XA0056537

IAEA-SM-358/33

SAFEGUARDS ON MOX ASSEMBLIES AT LWRs

J. ARENAS CARRASCO, I. KOULIKOV,
O.J. HEINONEN, R. ARLT
International Atomic Energy Agency, Vienna

K. GRIGOLEIT, R. CLARKE, M. SWINHOE
Euratom,
Luxembourg

Abstract

Operating within the framework of the New Partnership Approach (NPA) for unirradiated MOX fuel assemblies in LWRs, the IAEA and EURATOM have gained experience in safeguarding 13 LWRs licensed to operate with MOX assemblies. In order to fulfil SIR requirements, verification methods and techniques capable of measuring MOX assemblies under water have been and are still being developed. These encompass both qualitative tests for the detection of plutonium (gross attribute tests) and quantitative tests for the measurement of the amount of plutonium (partial defect tests) and are based on gamma and neutron detection techniques. There are nine PWR and two BWR where the reactor and the spent fuel pond can be covered by the same surveillance device. These are Type I reactors where the reactor and the pond are located in the same hall. In these type of facilities relying on surveillance during the MOX refuelling is especially difficult at the BWRs due to the depth of the core pond. There are two PWR type facilities where the reactor and the spent fuel pond are located in different halls and cannot be covered by the same surveillance device (Type II). An open core camera has not been installed during refuelling and therefore indirect surveillance is currently used to survey MOX loading. Improvements are therefore required and are under consideration. After receipt at the facility, there are a few facilities which must keep the received fresh MOX fuel in wet storage, not only for a short period prior to refuelling, but for more than a year, until the next refuelling campaign. In these cases timely inspections for direct use fresh nuclear material require considerable inspection effort. Additionally, where human surveillance of core loading and finally core closure are necessary there is also a large demand for manpower. Either an agreement should be reached with the operators to delay the MOX loading until the end of the fuelling campaign, or alternative approaches should be sought to optimise inspection efforts. State of the art technology in containment and surveillance devices and systems, as well as ongoing developments in NDA techniques have proven feasible for implementing an integrated safeguards approach in these types of facilities. In an unattended mode of safeguards, it is proposed to survey the loading of unirradiated MOX assemblies in complex design facilities using gate monitors (radiation detectors) combined with digital surveillance. This decreases the probability of failure of containment and surveillance during refuelling periods and reduces the manpower effort of the inspectorate. If there is a loss of continuity of knowledge during loading of MOX assemblies, it is proposed that NDA techniques be implemented, based on gamma spectrometry and neutron yield measurements to differentiate irradiated MOX from irradiated LEU assemblies. One such technique which is under development employs a high resolution CdZnTe, SPD 3 10 Z 205 which uses the neutron emission relative to burn-up (Cs-137 signal) to differentiate between irradiated MOX and LEU assemblies. This assures that MOX loading has occurred and re-establishes the continuity of knowledge.

I. Introduction

Since 1973 when the first MOX assembly was received at an LWR in an EURATOM facility till now 13 reactors are safeguarded: 11 PWR and 2 BWR are licensed to use MOX.

The Mixed Oxide Fuel (MOX) has in order of 8 kg of Pu (1 Significant Quantity) per assembly in BWR and up to 36 kg of Pu per assembly in PWR (4 SQ)

Pu concentration = 4% - 8%

Pu Quality ≅ 70%

For safeguards purposes we have classified the reactors in 2 types:

- Type I: Reactor and Spent Fuel pond can be fully covered by the same Containment /Surveillance (C/S) device and are both in the same containment.

- Type II: Reactor and SF can not be fully covered by the same C/S device, usually are in separate containment.

BWRs of type I, due to the deep core pond, offers difficulties to be covered by adequate direct surveillance of MOX loading, and reactors type II require enhanced C/S and use of radiation detectors (NDA).

The use of MOX fuel is enforced by contractual obligations to take back the plutonium from reprocessing contracts, often the number of assemblies exceeds the limits to be loaded in one refuelling campaign; therefore the MOX assemblies remain in the SF pond for a long time requiring inspection effort and adequate use of NDA to cover safeguards timeliness for direct use material.

