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PhD Dissertation

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Research and development of intelligent detectors and systems for detection of ionizing radiation for military and disaster management applications

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INTRODUCTION

The description of the scientific problem

Since the discovery of X-rays in 1896, measuring ionizing radiation has been a significant challenge for professionals. The measurement of ionizing radiation is almost as old as the discovery of radiation, because we are not able to detect radiation with human senses [1].

In the early days, ionizing radiation was not considered as dangerous, and it was used in everyday life. E.g., cosmetics and painting for illuminated posters. The danger of ionizing radiation was later realised by scientists and as well the public. Today the use of radiation-emitting materials and equipment in most parts of the world are regulated by law, because the fear of radiation is common in most societies.

After the discovery and application of nuclear weapons, regulatory organizations began to measure radiation in the environment. Nuclear accidents and disasters gave a further boost to the spreading of radiation detectors. Radiation reconnaissance is one of the critical capabilities of Chemical, Biological, Radiological, Nuclear (CBRN) first responders. Nowadays the use of radiation detectors is regular in CBRN accident evaluation, in dangerous goods shipment control process, and in detecting lost or smuggled radioactive sources. Measuring detectors have changed radically since their discovery.

Figure 1. An early radiation detector and a radiation measuring instrument used currently.
Source:[2], [3].

Figure 1. shows an early Geiger–Müller (GM) tube made in 1932 by Hans Geiger for laboratory use a handheld isotope search and identification instrument used nowadays.

In this dissertation, the applicability of intelligent radiation measuring detectors, algorithms and methods will be investigated in different applications to improve their capabilities. The availability of high-quality information in the right place and time can be an essential factor in disaster management. New measurement methodologies, algorithms can improve the quality of information and can reduce response time to an event.

The tasks of the first measuring devices were limited to measuring and showing results. Instruments used today can alert if the measured value is over a given alarm threshold. The detectors of the future will be able to give suggestions on what the user should do in a given situation and could give a warning before an actual accident occurs. The information available with new technologies can provide a much more accurate picture of the situation. Complicated measurement procedures require well-trained operating personnel. The challenge of the future is to simplify the processes for the operator to perform the necessary tasks and make it possible to use the device without any lengthy and challenging training.

Different radiation measurement technologies are avalible like: ionization chambers, proportional, and GM counters, scintillator and semiconductor detectors. An intelligent detector is intelligent because: it processes, analyses and interprets the analogue signal coming out of the sensor (GM tube, scintillator crystal); runs various algorithms on it, then generates information relevant to the user; performs tasks and stores data; and communicates with the outside world. A combination of different intelligent detectors can be built together into a system, which can supervise borders, facilities, entire countries or continents. In my research, I focus on two radiation measurement technologies: GM counters and scintillation detectors, because these technologies are available for me, and I found possible development regarding these technologies.

The first technology I investigated is based on GM counters. GM counters can be used in applications where wide measuring range and ruggedness is required. Figure 2 shows an example of a rugged intelligent GM counter radiation detector.

Figure 2. RadGM Intelligent GM counter radiation detector.

Source: [3].

The second technology I investigated deals with applications involving scintillation based detectors. This type of detector can be used when gamma-radiation isotope identification or a high level of sensitivity is required. Different scintillation based detectors can be seen in Figure 3.

Figure 3. NDI scintillation based radiation detectors.

Source: [3].

The results of this research can be used in the field of on-foot, and onboard radiation reconnaissance, border protection and early warning applications. This dissertation investigates the efficiency of intelligent detectors with different methods and tests and will come to conclusions based on those results. In this context, the intelligent detectors refer to detectros that provide more information than just the analogue measured values, they can also do data analysis and post processes to provide more detailed information for decision-makers.

Improvement of scintillation type detectors

Laboratory type scintillation detectors and GM counters are not suitable for military and disaster management tasks. The environmental resistance of such a devices are weak. Sensitivity to temperature, humidity, vibration and electromagnetic fields makes these units operational only under laboratory conditions . The data available from scintillation detectors is much more complicated than a simple count number coming from a GM counter. However, the information provided by this type of sensor is essential in the field. With the help of a scintillation detector, isotope identification, localisation and radioactive material characterisation tasks can be carried out. I will introduce different solutions on how to modify a scintillation detector to make it field ready. Field ready means endurance to temperature, humidity, dust, rain, pressure, shock, vibration and environmental conditions stated in military standards. [4]

New generation of radiation portal monitors

Scintillation type detectors have been used for radiation portal monitor application for decades. The scientific problem with these systems is that they provide limited information about the events. The information available from such a system are not enough to make the right decisions. If a portal monitor is not sensitive enough or works with an inappropriate algorithm, the system will allow contaminants to pass through a checkpoint, which could lead to a radiological disaster, or in case of smuggling can be used for terrorist attacks. False alarms at these portal monitors can cause severe damage. If the radiation portal monitor system marks a shipment as contaminated in which no radioactive material is present, it is called a false positive alarm. This alarm causes unnecessary panic and financial damage by having to evacuate the facility, suspending work and calling in an expert to clarify the situation. The method I am looking for can reduce the false alarm rate but still has a high level of sensitivity. There are proven technical solutions for the physical protection of radioactive sources that have been available for a long time. However, the algorithm used in the portal monitors can be changed to provide information to a security system, thus further increasing the protection level of the system.

Problems with on-foot reconnaissance

One of the tasks during on-foot radiation reconnaissance is to find hidden, or lost radioactive sources. The task can only be carried out in a very long time in the absence of the appropriate technical equipment and searching technique.

The radiation measuring devices used for this purpose are either not sensitive enough or do not have the necessary directional dependence to be able to give guidance to the person using it. By examining the possible measurement configurations, I selected the most effective solution that can provide an answer to this scientific problem.

The control of radioactive shipments can also be significantly improved with the help of intelligent detectors. At present, only simple control measurements are carried out on the outer casing of consignments, using dose rate measuring devices, and the formal requirements of travel documents are checked. The control is easy to circumvent for a professional. For example, artificial radioactive sources can be placed between natural shipments of radiation and the elevated radiation levels can be explained as the effect of natural radioactive materials.

Since most inspections do not allow the consignment to be open, only non-destructive external measurement solutions can be considered to improve the quality of the inspection. A solution to this problem can be a simple mobile application that calculates the dose rate at the wall of the container from the activity of the source stated in the shipment documentation. The result can be measured with a detector and compared. In addition to the measurable radiation level on the outside of the container, there are additional quantifiable data: mass, height and external shape, that help estimate the activity of the delivered radioactive source. This allows the shipment to be classified without the data from shipment documentation.

Challenges at emission monitoring systems

Activities with certain radioactive materials release gaseous or volatile contamination into the environment. Nuclear power plants, radiopharmaceutical manufacturers and hospitals are typically releasing radioactive contamination into the air. Measurement of emissions is essential if it is to prove that emissions have remained below the officially permitted maximum emission level for a given period. Emissions can be measured in several ways, but the most technology-friendly solution must be found, and several aspects must be taken into account. When choosing a possible solution, it is important that the high gamma background radiation does not affect the measured result, I am looking for a solution to this scientific problem.

Research objectives (RO)

In my research, I set basic conditions for the whole project and research objectives for each topic. Basic conditions:

- To use already existing technologies and results of applied research activities to improve products quality and performance.
- To create all the results of the research in such a way that it can be directly used in the daily work of CBRN first responders.
- Not presenting any company secret which is applied in an existing product or could be used in the future development of the company I work for.

Objectives of my research:

RO1: My goal is to find the new trends and essential requirements of radiation monitoring systems implemented for different applications. To achieve this goal I have to know the relevant regulations, standards and legislation, compare possible solutions and identify the correct method and architecture for such a system. From available algorithms and methodologies, I create new ones to achieve better system performances.

RO2: My research aims to develop new hardware and software solutions that can be integrated into intelligent measuring detectors, which will detect radioactive materials in the field of disaster management and the military. Create a new generation of detectors that are already suitable for field operation.

RO3: My research goal is to develop a selection criteria system for radiation portal monitor applications and to upgrade such system with the additional capability to provide more information for the operator when a radioactive source triggers an alarm, or someone is trying to steal a radioactive source from a supervised area. I prove that a radiation portal monitor is capable of supporting physical protection systems.

RO4: My goal is to create a radioactive source searching algorithm that can be used to find lost or hidden point type sources faster and more efficiently; simplify the qualification of radioactive shipments for the user, while collecting as much information as possible about the shipment and automatically checking the shipment documentation with smart detectors.

RO5: My further goal is to compare different emission control solutions and find the most suitable one for the given task. In addition to the high gamma radiation that often occurs in such systems, the realisation of measuring beta activity concentration.

Hypotheses (H)

In harmony with the definition of the research problems, I formulated the following hypotheses:

H1.: The efficacy of radiation monitoring systems can be increased and new capabilities can be added to radiation monitoring systems by using intelligent radiation detectors which compensate for environmental changes, run algorithms to make operation easier and decision making quicker, applies self-checks to be more reliable. (RO1).

H2.: Scintillation detectors can be adapted for field use, disaster management and military purposes by modifying specific hardware and software components of the detector. The modifications cover the scintillator coupling material, the assembly, the fixing of the applied components and the compensation for the environmental effects made possible by the embedded microprocessors. (RO2).

H3.: High-reliability detection of transported radioactive materials can be achieved with radiation portal monitor systems if the systems are used in the appropriate assembly, configuration and with the right operating algorithm. The further development of the algorithm implemented in the radiation portal monitors allows the generation of an alarm signal to the direction of the physical protection system if the supervised radioactive source is located in an unauthorised position. (RO3)

H4.: The process of on-foot radiation reconnaissance can be made more efficient with the help of an intelligent radiation detector and the appropriate search method. The localisation time of lost or hidden sources can be minimised. The control of radioactive shipments can be made more accurate by measuring the radiation levels on the surface of the transport container and the external physical parameters of the container, and calculating the activity of the delivered radioactive source. (RO4)

H5.: The selection of the appropriate system for the measurement of released radioactive material can be optimised with the available information and technology. In emission monitoring systems, the measurement of beta volume activity is possible at high, dynamically changing gamma dose rates, using the appropriate algorithm and intelligent detector assembly. (RO5).

Research methodologies

I conducted a literature search on publications, standards, and international recommendations from a freely available source relevant to the topic, in order to learn about solutions, their structure and operation from other similar systems. By looking at the many detectors and early warning systems built around the world, I observed the trends of development and examined the pros and cons.

Based on the known requirements, regulations and available technology and trends, I created hypotheses and suggestions that are expected to characterize the future monitoring systems. In order to verify my ideas, I implemented several solution algorithms and performed experiments and measurements, with the help of which I verified my assumptions. I analysed the obtained results and the collected data and information in order to move in the right direction. I figured out how to determine the activity of the radioactive material in a transport container. For this, I created the measurement assembly with the necessary electronic and mechanical components and I made the operating software. I recorded the data measured by the equipment and then created various tests using radioactive sources with known activity. I compared the measurement results with the known data and based on the deviations, I qualified the operation of the whole system.

In the course of the research, I made several incorrect assumptions, I managed to identify the faults and was able to avoid following the wrong path. One such incorrect assumption was when I wanted to search for a radioactive source using two scintillator crystals coupled next to each other. The behaviour of the two scintillators under different temperature conditions gave a false result, so I decided not to use this scintillator assembly anymore.

I made conclusions from the results, which helped to verify my hypotheses. The computing capacity that can be integrated into intelligent detectors has increased recently, so general and up-to-date electrical engineering knowledge was required to achieve my goal. During the research, I designed electronic equipment and printed circuit boards. I integrated two ultrasonic distance sensors and one radiation detector, a robotic arm, a turntable and a scale into one system. This assembly can provide a measurement process for radioactive transport container checking, which was not published before. In addition to electrical engineering knowledge, the task also required mechanical design knowledge to develop physical/thermal protection and housing for detectors. During the development, I designed experimental pieces and printed out prototypes with a 3D printer.

The assembled hardware components are worth nothing without operating software, so I created software for both computers and embedded microcontrollers. I also dealt with materials science to select the right materials used inside the detector.

The concise description of the examination conducted

Disaster management professionals need technical tools that enable the detection and monitoring of radiation threats. The source of information can either be early warning systems that allow continuous measurement of a parameter which can indicate a potential threat, or CBRN reconnaissance units with the support of mobile and fixed laboratories, which are deployed in emergencies.

The task of these technical devices is to measure ionizing radiation, to determine the concentration of toxic industrial substances or chemical warfare agents and to detect the presence of biological warfare agents.

Detectors used for disaster management purposes are different from conventional detectors in that they have to operate in extreme environments (wide temperature range [-30 °C … + 50 °C], high humidity [>90%], dust, rain [> IP66], pressure [500 … 1200 hPa], shock [0 …1600 m/s^2], vibration [5 … 500 Hz]), where other equipment has long gone faulty. The detectors used for such purposes are characterized by environmental resistance, wide measuring range, protection against mechanical impact, explosion-proof and radiation-resistant design.

The detectors used today digitize the analogue signal of the sensor and transmit it digitally to higher informatics levels. The unit containing the sensor and the electrical signal processor is called a transmitter or detector. The difference between a transmitter and a detector is that transmitters have no display and only serve as a source for measuring information. Detectors can have more features than just measuring environmental parameters i.e. audiovisual signals, display, battery. All transmitters are detectors, but not all detectors are a transmitter. Microcontrollers can be equipped with custom software, allowing the execution of many algorithms in a detector.

The goal of this research is to examine the optimal use of measuring tools with state-of-the-art technology for disaster management purposes and develop new methodologies that can make the right decisions at a given level on time, helping to speed up the process of disaster recovery.

Applying the right technology can save considerable human and material resources. The availability of the necessary information in the right place, time and form can be crucial in the event of a disaster.

The role of a measuring device was previously limited to measuring and displaying the measured value and creating an alarm signal at certain alarm levels. An alarming device does not provide enough information to make the right decision in the shortest time at a stressful situation. Because these types of alarms are not very common, operating personnels in such a situation are often unable to act appropriately, may panic, may forget to take the necessary steps, or may make incorrect decisions due to lack of routine or under-training.

As a result of this research, detectors and systems will be able to obtain additional information that will improve decision-making and, in some respects, take over responsibility from the operator. The final decision will still be made by the operator, but it will be much more comfortable and will be based on more data. The task of a measuring device does not end by alerting the user with the alarm, it should also assist in the handling of the alarm. From the start until the end of an event, different situation-dependent actions should be carried out. Measuring systems can be used not only for alarming purposes. It can also check whether a particular facility is exceeding its annual emissions quota or that its technology is undergoing changes that could lead to disaster. Officials can also be supported by special measuring equipments to inspect the compliance with radiation protection regulations and to avoid unnecessary exposure of workers or population. Intelligent measuring devices can also improve safety and security capabilities. An intelligent system can track the location and use of dangerous goods, log all activities, and create a security alert for unauthorized use or theft.

This area of research is relatively new because there were not enough resources (memory, processor speed) in a measuring unit to conduct further tasks. Performing additional functions while conducting the measurement requires a high speed embedded microcontroller with the capability of running concurrent tasks.

Intelligent measuring devices and systems can be used not only for disaster management purposes but also for monitoring the regular operation of nuclear facilities. Alternatively, security applications and counter-terrorism tasks may arise when it comes to detecting warfare agents or nuclear materials.

In the first chapter, I dealt with the development of scintillation detectors. In this context, I had to get to know the solutions that already exist and the technologies available that can help in the development of technology.

During the design of the new generation of detectors, I examined the various environmental parameters and impacts in order to compensate for their impact. I systematized the radiation measurement and detection systems that are currently used for military and disaster management tasks. Relevant domestic regulations, international recommendations and standards give the fundamental design of these systems. Among other things, I examined the current state of on-foot radiation reconnaissance, extended this activity to on-board and aerial radiation detection, and then studied the application of radiation portal monitors through several application examples. After that, I studied the CBRN early warning systems, many of which also serve in Hungary, supporting the home and law enforcement agencies. Examining the existing CBRN early warning systems, I managed to identify their basic structure, starting from the measuring devices to the data centers. I investigated the mechanisms of these systems to find patterns and possible new features. I was looking for the answer to which system organization architecture ensures the best availability of critical information in the shortest possible time. Starting from the simplest system architecture to high-availability multiple redundant systems, I analysed their potential. Based on these, I formed conclusions and suggestions for the further development of existing systems. The first generation of intelligent detectors is already serving military and disaster management systems. Among the capabilities of the detectors, the accuracy of the measured data is of primary importance, the speed of data processing and transmission is almost equally important, so authentic, essential data can reach the decision-makers and then the CBRN reconnaissance units as soon as possible. In this chapter, I have presented the structure and operation of several similar monitoring and alarm systems operating abroad. I examined the operational logics and algorithms implemented in existing systems. In the relevant publications, I looked for references that can be guidelines for building such a system. In this chapter, I sought synergies between radiation measurement systems and other chemical and meteorological monitoring networks used in CBRN defence. I examined in details the capabilities of these monitoring stations, with particular regard to the measuring ranges, the operating environmental parameters, and the response time of the system following a possible accident situation.

In the second chapter, I focused specifically on the development of scintillation detectors in order to make these detectors usable for military and disaster management tasks. I had to modify some components of the detector to reach this goal. The effectiveness of modification was verified experimentally.

During the developments, I made a change in, among other things, the scintillation crystal coupling material. The conventionally available coupling materials are able to operate in laboratory conditions only. I tested different coupling materials with a climate chamber to check the behaviour at different temperatures. The coupling material I found was able to withstand temperatures from -30 °C to + 50 °C. With the new technology, the detector became applicable to a wider temperature range than before. In addition to the coupling material, I investigated the production technology of scintillation crystals in order to improve the quality of the crystals under extreme conditions. The resistance of a conventional scintillation detector to drops and vibration is weak, but with the modifications I proposed, the detector can also be used in onboard vehicle reconnaissance systems. The scintillation detector is sensitive to electromagnetic radiation, and this radiation can significantly affect the measurement. The design of electromagnetic shielding is essential during the construction of such equipment. Scintillation detectors are strongly temperature-dependent, the change of this environmental parameter must be compensated, for which I have performed experiments and formulated modification proposals. Scintillation detectors are not able to function correctly at high dose rates (>100 mSv/h). In order to widen the measuring range, I measured with different scintillation detector materials at a high dose rates and investigated possible solutions for different signal processing methods. In addition to the traditional NaI(Tl) scintillator, I also examined BGO (bismuth germanate) crystals. I paid particular attention to the correction of the disunion errors of scintillation crystals, and I was looking for a solution to prevent the disunion, which can be caused, among other things, by a sudden temperature change. During the research, I tried to improve the quality of the scintillator, i.e. to keep the full width at half of the maximum value of the gamma spectrum peak to a given radiation source as small as possible.

In the third chapter, I examined the possible uses and assemblies of radiation portal monitors. To do this, I had to be sufficiently familiar with these systems. I had to identify the differences in each application and then make recommendations as to which components are best suited for what purposes. While searching for the best solution, new features and ideas emerged that I had to explore one by one. One such idea was born that I can introduce an additional feature to the monitoring system: generating an alarm to the physical protection system if the radioactive source has been stolen.

After a thorough understanding of radiation portal monitors structure and operation, I examined the algorithms implemented in such systems while looking for development opportunities. I researched the history of the radiation portal monitors and their implementations in Hungary. I found that the essential operation of the radiation portals can be expanded with additional devices (speedometer, license plate recognition), which make the detection process of radioactive sources more efficient. I made further investigations about using different intelligent detectors for different applications. As I expected, detectors should be modified if it is used as a mobile, or as a fixed-installed or as a vehicle-mounted measuring system. The applicability of intelligent detectors for use in the radiation portal monitors depends on the mechanical design, the physical size, which affects the sensitivity, and the algorithm, which mainly determines the logic of generating alarm signals, background compensation, and acknowledgement of alarms by users. To further develop radiation portal monitors, I was looking for features that became available as technology advances, such as online isotope identification and alarm suppression functionalities caused by natural radiating materials. I studied different types of portal monitors and created a selection system based on their areas of application, which can help to find the right radiation portal monitors. I have developed an algorithm that allows the alarm logic applied in radiation portal monitors to be used to provide additional signals to the physical protection system of radioactive sources.

In the fourth chapter, I analysed the efficiency of searching methods of lost and hidden orphan sources. To improve such methods, I had to be familiar with the existing methods. I proposed the modification of the detector assembly and algorithm. I made tests to check the efficiency of the change. I also collected information about inspection methods of the control of radioactive shipments. I realised that the information available at the site can help to determine the estimated activity of the delivered radioactive source. This information opens new perspectives in shipment control.

In this chapter, I compared on-foot radioactive source search methods. As a first step, I identified the existing procedures, then created new ones, selected the appropriate intelligent detectors, tested them under different conditions, and then drew conclusions based on the obtained measurement data, to determine the most efficient search method. I found that the measurement assemblies I studied, the lead ring-collimated, high-sensitivity scintillation detector is the best choice. If this detector is combined with the alarm algorithm used at portal monitors, the device will guide the user, after a few turns, in the right direction. It identifies a point source in the shortest possible time, even if there are several point type sources nearby.

I examined the control of properly transported radioactive materials and made proposals for its modernization. I have also developed two procedures; one simple procedure allows the shipment documentation to be checked using the data contained in the documentation. The other method is a complex method that does not rely on shipment documents, it only forms a picture of the shipment from measurement data and gives the result of the examination. The measuring device I have built estimates the activity of a radioactive point source in a cylindrical transport container by measuring the external radiation level, the weight and size of the container and conducts mathematic calculations. Based on the measurement, the transport container can be visualized, thus filtering out the inhomogeneity of the transport container, which may have been caused by hidden damage or an air bubble caused by a manufacturing defect. Through thinner shielding, those working near the container may suffer unreasonably high radiation exposures. The measurement can be further refined by isotope identification and smears sampling procedures. A complex set of specific analytics gives an accurate picture of a radioactive shipment, which helps the inspection process.

In the fifth chapter, I investigated the radioactive emission monitoring systems and created new methods and recommendations to implement the right assembly for the technology. I had to identify all the available monitoring methods for radioactive material releases. I realised that the gamma background radiation at these facilities is changing several orders of magnitude and affecting the measured values. Beta surface contamination measurement at high, dynamically changing gamma dose rates is a task that I had to investigate in detail, with actual experiments and a special detector assembly. In emission control systems and on-foot reconnaissance, this method is probably applicable to prove that I conducted many tests.

In this chapter, I presented radioactive material release control systems. After learning about the relevant regulations and finding all known monitoring configurations, I made a comparison and justified which applications to each solution can be used, what are their advantages and disadvantages. These systems, for example, are strongly affected if other radiation-emitting activities are performed in the area of the measurement, which adds to the emission value, falsifying it. With the assembly and operation, I developed, online surface contamination can be measured even with high (1 μSv/h … 100 mSv/h), fluctuating gamma background radiation. This method compensates the effects of nearby technologies releasing radiation and provides valid emission data.

This method can be used not only for emission measurement systems, but also for the detection of alpha and beta sources in a contaminated area, or in a reactor environment, to check the effectiveness of the decontamination.

The review of the relevant literature

To give a complete picture of the relevant literature concerning my dissertation, I have collected the available references for each chapter separately.

The literature of the first chapter radiation measuring detectors in application

To understand the importance and place of radiation measuring detectors in different application, first I have to find available solutions and analyse how they reduce the risk of an emergency. CBRN monitoring tools have been introduced in Hungary for a long time, and they have been integrated into the CBRN first responder systems. The primary tools of the CBRN emergency preparedness is the early-warning systems and the CBRN first responder units. These tools primarily belong to disaster management and the military [5].

Threats can arise not only as a result of a natural disaster but also as a result of a terrorist attack. Nowadays, a terrorist attack against a nuclear reactor is a real threat. Measuring systems like portal monitors can play a significant role to find a dirty bomb before it is placed on the location, where they want to use it. On the other hand, mobile measuring units can be deployed after the event takes place and can reduce the damage of the attack, with measuring the effectiveness of the decontamination, finding local hot spots [6].

The development of measuring tools for nuclear emergency response is only possible if the legal requirements also follow the international requirements. The primary task of nuclear accident prevention is to prevent deterministic effects and to reduce stochastic effects. Upper limits are regulated in Hungary following international recommendations. These limits are only worthwhile if the current measurement results are available and comparable to them. As part of the Nuclear Emergency Response Plan, measurements and the collection and evaluation of measurement data are included in order to determine the additional radiation exposure of individuals (population and workers) [7].

As part of the regulation, the measurement data must be directly accessible to experts of the authorities via remote access. If the authorities have no measuring system themselves, they will require available system operators (like the owner of a power plant) to share the measurement data.

In addition to environmental measurements, technology data from NPP is requested to detect problems as early as possible. However, it raises some questions as to how credible the data can be when it comes from the owner of the technology who created the dangerous situation [8].

There are international rules and recommendations, such as "Programs and Systems for Source and Environmental Radiation Monitoring". In these recommendations, the minimum requirements can be found for measuring detectors. The basic requirements for measuring detectors are regulated differently from country to country, so in practice, international organizations only make recommendations, the adoption of which is a political decision [9].

Publication about realised early warning systems shows the challenges of building and maintaining such systems in different countries. The Report on Collaborative Research and Development of Environmental Radiation Detection Stations (ERDS) article is about the process of the building of a radiation monitoring system. The basic requirements of the system were short response time alarms, low cost, minimal training required for operation, low false alarm rate, robust, remote access and isotope identification capabilities [10].

In another similar system, the emphasis was on airborne contamination dispersion calculation. Simulation of Algeciras, Spain Steel Mill Cs-137 Release analysed the results and lessons learned from a real-time disaster. In addition to nuclear measurements, the authors pointed out the importance of meteorological measurements [11].

In the Expansion and Upgrade of RadNet Air Monitoring Network publication, in addition to the capabilities of the system, post-event response times and intervention activities were presented. The latest trend is that a radiation detector may be suitable not only for environmental monitoring but also for emergency level surveillance. The following activities were classified into three categories in this work. The first category is events that take place 4 hours after the accident. The information generated within this timeframe is required for CBRN reconnaissance units to localize hot zones, prioritize tasks to be performed, and use resources most efficiently. This 4-hour period is just enough to make decisions based on data from online and continuous measurement systems. Events in the one year following the accident are in the second category, including the taking of samples, which take longer to be measured in laboratories.

The third category is tasks that take place longer than one year after accidents, where a series of measurements and trends can be examined, the contamination generated during the restoration can be measured, and the impact of the accident on the whole environment can be determined.

In these processes, mass of data is available and special big data analysing techniques should be used [12].

Networking of various monitoring stations began in the 1980s when the necessary communication tools such as the RS-485 standard were developed [13].

The first automated radiation monitoring system in Hungary used explicitly for CBRN tasks was built after the Chernobyl disaster (1986). There was a need for a device capable of monitoring radiation with sufficient speed and precision without human intervention. The military system, which is still operating today and has undergone several upgrades, has a data center which collects and display the measurement data and handles alarms. The system is primarily designed for the detection of radioactive contamination coming from external sources and affecting the area of Hungary. Besides to detect industrial accidents, the goal of this system is also to monitor the effects of the use of nuclear weapons [14].

The literature of the second chapter development of scintillation type detectors

One of the basic detectors used in monitoring systems is the scintillation detector. I collect all my development activity related to this type of detector in the second chapter. In order to start development, I have to get to know the relevant publications, standards, technical solutions about scintillation technology.

The “Present and future of scintillation detectors” publication gives general information about the structure and working operation of a scintillation detector and gives direction on what should be changed in the future in these types of detectors. If someone is willing to start any development, there are four possible routes: Research of scintillator material, Replacement of the photoelectron multiplier, modernization of the processing electronic unit, development of new evaluation algorithms [15].

From the possible four directions, I started my research in three development directions simultaneously. In the first direction, I worked with scintillation materials in order to make the crystals resistant to external impacts (mechanical shocks, temperature changes). The selection of the crystal materials was guided by Matthew Lowdon’s publication, which examines ten different scintillation materials to find the most suitable one for an unmanned aerial vehicle (UAV) application [16].

Gregory Bizzari’s publication is about the potentials and characteristics of inorganic scintillation materials. He stated that it is clear that scintillator performance will reach a higher level once the performance-limiting factors are controlled and the optimization of crystal growth and processing should be done [17]. According to Martin Nikl, a scintillation material is a kind of converter transforming the energy of one high energy photon or particle (proton, electron, neutron, a-particle, etc.) into a number of UV/visible photons, which are easily detectable with a conventional photomultiplier tube, semiconductor detector, etc. There is intense work in many laboratories in the field of the development and understanding of selected single-crystal scintillating materials which are currently attractive for various applications [18].

Charles Melcher investigated the perspectives on the future development of new scintillators, and he found that researches focus primarily on the field of medical imaging. From a production standpoint, scintillators usually offer a considerable advantage because much higher levels of impurities and defects are tolerable compared to semiconductors which require extremely low impurity levels in order to achieve adequate charge carrier lifetimes and mobilities [19].

There have been only a few publications on the development of existing scintillation crystals in the recent period. The majority of the publication like Development of new scintillators for medical applications is calling NaI scintillators the basic material, which is cost-effective and commonly used in high volume in medical application, so developments are needed in mass production [20].

In the second development step, instead of replacing the PMT, I investigated how the PMT sensor can be protected to be suitable for field use. The task is difficult because it is made of glass so it is highly sensitive to mechanical impacts. To find the correct solution, it was necessary to know the specifications that could be applied to equipment used for military purposes. The most commonly used tests standards (MIL-810) was introduced by the U.S. military, which, after several revisions, discusses the necessary test methods down to the smallest detail [21].

In the third development direction, I aimed to investigate the electronics of the scintillation detector. This development can reduce the spectrum instability caused by the temperature change. I have examined several publications on the subject. One paper tried to achieve spectrum stability with the help of LED light. In this paper the temperature dependence of LED caused further technical problems to be solved [22].

The literature of the third chapter investigation of radiation portal monitors

In most cases, radiation portal monitors are built from intelligent scintillation detectors. Radiation portal monitors are special applications that require an understanding of the way radiation sources are transported and the regulations that apply to them. There is a uniform set of rules in Europe regarding what materials can be transported and how [23].

The development of radiation portal monitors in all cases seeks to increase sensitivity and reliability. The goal is to catch the smallest smuggled radioactive material with the lowest false alarm rate. In addition to creating an alarm event, researchers are working on algorithms that provide additional information to operators. One such paper deals with how to deduce the type of radiation sources by using an algorithm on the spectrum produced by a plastic radiation portal monitor[24].

Optimizing the capabilities of radiation portal monitors requires the selection of the appropriate scintillator material. Research in this area has also yielded many results. One research compares the applicability of plastics and NaI(Tl) scintillators in radiation portal monitor applications, and found that both scintillator materials have their place in border security systems [25].

There is a publication from Raymond Klann, Jason Shergur and Gary Mattesich which analysis the current situation regarding homeland security. The goal of a radiation portal monitor system is to reach the highest sensitivity with the use of low-cost, large-volume detectors.. Mainly plastic-type portal monitors are installed, but there is a need for isotope identification, and for that purpose NaI(Tl) type detectors should be applied as a secondary screening unit. If the sensitivity of the NaI(Tl) type detector is high enough this unit can handle primary and secondary checking simultaneously [26].

The literature of the fourth chapter radioactive sources search and investigation methods

The development of the search for lost and orphan radioactive sources and the control of radioactive shipments has evolved a lot in recent years. Several studies have addressed the topic. In a paper by Thomas Hjerpe, the search process was supported by spectrophotometric evaluation to reduce background noise, and the effectiveness of several other procedures was also examined [27].

The control of radioactive shipments are well regulated, but the inspection methods are not researched deeply by anyone. The only reference regarding transportation is the dose estimation of workers handling such shipments [28].

The regulations and researches are mainly focusing on the radiation protection and physical protection aspect of transportation. The international standards specify the radiation levels next to a given radioactive shipment and impose strict rules on shipping containers, but do not address the issue of how the contents (the radioacítve source) of the shipment and the documents match [23]. My research is interested in validation of shipment documentation with the help of intelligent detectors.

The literature of the fifth chapter detectors applied in radioactive emission monitoring systems

In most countries, including Hungary, the release of radioactive materials into the air and water during the use of nuclear energy is regulated by law [29].

In order to verify the level of emissions compared to specified levels, a measuring system built up of intelligent detectors must be used. Several publications deal with the issue, but all of them only provide information about the measuring system installed in the given facility, it does not provide information about its selection mechanism. The best example is the publication about the Swedish nuclear power plant's emission control system, which accurately describes the system that has been put in place, but unfortunately says little about the design of the system [30].

In the case of emission control systems, due to the continuous operation and high gamma background radiation, the long-term operability of the equipment is also an important requirement. In creating the selection criteria system, I also considered the operational experience of emission control equipment installed in U.S. facilities displayed in the form of publication [31].

Emission control systems are difficult to use by the fact that work with radioactive materials in their vicinity strongly influences measurement. I propose a surface contamination measurement method which can be used at fluctuating gamma backgrounds. In this topic, I have found publications for measuring surface contamination in the traditional sense. These solutions are based on the fact that the background must be included in the measurement live and its extent must not change during the measurement. [32].

An interesting publication by József Solymosi solving gamma background compensation by using two methods in parallel.

The first method is based on the fact that the energy dependence of the counting efficiency of energy-selective radiation detectors under the effect of beta radiation shows a completely different picture than that observed with gamma radiation.

The second background compensation method takes into account the beta + gamma and pure gamma signal numbers. the different course of the energy dependence of the gamma counting efficiency during the beta + gamma and pure gamma measurements [33].

In the dissertion of József Solymosi, the outhor investigated a method for measuring surface contamination.

This method is characterized by measuring the signals (N_0, N_1,… N_m,) belonging to the given energy intervals (0, 1,… m,… n) in a standard geometric arrangement with an energy-selective radiation detector in at least two suitably chosen energy intervals and then respectively formed into the counts for the maximum beta energy (N_0). I found this method extremely novel in its day [33]. The determination of counting efficiency for this method can be seen in Figure 4.

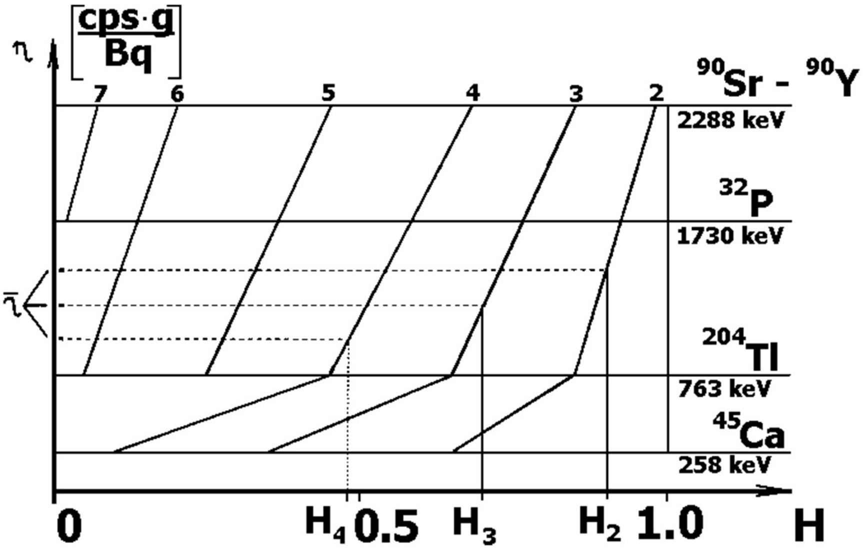


Figure 4. Determination of counting efficiency.
Source: [33]

In Determination of radioactive bulk and surface concentration by beta-detection publication the authors used a measurement system with two plastic scintillators [34].

The importance of emission monitoring at a nuclear powerplant is shown by the publication of Kristóf Horváth, Lajos Kátai-Urbán, Zsolt Sebestyén.

In order to control the release of radioactive materials and the radioactive impact on the environment, the Paks Nuclear Power Plant operates a widely established emission and environmental radiation monitoring system. The system consists of telemetry networks on the one hand and laboratory sampling tests on the other [35]. In a publication about “Wide range universal radiation measuring instrument”, the authors applying combined measuring procedures for scintillation detector which widen the efficiency of the detector.

Using this technique the detector can be used for near background and for disaster-level measurements. This detector feature could be a promising direction for using scintillation detectors in emission monitoring [36].

Conclusions about the literature summary

I have presented various radiation monitoring systems, their development with an emphasis on monitoring stations and their measurement techniques. Intelligent detectors have been analysed in detail and showed the place of such detector in different applications. The intelligent detector is a building component of a country size monitoring system. I collected patents related to radiation measuring instruments in Hungary. The summary of this collection can be found in APPENDIX 4. As Gamma Technical Corporation was the pioneer of developments in radiation detector manufacturing, I put together a Historical summary of Gamma Technical Corporation in APPENDIX 5.

1. RADIATION MEASURING DETECTORS USED FOR MILITARY AND DISASTER MANAGEMENT PURPOSES

The definition of radiation measuring detector used for military and disaster management is the following. A unit capable of measuring ionization radiation in extreme weather conditions, easy to operate, can resist a high level of radiation, and physical stress, yet capable of supporting decision with fast and accurate results.

One of the most commonly used sensor types for this purpose is GM counter. The sensor in a GM counter is a GM tube sensor. In a GM counter by applying a high voltage to the anode and cathode poles mounted into a noble gas-filled GM tube sensor, the ionizing radiation produces a discharge; thereby generating an electrical impulse. The count of the generated pulses per unit time is proportional to the radiation intensity. The GM counter can operate in a wide measuring range but is not suitable for selective energy measurements. GM counters, such as IH-12, appeared at Hungarian CBRN first responders in the 1960s [37].

I categorised the radiation measuring systems used for military and disaster management purposes into four groups according to their place of use: On-foot radiation reconnaissance,Aerial reconnaissance, Onboard reconnaissance and Installed early warning systems.

1.1. Different standards and regulations applying to the measurement of radiation.

The tasks of the development and operation of measurement and control and alarm systems for disaster management purposes is regulated in Hungary by the 2011 CXXVIII. law on disaster management and their implementation is described in 234/2011. (XI. 10.) Government Decree [38] [39].

