VeryFuel, a Liquid Scintillator-Based Fast Neutron Counter for Fresh Nuclear Fuel Measurements

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Abstract

The VeryFuel is an NDA tool for verification of modern fresh fuel assemblies. It is a liquid scintillator-based instrument detecting fast neutrons from induced nuclear fissions. The VeryFuel has the capability to measure the ^{235}U linear mass density with unprecedented speed and much lower systematic uncertainty in presence of burnable poisons. Tests have demonstrated verification of ^{235}U enrichment in 17x17 PWR with statistical uncertainty on coincidence rates lower than 1% in an acquisition time of 15 minute. The presence of 24 fuel rods containing Gd at 10% weight in 17x17 PWR assemblies causes a systematic bias lower than 3%, approximately half as much as current alternatives.

CAEN S.p.A. is currently designing the upgrade of the VeryFuel system for IAEA with a revised mechanical layout with modular elements. The mechanics has been redesigned to be integrated in a rugged case with 19” rack frame, with independent 19” rack mounted units: KVM (keyboard-video-mouse), high performance multi-core computer and custom defined crate in industrial VME-64X standard. The whole collar detector has been designed to improve the mounting and the positioning of the detector panels, with dedicated source slabs for accommodating in the internal cavity BWR, PWR and WWER fuel bars. CAEN S.p.A. is producing the VeryFuel for the International Atomic Energy Agency (IAEA) according to user requirements defined by safeguards operational divisions. The detectors and data analysis were developed thank to the IAEA and Member States Support Programs.

Keywords

Safeguards; Non-destructive assay; Uranium assay; Neutron coincidence counting; Fast-neutron detection; Burnable neutron poisons

Introduction

Fresh fuel assemblies (FFAs) containing low-enriched uranium are verified in ^{235}U content using active neutron coincidence counting (NCC), a non-destructive assay technique. Traditionally, NCC instruments such as the uranium neutron collar (UNCL) [1], using moderated ^{3}He thermal neutron detectors, have been well suited for this task providing fast, precise and accurate measurements of the ^{235}U content. Modern fuels commonly contain burnable neutron poisons, such as gadolinium oxide, to increase burn up and improve fuel economy. Such fuels present complications for verification by traditional NCC instruments due to high absorption of thermal neutrons by Gd.

This problem has been recently addressed following two approaches. The first is to apply a correction factor to the measurement which relies on a declaration of Gd content in the FFA. This cannot be independently verified and therefore presents a possibility that nuclear material could be diverted with a false declaration. The second is to use a cavity lining of Cd to remove thermal neutrons from the interrogation flux, thus significantly reducing the dependence of the measurement on Gd content [2]. The induced fission rate is suppressed and to compensate, the measurement times are extended to between two and three hours to achieve satisfactory statistics. Recent developments have aimed to reduce the measurement time by increasing the efficiency of a UNCL-type design by using high pressure ^{3}He tubes [3] [4].

The VeryFuel, pictured in Figure 1, utilises low-hazard liquid scintillation detectors and an integrated data acquisition system to measure coincident fast neutrons. When used in combination with a Cd cavity lining this leads to a minimal dependence on the FFA Gd content, removing the need for a correction. Additionally, no neutron thermalisation is required for detection thereby allowing the coincidence gate to be reduced from microseconds to nanoseconds. This virtually eliminates accidental neutron counts, the major source of measurement uncertainty in traditional NCC. Subsequently, measurement times for the same level of precision can be greatly reduced. The final stages of VeryFuel development, optimisation and field test measurements of FFAs with a variety of ^{235}U enrichments and Gd content are presented. CAEN SyS provided the VeryFuel to the International Atomic Energy Agency (IAEA) as the Fast Neutron Collar (FNCL) and its user requirements have been defined in the safeguards operational divisions [5] [6].

