Adapting Smart Dust for Nuclear Safeguards Application

Jawad R. Moussa*, Isaiah Padilla, and Shannon Abbott
Sandia National Laboratories, Albuquerque NM 87123
*jrmouss@sandia.gov

Abstract

Innovation and technological advancements continue to push the boundary of limitations set on how small a technology can be. Particularly, advances in microelectromechanical system (MEMS) technologies have enabled the development of wireless communication networks of small, low-cost, low-power, and multifunction sensors. Such systems are more commonly referred to as *Smart Dust*, a term synonymous with systems consisting of many millimeter- to nanometer-sized MEMS operating together as an integrated and massively distributed wireless sensor network (WSN). Although the technology is generally considered to have a low Technology Readiness Level (TRL) at this time, recent advancements in the field suggest that it is developing towards reaching the size and capability to make Smart Dust networks more successful and commercially accessible. Nevertheless, since the idea was first presented in the late 1990s, the concept of building a distributed network of wireless MEMS has impacted many sectors such as agriculture, industrial, medical, and the automotive industry. Adapting Smart Dust for nuclear safeguards application could provide a wide range of safeguards utility and the potential to advance areas within the space, such as Containment and Surveillance (C&S) and Material Control and Accountability (MC&A). In particular, Smart Dust's ability to execute programmed functions and record data given its size provides an opportunity for researchers and safeguards specialists to explore potential new data streams for monitoring materials at nuclear facilities. It also provides an opportunity to expand sensor networks into previously unreachable areas. This work provides a general overview of Smart Dust technology and its current state of development alongside scoping its applicability to the nuclear safeguards space. It aims to analyze the key drivers towards adoption and focuses on the analysis of potential use cases of Smart Dust in safeguards applications and the potential impact of such use cases. Detailed scenarios that would demonstrate Smart Dust's utility in the near- and long-term are also presented.

Introduction

Nuclear safeguards are a set of technical measures that are implemented domestically and internationally to ensure that nuclear material and/or technology is not being misused or diverted from civilian operations for clandestine use [1, 2, 3]. Internationally, the International Atomic Energy Agency (IAEA) independently verifies this through the conclusion of safeguards agreements with member States which allow the IAEA to establish safeguards measures at various levels. Such measures take different forms which include, but are not limited to, facility inspections, containment and surveillance, and design information verification (DIV) [4]. All of these measures entail data collection of some sort for later analysis. Considering recent advancements in WSNs, Internet of Things (IoT), and nanotechnologies, this work aims to investigate the potential application of these technologies within the nuclear safeguards space. Particularly, this effort is focused on the analysis of potential use cases of *Smart Dust* in safeguards applications along with the potential impact

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

of said use cases. This is achieved by, first, providing a general overview of the technology and its current state. Enabling technologies of which Smart Dust may depend on are also assessed in effort to analyze key drivers towards adoption as well as technical limitations and barriers. This information is then used to create likely scenarios that would demonstrate Smart Dust's utility in the near- and long-term.

Smart Dust Technology Overview

Background

Many definitions have been put forth to describe Smart Dust technology over the years, but it is a term that is most commonly used to describe a massively distributed WSN made up of millimeter scale nodes that utilize MEMS[5, 6]. Such systems are characterized by connecting many small low-cost, low-power, and multifunction sensors. The exact size that would constitute a *small* sensor is relative and has been continuously updated as technological advancements push the boundaries of size. These sensor nodes (motes) are the *dust* in Smart Dust and are designed to be self-sustaining and capable of processing and transmitting collected data.

