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Design of a prototype gamma-ray and neutron measurement station for spent fuel characterisation prior to encapsulation

Linus Ros[1], Markus Preston[2], Ulrika Bäckström[3], Emil Huuva[2], Henrik Liljenfeldt[4], Amela Mehic[2], Jan-Olov Stål[2]

1 Prevas Test & Measurement AB
2 Svensk Kärnbränslehantering AB
3 Vattenfall AB
4 Noemi Analytics AB

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Summary

Prior to encapsulation of spent nuclear fuel in Sweden, all fuel assemblies will be characterised using non-destructive measurements of gamma-rays and neutrons emitted from the fuel. Such measurements can provide an important validation of calculations of fuel properties that impact the safety of the encapsulated fuel. Furthermore, non-destructive radiation measurements can also be used to determine fuel properties of interest for nuclear safeguards. This opens a possibility for a joint measurement station which allows determination of fuel parameters both for nuclear safety (by the operator SKB) and nuclear safeguards (by safeguards authorities). A prototype of a measurement station that could serve these purposes has been developed by SKB. It uses a combination of gamma-ray and neutron detectors to allow determination of multiple radiation signatures of assayed fuel assemblies. This report describes the design of this prototype, gives an overview of the radiation signatures which are planned to be measured and gives a brief description of the methodology for analysing data collected with the prototype. This is done in particular in view of a measurement campaign which is planned to take place at Clab in Oskarshamn.

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1 Introduction

Over the past decades, the Swedish Nuclear Fuel and Waste Management Company (SKB) has been managing spent nuclear fuel from Swedish nuclear power plants as well as developing a method for final disposal of this spent fuel in a geological repository. The Swedish system for a geological repository for spent nuclear fuel is referred to as KBS-3 (SKB 2010). An important part of the KBS-3 concept is a facility for encapsulating spent nuclear fuel in copper canisters, which will be built as an extension to Clab, the existing interim storage facility for spent nuclear fuel in Oskarshamn, Sweden. The combined facility is referred to as Clink, where fuel assemblies currently stored at Clab will be brought out of interim storage and encapsulated in copper canisters.

Once a sealed copper canister has been placed in the final repository, three main barriers – the copper canister, the bentonite clay around it and the host bedrock – will protect the environment from the spent nuclear fuel within the canister. There are also several safety requirements placed on the properties of the fuel itself. These include decay heat, reactivity and radiation emission rates. To ensure that such safety requirements are met, a measurement station for characterising the spent nuclear fuel just before encapsulation using radiation detection is planned for Clink. Such measurements can be used to validate calculated properties of the spent nuclear fuel.

In addition to the measurements which are of interest to SKB from an operator point of view, all fuel that will be encapsulated should also undergo safeguards verification by safeguards inspectorates. The measurement system developed by SKB has been designed in such a way that it could, if agreed upon, be used as a single joint measurement system by SKB (to determine safety-relevant parameters) and safeguards inspectorates (to verify completeness and correctness of operator declarations).

1.1 Motivation

Since 2022, a project (KBP6004) at SKB has been ongoing with the aim of developing and testing a prototype measurement station for gamma-ray and neutron measurements on spent nuclear fuel. The design of this measurement-station prototype builds on earlier research on suitable properties for such a measurement station in view of the operational requirements from SKB as well as identified safeguards requirements. However, the project should not only be seen as a research project but a development of a full-scale prototype for testing in an industrial environment at Clab.

Gamma-ray and neutron measurement techniques are among the most common non-destructive assay (NDA) techniques for spent nuclear fuel (Kaplan-Trahan et al. 2024, pp 605-637) and allow determination of various spent fuel properties within limited measurement times. However, detailed quantitative radiation measurements on spent nuclear fuel also come with inherent challenges due to the high-intensity mixed radiation field in and around the fuel which places requirements on the choice of detector materials, electronics and overall instrument design in terms of radiation tolerance and count-rate capabilities. Furthermore, the geometrical dimensions of the fuel assemblies and the complex radionuclide content in the fuel introduces further factors which have to be considered in the system design. The prototype has been developed to allow measurements of gamma-ray and neutron signatures of spent fuel such that safety parameters of the fuel can be determined with as low uncertainties as possible without impacting the integrity of the fuel. In addition, the system has been developed such that also safeguards-relevant parameters can be determined.

The philosophy behind the design is based on research and development efforts of the wider research community over the past decades, where integration of multiple gamma-ray and neutron detection systems into a single measurement station has been proposed and researched, see for example (Tobin and Jansson 2013) and references within. A well-established NDA technique for use in safeguards verification is the Fork detector (Vaccaro et al. 2018), which measures total gamma-ray and neutron count rates. Integrating multiple systems allows measuring multiple complementary radiation signatures which together provide more detailed information about the assayed fuel assembly, which is of particular interest prior to encapsulation of fuel. The measurement station described in this report is an example of a system advancing the capabilities of such integrated systems by incorporating several measurable radiation signatures. Integrating multiple systems into a single measurement station with the particular application to fuel characterisation before geological disposal has also been evaluated by for example the ASTOR (Application of Safeguards to Repositories)

Group of Experts coordinated by the International Atomic Energy Agency (IAEA). SKB has been involved in this forum and conclusions drawn by ASTOR have been used as key input to the ongoing project at SKB.

Measurements with SKBs measurement-station prototype are planned to take place at Clab in late 2025, when around 50 to 100 BWR and PWR fuel assemblies will be measured to allow evaluation of the system performance. A schematic overview of the measurement setup at Clab is shown in Figure 1-1. As shown in this figure, measurements will take place under water, as is planned for future measurements before encapsulation at Clink. The fact that the measurement station will operate under water has had a significant impact on the design of the system, as will be described later in this report.