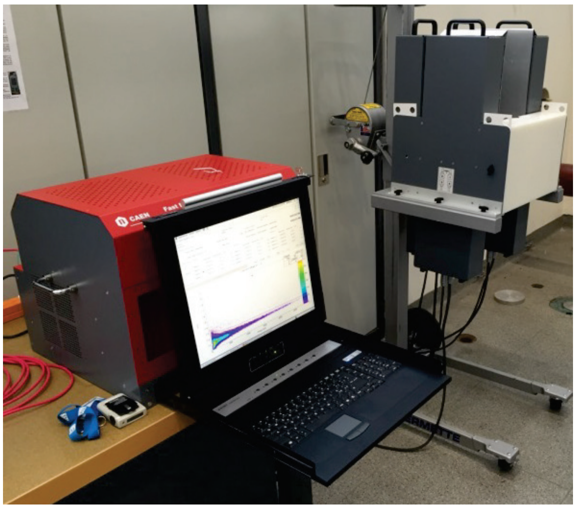

Figure. 1. The three-panel VeryFuel system during calibration with ^{252}Cf source measurement.

Description of the VeryFuel Detector

The VeryFuel embeds 12 scintillation detectors arranged in groups of 4 in 3 panels to directly detect fast neutrons from fission reactions as shown in Figure 2. The scintillation detectors are 10-cm cubic cells of EJ-309 [7] coupled to 7.6 cm diameter photomultiplier tubes (PMT, ETL type 9821 FLB) manufactured by Scionix.

The FNCL detector has been redesigned mainly to improve the robustness of the detector panels and their fastening on the supporting plate. The redesign of the panels makes them identical and independent from the mounting position, while in the previous version the 3rd panel was wider and weighting more, as shown in Figure 2. The new design imply that any panel can be exchanged with a spare part in case of need.

The detector panels are fastened a new supporting plate with increased thickness, to reduce to a negligible amount any incline of the panels respect to the perpendicular direction. Moreover, the support plate has an adjustable fixing for commercial forklifts meant to sustain the whole detector.

The overall design of the collar is meant to accommodate BWR, PWR and WWER fuel bars, without any change in the mounting procedures of the detectors. Three different polyethylene slabs, housing the interrogation sources, can be used to optimize the fuel verification.

Neighbouring detectors are spaced from each other by 1 cm of high-density polyethylene (HDPE) to reduce cross-talk between detectors. 1-cm lead and 1-mm Cd sheets are present on the inner side of the cavity to reduce gamma rays and thermal neutrons. The detectors, HDPE, lead and Cd are contained within aluminium housing. The source slabs hold the AmLi interrogation sources (typical emission 5×10^4 neutrons s^{-1} each), and are made of HDPE to moderate the interrogation field. A Cd sheet is also present here on the inner side of the cavity to remove thermal neutrons below 0.5 eV from the interrogation field. The detectors and source slabs are assembled on a wheeled trolley with adjustable height to facilitate fuel measurements.