The concept of Smart Dust first appeared at a workshop titled "Future Technology Driven Revolutions in Military Operations" that was held by the RAND corporation in 1994 for the Defense Advanced Research Projects Agency (DARPA) [7]. Several topics were covered throughout the workshop, of which *Micro & Nano Technologies* and *Very Small Systems* were featured prominently. The goal of this workshop was to explore how future technologies could shape the battlefield in 2025. However, the term Smart Dust did not appear until 1997, when Andrew Berlin and Kaigham Gabriel used it to describe the possible applications of MEMS in their paper "Distributed MEMS: New Challenges for Computation" [8]. That same year, Kristofer Pister and his team at the University of California, Berkeley submitted a proposal to explore the possible military and industrial applications of Smart Dust technology [9]. It is uncertain whether Berlin and Kaigham or Pister first coined the term *Smart Dust* in 1997; regardless, it has since become the established term to describe the technology.

While Smart Dust's battlefield application will likely fall short of what was initially envisioned for 2025, researchers continue to make progress and develop new use cases. A considerable amount of discussion around the concept of Smart Dust and its possible applications occurred since 1997. Several papers have been published on the topic proposing, and in some cases demonstrating, potential future applications and technological hurdles of Smart Dust technology.

Example Smart Dust Related Projects

Military Projects

- *Border Surveillance* – A WSN capable of monitoring thermal, magnetic, acoustic, and vibration shifts was developed to address the issue of cross-border terrorist activities [10]. This university project demonstrated that these sensors could be programmed to detect if any movement occurred in a target area, including large group or vehicle passage. Magnetic fields were used to identify the presence of weapons or military vehicles, while infrared radiation was used to identify human activity. If any of the sensors were triggered, the information was transmitted from the dust mote to a central monitor mote, where the data could be viewed and stored. Power consumption levels limited the lifetime of this specific system thus the incorporation of solar powered cells was planed for future iterations.

- *VigilNet* – The University of Virginia developed and distributed VigilNet to address the need for long-term surveillance during military mission deployments [11]. VigilNet is a flexible WSN that can be programmed to work across a variety of topologies, node densities, sensing and communication needs, and mission objectives over three-to-six-months periods. The sensors detect infrared radiation, vibration, and acoustic data, and can classify targets via their specific signatures to aid with tracking.

Environmental Sampling Projects

- *Air Pollution* – Numerous researchers have lab-tested WSNs with gas sensor nodes to study levels of air pollution present across various environments [12, 13, 14]. The viability of one particular system was successfully field tested through a deployment across the Indian Institute of Technology (ITT) Campus in Hyderabad, India [15].
- *Water Quality* – A European Union joint research project led by Hungary and Slovakia developed and deployed a WSN to measure pH, temperature, conductivity, dissolved oxygen levels, pressure, salinity, and redox potential to address the water pollution problem in their cross-border region [16]. The project concluded with a proof-of-concept experiment.
- *Early Warning Radiation Detection* – A WSN with a Geiger-Muller tube incorporated was simulated in a lab setting to address the critical need for early detection of radiation leaks [17]. Application of different media access control (MAC) protocols increased the lifetime of these monitoring networks in simulation and demonstrated their potential for success. Alternatively, the ability to monitor environmental parameters that vary rapidly when exposed to radiation including temperature, sound, smoke, and carbon monoxide using a wireless network of gas sensors was successfully tested in a lab setting [18].
- *Great Duck Island* – To monitor temperature, barometric pressure, humidity, light levels, and infrared radiation levels in duck habitats, a WSN was deployed on Great Duck Island [19]. The deployed nodes were designed to provide hourly updates on environmental conditions over a four-month breeding period. The median lifetime of the nodes was 52 days, and they compiled a dataset of more than 450,000 observations during the field experiment.

Structural and Logistic Projects

- *Integrity of Concrete Structures* – To monitor both temperature and humidity levels in concrete structures, a WSN was developed to provide long-term real-time data [20]. The experimental system accurately measured temperature and humidity using a singular sensor at a single point inside a concrete cube in laboratory setting. The data was collected and wirelessly transmitted back for observation over a period of two months.