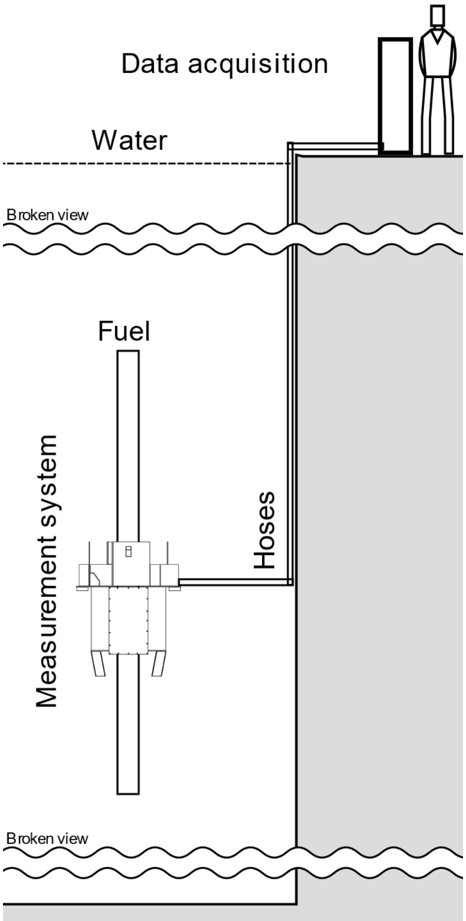


Figure 1-1. Schematic overview of the setup of measurements with the prototype at Clab. The prototype will be mounted on a rack in a fuel-handling pool and cabling in hoses will be connected to a data-acquisition beside the pool. Each fuel assemblies will be held still in the prototype with a fuel-handling machine throughout each measurement.

This document describes the developed measurement-station prototype, technical details on its design and operation as well as a description of the planned method for analysing and evaluating the data from the measurements planned for late 2025.

2 Measurable signatures

The radionuclide inventory in a fuel assembly which is to be encapsulated will impact properties such as decay heat, reactivity and radiation emission rates of that assembly. The radionuclide inventory also contains information about other properties and history of the fuel assembly in and out of the reactor core. A gamma-ray and/or neutron NDA measurement should use measurable radiation signatures to allow determination of such properties of the fuel assembly. The prototype developed by SKB contains both gamma-ray and neutron detectors surrounding a channel in which a single fuel assembly can be positioned. These detectors allow measuring multiple radiation signatures from a fuel assembly.

- Two gamma-ray scintillation detectors, positioned at two of the four corners of the fuel channel in the prototype: gamma-ray spectra and peak intensities.
- A total of 96 neutron detectors (divided into four containers, one on each of the four sides of the fuel channel in the prototype): total neutron count rate and neutron coincidences.

Together, these measurable signatures provide complementary information about the measured fuel assembly (for example, these signatures have different sensitivities to enrichment, burnup, cooling time and different sensitivities to different regions of the fuel assembly).

The measurable signatures, and the information they provide, will now be described briefly. More details on the particulars of the detectors and readout electronics are provided in Section 3.

2.1 Gamma-ray signatures

The use of gamma-ray scintillation detectors in the prototype allow measurements of gamma-ray spectra of the measured fuel assemblies. These detectors are located in two of the four corners of the prototype, allowing measurements at a specific axial position of the fuel assembly (or axial scanning by lowering or lifting a fuel assembly through the prototype). By rotating the fuel assembly, gamma-ray spectra from all four corners can be measured.

By incorporating gamma-ray spectroscopic capabilities into the prototype, individual line intensities as well as the total gamma-ray count rate can be determined. Of particular interest is the 662-keV gamma-ray line from ^{137}Cs, as this is well known for correlating well with the assembly burnup (Kaplan-Trahan et al. 2024, pp 611-612). The absolute detection efficiency of these 662-keV gamma rays will be determined for each fuel assembly type using a methodology described by Bengtsson et al. (2022), where an efficiency calibration with a known ^{137}Cs source is combined with a geometric factor which depends on the fuel assembly type. This procedure allows determining the ^{137}Cs activity in each fuel assembly. Because spectroscopic data will be collected for each fuel assembly, also other gamma-ray peaks (such as those from ^{134}Cs and ^{154}Eu) could be analysed.

The total gamma-ray count rate includes contributions from other radionuclides than ^{137}Cs, depending on the history of the fuel assembly and can provide joint information about the burnup and cooling time of a fuel assembly (Kaplan-Trahan et al. 2024, pp 610-611). As such, this parameter could provide additional information and will also be analysed.

2.2 Neutron signatures

The prototype contains a total of 96 neutron detectors divided into four detector pods, one pod on each of the four sides of the measured assembly. The general design of this part of the prototype is based on the DDSI technique described for example by Trahan et al. (2020), although with a number of changes in terms of detector material, detection principle, readout electronics, etc. The principles behind the DDSI technique are still valid, i.e. that both the total count rate in the detectors are registered but also coincidences between different detectors. These coincidences can be used to determine the Rossi-Alpha distribution, which depend on the properties of the measured fuel assembly. Time-correlated neutrons can either originate from the same fission event or from the same chain of fission events. The relative intensities of these processes will depend on both the intrinsic neutron source rate of the measured fuel assembly, but also on the multiplication of the fuel assembly. These processes will also give rise to various contributions to the Rossi-Alpha distribution: its amplitude and time characteristics will therefore depend on the neutron source rate and the multiplication. A parameter known as the early die-away time (determined from fitting a function to the Rossi-Alpha distribution) has been shown to provide valuable information about various properties of the measured fuel assembly (Trahan et al. 2020).

In addition to measuring time-correlated neutrons, also the total neutron count rate will be measured. This parameter is also sensitive to the properties of the fuel assembly, although in a different way than the early die-away time of the Rossi-Alpha distribution (Kaplan-Trahan et al. 2024, pp 618-619). Existing measurement techniques have used the total neutron count rate (together with the total gamma-ray count rate) to confirm spent fuel properties (Gauld et al. 2015, Vaccaro et al. 2018).

