A Prototype for passive gamma emission tomography

Tapani Honkamaa (1), Ferenc Levai (2), Asko Turunen (3),Reinhard Berndt (4) , Stefano Vaccaro (5) , Peter Schwalbach (5)

(1) STUK, Helsinki, Finland
(2) Budapest University of Technology and Economics, Hungary
(3) PROVEDOS Oy, Helsinki, Finland
(4) Joint Research Centre of the EU, ITU, Ispra, Italy
(5) European Commission, DG Energy, Nuclear Safeguards, Luxembourg.

Abstract. Combined efforts of multiple stakeholders of the IAEA Support Programme task JNT 1510: “Prototype of passive gamma emission tomograph (PGET)”, resulted in the design, manufacturing and extensive testing of an advanced verification tool for partial defect testing on light water reactor spent fuel. The PGET has now reached a proven capability of detecting a single missing or substituted pin inside a BWR and VVER-440 fuel assemblies.

The task started in 2004 and it is planned to be finished in 2014. The PGET head consists of 2 banks of 104 CdTe detectors each with integrated data acquisition electronics. The CdTe detectors are embedded in tungsten collimators which can be rotated around the fuel element using an integrated stepping motor mounted on a rotating table. All components are packed inside a toroid watertight enclosure. Control, data acquisition and image reconstruction analysis are fully computerized and automated. The design of the system makes it transportable and suitable for safeguards verifications in spent fuel ponds anywhere.

Four test campaigns have been conducted. In 2009, the first test in Ringhals NPP failed collecting data but demonstrated suitability of the PGET for field deployments. Subsequent tests on fuel with increasing complexity were all successful (Ispra, Italy (2012), Olkiluoto, Finland (2013) and Loviisa, Finland (2014)).

The paper will present the PGET design, results obtained from the test campaigns and mention also drawbacks that were experienced in the project. We also describe further tests which would allow evaluating the capabilities and limitations of the method and the algorithm used. Currently, the main technical shortcoming is long acquisition time. With redesigned electronics the system would be able to verify a VVER-440 assembly in 5 minutes, which meets the IAEA user requirements.

1. Introduction

Safeguards evolve, but credible and independent verification capability will remain a principal cornerstone of safeguards inspectorates. Therefore, continuous R&D effort in developing new verification tools is essential. Spent fuel verification is particularly difficult and, although international efforts resulted in availability of new tools such as the Digital Cherenkov Viewing Device, some verification challenges remain. The Passive Gamma Emission Tomography (PGET) is currently the most promising method to detect replacement of a single fuel rod in a light water fuel spent fuel assembly.

The research on PGET has started already in the late 1980’s. The motivation of R&D have been through the history the fact that the safeguards community has a very limited capability to detect partial defects on irradiated spent fuel items. Since 2004, Member States Safeguard Support Programmes (European Commission, Finland, Hungary and Sweden) joined efforts to develop this method under the IAEA Support Programme task JNT 1510: “Prototype of passive gamma emission tomograph (PGET)”. The Task resulted in the design, manufacturing and extensive testing of an advanced verification prototype tool for partial defect testing on light water reactor spent fuel. The PGET has now reached a proven capability of detecting a single missing or substituted pin inside BWR or VVER-440 fuel assemblies.

IAEA current policy is to carry out a partial defect test with high detection probability on all populations of easily dismountable spent fuel transitioning to storages where re-verification is either difficult or even impossible [1]. The partial defect tests carried out by the IAEA do not aim at measuring the nuclear material in spent fuel which is declared by the states from estimates calculated by depletion codes. Partial defect test safeguard objective is to verify the integrity of the declared spent fuel items. A modest but challenging detection sensitivity requirement is currently established at 50% of missing or replaced fuel rods and no re-irradiation of the replaced fuel rods is considered. Fork detectors and the Digital Cherenkov Viewing Devices are used to verify spent fuel before transfer to dry storage. Both instruments have strengths, However neither system produces “absolute” value for spent fuel attribute (gamma and neutron emission rates for FDET or Cherenkov light intensity for DCVD) and must rely on the median characteristics obtained by averaging the observables over the population of spent fuel assemblies that are subject to verification. Further, neither FDET nor DCVD can detect a single replaced fuel rod. PGET strength is in its extraordinary sensitivity to the diversion of irradiated material. PGET is an important component of the tool box of complementary partial defect test devices. Taking into account PGET’s cost and intrusiveness, the IAEA sees PGET to be deployed randomly at reactor spent fuel ponds supporting high detection sensitivity with low detection probability but high deterrence. Evolution of the technique towards unattended use is also an option for installation at specific facilities.