System Components & Enabling Technologies

It is important to note that Smart Dust is a term used to describe a collection of technologies combined into a system as opposed to a single technology in itself. Several technologies are packaged together in such systems to achieve a specific goal. This is one of the main reasons Smart Dust is so versatile, but it also inherently leads to each system being different depending on the application. The first design proposed following the "Future Technology Driven Revolutions in Military Operations" workshop was developed with a specific application in mind and is illustrated in figure 1. Since then, the concept has been adapted for different applications thus requiring design modifications. However, all designs shared common building blocks for a Smart Dust system. At a fundamental level these systems consisted of:

- Sensing Technology
- Power Supply and Storage
- Information Processing Technology
- Information Transmission/Communication Technology

No product currently exists such that Smart Dust can be acquired as a commercial-off-the-shelf (COTS) product. Nonetheless, Smart Dust systems can be designed and assembled by acquiring each sub-component independently. Smart Dust associated technologies such as MEMS, IoT, and WSNs have been advancing independently and have become more readily available over the past decade. That said, the process of developing a Smart Dust system would first require that a system is designed for a specific application. From there, each sub-component can be acquired independently and the system is assembled for deployment.

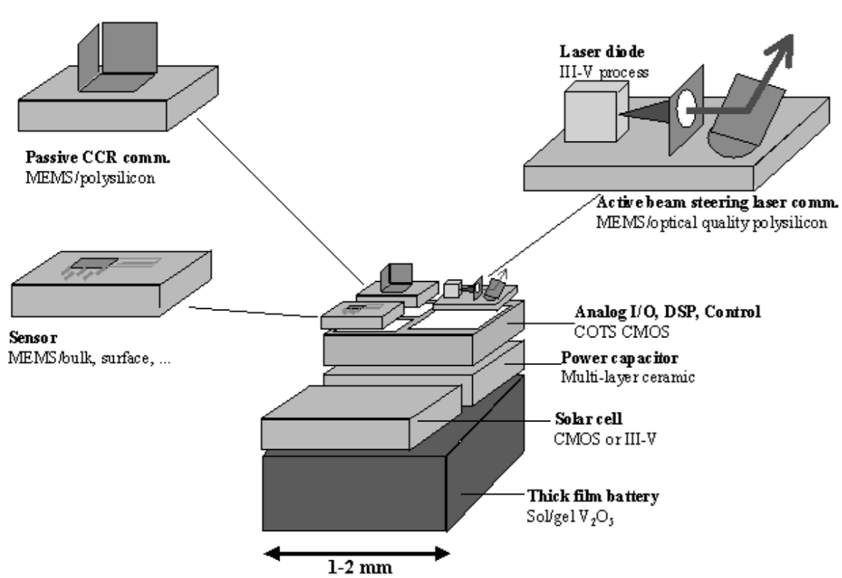

Figure 1: Original Proposed Design for a Smart Dust Mote [9]

Nuclear Safeguards Applicability

To assess the potential application of Smart Dust within the nuclear safeguards space, the first step was to identify current safeguards implementations and challenges at each stage of the nuclear fuel cycle from open literature. A generic nuclear fuel cycle was considered as illustrated in figure 2. Transportation was also considered as an intermediate step between different stages. Subject matter experts (SMEs) with experience working at the IAEA and whom are well familiar with international safeguards practices were also consulted to gain a better understanding of current safeguards measures and fill in any gaps that were unavailable through the open literature. With that, an assessment was performed at each stage of the nuclear fuel cycle to determine whether Smart Dust, in its current state, would advance existing safeguards implementations or introduce new safeguards capabilities that would advance the international safeguards space as a whole. This assessment was done through the generation of hypothetical use case scenarios for all applicable implementations.

It is noted that Locations Outside Facilities (LOFs) were not considered within this work, but the versatility of Smart Dust suggested that it has the potential to support IAEA safeguard activities at such facilities. Such implementation could be a promising path forward to deploy Smart Dust systems for nuclear safeguards application considering such facilities would have less roadblocks for implementation from a policy perspective. However, further analysis is required to better understand the existing challenges associated with safeguarding LOFs and how Smart Dust systems could potentially support such activities.