3 Prototype design

The mechanical structure of the prototype, shown in Figure 3-1, is made out of electropolished stainless steel. As shown in Appendix A, it has a maximum width of 1095 mm and a maximum height of 1453 mm. The total weight of the prototype is 1643 kg (in air), out of which 210 kg are hoses including cabling. All detectors will be housed in sealed and water-tight containers.

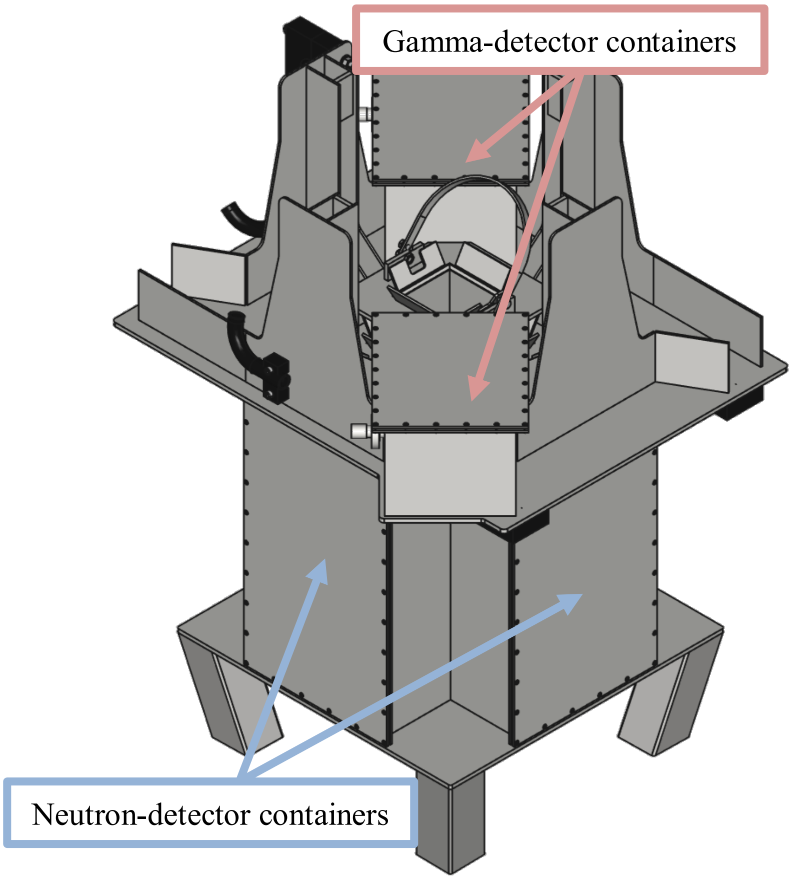


Figure 3-1. *Overview of SKB's measurement-station prototype. Containers for gamma-ray and neutron detectors are highlighted. The prototype also includes two neutron-detector containers on the opposite sides of the prototype (hidden from view here). Cables to and from the detectors are contained in hoses which are coupled to the prototype with water-tight connectors (connections shown in black). This image also shows the BWR insert in the centre of the prototype. This is only placed in the prototype during measurements on BWR assemblies which have a smaller geometrical cross section than PWR assemblies.*

During the measurements planned for late 2025, a BWR insert will be used when BWR assemblies are to be measured. This insert is a mechanical structure which can be inserted into the fuel channel and will act to remove water between the fuel assembly and the detector containers, which is important for the neutron measurements where the die-away time of the system is an important parameter. This insert is not needed when measuring PWR assemblies, as these will fill up a larger portion of the fuel channel. Additionally, a structure for holding a ^{137}Cs gamma-ray calibration source and a ^{252}Cf neutron calibration source in the prototype will be used for periodical calibration measurements. This holder can hold the ^{137}Cs gamma-ray source at the axial level of the gamma-ray detectors and is important for allowing determination of gamma-ray efficiency calibration factors (see Section 2.1). The holder can hold the ^{252}Cf neutron source at the axial centre of the neutron detectors and will be used for neutron-efficiency calibrations. During the measurements, especially the neutron detectors will be exposed to a high-intensity flux of both neutrons and gamma rays.

During the measurement campaign the expected dose to the neutron detectors will be several orders of magnitude lower than it would be when radiation-induced degeneration of the detectors is expected to be visible. Nevertheless, the sources will also be utilised to monitor any potential radiation-induced degradation of the detector performance.

The dimensions of the fuel channel in the centre of the prototype are such that a PWR assembly can be lowered into the channel. A 50 mm thick layer of lead (encased in the stainless-steel structure) is positioned between the spent fuel assembly and the neutron detectors to reduce the gamma-ray flux into the neutron detectors. For the prototype design, the lead thickness was limited to keep the weight of the system limited and to ensure that the prototype can be handled at Clab.

More detailed drawings of the prototype as a whole may be found in Appendix A. Now, the technical details of the gamma-ray and neutron detectors as well as the readout electronics will be described. It should be noted already here that the choice of detector types, geometrical configurations and the overall design of the prototype has been made to optimise the sensitivity to the measurable signatures of interest, which are described in detail in Section 2. These choices and optimisations have been made through a combination of simulations and experimental studies throughout this and earlier projects at SKB.

3.1 Gamma-ray detectors

As shown in Figure 3-1, the prototype contains two water-tight containers for gamma-ray detectors. These are placed at two of four of the corners of the centre channel of the prototype, meaning that the detected gamma rays will predominantly come from the fuel pins near the corners of the measured assembly. Each container contains a B380 lanthanum bromide ($LaBr_3$) scintillation detector (Luxium, n d) with the dimensions (width × height × thickness) 25,4 mm × 25,4 mm × 38,1 mm. This detector is embedded in high-Z materials with a thin slit in the direction of the fuel channel.