The MOX assemblies are usually not loaded in one batch, therefore inspector manpower and enhanced C/S are also required to cover the refuelling period and to have assurance of loading of the MOX assemblies into the core.

To cover from a loss of continuity of knowledge of C/S and to have credible assurance that the fresh MOX has been irradiated, “state of the art” NDA has been developed using neutron measurements and gamma spectrometry.

2. Criteria Requirements

2.1 Examination of records and reports, during each inspection, for correctness and internal consistency and, for the IAEA, comparison with state reports.

2.2 Physical Inventory Verification

a) Fresh MOX fuel under C/S (surveillance)

The C/S is evaluated and the assemblies are item counted, verified by serial number identification where applicable and measured with 10% detection probability for gross defects.

For assemblies under single C/S (seals) seal verification is performed with medium detection probability. Additionally, item counting, verification by serial number identification where applicable and re-measurement with 10% probability are performed on sealed items selected for re-measurements.

b) Assemblies not under C/S are item counted and verified with a high detection probability for gross and partial defects and by serial number identification where applicable.

2. 3 Verification of domestic and international transfers:

Item counting and verification with high detection probability for gross and partial defects, either at the shipping or receiving facility. Continuity of knowledge can be maintained using C/S.

2.4 Verification for timely detection

Verifications of fresh MOX fuel are carried out 12 times per calendar year at monthly intervals.

3. **Safeguards Approach implemented**

Of particular importance is the requirement to verify, the down-grading from unirradiated to irradiated direct use material by core loading. Currently most fresh MOX fuel assemblies are verified by NDA for gross and partial defects at the fabrication plant and shipped under seal. Only if the fabrication plant is not under safeguards, the verification is routinely done upon receipt at the reactor.

Safeguards measures at the reactor are normally limited to maintain C-o-K (continuity of knowledge) of the verification at the fabrication plant by application of C/S measures until the MOX assemblies are loaded into the reactor core and the core is closed. NDA re-measurement at PIV for gross defects is only necessary if some MOX assemblies are not loaded into the core but remain in the storage after refuelling. However, MOX assemblies must be re-verified within a timeliness period whenever C/S evaluation is not conclusive.

Regarding the implemented C/S measures three operational situations must be distinguished.

3.1 Receipt and transfer to storage

a) An inspector must be present to remove the seal(s) on the shipping cask. Only in exceptional cases the inspector must verify the received assemblies. Such a need arises when the MOX assemblies were not verified at the fabrication plant or not shipped under seal or if the sealing was inconclusive. Whenever possible this is done prior to the transfer into wet storage.

b) During the unpacking and transfer of MOX assemblies to their final storage position, C-o-K is generally maintained by human surveillance, complemented by temporary C/S measures and standard pond surveillance which is switched to shorter intervals.

3.2 Fresh MOX Assemblies in Storage

For safety reasons, fresh MOX assemblies are normally stored in wet storage in dedicated positions of the SF pond separated from other stored items. Only in a few cases MOX assemblies are stored in dry storage. Safeguards measures are:

a) In wet storage

Underwater TV cameras with short intervals (fig. 1). In addition standard pond surveillance is switched to shorter intervals.

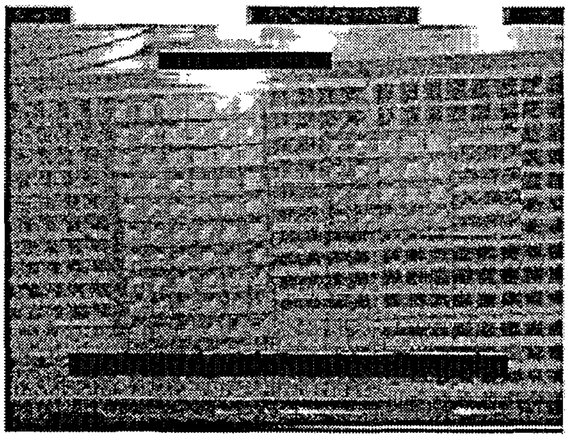


Fig. 1

Under water survey of fresh MOX assemblies

b) In dry storage

Each MOX assembly is sealed separately.
C/S measures in MOX storage must be evaluated in monthly intervals. If C/S evaluation is not conclusive positive re-verification for gross and partial defects with high detection probability is required. This is no longer possible as soon as the core loading commenced. In order to enable prompt follow-up action in case of any problem it is desirable to perform a review of surveillance records on site or to have remote monitoring.