Within the European Union, power reactor fuel assemblies are usually under continuous containment and surveillance (C&S). The PGET can be an important part of the tool-box of verification methods for at least two situations. One is the case where a C&S system failed and knowledge needs to be re-established. The other situation is the last verification before fuel assemblies are moved into a geological repository for final storage. This is the last time the assemblies are available for verification, normally several decades after production. A verification at that point is mandatory to confirm the quality and quantity of nuclear material moved into the final repository.

STUK has an interest to develop tomography for final disposal verification purposes. In Finland it is required that the final disposal process shall be designed in such a way that the authorities will be able to verify the nuclear material data (source data and usage history) of each fuel item by means of non-destructive methods prior to the encapsulation of the fuel items [2]. Verification at final disposal must be done without compromises, because no verification will be possible afterwards. The NDA method is open, but at present no method exists to fully verify nuclear material data, as required. PGET is a good candidate for this solution. PGET may be used as a key element in the final verification among other methods.

2. Description of the Prototype PGET system

2.1 Method and arrangement

Emitted radiation along different directions is detected by a directionally collimated detector array system. A section image is calculated from this measured dataset. The image shows a rod–to–rod distribution of the gamma emitter concentration. Replacement or missing of rods can be revealed by visual or computer based evaluation of the image [3]. Gammas from ^{154}Eu (1274 keV) are preferred for imaging purposes than more prominent 662 keV ^{137}Cs gammas, due to higher penetrability.

Levai et al proposed the PGET design, where two arrays rotate (step by step) around the assembly [4]. At each step measurements are made by all detectors of both arrays. Each array measures a full 360 degree scan with 4 mm sampling, and the positions of the two arrays are 2 mm apart..The two data files of the two opposing arrays will be composed into one data file resulting in a 2 mm, 360 degree sampling.

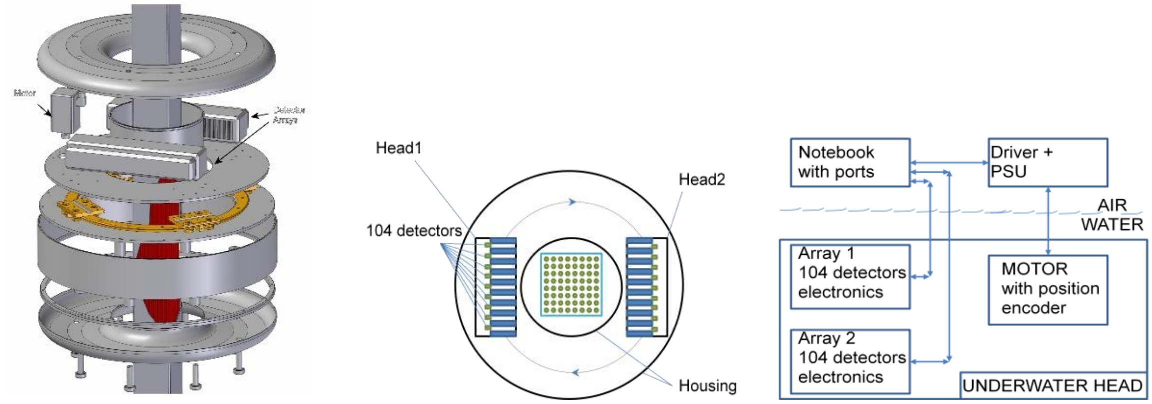

Fig1. a) Exploded view of PGET b) Prototype Arrangement c) System components

2.2 Gamma detector arrays

The decision to build a prototype was made in 2004 and task was established. The work started with the specification of Detector Arrays for a competitive tendering process. The contract was awarded to Baltic Scientific Instruments (BSI).