The peaceful use of nuclear energy is regulated in Hungary by Act CXVI of 1996 [40] the implementation of the Act is described in the 167/2010 (V. 11.) [41] Government Decree on the national nuclear emergency prevention system and in the 487/2015. (XII. 30.) [42] Government Decree on the protection against ionizing radiation and the related licensing, reporting and control system and in the 190/2011. (IX. 19.) [43]

Government Decree on physical protection and the related licensing, reporting and control system in the field of nuclear energy and in the 490/2015. (XII. 30.) [44] Government Decree on notifications and measures related to missing, found and seized nuclear and other radioactive materials, as well as on other notifications related to nuclear and other radioactive materials. Detectors, used by the military, commonly measures air kerma gamma radiation in Gy/h units. Still, NATO standard requires that radiation detectors should use cGy/h units. Such a detector is capable of displaying data in units of different standards, cGy/h or Gy/h. The new generation of such devices like the: IH-95, has a built-in algorithm, which helps to make the right decisions based on the values read from the detector instead of complicated manual conversion tasks. The alarm levels can be set in the detector in different units (Gy/h, cGy/h) and the detector will do the conversion. The operator will be notified by the detector when it is time to start an evacuation process or abord a mission.

There is another measurement unit used by disaster management: the ambient dose equivalent rate (H*(10)) in Sv/h according to IEC 60846:2009. This measurement unit determines the damage to human tissue rather than the energy absorbed in air. Detectors compliant to IEC 60846: 2009 must have a physically different filtration than air kerma measuring detectors, a conversion is not possible by changing the software settings in the detector. A reconnaissance task consists of gamma dose rate measurement and surface contamination measurement. The standard procedure for determining the surface contamination of a terrain section is to measure gamma background radiation at the height of 1 meter with a gamma dose rate meter at a given point, and then beta + gamma surface contamination as close as possible to the surface. The surface contamination can be determined using Formula 1.

Formula 1. $$\mathbf{D_b = (D_2 - D_1 * K_f) * H_b}$$

where:

D_b: Surface contamination [Bq/cm^2]

D_2: Cs-137 equivalent dose rate [Gy/h] cumulative beta, and gamma radiation recorded by beta, and gamma detector

D_1: Cs-137 equivalent dose rate measured by the gamma dose rate transmitter [Gy/h]

K_f: Factor for gamma dose rate transmitter and correction for an beta, and gamma detector

H_b: Beta efficiency factor for background compensated dose rate of beta, and gamma Detector (individual factors for Sr-90, Tl-204, C-14, Am-241) [Bqh/cm^{2}Gy]

1.2. On-foot radiation reconnaissance

The essential equipment of an on-foot radiation reconnaissance is a handheld detector. One of the most significant military handheld detector developed in Hungary is the IH-95 radiation level and contamination meter. Its development began in 1996, but thanks to modernization in 2010, the IH-95 is still in active service. I participated in the modernisation process of the IH-95 as one of the developer and supervisor of the modernisation and validation process. The upgrading consisted not only of replacements of parts but also of modifications to improve technical parameters and functions, resulting in, for example, shorter response times, temporary storage of data and conversion to NATO standards. The IH-95 performs two different measurement functions integrated into a single detector. In its carrying case, it is a highly sensitive gamma dose and dose rate meter, without the case works as an alpha and beta contamination meter. The civilian version of IH-95 is the BNS-92S, which measure the dose rate in Sv/h [37]. The picture of the device is in Figure 5.

Figure 5. BNS-92S Handheld radiation level and contamination meter. Source: [3]

In the past, during a radiation reconnaissance mission, continuous determination of the actual stay time was a significant challenge. The commander had to simultaneously know the current dose rate, the dose suffered during the mission for every person in operation separately, and the maximum dose for this mission. Formula 2. shows the calculation of stay time.

Formula 2. $$\mathbf{T} = \frac{(\mathbf{D_m} - \mathbf{D})}{\mathbf{D_t}}$$

where:

T: Stay time [h],

D_m: Maximum permissible dose during the mission [Gy],

D: Dose absorbed since mission start [Gy],

D_t: Current dose rate [Gy/h].

An intelligent detector can determine the stay time and not only showing the estimated value but also provide an alert when the stay time has reached the pre-set alert level, could be useful. An alarm at the right time makes it possible to leave the contaminated area without unreasonably high radiation exposure.

1.3. Aerial reconnaissance

On-foot radiation detection is one of the most accurate measurement methods and even the only one that can be used to measure surface contamination. However, it is not very efficient in terms of detection speed. The fastest method known today for finding radioactive materials on a large-scale terrain is aerial radiation reconnaissance procedure.

The great advantage of an aircraft-mounted radiation measuring system, in addition to its speed, is the ability to collect data remotely during detection, including in areas that infantry units cannot reach, e.g., due to extremely high radiation levels. The purpose of the aerial reconnaissance system is to to localise lost or hidden radioactive materials or determine the radiation level and position of extensive contamination. Aerial reconnaissance was already used by the Hungarian Defence Forces (MH) in the 1980’s as a standard combat procedure.

The current form of the aerial reconnaissance system of the Hungarian Defence Forces called: LABV. The system mounted on a combat helicopter. There are two radiation detectors, a GPS receiver, a barometric altimeter, and a data logger that sends data to the onboard notebook or trough radio to the ground station computer. One of the two detectors uses a GM counter dose rate transmitter (BNS-98) to calculate the radiation level at 1 meter. Different aerial reconnaissance systems can be seen in Figure 6.

I participated in the LABV system development as a designer of the hardware architecture and was responsible for the data storage unit of the system.

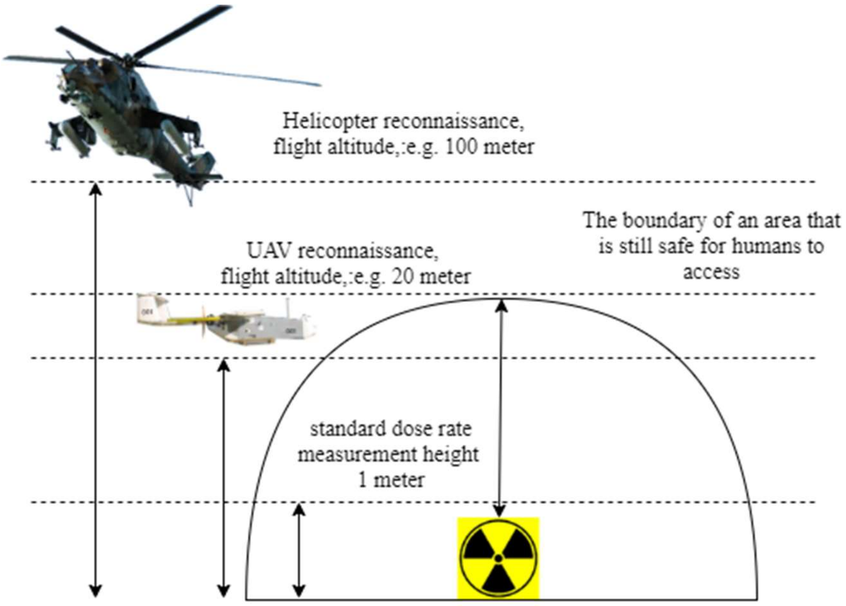


Figure 6. Aerial reconnaissance block diagram with essential distances. Source: [3]

The algorithm implemented in the LABV system uses the measured dose rate at the aircraft, and the flight altitude compensating with atmospheric and ground condition factors see in Formula 3. [45].

Formula 3. $$\mathbf{D_1 = k_1 * D_h * e^{k_2 h}}$$

where:
D_1: calculated radiation level at 1 meter [Gy/h],
D_h: dose rate measured at “h” meter height [Gy/h],
h: flight altitude [m],
k_1: absorbance coefficient for terrain (1.7-2),
k_2: atmospheric absorption factor (0.007-0.012).

The LABV system also includes a scintillation detector. Scintillation detectors are more sensitive to gamma radiation than GM counter detectors. However scintillation detectors have narrower measuring range, and more vulnerable to electromagnetic interference, temperature changes and vibration. They can be used for gamma-ray isotope identification measurements. Specially designed intelligent detector based on scintillation technology used in the LABV system. Thanks to the intelligent scintillation detector, it analyses not only the radiation level but also the energy of radiation during flight.

The amplitude of the pulses generated in the scintillation detector is proportional to the radiation energy received by the detector. The algorithm splits the amplitude spectrum into five ranges. The ranges are depending on the application, here is an example setting of the five gamma energy range.

Low energy range: 36 keV … 84 keV,
Medium low energy range: 96 keV … 421 keV,
Medium high energy range: 433 keV … 1408 keV,
High energy range: 1420 keV … 3069 keV,
Total energy range:. 30 keV … 3069 keV,

The detector gives a new measurement data every 0.5 seconds. With this short measuring time and high sensitivity, the system is able to find low activity point type radioactive sources at high seep from a low altitude. The radiation coming from the source reaches the detector and cause a significant change in the background radiation at the detector.

After the success of the LABV system, a smaller, but less sensitive system was installed on an unmanned aerial vehicle (UAV). This system called RABV is designed for a situation where the radiation can be so high, that the crew of the helicopter operating the LABV system could be in potential danger. This system can fly a few meters above the ground and determines the dose-rate level of any terrain, taking into account flight altitude, atmospheric and ground conditions (humidity, moisture etc.). Compare to other airborne systems the RABV system can fly much closer to the ground, so the detector will be able to detect smaller radioactive sources. The LABV system has a flight altitude of 100 meters and the RABV system has a minimum flight altitude of 2 meters during reconnaissance.

1.4. Onboard reconnaissance

The vehicle-based onboard radiation reconnaissance compared to aerial reconnaissance is a less effective method , because it needs more time for covering the same area. However, a vehicle, as a carrier platform, is capable of transporting heavy detectors, and the crew can conduct sample taking and can conduct extended in-situ measurements as well.

The Hungarian Defence Forces used VS FUG, VS BRDM and VS UAZ vehicles for CBRN onboard reconnaissance purposes. VS BRDM was modernized in the year of 2001 under the name VS-BRDM2, and a CBRN reconnaissance combat vehicle was also developed on the base of the BTR-80 [4].

The VS-BRDM2 and VS-BTR vehicles CBRN reconnaissance system is called: FABV. It is capable of detecting ionizing radiation, chemical warfare agents and measuring meteorological parameters as well. The FABV system displays and stores measured data using a GPS positioning system. Based on the collected data, the user can create various NATO compatible NBC reports and can send it into C2 systems.

The FABV system was integrated into the Light Chemical, Radiation Detection Vehicle (KVSF) as well.

The development process of the RDO-3221 ABV Komondor, which is a made in Hungary CBRN reconnaissance vehicle, has begun in 2010. The Komondor is an armoured lightweight, anti-tank, multi-purpose combat vehicle. The design of the base vehicle took into account the features required for a CBRN reconnaissance vehicle.

I participated in the Komondor CBRN reconnaissance vehicle development as the system architecture of the detector system and supervisor of the development process.

The vehicle equipment and onboard detection system include chemical, radiation and biological detectors, sample taking subsystem and collective protective equipment. The picture of the CBRN reconnaissance vehicle is in Figure 7.

Figure 7. RDO-3221 ABV Komondor CBRN reconnaissance vehicle
Source: [3]

On both sides of the vehicle, independent detectors were installed, which enabled the vehicle to detect the boundaries of contaminated areas and to find a less dangerous route. Because the vehicle has a significant attenuation factor, a detector mounted externally to the vehicle body measure less than the actual radiation level would be without the presents of the vehicle.

During the first half of the 1990's, mobile CBRN reconnaissance units with radiation reconnaissance functions were placed in operation at the Hungarian disaster management. Since 2000, they have carried out intervention, information collection and decision support tasks under the name of Emergency Response Teams (VFCS) [46].

The VFCS CBRN reconnaissance vehicles were initially equipped with handheld radiation and chemical measuring instruments; later on, chemical, radiation and meteorological detectors were added to this system. In 2008, high sensitivity, onboard radiation reconnaissance detector was installed into the VFCS vehicle.

In 2012, the VFCS organization was transformed and continued to operate under the name Disaster Management Mobile Laboratory (KML). With the latest developments, a new KML and KML-ADR vehicles were created. These vehicles have been designed to meet the same standard as the predecessor and additional new capabilities were also added, like biological detection, chemical and radiological identification, personal decontamination of civilian and CBRN first responders [47]. The picture of the KML and KML-ADR vehicles are in Figure 8.

Figure 8. KML and KML-ADR mobile laboratories.
Source: [3]

In KML and KML-ADR vehicles, onboard radiation reconnaissance task is performed by a scintillation based detector the BNS-94FM, which can be used as stand-alone or as an on-board integrated detector. The BNS-94FM is capable of continuously monitoring gamma background radiation.

When it detects the presence of a lost or hidden radioactive source, it creates sound and light alarm signals. It also detects neutron radiation simultaneously with gamma radiation. The BNS-94FM is capable of continuously monitoring of vehicles and persons passing by. Thanks to its built-in collimated high-volume scintillation sensor, the BNS-94FM has high sensitivity and direction dependence. The direction dependence significantly helps in the process of localisation of the radioactive source. If a BNS-94FM unit is installed at the exit of a decontamination station, it will check the efficiency of the whole decontamination procedure. Another application possibility for BNS-94FM is setting up a temporary checkpoint at the border of a contaminated site and checking if vehicle leaving the area should be deconatmainated or not.

The BNS-94M portable radiation portal monitor is more suitable for such temporary vehicle entry checking application because it consists of two detector units. Detectors are installed on both sides of the road, as close as possible to the vehicle traffic making the whole system more sensitive as a system with only one detector. The measurement method used in the BNS-94FM and M automatically determines the alarm level by taking into account the natural background radiation changes, the vehicle speed, the shielding effect of the vehicle. The picture of the BNS-94M mobile radiation portal monitor is in Figure 9.

Figure 9. BNS-94M mobile radiation portal monitor during operation.
Source: [3]

After the vehicle enters into the inspection area, the radiation portal measures the radiation level of the vehicle and then compares the measured value to the background compensated alarm threshold, if the measured value is significantly higher than the actual background it will create an alarm signal. After the vehicle leaving the inspection area the background measurement will continue. This feature makes it possible to reach higher sensitivity.

Nowadays, in case of a nuclear emergency first responders using drones and robots to reduce human exposure, but still human present is necessary near to the contaminated area. The first Radiation-Shielded Emergency Vehicle RSV-Komondor can play a significant role in case of a nuclear emergency, transporting personnel near to a contaminated area in a controlled way. The onboard radiation monitoring system calculates the dose for every person carried by the vehicle, to support the commander with vital online information regarding radiation levels, exposition dose, remaining mission time.

The intelligent system supports the driver with instructions to avoid high radiation level areas. With this information, the driver can reduce the suffered dose significantly for himself and the passengers as well. With the help of a measuring system, it is possible to determine the gamma dose rate without the shielding effect of the vehicle. The onboard radiation monitoring system contains multiple intelligent detectors inside and outside of the vehicle. The detectors have a wide measuring range to serve as sensitive environmental radiation measuring equipment and a high dose level meter as well (30 nSv/h … 10 Sv/h). The vehicle has a collective protection system, which prevents non-filtered, possibly contaminated air entering into the cockpit, and with additional lead shielding the vehicle can enter into highly contaminated areas. The vehicle can transfer contaminated passengers, without effecting on the driver or to the commander. Tests were made to see the capabilities of the vehicle. Not just the off-road capability but the shielding and monitoring capability was also checked. The first vehicle is on service since 2015.

There is a need for transporting persons into and rescuing from a contaminated area. The requirement of the RSV-Komondor was to build a robust custom-designed vehicle with off-road, radiation monitoring, lead shielding and collective protection capabilities and it should be used anywhere without any special traffic permission. After the RSV- Komondor leaves a contaminated zone and transports contaminated passengers, the outside and the inside of the vehicle can be contaminated, so after a mission, an effective decontamination procedure should be conducted. In case of a civilian car, the cleaning process of the interior is always a hard and challenging task, vacuum cleaning in case of radioactive contamination is not sufficient. The vehicle has separate driver and passenger compartment, the interior treated with a special coating layer, which can be decontaminated with the help of high-pressure decontamination technology.

To use the RSV-Vehicle safely in a dangerous situation, there are some steps the operators should follow. The first step is to turn on the on-board monitoring and the collective protection subsystems, after that, the vehicle can enter into the contaminated area. If the personnel have to leave the vehicle and opening the door, they have to take on personal protective equipment and should use handheld measuring detectors. The driver and the passengers are connected with an intercom system. After leaving the hot zone, the vehicle should be decontaminated and prepared for the next mission.

The intelligent monitoring system gives the driver instructions and vital information to avoid areas where the radiation level is higher than a preset threshold.

The commander has a dedicated display. On that screen, the commander can see the suffered dose values visualised separately the driver's, the passenger's and his dose readings. The passenger and the driver area have their own detector, each detector is mounted on the interior wall of the compartments. The commander can set the dose limits for the mission and enter the initial doses separately for driver, for passengers and for himself. After that the system will measure and count the dose values seperatly and the remaining mission time. This information will help to decide when its time to return from the mission and replace someone in the vehicle. The actual outside and inside dose rate level data are continually available for the commander. A screenshot of the commander display is shown in Figure 10.

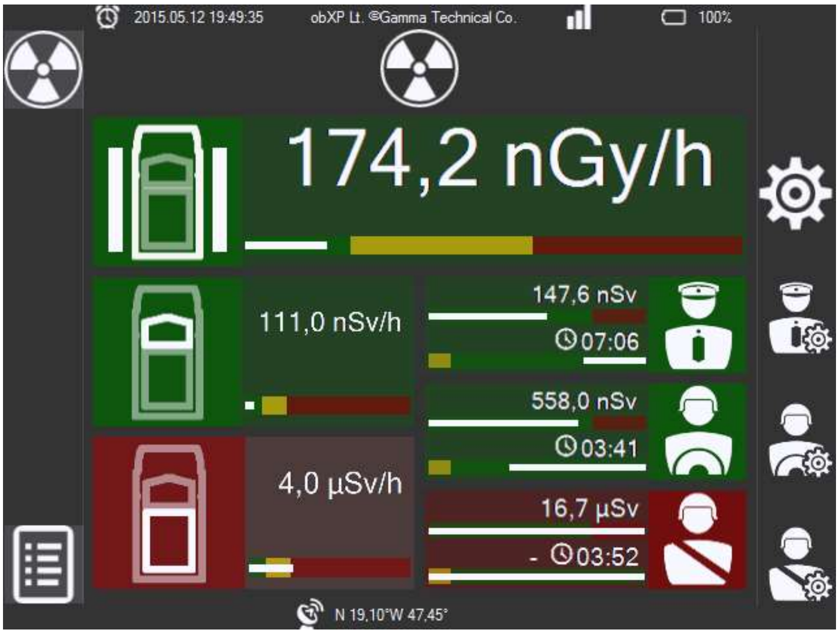


Figure 10. Software screen of the RSV-Komondor dosimetry system.
Source: [3]

The outside detectors are collimated with lead in 60 degrees from the central axis, so they are sensitive only from one direction. This characteristic of the detector makes it possible to indicate to the driver how to avoid areas with high radiation level. This system can be used by following the direction indicated by the detector with the highest measured valued to find lost or hidden radioactive sources.

Measuring the dose rate next to a shielded vehicle is challenging because the body of the vehicle itself will reduce the measured value. So the dose can be calculated from the measured value of two detectors placed on both sides of the vehicle. With that, the shielding effect of the vehicle can be reduced.

The detectors should have a wide measuring range (e.g., from 10nGy/h to 10 Gy/h) to serve as sensitive environmental radiation measuring equipment and as a high dose level meter as well.

The system was designed to prevent airborne radioactive particles entering into the cockpit. The collective protection system consists of airborne particle aerosol and activated carbon filters and ventilation part. The filters can be changed from outside of the vehicle, without contaminating the inside of the vehicle. The vehicle's camera system is providing full visual coverage of the surroundings. Furthermore, it is beneficial as parking assistance. The GPS coordinates and the images of the camera can be reached remotely so that the driver can be supervised from a remote command central. Two internal cameras are also installed for monitoring the activity of the driver and passengers. I took part in the testing process of the vehicle. The goal of the tests was to see the capabilities of the vehicle. Not just the off-road capabilities but the shielding and monitoring performances were checked.

The physical protection capability of the vehicle can be improved. Additional armour can be added to the body of the vehicle to reach a higher level of ballistic protection. Because of the shielding, the weight of this vehicle is 16 tons. The vehicle has participated several times at local exercises and public events. The vehicle is a much better tool to show the emergency preparedness for the public as reports and articles about radiation. This shielded vehicle is part of the vehicle family, which can be customized for a different type of application.

Other vehicle versions from Komondor family:

First, there is a multirole modular vehicle system with a lot of interchangeable superstructures. One vehicle can be used, as a firefighter or as radioactive material transporter or as technical rescue vehicle depending on the interchangeable superstructior carried by the vehicle.

Nowadays, the risk of attacking trucks, carrying high activity sources in areas like Africa is very high. At the moment, commercial trucks are used without any physical protection.

In case of an emergency, an unprotected vehicle can play a significant role as well. Mobile laboratories made for the disaster management can stop at the border of the hot zone, and the CBRN first responders can enter the area by foot and carry instrumentations into the contaminated area, or they can leave a mobile monitoring station, or the complete vehicle there and have a mobile surveillance system, with camera and sensors on site.

1.5. Early warning systems

The essential component of an every country size monitoring system is a station which has the measuring, data collection and data transfer capability to support the data center with relevant information.

I found that int the last 30 years there is an improvement tendency in the capability of the monitoring stations. The first monitoring stations were capable of measuring only a few parameters, today's stations have intelligent detectors with a wide range of measurable environmental parameters. Essential measured parameters of the stations like temperature, wind direction wind speed, gas concentration, radiation level have been expanded with parameters such as humidity, air pressure, the activity concentration of airborne radioactive alpha, beta, gamma active particles. In the future, the capabilities of the stations will include nuclide identification or, in case of gas sensors, the ability to determine the chemical composition. In addition to directly measured parameters, the determination of post-processed parameters has been added to the monitoring system capability list. Post-processed or indirect calculated values like comfort temperature, dew point, the cloud base can be determined with the help of directly measured parameters, and specific formulas. Nowadays, the post-processed data can be set up in most monitoring systems, in some cases, even user-configurable.

After World War I, wind speed and wind direction parameters were used to determine the dispersion of CWA clouds. However, these two parameters are by themselves not sufficient to accurately determine the dispersion.

For a more accurate determination of dispersion, it is needed to know more information about the source of the contamination (i.e., which material, the amount of released gas, the vertical air movements...). The vertical movement of air can be calculated from temperature parameters measured at several heights. Usually, dispersion calculation models use local, low altitude (<10 meters) meteorological data the determine air stability. There are various calculation models for the dispersion of chemical and radiative materials. The results of the models can be visualised on a Geographical Information System (GIS). The actual and possible future dispersion diagrams placed on a map can give an accurate picture of the areas that may be affected by a given accident. If the model is linked to a population database (e.g., residence, facility information), the number of people affected by the accident can be filtered out, and e.g., evacuation process can be supported with enough transportation vehicle.

The level of integration in the Hungarian early warning monitoring system (MoLaRi) is very high, as it provides the number of affected people by age group, which further helps the organization of a possible evacuation or intervention.

With technology improvements, new detection technologies have become widespread, enabling online measurement of previously unmeasurable parameters. Such an ability is to determine the activity concentration of airborne radioactive alpha, beta, gamma active particles. Previously, these abilities can only be part of offline, after event, monitoring system, because samples had to be measured using laboratory tools.

Usually, laboratory measurements take days to conduct, this slows down system response time to events significantly. Implementation of the measurement at the monitoring station was often hindered by the fact that it was not possible to perform the required measurement in the field outside of a laboratory. There were several reasons for this: the measuring detector could not withstand extreme environmental conditions. Typically, in Europe, a temperature range of -30 °C to + 50 °C causes a problem for an analyser designed to operate at + 25 °C ± 5 °C environment. Efforts were made to build a separate container around laboratory detectors, with that it was possible to maintain a constant climatic condition around the detectors, however with that climatisation the cost of a monitoring station significantly increased.

Along with the increase of measurement capabilities, the issue of physical protection has also come to the surface, as high-value measuring equipment has been placed in external locations without direct human supervision. Furthermore, here it is not just a matter of protecting against theft, but of guaranteeing the validity of the measured values. Standard security solutions can be used to build the physical protection of a monitoring station. Opening, tamper sensors, video surveillance and multi-level access management can be mounted on a monitoring station.

Global positioning systems (GPS) technology allows tracking the position of a given monitoring station and associating the measurement data with an accurate time stamp and coordinates. Continuous sending of coordinates is unnecessary for a station that is permanently installed, but essential for a mobile station.

Mobile monitoring stations can be part of a national early warning network due to wireless communication channels. Mobile stations can be a great help in managing disasters, as mobile monitoring stations can be installed rapidly near to any emergency and provide vital information during the whole event handling process.

In Hungary, there is a government regulation about the National Nuclear Emergency Response System. This regulation gives the task to install, operate monitoring systems and use the collected data as part of the National Radiation Monitoring, Signaling and Control System (OSJER) [41].

Since 1962, the Hungarian Defense Forces (MH) has been responsible for the establishment of a unified radiation monitoring and evaluation system. In 1993 the MH established a telemetry network with 50 automatic monitoring stations. The monitoring station (TVS-3) in the MH Automated Measuring and Data Collection System (AMAR) has been installed since 2000 and has been renewed several times. The AMAR automatic environment monitoring system capable of continuously and independently measuring the gamma background radiation of a given area and supplying information into the OSJER system.

The other monitoring system in the OSJER system called the Automated Radiological Industrial Safety Telemetry Network (RTH) operated and maintained by the National Directorate General for Disaster Management (BM OKF). This system is using TVS-3 monitoring stations to measure different environmental parameters. A TVS-3 monitoring station collects the measured data, provided by intelligent detectors installed on the station, stores it, and transmits it through various communication channels (e.g., GSM, GPRS, TETRA and Ethernet) to a data center. In addition to measuring gamma background radiation, the TVS-3 station can also analyse toxic industrial chemical gases and meteorological parameters: wind direction, wind speed, temperature, soil temperature, relative humidity air pressure, rainfall, precipitation status.

Two GM counter dose rate transmitters (BNS-98 and BNS-98S) were installed at TVS-3 monitoring stations to measure the gamma background radiation. The combination of the two detectors gives redundancy to the station, which increases the reliability of the whole system. The GM counter transmitters are capable of measuring gamma radiation with a wide measuring range in extreme environmental conditions.

Monitoring stations

Military and disaster management monitoring systems require monitoring stations that have advanced measurement capabilities and provide the appropriate information in the shortest time.

Monitoring stations are now expected to have the ability to self-diagnose, allowing errors to be identified in time or even before the actual failure occurs. The data center must be able to receive and evaluate the data sent by monitoring stations. The data center can be installed in a building or in a vehicle or even in a bag-sized case so that the operator can access the measurement data in all circumstances.

In addition to data collection, data centers can be connected to other subsystems used by military or disaster management for different application e.g., command and control, geospatial and dispersion calculation subsystems. Usually, for such subsystems, the monitoring statins should provide basic information, i.g., alarms, GPS coordinates.

The most common measuring capabilities of CBRN monitoring stations are:

- Gas concentration level of toxic industrial chemical and chemical warfare agent,
- Ambient gamma dose rate,
- Activity concentration of airborne radioactive alpha, beta, gamma active particles,
- Meteorological parameters (temperature, wind, humidity and pressure)

The measured parameters at monitoring station should be collected, preprocessed, stored and transmitted to data centrals.

Monitoring stations are equipped with communication data transmission means that ensure the secure exchange of data between the station and the data collection centers. For on-site evaluation of the data, a handheld readout and display unit can be used, which can even download data and perform service activities over a wireless connection.

The detectors located in the monitoring stations measure the given environmental parameters. Then a signal proportional to the measured value is stored, sometimes processed and transmitted to the data center. The data center can receive data from all monitoring stations, displaying signals, information and alerts to operators.The use of multiple data centers requires that the system communicates over various communication channels and that each data center can be operated in parallel.

Mobile and fixed monitoring stations can be part of a monitoring system. Stations can communicate simultaneously across multiple communication channels. At the same time, the system can be monitored by the operator from a central location, either on board of a vehicle or through a bag-sized control center.

Components of a monitoring station

First-generation measuring devices have transformed the environmental parameter into a human-readable value. The mercury thermometer is the best example of this.

As the temperature changes, the mercury level changes, which can be read on a scale. This technology is complicated to adapt to an automated monitoring system, so for the second-generation analogue probes converted environmental parameters into a measurable electrical signal that feeds into a multi-channel measuring unit (local center unit) which digitizes the signals and determines the measured values. The disadvantage of this technology was that analogue signals are transmitted through wires, exposing the measured value to significant environmental noise. Another disadvantage of the second generation units is that the central processing electronics had to deal with each of the connected analogue sensors separately, do all their compensation, and provide data to the higher informatic system, resulting in too much realtime processing tasks for the local central units, and the need for processing resources. Nowadays, the analogue output of the sensor is digitized as near as possible. Moreover, a dedicated microcomputer is directly connected to the sensor to establish a standard interface. All it has to do is measure the analogue signal produced by the sensor and query the measured value on a standard communication interface. The advantage of this technology is that a low power device can meet all the needs of the detector, reduces the role of local central units, detector malfunction and does not drag the entire system, as other intelligent detectors can continue to operate.

Intelligent detectors enable more accurate measurement of environmental parameters. An intelligent detector consists of:

- sensor part, which provides the analogue signal,
- analogue/digital converter, which makes possible to the processor to read the signal,
- processor, which can do compensation, and create average values,
- a communication unit, which can send the digitalized measured value to higher informatic level.

The parts of a general-purpose sensor can be seen in Figure 11.

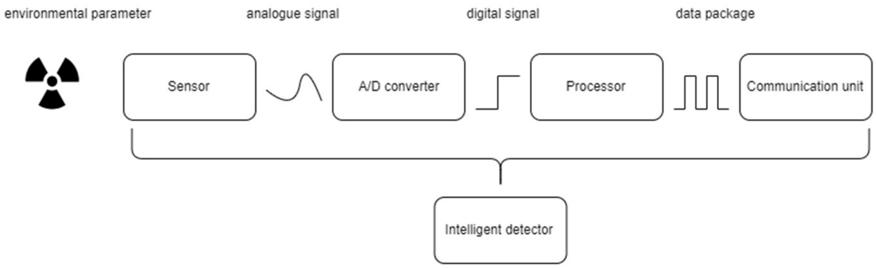


Figure 11. Structure of intelligent detector.
Source: compiled by the author.

Most sensors (the unit that converts an environmental parameter to a measurable raw analogue electrical signal) have temperature, humidity dependency, and in many cases, non-linearity over the full measuring range. Errors caused by environmental changes can be compensated. An intelligent detector is placed in a climate chamber together with a thermometer, and the temperature is stabilised at different discrete levels to calibrate the temperature sensor of the detector and measure the analogue signal changes according to temperature. The deviation in analogue values for different temperatures are stored in compensation factors, and later on, the detector will use them to compensate for the measured value at real operational measurement. Similarly, humidity dependency and non-linearity can be compensated.

The intelligent detector can automatically calibrate itself before or during a measurement. The micro-controller needs to interrupt the measurement at a given moment by placing an etalon source (reproducing a known environmental parameter quantity) in front of the sensor, with the detector being able to adjust itself. An example of this operation is the LED used for scintillation detectors, which illuminates light to the scintillator crystal to create artificial light, which create an electrical signal and it should give a standard result peak in the spectrum. If it is not correct, the electronics have to change the system's high voltage until the system produces the expected signal. The light from the LED is similar to the light produced by the scintillator in case of the presence of ionising radiation. That is why a LED could be an ideal etalon for calibration. The ageing and the temperature dependence of the LED could cause an error in the measurement.

Measuring range of monitoring stations

The measuring range parameter for a monitoring station is one of the most critical parameters. As technology progressed, the range of measurements getting wider, or it was often the case that the range itself did not change, but the measurement error decreased, or the stability of the measured value changed favourably.

For ambient gamma dose rate measurements, it is essential to record the slightest changes in the background, so the lower limit of measurement range should be close to the background (e.g., 50 nSv/h). Low background measurement range is only possible if the size of the sensor is large enough to indicate near-background radiation within a short period. This large size quickly becomes a disadvantage when the dose rate begins to increase.

At high dose rates, the scintillation detector produces so many pulses at few mSv/h that it cannot be processed with standardised electronics.

The solution is to use more type of detectors like two detectors, one large size specifically for environmental measurements and the other smaller for higher dose rates. Recent developments allow multiple GM tubes to be handled in a single transmitter. With the two-GM tube solution, up to 10 Sv/h can be achieved.

A wide measuring range detector is particularly useful in an emergency as well in general operation. In the future, the environmental measurement systems will be further merged with emergency measurement systems. In the past, completely independent measuring systems were built, but due to the wide measuring range detectors, it has become unnecessary to build a duplicate system.

There are two measuring ranges for every radiation detector, the indication range and the effective measuring range. Within the indication range, the detector is still able to measure, but its accuracy or linearity cannot be guaranteed at a given level.

In the effective measuring range, the error shall not be higher than a specified value; this value usually is stated in international standards [48]. It is now a requirement that detectors can be overloaded so that the detector should return to normal operation after high radiation exposure. Usually, this overload rate is ten times the highest value the unit can measure.

Gamma dose rate detectors are also characterized by their measurable gamma photon energy range, which features also affects applicability. For example, a thicker detector housing absorbs low energy gamma rays and becomes unmeasurable to the detector. On the other hand, a thick casing can provide excellent physical protection, which is not a negligible parameter for a field detector.

Beyond energy dependence, the direction dependence determines where the detector can be used. For ambient gamma dose rate measurements, it is expected to be as sensitive as possible in all directions. By contrast, the operation of a radiation portal monitor, it can only be sensitive to the direction of the object, which is under investigation, so that makes it possible to identify the object from which the radiation originates clearly.

The wide measuring range means nothing at a detector used in an automatic monitoring station if the detector stability is poor. Self-calibration and self-testing systems that can detect, or even correct, their malfunctions can be an improvement in this area. During calibration, not only the standard but also the response to the gamma background is useful information and allows the detector to operate more accurately. There are naturally occurring isotopes like K-40. This isotope most probably will be part of every gamma background measurement, can be used for long term stabilisation of a detector. (K-40 has a half-life of 1.248 billion years)

The intelligent detector can start a long-term measurement in the background, watching the position of the K 40 (1460 keV) peak in the gamma energy spectrum, and if the peak position changes, the detector can automatically recalibrate itself.

Reaction time of monitoring stations

CBRN monitoring stations, as part of a decision support system, are characterized by the fact that the measurement data must be in the data center within a few seconds. However, the frequency of measurement times does not need for more frequent data generation as 10 minutes. Thanks to the intelligent data logger, the system can switch to more frequent data acquisition in case of an alarm, e.g. 1 minute. The response time of the entire monitoring system can be determined by the time from the time the dangerous substance appears at the sensor to time an alarm event is displayed on the operator screen at the data center. To shorten this time, alarms in new generation devices have priority over standard measurement data packages. Traditional system architecture in which the data center polling one by one of the connected stations is asking for new measurement data. In the worst case, the alarm on a given station will not be resolved until all other stations in the system are asked by the data center software. The best results can be achieved if the data connection initiated from the station, or alert message is sent asynchronously via another independent communication channel to the data center.

The advanced technologies make possible a lot of new features at CBRN monitoring stations. However, it should be considered, that the higher the integration of an electronics, the more sensitive it is to the destructive effects of ionizing radiation [49].

1.6. Aerosol monitoring

Gamma background radiation monitoring stations are not capable of detecting alpha or beta particles in aerosols. There have been several ignificant radioactive contamination events in recent years, which, although not accompanied by an increase in gamma background radiation. This environmental condition can be dangerous to humans by inhalation of contaminated air.

In the event of a nuclear emergency, the following action can be done for the safety of the general public:sheltering, iodine prophylaxis, evacuation. The timely and sufficiently accurate and detailed information can help to take the correct action, thus avoiding significant damage.

An example of this issue was the lacking of the iodine prophylaxis following the Chernobyl disaster on April 26, 1986, which led to a considerable (4,000 registered) thyroid cancer incidence in the area, according to a 2006 World Health Organization (WHO) report (Most of them were doe to drinking contaminated milk) [50].

If only the officially registered 4,000 cases of Chernobyl disaster (estimated for the whole victims for future) are taken into account, the resulting damage can be estimated. According to a study, € 100,000 should be spent in 2015 on treating a patient with thyroid cancer [51].

For 4,000 people, this equates to € 400 million and excludes indirect costs: early death, early retirement, other sicknesses, and many other expenses.

A radiological monitoring system is capable of not only the monitoring of nuclear accidents, but it also measures the additional radiation generated by the use of nuclear weapons. The maximum annual effective dose from radionuclides produced in atmospheric nuclear testing was 69.3 μSv in 1964 this value is decreased to 5.51 μSv in 1999 [52]. Monitoring stations allow for the collection of more detailed and accurate information to prepare the authorities for a nuclear emergency, whether it is caused by intentional human intervention or an accident. Such measuring systems use known technologies, such as ionizing radiation measurement based on the scintillation crystals or GM tubes. Still, the optimization and processing of information and the level of integration to support decision making make this resource unique.

The ideal monitoring station for this task is capable of simultaneous measurement of alpha, beta and gamma radiation, supplemented by the ability to be at least one order of magnitude more sensitive than conventional radiation measuring devices. With this solution, contamination coming from long distances e.g.: from other countries and other continents can be detected. Thanks to energy selective measurement, more information can be reached about the contamination. The additional information obtained this information can significantly help in the proper choice of protection.