3.3 Core Fuelling

The current intention is to apply surveillance for tracing the path of each fuel assembly to the core and to confirm that it has not been removed from there until the core is closed and standard C/S measures for the core are re-applied. Two types of reactor designs must be distinguished.

(i) Type I reactor:

Spent fuel pond, transfer gate and core pit are all inside the reactor containment and can be covered by the same system of surveillance measures (fig. 2).

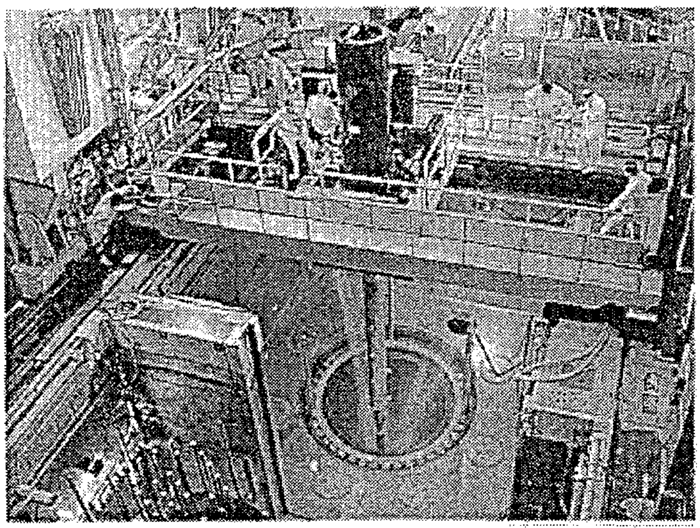


Fig. 2
Type I reactor

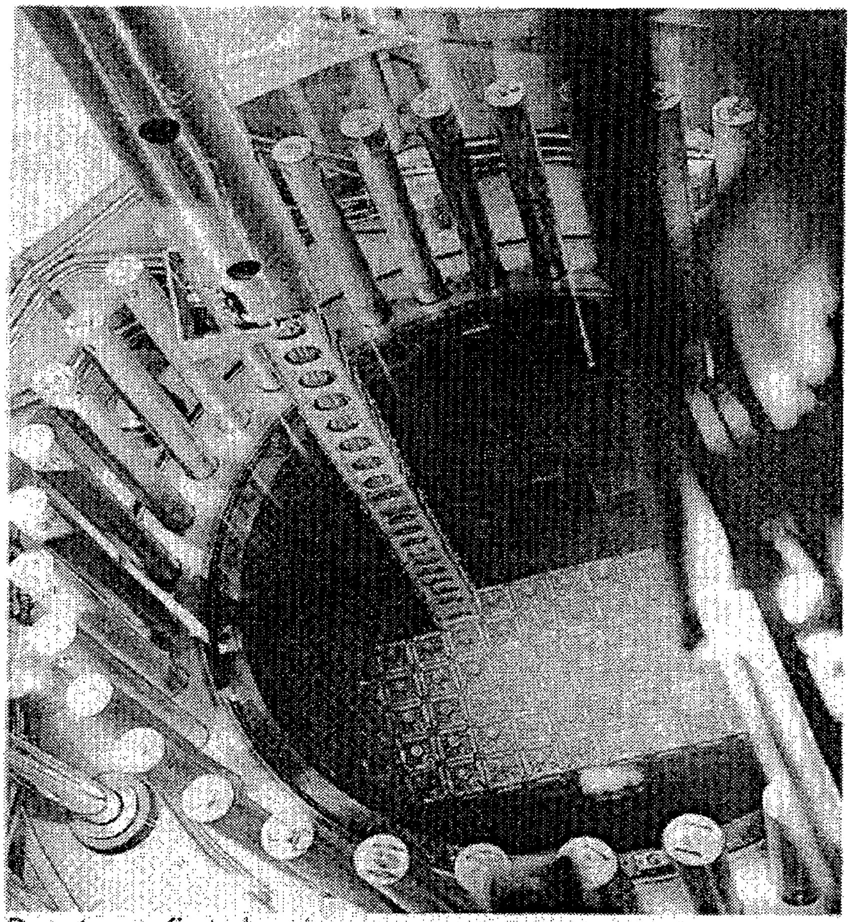
(ii) Type II reactor:
The spent fuel pond is a separate building connected by a transfer channel with a temporary reactor pond, and the reactor pit. Separate systems of C/S measures must be applied to cover the spent fuel pond, the transfer channel, the temporary reactor pond, and the reactor core pit.