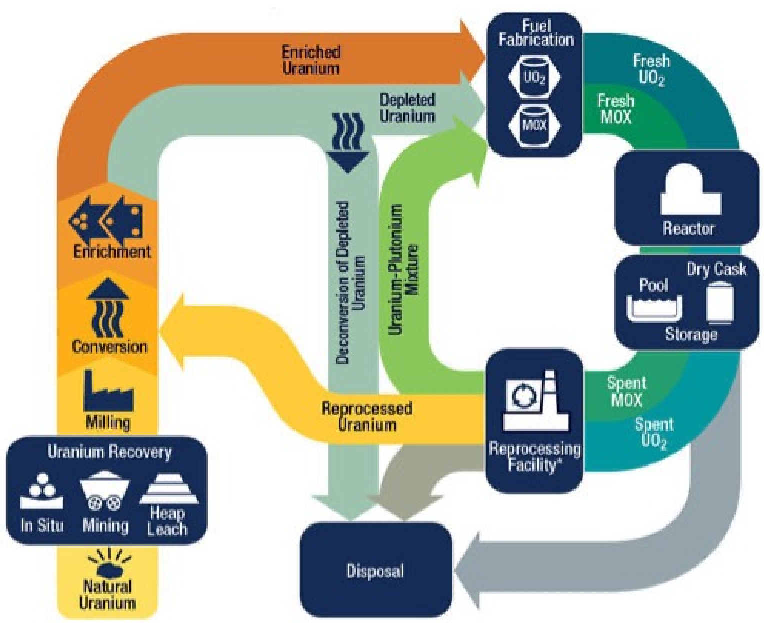

Figure 2: A generic nuclear fuel cycle that was considered for analysis [21]

Nuclear Fuel Cycle Considerations

Nuclear safeguards measures vary from one stage of the nuclear fuel cycle to another. However, general similarities can be observed between like stages making it easier to assess if a particular technology can contribute to the field at that stage. For instance, mining and milling are two separate stages of the nuclear fuel cycle that serve different purposes relative to one another. The mining of natural uranium entails the extraction of uranium (U) ore from underground deposits through open pit mining, underground mining, or In-Situ Leaching (ISL) while milling pertains to the production of uranium ore concentrate (UOC) from the extracted ore [22]. The processes of mining and milling usually go hand-in-hand and rarely exist independent of each other. Hence, they were analyzed concurrently in this study. The same would apply to conversion, enrichment, and fuel fabrication. Each is considered to be its one stage but they share a common goal in terms of nuclear safeguards. That is, to ensure that all material that goes in comes out in an identifiable form or can be otherwise accounted for [23]. The stages of the nuclear fuel cycle considered in this study were:

- Mining & Milling
- Conversion, Enrichment, & Fuel Fabrication
- Reactor Applications
- Storage & Waste Disposal
- Reprocessing & Recycling
- Transportation

Use case scenarios for the application of Smart Dust were developed at each of these stages. However, some use cases were not exclusive to a specific stage and can be easily extended to other stages when applicable. This overlap is only natural, and very much expected, considering that some safeguards measures are common across multiple stages. A few examples of the developed scenarios are listed here for illustrative purposes.

Example Use Case Scenarios

Mining & Milling – Smart Dust could potentially play a role in the verification of decommissioned mines. A hypothetical scenario for this use case would be to place a Smart Dust sensor network throughout a decommissioned mine and use satellite imagery to monitor the site. If there happens to be any unexpected activity observed through satellite imagery, then the Smart Dust sensors can be retrieved and analyzed to verify if indeed there has been undeclared activity at the site. Additionally, under certain circumstances, some facilities may mine U ore for six months and mill to produce uranium oxide (U_3O_8) for the remainder of the year. This means that the application of Smart Dust could potentially extend beyond the use to verify decommissioned facilities, but it could also be used as a method to verify that facilities are operating according to their State declaration to the IAEA.