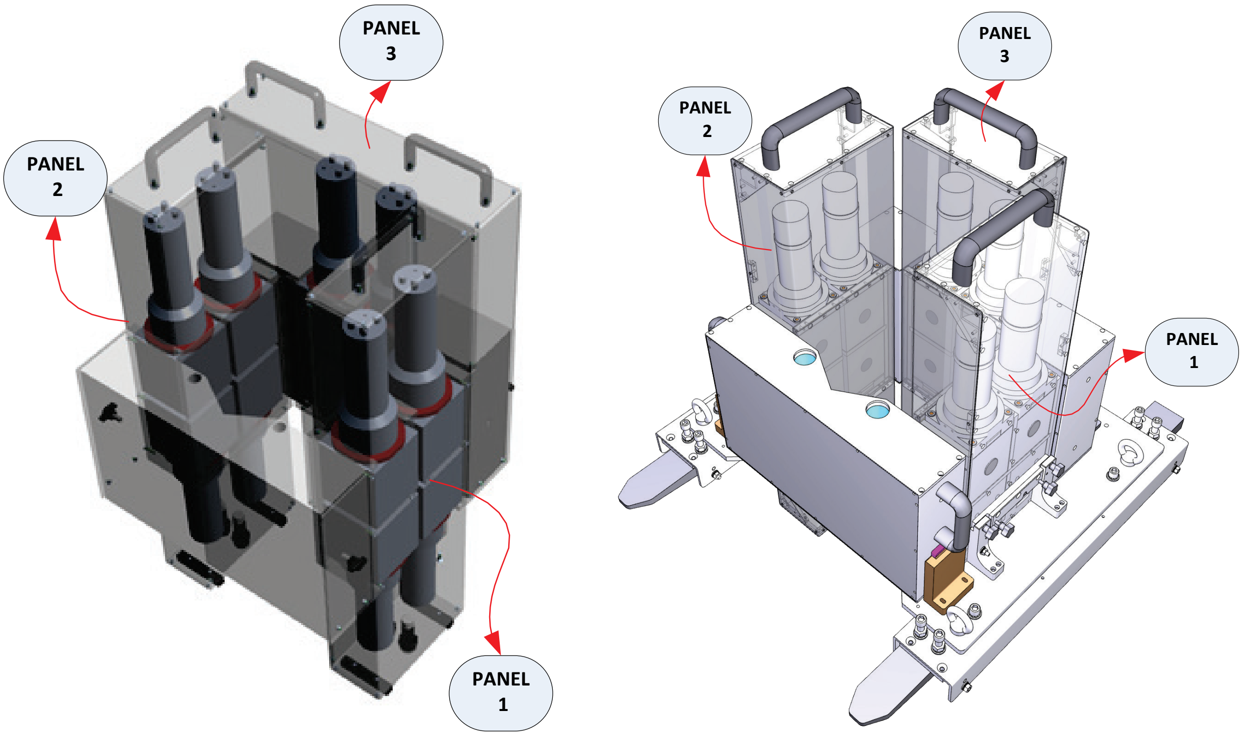

Figure 2: VeryFuel – Current and next coming configurations (both with 12 EJ-309 cells)

Description of the VeryFuel Data Acquisition

The DAQ system is composed by independent modules rack mount for the 19” mechanical frame. This gives the flexibility of exchanging the building blocks independently and potentially guarantee a long-term maintenance capability of the system. The DAQ is embedded in a commercial rugged and transportable case with a 7 unit high 19” frame. The DAQ system is shown in the Figure 3.

The signals coming from the scintillation detector are digitized with fast Analog-to-Digital-Converters (ADC) hosted on board of 4 V1730D VME waveform digitizers, manufactured by CAEN SpA, providing a sampling rate of 500MS/s and a resolution of 14 bits over a software programmable dynamic range of 0.5 or 2.0 Vpp. The communication interface of each the V1730D digitizer with the data processing unit is an optical link. The optical link is both used for board configuration and data acquisition, with data transfer rate up to 80MB/s. The total data throughput of the waveform digitizer is then approximately 320 MB/s.

In addition to the 4 digitizers module, the crate hosts 2 CAEN V6533 VME High Voltage power supply modules, used for the bias of 12 photomultiplier. Each board houses 6 power supply channels with a maximum output voltage of 4 kV and maximum output current 3 mA. The power supply modules are controlled by the software via the CAEN V1718 VME Bridge.

Figure 3: VeryFuel electronic modules for data acquisition and detector bias. The electronic modules are installed in an 8-slot 6U VME industrial standard.

In addition, the DAQ system integrates a PC server as data processing unit. The CAEN A3818 PCI Express controller card with 4 links available is mounted on the motherboard and allows direct control and data readout from the 4 digitizer boards.

The VeryFuel software allows the user to fully configure the detector and data acquisition parameters, calibrate the system, monitor the status and results of verification measurements.

Data collected by the detectors are analysed on-the-fly by the on-board PC with the following discrimination algorithms, ordered as listed below for data processing optimisation.

- The coincidence filter removes events which do not coincide within a user-specified time gate (typically 70 ns). Cross-talk events occurring in adjacent detectors within a user-specified time gate (typically 14 ns) are also removed.
- The energy discrimination filter integrates waveforms and removes pulses below a configured energy (typically 0.5 MeV recoil proton).
- The pulse-shape discrimination filter calculates the PSD value for each event according to the equation PSD =1+L/S, where L and S are the signal integrals in a long and short time intervals configured by the user. The gamma rays are removed according to a user-defined line or polygon in PSD-energy 2-dimensional plot.