The $LaBr_3$ detector was chosen due to its relatively high energy resolution (≤3,5% at 662 keV according to manufacturer specifications) and high count-rate capabilities. Each detector is embedded in a cylinder of densimet D185 (Plansee 2024) – a tungsten-based material with good gamma-ray shielding properties – and a block of lead. Through these high-Z materials, a 209 mm long, 10 mm wide and 1.5 mm high collimator slit is directed towards the fuel channel. An exploded view of the gamma-ray detector and other materials in the gamma-ray detector container is shown in Figure 3-2.

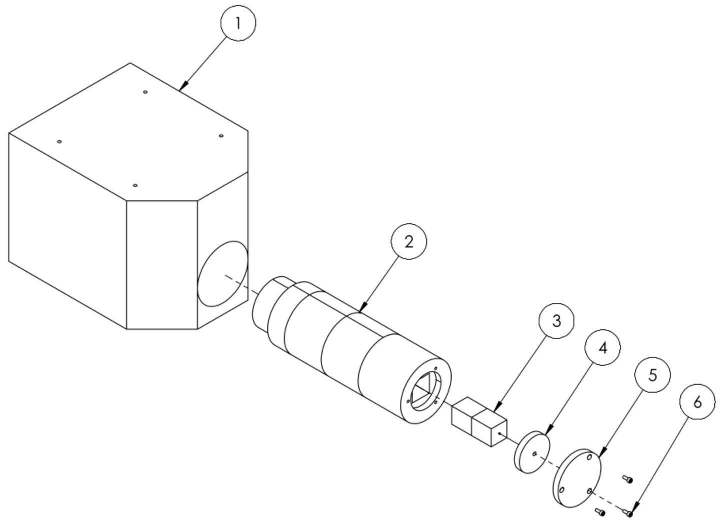


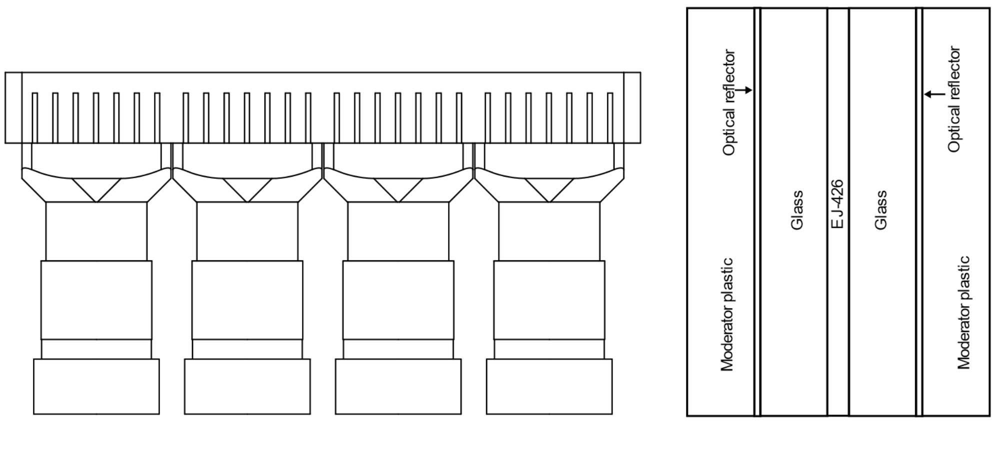
Figure 3-2. *Exploded view of one of the two gamma-ray detectors in the prototype. The water-tight gamma-detector container shown in Figure 3-1 contains a block of lead (1), in which a cylinder of densimet D185 (2) is embedded. A thin collimator slit with a length of 21 cm exists through these materials. A LaBr3 crystal coupled to a photomultiplier tube (3) are embedded into the back end of the densimet cylinder. This end of the cylinder is sealed by two densimet plates (4 and 5) and kept together with screws (6).*

The signals from each gamma-ray detector are read out using a Hamamatsu R11265 photomultiplier tube (PMT) (Hamamatsu 2019). The signal from the PMTs are output via coaxial cables, contained within water-tight hoses leading to a data acquisition system at the pool side. There, the signals are shaped using a Cremat CR-200 shaping amplifier (Cremat 2017) from which the shaped signals are sent to a Red Pitaya data acquisition board (see below). Each gamma-ray detector is supplied with high voltage from a Caen NDT1470 module (Caen, n d-a). All cables to and from the prototype are contained within water-tight hoses that are attached to the prototype and connected to a data acquisition system by the side of the pool.

Each gamma-ray detector is individually connected to an input channel on a Red Pitaya SIGNALlab 250-12 device (Red Pitaya, n d-a), which has a sampling frequency of 250 MSPS and an ADC resolution of 12 bits. The readout electronics board contains an FPGA which processes data from the two input channels, analyse the signals (i.e. their waveforms) in real time and trigger on individual pulses of interest. For each detected pulse, the time and amplitude of each pulse is determined on-line by the FPGA. The pulse height is approximately 1 V. The pulse-height resolution, which is the primary quantity of interest for gamma-ray detection, is 0.49 mV given the 12-bit resolution of the ADC. The time and pulse-height information are acquired for each detected signal and stored for analysis.

3.2 Neutron detectors

As shown in Figure 3-1 the prototype contains four water-tight containers for neutron detectors (two of these are hidden from view in Figure 3-1). These are placed at all four sides of the centre channel of the prototype. The motivation for this is to increase the total neutron detection efficiency and to reduce the potential impact of fuel assemblies possibly being slightly non-centred in the fuel channel. Each container contains 24 neutron detectors, all of these being embedded into a block of polyethylene for neutron moderation. Each neutron detector consists of EJ-426-0 scintillators (Eljen Technology 2021) in a sandwich configuration shown in Figure 3-3. EJ-426 is a material which combines ^{6}LiF and ZnS. When neutrons interact in ^{6}LiF, charged particles (^{3}H and ^{4}He) may be released in nuclear reactions. When these charged particles interact with ZnS, scintillation light is produced. Each sheet of EJ-426 is sandwiched between two glass sheets which are covered on the outside by reflective foil. These acts as light guide transporting the scintillation light to a Hamamatsu R6237 PMT (Hamamatsu, n d). Each neutron detector contains seven such sandwiched EJ-426 sheets. All sandwiched detectors in the detector container are embedded in a polyethylene moderator plastic to thermalize neutrons entering the detectors. The thickness of the polyethylene is 36 mm and the slits for the sandwiches are 25.5 mm deep. This particular detector design (i.e. sandwich design, number of scintillator sheets per PMT and so on) was made such that the neutron detection efficiency and the neutron die-away time of the system are optimised.