The arrays consisted of multi slit collimators made of tungsten. CdTe crystals, delivered by Acrorad, were used for development and fabrication of the detectors. The number of detectors in one array was 104. The measurement array has a sealed chamber where detectors and on board-holders with supply circuits, are installed on the ASIC boards. Four ASIC motherboards of the detectors for analog signals procession and one board of the signals digital procession are fixed on the load bearing frame in the chamber. Each of the four analogue boards processes the information of 26 detectors. The electronic arrays, their properties and calibration are described more detail on Sokolov et al. [5].

In the system integration phase, the detector arrays created most problems. They did not function correctly and after subsequent repairs their calibration had to be done repeatedly. Also, the reliability of the measurements system was an issue. The integration of the array with the detector mechanics proved to be problematic, since the high current of the stepping motor generated interference to measurement electronics. The unfortunate thing in the design is that parallel readout of individual detectors is not possible. This makes it impossible to complete a measurement in the requested 30 min time.

2.3 System Design and Mechanical construction of the PGET device

Mechanical dimensions and weight of the arrays were the basis of mechanical construction design. The underwater device consists of the tomographic instrument with cabling, and facility specific supports or structures. In Ringhals a support used was placed directly on spent fuel racks in the pool. In Ispra, Olkiluoto and Loviisa a specific triangular support table was used, which was positioned on the spent fuel pool bottom. The PGET has the outside appearance of a torus with a central hole for the fuel element. It weighs 520 kg in air and 300 kg under water. Each of the two detector arrays contains 104 detectors with collimators. The fuel element will be placed in the central tube of 450 mm height and of 325 mm inner diameter. The central tube is large enough to surround PWR 17x17 type of fuel. The large flange has an outside diameter of 955 mm.

A circular rail goes around inside the toroidal casing. The two detector banks are positioned onto the rail and can make a slow rotation movement around the centre from -10 to +370 degree. This movement is absolved in individual steps of 1 degree, controlled by a stepping motor. The nuclear measurement electronics consists of two boards, which are inside the two detector banks.

In addition, the measurement system consists of an electronics part, which comprises:
1. The Control Box containing: stepping motor driver, Electric Current Power supplies Main switch, emergency stop button and alarm light for the leakage.
2. Operator PC for control of the system and acquisition of data. The electronics part will be positioned on the table at the pool and operated from there.

2.4 PGET software

The software is a major component of PGET measurements. Data analysis of the prototype is attended but is performed automatically with full control of the computer. Manual operation is possible for test/calibration. The software provides a single man-machine interface. PGET determines automatically whether pins are missing as compared against a set of operator declared information including fuel types with normally missing pins (design dependent) and possible displaying the missing pins. The interpretation of the measurements does not require any particular expertise. The time needed for evaluation of the result is only a few seconds, which is short compared to measurement time. The software has two main components, which are separated modules: Control software and Data processing software.

The software consists of two parts, control and data processing.

The function of the Control software is to control the Hardware units. The Control software is used to set up of the detectors and detector electronics (set energy discrimination, control of the detector motion and synchronize the measurement cycle, collection and storage of measurement data). The unprocessed (raw) data are saved at all measurements. At the end of each measurement, the Control software automatically invokes the data processing software.

The input for the Data processing software is the raw data set. Outputs are images with a lot of additional information. The image partitioning feature provides the possibility to display images of normal rods, water channels and replacements separately. The software has diagnostic modules to check the correctness of input data and to test hardware failures. The software also comprises automatic corrections for detector failures and non-uniformity of detectors.

The data processing software is well structured, consisting of two parts as TomoWin framework software and several Sequence files. The sequence files are subroutines, each executing a particular mathematical operation. A large amount of these mathematical operations is built in the system. Sequence files can be set up (by using a text editor) resulting in an algorithm, which is called and executed by the framework software. New sequence files can be added. This feature provides flexibility for executing any algorithm composed of built in sequence files. The input data can be processed automatically using more than one algorithm, which provides possibility for testing new algorithms as well as it can improve the reliability of evaluation by using different algorithms for the same input data.

The data processing software is independent of hardware configuration. Any saved input dataset can be processed by any of the selected algorithms. For routine use, prepared sequence files are available for full automatic measurement of BWR, PWR, and VVER fuel assemblies.