- The pile-up rejection filter interrogates waveforms and rejects events containing multiple pulses.
- The coincident neutron filter removes any events which do not have coincidence following the application of the other filters.
- Data passing through the filters are then analysed to find the neutron doubles rate by directly counting doubles events.

The net neutron doubles rate for a detector is calculated as the difference between counts in active and passive acquisition. The result is then used with an experimentally verified calibration curve to calculate the ^{235}U linear mass density and uncertainty in g/cm.

Software Redesign

The International Atomic Energy Agency has requested the upgrade of the analysis software interface and the implementation of additional features.

The major change in the FNCL software is the possibility to execute the calibration of the system and the fuel bar verification through a guided procedure, “inspector mode”, which improves the usability and eliminate the chances of producing incorrect data by mistake. The system remains however opened to modifications and optimizations, which can be introduced in the interface of the “technician mode”. The user can login in the operating system of the DAQ system with technician or inspector access credentials; automatically, when the FNCL software is launched pressing on the icon in the tool bar, the relative interface for inspector or technician is showed.

During the acquisition different quality check are executed. The software controls the counting rates of the acquisition channels:

- controls that all acquisition rates are above a fixed low level;
- controls if the current acquisition rates are consistent with the average acquisition rates in the run;
- controls if the independent acquisition rates are consistent with the average acquisition rates of the other detectors in the system.

Moreover, the energy calibration of the system is automatically processed in the inspector mode and the software monitors the good result of this calibration.

The software generates verification reports at the end of the measurements. The reports include a series of summary plots, which ease the control of the results.

Monte Carlo modelling

The VeryFuel system, interrogation sources, calibration sources, fuel assembly configurations and associated gamma-ray and neutron transport are modelled [8] to produce time-dependent particle interactions with the VeryFuel detectors, where applicable fission gamma rays and neutrons are included in the simulations with weighted angular emission distributions. These information is also used to generate light-output pulses from each detector as a function of time.

The model is benchmarked using ^{137}Cs and ^{252}Cf calibration sources. Gamma-ray singles rates from ^{137}Cs agreed within 3% for both configurations and neutron doubles rates from ^{252}Cf agreed within 6% for the three-panel system and within 3% for the two-panel system. The slightly larger disparity in neutron doubles rates is attributed to uncertainty in the angular neutron emission distribution.

System set up and optimisation

The high-voltage settings for each detector were calibrated individually by collecting a ^{137}Cs spectrum and adjusting voltages such that the Compton edges were aligned. The alignment position was chosen such that the ADC covered recoil protons up to 8 MeV. The energy calibration procedure was then used to provide a linear fit between energy and channel. The waveform trigger amplitude which determined pulse digitization and storage was set at approximately 50 keV and was checked by observation of the 59 keV peak of an 241Am source. The energy discrimination filter was set to 72 keVee equivalent to 500 keV recoil proton energy.

PSD is optimised using experimental data obtained from a measurement of a ^{252}Cf source (4.53 × 104 neutrons s-1). The short and long gates are varied and the PSD distribution is fitted and assessed for a FOM as shown in Figure 4.

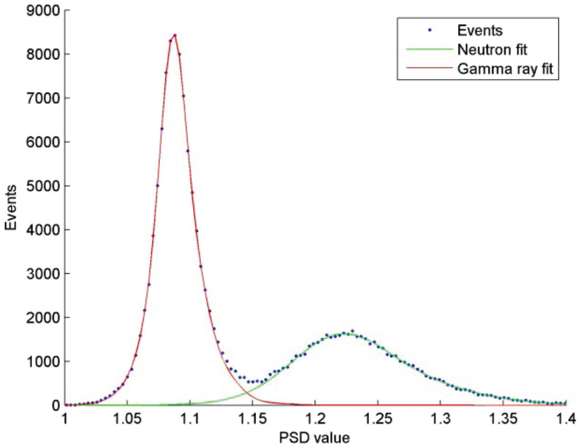

Figure 4. Experimental results of measured PSD distributions of events from ^{252}Cf fitted for gamma rays and neutrons. The PSD discrimination is optimised at 99% gamma-ray rejection, PSD = 1.15.