(a) *(b)*

Figure 3-3. *(a) Top view of one neutron-detector container, showing the sandwich configuration of EJ-426 scintillators coupled to photomultiplier tubes. 7 sandwiched scintillator sheets are coupled to each PMT and all sandwich structures are embedded in moderator plastic (polyethylene). (b) A detailed view of the sandwich configuration of a single scintillator sheet. Each sheet of EJ-426 is sandwiched between two glass sheets which on the outside are covered by a reflective foil (the glass acts as a light guide for the scintillation light).*

The signals from each neutron detector are read out using a Hamamatsu R6237 PMT (Hamamatsu, n d), which has a square surface which fits the dimensions of the sandwiched detectors (these PMTs are spaced 1 mm apart within the array of 24 detectors in each neutron-detector container. The signal from the PMT is output via a coaxial cable. Each neutron-detector container is supplied with a total of 12 high-voltage cables from a Caen A7435 high-voltage supply (Caen n d-b). That is, every pair of detectors in the container share a single high-voltage input (again, there are 24 detectors per neutron-detector container).

The inside surface of each neutron-detector container is coated with cadmium to limit the flux of thermal neutrons from the fuel channel into the detector block. Instead, the aim is to let faster neutrons pass into the detector block, thermalize in the polyethylene and give rise to signals from the thermal-neutron detectors. The rationale behind this is that the system is sensitive to fast fission neutrons (either from spontaneous or induced fission) from the fuel assembly. Furthermore, the die-away time of the system is reduced by this approach.

Each neutron detector is individually connected to an input channel on a Red Pitaya STEMlab 125-14 4-input device (Red Pitaya, n d-b), which has a sampling frequency of 125 MSPS. Given that a total of 96 neutron detectors are read out, 24 such readout electronics boards are used, each having four individual input channels. The readout electronics board contains an FPGA which processes data from all four channels, analyse the signals (i.e. their waveforms) in real time and trigger on individual pulses of interest. For each detected pulse, the time and amplitude of each pulse is determined online by the FPGA. The resulting time resolution, which is the primary quantity of interest for neutron detection, is 8 ns. The time and pulse-height information are acquired for each detected signal and stored for analysis. This means that the prototype acquires list-mode data which can be used to determine e.g. the Rossi-Alpha distribution for the measurement.

3.3 Water and temperature sensors

Because the prototype will be used underwater, it has been constructed such that all components are housed in water-tight containers and all cables contained within hoses with water-tight connections to the prototype. To further mitigate the risks associated with water leakage into the detector containers, the prototype includes a total of 12 GRI 2605 water sensors (George Risk Industries, n d) in the different detector containers. These sensors are sensitive to moisture and will give an alarm if moisture is detected within any of the detector containers. Should this happen, the prototype can be removed from the pool and examined. During the year the temperature in the pool varies with the season. These temperature changes will have an effect on e.g. the gamma-ray attenuation in the surrounding water and neutron interactions in the surrounding water. Also the response of the detectors can be impacted by temperature changes. These effects are small, but to have the ability to correlate events seen in the data with the temperature two Pt100-Resistance thermometer temperature sensors (TiTEC 2017) are mounted in the gamma-ray detector containers. These are connected to a Red Pitaya STEMlab 125-14 device (Red Pitaya, n d-b) via Click Shield (Red Pitaya, n d-c) and MIKROE Click Boards (MIKROE, n d-a, MIKROE, n d-b). The signals from these sensors will be continuously monitored during the measurement campaign.

3.4 Data collection and on-line monitoring

During the prototype measurement campaign, all readout electronics, high-voltage supplies and data acquisition hardware will be housed in a rack at the side of the pool. All the needed hardware has been integrated into the autonomous control and data acquisition system Constellation (The Constellation authors, n d), this to ensure seamless control, data acquisition and monitoring. The control and analysis software have been written in Python (Python, n d) and all the monitored data is stored in an InfluxDB (InfluxData, n d) database and are visualised using Grafana (Grafana, n d). During measurements, data quality can continuously be monitored directly on the data acquisition computer. An example of the visualisation of some of the monitored parameters is shown in Figure 3-4.

Figure 3-4. *Example of visualization of three of the monitored parameters in the Grafana interface: triggers per second per detector (top), CPU load of each readout board (middle) and high-voltage level for each pair of detectors (bottom). These data were collected during a measurement with a* ^{252}*Cf calibration source.*

All measurement data will be stored in The Hierarchal Data Format version 5 (HDF5) (The HDF Group, n d). The HDF5 format is a binary data format that supports large amount of complex heterogenous data. This allows for the possibility to re-evaluate the data and also the possibility to perform offline analysis elsewhere. A graphical user interface for direct analysis of the acquired HDF5 data has been developed. Figure 3-5 shows an example of how this user interface can be used to fit an exponential function on a flat background to the acquired Rossi-Alpha distribution, in this particular example acquired from measurements on a ^{252}Cf calibration source. This fit can be used to determine the early die-away time (see Section 2.2).