3. Test campaigns

During the task JNT 1510 four test campaigns has been conducted: Ringhals, Sweden in 2009, Ispra, Italy, 2012, Olkiluoto, Finland 2013 and Loviisa Finland 2014. Test in Ringhals failed to collect any measurement data due to hardware error in measurement electronics. Later on it is easy to note that time for testing was not sufficient. Ringhals nuclear operator was very cooperative, professional and helpful, but available campaign dates were constrained and had to be fixed early because of internal scheduling of the nuclear power plant. However, the test demonstrated suitability of the PGET for field deployments.

The Detector Arrays were sent to manufacturer for repair and recalibrated According to their report high ripple of voltage in the supply unit and electrical disturbance are responsible for the failure.

3.1 Ispra, June 2012

The lesson learned from Ringhals was that the system functionality should be more reliable, before next campaigns can be arranged in power plant environments. Therefore, Ispra ESSOR research reactor was selected as a location for next campaign. Ispra site is waiting for decommissioning; therefore there were no time-dependent constraints. Measuring campaigns can be arranged flexibly.

Shortcoming of the Ispra site was limited availability of irradiated fuel items. Three items were measured containing 6, 8 and 12 irradiated fuel rods, respectively. These items were a collection of old research reactor fuel rods from NPS Obrigheim, NPS Wuergassen and Trino Vercellese; their burn up varied from 4000 MWd/t to 30 000MWd/t. Cooling times of spent fuel was 40-50 years, so the signal was rather weak.

JRC Ispra prepared a tripod table for the tests. It is a 1 m high structure to support the Tomographic head at the bottom of the pool, sufficient for small items available in Ispra. The same table was used later in Olkiluoto and Loviisa tests. For longer NPP fuel elements the height of the table is too small, only the lower section of the fuel can be verified. For the test reasons this was sufficient but for operational system there shall be a possibility to verify upper parts of the fuel as well.

The results were positive; all rods were observed after analyses. A more detailed report was prepared. [6] However, it was noted that another array did not perform satisfactorily and it was not used in analyses. Data from just one array was sufficient because of the geometric simplicity of the object. Sample images can be seen in fig. The measured fuel assemblies were very simple compared to PWR assemblies; however, experience obtained can be useful for imaging large compact objects. No spent fuel of such a long cooling time has ever been measured, thus better knowledge about measuring long cooled assemblies was gained. A rough estimate of the ratio of detectable ^{137}Cs to ^{154}Eu is obtained. The results can be compared with those of former test with BWR assemblies with cooling time of 10y.

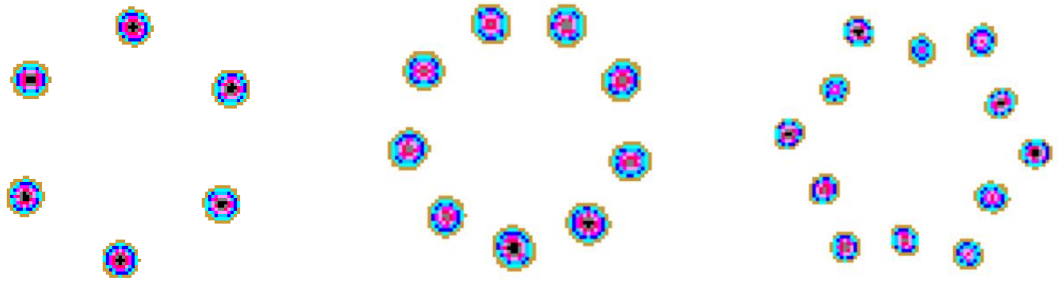

Fig 2. Groups of ISPRA fuel rods, sections measured with ^{137}Cs radiation emission

Some problems with the PGET system were revealed, which would be much more difficult to test by an arrangement using only Co radiation source. Many days of continuous operation provided experience about accuracy and stability of the system.

Due to the long cooling time the radiation level is low and good statistics could be obtained only if ^{137}Cs photons are detected. This is possible as the self-absorption is very low, all the rods are in the periphery positions, and no internal rods are shielded by the peripheral rods. The spacing between fuel rods is wide, therefore all assembles could be imaged using data of only one Array. Image evaluation and reconstruction was simple compared to evaluating large size compact assemblies.

3.2 Olkiluoto, March 2013

The Olkiluoto reactors are of BWR type. The fuel is considered as a relatively easy case for PGET, because of relatively sparse rectangular lattice and small diameter. A BWR fuel assembly was imaged earlier in 1999 with an old 4 detector system with excellent results [4]. A large variety of assemblies were available: 8x8 and 10x10 pin assemblies, cooling times from 3y to 32y and burn up levels from 15 to 52MWd/kg.