Analyzing the composition of the sample makes it possible to determine the specific factory releasing the contamination. Thanks to recent developments, measuring systems can also be used in emergencies as well. The station, which measures in normal mode at near the background radiation level with high sensitivity sensor, and in case of an accident where the measured value may increase up to 100 million times the background, changes mode and continues to provide data.

In other systems with such overload, the high sensitivity detector only malfunctions or it triggers a secondary detector that is only capable of providing data at high dose rates.

In addition to gamma background radiation measurement, aerosols should also be measured as there have been several recent events around the world whose effects can only be detected with aerosol detection capable monitoring stations.

The recording of airborne contaminants is especially crucial in the event of a nuclear accident, or case of an accident involving the shipment of radioactive material. Thanks to new detectors, low detection limits at environmental measurements and emergency level measurements are also feasible. Regulatory bodies, organizations that produce or use isotopes, medical institutions, isotope laboratories, irradiation facilities, radioactive material processing plants, radioactive waste storage facilities can be a user for such a system.

It has become a general requirement for monitoring stations that they should be used not only as a fixed installation but also as a mobile application, in many cases as an onboard system. For onboard product, the meteorological parameters like wind direction and speed should be measured with equipment without moving parts.

In addition to local near-ground meteorological measurements, high atmospheric measurements and meteorological forecasts will play an increasingly important role in the future as the information can reach through advanced communication to mobile units.

Although there is much organisation in the world willing to shut down nuclear power plants, there is no real alternative, humanity's power consumption is continuously increasing, so the emphasis shifts from decommissioning to safety, the equipment I investigating, allowing even more accurate monitoring of these power plants. To have standardised alpha and beta measurements results, it needs sample taking, and preparation, then the measurement itself [53]. The process could take days, for emergency purposes there is a need for quicker response and I investigate the possibility of reducing the time need.

1.7. The data center of monitoring systems

In addition to the monitoring stations, the data centers were also being upgraded in recent years. For general monitoring systems, it is common for stations to communicate with only one data center at a time. However, it is nowadays required that multiple data centers should be able to operate simultaneously, increasing the availability of the whole system. In an emergency, the entire system is rendered inoperative if the data center fails. This situation can happen for several reasons.

Data center power is lost, data communications are interrupted, or only the hardware, software components in it are malfunctioning or corrupted. As a result, data centers nowadays are not just a fix installed server in a building but can be either onboard or in a suitcase.

The data center may be damaged due to an earthquake, it loses its ability to collect data from the monitoring stations, and so the information needed by decision-makers will be not available.

This situation can be solved if a secondary data center takes over the role of a failed data center. By launching a mobile data center, the information service can be restored or even moved to a place where it can be safely operated.

An ideal solution is to have at least two fixed data centers, as far apart as possible, with independent infrastructure support. A natural or man-made disaster rarely extends to a nationwide scale, leaving one data center with a good chance of survival. In addition to the two fixed data centers, a mobile data center also provides significant system security, as it is more comfortable to move and more durable in emergencies with portable power generating units.

The possibility of parallel data centers raises several issues.The first problem is that sending data generated by the stations to the two data centers causes unneeded duplication of data traffic, especially since the stations in most cases have wireless data transmission, where the data transmission fees are already higher. Therefore, it is advisable to configure the secondary data center to operate so that communication with the stations only begins when the primary data center has failed. Direct data synchronization between primary and secondary data centers can also be useful, provide up-to-date data at both locations.

The other problem with parallel data centers is the difficulty of organizing the different data transmissions. The stations usually have local data storage capacity. This feature allows to store the locally measured data in the event of a communication error and to send the stored data once the communication channel has been established again. In more advanced systems, the alarm data packages are sent before the standard, background measurement data packages. If the station does not favours the alarm packages, the alarm message will not be able to reach the data center for up to several hours, as only stored standard historical data is transmitted instead of sending alarm message first. Another alarm management option is that the alarm message is transmitted to the data center via a route independent of the standard data traffic channel. E.g. the data is sent over GPRS packages, while the alert message is sent in SMS. For this solution, both data channels must be available between the station and the data center.

An additional alarm event management process can be the deleting of the previously measured standard data before the event. The disadvantage of this is that the pre-alarm data will be missing from the archive, which may cause decision uncertainty.

There are two major types of data transmission between stations and a data center.

- Polling type data transmission (Master-slave)
- Multiple sender type of data transmission (Multi-Master).

Polling type data transmission (Master-slave).

The data center will periodically ask each station to see if there is any new data available, and if so, it will collect it. Figure 12. shows the polling architecture of a monitoring system. The advantage of this solution lies in its simplicity. The data center can allocate its data channel resources and communicate at the appropriate synchronous time. The disadvantage is that an alarm event can only arrive at the data center for a long time. In a multi-station system, in the worst case, the alarm triggering event occurs on a station just after the data transfer from this station to the data center is finished, so the system will only be notified of the alarm event after all other stations have been handled and the alarming station again gets in the row. If a system uses 2G data calls, the time of data transfer per station can take up to 3 minutes. In case of a few dozen stations, the alarm event can be unnoticed for hours.

Much better results can be achieved if the data center can handle multiple stations simultaneously, or if the monitoring system uses a faster data transfer method. Data transfer using TCP/IP packets based on 3G/4G/5G technologies allows further acceleration. The full response time of the system depends on the speed of the data channel and the response time of the endpoints devices. In this polling mode, the data center cannot proceed to query the next device until the current device responds.

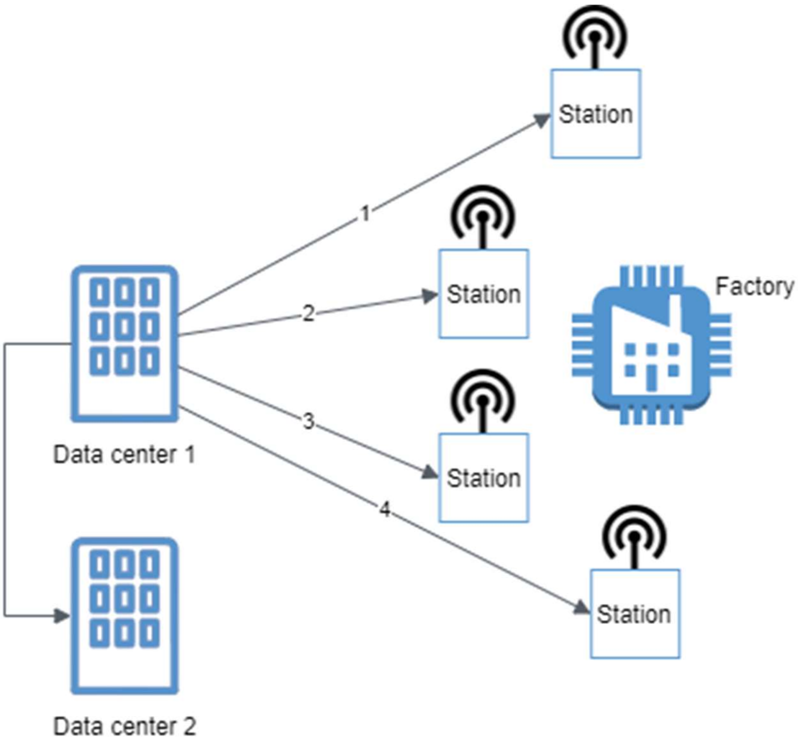


Figure 12. Polling architecture of a monitoring system
Source: compiled by the author

If the device fails, there is no response, so the data center must start a timer after the request was sent to the station. If there is no answer from the station during this period, the data center should continue the data collection with another station. The waiting time should be picked carefully, as a short waiting time will cause a system to declare a slow device to be defective, and a long waiting time may unnecessarily increase the overall query time.

Multiple sender type of data transmission (Multi-Master).

Every station has the right to send data to the data center asynchronously, without losing information. Multiple implementations of this data communication method are possible. Figure 13. shows the Multi-master architecture of a monitoring system.

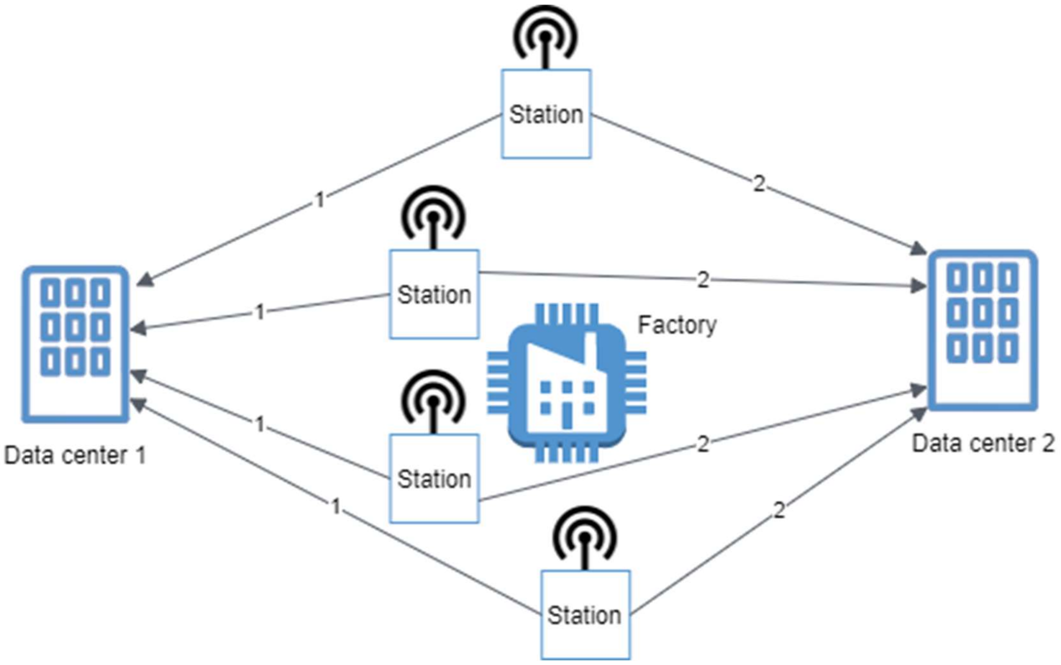


Figure 13. Multi-master architecture of a monitoring system
Source: compiled by the author

One organization architecture example is based in the MQTT protocol, designed for mass querying of sensors, which allows managing the mass of sensors over the Internet. The sensor subscribes to a channel in the data center where it can send a message at the time it chooses. This technology is ubiquitous in civilian life, using the Internet of Things IoT technology, which is the common name of how smart sensor connected to the Internet. The advantage of this technology is easy implementation, and there are many providers in the cloud to collect sensor data. The disadvantage is that it is less secure due to its simplicity and challenging to integrate into multiple data center systems.

An other Multi-Master organization architecture example is using data transmission through TCP/IP ports. The stations open a TCP/IP channel at the data center and in case of an alarm, first the alarm packet and then the typical measurement results are sent to the data center. The data center returns a confirmation message, after which the station can send the next packet until all stored data is sent. This solution provides increased availability, reduces data loss, and provides data security with encryption. This working method can serve multiple data centers if the station does not receive any confirmation; it can send data to a secondary datacenter. In addition to the asynchronous auto-send mode, the station can also be requested from the data center, and it is possible to allocate time slots to each station so that data transmission can be distributed evenly according to the limited bandwidth.

Bottom-up data transmission also allows solar-powered, energy-efficient operation. The detectors are turned off by default. For each measurement cycle, it will wake up for one measurement task, then turn on the data transfer unit and send the data to the data center. This technology is a great temptation because no power supply or data transmission cabling is required during installation, significantly reducing installation costs. Unfortunately, this solution is not applicable in early warning systems because the sensors must be continuously on and should send an alarm as soon as the alarm level is exceeded [54]. If the sensor is in a power-off mode in the majority of the time, a short rise on the radiation level will not be detected by the system.

1.8. Conclusions about the monitoring systems

This chapter has reviewed the radiation measuring detectors for disaster management and military purposes. In these applications, different algorithms have been implemented within intelligent detectors. With monitoring systems the time between the first sign of a disaster appears and deciding to prevent it has been significantly reduced. I investigated the already existing application and proved that there is a need that the measurements should be more accurate, measuring ranges should be wider and must be easy to use in field conditions.

2. DEVELOPMENT OF SCINTILLATION DETECTORS

There are several proven technologies for measuring radioactive radiation, such as GM counter or semiconductor radiation detectors. This chapter deals with scintillation based radiation detectors. The physical phenomenon of scintillation underlying scintillation detectors was discovered by Crookes, Elster and Geitel in 1903 when he discovered that the zinc sulphide crystal emits light through alpha radiation [15].

Initially, scintillator flashes were counted by humans using a microscope, but this did not prove to be an advantageous and accurate method. It was a significant step forward when Curran and Baker coupled a scintillator in 1944 with a Photoelectron Multiplier Tube (from now on referred to as PMT) [55].

The scintillator and the PMT produces a measurable signal depending on the energy and intensity of the radiation. Since its discovery, scintillation detectors have evolved and are now used in medical, industrial and military applications. The main advantages of scintillation detectors are their high sensitivity to radiation. They are applicable for selective energy measurements, as well as the identification of isotopes and determination of the activity of radioactive sources. By determining the qualitative and quantitative parameters of radioactive materials, industry safety and disaster management specialists can verify for example whether or not the radioactive material corresponding to the shipment documents is present in the transport of dangerous goods by road. Shipment documentation is regulated by the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR).

One of the tasks of the Disaster Management Mobile Laboratory (KML) is to perform ADR checks. A scintillation measuring device is also included in the vehicle kit [56].

In case of a radiological accident, the identification of the contamination helps to select the appropriate intervention. If radioactive material is released into the environment and the isotope is found has a very short half-life, it may be sufficient to close the area and wait for the emergency to resolve itself with time. The priority in case of long half-life isotope contamination is to contain the contaminant. The second task is to decontaminate it as soon as possible.

There are solid, liquid and gaseous scintillators. Solid-state scintillators are primarily used in military and disaster management equipment since the use of gas, and liquid scintillators would be difficult in field conditions.

Scintillators may be organic or inorganic by their material composition. Organic scintillators are characterized by their large-scale production but are not suitable for energy-selective measurement of gamma radiation. Inorganic scintillators are useful for isotopic identification and typically have higher optical yield than organic scintillators. Both organic and inorganic scintillators are used for military and disaster management purposes. Other types may be distinguished by their chemical structure, e.g., thallium-activated sodium iodide (NaI(Tl)). General NaI(Tl) scintillators can be seen in Figure 14. There is another scintillator like $LaBr_3$:Ce, which could be useful for a similar application as NaI(Tl). The LaBr3:Ce scintillator offer a high light yield and subsequently energy resolutions (2.6% FWHM) superior compared to the traditional NaI(Tl), but the price of a LaBr3:Ce scintillator is much higher than NaI(Tl) scintillators [16].

Europium activated strontium iodide scintillators also used for gamma spectrometry purposes. The energy resolution of SrI2(Eu) scintillator is also promising (2.93% FWHM at 662 keV) [57], but the production of scintillator with significant volume is still difficult.

Scintillators with different chemical compositions have different properties, and these properties can be used to determine what they are suitable. Some scintillators have a high optical yield, making them more sensitive, other scintillators can produce a high-resolution spectrum and are capable of identifying isotopes, but some types can handle a high dose rate.

It is difficult to use equipment containing scintillation detectors for military and disaster management application because they are sensitive to external environmental changes. While other applications can provide laboratory conditions such as indoor space, constant temperature (+ 25 °C ± 5 °C), fixed geometry, all external environmental parameters may change during military, disaster management tasks. The ideal field detector is insensitive to changes in air temperature, pressure, humidity and electromagnetic fields, can operate over a wide measuring range, and can withstand extreme physical impact such as vibration, dropping. Measuring equipment designed for laboratory use in extreme weather conditions simply unable to start up or will give an unacceptable accuracy.

Figure 14. Scintillation crystals.
Source: [3].

2.1. Scintillation detectors in high humidity condition

One of the most commonly used scintillators for gamma radiation measurement is the NaI(Tl) scintillation crystal, which is capable of producing a high-resolution spectrum with high efficiency.

The NaI(Tl) scintillator itself is hygroscopic, meaning it absorbs moisture, turns yellow and deteriorates in quality. Detectors used for military and disaster management purposes must be operational when the humidity level is over 80%. The NaI(Tl) scintillator is most easily protected from moisture by hermetically sealing it against the outside so it will not be able to absorb the moisture content of the air. The hermetically sealed NaI(Tl) scintillator is necessary in case of laboratory use as well.

The fight against moisture begins when scintillation crystals are produced. Usually, the growth of the NaI(Tl) crystal begins with the activation of the purified sodium iodide material with thallium and then in a powder state inputted into a growth furnace.

The NaI(Tl) crystal is growing at high temperature in a sealed glass tube. The closed technology allows the crystal to crystallize in a medium free of dirt and moisture. The raw crystal can be cut, pressed and cut to the desired shape. Once the crystal has reached its final shape, it is placed in an aluminium housing, which is completely sealed by a glass window. Once the crystal is sealed, moisture can no longer reach the scintillator. The structure of a NaI(Tl) detector can be seen in Figure 15. The quality of the scintillator can be checked after sealing the crystal using a test detector. By placing the crystal on the PMT of the test detector and putting a known radioactive source on the top of the crystal, the quantity and quality of the signal coming from the test detector can be examined. If too many pulses are generated, the light barrier is likely to be inadequate.

Moreover, external light like noise is added to the measured value. If too few pulses are generated in the detector, it is worth checking the joints or material quality. In the amplitude spectrum, the width of the peak for the measured Cs-137 isotope is also a quality parameter, called the full width at half maximum (FWHM). The smaller the FWHM of the crystal, the more useful the crystal for isotope identification. If a quality problem arises, the scintillator can be re-encapsulated or re-processed. The possibility of recycling scintillation crystals is also an essential issue for old crystals intended for disposal, as the thallium content makes the crystal a hazardous substance.

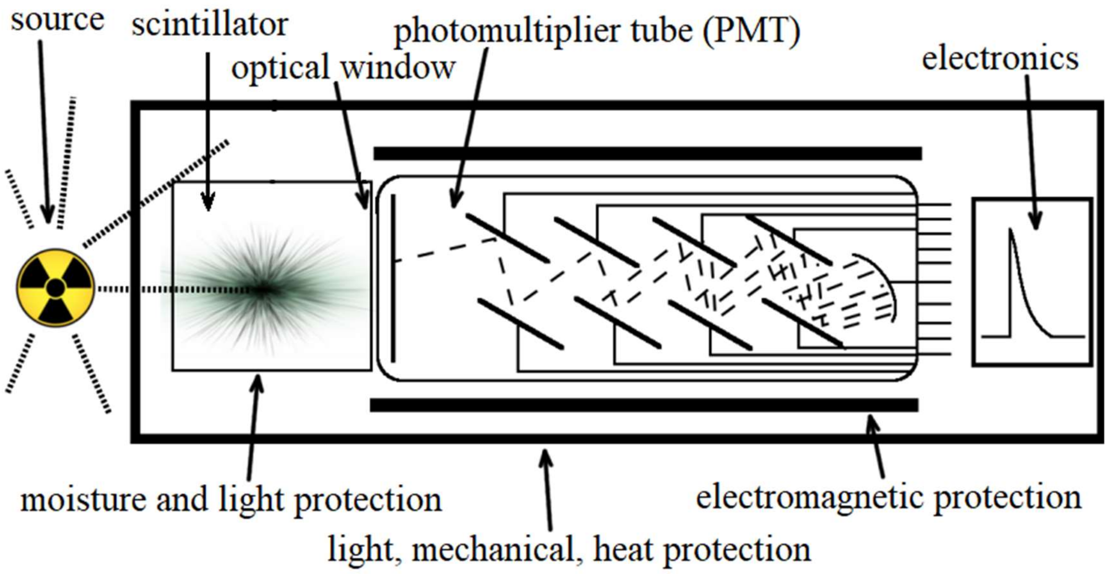


Figure 15. Structure of a scintillation detector.
Source: [58].

2.2. External light processing at scintillation detectors

The scintillator converts the ionizing radiation into a light-impulse of 300 to 700 nm wavelengths. Light can only escape from the scintillator through the optical window. The transmitted light is transformed into an electrical signal by a photomultiplier tube (PMT) fitted to the optical window. PMTs for scintillation detectors are the most sensitive in the wavelength range of the light emitted from the scintillator, but they also detect light in the other wavelength range. Therefore, it should be ensured that only light coming from the scintillator can enter into the PMT.

Blocking the light coming from the environment seems like a simple task.

However, in many cases, it is difficult to do so because for light blocking sufficiently dense and thick material is needed, when measuring alpha, beta or low energy gamma radiation, this dense material absorbs the radiation before reaching the scintillator. In these types of measurements, the detector is usually covered with a thin material as possible (e.g. metal-steamed foil), and the scintillator is placed as close as possible to the measured radioactive source.

However, in such cases, this thin protective layer can be easily damaged, and mechanical protection can only be achieved by reducing the accuracy of the measurement result.

The coupling of the scintillator and the PMT plays an essential role in achieving good FWHM value.

When the light exits the scintillator, it must pass through two layers to reach the cathode inside the PMT. At each component boundary, a refraction phenomenon occurs, which may alter the result of the measurement. Optical coupling, between the scintillator and the sealing glass plate, and between the PMT and the scintillator, is required to achieve the best quality. The size, material and design of the scintillator determine what kind of radiation can be measured with it.

Removal of the scintillator from the PMT can be done in a dust-free, clean room, the coupling is time-consuming and requires a skilled technician, so this operation is not usually done in field conditions.

2.3. Physical protection in scintillation detectors against vibration and dropping

The scintillation detector contains several components that are sensitive to external physical impact. Protection against vibrations and drops is essential in military applications.

Shock absorbers are used for the internal components of the detector. Furthermore, another absorber used for mounting the detector to the outside components. If the expected vibration, drop resistance, and dimensions requirements of the device are known, it can be simulated how the device will behave. Unfortunately, the results of the simulation and the reality often differ, so such equipment requires testing to reveal the design and manufacturing problems and to prove the conformity.

For field detectors, every piece should be tested separately to find individual manufacturing faults. The detector should be able to fulfil military standards i.e. MIL-STD-810 [21].

Perhaps one of the most demanding requirements regarding physical protection has an aerial radiation reconnaissance application. The LABV aerial radiation reconnaissance system was born as a result of a Hungarian development at Gamma technical corporation and has been used for several years at the Hungarian Defense Forces. The task of LABV is to fly over the contaminated terrain to measure gamma radiation, localise point and extensive contaminants, and determine ground-level radiation. Radiation detection at the height of 100 meters allows rapid scanning of large areas, but due to its distance, only a fraction of the radiation reaches the sensor.

A large size NaI(Tl) based detector built into the LABV system is capable of detecting low-intensity radiation effectively. The scintillator is mounted together with a collimator (ring of lead). The collimator is designed to make the detector primarily sensitive to radiation coming from the direction of the ground. Because of the large crystal and the lead collimator, the detector weighs more than 20 kg. The measuring system is housed in a container under the wing of the helicopter, which in itself has anti-vibration protection, and a separate superstructure inside the container protects the detector.

2.4. Electromagnetic noise at scintillation detectors

Electrical components used in scintillation detectors, including the PMT, are sensitive to electromagnetic noise. Equipment such as a radar or telecommunications stations that emit significant electromagnetic radiation may interfere with the function of an improperly designed detector.

Shielding around the PMT reduces the effects of electromagnetic radiation. To further improve the resistance, the detector housing should be made of metal and should be grounded to protect the electronics inside of the enclosure.

For the operation of the PMT high voltage, approx. 1000V is required. High-voltage power supplies emit electromagnetic radiation due to their switching operation. Detectors are required to ensure that the emitted electromagnetic radiation does not interfere with the operation of other electrical equipment. The electromagnetic radiation emitted by the detector and its resistance to electromagnetic radiation can be objectively investigated using test instruments.

The operation of the detector can also be influenced by the noise coming from the power and communication lines. There are monitoring systems where wiring can be up to a few kilometres in length. On long wires, the signal-to-noise ratio deteriorates significantly, which can lead to data distortion and loss, in such application shielded wires are required, and detectors should use digital data communication with error-protected protocols. This data transmission mode is significantly more noise-resistant than analogue signals, and it allows multiple detectors to be connected to a single cable. After lightning or other power failures, multiple times the nominal power supply voltage may appear at the detector input, and therefore, surge and noise protection are needed.

2.5. Temperature dependents of scintillation detectors

The applicability of scintillation detectors in the field is limited by the temperature range. Furthermore, usability also affected by the intensity of the temperature change. Measuring the same radiation field at different temperatures results will give modified results. The degree of deviation also depends on the dynamics (how fast it increases or decreases) of the temperature change. Certain scintillators undergo a physical change above a given temperature, for example, a discolouration on their surface which impedes the passage of light, rendering it unusable. In this respect, the most extreme application is not related to military or disaster management applications, but to geological surveys where the detector must withstand up to 120 °C for a long time. NaI(Tl) scintillators are particularly sensitive to quick temperature increase. The simplest solution is to protect the detector with proper insulation and shielding against direct sunlight. The insulating material protects against quick changes in temperature, and the inside temperature of the detector only takes the outside temperature much slower.

The advanced detector has built-in compensation for temperature dependence. For making this compensation, every piece should be placed in a climate chamber where measurements are made at different temperatures, and the calibration factors for that temperature are determined.

During regular operation, the detector continuously measures its temperature and adjusts the measured result with a correction factor corresponding to the given temperature. This method will allow the detector to measure at all temperatures accurately. The compensation diagram can be seen in Figure 16.

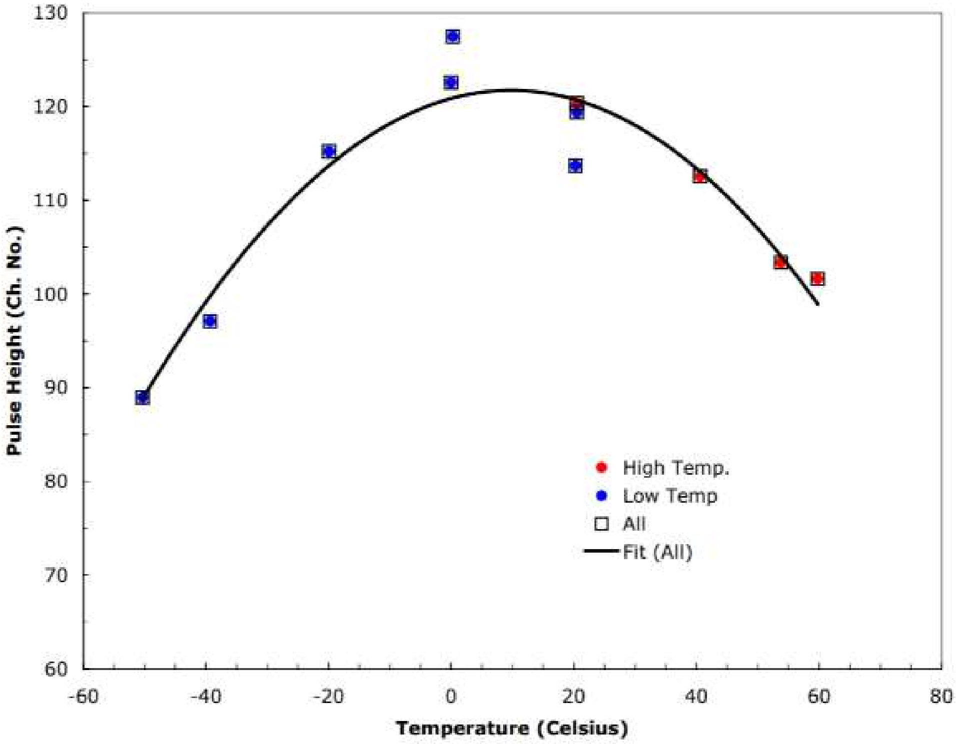


Figure 16. Temperature dependence of a Na(Tl) scintillator tested with a Cs-137 isotope. Source:[59]**.**

Another way to compensate detector parameters is to calibrate the detector with a reference light source or with a built-in radioactive source. The calibration is based on the fact that the position of the peak belongs to the source should not change in the spectrum, so the electronics can automatically adjust itself.

2.6. Ionizing radiation resistance of scintillation detectors

Scintillator based detectors are commonly used in radiation protection systems, due to their high sensitivity and their energy selective measurement capability. These detectors are not used to measure high dose rate fields over a few mSv/h.

In nuclear accident situations, high dose rate can occur quickly, so it is essential to know the conditions under which disaster management detectors can be used. Scintillation detectors over 30,000 cps cause severe problems at the analyser electronics. Along with the increase in dead time, the measured amplitude spectrum is significantly distorted, its energy changes, and the spectrum becomes unrecognizable.

Irradiation may cause both the scintillator material and the photoelectron multiplier to become inoperable for a shorter or longer period. The detector characteristics are slowly returning to their initial value after the radiation is reduced. After a high level of irradiation, a new calibration is necessary to check all parameters are returned to the there original state.

The upper measuring range can be increased with the measurement of anode current at the PMT. At this level, the detector loses the energy selective measurement capability but will remain in operation. The solution requires a combined measurement of the average of the anode current and the measurement of amplitude and width spectra of the incoming pulses.

There is another technique which can be used at high dose rates to keep the detector operational. The reduction of high voltage over several orders of magnitude makes it possible to prevent overflow by incoming pulses. After the high dose rate is over the high voltage can be increased back to the normal level.

By optimally selecting the material of the scintillator, recovery time can be reduced to less than a few seconds. A suitable scintillator is the Bismuth germanate (BGO). The advantage of the BGO scintillator is that it is capable of providing an almost linear response at high dose rate (up to 1 Sv/h) with anode current measurement the diagram in Figure 17 demonstrates the results.

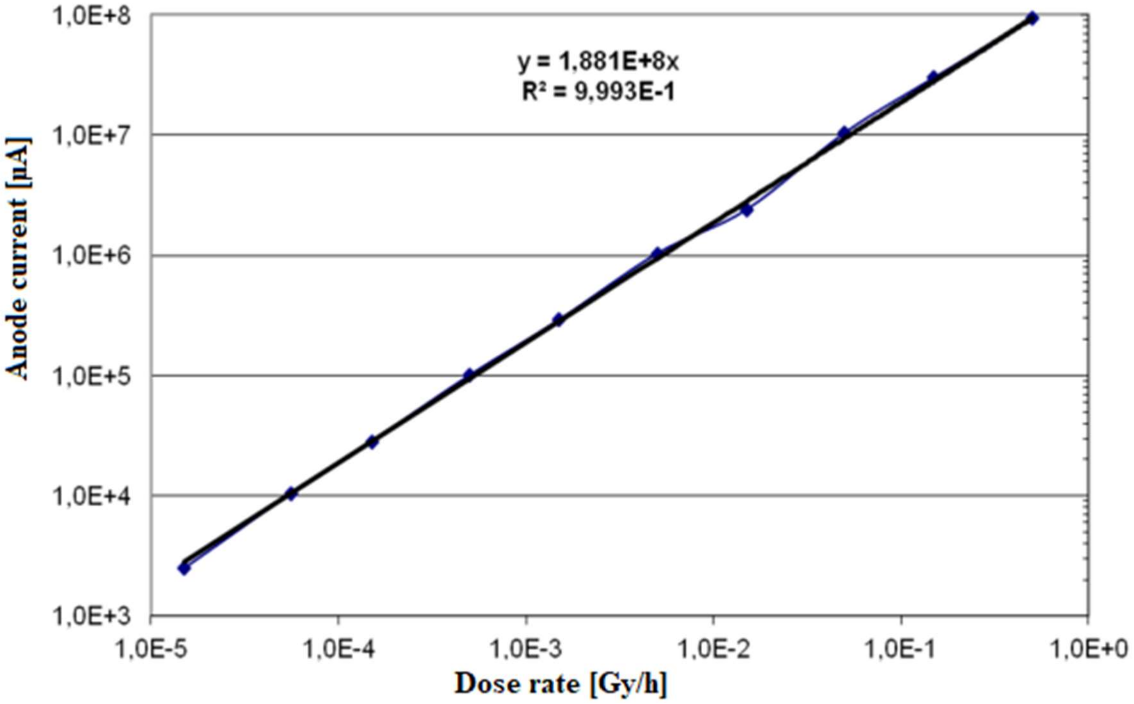


Figure 17. Anode current measurement with BGO scintillator type detector.
Source: compiled by the author.

The use of scintillation detectors for military and disaster management purposes is possible and even advantageous due to the high sensitivity, but this requires the use of various engineering solutions customised to field conditions.

When assembling the detector, the coupling materials and light barrier help to prevent the ambient light from affecting the measurement. Vibration and dropping requirements are challenging to accomplish for scintillation detectors due to their fragile components, but they can withstand physical impacts using external and internal absorber techniques. Electromagnetic radiation (both emitted and absorbed) can cause problems with the detector. A well-designed combination of electrical components, shields, and grounding can prevent the detector from interfering with external electromagnetic radiation or the detector from interfering with other electrical equipment. Changes in temperature lead to significant errors in measurement results, so it is worthwhile to use temperature compensation, which is based on temperature measurement and automatic calibration with the help of etalon sources. Adequate insulation can protect against sudden changes in temperature.

After a high dose rate (>100 mSv/h) irradiation the NaI(Tl) and CsI(Na) scintillators only return to their original values after along time.

This problem can be solved by the BGO scintillator, which is capable of continuously measuring the intensity of radiation without any after glowing effect, or the anode current measurement can also be useful at high dose rate measurement [58].

2.7. Development of sodium iodide scintillator for using in military application

The advantage of scintillation type radiation detectors over GM counters is that the energy of the given radiation can be determined for gamma radiation. Semiconductor detectors have better performances in energy selective measurements and more expensive as scintillator detectors and needs cooling.

Most commonly used scintillator is the thallium-activated sodium iodide scintillation crystals, which are primarily capable of detecting gamma-quantum. The history of scintillation crystals goes back to the early 20th century. In 1903 it was discovered that zinc sulfide crystals emit light when exposed to alpha particles. Initially, the flashes were counted under a microscope. Later, in 1945, a photomultiplier was used to produce an electrical signal to measure photon energy. In 1948, the first thallium-activated sodium iodide [NaI(Tl)] crystal was grown to measure photon energy [60].

The scintillation crystal was first grown in Hungary in 1952-53, thanks to the development work of János Nagy, Imre Tarján, György Turchányi and Rudolf Voszka at the Medical Physics Institute of the Budapest University of Medicine. Gamma Technical Corporation (GAMMA) first began in 1960 the production of NaI(Tl) crystals [61].

Growth of sodium iodide crystals

The production of NaI(Tl) crystals requires the growth of single crystals in which the light, produced by the effect of scintillation, can diffuse through an optically homogeneous medium and leave the crystal at the optical window. The polycrystalline NaI and the corresponding portion of Tl are heated in a furnace above the NaI melting point (651 °C). A controlled heating process causes the single-crystal growth to reach the desired height in several days. There are several ways to ensure even heating, either by keeping the inside of the growing chamber at a constant temperature while the melted crystal material is being pulled out slowly or by allowing the growing chamber to cool slowly while the melt is standing still. Both growth processes require the use of control electronics since single crystal growth only occurs at appropriate temperature conditions.

There is no significant difference between the two processes regarding the quality of the end product. The advantages of the non-moving technology are that the whole process can be monitored by temperature sensors, and with multiple heating loops, different temperature zone characteristics can be set, more options are available compared to pulling out the crystal from the growing chamber. Figure 18. shows two methods to grow NaI(Tl) crystal. The control electronics measure the temperature with the help of a thermocouple placed in the stove and decide whether to heat the chamber or allow it to cool down.

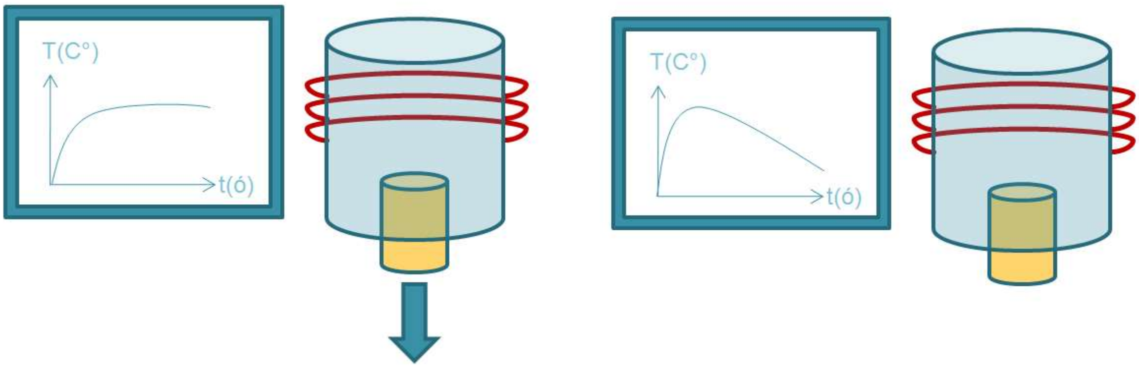


Figure 18. Two methods to grow NaI(Tl) crystal.
Source: compiled by the author.

Initially, GAMMA used only the extraction technique because maintaining a constant temperature and uniform extraction did not require complicated control. The first computer-controlled control system supported both growth technologies, as the computer control was able to handle the heating curves simultaneously on multiple chambers. The disadvantage of central control is that in the event of a failure of the control computer, all growth chambers may stop. In 2008 a new computer-independent control system with shared intelligence was installed. The growth is done according to the specific characteristics of every growing chamber, independently of one another. Failure of a control unit does not compromise the operation of the entire production line, and the computer plays only a monitoring and programming role in the system. Figure 19. shows two NaI(Tl) crystal growing systems.