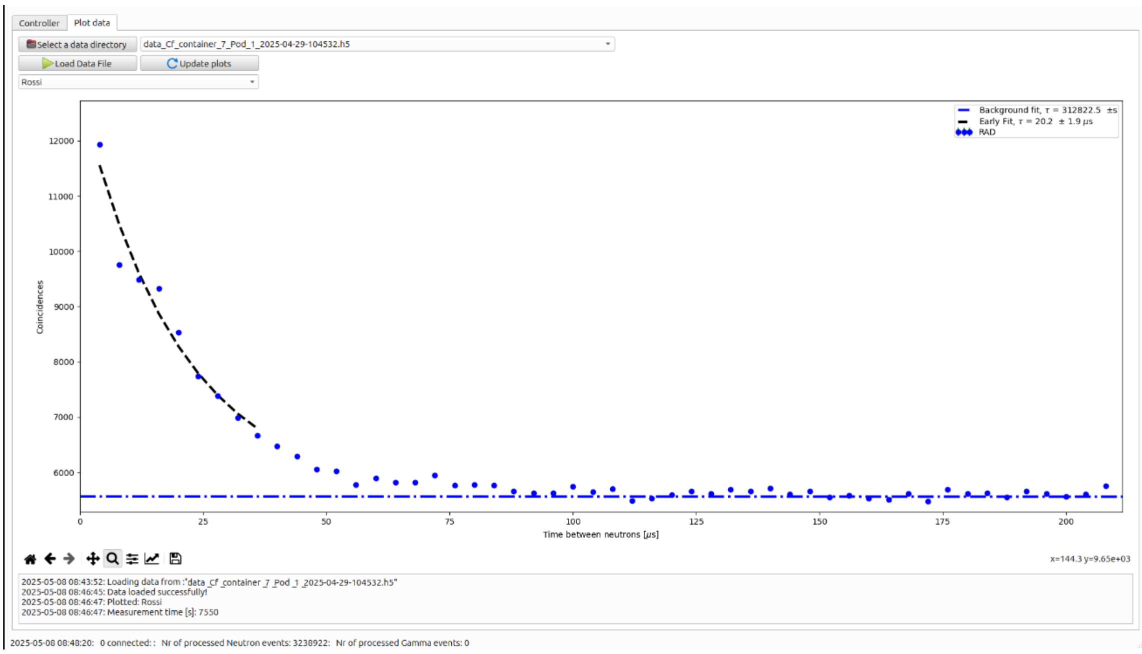


Figure 3-5. *The analysis part of the graphical user interface which can be used to analyse measurement data. In this case, the early part of a Rossi-Alpha distribution (acquired by measurement on a* ^{252}*Cf calibration source) has been fitted with an exponential function and a flat background to determine the early die-away time.*

4 Modelling of the prototype

As described in Section 2, the prototype can be used to measure a number of radiation signatures from a fuel assembly. When combined, these signatures probe various properties of the measured fuel assembly. At the same time, SKB has records of the history of each fuel assembly in and out of core, which are to be confirmed through measurements with the prototype and eventually at Clink. These records allow calculations of the radionuclide inventory in each fuel assembly which is to be measured in the planned measurement campaign. By combining these inventory calculations with a detailed Monte Carlo model of the prototype, the expected measurable signatures can be simulated.

4.1 Radionuclide inventory and source terms

SKBs data on fuel assemblies at Clab allow calculating the expected radionuclide inventory in each assembly as well as the gamma-ray and neutron source terms for that assembly. These calculations will be performed using SNF (Studsvik Scandpower 2024) and SCALE (Wieselquist and Lefebvre 2024). The calculated parameters describe the best estimates given the available data on each fuel assembly. These calculations incorporate information such as irradiation history, void history (both of these with data on axial distributions) and other such parameters which could impact the measurable signatures.

4.2 Modelling of measurable signatures

A detailed Monte Carlo model of the prototype has been developed in MCNP (Kulesza et al. 2022) and includes both the entire measurement system and all fuel geometries which will be measured during the 2025 measurement campaign. The radionuclide inventory and source terms of the fuel (determined as described in Section 4.1) are used as inputs to this model to allow modelling of detector responses to the selected fuel assemblies. This means that the model will predict the values of the measurable signatures for each fuel assembly given the best estimates on the properties of that assembly. Once the measurements have been performed, the measurements can be compared with the predictions from the model for each assembly.

5 Data analysis and evaluation

The prototype will output so called list-mode data from all detectors, meaning that individual measured signals will be time-stamped and stored by the data acquisition system. This allows great flexibility in the analysis and also allows determination of all measurable signatures described in Section 2. For each measured fuel assembly, there will be a set of signatures which have been estimated through calculations and determined through measurements.

- Gamma-ray spectra.
- Total gamma-ray count rate.
- Rossi-Alpha distribution and early die-away time.
- Total neutron count rate.

The calculated values of these parameters for each fuel assembly will be based on the best available knowledge about the properties of the fuel assembly, which have been assumed in the MCNP modelling. The true underlying properties of the fuel, which are to be confirmed by the comparison between measurement and calculations, will impact both the measurable signatures in different ways as well as the important parameters such as decay heat.

A comparison between the measured and calculated parameter values will make it possible to determine whether the assumed fuel parameters have been confirmed by the experimental data or not. If the two do not agree, further investigations can be performed.

The proposed approach of comparing experimentally measured data with data from detailed simulation of measurement systems, builds upon earlier work such as in (Gauld et al. 2015, Vaccaro et al. 2018). However, the prototype described here incorporates additional measurable signatures which provide additional information about the assayed fuel assemblies. Because the various measurable signatures utilised in the prototype probe different properties and geometrical regions of the fuel assembly, the combination of these signatures are expected to provide a high degree of accuracy for confirming the properties of the fuel assemblies to be measured in the 2025 measurement campaign and that the same technique could also be used to confirm the properties of fuel before encapsulation. The utilised measurement techniques are well-established for spent fuel measurements and have also been used and proposed for use in the context of nuclear safeguards.