During the 2.5 day campaign, 4 different assemblies were measured, some of them several times with different statistics. The number of measured views was 48-60, integration time selected from 0.1-0.6s. Those measured with 0.1s were too noisy to obtain acceptable results, but 0.5s with 60 views resulted in good images for all cases. Imaging was done based on ^{154}Eu photons for assemblies with cooling time larger than 3y. Short cooled assembly is also imaged using ^{144}Pr photons. Due to much lower self absorption, image reconstruction resulted good outcome with poor statistics as well.

Some failures were observed. Another array failed at times. Calibrations and noise level were also differing between arrays. The system contained 10 fully failed detectors, and 10 detectors causing significant deviation from neighbouring signals resulting in abrupt changes. Despite the difficulties, the system was capable of creating cross sectional images, where almost all pins were observable and small amount of artefacts. The easiest case was 8x8-1 fuel assembly with 27 y cooling time. Both detector arrays were working and measurement results were good. Water rods inside the assembly can be easily seen (Fig 3). Conclusion from the measurement and analysis was that the prototype is capable of detecting a missing pin inside BWR fuel assembly. The detection was, in most cases, successful.

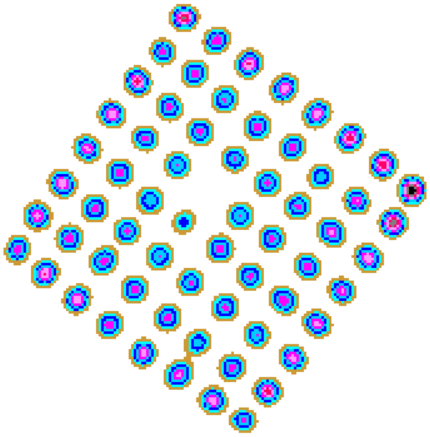

Fig 3a) Assembly 8x8 with 1 water channel. Cooling time 27y Burn up 41466, imaged with ^{154}Eu 1274 keV photons.

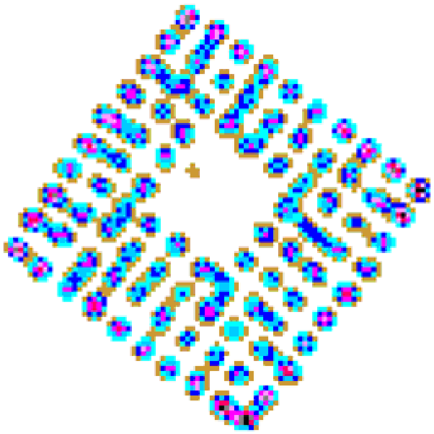

Fig 3b) Assembly 10x10-9. Cooling time 10y Burn up 38117MWd/t , imaged with ^{154}Eu 1274 keV photons.

3.3 Loviisa, January 2014

Simulations based on earlier tests show that repair of detector arrays is necessary prior the tests in Loviisa VVER-440 fuel. Loviisa is VVER type reactor and fuel elements are hexagonal. The diameter of the fuel is not large, but the tight lattice increases the imaging resolution requirement. Both detector arrays should be operational, as 2 mm sampling is needed. Also readings of failed detectors should be corrected.

Prior to the measurements in Loviisa, the detector arrays were both checked for their functionality. Faulty detectors were moved to peripheral positions and both arrays were re-calibrated. The electronics worked in acceptable way during the campaign. Altogether 5 assemblies were verified during the campaign lasting two and half days. Cooling times varied from 10.5y to 33.5y, and burn-up levels from 36 to 46MWd/t. One assembly, having 3 missing rods, was measured twice. Other assembles had no missing rods, only water channels in the middle position, which is a normal feature of the fuel. As the water channels are in the middle position they were much more difficult to detect than missing rods in the peripheral position.

ASIC failure caused incorrect noisy data in one measurement. Altogether 5 scans out of 120 produced distorted data and this error was possible to correct in post-processing. Also large jumps between ASIC signals were observed. The system had also a new problem with mechanics. Altogether 120 steps (3 degrees intervals) were used in the scanning. The stepping motor did all 120 steps, but at the end of the scan it did not reach 357 degrees, but was about 6 degrees short. This was not observed during the measurement, but only after the more detailed analysis of raw data.