The short and long gates is varied and the PSD distribution was fitted and assessed for a FOM defined in Eq. 2.

$$\boldsymbol{FOM(PSD) = \frac{\overline{PSD_n} - \overline{PSD_\gamma}}{FWHM_n + FWHM_\gamma}} \tag{2}$$

where the expected value of $PSDn$ and $PSD\gamma$ are the average of the neutron and gamma Gaussian distribution respectively; $FWHMn$ and $FWHM\gamma$ are the full width half maximum of the neutron and gamma Gaussian distribution. The short gate and long gate parameters were optimised according to maximum FOM. The discrimination line was chosen at PSD = 1.15 based on a gamma ray rejection rate of 99% which was found to produce satisfactory results for false positives on neutron doubles.

The coincidence gate width is determined by plotting the time distribution of neutron doubles during active measurement. This plot demonstrates the fast die-away time and low accidentals rate achievable with fast neutron detectors. The coincidence gate width is set at 70 ns.

One drawback of fast-neutron detection is that they can scatter in multiple detectors of the panel leading to a cross-talk effect. The distribution of these events demonstrates that most of the cross-talk occur within detectors in the same panel within 20 ns. To remove these events an anti-cross-talk filter rejects events occurring between detectors in the same panel within a time gate; 14 ns is found to be acceptable for cross-talk removal.

The pile-up rejection filter is optimised using experimental data where rejection in passive PWR measurement data (many pile-up events) is maximised and rejection in ^{137}Cs data (few pile-up events) is not more than 1%. This is further assessed using a Monte Carlo approach.

Experimental measurements

Measurements performed at the Institute for Transuranium Elements, Karlsruhe, Germany are here reported. The test is performed with a configurable mock-up 17 x 17 PWR fresh fuel assembly. The assembly contains 264 uranium rods and has 25 guide tube positions.

Twenty-four hollow steel rods with geometry corresponding to the uranium fuel rods manufactured by the IAEA are used. The rods filled Gd_2O_3 powder provide an “active length” of 120 cm with approximately equivalent Gd loading to a uranium rod with 10% weight Gd_2O_3. The fuel assembly at 3.36% average enrichment, corresponding with 43.71 g/cm linear mass density, is configured over a range of 0 to 11.76 g/cm of Gd_2O_3 as outlined in Table 1.

# Rods	wt% Gd_20_3	Gd_2O_3 loading (g/cm)	Mass ratio Gd_2O_3:(Gd_2O_3+UO_2)
0	0	0.00	0.000%
4	~10	1.96	0.138%
8	~10	3.92	0.275%
12	~10	5.88	0.412%
20	~10	9.80	0.685%
24	~10	11.76	0.821%

Table 1. Uranium and gadolinium oxide loading in the mock-up fuel assembly at ITU.

The VeryFuel is assembled in the configuration alternatively in the three-panel or two-panel configuration. The energy calibration is then performed, followed by background measurements. The energy calibration is additionally repeated every half-day. The fuel assembly with desired ^{235}U loading and Gd_2O_3 is tested into VeryFuel cavity using the fuel-handling crane. Figure 5 shows the fuel assembly in the measurement position. A passive measurement is performed for 600 s followed by an active measurement (with AmLi sources) performed for 600 s.

The total neutron emission rates from AmLi sources is 9.5×10^4 neutrons s-1 and 1.9×10^5 neutrons s^{-1} for the three-panel and two-panel configurations respectively. The experimental results of the mock-up fuel measurements at 43.71 g/cm ^{235}U with 0 to 24 Gd rods can be seen in Figure 6. The data show the trend of decreasing doubles rate with increasing Gd loading; a linear fit is performed. The effect of the Gd rods on the doubles rate is simulated using Monte Carlo, the experimental and simulated drops are summarised in Table 2.