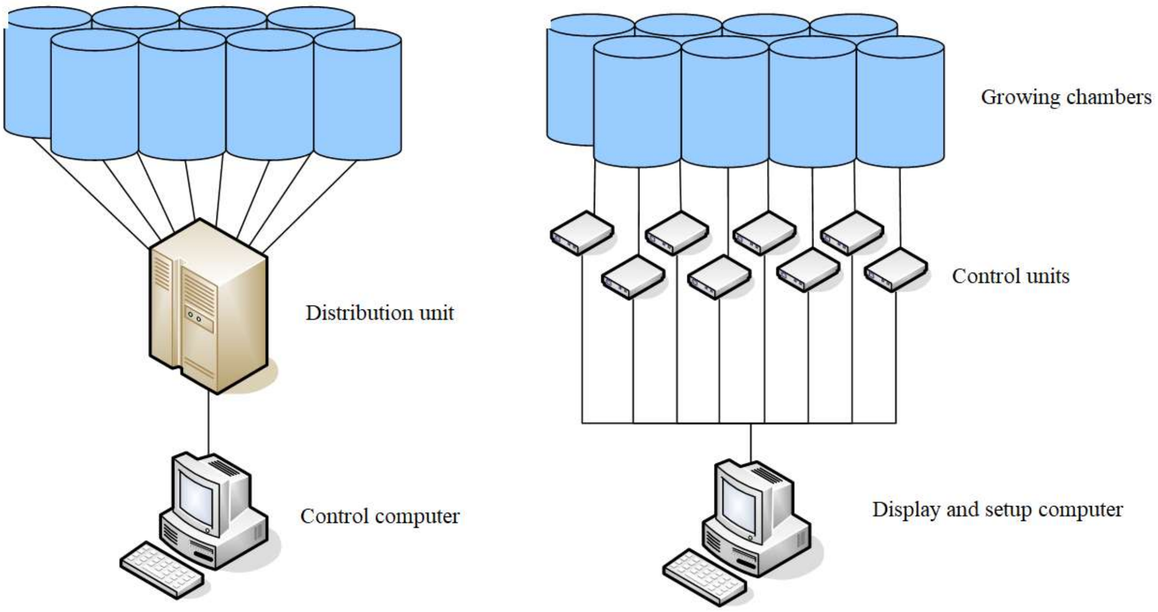


Figure 19. NaI(Tl) crystal growing systems.
Source: compiled by the author.

Each control unit incorporates a proportional–integral–derivative (PID) algorithm, which allows more accurate curve tracking compared to the hysteresis controls used previously. During hysteresis control, the chamber heater is turned on if the measured temperature is below the lower level of the hysteresis range relative to the reference level, and off if it exceeds the upper limit of the range.

PID control reduces overheating caused by a sudden change, reduces external noise and can follow the reference curve with slight overshoot. The result of the PID control is less dislocation and more even distribution of Tl in the crystal, less waste and better energy resolution. Figure 20. shows diagrams hysteresis and PID control of temperature.

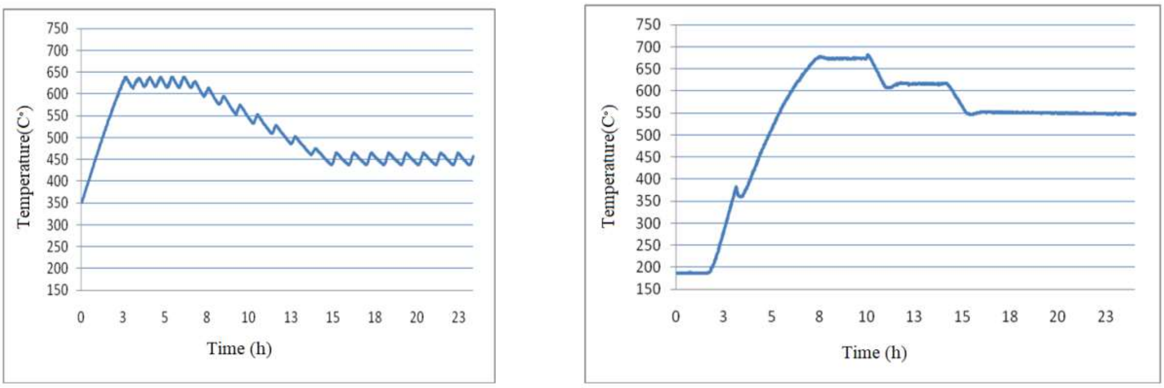


Figure 20. Hysteresis and PID control of temperature.
Source: compiled by the author.

Enclosing of sodium iodide crystals

The NaI(Tl) crystal is very hygroscopic (tending to absorb moisture from the air), the surface of the crystal becomes yellow in the open air, at room temperature, liquefies due to the humidity of the air, so the NaI(Tl) crystals should be sealed hermetically. Encapsulated NaI(T1) crystals are manufactured in various sizes, shapes, and compositions, depending on the application. The crystal is encapsulated in an aluminium housing. The photons are emitting from the crystal exit through an optical glass window and usually detected by a PMT.

It is necessary to build the NaI(Tl) scintillation crystal into a sealed aluminium housing. Figure 21. shows the model of a sealed scintillation crystal. The assembly is carried out in a low humidity chamber (less than 10% of air humidity) due to the hygroscopic property of NaI. During installation, the crystal must be cleaned of the surface contamination. The part in contact with the aluminium housing must be coated with a reflective material (e.g. magnesium oxide), and the free crystal surface must be coupled with a guide which is conducting light.

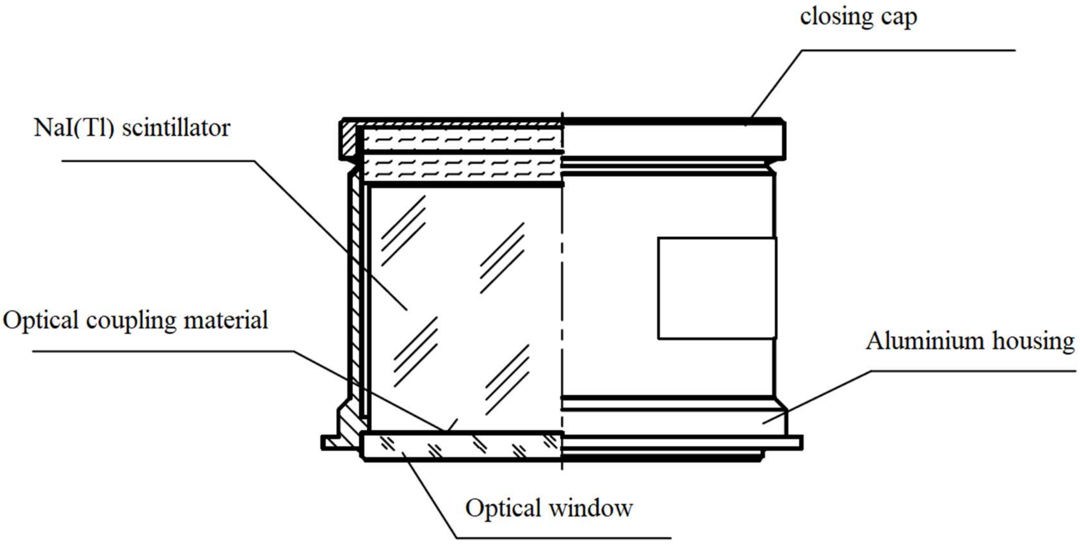


Figure 21. Sealed scintillation crystal.
Source: compiled by the author.

With the sealed, finished crystal, an amplitude spectrum is recorded using a radioactive reference source. In the spectrum, the FWHM value belongs to the Cs-137 radioactive source peak determines the quality of the crystal.

The narrower the peak, the better the crystal is. Gamma radiation-sensitive scintillation crystals with a diameter of 50 mm and a height of 50 mm have a typical relative FWHM with Cs-137 test source in the range of 6.8 to 9%. Figure 22. shows the amplitude spectrum of a Cs-137 measured with NaI(Tl) crystal and the FWHM is approximately 7%.

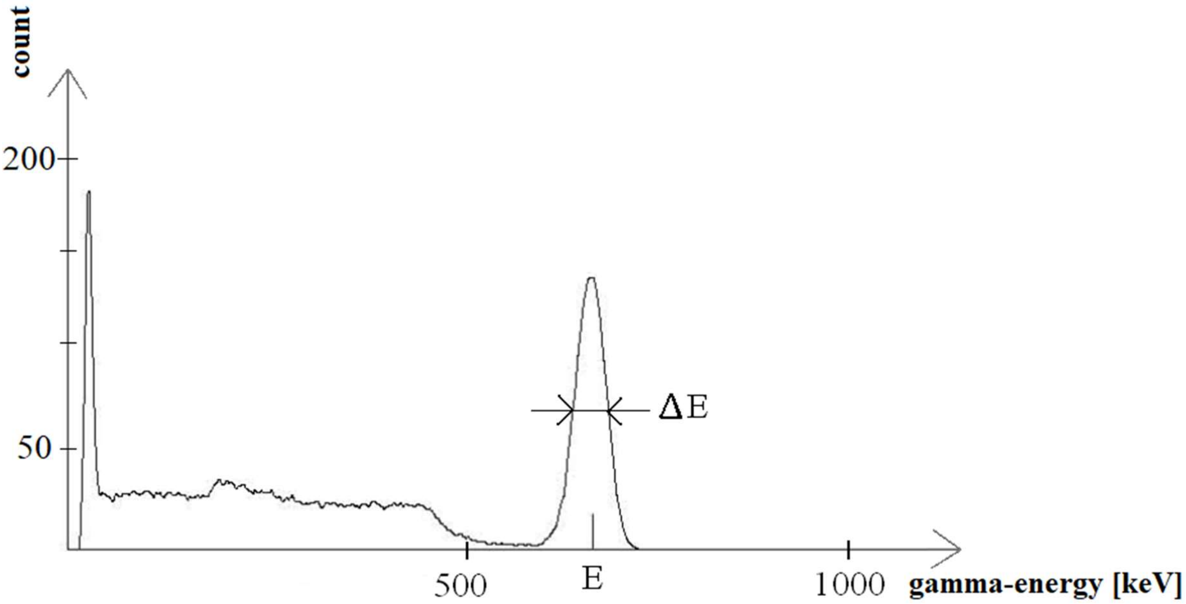


Figure 22. Amplitude spectrum of a Cs-137 measured with NaI(Tl) crystal.
Source: compiled by the author

2.8. Scintillation crystal disunion

Since the NaI(T1) crystal has been produced, the phenomenon of disunion has been known. The crack between the glass plate and the crystal is an air/vapour bubble that is visible at different locations and can appear in any shapes. Depending on the location and size of the disunion, the detector efficiency and resolution are reduced. The disunion may appear immediately after production but may take several years to appear.

It can be caused by:

- the optical coupling material, the scintillator and the socket have different coefficients of thermal expansion and therefore react differently to changes in temperature,

- the fitting between the socket and the crystal is not perfect. Vibration may cause the crystal to move, causing disunion,

- the optical coupling material contains air bubbles, which over time may form a bigger bubble.

There are several types of disunion. One example of disunion can be seen in Figure 23. Based on the formation of the disunion, a bubble can come up in the middle of the crystal. Disunion can take the form of a tree branch starting from the edge of the crystal. Some of the disunions disappear over time, a phenomenon that mainly occurred immediately after production. In samples that have been parted for years, the disunion has spread over time. Moreover, the detector has become cobwebbed.

Figure 23. NaI(Tl) crystal disunion example.
Source: [62]

The phenomenon of disunion has not been dealt with for a long time, partly because it only occurred very rarely after years of use, and partly because its effect could be reduced by regular calibration or by an automatic background compensation algorithm. This phenomenon was considered to be the own fault of the detector, and regular calibration compensated its effect. However, in recent times, applications have become more widespread, and the use of scintillation detectors in vehicles has become a necessity. In these applications, disunions have occurred more rapidly and more extensively.

Development of scintillation crystal production

The first step was to make the disunion phenomenon reproducible. The encapsulated NaI(Tl) crystal was subjected to mechanical vibration with the following parameters: frequency: 50-60 Hz, amplitude: 1-1.2 mm, acceleration: 10-12 g (98-118 m/s^2), then the outside temperature from room temperature to 0 C then to 55 C at a temperature change rate of 5 C/h.

The choice of test conditions had to take into account that vibration and excessive conditioning could cause permanent damage or cracking of the crystal. After completion of the procedure, the samples were visually inspected, and the FWHM value determined. Crystals that did not show visible disunion and had an FWHM value below 10% passed the test. I took part in the planning and evaluation phase of the development work and supervised the actual activities.

In order to eliminate disunions, development was started in several directions.

1. Crystals and optical coupling material were purchased from different sources and tested with the method explained earlier. The result was the same as before.

2. The socket has been redesigned to allow the optical coupling material to have a recess in which unnecessary material may be spread. The glue used to fix the glass filled the recess, so the experiment was unsuccessful.

3. An attempt was made to eliminate the presence of bubbles by a method commonly used for vacuum impregnation. Despite the vacuum and ultrasonic treatment, the tiny bubbles remained in the optical coupling material, and disunion still occurred.

4. New materials have been tested as optical couplers. Eventually, these experiments were successful.

Investigations revealed a correlation between the thixotropic property of the optical coupling material (the viscosity of the material decreases under specific mechanical stress) and the formation of disunion. In all cases, thixotropic coupling materials were not able to pass the disunion test.

A specification was made for the coupling material:

- heat resistant,
- transparent in the temperature range 0-50ºC,
- its refractive index is nearly the same as that of glass or crystal.

After extensive experimentation, an optical coupling material was found that meets the above requirements. The new optical coupler, which meets the above specifications, has many advantageous properties, for example, it maintains its flexibility over a wide temperature range (-55ºC to 200ºC), the heat resistance can be increased up to 310ºC with various stabilizers; has excellent chemical properties which are entirely inactive from a chemical point of view, and providing a bubble-free interface between the crystal and the glass [62].

2.9. Conclusion about scintillation crystal development

As a result of this development, a new generation of assembled scintillation crystals has been born, which have a longer lifetime, are more vibration resistant and can be used in a wider operating temperature range. I found a new unique coupling material which could solve the disunion issue. The exact components of the coupling material are company secret, more detail is not available for publication. I created a new testing process to prove the quality of NaI(Tl) scintillation crystal quality. Scintillation crystals produced by this new process are already used in multiple detectors like in the BNS-94FM onboard radiation reconnaissance system. The new scintillation crystals can be installed in applications for CBRN reconnaissance vehicles, military reconnaissance vehicle, and as a stand-alone measuring unit.

3. INVESTIGATION OF RADIATION PORTAL MONITORS (RPM) FOR THEIR USE WITH MILITARY AND DISASTER MANAGEMENT PURPOSES

Since the discovery of radioactivity, materials and devices emitting ionizing radiation have been in use continuously. Technologies emitting ionizing radiation have become part of everyday life, be it medical (e.g. dental x-ray, nuclear medicine) or industrial (e.g. energy production) applications. However, its dangers must not be overlooked. Ionizing radiation is colourless, odourless, and depending on the quality of the radiation, it can penetrate most substances and destroys the living organism.

The radiation-emitting material is visually unrecognizable. The radiation causes immediate symptoms only when a high dose is suffered. The effects of small doses can cause health issues only after years, decades [63]. Part of the defence against radiation is detection, for which it must be possible to say with great certainty whether there is radiation contamination at a given point or not. Radiation contamination can only be determined by detectors. Radiation portal monitors are radiation-sensitive equipment that allows the detection of hidden sources as well as radioactive contamination. The importance of these systems is illustrated by the fact that a litre of (highlyenriched) uranium can be used as an atomic bomb, and can easily be hidden in a vehicle so that it cannot be detected by conventional tools but only by a radiation portal gate.

Following the practice of recent decades, high-sensitivity radiation portal monitors capable of continuous, autonomous operation are used for detecting radioactive sources or contamination at permanent or temporary checkpoints. The measurement with the radiation portal monitor is performed while the object on interest (vehicle, person, package) is positioned in a controlled way next to the detectors of the RPM.

The radiation is absorbed by the shielding effect of the container. The intensity of radiation is reduced by the distance (air gap) between the package and detector. The detecter should be installed as close to the vehicle a possible. Moreover, should stay within the sensitive field of the detector as long as reasonable.

In this chapter, I examine the designing and developing of RPM systems used at border control, at scrap metal reprocessing, and military applications. I also try to integrate new technologies into RPMs to make radiation detection even more efficient.

3.1. Structure and operation of radiation portal monitors

The capabilities of a radiation portal monitor are determined by its components and their cooperation.

The main parts and their functions are as follows and can be seen in Figure 24.:

- Detector unit: Its function is to detect radiation, generate an alarm signal and send measurement data to the alarm unit several detectors can be placed in one detector unit. The detector should be as sensitive as possible to changes in the radiation of the test object or person. One way to ensure directional dependence is to collimate the detector with a lead ring. If the detector identifies a significant increase in radiation, it sends an alarm signal to the alarm unit.
- The alarm unit manages the sensor units, in case of an alarm, it triggers a visual and audible alarm and provides data to the display unit. The alarm can also be acknowledged by the user on this device.
- The display unit shows the measurement data as well as the current status of the RPM. Collecting, storing of data are the task of the display unit.

The display unit makes it easier and more accurate for a user to handle a post-event action plan. The software will tell the user what to do, provide decision support, ask relevant questions to the operator and give the appropriate instruction based on the answers of the operator. (e.g., the procedure should be different when the driver is radiating, and another is when the vehicle itself is causing alarm signal. An advanced radiation portal monitor can make the handling process of an event more efficient by providing the phone numbers that the operator should call. If first-person on the phone list is unavailable, the system suggests the next person phone number automatically from the situation escalation phone list.

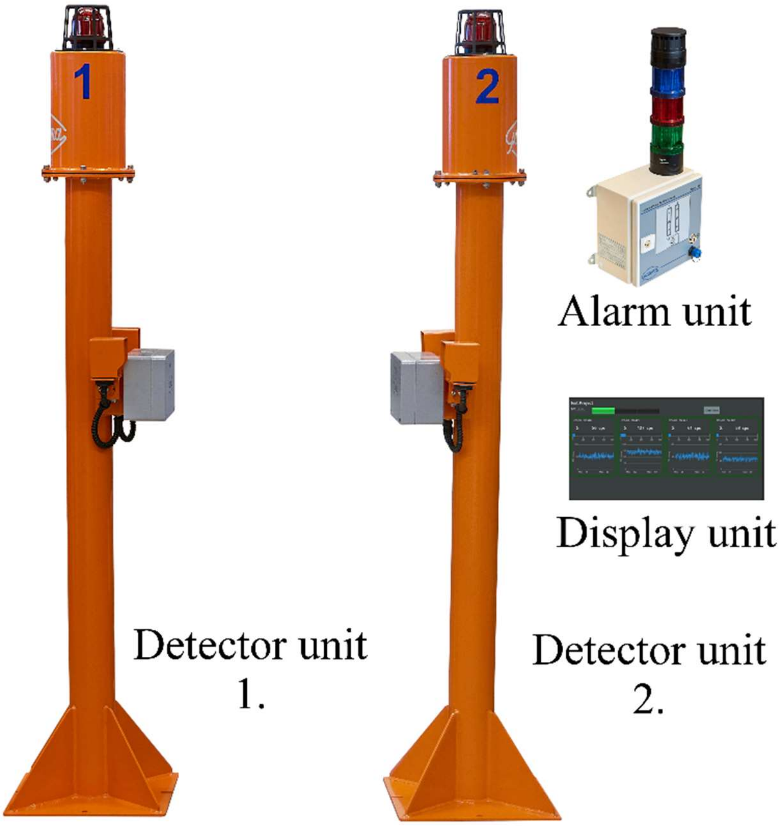


Figure 24. Main parts of an RPM.
Source: [3]

A well-configured radiation portal monitor can give a command to the operator to cordoning the vehicle around if the measured values so high that the radiation can cause health issues to be near to the vehicle. In the case of an alert caused by a radiation level of near background radiation, the system may allow the operator to approach the vehicle and localise the radiating material by further on-foot reconnaissance.

3.2. Additional capabilities of RPMs

Radiation portal monitor systems can be supplemented with an occupancy sensor, video surveillance, license plate recognition, shipment label identification. A full-fledged portal monitor structure can be seen in Figure 25. The data can be used to retrieve background information about the shipment from a database. At ADR shipments, it is mandatory to have a label on the outside of the vehicle for identifying the dangerous substance [23].

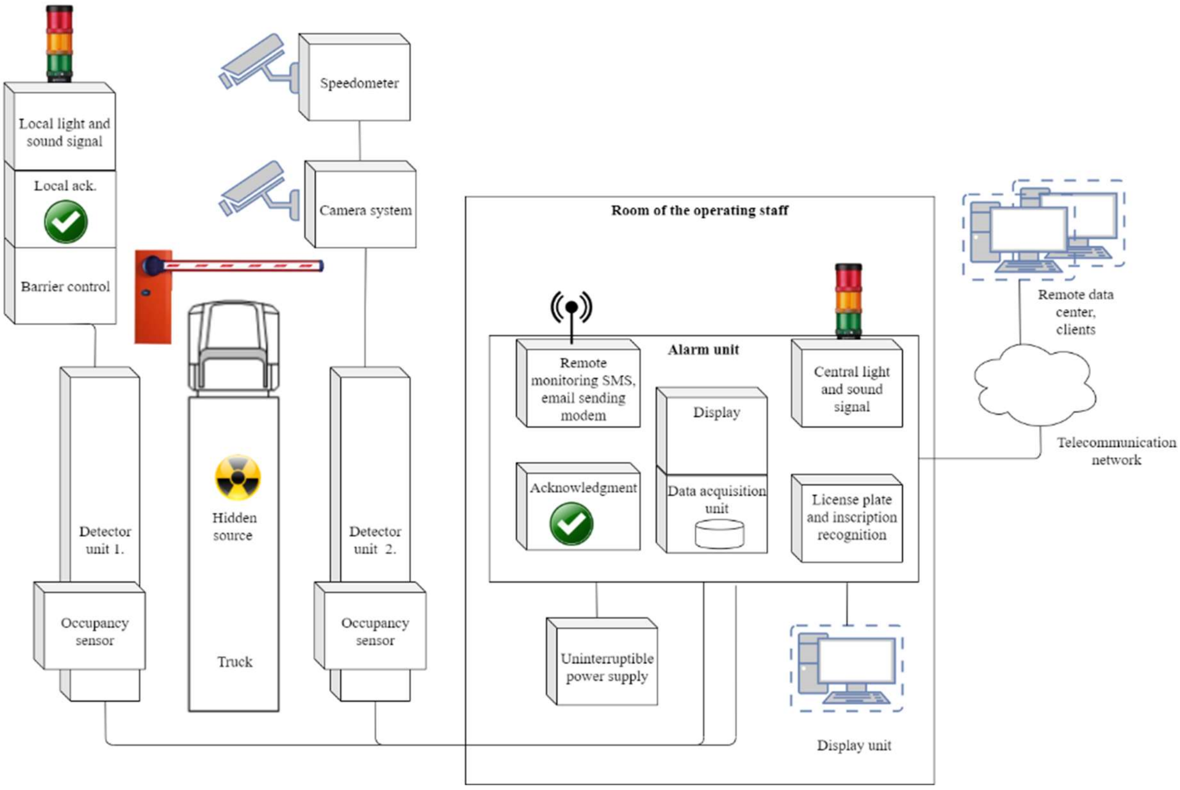


Figure 25. Structure of a radiation portal monitor.
Source: [3]

A wheel counter connected to the radiation portal monitor can indicate where to find the source in a train. This additional feature is necessary for train surveillance because a train can of up to 500 meters in length.

RPMs integrated with security systems can allow or even block passage. Measured data and events can be sent to a data center, allowing hundreds of RPMs to be monitored from a single location.

3.3. Intelligent detectors of an RPM

The minimum expected feature of a radiation portal monitor to be able to detect gamma radiation. Different types of detectors are available for this purpose. Among the available technologies, the gas-filled detectors have the most straightforward operating mechanism (ionization chamber, proportional counter, GM counter). The sensitivity of RPMs equipped with such detectors is less than that of scintillation detectors.

That is why detectors based on the scintillation principle, (NaI(Tl) or plastic scintillators), are most often used at radiation portal monitors. Scintillators convert radiation into light, which can be transformed into an electrical signal to determine the level and energy of radiation.

The advantage of the plastic radiation portal monitors is that large scintillator can be manufactured economically. It is excellent for detecting high energy radiation, but its intrinsic efficiency and spectral resolution does not reach the capabilities of the NaI(Tl) type detector [25]. A further disadvantage is that the directional dependence of the plastic detector is not achievable (thick lead collimation cannot be used) due to the large detector size, so radiation coming from behind the detector may interfere with the measurement.

A detector equipped with a NaI(Tl) scintillator is an excellent choice for detecting low and medium energy gamma radiation and for energy selective measurements. The overall system based on NaI(Tl) scintillator is more advantageous than a system based on plastic scintillators in terms of size, weight and price. The proper spectral resolution of NaI(Tl) allows isotope identification for gamma radiation. The isotope identification function makes it possible to distinguish between natural and artificial isotopes. Identification can only be performed within a few seconds at high radiation levels, so in most cases, the identification process will only start once the first detection has already happened. Usually, after the first alarm event happened, the vehicle carrying the probably dangerous radiating material is taken to a secondary checkpoint where the identification process can also be conducted. It is no longer a requirement at secondary checkpoints that the vehicle should be inspected as soon as possible. With longer measurement time, it can get a much more accurate picture of the radiation. False alarm rate can be reduced by using the secondary checkpoints.

Neutron radiation measurement

In addition to gamma radiation, measuring neutron radiation is also an important task. The most commonly used method is applying He-3 gas-filled detectors, which selectively measure the neutron radiation with high sensitivity. Helium-3 on earth is entirely supplied by tritium that was created by either the United States or Russia to maintain nuclear weapons and has now radioactively decayed into helium-3 the stockpile. Despite a nearly constant annual rate of production of helium-3 as the tritium decays, the stockpile has been steadily decreasing since 2001. Caused by this factor the price of He-3 gas is increasing year by year.

Neutron radiation can also be measured with other technologies, but with lower sensitivity than He-3 and with significant gamma cross-sensitivity [64]. Boron loaded plastic scintillator is an alternative to measure neutrons radiation. There was a comparison between two kinds of detectors (Boron loaded plastic scintillator and unloaded plastic scintillator) is done exhibiting that boron loaded plastic scintillators, despite their high gamma rays efficiency, could be also used instead of Helium-3 gaseous detectors for waste cells measurements [65].

A combined gamma (NaI(Tl)) and neutron (Boron loaded plastic) detector is a solution to cross-sensitivity. When using multi-layer (sandwich) detectors, different radiation cause light flashes (scintillation) in different layers. The flashes can be separated by measuring the width of the electronic pulses generated in the detector so that signals from gamma and neutron radiation can be distinguished. Based on the width of the pulses, the incoming pulses generate a width spectrum. Validated gamma and neutron ranges must be defined in the width spectrum for efficient separation. This requires calibration with real sources. To determine the neutron range, it is advisable to use a Cf-252 neutron calibration source, and for the gamma ranges Am-241, Cs-137 and Co-60 gamma calibration sources, so that the effect of gamma radiation sources of different energies can be well separated from the neutron range.

3.4. Operation of the radiation portal monitors

The primary function of an RPM is to generate an alarm when a source is in the portal. In most cases, the vehicle/person to be tested spends only 1-2 seconds at the gate, there is no time for a remote computer unit to determine the alarm, so the algorithm that decides over alarms is programmed into the radiation detector unit. In order for vehicles to pass through the RPM without stopping, the detector used there must decide, within half a second, whether to allow the vehicle/person to continue their journey or to trigger an alarm event and stop it.

After powering on, the radiation portal monitor performs a self-diagnostics and a background measurement against which it can examine later the rise in radiation levels. During normal operation, it performs a measurement every half a second and evaluates the results immediately. It takes into account whether there is any traffic passing through the portal. When there is no vehicle in the portal and no significant change compared to the background, the detector automatically updates the background radiation value, thus being able to track natural background radiation fluctuations.

The algorithm implemented in the detector checks the measurement results using the following formula:

Formula 4. $$\mathbf{M_{i,\tau} > N_{hi,a} + S_1 * \sqrt{\frac{N_{hi,a}}{\tau}}}$$

where:

$M_{i,\tau}$: average pulse rate [count].,

Formula 5. $$\mathbf{M_{i,\tau} = \frac{\sum_{i=1}^{\tau} N_i}{\tau}}$$

N_i = the number of pulses measured during the measuring period [count/0.5 sec],

τ = “Time constant” is the number of averaged measurement cycles [sec],

$N_{hi,\mathbf{a}}$ = average of the background [count].

Formula 6. $$\mathbf{N_{hi,a} = \frac{\sum_{i=1}^{a} N_i}{a}}$$

a = the number of averaged background measurement cycles,

S_1 = multiplication factor for the desired significance factor. Default factor is 4,6.

If the condition described in Formula 4. is met, the measurement result is significantly higher than the background radiation, and the system generates an alarm. As the time spent in the field of view of the detector increases, the sensitivity of the detector increases.

Background radiation fluctuations, alarm levels changes can be seen in Figure 26.

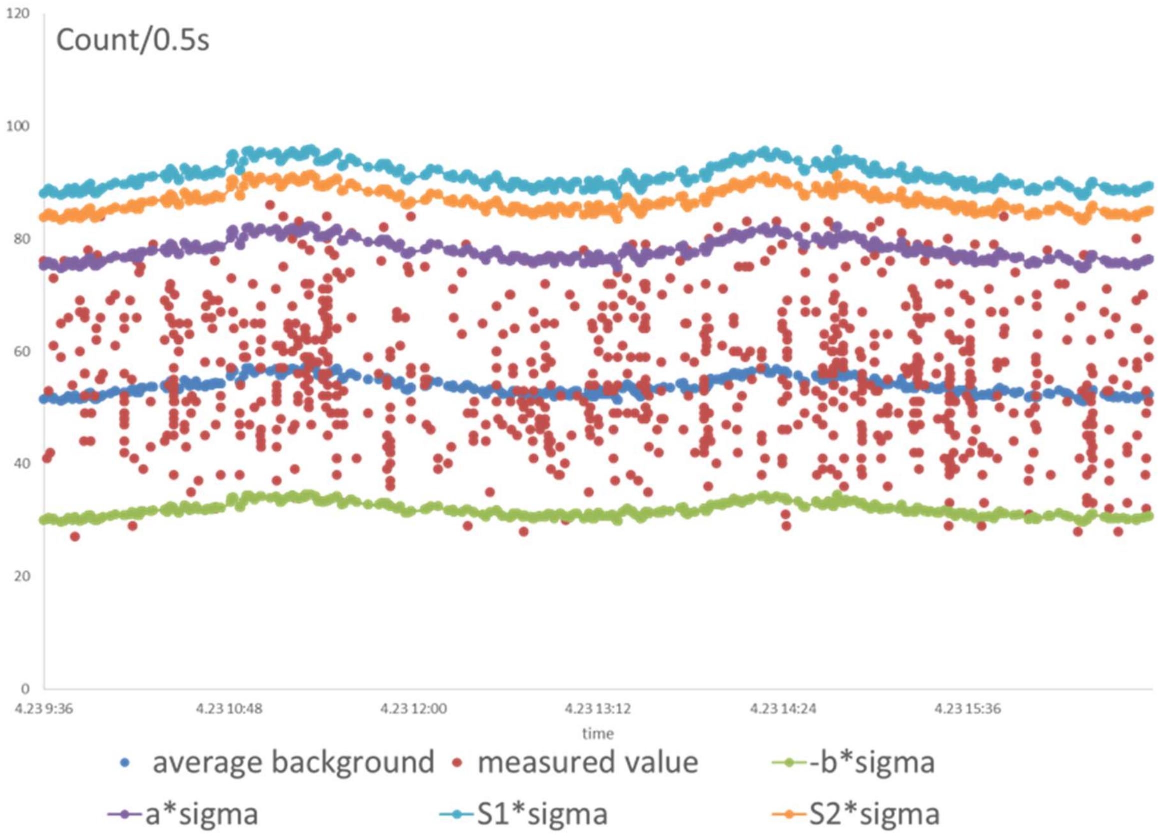


Figure 26. Background radiation fluctuations, alarm levels change.
Source: compiled by the author

The a, b values signification levels for changing from normal mode into warning mode, The S1, S2 are signification level for alarm with occupation S1 and without S2 is.

False alarms can be filtered by examining the recorded gamma spectrum by an algorithm. The algorithm tries to identify the isotopes in the source based on the spectrum, and if it finds only a naturally occurring isotope, it either blocks the alarm or generates a low-level warning. The question arises, whether alarms from natural sources can be disabled? It is annoying for the operating staff to take to many times action because of innocuous natural radioactive containing shipments, so many radiation portals offer the feature to disable alarms caused by natural sources. However, it allows smugglers to hide dangerous radioactive or nuclear sources alongside large quantities of natural radioactive materials.

The short measurement time does not allow small activity dangerous artificial source to be detected by the radiation portal monitor next to a large natural radioactive shipment, so it is worth to install a secondary screening system. The first step of the multilevel checkpoints is the primary control point through which all traffic can pass only with a speed limitation. In these systems independently from the quality or type of the radiation, the RPM generate an alarm when the radiation level exceeds the threshold.

The alarm triggering vehicle is routed to a secondary checkpoint, where isotope identification can be performed with a more extended measurement period. Based on this more accurate result, an algorithm can distinguish between natural and artificial radiation. Plastic and NaI(Tl) type radiation portal monitors can be seen in Figure 27. On the left side of the picture the plastic-type detector and on the right side of the picture the NaI(Tl) type detector can be seen.

Figure 27. Plastic and NaI(Tl) type radiation portal monitors.
Source: [3]

If the secondary radiation portal monitor indicates radiation from an artificial source, the consignment shall be dismantled, and the contamination shall be localized by manual source detection techniques. The cause of the alarm is not just the shipment, but in many cases, the driver himself, because he has received medical treatment that causes radiation. The vehicle body may also be contaminated. The radiation portal monitors can distinguish between point type and extensive contamination based on the duration of the alarm signal level.

The significantly increased measured value caused by a point type contaminations can be presents in on or two half-second measurements, and after that, the level will decrease back to the background level. In the case of extensive contamination, the increased values are present at least three or more half-second measurement. Extensive contamination can be that the whole vehicle is contaminated and it will stay in the portal monitor a few seconds. The time limits for point type sources should be changed if the speed of the vehicles is higher than 5 km/h. An extensive contamination alarm usually indicates that the vehicle is contaminated from the outside, while a point type contamination indicates a hidden source inside of the vehicle.

3.5. The history and development of RMP systems in Hungary

The history of RPM-s started in Hungary when there was a need to install radiation portal monitors for checking shipments entering from the Soviet Union after the Chernobyl disaster. The new challenge required new technical solutions for a measuring system capable of continuous operation without supervision. The system automatically takes into account the instantaneous background radiation level to determine the actual alarm level, the speed of the vehicle passing through, and the shielding effect. The International Atomic Energy Agency now requires automatic background compensation and time constant correction as minimum requirements for radiation portal monitors. Expansion of the observation network continued in 1997, funded by the Ministry of the Environment. During the preparation of entering into the European Union, the National Commander of the Hungarian Customs and Finance Guard further expanded this system, partly within the framework of EU (PHARE and EuropeAid) programs [37]. As originally intended, at all border crossing points designated for the transport of dangerous goods, at least one road or rail lane has been checked by RPM.

Afer Hungary entered into the European Union and the Schengen area, the radiation portal monitors were moved from the Austrian, Slovakian and Slovenian border sections to the Schengen borders. It is a common approach to countries trying to prevent the transports of sources to control only shipments arriving in the country. Plastic and NaI(Tl) type radiation portal monitors can be seen in Figure 28.

Figure 28. Radiation portal monitors at the border of Hungary.
Source: [3]

Applications of radial portal monitor systems nowadays

The widespread use of radiation portal monitors was facilitated primarily by the prevention of nuclear smuggling following the Chernobyl events and the break-up of the Soviet Union.

While controlling cross-border shipments was an important task, it was only one of how RPMs could be used. Different modes of transport have required different technical solutions at the RPM. When designing a radiation portal monitor, it should be taken into account that there is different space available for road and rail transport. At road traffic, it also matters whether it is a passage for trucks or cars. Radiation portal monitors were soon available for new applications.

In May 1998, a Cs-137 radioactive source was accidentally melted at an Acerinox metal processing plant in Spain. Airborne radioactive Cs-137 has also been detected in France, Switzerland, Germany and Austria. The cost of restoration and production lost exceeded 26 million USD [11].

This unfortunate event also highlighted the enormous damage that can be caused by accidental contamination at a factory plant. Intentional terrorist acts with radioactive materials can be more serious. After applying RPMs at border protection, the next users of radiation portal monitors are metal processing plants. Radioactive materials of various origins are widespread in scrap metal.

If radioactive metal enters the blast furnace, it could cause billions of forints of damage. The damage is not only to rebuilding cost of the blast furnace, but the market loss is also to be expected due to the loss of production. Therefore, initially, the equipment used at the border crossing points, and later the versions optimized for this particular task, were used by metal processors.

If environmentally hazardous contamination (for example, at metal collected for export and reprocessing) is found at the border crossing, the entire shipment may be reversed and returned to the shipper. The cost of one shipment rejection can be higher than installing a radiation portal monitor. Therefore blast furnaces, scrap metal collection facilities have also decided to the use of RPMs. Radiation portal monitors were used to filter out any contaminated material that might be present in the shipment arriving at the site so that it could not reach the site. With the use of a radiation portal monitor, it was possible to prevent the shipments from being re-routed from a central metal collector facility or the border, and the RPMs successfully protect their employees against the impact of radiation. The use of RPMs at metal collection plants, scrap yards and metallurgy is becoming more and more common in Hungary. An example of a waste yard RPM is shown in Figure 29.

Figure 29. Radiation portal monitors at the entrance of a scrapyard.
Source: [3]

Radiation portal monitors can also play a significant role in communal waste yards. If the waste deposit site becomes contaminated by radiation, it may require recultivation and decontamination of the entire site. The cost of renovation, not to count the environmental damage, can be much more than installing a radiation portal monitor.

In Hungary, if a radiation portal monitor finds a radioactive source, its removal and final deposition is the responsibility of the competent authority [44].

As the RPMs have evolved, their sensitivity has increased, their size and price have decreased. RPM solutions have been offered to a growing number of particular problems. Radiation portal monitors have been developed that can be used to detect beta surface contamination of the hands and feet, and gamma contamination of clothing, These portals usually located at the entrance of isotope laboratories, military or nuclear facilities.