During data processing the imaging resolution level is set to the maximum value achievable with 2mm sampling. All water channels can be detected on the image. On some part of the image resolution degradation is observed, as some rods can not be seen separately. This was due to degradation of some of the detector channels in the array. Sample images can be seen in fig. 4.

The automatic analysis software worked, it was able to generate conclusive image within a few seconds without human intervention. This was a promising result for the unattended use of the device. The analysis also revealed that the present prototype is a correct technological choice, at least for a transportable, relatively small size system.

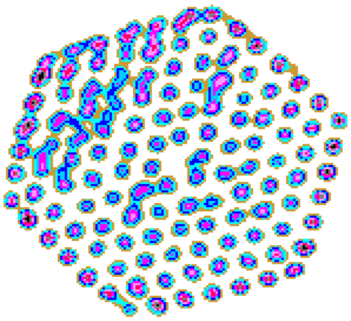

Fig 4a) VVER-440 fuel image: Cooling time 12y, burnup 43685 MWd/t.

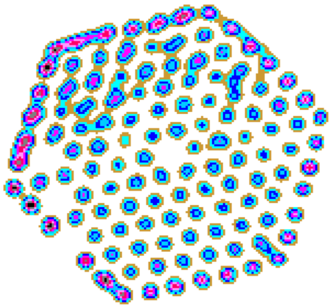

Fig 4b) VVER-440 fuel with 3 removed pins. Cooling time 24y, burnup 40949 MWd/t.

4. Summary and future directions

A Passive Gamma Emission Tomograph has been designed, manufactured and successfully tested under IAEA support Programme task JNT 1510. The tests show that the system is able to detect missing pin from BWR and VVER-440 assemblies. Successful tests with PWR fuel are not yet being conducted, but simulations predict that the result is most likely successful. . This work covers directly capability needs described in the IAEA's Long Term R&D Plan under chapter 5 (5.7: Develop more sensitive…NDA instruments to perform partial defect test on spent fuel assembly prior to transfer to difficult to access storage).

As PGET ability to image irradiated spent fuel assembly is now demonstrated, readiness for deployment and availability for real verifications need to be sustained. Improvement of the electronic readout is a prerequisite for acceptable measurement time that could also be further reduced by constant motion of the detectors.

The next important steps will be to provide unattended operation for passive gamma emission tomography on spent fuel. The quantitative evaluation of cooling time and burn up for each fuel rod within the assembly would provide credible coverage and deterrence for complex diversion or undeclared generation of nuclear material involving irradiation after fuel rods replacement.

REFERENCES

[1] Lebrun A., Zykov S. `` Status of NDA techniques in use for IAEA verification of light water reactor spent fuel``, Proceedings of 55th INMM Annual Meeting (2014)

[2] STUK GUIDE: YVL-D.1 REGULATORY CONTROL OF NUCLEAR SAFEGUARDS 15 Nov 2013, para 358. (2013).

[3] Lévai F, Dési S, Tarvainen M, Arlt R, Use of high energy gamma emission tomography for partial defect verification of spent fuel assemblies. Final report on Task FIN A98 of the Finnish Support Programme to IAEA Safeguards. STUK-YTO-TR 56. (1993).

[4] Lévai F, Tarvainen M; Honkamaa T, Saarinen J, Jacobson S, Rialhe A, Arlt R, Feasibility of gamma emission tomography for partial defect verification of spent LWR fuel assemblies. STUK-YTO-TR-189, Task JNT A1201 (2002).

[5] Sokolov A, Kondratjev V, Kourlov V, Levai F, Honkamaa T. CdTe Linear Arrays with Integrated Electronics for Passive Gamma Emission Tomography System. 2008 IEE Nuclear Science Symposium Conference Record. N02-221, pp. 999-1002 (2008).

[6] Reinhard Berndt, Carlo Rovei, Tapani Honkamaa, Asko Turunen, Ferenc Levai, Lorenzo DiCesare, Paolo Timossi, Roberto Covini. Passive gamma emission tomograph for spent nuclear fuel. Test in the ESSOR spent fuel pond at JRC, Ispra, JRC Scientific and Policy Reports (2012)