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Appendix A – Technical drawings of prototype

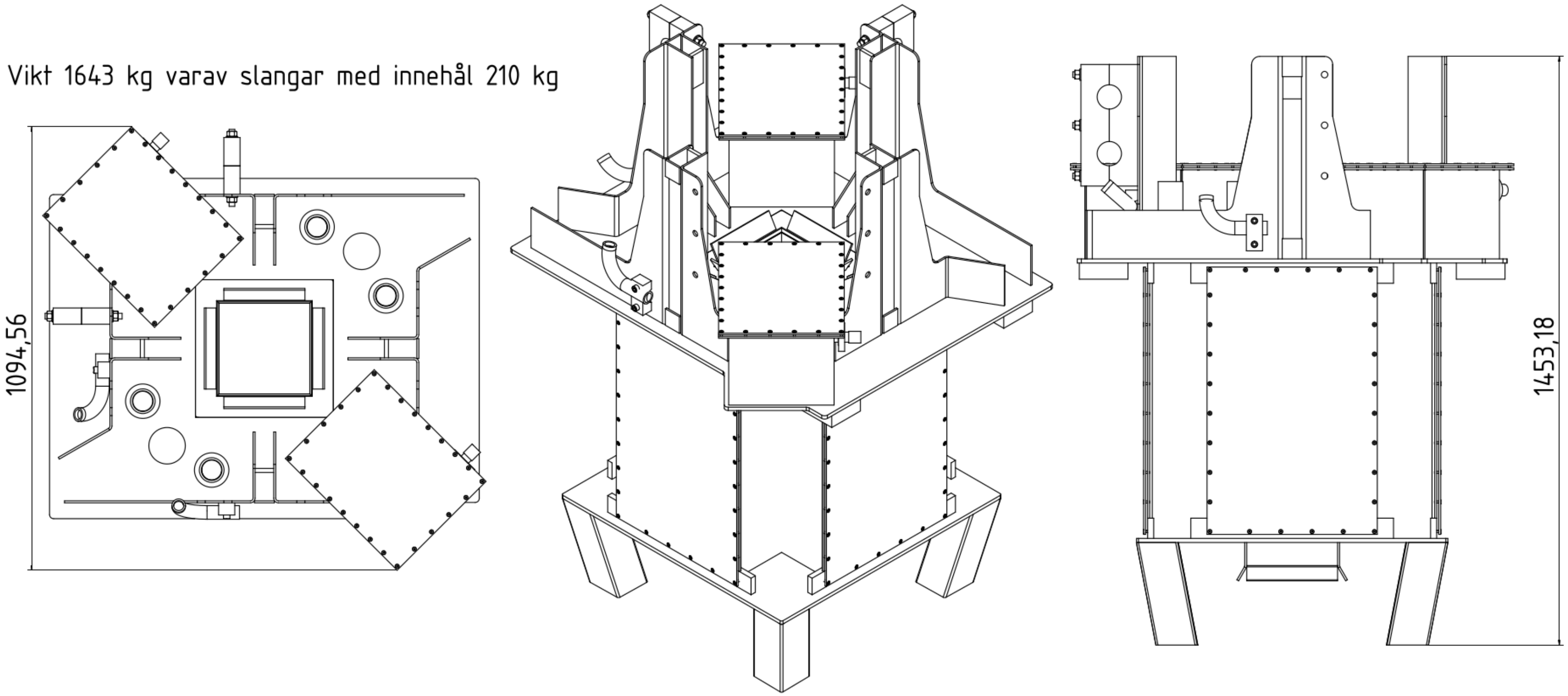

Figure A-1. Drawing of the prototype seen from the top, top-side and side. Dimensions are in millimeters. The text in the figure states the total weight of the system: 1643 kg (in air) out of which 210 kg are hoses containing cables for the detectors.