Nowadays, radiation portal monitors are being used for the immediate measurement of the contamination of cargo and persons passing through the road, rail, water border crossing points, airports. Detectors used in radiation portal monitors are also applied in aerial radiation detection systems, where they are used to locate and analyse during flight lost or hidden point type sources and terrain contamination.

Due to the smaller sizes of new RPM system, after fixed installed radiation portal monitors, mobile and mobilizable equipment appeared on the market, and nowadays there are systems they can be integrated into a variety of vehicles. The first users in the mobile and onboard reconnaissance field also came from the state. Mobile RPMs in the decontamination system appeared as auxiliary equipment and began to systematically check shipments, people or cars leaving from the contaminated areas. Mobile radiation portal monitor checking the contamination of a vehicle in Figure 30.

Figure 30. Mobile radiation portal monitor.
Source: [3]

RPM is also used as a tool in the fight against terrorism to detect isotopes or dirty bombs that want to be used against individual targets. An RPM installed in a carry bag has also been released into the market to prevent the killing of a significant person (VIP) slowly but surely with placing radioactive isotope next to there office.

In the final stage, mobile devices have emerged as a complement to fixed systems already used by freight companies and mail controls.

In 2009, RPMs were operating on land and in the air, as a result of new development, a detection system was created for supporting the surveillance of Illicit traffic in river transport routes. The complete system has a very high sensitivity, which has also made it possible to control the cargo of large barges. The detector is combined to detect both gamma and neutron radiation.

In many cases, the contamination is a point type source in a large amount of waste or other material, so finding it is not an easy task. For this task, it is recommended to use a radioactive source detection device which can localise the source in the shortest time. Today, handheld isotope identification devices with radiation portal monitor functions are available that allow rapid shipment scanning.

3.6. Further development possibilities of radiation portal monitor systems operated by professional bodies in Hungary

The first systems have been installed in Hungary for more than 25 years, and since then most have been operating continuously. Therefore, it is time for doing some upgrade on the system. The first step in the technical upgrade of radiation portal monitors may be to replace the detectors. Replacement of the earliest installed analogue detectors with intelligent detector, which would ensure economical operation of the system and replacement parts supply for another 25 years.

Currently, radiation portal monitors at the border have a technology that is capable of detecting gamma and neutron radiation but is unable to separate gamma and neutron radiation alarms. This separation functionality is beneficial for border control or roadside mobile control station, as neutron radiation can indicate the presence of nuclear material. Today, there is a solution that makes it possible to separate the types of radiation.

Isotope identification capability is a growing user demand in the field of radiation measurement and is expected to be implemented in the radiation portal monitors.

Radiation portal monitors installed at border crossing points can be equipped with intelligent probes which could be used for isotope identification for gamma. Video surveillance systems can be attached to the radiation portal monitor systems, which can be used to store visual information before, during and after an alarm event.

By default, the radiation portal monitors at the border have only local alarm and display. The remote management function is useful for operating the system in a large number of large areas in a coordinated manner. With a few well-trained staff and a complex border control system hundreds of RPMs can be operated economically.

The Hungarian National Radiation Monitoring, Signaling and Control System (called: OSJER) continuously measures background gamma radiation values at more than hundreds of locations in the country. The system is continually being upgraded, but there are no OSJER-based sensors at the Hungarian borders, so any radiation contamination from neighbouring countries is only detected late, well within the Hungarian borders. The radiation portal monitors can also be expanded with detectors used in the OSJER system [14].

3.6.1. Enhancing the capability of the physical protection system for radioactive sources with radiation portal monitors

After investigating all possible use of radiation portal monitors, I developed a method using a radiation portal monitor algorithm, which can enhance the capability of the physical protection systems.

In most of the countries, the radiation protection rules are declared by a governmental regulation [42], and some various recommendations form international organisations and standards help to establish an effective radiation protection system [66].

In addition to managing radiation protection risks, the physical protection of radioactive sources must also be ensured. This issue must be addressed so that dangerous objects do not fall into the wrong hands. The physical defence system must prevent terrorists from creating a dirty bomb, for example, by assembling a stolen radioactive source and explosives. In the field of physical protection, there are also official regulations that must be applied to the protection of radioactive sources [43]. In order to meet these requirements, an appropriate physical protection system must be built. Electronic safety devices allow us to monitor and control the environment of radioactive sources. However, high activity radioactive sources cannot be installed next to electronic devices because the components are unable to withstand the destructive effects of ionizing radiation for a long time. Radioactive sources are stored either in lead-shielded containers or in underground shafts in unique buildings designed for this purpose.

I am looking for a solution to detect the presence of a radioactive source without a direct visual view on the source. I assume that the radiation coming out of the radioactive source passes through the wall of the container to a reduced extent and with a radiation measuring detector it can be deduced from the change of the radiation whether the given radioactive source is in place or its position has changed.

I realised that the radiation portal monitor algorithm (finding significant changes in background radiation) with a small modification (only slow changes in radiation level and only specific measuring ranges causing alarms) can be used for supervising radioactive sources. The situation is aggravated by the fact that the radioactive source is moved generally in most applications, i.e. the level of radiation changes. In an irradiation device, the radioactive source is lifted out of the storage position by automation and set to the irradiation position, i.e. the radiation can leave the device freely only in a given direction.

The Figure 31 shows an image of such an irradiator device. After irradiation, the radioactive source is returned to the storage position. Some irradiators handle multiple radioactive sources to create different dose ranges. The sources in the irradiator are used for calibration of detectors.

Figure 31. Irradiator with multiple source positions.
Source: [3]

Most irradiators use so-called gamma relays for radiation protection purposes. The purpose of these radiation measuring devices is to give a light signal during irradiation, when the radiation rises above a certain level, to warn the occupants that a hazardous activity is taking place in the room, or if it detects a level higher than the level expected during normal irradiation. The gamma relay also serves the purpose of not allowing the operating personnel into the room if the source has not been successfully replaced and the source is still free.

Figure 32. shows the operating ranges of a typical gamma relay and a series of measurements taken during irradiation. The radioactive source is located in the storage position at the beginning of the measurement, so the system is in the default state (Figure 32.: green range). By starting the irradiation, the gamma relay detects that the radiation level has risen, so it changes state and informs the operating staff that the radioactive source is in use. In this mode, it is forbidden to enter the irradiation room (Figure 32.: yellow range). After irradiation, the measured value returns to the initial range, the gamma relay returns to the primary state, the room can be entered.

During the irradiation period shown in Figure 32, the radiation level did not rise in the alarm range, so the system did not issue an emergency alarm. The gamma relay, on the other hand, did not notice that the radiation level had decreased at 17:14 minutes after irradiation, which could also mean that the radioactive source had been removed.

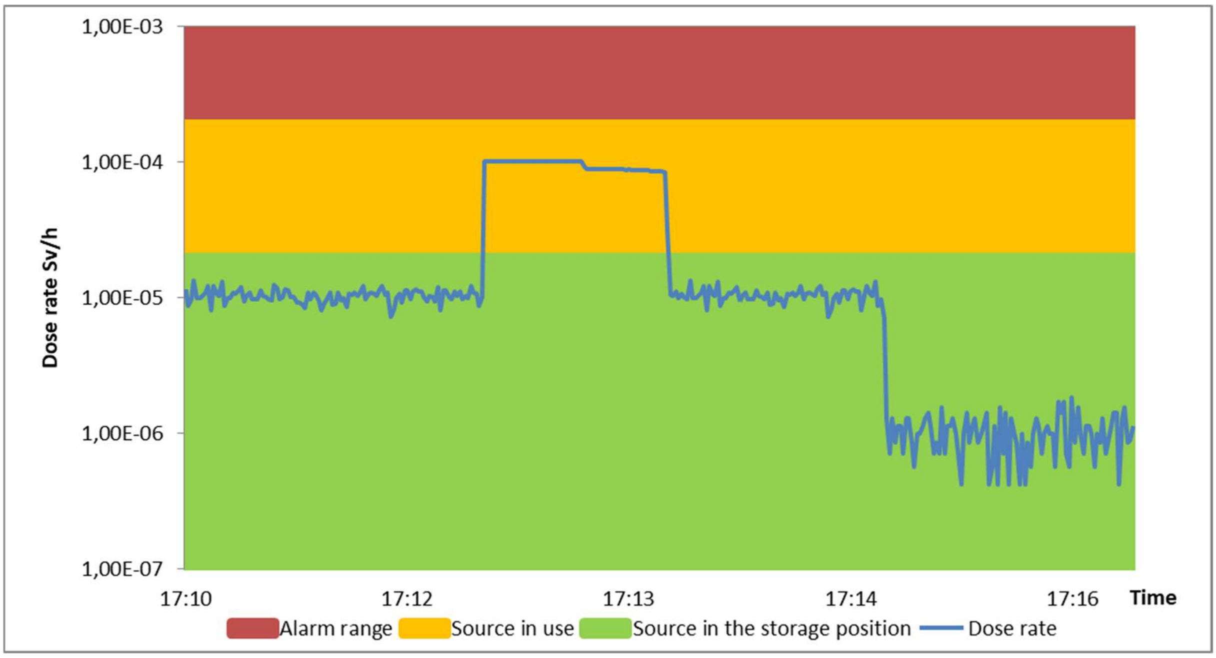


Figure 32. Gamma relay operation during irradiation.
Source: compiled by the author

3.6.2. Measuring assembly for enhancing physical protection system

In order to detect the movement of the radioactive source, the radiation detector must be placed in a location where the radiation emitted by the radioactive source can still be measured. However, the intensity of the radiation is not such that radiation can damage the detector electronics during prolonged use. The optimal location is the point where the radioactive source generates 2-3 times the background radiation at the place of the detector. The measurement level corresponding to the storage position of the radioactive source can be well distinguished from the background radiation.

When placing the detector, care must also be taken to ensure that the radiation measuring detector is not exposed to an unreasonably high dose during irradiation. Repeated exposure to high doses can shorten the life of the detector. The measuring range can be optimized by changing the distance between the radioactive source and the detector.

If the measuring range cannot be set economically with the distance (there is not enough free space in the room), a radiation shield (e.g. lead bricks) can also be placed between the detector and the radioactive source. In order to prevent the measurement from being affected by scattered radiation originated from the target or by other radioactive sources transported in the irradiator room, it is advisable to install the detector collimating behind the irradiation device in the direction of the radioactive source. For the measuring system to function correctly, the normal operating conditions of the system must be finite, i.e. the radioactive source must be in certain positions permanently during the entire irradiation process. If this condition is met, the radiation levels measured by the detector for the given irradiation and storage conditions will fluctuate around discrete values. Figure 33.: illustrates a schematic diagram of an irradiation room where an object is exposed to irradiation while a radiation meter monitors the operation of the system.

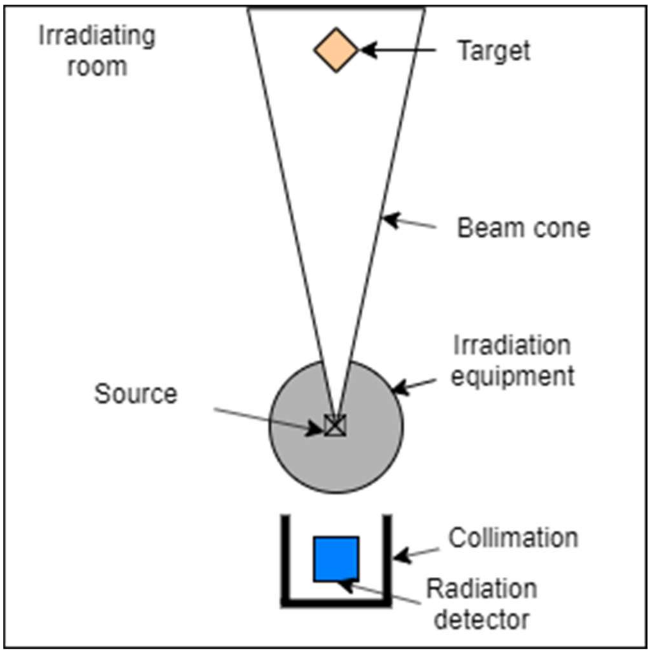


Figure 33. Placing a radiation detector in an irradiator.
Source: compiled by the author

The theoretical background of the operating algorithm

The algorithm that can be integrated into the detector implements the operation of the previously mentioned gamma relay. It indicates the use of the radioactive source and immediately alarms if the radiation level rises above the alarm level. The additional capability implemented in the algorithm generates an alarm when the source is moved into a not normal position (someone tries to steal it). When installing the system, all normal operating conditions must be established with the irradiator so that the intelligent radiation detector can record the radiation levels belongs to each operating condition. The algorithm will then examine deviations from these normal operating levels. The permissible deviation is adjustable (default setting: ± 20% of the normal operating level). Normal operating levels measured by the detector may change over time from initial levels. The accuracy of the detector can deteriorate over time - the accuracy can be kept at the acceptable level by regular calibration and verification - on the other hand, the activity of the radioactive source changes with the time according to the half-life of the isotope and will cause an error. An intelligent detector may be able to compensate for the effect of half-life based on Formula 7.

Formula 7. $\mathbf{X_t = X_0 * e^{-\lambda t}}$

where:

X_t: counts at "t" time,

X_0: counts at start time,

t: Time elapsed since the start time [s].,

λ: Isotope-specific decay constant [1/s]..

The characteristics of isotope in the irradiator must be specified for the algorithm to compensate for the half-life effect. An incorrectly specified isotope type can cause a significant error, as the half-life may vary depending on the isotope type. If several different types of radioactive sources are monitored, the half-life effect must be compensated per isotope. Separation of the counts belonging to each radioactive source is only possible using an energy selective detector.

By default, the detector measures the irradiator, in storage positions in constant half-second cycles. The algorithm checks how accurate the current measured value is.

It compares with the previously measured values and determines the standard deviation based on Formula 8.

Formula 8. $$\boldsymbol{\sigma} = \sqrt{\frac{\sum_{i=1}^{n}(X_i - M)}{n-1}}$$

where:

σ: Deviation,

n: Number of measurement results taken into account (default setting: 10),

X_i: The number of counts associated with the measurement [count],

M: The average of all measurements taken into account [count].

If the standard deviation falls below a certain level (default setting: 15%), the algorithm considers the measurement to be stable. In the stable state, the detector checks that the measured average value is within the allowable normal operating range. Slip in the measured value, either down or up from the range, indicates that the irradiator is in abnormal operation condition. The discrepancy may be caused by the source being removed from the irradiator, or the source being stuck in an intermediate state, or the detector may measure incorrectly. Figure 34. illustrates that the system generates an alarm event if it detects that the measured value has stabilized in a range where no normal operating range has previously been entered into the system.

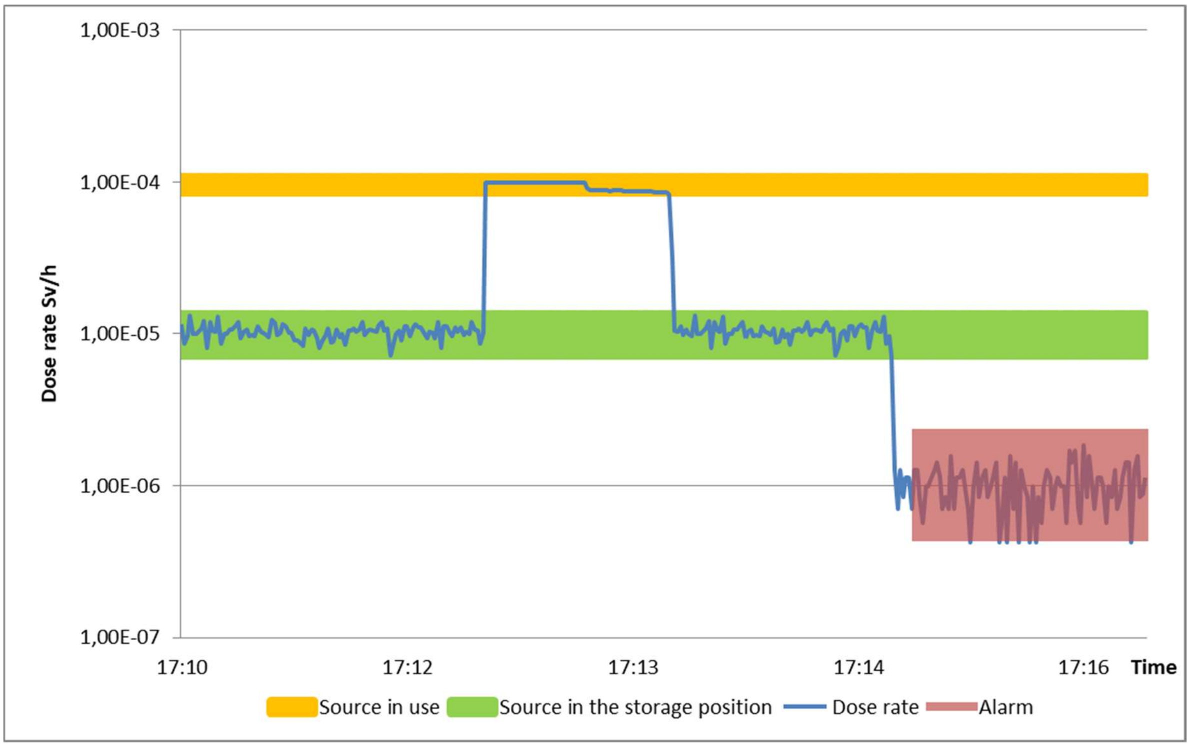


Figure 34. Intelligent detector operation.
Source: compiled by the author

During the measurement shown in Figure 34, the device produced dose-rate values. The operation of the algorithm cannot be too fast, as the detector will measure out-of-range values while the source is moved from one normal operation position to another, which cannot be considered an alarm event. To identify such acceptable out-of-range measured values, the intelligent detector starts a countdown timer and checks that the measured value returning in normal operation range before the timer run out. The algorithm should detect any significant change in the measured value.

The countdown timer must be set so that it does not run out until the irradiator change from one normal operating state to another. As long as the timer is running, the detector does not emit alarm signals. If the timer run out and the system is unable to return to a stable state, it will cause an alarm. Short-term changes may result from other radioactive sources moving near the detector. The system must ensure that maintenance work can be carried out on the irradiator. For such situations, the user must predefine a period of time until the detector can overset alarm level values. In maintenance mode, there will be no alarm signals, but all events are recorded in the detector log, just as it will be in the log that someone has put the detector into maintenance mode. Such user intervention can only remain in effect for a certain period of time, the system will return to its original operating state after the set time frame has elapsed.

3.6.3. Possible further developments of radiation surveillance system

Changes in radiation levels are just one parameter that such a protection system can monitor. Additional logic can be developed in addition to the data from other sensors built into the irradiator. E.g.: an examination of radiation quality could improve the system. Performing continuous isotope identification with a scintillation detector can generate an event if a new isotope appears or just disappears in addition to the predefined isotopes. Such a system can also be used to monitor storage facilities where different radioactive sources are handled. Figure 35. shows an intelligent detector in which unique algorithms can be implemented in the embedded microprocessor, this detector capable of isotope identification for gamma radiation isotopes, thereby providing additional information to a complex decision support system.

In addition to the radiation detector, it can also be used with movement and tamper sensors, as well as GPS positioning technology, to track and control radioactive shipments.

The measurement system, equipped with data storage and data transmission functions, would make it possible to create a similar unite like a black box used on aircraft, allowing authorities to reconstruct events based on objective data.

Figure 35. RadNDI scintillation radiation detector which is capable of isotope identification from gamma spectrum.
Source: [3]

With the help of a data modem, data can be sent into a data center providing information to an early warning system [47], or to a mobile laboratory [56]. The construction of several radiation measuring detectors around the radioactive source allows the accurate observation of the spatial displacement of the radioactive source, the detection of the damage of the protective structure. The multi-detector solution is useful in storages where there are many radioactive sources next to each other, such as radioactive waste repositories.

Artificial intelligence can analyse the incoming raw data to increase the level of security, as ever-changing measurement parameters can hide additional information that a self-learning system can easily recognize and alert the user at suspicious trends.

3.7. Conclusions about radiation portal monitor systems and methodology for enhancing sources physical protection

In this chapter, I investigated the radiation portal monitors itself and an application which is based on the radiation portal monitors algorithm and can improve physical protection. Several factors influence the operation of a radiation portal monitor, which can, in many cases, determine whether or not it can detect a hidden radioactive source.

- The first factor is the size of the detector. Scintillation detectors are the most suitable in this field, but different sizes can be used according to the task. The size of the scintillator will increase the sensitivity, but also increase the price, and the background noise. The resolution of the scintillator detector will drastically reduce by the increase of the crystal size. The optimal size for this application is a 50 mm diameter and 150 mm height NaI(Tl) scintillator.

- The second factor is distance. The closer the detector is to the target/person being tested, the higher the amount of radiation reaches the detector. Detector units should be located as close as possible to the traffic corridor/road, but not yet obstructing traffic. For practical reasons, detector units should be installed on the pavement right next to the roadway, with adequate physical protection. If possible, a detector unit should be placed above the vehicle traffic, because usually, the thinness walls are at the top of the vehicle body.
- The third factor is the test height. Detector units may have different sensitivities at a given height. The opening cut out on the detector collimator defines the test angle, which is typically conical. The test height range for a passenger vehicle is significantly less than for a truck, train or bus. Choosing the correct installation height for the detector, or installing multiple detectors on top of each other improves the effectiveness of target/person control.
- The fourth factor is the speed of passage when using radiation portal monitor. The faster the subject, object, or vehicle passes through the gate, the less time is available to make a measurement and make a decision, so the speed of passage should be limited when entering into the RPM. For most RPM systems, the optimum passage speed is below 5 km/h.

In addition to fixed gates, there are mobile, onboard, and even handheld variants. Handheld versions are useful when the target subject/person is unable to pass through the RPM. Handheld and mobile radiation portal monitors can also be used to test the effectiveness of a temporary decontamination system.

I examined the currently available radiation monitoring systems and developed an additional algorithm that allows radiation measuring detectors to support physical protection systems. Radiation portal monitor algorithm can be modified to identify abnormal radiation levels at irradiators. To achieve this the radiation portal monitor algorithm (finding significant changes in background radiation) should be changed only slow changes in radiation level and only specific measuring ranges causing alarms. Normal operation measuring ranges should be determined before use of the system to restart the background measurement when the source arrives at there normal position.

4. RECONNAISSANCE METHODS AND MEASUREMENT ASSEMBLIES FOR FINDING AND ANALYSING RADIOACTIVE SOURCES

At first, glance, searching for radioactive sources may seem like a straightforward task, but finding the right technology for effective searching could be difficult. On several mobile laboratory exercises, there were tasks to find hidden radioactive sources [67]. Before the actual measurement, the organizers placed various radioactive point type sources on a field so that they could not be seen by the naked eye. To complete the task, participants searched using their detectors and according to their methodology. Some of the search units were unable to find all the sources. While many could only complete the task with hours of exploration. Most of the problems were faced by teams equipped with only handheld dose-rate measuring devices.

In order to find the appropriate detection method, it is necessary to determine what type of radiation can be searched and what tools and associated methodologies are available. Then it is needed to look at how to improve the search efficiency. Finally, the chosen optimized method must be validated to see if it gives better results than other methods.

4.1. Possible radiation during a reconnaissance

Radioactive sources can emit various types of radiation, including alpha, beta, gamma and neutron. In order for a measuring device to be able to detect ionizing radiation, the radiation must reach the detector built into the measuring device. The radiation causes some kind of physical change in the detector. The change is converted into an electrical signal and can be measured by the measuring device.

Alpha radiation is hardly detectable in the field with a handheld detector because alpha radiation has the highest linear energy transfer (LET) factor compared to other types of radiation, which can be absorbed up to a few millimetres in the air or on a sheet of paper. If the task is to detect alpha radiation, the detector should be located as close to the source as possible, and a detector wall should be thin enough, not be an obstacle for alpha particles.

Detecting beta radiation is no easier task either, as the beta radiation can be absorbed in a thin layer of plexiglass or even in the air. Therefore, during on-foot reconnaissance with a handheld detector held at 1-meter height, will only be able to measure beta radiation with reduced efficiency. If it is needed to look for a beta source, a thin-walled detector should be used mounted on the end of a long rod, which will reduce the distance to the target area.

Detecting gamma radiation is a more straightforward task because gamma radiation can be measured farther (several meters) away from the radioactive source. After all, it can easily penetrate the air or the thicker cover of a detector. Neutron (mainly fast) radiation is also easily detectable, but the occurrence of such sources is much less frequent than gamma radiation. It can be stated that performing the on-foot radiation reconnaissance task is primarily means the detection of gamma radiation.

Radiation measuring detectors for on-foot reconnaissance

In most cases, a measuring device for the determination of gamma dose-rate is equipped with a gas-filled sensor. A gas-filled sensor can be a GM tube, a proportional tube or an ionization chamber. These sensors are well-suited for dose rate determination since they have nearly the same sensitivity in all directions. This directional independence makes gas-filled sensors challenging to use to search for a radioactive source, and their sensitivity is significantly lower than the sensitivity of scintillation crystals. Scintillation crystals convert ionizing radiation into light, which is proportional to the intensity of the radiation and even contains information about the energy of the radiation.

If a gas-filled dose rate detector is carried around a point source in a circle, the measured value is expected to be approximately the same throughout the circle. The reason for this phenomenon is that gamma photons are expected to leave the source in all directions with the same probability, and the detector will register impacting particles with the same sensitivity from all directions.

Theoretically, if the measuring device moves in the right direction towards the radioactive source, the measured value increases, as it moves away, it decreases. However, in practice, the measured values can change in the opposite direction. This phenomenon is explained by the fact that the background radiation can fluctuate significantly over a short period (a few seconds). This can happen only if low-intensity radiation is present with a high background radiation level or the source is at a large distance from the detector. In Hungary, dose rate readings in most areas can take any value from 50 nSv/h to 150 nSv/h in the next second.

Therefore, in a search process, determining the "good direction" from measured value can work, if the measured dose-rate at the sensor caused by the radioactive source differs significantly from background fluctuation. An algorithm should be implemented in the measuring device to detect small activities, which indicates if there is a significant increase in the readings. The detector must perform dynamic background compensation. It must take into account the radiation values previously measured and examine any deviations from there [68].

The point of the algorithm is that if the instantaneous measured value is near to the background radiation, the new instantaneous value updates the moving average value associated with the background radiation, which follows the fluctuations of the background radiation. If the new instant value is outside the background range, the algorithm examines the difference from the moving average of the background radiation using Formula 9.

Formula 9. $\mathbf{n_i > n_a + S_1 * \sqrt{n_i}}$

where:

n_i: The current new instantaneous value,

n_a: The background radiation moving average value,

S_1: The sigma multiplier, which determines how sensitive the detector is and thus, the false alarm rate. The more sensitive the detector is, the higher the false alarm rate will be. Default value for S_1 is 4.6.

The measurement is further complicated by the fact that each device has a delay due to the time it takes for the electronics to measure the radiation and then show it on display. In the meantime, the user can move so that the measuring device is no longer at the location, where the higher reading was displayed. This error can be eliminated by not proceeding until at least one measurement cycle has been completed. The delay time may vary from detector to detector. For search detectors, it may take 0.5-2 seconds to display the next measured value.

The minimum detectable activity (MDA) calculation can be a subject of further research. The problem with MDA calculation is that the physical geometry of the measurement place and the speed of the detector is changing during the measurement. [69].

4.2. Investigation of search methods

I have investigated several search methods in order to compare the different radioactive source search methods and find the most suitable one.

All of the methods I investigated are functional, and they can be used to find radioactive sources, so I primarily checked how quickly and effectively they lead to results.

The methods listed here are only applicable if the detector readings change significantly after a few steps compared to the background radiation.

The first method is called "pendulum" (Figure 36.) because it consists of back and forth movements.

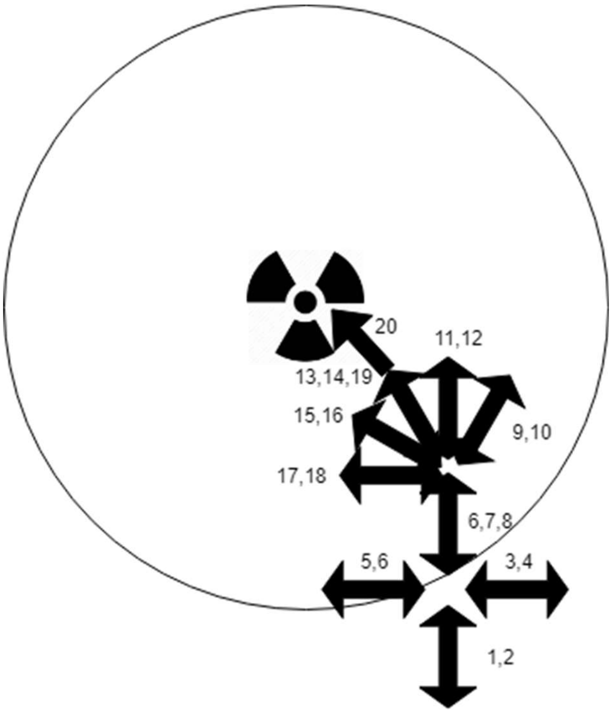


Figure 36. Searching for a radioactive source using the "pendulum" method.
Source: compiled by the author

For the first series of actions, measurements shall be made at a distance of 1 step (approximately 1 meter) from the starting point to each of the four cardinal directions (north, east, south, and west). The largest of the four measurement results shall be selected, and one step in this cardinal direction shall be taken from the starting point, and further measurements shall be made. Once the main direction has been determined, it is sufficient to follow the steps only in the spatial angle to the main direction, so smaller turns (about 30 degrees) should be made. With this method, the direction of travel to the radioactive source becomes more accurate after each series of measurements. The disadvantage of this method is that it often has to take measurements in the wrong direction, which is a waste of time, and if the search method goes over the source without realizing the source itself, it can easily lead the search into the wrong direction.

I called the second method a "spiral"(Figure 37.) because, with this method, the scout moves forward until it measures more significant than the previous only changes direction if the measured value decreases.

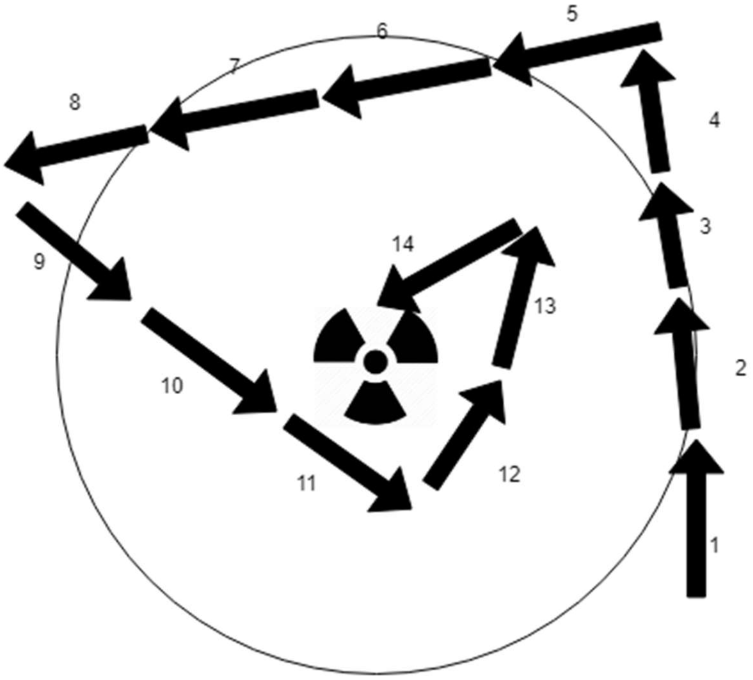


Figure 37. Searching for a radioactive source using the "spiral" method.
Source: compiled by the author

If the displayed value increased, the scout went in the right direction, if it decreased must change direction. If the direction change cause decrease of the measured value, the direction change was not in the right direction, the scout should turn around. This method can lead to success in a reasonable amount of time but is not very useful since even with the right direction, many unnecessary distances have to be covered and many additional measurements can only achieve the target. Not to mention that the presence of a possible second source completely upsets the search.

The third method is called the "matrix" (Figure 38.) because regardless of the measured value, measurements have to be made at a fixed distance, the search area is divided into a square grid, one must be measured at each node.

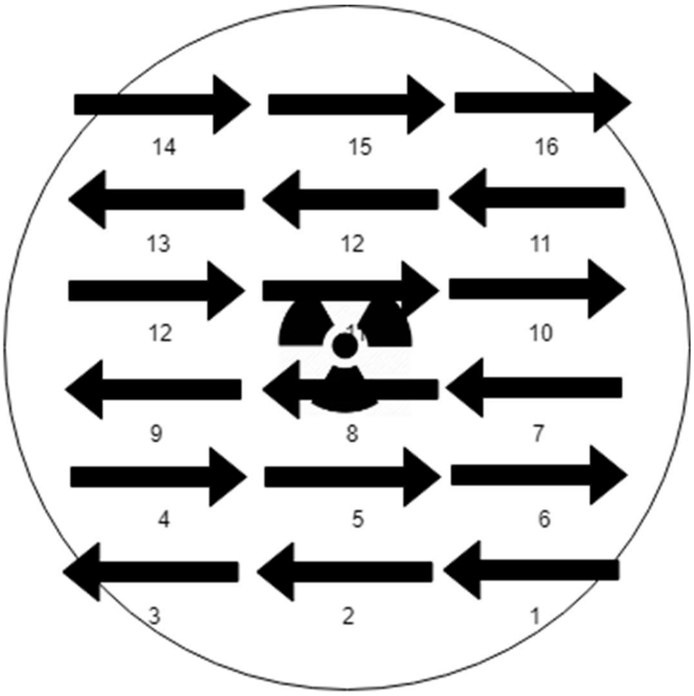


Figure 38. Searching for a radioactive source using the "matrix" method.
Source: compiled by the author

The source is searched after the results have been evaluated. The advantages of this method are that the search can be reproduced well, tasks can be divided, this method is also used in international recommendations [70]. This method can be well-automated and comfortable can be executed with the help of a robot or helicopter [45]. The main problem with the "matrix" method is that if there is a long distance between two measuring points or the area under investigation is inaccurate, a source of radiation may not be noticed. Besides, it is the slowest of the methods I have studied. The determination of the searching area and the distance between two measurements is a challenging task. To short steps or too large seírching area, could cause additional unnecessary measurement activites.

The fourth method is called "rotation" (Figure 39.). This procedure requires a direction-dependent detector, which allows it to determine the direction from which the highest intensity of radiation comes from during a rotation.

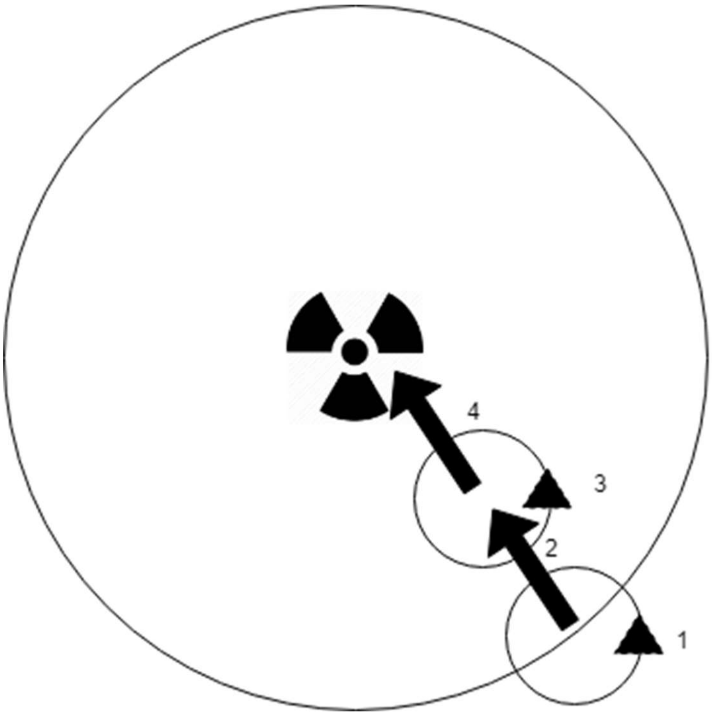


Figure 39. Searching for a radioactive source using the "rotation" method. Source: compiled by the author

The great advantage of the "rotation" method is that you can immediately move in the right direction in a few steps, and you can determine the directions of several radioactive sources in a single rotation. For this method, a collimator is required to provide directional dependence, which prevents the detector from being sensitive to lateral radiation. The disadvantage of this method is the collimator; it can significantly increase the weight of the detector, which can be a severe problem for a handheld detector. The collimator can be made from high-density materials, like lead or tungsten.

I prefer the "rotate" method for searching for radioactive sources because the effectiveness of the method is the highest. Due to the direction dependence, several measurements are required in one position. However, the time need for one measurement is not exceeded half a second, while no movement needed between two measurements. The best results were obtained with a detector collimated in 60 degrees from the central axis. After choosing the right direction, the movement is made only in the right direction with minor corrections. The effectiveness of this method was validated by checking the result of a mobile laboratory exercise. The result shows that the "rotate" method used to found all sources with fewer measurement points, such as the "matrix" search method. The results of different search methods can be seen in Figure 40. In the figure, purple triangles show the location of hidden sources.

Each coloured dot represents the measurement results performed by a team participating in this exercise. I participated in this exercise and the purple “GAMMA” dots were the measurements points of my team.