Conversion, Enrichment, & Fuel Fabrication – Deploying a Smart Dust network in locations otherwise inaccessible would make it much easier to identify any changes made to a facility during DIV activities. Especially changes that wouldn't be noticeable to the naked eye, or those made in areas where the currently used technology cannot reach. Another aspect of DIV that is specific to enrichment facilities is the use of cascade monitoring to verify the operational status of centrifuges. Smart Dust could help make this process much more efficient if applied on the roof of an enrichment facility to obtain a detailed temperature profile. Since temperature is a good indicator of operational status of a centrifuge, this information could be used to compare the operating temperature profile to an expected profile based on declared information. Lastly, Smart Dust could potentially be placed in seals, where it would record movement or changes in environmental parameters. Better yet, it could be used as a temporary seal during inspections by placing it on containers that have been inspected to ensure they are not tampered with post inspection. This application would also help identify if any containers were moved or temporarily relocated.

Transportation – Although transportation is not a traditional stage of the nuclear fuel cycle, it was included within this work due to the high frequency at which material is moved and the central role it plays in connecting the various stages together. This could either be the temporary relocation of material within a facility or the shipment of material from one facility to another. A use case scenario for Smart Dust at this stage would be material monitoring during temporary moves within a facility and/or between facilities. Smart Dust would be implemented for the purpose of verifying that the material arrives at its expected destination without diversion. For instance, after spent fuel has cooled in a temporary storage pool for an adequate period of time, it is loaded into long-term storage casks that are then transferred to a storage facility. The casks are welded shut prior to being transported and the weld is inspected for signs of tampering once it is received at the storage location. Smart Dust would serve as a convenient method of external monitoring during this process where it could be placed on the surface of the casks to ensure seals are not broken and material has not been tampered with.

Smart Dust as a Passive Sealing Method

Numerous applications of Smart Dust systems were identified across the nuclear fuel cycle, both at individual stages and its entirety. Of those applications, the use of Smart Dust to enhance passive sealing methods currently in use was the most promising and most likely to successfully impact the nuclear safeguards mission space. Seals are commonly placed on safeguarded material, facility equipment belonging to the operator, and IAEA property that remains at the facility. These seals are inspected and replaced by IAEA inspectors during routine and/or unannounced inspections. For example, a low-cost, reliable, and widely used seal type is the E-CAP metal seal (CAPS) [24]. In addition to having distinct serial numbers, these seals feature unique markings or etchings on the inside that can only be viewed when the seal is unattached and open. Before use, the serial number is recorded, and images are taken of the cap and inside markings. This process serves as a tamper-indicating feature, but it requires replacement of the seal with every inspection as it must be retrieved for verification. A modernized iteration of these seals is the field verifiable passive seal (FVPS), which does not require replacement with every inspection [25]. figure 3 shows an illustration of both seals.

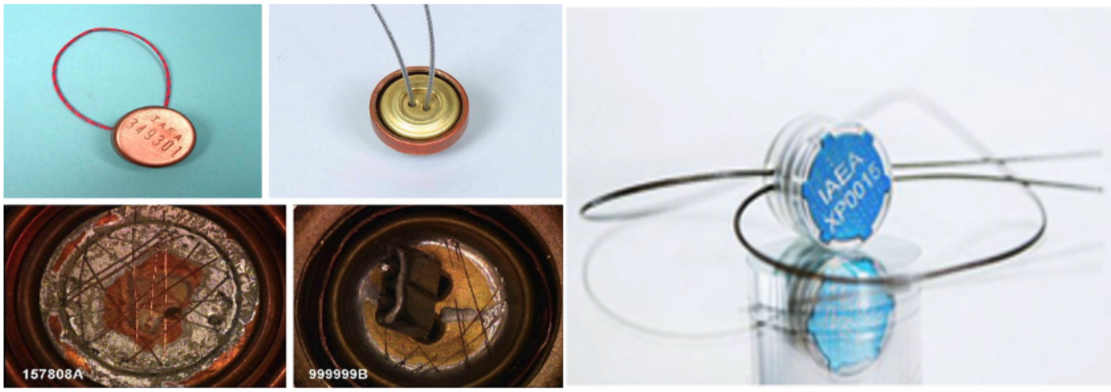

Figure 3: Passive Seals Currently Used by the IAEA [24, 25]