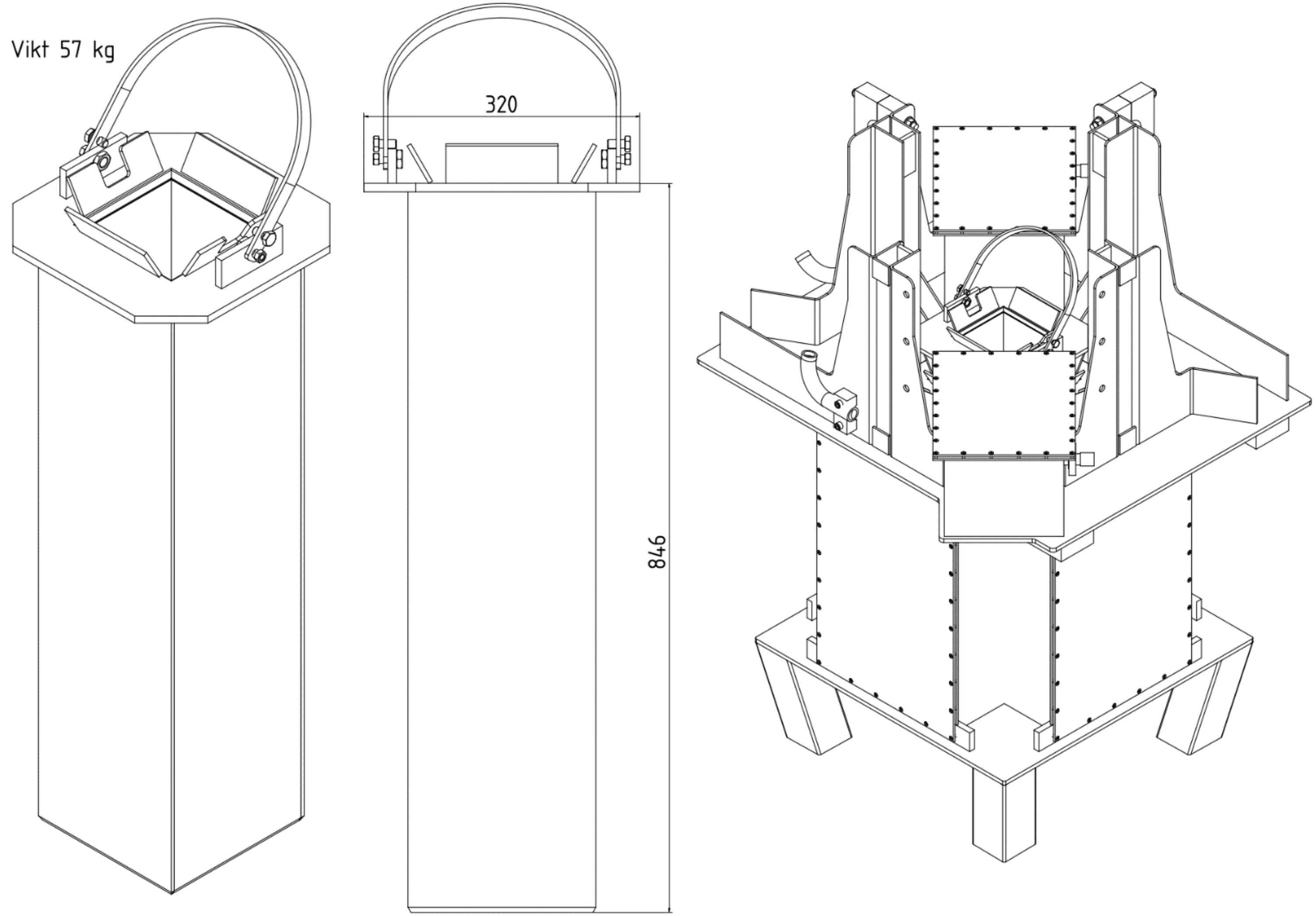

Figure A-2. *Drawing of the BWR insert (used only when measuring BWR assemblies, see Section 3) seen from the topside, side and inserted into the prototype. Dimensions are in millimeters. The text in the figure states the total weight of the BWR insert: 57 kg (in air).*

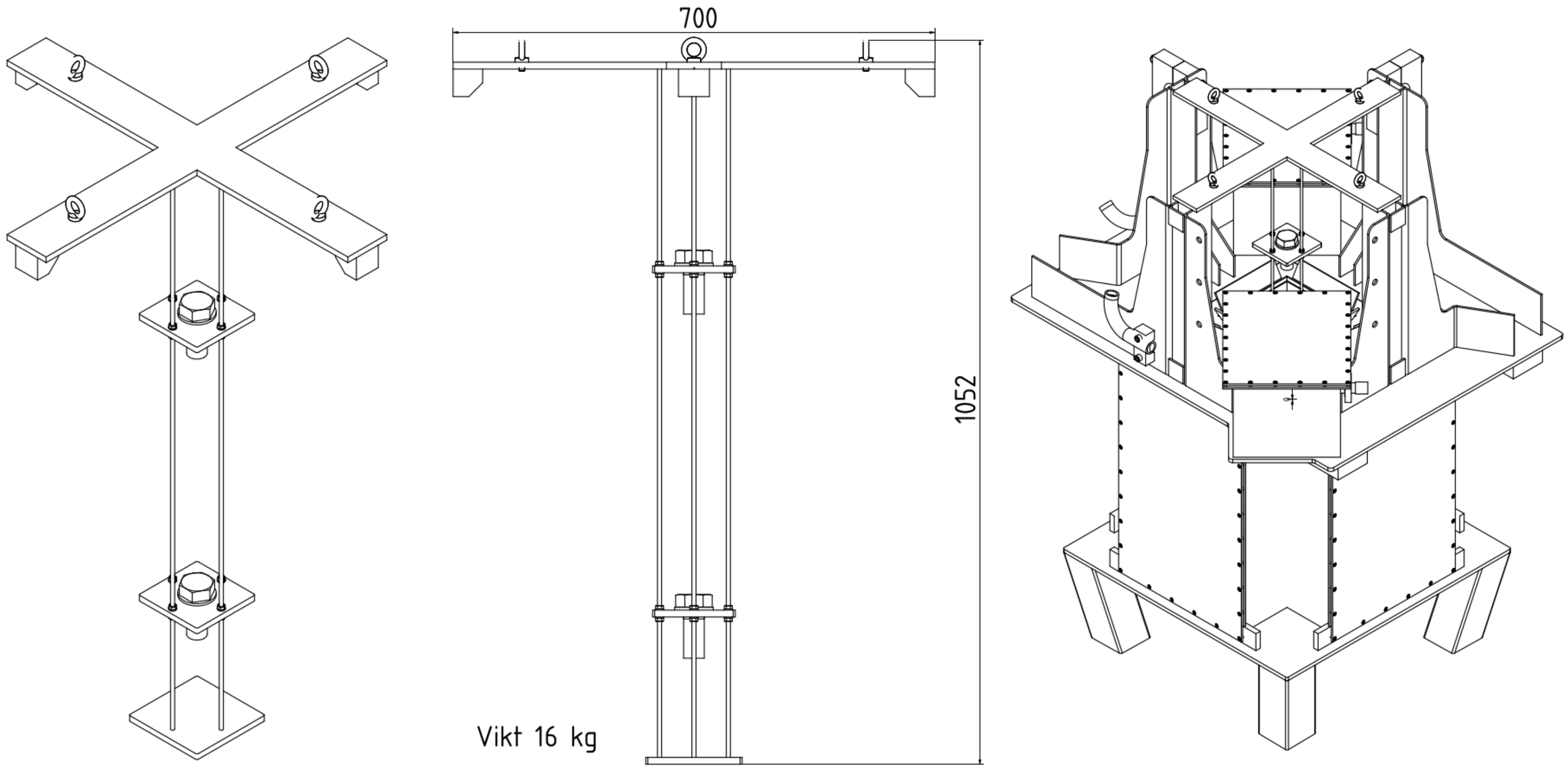

Figure A-3. *Drawing of the holder for the* ^{137}*Cs gamma-ray calibration source and the* ^{252}*Cf neutron calibration source (see Section 3) seen from the top-side, side and inserted into the prototype. Dimensions are in millimeters. The text in the figure states the total weight of the source holder: 16 kg (in air).*