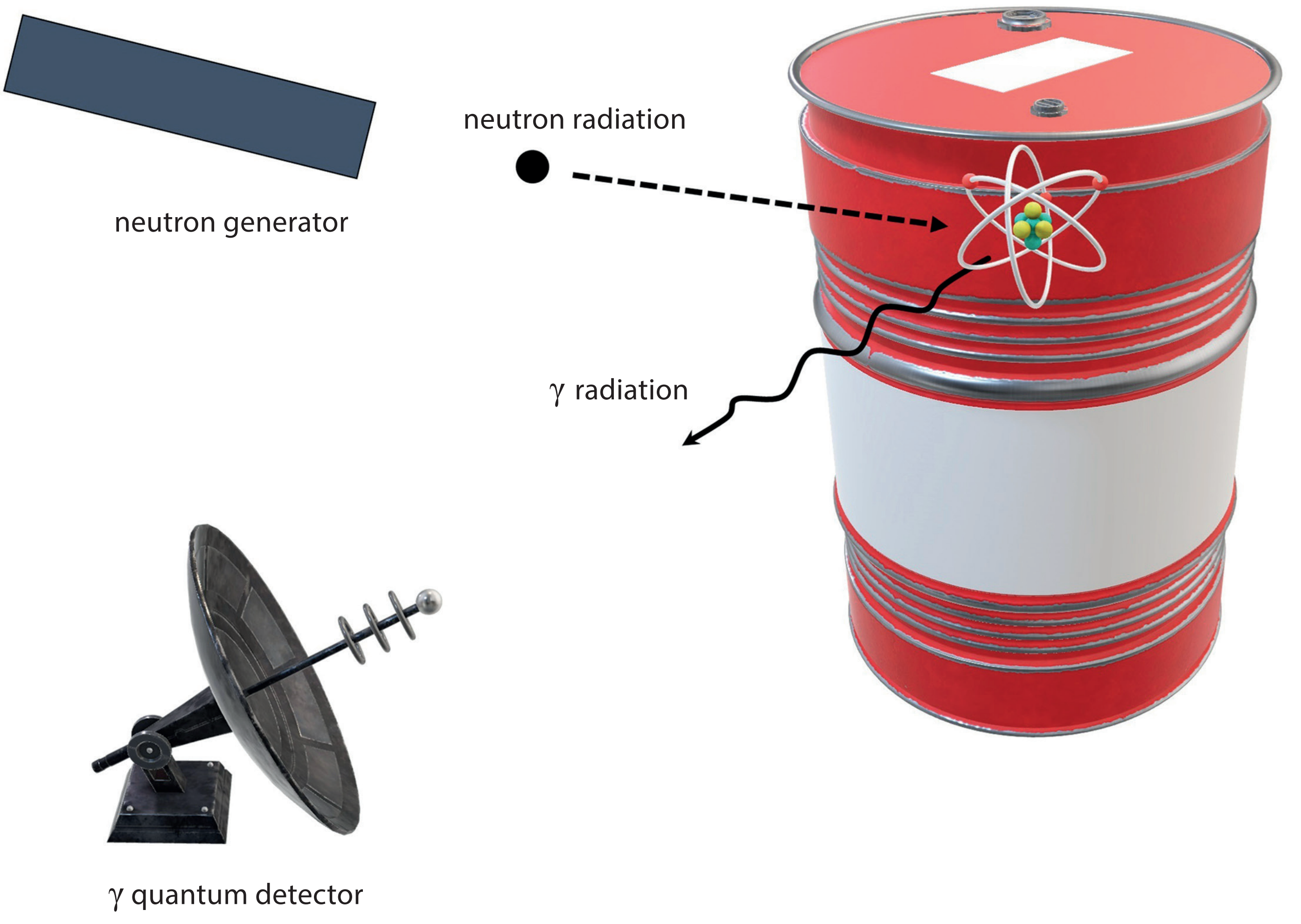
Needle in a haystack

Detecting and classifying objects on the seabed begins with magnetometers and sonars, which can image large areas but only reveal the shape of objects, not their chemical composition. Additional verification is required and it often reveals preliminarily tagged objects to be merely harmless debris (e.g., steel remnants from fishing equipment). Identification is typically carried out using underwater vehicles equipped with cameras or by sending divers who can recognize ammunition but often cannot determine the chemical substances inside corroded shells. This process is costly and time-consuming, significantly delaying clearance efforts. Environmental studies also involve

Michał Silarski, PhD

is an Assistant Professor at the Faculty of Physics, Astronomy, and Applied Computer Science at Jagiellonian University. His research focuses on testing fundamental symmetries in particle physics through kaon decay experiments and developing applications for fast neutrons in the non-invasive detection and identification of underwater hazardous substances. He is also actively involved in advancing boron-neutron capture therapy (BNCT), particularly in methods for monitoring boron distribution in patients' bodies by detecting secondary radiation produced during therapy.

michal.silarski@uj.edu.pl



A schematic representation of non-invasive material identification using fast neutrons. Neutrons produced in a deuterium-tritium neutron generator penetrate the walls of the examined object and excite atomic nuclei, causing them to emit gamma quanta with energies characteristic of specific isotopes. The resulting secondary radiation is then detected and analyzed to identify the composition of the material

collecting sediment samples from wide areas, which are analyzed in laboratories using mass spectrometry. Investigating wrecks for submerged fuel requires drilling into ship hulls to analyze controlled leaks – a risky operation that can damage corroded tanks, leading to uncontrolled spills of heavy fuel oil into the environment. The ideal solution to these challenges lies in non-invasive methods for determining the chemical composition of substances. One such approach is known as Neutron Activation Analysis (NAA).