The tamper-indicating feature of these seals could potentially be enhanced when used in conjunction with Smart Dust. The uniquely small size of Smart Dust would enable the collection of tampering data and movement of sealed containers. A Smart Dust mote would be placed within the seal to monitor the motion, impact on, and vibration of the seal. The collected data can then be reviewed during an inspection for any anomalies or changes. Any unexplained signs of pressure on the wire or vibration could be an indicator for tampering with, or attempting to tamper with, the seal. Alternatively, Smart Dust could be used to detect the movement of a container, material, or equipment to which the seal is attached. Seals are often placed on items that are expected to be stationary in a facility and, if moved, may not always be easily identified on inspections. The Smart Dust mote would indicate movement during a specified period, especially for any items moved from the original location and back when inspectors are not present. Conversely, the Smart Dust motes could track items that are expected to be moved, thereby verifying the correct destination without diversion.

Conclusions

Advances in IoT, MEMS, and wireless sensor networks continue to push the needle towards making Smart Dust available at a commercial scale. Yet, challenges remain that must be addressed for that to happen. When the term *Smart Dust* is used, one might think of many sensors the size of dust motes floating in the air. However, that is not the current state of Smart Dust technology. By analogy, one might say that we are currently capable of deploying Smart Pebbles as opposed to the Smart Dust that was once hypothesized. Fortunately for the case of nuclear safeguards, the concept of *small* is relative to the application. For instance, using Smart Dust for DIV in enrichment facilities to obtain a temperature profile during operation wouldn't necessitate a network of wireless sensors on the nanometer scale. Micrometer or millimeter sized sensors would suffice for such applications. That is not the case for Smart Dust being deployed in metal cup seals to enhance passive sealing methods currently used. That would require sensors that are much smaller. Although further research and development may be required for Smart Dust to reach the point most people think of when they hear the term, the current state of development suggested that it could potentially be ready for deployment in the nuclear safeguards space. Nevertheless, feasibility testing would still be required to gain a better understanding of how Smart Dust would fit into the current nuclear safeguards picture and what might still be needed for successful deployment. For instance, one of the most promising applications is the use of Smart Dust systems to enhance current passive scaling methods used by the IAEA. Recognizing that Smart Dust is a system that can be designed and configured in many different ways, questions pertaining to which specific sensors would go into the seal, how these sensors would be powered, and the logistics of what information should be collected and how must all be addressed. Further investigation of these specific considerations should form the topic of future efforts pertaining to adapting Smart Dust for nuclear safeguards application.

Acknowledgments

This work was funded by the U.S. Department of Energy National Nuclear Security Administration's Office of Nonproliferation and Arms Control, International Nuclear Safeguards program (NA-241), Concepts & Approaches portfolio. the authors would also like to Alexander Solodov, Katie Spence, and Sarah Logan for helpful discussions and their contribution to this work.

References

[1] The International Atomic Energy Agency. *Basics of IAEA Safeguards*. URL: `https://www.iaea.org/topics/basics-of-iaea-safeguards`.

[2] US Nuclear Regulatory Commission. *Safeguards*. 2021. URL: `https://www.nrc.gov/reading-rm/basic-ref/glossary/safeguards.html`.

[3] Eurepean Commission. *Nuclear safeguards and security*. URL: `https://joint-research-centre.ec.europa.eu/scientific-activities-z/nuclear-safeguards-and-security_en`.

[4] The International Atomic Energy Agency. *Safeguards explained*. URL: `https://www.iaea.org/topics/safeguards-explained`.