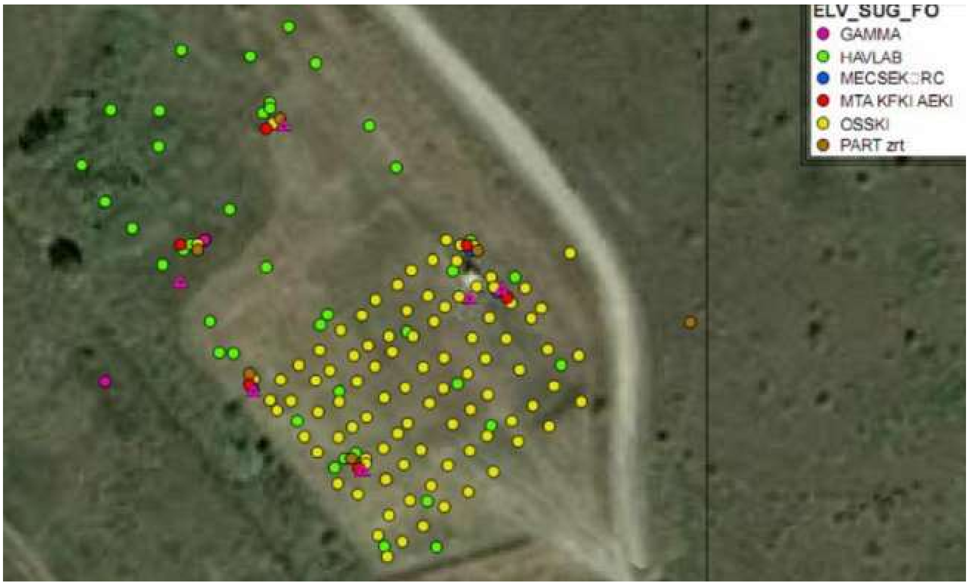


Figure 40. Radioactive source search results at Püspökszilágyi mobile lab exercise. Source: [67].

Detector direction dependence

I have investigated three solutions to implement direction dependence. In the first directional detector assembly, instead of a lead collimator ring, a lead plate was inserted between 2 scintillators which were connected to electronics. The signals from the CsI(Tl) and NaI(Tl) scintillators were separated by the electronics to determine which spatial angle the radiation came. The use of two different types of scintillation crystals seemed advantageous because by separating the signals, a single detector can be used to determine from which direction the radiation is coming. The structure of the detector and the result measured from different directions are shown in Figure 41. In this case, the irradiation was performed from three directions with a Co-60 source. When irradiation was performed in parallel with the lead plate, nearly the same count number was measured from the two scintillators. The slightly higher count number from the NaI(Tl) crystal is due to the fact that the efficiency of the NaI(Tl) scintillator is better than the efficiency of the CsI(Tl) scintillator. When irradiation was perpendicular to the lead plate, a count number reduced by the lead plate attenuation factor was measured from the scintillator behind the plate. The idea was to compensate the NaI(Tl) counts by the NaI(Tl)->CsI(Tl) efficiency factor under parallel irradiation to bring the initial measured count similar for both scintillators.

If the count number from the CsI(Tl) scintillator is higher then the count number from the NaI(Tl) scintillator, the irradiation is coming from the left. If the count number from the NaI(Tl) scintillator is higher then the count number from the CsI(Tl) scintillator, the irradiation is coming from the right.

With this solution, the weight of the detector was significantly reduced, and the detector was able to indicate in which direction (right or left) it would be useful to continue searching without turning.

Unfortunately, the result of the experiment gave false directional signals in several cases due to the different light output of the two scintillators. The different temperature dependence of CsI(Tl) and NaI(Tl) scintillation crystals also caused an error in this measurement assembly.

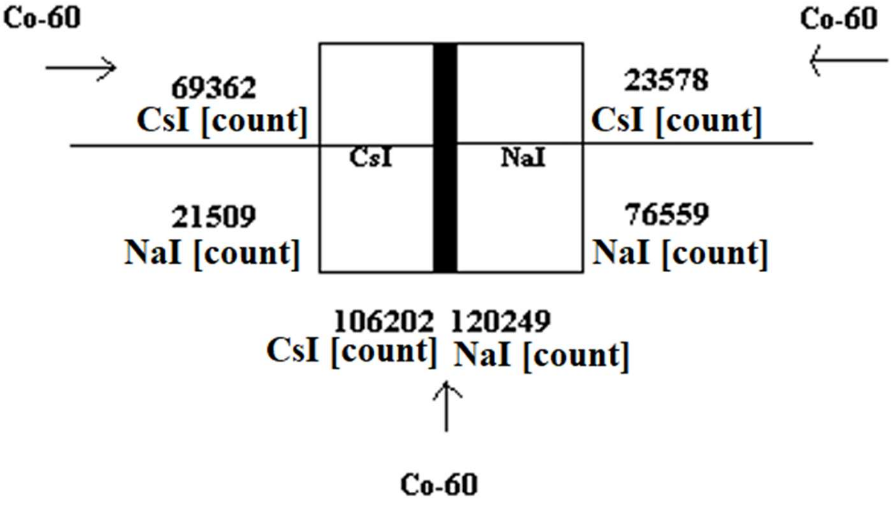


Figure 41. Directional detector with two scintillators.
Source: compiled by the author

In the second direction-dependent detector assembly, a lead disk was placed in front of the NaI(Tl) scintillator to achieve a significant reduction in the measured value toward the radioactive source. Unfortunately, due to the scattered radiation, this solution failed.

The third direction-dependent detector assembly with a lead collimator ring produced the best results. The search procedure was tested using a Co-60 source. The detector is only indicated when the open portion of the collimator on the detector is facing the radioactive source during rotation. Multiple measured values confirm that this detector responds to the source at a sufficient rate (0.5-second delay) in the correct direction. The test results can be seen in Figure 42. In the figure, the direction of rotation is shown on the right-hand axis in the range of 0..360°.

I used 0° when the detector facing the back of the source and 180° when facing the detector to the source. A pink line shows that the detector starts the movement at 75° and turns at equal speeds until arriving at 240°. The left-hand axis belongs to the measured counts by the detector. The blue line shows that significant measurement values are measured in the direction of 180°. The green line indicates is a threshold level if the measured value is above this line, the detector indicates that it facing the correct directing.

The "rotation" method requires carrying the most extra weight, but it has better search efficiency than the other two methods [71].

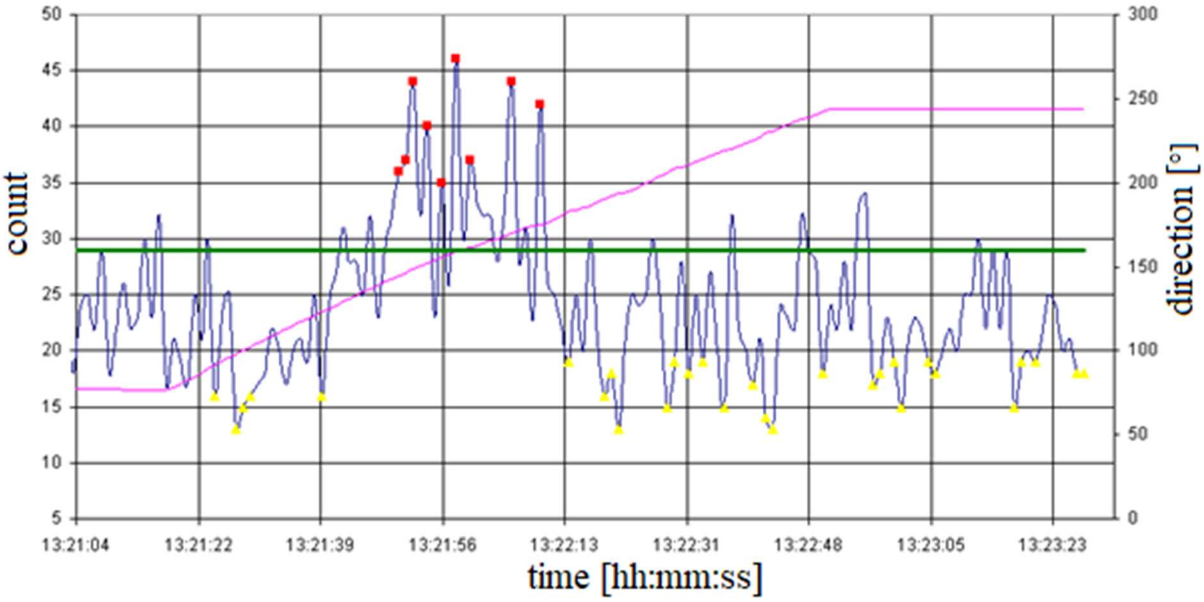


Figure 42. Co-60 source search time chart.
Source: compiled by the author

4.3. In-situ, rapid inspection methods for radioactive material transportation

The purpose of this chapter is to find out whether the capabilities of officials responsible for controlling radioactive transport can be improved. International standards recommend checking transports with radiation detectors. The IAEA suggests using a handheld detector that should be held against the surface of the package to measure the dose rate [72].

The regulation in the EU for Dangerous Goods by Road (ADR) gives a maximum radiation limit of 10 mSv/h at any point of the package and categorizes the packages according to measured dose rate at the surface and 1-meter distance from the package [23]. All international regulations aim to have a reasonably acceptable level of radiation level for the personnel involved in transportation. All these levels are calculated back to the personal and collective dose limits of the current regulation. There is no intention in these regulations to question the veracity of the information declared by the supplier. Although an incorrectly categorized shipment can cause severe environmental damage, nuclear accident or unnecessary radiation exposure [73], [74].

4.4. Basic inspection method

Radioactive material transportation requires much documentation. In these documentations, there are some parameters, which could be the input data of an inspection. Some parameters can be checked easily without any measuring detectors, and there are measured parameters to validate the theoretically stated values and category levels.

The first step of a necessary inspection is to collect all the available data from the documentation. The second step is to check if there is any contradiction. Knowing all category levels and comparing them with the available data needs time and experience. In order to make the inspection quicker and easier, a demo application called Radiation Inspector was created. The officer has to type the data into the mobile software, and the application will make the comparison.

The following information should be available in the documentation to conduct a necessary inspection: Type of the radionuclide, the activity of the source, the date when the activity measurement was conducted or calculated, the dimension of the package (height, weight, and diameter of the container), shielding wall thickness, the material of the shielding, transport index, criticality safety index, category according to ADR rules.

After filling out a form in the mobile application, the data is stored and analysed. With the help of compares and calculation algorithm, the following potential issues can be filtered out:

- Shipment documentation contains higher activity as the allowed limits.
- The package is not categorized correctly according to ADR rules [23].
- Stated parameters contradict each other, e.g., The volume of the container calculated from the dimension is different from the volume calculated from the weight.

Comparing data with limits is an easy task, there is no need for further explanation, but finding contradiction related to the stated source activity is more challenging. The source with the stated activity should generate a theoretical dose rate at a specified distance in the air, which is reduced by the shielding effect of the container. Formula 10. shows that the theoretical dose rate can be calculated from the activity [75].

Formula 10. $$\mathbf{Dr = 5,77 * 10^{-4} * \frac{A}{4\pi d^2} \sum_i^n E_i P_i \left(\frac{\mu}{\rho}\right) B_i e^{-\mu x}}$$

where:

Dr: theoretical dose rate [μSv/h],

A: activity of the source [Bq],

d: distance between the source and virtual detector [m],

E: gamma emission energy [MeV],

P: emission probability per disintegration respectively,

μ/ρ: mass absorption coefficient for tissue [cm^2/g],

x: shield thickness [cm],

μ: linear attenuation coefficient for shielding[cm^2/g],

B_i: build-up factor.

Particular parameters, like the build-up factor, are properties of the shielding material. To determine the theoretical dose rate some parameters (isotope type, shielding thickness, distances) can be measured other necessary static parameters (mass absorption coefficient, gamma emission energy) available in standards and databases [76].

The theoretical dose rate can be checked by a real dose rate meter. If the measured value is in the same range as the theoretical dose rate, the validity of the activity stated in the transportation documentation is correct. For this measurement, the most suitable detector is a certified dose rate meter which has a wide measuring range in energy and dose rate and can be connected to a data collector that can collect other parameters as well. I used the RadGM dose rate transmitter for this measurement, which has the energy range of 50 keV - 3 MeV and the dose rate range of 30 nSv/h … 10 Sv/h. The RS-485 interface and the compact size makes it ideal for this task.

If the activity is unknown, it should be determined from the dose rate measured without opening the package. Many issues could add error to this measurement. E.g., The error of the detector, the effect of other radioactive material. It is essential to establish a controlled environment for this measurement.

Another problem with this measurement is that usually some of the parameters are not available in the documentation or could be incorrect. E.g., the container parameters (wall thickness, material, etc…) are not mandatory to include.

Radioactive sources are transported in different packages, an example can be seen in Figure 43. High activity level sources are typically transported in cylindrical shape lead containers. The radiation leaving the source in every direction has to go through the lead shielding of the container. The intensity of the radiation is reduced according to the wall thickness of the container.

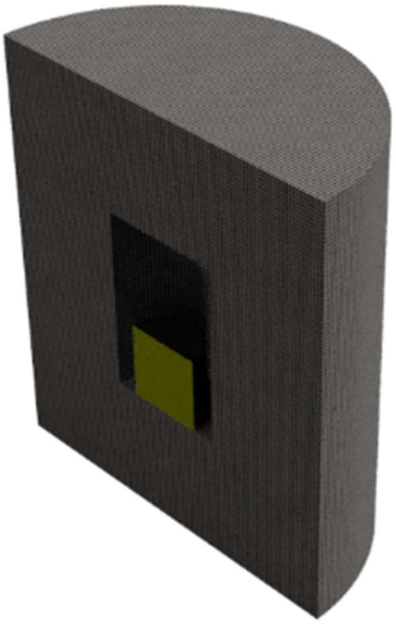


Figure 43. Schematic of a radioactive transport package
Source: compiled by the author

The wall thickness is an essential parameter because it needs to be used for the calculation of the dose rate. The thickness can be measured directly only by opening the container, which can cause unnecessary exposure to the conducting officer. On the other hand, it can be calculated solving the following equation (Formula 11.) using parameters, which can be measured outside of the container without any radiation exposure risk:

Formula 11. $$\mathbf{0 = -2x^3 + (4r + m)x^2 - (2r^2 + 2mr)x + mr^2 - (V_t - V_s)/\pi}$$

where:

x: shield thickness [m],

r: radius of the container [m],

m: height of the container [kg],

Vt: total cylinder volume of the full container calculated from the outer dimension [m^3],

Formula 12. $$\mathbf{V_t = m\pi r^2}$$

Vs: solid cylinder volume of a substantial lead container calculated from the weight of the container [m^3],

Formula 13. $$\mathbf{V_s = \frac{s}{\rho}}$$

s: the mass of the container [kg],
ρ: density in case of lead: 11,4 [kg/m^3].

The total cylinder volume and the substantial cylinder volume can be calculated from the transportation documents and from measured parameters made by standalone instruments like a scale or measuring tape. If the measured and stated data are not in the same range, further inspection is needed. The deviation between the two volumes can be explained by the different material of the container (non-lead), or there can be some other goods (e.g., illegal drug) placed next to the source. Standard containers are surrounded by steel. The default steel content used by the algorithm 10% of the full container weight.

4.5. Advanced inspection method

The advanced inspection method uses several different detectors. This method leaves out all parameters stated in the documentation and relies only on the actual measured data.

Currently, I tested this inspection method only with a cylindrical isotope container and with one source per container, without the effects of other nearby radioactive packages.

The container was placed on an automatically rotating platform (Figure 44., part 2.). The platform has a built-in scale (Figure 44., part 3.) to measure the mass of the container. A robotic arm (Figure 44., part 8.) was installed next to the rotating platform, which can move the sensors automatically next to the surface of the container. In this application, the robotic arm was used for two reasons. Firstly, the radiation level next to a container can be high. Thus human exposure can be avoided. Secondly, the container should be measured around at the same distance and with constant speed. Holding the dose rate meter by hand will add errors to the process, a robot does this task more accurately.

At the end of the robotic arm, a couple of sensor modules were installed. An ultrasonic distance sensor (Figure 44., part 7.) is responsible for measuring the height of the container.

The second distance sensor (Figure 44., part 6.) controls the robotic arm to move the sensor head as close to the container as possible, and after one turn it calculates the diameter of the container. A laser pointer module (Figure 44., part 5.) is also placed on the platform to see the actual point of interest in the container. A dose rate meter (Figure 44., part 4.) is used for registering the actual radiation level around the container. The detector should be calibrated according to the "IEC 61017:2016 Radiation protection instrumentation - Transportable, mobile or installed equipment to measure photon radiation for environmental monitoring standard" to reduce errors [48].

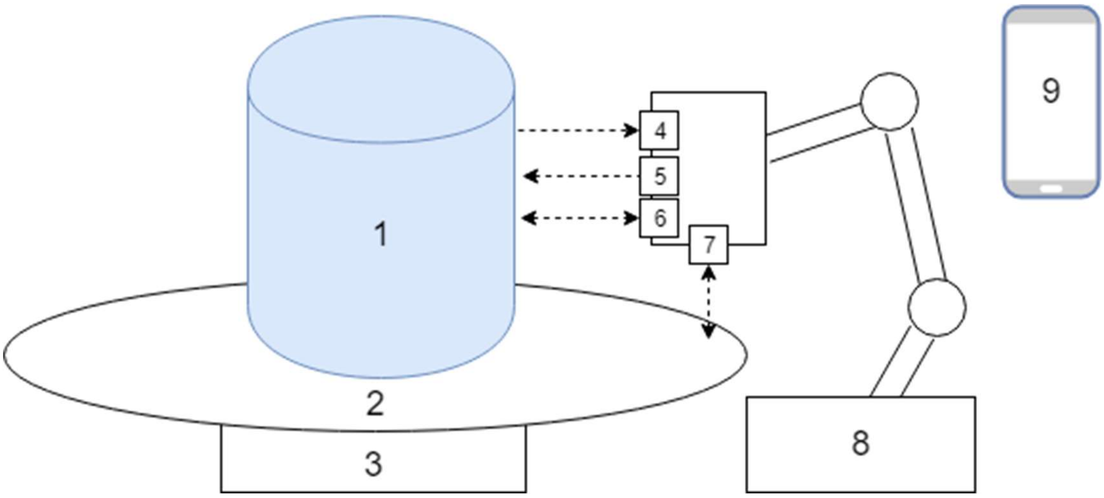


Figure 44. Schematic of an advanced radioactive package inspector system.
Source: compiled by the author

1. cylindrical isotope container
2. rotating platform
3. built-in scale
4. dose rate meter
5. laser pointer module
6, 7 distance sensors
8. robotic arm
9. mobile application

After starting a measurement, the detector follows these steps:

The robotic arm tries to navigate the dose rate meter as close to the surface of the cylindrical isotope container as possible. . The turntable starts rotating. After one round the arm will lift the detectors head.

The rotation and lifting process will continue until the top of the cylinder is reached. The whole surface of the container is scanned with this method. After analysing the data, the following information will be available:

The highest dose rate at the surface of the container. It can create an alarm event if it is higher than the ADR limit.

The shielding efficiency and consistency of the container. The primary purpose of the container is to reduce the radiation coming from the source inside of the container. The radiation can escape in all directions. If the wall of the container is not homogeneous, or the source is not in the correct position, the radiation will be higher at one specific spot. This hot spot can be the consequence of an air bubble in the lead created during manufacturing or a fracture of the container as the result of an earlier accident. Every container which suffered damage should be excluded from any transportation.

The diameter, height and the mass of the container. With all this information, the thickness of the shielding wall, activity of the source can be estimated. The estimated activity of the source. The calculated activity can be compared with the activity stated in the shipment documentation and the category of the shipment. The measured value will have errors because I designed as a rapid, onsite measurement, but significant differences between measured data and stated information can start further detailed investigation procedures.

Building the detector

I created a fully automated rotating platform. It is capable of doing a complex preprogrammed movement, set by the user with software or can be controlled by a robotic arm. I created a Windows PC setup software, written in C# language in Visual Studio 2017to set up the movements and give orders to the turntable. The device can work without a PC. It has three buttons, to do simple movements (rotate left/right and start/stop the program), but the full potential can be reached with the turntable control software. It can handle eight different programs. In one movement cycle can be customized the speed, direction, duration, and repetition. The duration can be a specific period or several steps, or it can rotate as long as it senses a magnet at the built-in hall sensor. If a magnet is placed in the right place on the table, when this magnet reaches the sensor, the rotation will stop. Every program type can be repeated as many times as it is needed.

Used components:

- Stepper Motor I chose a durable stepper with high torque, but it is still small enough to be hidden below the table. I made some test with weaker/smaller motors. The result was not good enough, because the table did not start turning. I tried to use a transmission drive, but with that, I lost speed and dynamics. This motor can handle 20 kg mass easily.
- AC/DC power supply OUT 24V 5A For choosing this module, it was essential to have 24 VDC output and at least 3 A. When it starts moving, I measured 2A peaks.
- SHF8 Shaft Support. This shaft support is strong enough to hold the whole table and the mass on it.
- TB6600 stepper motor driver can switch up to 4A. The built-in heatsink should be left free because, during operation, it could heat up.
- LM2596 DC-DC step-down power Supply module. This module reduces the 24DC to 5 DC for the microcontroller and the sensor. I choose this unit because it is a step-down switching power supply so it can do the transformation at high efficiency.
- Turntable, three buttons, a display unit, a processor module, a Hall effect sensor. This module is optional. I installed it because with that I was able to do precise movements.

Assembly

First, I assembled the turntable. I fixed the shaft support to the center of the upper plate. I fixed the servo to the lower plate with some adhesive. With one screw, the upper and the lower part can be attached.

The next step was the cabling for connecting the components according to the schematics. The custom made housing was designed for the electronics and the buttons and the display. After attaching the buttons and display to the front panel, the hardware was ready for software upload.

The code is simple. In the main loop it waits, until it gets an order from the serial port or a button is pressed. If it gets the start program order, it begins with the first movement and will continue until it arrives at the last movement, or the next movement is not enabled. One movement can end with a timer, or motor step counter or magnet sensor event.

After the embedded program is uploaded, the same serial port should be opened with the PC program (called: TurnTable controller) created for testing the unit. There is no installation needed to use this software. It can run directly from any Windows PC.

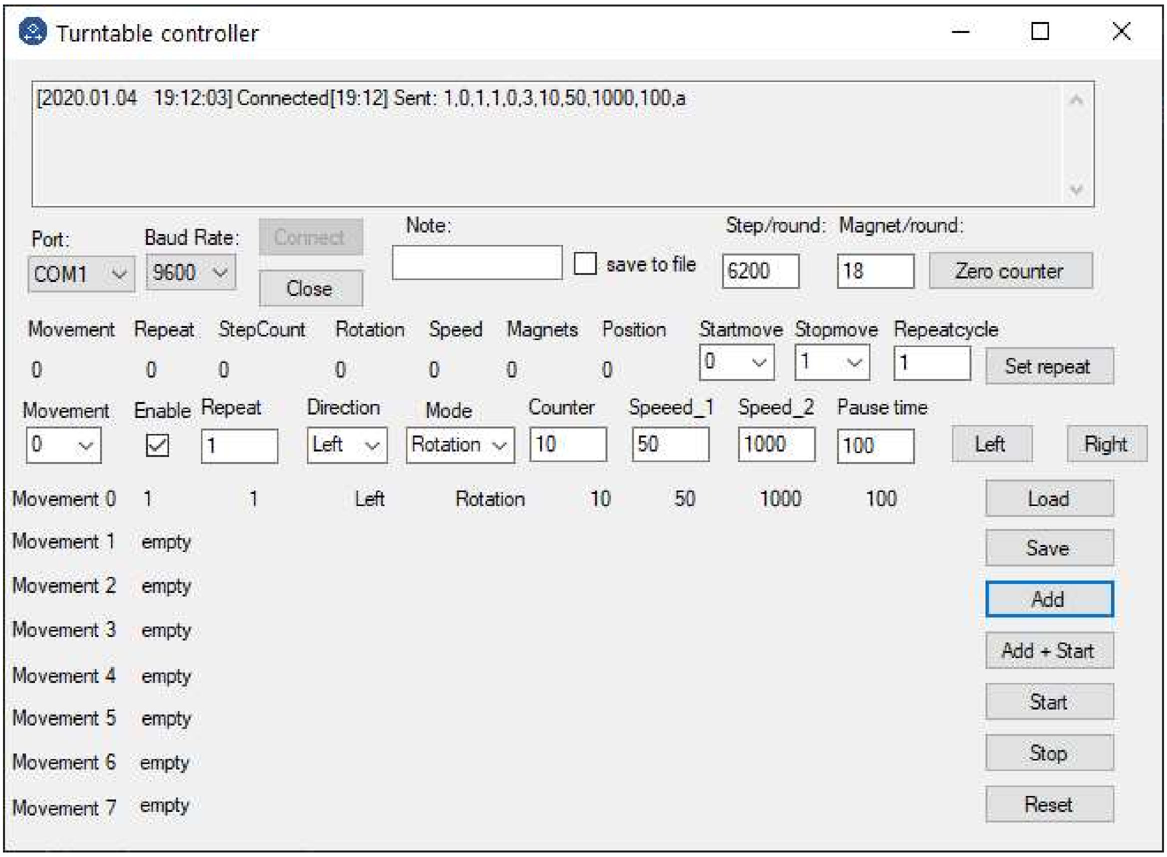
The following function was realized in the PC-s software, the screenshot of the software is shown in Figure 45.:

- Connect: It will open the PC serial communication port with the parameters set above this button. Only the port should be changed. Baud rate, parity, data bits, stop bits are set as in the processor.
- Close: It will close the PC serial communication port, and can change the port settings.
- Left, right buttons: are the same as a button press on the turntable, it just rotates the table with a few steps.
- Start button: before pressing this button, the configuration should be done. When this button is pressed, the configured program will start.
- Stop button: It will stop the program.
- Reset button: It clears all configuration from the program.
- Add: Before pressing this button, the Movement, Enabled, Repeat, Direction, Mode, Count, Speed1, Speed2, Pause time parameters should be set. It will send these parameters to the Arduino and saved in the program.
- Add + Start: The same function as the "Add" button plus it will start the program.
- Movement: A program has a maximum of 8 movements. This parameter determines the number of movement.
- Enabled: If this is set, then the movement will be active if the previous movement is passive, then this will be passive as well.
- Repeat: this movement will be repeated according to this number
- Direction: the movement will be left, or right
- Mode: The end of the movement can be triggered by time, motors steps or sensor.
- Time mode: The program will start a counter for "count" field seconds, then it will stop
- Step mode: The program will give "count" steps to the servo.
- Sensor mode: It will run until the hall sensor change their state as many times as it is set in the "count" field.

Speed and acceleration

The speed and acceleration of the stepper depend on the Speed1, Speed2, Pause time parameters in the program and the DIP switches of the stepper motor driver.

- Speed1: The stepper motor driver is active for this period
- Speed2: The stepper motor driver is disabled for this period
- Pause time: After a cycle, it will wait for this period.



```
[2020.01.04   19:12:03] Connected[19:12] Sent: 1,0,1,1,0,3,10,50,1000,100,a
```

Port: COM1
Baud Rate: 9600
Note:
☐ save to file
Step/round: 6200
Magnet/round: 18

Movement	Repeat	StepCount	Rotation	Speed	Magnets	Position	Startmove	Stopmove	Repeatcycle
0	0	0	0	0	0	0	0	1	1

Movement	Enable	Repeat	Direction	Mode	Counter	Speeed_1	Speed_2	Pause time
0	☑	1	Left	Rotation	10	50	1000	100
Movement 0	1	1	Left	Rotation	10	50	1000	100
Movement 1	empty							
Movement 2	empty							
Movement 3	empty							
Movement 4	empty							
Movement 5	empty							
Movement 6	empty							
Movement 7	empty							

Figure 45. Control software for Turntable
Source: compiled by the author

The construction of the system took place in several phases. In the first step, the turntable is made up of a control processor, a stepper motor and sensors. The system easy to assemble, it is modular and to be used for different tasks. One such application is the direction dependence and performance analysis of nuclear detectors. With the embedded microcontroller program, the rotary motion can be pre-programmed within a given angular range with the detector mounted on the swivel. The angle of the movement can be preset in terms of its frequency, direction, speed, and various sequential programs can be constructed. In a radioactive shipment control application, the turntable is used to rotate the radioactive container at a constant rate while the system measures the radiation levels around the container.

The radiation detector is controlling the turntable and the robotic arm. It gives a command to start moving the robotic arm closer to the container placed in the center of the turntable. When the sensor is close enough to the wall of the container, it stops moving. Then, on command, the turntable starts rotating until the verification process is completed.

All measured data comes to the radiation detector because only the detector can decide when to start or end the control. A wired two-way data line connects the radiation detector and the robotic arm since there is no great distance between the bogie and the beacon, TTL UART communication interface was used with standard bidirectional communication. In the second phase, the control of the platform was completed by moving the robot arm. For this task, I selected a microcontroller module with many inputs and outputs. The higher capacity allowed the robot arm to control the movement of multiple servo motors and read the mass sensor data. The robot arm is designed to change the position of the radiation meter so that it is as close as possible to the radioactive source container so that the radiation meter can scan the entire surface of the radioactive source. By collecting data from all measuring sensors (mass, radiation, distance, position, rotation), the program can perform the evaluation. The robotic arm servomotors, a total of five, allow the radiation detector to move at a high degree of freedom. However, it is difficult to determine the exact position. The circuit diagram for the control and display unit is shown in Figure 46.

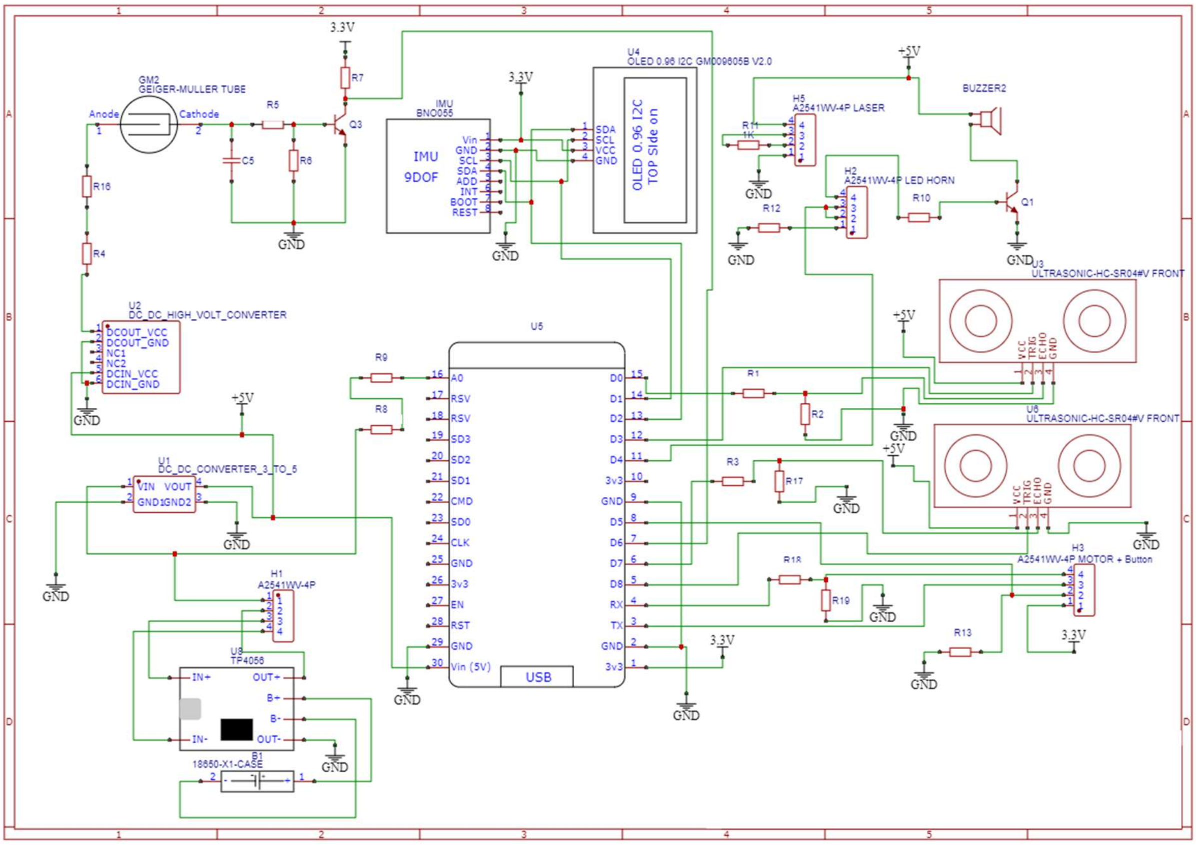


Figure 46. Schematic of Radiation detector.
Source: compiled by the author

The GM tube in the radiation detector must be perpendicular to the surface of the platform during the entire measurement, providing an objective angle. The built-in absolute rotation sensor determines the position of the detector. In the BNO055 sensor module, a triaxial 14-bit accelerometer, an accurate close-loop triaxial 16-bit gyroscope, a triaxial geomagnetic sensor and a 32-bit microcontroller help determine the exact absolute position.

The absolute position is automatically determined by a single integrated microcontroller that gathers magnetometer gyroscope and acceleration sensors without the need for user intervention. The sensor provides instant data, but also provides information on how secure each sensor data is. Each sensor provides more accurate values while in use, and the system automatically calibrates as the robotic arm moves.

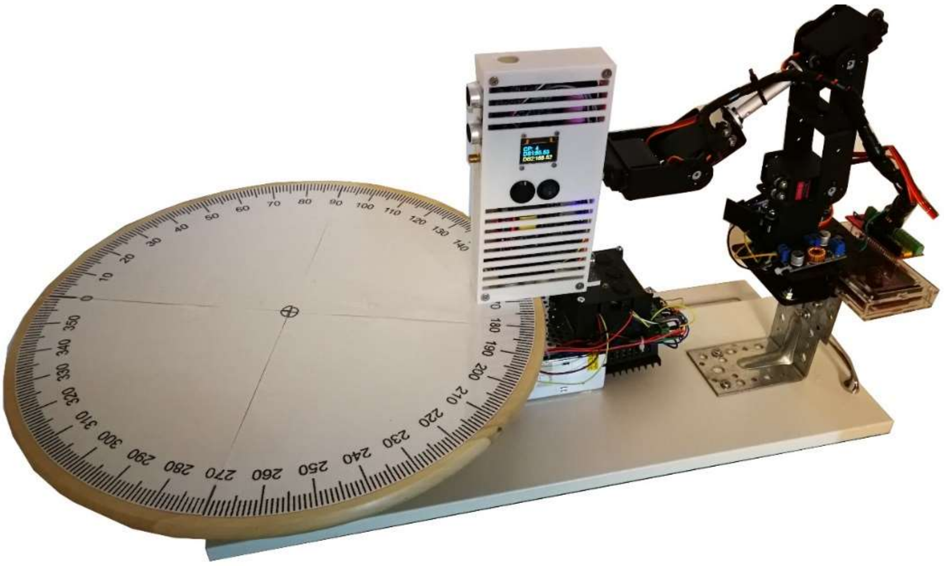
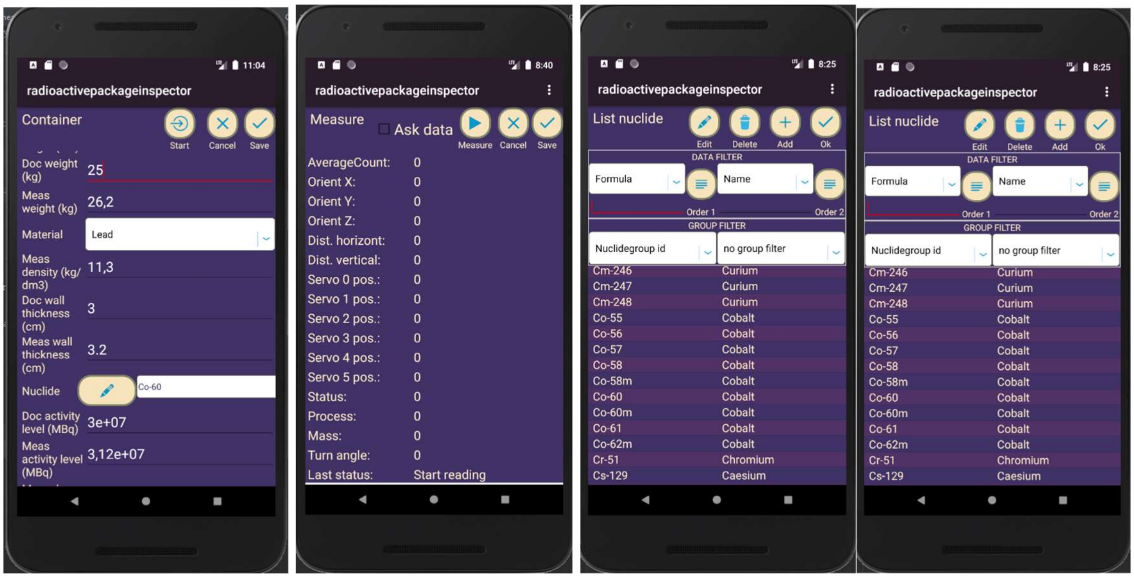


Figure 47. The prototype of the isotope transport inspection detector
Source: compiled by the author

The scales built into the rotating beacon determine the mass of the container placed on it and convert it into a digital signal, which is transmitted to the radiation detector, where it is stored and processed with other sensor data. The assembled whole inspection system can be seen in Figure 47.

Data can be accessed wirelessly via the radiation detector through a WiFi connection. The mobile phone is connected to the radiation detector at there built-in webserver. WiFi is rather unsafe, but this is the only communication interface available on every mobile phone. The program running on the mobile phone obtains the necessary data from the radiation detector based on a continuous query and uses this algorithm to determine the decision-support information needed.

The measurement can be started from the phone, and at the end of the measurement, the results are displayed. The system also attempts to determine the height of the cylindrical container, but the user can modify this value. I created an Android application (Radioactive Package Inspector) to control the complete instrument and visualise the measured values. I used java and Android Studio to implement this software. It can run on any Android mobile phone which has at list Android 5.0 operating system (Lollipop). The screenshots of the application can be seen in Figure 48.