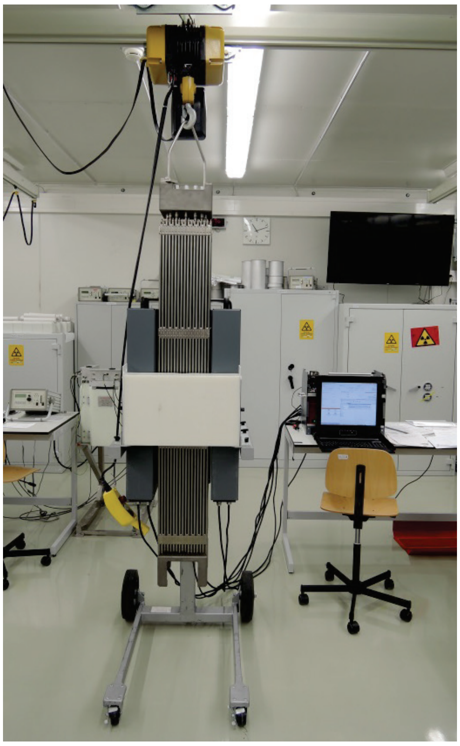

Figure 5. Photograph of FFA measurement with VeryFuel.

This decrease is larger than expected when compared with simulations for commercial assemblies of the same geometry containing 24 Gd rods at 10% weight, while a drop of around 3-4% is expected. The disparity is caused by the steel cladding on the mock-up Gd rods, not present in commercial fuels. Iron has an interaction cross-section of around 3 barns with neutrons in the 0.5 – 10 MeV energy range and therefore is responsible for affecting the doubles rate through neutron scattering interactions. To quantify this effect, a simulation is performed where the cladding is removed from the rods leaving only the Gd_2O_3. The associated percentage decreases, included in Table 2 demonstrate that the expected drop due to Gd_2O_3 only (without the effects of stainless steel) is around 3.4% which is more closely representative of commercial fuel geometries.

With knowledge of the passive and active doubles rates the optimised measurement times for each component to obtain 1% RSD in doubles rate is calculated for the 43.71 g/cm ^{235}U loading fuel assembly with no Gd rods. The optimum acquisition times is in 222 s passive measurement and 606 s active measurement.

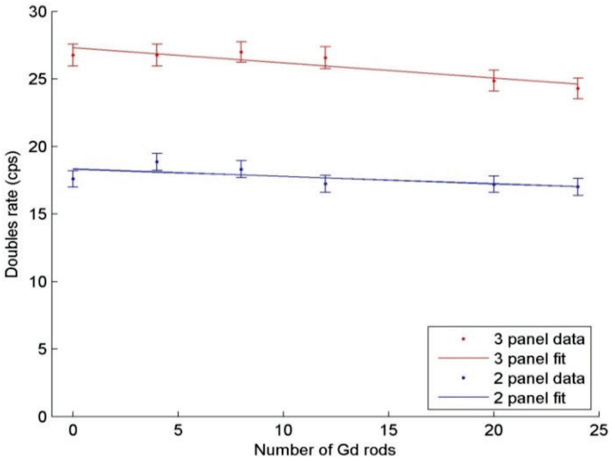

Figure 6. Experimentally measured doubles rate from 43.71 g/cm ^{235}U fuel assembly with addition of mock-up Gd rods for both system configurations. Linear fits is performed on the data. Uncertainties are shown with uncertainty at the 3σ level.

Configuration	Max decrease experiment	Max decrease simulation
three-panel	9.9 ± 2.7 %	8.2 ± 1.0 %
two-panel	7.1 ± 1.9 %	5.9 ± 1.3 %
three-panel (no SS)	-	3.4 ± 0.6 %
two-panel (no SS)	-	3.4 ± 0.8 %

Table 2. Maximum decreases in doubles rates due to addition of up to 24 mockup Gd rods for experimental and simulated data. No SS indicates simulations where stainless steel cladding is removed.

Conclusions

The VeryFuel has been tested in two configurations to measure 17x17 PWR FFAs with varying ^{235}U and Gd content and the instrument response has been documented. The VeryFuel has been optimised to give precision measurement on net neutron doubles faster than thermal neutron detection systems by utilising fast neutron detection with ns-level time resolution NCC. The dependence of the neutron doubles rate to Gd content agrees with Monte Carlo predictions and is expected to be up to 4% on net doubles rate for maximum commercial loading. Due to the low level of accidentals, it is important to note that measurement time will decrease with increasing AmLi emission rate allowing further improvement to performance.

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