Non-invasive spies

Neutron radiation has been used for analyzing the elemental composition of substances for many years, primarily in laboratories associated with nuclear reactors. These reactors provide high-intensity thermal neutrons (with kinetic energy corresponding to the average energy of gas molecules at 20°C). These neutrons interact with the atoms of a substance through radiative capture reactions, where neutrons are absorbed by atomic nuclei. This process creates new isotopes, often radioactive, which frequently emit secondary gamma radiation—high-energy electromagnetic waves released by excited atomic nuclei. The energy of this gamma radiation is unique to the isotope, allowing scientists to determine the concentration of various elements in the substance by analyzing the gamma radiation's energy spectrum. This method can be used, for example, to estimate the content of gold, silver, or manganese in a sample.

For field applications, portable neutron sources – known as neutron generators – are commonly used. These are essentially small accelerators that collide deuterium ions with a tritium-containing target. This reaction fuses the two hydrogen isotopes, producing an alpha particle (a helium nucleus) and a neutron with a well-defined, high energy of 14 mega-electronvolts (MeV). These neutrons can be used for activation analysis but also for inelastic scattering, where a neutron excites the nucleus without being absorbed. In this case, no new isotope is formed; instead, gamma radiation characteristic of the excited nucleus is emitted. The use of fast neutrons brings a key advantage: their high penetration power. This allows the excitation of substances in sealed containers, buried underground, or hidden behind walls. Additionally, some elements in hazardous substances, such as sulfur, carbon, and oxygen, are almost exclusively excitable through inelastic scattering with high-energy neutrons. Other elements, like chlorine and nitrogen, react with thermal neutrons that have been moderated (slowed down) within the substance being analyzed.

In laboratories, gamma rays produced by neutron irradiation are detected using high-purity germanium detectors (HPGe), which can distinguish photons with very similar energies. However, these detectors need to be cooled, usually with liquid nitrogen, which makes them less portable. Additionally, they degrade over time when exposed to neutron radiation, limiting their ability to operate continuously in such environments. For non-invasive detection of hazardous substances, scintillation detectors are more commonly used. In these detectors, gamma radiation transfers its energy (or part of it) to electrons in the detector's active material, producing flashes of light (scintillations). A portion of this light is converted by a photomultiplier into electrical pulses, whose charge or amplitude provides information about the energy deposited in the scintillator.

Several existing systems use neutron activation to identify explosives on land (e.g., CALSEC from the United States); a prototype of one such system, called SWAN, has been developed at the National Centre for Nuclear Research in Świerk, Poland. These systems consist of compact neutron generators and scintillation detectors, which, along with their power supply and electronics, fit into a medium-sized case. They can be mounted on robots, small vehicles, or drones, enabling the remote identification of suspicious objects.

Neutron generators (and all neutron sources, for that matter) emit neutrons in all directions with nearly equal probability. This presents a significant drawback, as it generates considerable gamma radiation in the surroundings that does not originate from the analyzed object, creating background noise for devices relying on neutron activation analysis (NAA). This issue is particularly pronounced in underwater applications, where neutrons are likely to interact with water, which contains elements similar to those being detected. Additionally, water strongly absorbs and moderates both neutrons and gamma radiation, requiring the sensor to be positioned very close to the analyzed object for identification to be successful.

These challenges mean that no commercially available devices currently exist for non-invasive identification of substances in water. To date, only one prototype has been developed (the UNCOSS project), and another is under development by our team at Jagiellonian University within the SABAT project. By integrating special neutron and gamma quantum guides and advanced background rejection methods, including machine learning algorithms, our Polish sensor will be able to detect charges containing as little as a few hundred grams of explosives or chemical warfare agents resting on the seabed.

Future prospects

The use of neutron activation techniques offers a promising opportunity to significantly reduce the cost and time required for clearing explosive items from both aquatic environments and large land areas. These techniques could also greatly improve the safety of such operations and better protect civilians. Miniaturization is likely to advance further, driven by innovations in neutron generation (e.g., the development of the neutristor, a miniature neutron generator, in the United States) and gamma radiation detection. Sensitivity could be further enhanced in the near future by combining neutron activation with other techniques, such as deep inelastic scattering of thermal neutrons or neutron transmission. While these methods require sample collection, modern underwater vehicles (e.g., ROVs) can easily perform this task, with analysis conducted almost immediately.

> In the near future, it will be possible to accurately identify hazardous substances in the Baltic Sea and monitor them continuously. However, a much more complex and urgent challenge will remain: how to ultimately remove and neutralize this ecological time bomb.

This opens the possibility of accurately identifying hazardous substances in the Baltic Sea and ensuring continuous monitoring. However, a much more complex and urgent challenge will remain: how to ultimately remove and neutralize this ecological time bomb. International research teams are actively working on solutions, including the newly launched BALTWRECK project, led by Poland. ■

Further reading:

Dodson B., World's smallest neutron generator – it's not just for nukes anymore. *New Atlas*. 2012. https://newatlas.com/sandia-neutristor-neutron-generator-chip/23856/

Silarski M., Hunik D., Moskal P., Smolis M., Tadeja S. Project of the Underwater System for Chemical Threat Detection, *Acta Physica Polonica A*, 2015, 127.

Chemsea Report: Results from the Chemsea Project – Chemical Munitions Search and Assessment. http://www.chemsea.eu/admin/uploaded/CHEMSEA%20Findings.pdf