[5] Mohammad Ilyas and Imad Mahgoub. *Smart Dust: Sensor network applications, architecture and design*. CRC press, 2018.

[6] Nanowerk. *What is smart dust and how is it used?* URL: `https://www.nanowerk.com/smartdust.php`.

[7] Richard O Hundley and Eugene C Gritton. *Future technology-driven revolutions in military operations. results of a workshop*. Tech. rep. RAND CORP SANTA MONICA CA, 1994.

[8] Andrew A Berlin and Kaigham J Gabriel. "Distributed MEMS: New challenges for computation". In: *IEEE Computational Science and Engineering* 4.1 (1997), pp. 12–16.

[9] Kristofer Pister. *Smart Dust. Proposal Abstract*. 1997. URL: `https://people.eecs.berkeley.edu/~pister/SmartDust/SmartDustBAA97-43-Abstract.pdf`.

[10] Kishore Kumar S. "Smart Dust for Tactical Border Surveillance to Detect, Classify and track Enemy Intrusion Using Acoustic-magnetic-thermal Vibration Signatures". In: *Proceedings of IRAJ International Conference*. IEEE. 2013.

[11] Tian He et al. "Vigilnet: An integrated sensor network system for energy-efficient surveillance". In: *ACM Transactions on Sensor Networks (TOSN)* 2.1 (2006), pp. 1–38.

[12] Umesh M Lanjewar and JJ Shah. "Air pollution monitoring & tracking system using mobile sensors and analysis of data using data mining". In: *International Journal of Advanced Computer Research* 2.4 (2012), p. 19.

[13] Ryan Bishop. "A Triptych of Indeterminate Objects in the Urban Metabolism: Glass/Dust/Bomb (After Paul Virilio)". In: *Media Theory* 3.2 (2019), pp. 189–204.

[14] C Balasubramaniyan and D Manivannan. "Iot enabled air quality monitoring system (AQMS) using raspberry Pi". In: *Indian Journal of Science and Technology* 9.39 (2016), pp. 1–6.

[15] Kan Zheng et al. "Design and implementation of LPWA-based air quality monitoring system". In: *IEEE Access* 4 (2016), pp. 3238–3245.

[16] Ákos Milánkovich and Krisztina Klincsek. "Wireless Sensor Network for Water Quality Monitoring." In: *EPS*. 2015.

[17] Jannat H Elrefaei et al. "Energy-efficient wireless sensor network for nuclear radiation detection". In: *Journal of Radiation Research and Applied Sciences* 12.1 (2019), pp. 1–9.

[18] SR Ashwini et al. "Wireless Sensors Network for environmental radiation monitoring using IOT". In: *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*. IEEE. 2018, pp. 2373–2376.

[19] Robert Szewczyk et al. "An analysis of a large scale habitat monitoring application". In: *Proceedings of the 2nd international conference on Embedded networked sensor systems*. 2004, pp. 214–226.

[20] Norberto Barroca et al. "Wireless sensor networks for temperature and humidity monitoring within concrete structures". In: *Construction and Building Materials* 40 (2013), pp. 1156–1166.

[21] US Nuclear Regulatory Commission. *Stages of the Nuclear Fuel Cycle*. 2020. URL: https://www.nrc.gov/materials/fuel-cycle-fac/stages-fuel-cycle.html.

[22] World Nuclear Association. *Uranium Mining Overview*. 2022. URL: https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/uranium-mining-overview.aspx.

[23] The International Atomic Energy Agency. *Safeguards for Reprocessing and Enrichment Plants*.

[24] Russell E. Johns and Mark Schanfein. *Nuclear Safeguards, Security, and Nonproliferation (Second Edition)*. Butterworth-Heinemann, 2019. Chap. 7 - Nuclear Material Accounting and Control, pp. 157–229.

[25] Jennifer Wagman. "Small device, big effect. Field verifiable passive seals". In: *IAEA Bulletin* 63.3 (2022). URL: https://www.iaea.org/bulletin/small-device-big-effect.