Doc weight (kg): 25
Meas weight (kg): 26,2
Material: Lead
Meas density (kg/dm3): 11,3
Doc wall thickness (cm): 3
Meas wall thickness (cm): 3.2
Nuclide: Co-60
Doc activity level (MBq): 3e+07
Meas activity level (MBq): 3,12e+07

☐ Ask data

AverageCount: 0
Orient X: 0
Orient Y: 0
Orient Z: 0
Dist. horizont: 0
Dist. vertical: 0
Servo 0 pos.: 0
Servo 1 pos.: 0
Servo 2 pos.: 0
Servo 3 pos.: 0
Servo 4 pos.: 0
Servo 5 pos.: 0
Status: 0
Process: 0
Mass: 0
Turn angle: 0
Last status: Start reading

Cm-246	Curium
Cm-247	Curium
Cm-248	Curium
Co-55	Cobalt
Co-56	Cobalt
Co-57	Cobalt
Co-58	Cobalt
Co-58m	Cobalt
Co-60	Cobalt
Co-60m	Cobalt
Co-61	Cobalt
Co-62m	Cobalt
Cr-51	Chromium
Cs-129	Caesium

Cm-246	Curium
Cm-247	Curium
Cm-248	Curium
Co-55	Cobalt
Co-56	Cobalt
Co-57	Cobalt
Co-58	Cobalt
Co-58m	Cobalt
Co-60	Cobalt
Co-60m	Cobalt
Co-61	Cobalt
Co-62m	Cobalt
Cr-51	Chromium
Cs-129	Caesium

Figure 48. Radioactive package inspector Android mobile phone application screenshots

Source: compiled by the author

Visualization of the measured value

If the container has a weak point in the shielding, the advanced inspection method will give only the highest dose rate as a result, but there will be no information about the location of this specific point. It is hard to give any point of reference to find the problematic part of the container. The best way is to visualize the whole container coloured according to measured values. For this purpose, the dose rate was stored for every angular sector during the rotation. The saved values were combined with a cylindrical model and Figure 49. shows the results.

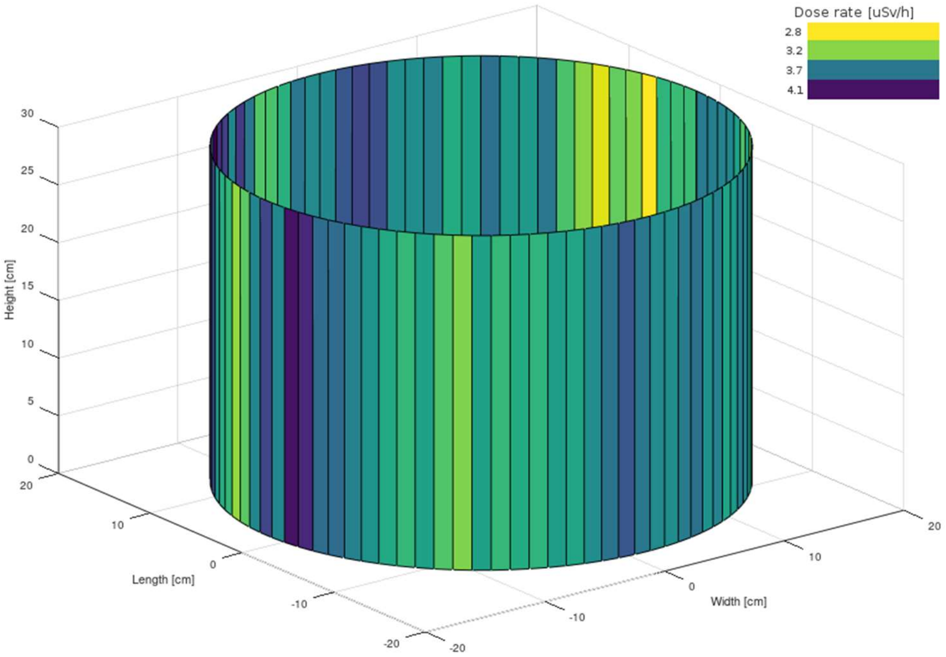


Figure 49. Visualization of the radiation level of a container loaded with Cs-137. Source: compiled by the author

The container presented in Figure 49. suffered no external damage, but the picture shows shielding inhomogeneous, or the source is placed not in the center of the container. The whole checking process takes 45 seconds, containing 90 measurements in one round and every measurement takes 0.5 seconds.

Isotope identification

A potential error factor can be in the process of activity estimation. If the type of isotope is not stated correctly in the documentation, the activity calculation will give a wrong result. The source in question should be identified to avoid this type of errors. The identification can be conducted without opening the container. For this purpose, a search and isotope identification unit could be applied. A search and isotope identification unit called SFK can be seen in Figure 50. If the identification is not successful, the identified energy peaks and the count number at these peaks will give the energy level and probability of the gamma radiation, which can be used for the calculation as well.

Figure 50. SFK search and isotope identification unit
Source: [3]

Surface contamination of the package

There is one additional factor that can cause a calculation problem. If the surface of the container is contaminated with radioactive material, the calculation can give a wrong activity estimation. Every surface contaminated container should be excluded from transportation. Using a traditional surface contamination monitor cannot be used in this case, because the effect of the source inside the container will modify the measured value. The best way is to take a smears sample from the surface of the container and check it far from the container in a low background measuring place with beta and gamma measuring unit. The IH-111L mobile spectrometric detector is ideal for this application, see in Figure 51. I participated in the development of this device by writing embedded software code and designing hardware components.

Figure 51. IH-111L Portable radiological measuring detector.
Source: [3]

4.6. Validation of the inspection method

The validation of the inspection method was conducted by using real radioactive test sources in laboratory conditions. A 93.14 MBq activity Cs-137 source was placed in a lead container. The dimension and mass of the container were measured: height: 20,5 cm, diameter:10 cm, mass:16,7 kg. Wall thickness was calculated from these parameters: 3,23 cm.

The wall thickness of the container was measured with callipers. The result of this measurement was 3,45cm wall thickness. The calculated and measured wall thickness already has a difference of 0.22 cm. This difference can be explained by the uneven wall thickness of the container.

The measured average dose rate at a distance of 30 cm from the detector was 3,1 μSv/h. The calculated activity was: 198 MBq, which is 104,8MBq more than the activity inside of the container. There are multiple causes of the difference: First, the use of average dose rate, secondly, the use of standard lead parameters (build up factors). The container consists not only lead but steel as well. If the radionuclide type is not correct, i.e. instead of Cs-137 the calculation used Co-60, the result will be 2.6 MBq, this significant error shows the importance of isotope identification [77].

4.7. Conclusions about radiation search and inspection methods

I investigated possible search methods and measurement configurations. I have found that the use of a detachable ring collimated scintillation detector is the most efficient method for searching a radioactive source. There are other types of detectors, but among the detectors available to me, I was able to achieve the best results with this scintillation detector. The entire process of searching for a source consists of the following steps:

The first phase is detection. The collimator should be removed from the detector, and it should be working in radiation portal mode. In case of any significant change in the background, radiation will make an alarm, and the second step should be conducted.

The second phase is to determine the location of the radioactive source. The lead collimator should be placed on the detector, and the searching should be started with the method of “rotation”. In a few steps, the source should be localized.

I analysed different levels of inspection methods. I created basic and advanced level inspection methods. The basic level inspection method does not need any special tools or equipment. The advanced inspection method relays only on measured parameters, and not trusting the transportation documents. The models work in laboratory conditions but at high error rate. In order to achieve more accuracy, the model should be modified. More tests should be conducted at different distances with different isotopes (e.g., Cs-137 and Co-60) and with different containers (e.g., lead, tungsten, steel), the algorithm should be able to handle more container types (e.g., rectangular). The advanced inspection method can be improved with multiple collimated radiation detectors. These new methods will speed up the inspection time, and with collimation, the source localisation process can be more accurate. The detectors can be a useful tool to prevent a significant industrial accident.

Integration of spectrometric detectors to the system could give more information, and it can be used in other application, like waste measurements.

5. INTELLIGENT DETECTORS APPLIED IN RADIOACTIVE EMISSION MONITORING SYSTEMS

Systems for the measurement of radioactive materials released into the air and water have long been operating in nuclear facilities. The existence of such a system is a prerequisite for the establishment and operation of such a facility.

These systems may be different in design and implementation, but they are intended for the same purpose. Emission control systems are required to provide measurement data to determine the amount and quality of the emission released by the technology using radioactive materials. When designing and permitting a radiation-related technology, it is necessary to determine the increase of collective dose for residents and workers. In most countries, pre-planned processes for airborne or liquid radioactive releases are subject to regulatory approval, and emission limits are required. These limits generally determine the activity levels per isotope for each activity, individually stated to each licensee over a given period (usually one year). In Hungary, this issue is regulated by the Government, according to 15/2001. (VI. 6.) [29].

The specifically authorized dose constraint value for the population shall be used to determine the permitted release activity. It is necessary to determine, for every isotope, the specific radiation exposures for the designated critical group of the population. The calculations used in the determination shall be reported and must be accepted by the licensing authority. As an example, the Environmental Permit of the MVM Paks II. Nuclear power plant values have been determined for the two new reactor blocks to be constructed, which have been verified by the Environmental Impact Assessment Study [78]. In addition to the results measured, an emission measurement system should be able to provide data about the emissions released by the technology to use it in emergence prevention models.

An emission measurement system may also generate an alarm event if it detects a condition other than normal operation. In this case, it can notify the operating staff by sound and light signals and initiate direct action, e.g. by switching on emergency filter-ventilation systems.

This chapter describes and investigates measurement methods that may be used in the measurement of radioactive emissions. The research aims to find the most suitable measurement method for emission control by comparing the various technical solutions and collecting all advantages and disadvantages of such systems.

Theory of emission monitoring

There are several ways to group radioactive releases. A radioactive emission can be characterized by its location, the physical state of the carrier medium, the composition of its isotopes and their activity. The simplest method is to group the state of the carrier of the release medium. On this basis, the relevant regulation distinguishes between emissions to air and wastewater [29].

This physical state of containment does not mean that the hazardous substance itself can only be gaseous or liquid. In many cases, the contamination is substantial but escapes into the environment in a liquid or gas stream. Radioactive emission can also be grouped according to the type of isotopes present at release or their chemical form.

The actual instantaneous release in activity concentration (Bq/m^3) the released amount for a period in the activity (Bq/hour, Bq/day, Bq/year) shall be given. Most radioactive material emitting technologies can release a definite number of isotopes, these isotopes shall be monitored, and their activity should be determined. In specific locations, release limits are calculated from dose constraints. Every emission values added together for the whole facility, which will determine the increase of the annual collective dose to the critical population living near the facility and would be possibly affected by any release [79].

Several types of emissions can be distinguished according to the place of release. In most cases, when the technology in normal operation, contaminant leave the facility through controlled circumstances trough a stack after the technological filters, this release is considered to be standard operational emissions. In complex systems, a technological unit may have its emission, for every releasing point, an autonomous measurement/control system should be installed. Contamination can be released at other unintended points in the event of an accident or emergency.

5.1. Offline emissions measurement based on sample taking

One way to measure airborne emissions is to take a representative sample from a specific point of the ventilation system, then analyse the activity of the sample and use the airflow data to determine the level of emissions. The schematic of such a system is presented in Figure 52.

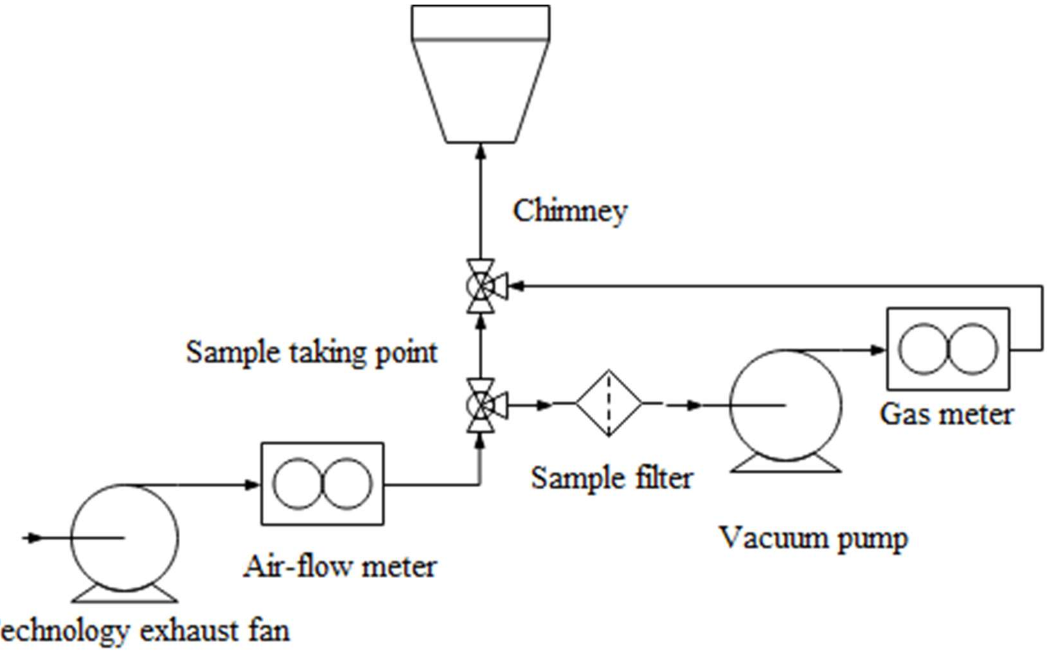


Figure 52. Schematic diagram of offline airborne emissions monitoring system.
Source: compiled by the author

The emissions for a given sampling period can be calculated from the value of the sample activity, compensated by the amount of sample taken and the amount of material released. The weekly, monthly and annual emission values can be calculated by adding together all emission values for the specific period.

Formula 14. $$\mathbf{A_t = \frac{A_m \cdot V_t}{V_m}}$$

Where:

A_t: Total emission value during the sampling period [Bq],

A_m: Activity of air sample taken during the sampling time [Bq],

V_t: Total airflow at the time of sampling [m^3],

V_m: Quantity of sampling line at the time of sampling [m^3].

The problem with this method is that it is not fast enough. The emission is first captured by a filter that is dismantled over time, then measured at a measuring point before the result can be calculated, ideally in hours, usually in days. Other problems are that the filter is only capable of filtering contamination at a given efficiency and that as time passes the contamination can go through the filter, and the sample activity is also reduced by the half-life of the isotope. The inaccuracy of the sampling, the air flows and the nuclear measuring detectors add further increase to the measurement uncertainty. This measurement does not make it clear whether the elevated measured value is caused by continuous flow or one "impulse-like" emission. Once a single release has occurred, its exact date and time cannot be reconstructed.

The measurement method has the advantage that the sampling is simple, inexpensive, and the activity on the sample is proportional to the activity emitted. The further advantage is that the sampling is insensitive to changes in background gamma radiation at the sampling site. In a facility where radioactive materials are handled, background radiation can fluctuate greatly. The reason for the fluctuation may be that high activity materials are transported or moved within the facility. Since the gamma background radiation fluctuation does not affect the radioactive contamination on the filter, subsequent measurement of the sample in a laboratory away from the technology will give a more accurate result, a lower limit of detection.

Another way to measure offline emissions is to use the mass balance method. This method can be used if the activity enters into the technology and the activity of the material leaving and discharging during work are precisely known. In such cases, degradation, chemical processes and measurement uncertainty must also be taken into account. After the process, the missing activity can be considered as emission. The disadvantage of this solution is that the contamination released from the technology may be released in different directions, in different states, in unknown proportions, e.g. part of it is trapped in an air filter, and the other part becomes liquid after release.

5.2. Online emissions measurement built into the pipeline

Another emission measurement method is a direct measurement in the ventilation system. Where the detector is installed directly inside of air supply piping. This solution can be used to measure radioactive contaminants passing in front of the detector.

Working with radiation next to the pipelines can cause an increase in the background radiation (e.g. source transportation behind the detector). This error can be eliminated by automatic online background compensation. The effectiveness of this method has been demonstrated in an experiment. Two GM counter detector was used for the measurement. I was part of a team how conducted this measurement and I participated in the planning and evaluation process of the measurement.

One GM tube sensor had a thin mylar film in front of the end window, while the other had the same type of GM tube sensor with an alpha-beta aluminium filter. The detector with the beta aluminium filter was able to measure only gamma radiation, whereas a detector without a filter registered beta and gamma radiation. The two detectors were installed directly in the duct after the point of release but before the technological filters. Measuring the inside of the tube made it possible to detect changes in the system as quickly as possible.

The difficulty of the measurement was that the residence time of the radioactivity before the detector was short so that the radioactive material released rapidly ("impulse-like") appeared in only one measurement, see the measured result in Figure 53.

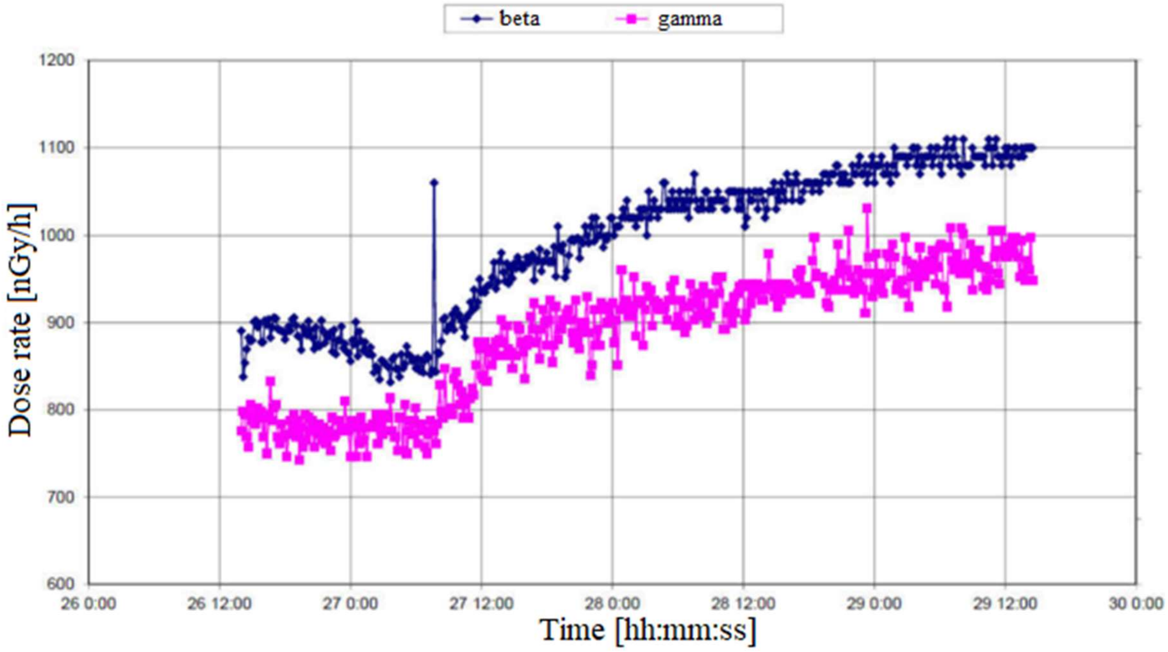


Figure 53. Online emissions measurement built into the pipeline.
Source: compiled by the author

The value thus obtained must be derived exclusively from impurities passing through the tube before the detector, since no beta radiation from other sources may reach the detector.

The beta radiation from the outside is absorbed in the tube wall, and only the gamma radiation can reach the detector.

The advantage of this measurement setup is that short, "impulse-like" emissions from each technological step can be observed in real-time. The short measurement time, the contamination of the pipe wall, the wide intensity range and the fluctuation of airflow all contribute to the uncertainty of the measurement.

The sensitivity of the measurement assembly can be further improved by building in lead shielding around the affected pipe-line section. The measurement can be further simplified by incorporating only one gamma dose rate meter into the tube section. With this solution, automatic background compensation is not feasible, but the resulting error in an accident situation is negligible. The adsorbed and later desorbed radioactive fine particles on/from the tube wall causing additional errors in the measurement. The thickness and quality of the shielded material can change the effect of the surrounding gamma radiation fluctuation on the measured value.

Additional information on the emitted material can be obtained by installing a scintillation detector at the fixed measuring point. The scintillation detector is more sensitive than the GM counter detector and can also be used for gamma spectrum acquisition, which allows the identification of emitted isotopes. The scintillation detector equipped with the BGO ($Bi_4Ge_3O_{12}$) crystal can be used at a higher dose rate, but still significantly below the upper measuring range of a GM counter detector.

5.3. Online emission measurement on technological filters

Another method of emission measurement is the direct measurement at technological filters. This measurement should take into account that filters may produce high dose rates (> 100 mGy/h) and therefore require a detector with a wide measuring range and, in such systems, the electronics should be protected against the effects of the damage of high radiation levels. The advantage of the assembly is that the technological processes are well traceable, short-term emissions appear over several measurement cycles and remain until the contamination leave the filter or degraded. Another advantage of the method is that it also provides information about the state of the filter. The measured values can be used to decide when to replace the filter or after a period of rest period when it is time to re-use the filter. In such systems, it is worth implementing a multi-level, complex alarm system.

During regular operation, a fixed alert level should be set for the expected release, so that work with radioactive materials can be carried out smoothly as long as the intended release remains within the planned limits. After completion of the work in the technology, the value measured on the filter should not increase, so the system will then have to switch to radiation portal mode. In this mode, alarms on the significant increase in radiation allow stoppage of uncontrolled leakage of contaminated technology. The disadvantages of the technology are the slow response time and insensitivity to emissions that cause little change when the filter is full. Lead/tungsten shielding should be inserted between the air filter and the detector, and the distance can be increased so that the radiation intensity remains in the measuring range of the detector.

5.4. Air sampling and online emissions measurement

The essence of the online sampling method is a continuous representative sampling of the piping system. The sampled air passes through elemental, organic, inorganic iodine, aerosol filters, placed in front of the detector (s) and then arrives in a container where the noble gases can be measured. For accurate measurement, each type of filter (aerosol, iodine) and the noble gas tank must be assigned a separate detector. The four measuring places can be combined into one unless specific emission limits for the chemical forms of each iodine are required.

The combined detector assembly, with the schematic of the whole system, can be seen in Figure 54. Efficiency can be further enhanced by an automatic filter changer that ensures that a new filter is placed in front of the detector in case of air sample filter clogging, tear, or high activity.

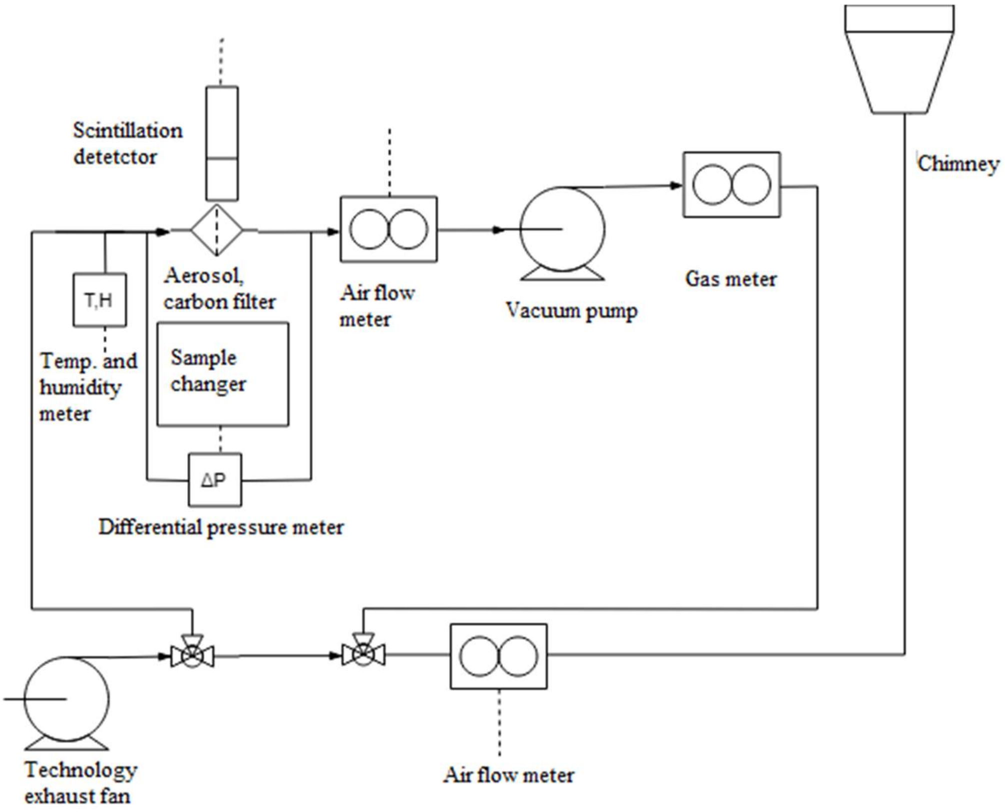


Figure 54. Schematic diagram of an online emission monitoring system with combined aerosol, elemental, organic, iodine and noble gas measurement.
Source: compiled by the author

The online monitoring system performs measurements at a set cycle time. At each measuring point, the activity increased on the filter per cycle will be proportional to the emission. The system identifies the radionuclides specific to the particular filter or contained in the noble gas container. The sensitivity of the system is determined by the minimum detectable activity (MDA). MDA is influenced by the detector, its geometry, main and sampled airflow rates, isotope half-life, residence time, and measurement time. The MDA can be reduced by increasing the measurement time and adding consecutive measurements, but this increases the system response time and reduces the detection of short-lived isotopes. If identification from the summed spectra is not possible, the MDA can be a conservative estimate of emissions.

There is no "cumulative activity" at the noble gas site. Only the current activity concentration can be measured. The absorption of the noble gases is not possible with absorbers.

By measuring the activity of the sample and the air flows at the sampled and the main pipe, it is possible to determine the current activity concentration for the whole system and the emitted energy selective activity over a given period. The disadvantage of this solution is that increases in the external gamma background can result in higher emission values, which can be controlled by keeping the measurement as far away from radiation-emitting technology as possible and by measuring at a low-background measurement chamber [80].

The great advantage of this method is that the measuring system can be calibrated without the need for a large amount of radioactive material to enter the ventilation system. If it can be demonstrated that the sample is representative of all airflow, then it is sufficient to perform calibration per detector with low activity reference etalon sources.

Determination of emissions from environmental measurements

The emission control methods described above will only give an accurate picture of the emissions if the radioactivity is discharged through the ventilation system piping. In an accident situation, it is easy to get contamination into the environment other than through the chimney. In such a case, conclusions can be drawn from the environmental measurements around the point of release, indicating the amount of radioactivity emitted. Measured radiation levels, as well as current meteorological parameters, can be used to model emissions [81].

The disadvantage of the method is that it only works in cases where the emission is so high that it can be detected at the measuring point, sometimes with detectors hundreds of meters away from the emission. The measurement is further complicated by the fact that the radioactivity may come from other facilities or countries. With highly sensitive measuring equipment and appropriate spreading calculation software, the location of the release can be determined and the amount released can be estimated [82]. I investigated different emission monitoring systems and tried to found the most suitable for a given task. I took part in measurements to prove the effectiveness of specific emission monitoring system.

5.5. Surface contamination measurement at high gamma background

After discussing all possible emission monitoring systems, I decided to analyse the online emissions measurement system, which is built into the pipelines. This system requires surface contamination measurement at high gamma dose-rate.

In most cases, handheld detectors are used to measure direct surface contamination of people and objects.

The most commonly used detectors are the large-area end-window GM counter detector (one or more) for beta counting or the ZnS(Ag) scintillator based for alpha measurement. These detectors enable fast and efficient measurement of surface contamination.

Before starting the checking of surface contamination, a background measurement should be conducted under clean conditions to make sure that gamma background radiation does not affect the measurement. The problem with this method is that the gamma background radiation may not be constant during the measurement, especially in the case of a nuclear accident increases the gamma background radiation, or simply if a radioactive source moves near the measurement area. Measuring quick and accurate surface contamination with such increased gamma dose rate has always been a challenge for professionals. To perform this measurement task, the combination of two detectors is most appropriate: a gamma dose rate transmitter and a beta and gamma meter.

Principle of the operation of two detectors

In a two-detector measurement set-up, the two detectors measure independently, but there is a central intelligence unit that determines beta surface contamination from independent measurement results. The central intelligence unit can calculate beta surface contamination and statistical error by real-time or after event evaluation using Formula 1.

5.6. Detectors of contamination monitor

Characteristics of gamma dose rate transmitter used for measurement:

Measuring range: 50 nGy/h ... 0.5 Gy/h.

Indication range: 30 nGy/h ... 10 Gy/h.

Energy range: 50 keV ... 1.5 MeV

Relative error: max. ± 15%

Statistical fluctuation trough the whole measuring range: max. ± 10%

Overload capacity: up to 100 Gy/h.

Energy dependence (relative to Cs-137): ± 25%

Temperature dependence trough the whole measuring range [-30 °C … + 50 °C]: ± 2%

Voltage dependence trough the whole input power range [9 V... 32 V]: less than ± 5%,

Characteristics of the beta and gamma detector used for measurements:

Measuring range: 0.2 Bq/cm^2 to 500 kBq/cm^2

Measurement uncertainty: ± 30%

The detectors used in this application are equipped with GM tube sensors and can operate over a wide measuring range. The wide measuring range is achieved by switching the anodes of the GM tubes and by feeding it in a time-proportional manner. In the most sensitive measuring range, all ten anodes of the GM tube are connected to high voltage. At higher dose rates, the detector can automatically reduce the high voltage for nine anodes so that only one anode remains turned on.

As a result of the incoming pulse, the voltage at the anode is reduced for a short period until the charge in the gas space of the GM tube is eliminated. This principle of operation results in a wider measuring range and longer lifetime.

Contamination measurement with two detectors

It is worth performing factory level calibration before the detector is used for the first time. At least every year, the factory level calibration process should be repeated. Before everyday use, it is sufficient to place the two detectors side by side and start a background subtraction user-level calibration.

The two detectors must be calibrated separately. A rubber cap should be placed on the beta and gamma detector to prevent beta radiation from entering the detector. The first step is to determine the gamma dose rate factors needed to calculate the dose rate from the count. Measurements should be taken in 10 anodes mode in a Cs-137 low gamma dose rate field, and then in 1 anode mode in a Cs-137 high gamma dose rate field. The factors should be corrected so that the results are within the margin of error. Measurements should be made in a one anode mode in a Cs-137 high gamma dose rate field to determine the dead time factor. The energy dependency is calibrated with an Am-241 etalon source, but this setting only needs to be made on the gamma dose rate transmitter, as it can only change the gamma energy filter. After measurements with etalons, the background subtraction must be set at a low background test site.

Measurements must be made with pure beta emitter Sr-90, Tl-204 and C-14 etalon sources to calibrate the beta and gamma detector surface contamination. Before surface contamination measurements, the rubber cap of the beta and gamma detector must be removed. For different beta energy etalon sources, different beta efficiency factors need to be determined. For later use, it is necessary to select the efficiency factor for the nuclide energy to be used before measurement. For measurements over a wide measuring range, efficiency factors must be determined in both 1 and 10 anode modes.

As the detectors operate over a wide temperature range, they are subjected to all climatic tests, whereby the background radiation measured by the detector must not deviate by more than ± 30nGy/h from -25 °C to + 55 °C.

Because of their field use, the detectors have to be vibration-resistant, so they are subjected to all assembly vibrations, which are: a 15 minutes vibration of 2g, followed by the back-testing of gamma and beta sources.

The following series of measurements were conducted to check the performance of the detector. For measurement, the two detectors must be connected to the central intelligence unit. The central unit determines the beta surface contamination using the formula described above. Known sources of 10 kBq/cm^2 Sr-90, Tl-204, and C-14 were measured first at normal, and then at high > 20 mGy/h gamma background radiation. The measurements can be considered successful, as surface contaminants measured at high gamma backgrounds differ by less than 30% from surface contaminants measured at the normal background.

Surface beta contamination measurement

The procedures described in the previous paragraphs can be used in various applications and will be presented through practical examples.

One of the applications of the algorithm is when it is necessary to measure surface contamination where several high-activity gamma sources may influence the measurement, for example, in a nuclear facility, when inspecting components or equipment that cannot be removed from their places. If decontamination is carried out on the surface of such an apparatus, this solution can be used to control the efficiency of a decontamination process. There is a need to use the direct measurement method when: there is no way or time to perform surface sampling, to measure and evaluate the sample in an inactive environment, or simply the area to be checked is too large and representative sampling is inadequate. In Hungary, one of the first practical application of the procedure was the measurement of the contamination after the Paks incident in 2003.

A unique surface beta contamination transmitter was developed for this purpose. I was part of the developer team, which created this transmitter, my responsibility was hardware design. The BNS-298 detector had a combined beta-gamma and a gamma dose rate transmitter. The device is shown in Figure 55. Both transmitters contained the same end-window, large surface area, and a large volume GM tube sensor. In front of the gamma detector, an aluminium plate shielded the beta radiation, while the end window of the beta and gamma detector was separated from the outside by a film of 0.9 mg/cm^2 surface density.

The transmitters were calibrated for Cs-137 gamma radiation; the difference between them was less than 1%. The two intelligent transmitters measured separately, and beta surface contamination was determined by computer data processing after the measurements were conducted.

Figure 55. BNS-298 two GM counter surface beta contamination detector.
Source: [3]

A computer program controlled the measurements via the RS-485 communication line. The PC program queried the detectors every 2 seconds for measurement results and accuracy. Before the measurement, a background measurement had to be performed. By placing a rubber filter on the beta detector, the detector became insensitive to the beta radiation. During the background measurement, the difference in gamma dose rate measured with the two detectors was set to zero with a statistical error of less than one-quarter of the detection limit. After the background measurement, the beta filter was removed, and the surface contamination measurement started. From the data collected, the program calculated beta contamination. The measurement was continued until the accuracy, and the detection limit had dropped below the prescribed value. The measurement also stopped if the measurement time had reached its maximum value. This period was preferably the same as the background measurement time. The measurement took as short a time as possible.

After the transmitters started a joint measurement, the transmitters calculated the Cs-137 equivalent dose rate values, the measurement error every 2 seconds. The data transmission was computer-initiated, master-slave communication, which ensured the same measuring cycles for both transmitters and allowed the two transmitters to be connected to one RS-485 bus. No data loss or data pack collision occurred during the measurement. The computer retrieved the data every 2 seconds, performed the background subtraction and calculated its statistical error.

Several measurements have been completed in the Paks area affected by the incident. The results of the measurements helped to carry out the reconstruction work.

5.7. On-foot radiation reconnaissance

The Surface Beta Transmitter (BNS-298) used at Paks Nuclear Power Plant was well-tested in an industrial environment, but its design (2 detectors + PC) did not allow it to be used as a handheld detector. An essential element of nuclear accident prevention is the detection of contamination of a road or a contaminated area. There is a method for this reconnaissance task that consists of the following steps: the first person measures gamma background radiation at 1-meter height with a gamma dose rate meter. The second person, behind the first one, measures with a beta + gamma detector as close as possible to the surface of the ground (in many cases crouching). The measurement results are recorded on a piece of paper, along with the time and location coordinates, and then surface contamination is calculated.

In order to simplify the method described above, a novel detector (IH-295) was developed, which became the advanced version of the two-detector (BNS-298) transmitter, previously described. The IH-295 device is shown as it is used in Figure 56. I was part of the developer team, which created this device, my responsibility was the system design and evaluation of the end result.

Figure 56. IH-295 surface contamination monitor in operation.
Source: [3]

The calculation task of the PC was taken over by an embedded microcontroller, so in a small unit with low power consumption, the same result could be obtained. The device also received a quick search function which made it possible to see the result of the calculation not only at the end of the measurement but also every 2 seconds during the measurement. As a result of the method used in IH-295, the display of the detector in search mode is less statistically fluctuating than that of conventional detectors, but at the same time, it responds quickly. This short response time makes the detector capable of rapidly detecting a point source of both gamma dose rate and beta surface contamination.

Portable versions of the dual-detector (BNS-298) transmitter were created in 2005. Two detectors were completed, the IH-295 and the BNS-295. The IH-295 uses two identical GM counter detectors and is part of a beta and gamma detector located at the end of a long probe handle, while the BNS-295 consists of a hand-grip surface contaminant of 4 GM counter detectors. For these devices, the measured data were evaluated, and the gamma background-corrected surface contamination was calculated without the use of a computer, but by using the detector's electronics.

For the IH-295 and BNS-295 detectors, a non-conventional search algorithm was used. In conventional detectors, the requirements of IEC 61017 for statistical fluctuation compensation of natural background implemented by averaging the instantaneous measured values for the recent period. This method gives a quick setting time as the radiation level increases, but the recovery time will be much longer because after the radiation level decreases, the previously measured high levels keeping the average at a high level. In practice, this means that a sudden drop-in gamma dose rate absorbed by air at 6 μGy/h near the typical background (80 nSv/h) will give an accurate result after approximately 128 instantaneous values so that recovery time can be as high as four minutes. A modified search mode has been implemented in IH-295 and BNS-295 detectors. The detector will produce an accurate average until a significant change occurs, then it will generate an instantaneous value for three cycles and then start averaging again. This process significantly speeds up the recovery and helps the user to search.

As a result of this procedure, the detector shows in search mode less statistical fluctuation (using an average value instead of an instantaneous value), but at the same time responds quicker, generating an alarm when the alarm threshold is crossed.

This behaviour makes the detector capable of rapid detection in terms of both gamma dose rate performance and beta surface contamination.

Alpha-contamination indication is also possible with these detectors. The alpha radiation can go through a Mylar foil window, which has the thickness of maximum 2 μm, placed before the detector. Menu settings can also be used to obtain cumulative alpha, beta and gamma contamination values in cps without background subtraction. The sample must be measured in cps mode without any barrier, to determine the amount of alpha radiation, and then, applying two layers of foil film to the detector, the alpha radiation is absorbed there, the difference between the uncoated and the foil value being caused by alpha contamination [83].

5.8. Conclusions about emission monitoring and surface contamination monitoring methods

From the emission measurement methods presented, it cannot be said that there is one that is ideally suited for all purposes. I summarized the possible system assemblies and created a system of criteria to aid the choice. Each has advantages and disadvantages. The choice of the ideal method for a given measurement task can depend on many things, such as the development of technology, the resources available, other activities in the environment.

If the response time is not essential and the released isotopes have long half-life, the offline-measurement based sample taking method is ideal and has the lowest detection limit and the most insensitivity to environmental radiation. The technology can be observed the most closely with the monitoring system installed directly on the technology air filters. The fastest detection time is achieved by direct measurement in the pipe system. Sampling Online Emission Measurement, with a rapid alert, allows for energy selective activity concentration measurement.

Measuring methods and related technical solutions can provide more and more accurate information as technology advances. However, the best results can be achieved if several of the above methods are integrated into the monitoring system. Redundant measurement assemblies based on various technologies increase the reliability and availability of the entire system.

The method can be used in several applications where on-line gamma background compensation is needed for beta measurement.

Gamma compensation algorithm also works in total beta measuring systems, where the goal is to determine the beta activity of a sample rather than calculate surface contamination. Two intelligent scintillation-type detectors, integrated into a low-background chamber, work together to perform this measurement.

Another application of the beta measurement algorithm with a variable gamma background is emission control. Surface contamination algorithms are the basis of several applications, making them well suited for both detection and laboratory analytical purposes. The scope of possible applications is much broader than the ones described here.

I created measuring assembly and an algorithm that can be used in multiple areas and tested its effectiveness with several methods. The measurement set-up could gain additional accuracy by performing calibration with etalon sources before each measurement.

One of the weak points of the system is that the GM counter detector cannot determine the energy level of the beta radiation, so the user should choose from three nuclides (Sr-90, Tl-204, C-14) with different energy levels, the detector uses the chosen nuclide efficiency factor for the measurement.

SUMMARISED CONCLUSIONS

The radiation monitoring systems for disaster management and military purposes are already using intelligent detectors, with the improvement of the capabilities of these detectors can open new possibilities in decision support systems. The processes that have been used in these intelligent detectors can be improved to achieve more information on the shortest time. As a consequence of applying new intelligent detectors, the time between the first sign of a disaster and the first response of preventing the disaster has been significantly reduced. The tendency I observed that the results are more accurate, measuring ranges getting wider, and usage has become more comfortable in extreme conditions as it was in the past.

I investigated different monitoring systems, focusing on the capabilities and their measurement techniques. I proofed that scintillation detectors can improve significantly the capability of environmental monitoring systems. (H1)

Scintillation technology is advantageous due to the high sensitivity but requires the use of various engineering solutions customised to extreme field conditions.

I collected all the effects should be considered to build a detector should be used for military and disaster management purposes. The coupling materials and light barrier help to prevent the ambient light from affecting the measurement. Detectors can withstand vibration and dropping using external and internal absorber techniques. External and internal electromagnetic radiation should be handled at the detector level. Electrical components, shields, and grounding can prevent the detector from interfering with external electromagnetic radiation or the detector from interfering with other electrical equipment. Changes in temperature lead to significant errors in measurement results, so it is worthwhile to use temperature compensation, which is based on temperature measurement and automatic calibration with the help of etalon sources. Adequate insulation can protect against sudden changes in temperature.

After extremely high dose rate (>100 mSv/h) irradiation the NaI(Tl) and CsI(Na) scintillators only return to their original values within hours and over a given dose rate they are no longer capable of measuring radiation. These problems can be solved by the BGO scintillator, which is capable of continuously measuring the intensity of radiation without any after glowing effect, or the anode current measurement can also be useful at high dose rates.

The result of this development is the extension of a lifetime, the increase of vibration resistant and widening the operating temperature range of NaI(Tl) scintillators to be able to fulfil military standers i.e. MIL-STD-810. I solved the separation issue of NaI(Tl) by using a unique coupling material. I created a new testing process to prove the quality of NaI(Tl) scintillation crystal quality. Scintillation crystals produced by this new process are already used in multiple detectors like in the onboard radiation reconnaissance system. I proved that modified scintillation detectors can be used for military and disaster management purposes. (H2)

Several factors influence the operation of a radiation portal monitor, which can, in many cases, determine whether or not it can detect a hidden radioactive source. I identified different configurations for various application regarding gamma and neutron radiation detection. In addition to fixed portal monitors, there are mobile, onboard, and even handheld variants. I proofed that high-reliability detection of transported radioactive materials can be achieved with radiation portal monitor systems if the systems are used in the appropriate assembly, configuration and with the right operating algorithm. (H3)

I examined the currently available radiation protection monitoring systems and developed an additional algorithm, similar to the radiation portal monitor algorithm that allows radiation measuring detectors to support physical protection systems. I made theoretical analysis, and with that, I proofed that the radiation portal monitor algorithm allows the generation of an alarm signal to the direction of the physical protection system if the supervised radioactive source is removed. (H3)

I tested many search methods and measurement configurations for finding hidden orphan sources. I concluded that the detachable ring collimated scintillation detector configuration is the most efficient.

The most suitable search method for finding a source consists of the following steps:

1. Detection with a multi-directional, high sensitive scintillation detector using in radiation portal mode.

2. After detection, the actual localisation should be started with the lead collimator should be placed on the detector, and the searching should be started with the method of “rotation”. In a few steps, the source should be localized.

3. The searching method may be continued with isotope identification for gamma radiation nuclides and activity determination.

I developed different inspection methods of radioactive transports. Only a mobile phone is needed to conduct the necessary inspection. The advanced inspection method relays only on measured parameters, and not trusting the transportation documents. The prototype I created work in laboratory conditions and only with cylindrical isotope holder. In order to achieve more accuracy, the model should be modified. To improve the result of the algorithm more tests should be conducted at different distances with different isotopes (Cs-137 and Co-60) and with different containers (lead, tungsten, steel), the algorithm should be able to handle more container types (e.g., rectangular). The advanced inspection method can be improved with multiple collimated radiation detectors.

The method I invented will speed up the inspection time, and with collimation, the source localisation process can be more accurate. The detector can be a useful tool to prevent a significant industrial accident. Integration of spectrometric detectors to the system could give more information, and it can be used in other application, like radioactive waste measurements. (H4)

I investigated the radioactive emission measurement methods. The result of my investigation was that there is no perfectly suited configuration for every technology releasing contamination. I declared basic guidelines for different measurement tasks. The guideline considers it the development level of the technology, the resources available, other activities in the environment.

If the response time is not essential and the released isotopes have long half-life, the offline-measurement based sample taking method is ideal and has the lowest detection limit and the most insensitivity to environmental radiation.

The technology can be observed the most closely with the monitoring system installed directly on the technology air filters. The fastest detection time is achieved by direct measurement in the pipe system. Sampling Online Emission Measurement, with a rapid alert, allows for energy selective activity concentration measurement.

Measuring methods and related technical solutions can provide more and more accurate information as technology advances. However, the best results can be achieved if several of the above methods are integrated into the monitoring system. Redundant measurement assemblies based on various technologies increase the reliability and availability of the entire system.

Beta surface contamination monitoring at high gamma dose rate method can be used in several applications where on-line gamma background compensation is needed for beta measurement. Gamma compensation algorithm also works in total beta measuring systems, where the goal is to determine the beta activity of a sample rather than calculate surface contamination.

Another application of this type of beta measurement algorithm with a fluctuating gamma background is radioactive emission control. Surface contamination algorithms are used in many applications, making them well suited primarily for detection of contamination. The measurement setup could gain additional accuracy by performing calibration with etalon sources before each measurement. (H5)

CONCISE DESCRIPTION OF NEW SCIENTIFIC ACHIEVEMENTS

T1.: **I proved** that different capabilities implemented within intelligent detectors can improve the efficacy of radiation monitoring systems. With the help of such systems, the time between the first sign of a disaster and the first reaction to prevent it has been significantly reduced. I proved that the already existing application should be updated to increase accuracy, to widen the measuring ranges and to use in field conditions. (H1).

T2.: **I proved** that NaI(Tl) type scintillation detectors are usable for disaster management and military purposes if the detector is protected against temperature changes, mechanical shocks, electromagnetic radiation, and errors due to sudden temperature fluctuations, extreme high ionizing radiation. I created a hardware and software recommendation for scintillation detectors which can optimise the feature of the detector to use in extreme condition. (H2).

T3.: **I developed** a system of criteria for radiation portal monitor systems to have the most suitable assembly, configuration and operation procedure, which can improve the efficiency of detection of hidden transported radioactive materials. I integrated the radiation monitoring software into the physical protection system of irradiators to make an alarm if the supervised radioactive source has been removed. (H3)

T4.: **I developed** a search method to make the on-foot radiation reconnaissance process more efficient with the help of narrow collimated scintillation detectors and with time optimised searching strategy. I defined basic and advanced inspection methods to improve the control of radioactive shipments by measuring the external physical parameters and radiation level of the container. (H4)

T5.: **I developed** a system of criteria for radioactive emission monitoring systems to find the ideal measurement assembly for different technologies. I integrated an intelligent detector assembly into emission control systems, to measure beta surface contamination at high, dynamically varying gamma dose rates. (H5)

RECOMMENDATIONS

Based on the conclusions formulated in the individual chapters of my dissertation further scientific research can be started.

I recommend further studies to improve the efficiency of radiation reconnaissance on the field. More tests should be conducted which can give additional feedbacks for developments of such devices, or processes. I am sure that all measurements assembly I investigated can be changed to get quick and more accurate results. With the improvements of technology sooner or later new ideas and solutions will surface that will revolutionise the methodology for radiation measurements. The computing capacity and speed of a handheld device will increase in the future, opening doors for endless possibilities.

The newest equipment which is releasing radiation only for a short time generating pulsed type radiation fields will give a lot of challenges for professionals, to measure these fields correctly.

Terrorists trying to use radioactive materials for creating dirty bombs, getting more and more educated. They know exactly how to transport illegal radioactive material unnoticed, or cover the presence of artificer radioactive material with naturally occurring materials, at borders, to smuggles goods.

Fulfilling the requirements for radiation monitoring equipment is challenging, because the end-users are used to technologies, and they are expecting that all detectors should be handled easily.

The education cost of well trained CBRN expert is very high, and it took years of training. In case of emergency, there will be not enough experts to handle the situation, that is why the technology makes it possible to handle enormous events security with a small group of professional.

My research answered some of the questions regarding radiation measurements but also created new questions, which could be the base of a new PhD dissertation.

POTENTIAL PRACTICAL USE OF THE RESEARCH FINDINGS

The results achieved in this synopsis can help to develop the following capabilities for military and disaster management applications:

- Early warning monitoring,
- On-foot, onboard, aerial reconnaissance,
- Searching for orphan isotopes,
- Inspection of isotope transports,
- Uknown isotope identification,
- Command and decision support,
- Integrated building management.

All of the theses I created can be used for the direct implementation of different products; some of these are already in use.

A lot of engineering task should be done to put these concepts into a product, and validation processes need to be conducted. With the help of this research, a new generation of scintillation detectors can be created, which can be used in field conditions. With the capability of outdoor use, the detector will be used for disaster management and military purposes.

Following the system of criteria for selecting a radiation portal monitor equipped with the appropriate assembly, configuration and operation algorithm can provide higher reliability as in the past and can realise addition feature to the monitoring system, i.e., generating an alarm to the physical protection system if the radioactive source has been stolen.

Searching methods of lost and hidden orphan sources can be improved by adapting the detector assembly and algorithm I proposed. Different level of modification can be made at the inspection methods of the control of radioactive shipments. With the estimated activity of the delivered radioactive source, the deliveries of radioactive materials can be more secure.

The release of radioactive materials at different artificial technology is a serious threat to the environment. The measuring of these levels is challenging because the background radiation at these measurements is affected by work with isotopes.

The system of criteria, I established, for selecting an emission control system can support different technology, and can lead to a more accurate measurement of emission and with that lower the environmental damage.

Beta surface contamination measurement at high, dynamically varying gamma dose rates in emission control systems and on-foot reconnaissance could be a useful tool. It can be applied at normal and emergency conditions. Among realtime methods, this is the most precise one if the goal is to measure surface contamination at high gamma dose-rate.

MY PUBLICATIONS IN THE SUBJECT

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APPENDIX 1 Problems, objectives, hypotheses and scientific results

No.	Scientific problems	Research objectives	Hypotheses	Proposed research results
1.	The incorrectly chosen technology and architecture are preventing collecting high-quality information in the right place and at the right time. The availability of information can be an essential factor in disaster management. The challenge of the future is to simplify the processes for the operator to perform the necessary tasks and make it possible to use the device without any lengthy and challenging training.	My goal is to find the new trends and essential requirements of radiation monitoring systems implemented for different applications. To achieve this goal I have to know the relevant standards, legislation, compare possible solutions and identify the correct method and architecture for such a system. From available algorithms and methodologies, I create new ones to achieve better systems performances.	The efficacy of radiation monitoring system can be increased and new capabilities can be added to radiation monitoring systems by using intelligent radiation detectors, which doing compensation of environmental changes, running algorithms to make operation easier, and decision making quicker, applying self-checks to be more reliable.	I proved that different capabilities implemented within intelligent detectors can improve the efficacy of radiation monitoring systems. With the help of such systems, the time between the first sign of a disaster and the first reaction to prevent it has been significantly reduced. I proved that the already existing application should be updated to increase accuracy, to widen the measuring ranges and to use in field conditions.

No.	Scientific problems	Research objectives	Hypotheses	Proposed research results
2.	Laboratory type scintillation detectors are not suitable for military and disaster management tasks. The environmental resistance of such a device is weak. Sensitivity for temperature, humidity, vibration, electromagnetic field makes this unit an only at laboratory conditions operational equipment. With the help of a scintillation detector isotope identification, localisation, radioactive material characterisation tasks can be carried out. I will introduce different solutions about how to modify a scintillation detector to make it field ready.	My research aims to develop new hardware and software solutions that can be integrated into intelligent measuring detectors, which will detect radioactive materials in the field of disaster management and the military. Create a new generation of detectors that are already suitable for field operation.	Scintillation detectors can be adapted for field use for disaster management and military purposes by modifying specific hardware and software components of the detector. The modifications cover the scintillator coupling material, the assembly and fixing of the applied components, and the compensation for the environmental effects made possible by the embedded microprocessors.	I proved that NaI(Tl) type scintillation detectors are usable for disaster management and military purposes if the detector is protected against temperature changes, mechanical shocks, electromagnetic radiation, and errors due to sudden temperature fluctuations, extreme high ionizing radiation. I created a hardware and software recommendation for scintillation detectors which can optimise the feature of the detector to use in extreme condition.

No.	Scientific problems	Research objectives	Hypotheses	Proposed research results
3.	The scientific problem with Radiation portal systems, that they provide limited information about the events. The information available from such a system are not enough to make the right decisions. If a portal monitor is not sensitive enough or works with an inappropriate algorithm, the system will allow contaminants to pass through a checkpoint, which could lead to a radiological disaster, or in case of smuggling can be used for terrorist attacks. False alarms at these portal monitors can cause severe damage.	My research goal is to develop a selection criteria system for radiation portal monitor applications and to upgrade such system with the additional capability to provide more information for the operator when a radioactive source triggers an alarm, or someone is trying to steal a radioactive source from a supervised area. I prove that a radiation portal monitor is capable of supporting physical protection systems.	High-reliability detection of transported radioactive materials can be achieved with radiation portal monitor systems if the systems are used in the appropriate assembly, configuration and with the right operating algorithm. The further development of the algorithm implemented in the radiation portal monitors allows the generation of an alarm signal to the direction of the physical protection system if the supervised radioactive source is located in a not authorised position.	I developed a system of criteria for radiation portal monitor systems to have the most suitable assembly, configuration and operation procedure, which can improve the efficiency of detection of hidden transported radioactive materials. I integrated the radiation monitoring software into the physical protection system of irradiators to make an alarm if the supervised radioactive source has been removed.

No.	Scientific problems	Research objectives	Hypotheses	Proposed research results
4.	One of the tasks during on-foot radiation reconnaissance is to find hidden, or lost radioactive sources. The task can only be carried out in a very long time in the absence of the appropriate technical equipment and searching technic. The radiation measuring devices used for this purpose are either not sensitive enough or do not have the necessary directional dependence to be able to give guidance to the person using it. The control of radioactive shipments can also be significantly improved with the help of intelligent detectors.	My goal is to create a radioactive source searching algorithm that can be used to find lost or hidden point type sources faster and more efficiently. Simplify the qualification of radioactive shipments for the user, while collecting as much information as possible about the shipment and automatically checking the shipment documentation with smart detectors.	The process on-foot radiation reconnaissance can be made more efficient with the help of an intelligent radiation detector and the appropriate search method. The localisation time of lost or hidden sources can be minimised. The control of radioactive shipments can be made more accurate by measuring the radiation levels on the surface of the transport container and the external physical parameters of the container and calculating the activity of the delivered radioactive source.	I developed a search method to make the on-foot radiation reconnaissance process more efficient with the help of narrow collimated scintillation detectors and with time optimised searching strategy. I defined basic and advanced inspection methods to improve the control of radioactive shipments by measuring the external physical parameters and radiation level of the container.

No.	Scientific problems	Research objectives	Hypotheses	Proposed research results
5.	Activities with certain radioactive materials release gaseous contamination into the environment. Measurement of emissions is essential if it is to prove that emissions have remained below the officially permitted maximum emission levels. Emissions can be measured in several ways, but the most technology-friendly solution must be found, and several aspects must be taken into account. When choosing a possible solution, it is important that high gamma background radiation does not affect the measured result.	My further goal is to compare different emission control solutions and find the most suitable one for the given task. In addition to the high gamma radiation that often occurs in such systems, the realisation of measuring beta surface contamination.	The selection of the appropriate system for the measurement of released radioactive material can be optimised with the available information and technology. At emission monitoring systems the measurement of beta surface activity is possible at high, dynamically changing gamma dose rate, using the appropriate algorithm and intelligent detector assembly.	I developed a system of criteria for radioactive emission monitoring systems to find the ideal measurement assembly for different technologies. I integrated an intelligent detector assembly into emission control systems, to measure beta surface contamination at high, dynamically varying gamma dose rates.

APPENDIX 2 List of terms and abbreviations

ADR: European Agreement concerning the International Carriage of Dangerous Goods by Road.
AMAR: Automata Mérő és Adatgyűjtő Rendszer. Automated CBRN parameters Measuring and Data Collection System of the Hungarian Defence Forces.
BGO: Bismuth Germanate (Bi4Ge3O12) is a scintillator material; it has a short recovery time after irradiation, ideal for high dose rate measurements.
BM OKF: BelügyMinisztérium országos katasztrófavédelmi főigazgatóság. National Directorate General for Disaster Management.
BNS: Radiation detector family name at Gamma Technical Corporation.
C2: Command and Control.
CBRN: Chemical, Biological, Radiological and Nuclear.
CWA: Chemical Warfare Agent is a chemical substance whose toxic properties are used to kill, injure or incapacitate human beings.
Deadtime: During this time, the detector is not able to detect any new incoming signals. Usually, this value increases when the count rate of the incoming signal increases.
FABV: Földi Atom, Biológiai, Vegyi felderitő. Nuclear, Biological, Chemical Reconnaissance System for VS-BRM2, VS-BTR, VS-BTR2 vehicles.
FWHM: Full Width at Half Maximum. A parameter used for checking scintillation crystal resolution.
GM counter: Geiger–Müller counter is a detector containing a GM tube and electronics used for detecting and measuring ionizing radiation.
GPRS: General Packet Radio Service. A standard communication form used for wireless systems.
GPS: Global Positioning System. A standard used to determine the position of a unit.
GSM: Global System for Mobile Communications.
Gy: The symbol of Gray. It is a derived unit of ionizing radiation dose in the International System of Units (SI). It is defined as the absorption of one joule of radiation energy per kilogram of matter.
H*(10): Ambient dose equivalent. The dose in 10 mm tissue depth (directional equivalent dose) from ionizing radiation.

IH: Radiation detector family name at Gamma Technical Corporation.

IoT: Internet of things.

KML: Katasztrófavédelmi mobil labor. Disaster Management Mobile Laboratory.

KVSF: Könnyű Vegyi-, SugárFelderítő jármű. Light Chemical, Radiation Detection Vehicle.

LaBr: Lanthanum(III) bromide is a scintillator material, it has an excellent resolution, suitable for spectrometric application.

LABV: Légi Atom, Biológiai, Vegyi felderitő. The name of the aerial reconnaissance system of the Hungarian Defence Forces.

LET: Linear Energy Transfer is the amount of energy that an ionizing particle transfers to the material traversed per unit distance.

MDA: Minimum Detectable Activity.

MH: Magyar Honvédség. Hungarian Defence Forces.

MoLaRi: Monitoring és Lakossági Riasztó Rendszer. Automated Monitoring and Alert System of the Hungarian National Directorate General for Disaster Management.

MQTT: MQ Telemetry Transport.

NaI(Tl): Sodium iodide is a scintillator material. High sensitivity for radiation.

NATO: North Atlantic Treaty Organization is an intergovernmental military alliance between 29 North American and European countries.

NBC: Nuclear, Biological, Chemical. It was used before CBRN.

OSJER: Országos Sugárfigyelő, Jelző és Ellenőrző Rendszer. Hungarian National Radiation Monitoring, Signaling and Control System.

PID control: A proportional–integral–derivative controller is a control loop mechanism employing feedback.

PMT: Photoelectron Multiplier Tube. Used at scintillation detectors multiply the current produced by incoming light.

RABV: Robotrepülő Atom, Biológiai, Vegyi felderitő. The name of an unmanned aerial reconnaissance system produced by Gamma Technical Corporation.

RDO-3221:ABV Komondor CBRN reconnaissance vehicle.

RS-485: Standard defining the electrical characteristics of drivers and receivers for use in serial communications systems. It is used for connecting embedded systems.

RTH:	Radiológiai Távmérő Hálózat. Automated Radiological Industrial Safety Telemetry Network of the Hungarian National Directorate General for Disaster Management.
SFK:	Name of a spectrometric radiation detector at Gamma Technical Corporation.
Sv:	Sievert is a derived unit of ionizing radiation dose in the International System of Units (SI) and is a measure of the health effect of low levels of ionizing radiation on the human body.
TCP/IP:	Transmission Control Protocol (TCP) and Internet Protocol (IP).
TETRA:	Terrestrial Trunked Radio. A standard for wireless communication.
TVS-3:	Name of the automatic monitoring station measuring radiological, chemical, meteorological parameters produced by Gamma Technical Corporation.
UAV:	Unmanned Aerial Vehicle.
VFCS:	Veszélyhelyzeti Felderítő Csoportot. Emergency Response Teams.
VS FUG:	The name of a CBRN reconnaissance system used by the Hungarian Defence Forces.
VSBRDM:	The name of a CBRN reconnaissance system used by the Hungarian Defence Forces.
VS UAZ:	The name of a CBRN reconnaissance system used by the Hungarian Defence Forces.
VS-BTR:	The name of a CBRN reconnaissance system used by the Hungarian Defence Forces.

APPENDIX 3 Reference list of figures

APPENDIX 4 Historical outlook. Patents related to radiation measuring instruments in Hungary

In Hungary, the database of patent registrations is freely available. This database also includes patents that have been registered for several decades. In this appendix, I present the patents registered in Hungary and related to radioactive radiation measurement, in order to give a general historical overview of the researches in the field of ionization radiation measurement.

The first patent I found was registered in 1971 and it was issued by Zjednoczone Zaklady Urzadzen Jadrowych "Polon"; Warszawa. The patent title is: Pocket dosimeter to indicate ionizing radiation [84].

Inventor: Chojnacki, Wladyslaw

Entitled to: Zjednoczone Zaklady Urzadzen Jadrowych „Polon"

The patent is about a pocket dosimeter which containing an ionization chamber with a capacitor, an amplifier, a loudspeaker, a sound generator, a power supply, voltage stabilizing and voltage regulating circuit and a multi-position switch. The instruments contain only analogue circuits and convert high radiation level into an audible and visual signal.

Most Hungarian patents in the radiation measurement topic were registered in the year of 1984 and 1985.

The “Method and device for evaluating outer radiation load caused by radioactive radiation sources [85]” was the first patent in this field created by Hungarian authors in 1984.

Inventors: József Solymosi, Ede Bäumler, Sándor Kőrösi, Lajos György Nagy, Péter Zagyvai, Iván Deme, László Dorogi, Árpád Gujgicze, Iván Gresits, János Ruip.

Entitled to: “Gamma Művek”

The patent is about a method and instrument for evaluating the absorbed dose from radiation exposure caused by unknown radioactive sources.

Another patent from 1985 is about charging of a dosimeter, which has a self-reading ionisation chamber [86].

Inventors: Ede Bäumler, Iván Deme, János Tömör.

Entitled to: “Gamma Művek”

The patent is about a charger that can be used to charge a self readable personal dosimeter.

Another patent from 1985 is the “Method and apparatus for measuring the activity of a sample containing beta-emitting isotopes in a high-intensity gamma-radiation background [87]”.

Inventors: József Solymosi, Ede Bäumler, Iván Gresits, Lajos György Nagy, Árpád Gujgicze, László Horváth, Sándor Kőrösi, Ferenc Németh, András Sarkadi, Péter Zagyvai.

Entitled to: “Gamma Művek”, “Budapesti Műszaki Egyetem”.

A system is described in this patent, which allows the evaluation of a sample containing beta-emitting isotopes in a high-intensity gamma background radiation background. A filter in front of one detector prevents the beta particles to reach the detector so that the beta radiation can only be measured by the other detector. Subtracting the results of the gamma detector from the beta-gamma results the activity of beta particles in the sample can be determined.

The following patent: Method and circuit arrangement for measuring surface radioactive contamination [88] are about the determination of the beta surface contamination level of an unknown source.

Inventors: József Solymosi, Ede Bäumler, Iván Gresits, Árpád Gujgiczer, Ferenc Németh, Lajos Nagy, László Horváth, Aandrás Sarkadi.

Entitled to: “Gamma Művek”, “Budapesti Műszaki Egyetem”.

Before the measurement, the patented method uses standard etalons to calibrate the instrument and determine the counting efficiency-energy calibration factors. Then using this factor to compensate the count rate during the actual measurement.

The next patent was registered in 1994, and the title of the patent is: Method and apparatus for detecting radioactive contamination of vehicles and/or their cargos [89].

Inventors: Ede Bäumler, Kálmán Erdős, András Sarkadi

Entitled to: “GAMMA Mûszaki Rt”

The method described in this patent examines the current measurement data against a longer averaged value created in the previous measurement interval. This method uses changing references from the previously collected information and compare it whit instantaneous values. Based on these result it can start a signalling procedure.

The next patent is registerd in 1997 with the title of: “Universal radiation meter and method, as well as circuit arrangement for extending its range[90]”

Inventors: Ede Bäumler, Kálmán Erdős, István Pintér, András Sarkadi, Árpád Gujgiczer, József Solymosi, Ferenc Németh, László Nagy, György Plachtovics. Zoltán Illés, Endre Szabó

Entitled to: “GAMMA Műszaki Rt.”; “Honvédelmi Minisztérium Technológiai Hivatal”; “Budapesti Műszaki és Gazdaságtudományi Egyetem”

This patented method is about extending the measuring range of a radiation measuring instrument, which contains a multi-anode GM tube that automatically shuts off a certain number of anodes at high dose rate tp prevent the GM tube to saturate.

The newest patent in this field was registered in 2003. The title of this patent is: Method and system for deciding edibility of food contaminated with radioisotopes [91].

Inventors: Ede Bäumler, Kálmán Erdős, András Sarkadi

Entitled to: “GAMMA Műszaki Rt.”;

The method of the patent is determined the consumption of foods and liquids contaminated with fission and activation radioisotopes following a nuclear emergency. The method is using a scintillation measuring instrument in which beta-emitting isotopes are divided into soft-beta and hard-beta gamma-emitting isotopes are divided, soft gamma groups and hard gamma groups.

This appendix examines the patents registered in Hungary and focusing on patents related to ionisation radiation measurement.

In total, several patents have been issued in the last 50 years, all but one of which are the result of the work of Hungarian authors.

In addition to patents, several publications on radiation measuring instruments were created in the last 50 years in Hungary. Unfortunately, the full-papers made at the beginning of this time period have not been published on Internet-based journal, so the source is only available to a limited extent. However, the titles of the publications are available on databases. Based on these titles of the publications, it can be stated that the research was carried out on several topics, which was carried out in cooperation with several organizations at that time.

APPENDIX 5 Historical summary of GAMMA Technical Corporation

This Appendix presents the history of GAMMA Technical Corporation, focusing mainly on radiation monitoring system development and manufacturing. On the 18th of May 1920 a mechanical engineer, an electrical engineer and a dealer established the GAMMA Technical Joint Stock Company. Its workshop on Koszorú Street, which was only 45 m^2 in size, was set up in the company of two old-fashioned lathes, a milling machine and a drilling machine, mainly for the sale of patents and the production and repair of mechanical equipment and machine parts. After an initial mood of near-bankruptcy, the company's outlook began to take shape from the second half of the 1920s when the Juhász brothers bought the company. Soon outgrew the small workshop on Koszorú Street, and the development and production facilities were relocated to Fehérvári Street on July 1923, in addition to the gradual expansion of the factory site. After the first patent, it was essential not only to increase the number of workers and create the appropriate engineering background but also to involve new plants in production. Thus the new optical department was founded in 1935.

In the pre-war years, the vast majority of products were created to serve military needs. Between 1932 and 1944, several versions were manufactured of the GAMMA-Juhász automatic predictor (aiming machine for anti-aircraft guns, the sales of which increased the country's export revenues at that time significantly. The equipment was an air defence aid whose task was to follow the targeted aeroplane and to support the aiming of the projectile based on its flight path, taking into account its ballistic properties.

In 1944, Budapest became a battlefield. The number of GAMMA's employees dropped from thousands before the war to a few hundred. The damage was enormous, the buildings were damaged, 70% of the equipment and machinery were lost. Neither the German nor the Soviet presence favoured the availability of hand-held equipment, instruments and high-value raw materials. A period of regeneration followed. Due to losses and lack of orders, they could not start production according to the company profile for a long time. Initially, the typewriters of the Soviet headquarters in Budafok were converted to Cyrillic, making aluminium pans, which were exchanged for food in the countryside, thus ensuring the supply of the workers. The demolition of the ruins of the capital has begun.

GAMMA workers were involved in the renovation of public buildings, schools and flats, which was often accompanied by only a small amount of food in difficult times.

After the World War, despite the efforts, the company reached an economic low point, eventually losing its corporate status in 1947, GAMMA became state-owned. Under the first five-year plan after the war, the company recorded a significant increase in production, expanded its area and invested a lot of energy in educating the younger generation. In the late 1940s and early 1950s, they focused primarily on the development and production of smaller, low-cost, high-volume consumer goods. Perhaps this period can be called the heyday of the GAMMA optical department. In addition to spectacle lenses, the development of microscopes, theodolites, photographic instruments and projectors began simultaneously. An outstanding photo apparatus was named after Jenő Dulovits Duflex, or the "Kinga" and "Pajtás" cameras, which were also pioneering in an international context.

From the mid-1950s, the nuclear threat associated with the onset of nuclear armaments not only gave great impetus to the domestic nuclear industry but also significantly reshaped the production profile of GAMMA. The technical and intellectual background of contemporary nuclear culture was provided by the "Központi Fizikai Kutatóintézet" (KFKI, Central Physical Research Institute). At the dawn of the development of scintillation measurement technology, Csillebérc excelled primarily in electronic developments, while the first crystals were grown at the Department of Medical Physics of the Budapest University of Medicine. The first Hungarian-made dosimeter was developed at the Institute of Oncology with the help of Professor Dr. László Bozóky. The decision made at the upper level, according to which GAMMA was designated as the industrial base of the domestic nuclear instrument industry, played a decisive role in the development of the nuclear profile of GAMMA. Following the profiling, not only the civilian and military needs of nuclear instrument manufacturing had to be met, but also capacity had to be provided for producing complex military CBRN products. To this end, the transfer of the optical profile to the "Magyar Optikai Művek" (MOM) has started together with the entire team of professionals. The success of the military technology developments of the 1960s, especially in the field of nuclear, biological and chemical (ABV) defence equipment, was largely due to the fact that the government primarily supported the development of smaller and less money-intensive "weapons". The first development regarding radiation measuring instrument was carried out by the "Irodagépipari" Company on behalf of the Institute of Military Technology.

In the early 1960s, large-scale production of first-generation instruments such as the IH-2 ion chamber detector (1962 - 1966), the IH-3M on-board radiation detector and the GM tube-based IH-12 radiation detector.

In addition to the military profile, medical applications on the civilian line represented a larger market for nuclear instruments. The development of laboratory-type measuring units has started. The automatic isotope measuring point (hollow measuring point, automatic sample changer) has been introduced. The liquid scintillator beta radiation meter has been developed to perform special measurement tasks. In the meantime, the display possibilities of transistor technology were opened up by incorporating radiation measurement capabilities into a smaller, lighter instrument, thus creating a semiconductor-based radiation meter called Transrate, which was manufactured for civilian use.

The second and third-generation instrument families were developed in the 70s and 80s. In this period, the series production of semiconductor detector instruments has been completed. The IH-5 was a radiation level measuring instrument that met the military requirements, operating even in extreme climate conditions, which could also be used to determine the surface beta contamination of equipment and food by adjusting the window on the probe. The IH-81 was also a combined radiation and contamination measuring instrument that measures the allowable occupancy time on a given terrain section based on preset limits. As a result of the cooperation, new instruments have also been systematized in the field of CBRN, such as the Automatic Chemical Indicator (AVJ) or the Fast-Reacting Chemical Indicator (GVJ).

The SVJ-1, 2 radiation hazard level indicator was added to the production line in 1984. SZÉM-1 gives instructions on the consumption of food and liquids from the changes in the composition of fission products and the calculation of the fall-out time.

In 1993, the company was again privately owned through a group of investors.

The IH-90 hand-held instrument for measuring radiation contamination, with its alpha and beta detection capabilities, has also been a great success. Semiconductor technology has been replaced by large-area GM tube instruments from the second half of the 1990s. In the IH-95, which is still in production today, the measuring range has been extended. A feature of the portable application is that the same instrument, except for its carrying case, is also suitable for the detection of surface alpha, beta contamination through the end-window GM tube.

This multi-functional hand-held unit allowed the soldier to obtain dose, dose rate, and surface contamination measurement data on a single display instead of using multiple instruments simultaneously.

The civilian version of the instrument is the BNS-92S, which is suitable for measuring the ambient dose rate (H * (10)). Whether it is a mobile or transmitter version, the GM tube applications represent a well-developed, reliable technology.

The IH-111 radiological field food tester allows rapid radiological examination of solid or liquid foods. With the help of multilayer scintillator detector, it is able to separate the gamma and beta waveforms and display the level of the contamination of the tested substance. In addition to food testing, it is excellently suitable for the analysis of environmental samples of any origin with a PC connection and spectrometry software package.

Currently, one of the most versatile product families in GAMMA is intelligent scintillation detectors. By shrinking the rack cabinet-sized measuring system into a hand-held instrument, it can be used in a wide variety of applications, like in a low background laboratory, educational or aerial applications.

The fastest and perhaps the most efficient method for reconnaissance of large terrain area is using aerial radiation monitoring systems. The LABV reconnaissance system, which is now standardized in the Hungarian Defence Forces, is housed in a container that can be hung on a combat helicopter. Following the redesign of the LABV system, the UAV-mounted RABV series was created, which is well-proven for the detection of point-like radiation sources even in extreme meteorological conditions.

The development of ground vehicle on-board reconnaissance devices began in the 1950s, and a modernisation had been started in the early 1990s with the compromise conversion of Russian-made base vehicles. This is how the FABV system was installed in the VS-BRDM 2 and VS-BTR vehicles.

The FABV system is able to detect radiation, and chemical warfare gases, measure meteorological parameters and transmit the data in a NATO standard format report. The Disaster Management Mobile Laboratories (KMLs) were developed in 2012 to support on-foot and on-board reconnaissance, route monitoring. On-board radiation portal monitor BNS-94FM was integrated into this vehicle. The instrument is a scintillation detector containing a NaI(Tl) scintillation crystal equipped with a neutron-sensitive layer, which has high sensitivity and a significant directional dependence due to its built-in collimator. The BNS-94FM can be used for localization of point-type radioactive sources.

Also can be mounted on a tripod, it is excellent for monitoring vehicles or persons passing through supervised checkpoints.

As a result of a development that started in 2010, the family of light armoured combat vehicles, named Komondor, was born and created at GAMMA.

A CBRN reconnaissance version has also been created, as well as a rapid response vehicle specifically for use in a radiation-contaminated area to evacuate injured/contaminated persons.

GAMMA has installed an early warning system for the Hungarian Defence Forces, the so-called Automatic Measurement and Data Acquisition System (AMAR), which was upgraded in the early 1990s using the TVS intelligent nuclear and chemical monitoring station. The station has a modular structure and can be equipped with self-calibrated meteorological, chemical or nuclear transmitters. The TVS family has since been used in a number of applications, and the latest developments also allow for isotope identification. Among the nationwide networks, GAMMA supplied and serviced the monitoring stations of the Radiological Telemetry Network (RTH) operated by the BM OKF, as well as the monitoring subsystem of the Monitoring and Public Alarm System (MoLaRi), which is currently the largest monitoring system in Hungary used for supervising the released dangerous gases from chemical factories.One of the defining applications of scintillation measurement technology is the control of illegal radioactive and nuclear material at border crossing points and other cargo and baggage inspection points. The BNS-94 radiation portal monitor family is used to detect radioactive sources carried by vehicles or persons and their cargo, and its internal measurement procedure automatically takes into account momentary changes in background radiation.

As a result of a strategic partnership with Respirator Company, founded in 1928, GAMMA moved to a new location at Illatos street 11/b on the Pest side of Budapest. The merging of Respirator in 2015 opened new horizons for GAMMA, as the personal protective equipment and decontamination systems manufactured by Respirator complement the detection capability of GAMMA, thus providing customers with full CBRN support service.

After the merging of the two company new developments were started and the Komondor Armored vehicle family was born. The first vehicle in the family was a CBRN reconnaissance vehicle, which was designed especially for this purpose. With this development step finally, a Hungarian made CRBN reconnaissance system was integrated into a Hungarian made vehicle. This appendix presented the history of GAMMA from its beginnings to the present day [92].

János Tamás Petrányi   Budapest, 2020.11.13