Regarding the surveillance coverage of MOX loading to the core different approaches have been implemented:

a) Human Surveillance of Core Loading
Inspectors are present 24 hours a day starting from the first MOX fuel transfer until core closure. They observe the loading of the MOX assemblies into the core and must ascertain that none of them is removed, concealed as the discharge of spent fuel or a dummy. Human surveillance is complemented by the underwater surveillance of the wet MOX storage and by standard LWR surveillance which is switched to a higher recording frequency of effectively one minute. In some cases additional cameras are installed. For Type II reactors 2 inspectors per shift may be necessary to cover storage pond and reactor core

b) Unattended Surveillance with open core camera

This is the "classical" approach implemented under the New Partnership Approach. An unattended surveillance system consisting of underwater surveillance of the MOX storage area in the pond, of the open core and (for type II reactors) the transfer channel is installed which is complemented by the standard LWR surveillance system switched to higher recording frequency. This arrangement should ensure that the movement of a MOX assembly can be followed during surveillance review from the storage position in the core. It should also be possible to confirm that MOX assemblies are not moved back from the core to the pond (fig. 3).



Reactor — first charging

Fig. 3
Open core camera at PWR

4. Technical Safeguards measures for MOX LWR Type assemblies

Criteria shall be verified for Gross and Partial defects.

Gross (Attribute) defect test - a qualitative test. For a positive result of a gross defect test, the detection of plutonium presence is sufficient.
Partial defect test - a quantitative test. The amount of plutonium in the verified assembly must be measured with a specified accuracy.

A spent (irradiated) MOX assembly stored in a spent fuel pond is so-called "self-protected" by extensive gamma-radiation and contains indirect use material. Only a gross defect test is required for a spent MOX assembly. However, if the spent MOX assembly is to be transferred from the plant into the dry storage (difficult to access area) it must be verified for partial defects as any other spent fuel assembly.

4.1 Methods and techniques for fresh MOX LWR type assemblies underwater verification

The main plutonium specific features which can be used for gross and partial defects tests of MOX assemblies are:

- well identified gamma-lines of different plutonium isotopes;
- spontaneous fission neutrons of even (mainly Pu-240) plutonium isotopes.

It should be noted that any kind of underwater MOX fuel assembly measurement in a spent fuel pond is always intrusive, because it requires movement of the assembly or, at least, partial withdrawal from its position in the rack. Without movement (measuring from the top) even the gross defects test is not feasible, because of the long distance to the fuel zone. However, for reasons of safety fresh MOX assemblies are often not stored adjacent to each other. In these cases - if no spent fuel assemblies are stored in the vicinity - in situ gross defects tests can be done, by inserting a detector into an empty storage rack location next to the assembly to verify.

For gross defects tests one relatively simple and easy to use method is being introduced in safeguards inspection practice - the use of a watertight collimated compact spectrometric CdZnTe detector [1] which is lowered under water on a long cable from the pond bridge or from the edge of the pond. The detector is positioned as closely as possible to the side of assembly, which is partly withdrawn from the rack. The gamma spectrum is accumulated and displayed by an energy calibrated miniature MCA. The energy resolution of the detector is good enough to detect underwater at least one plutonium gamma peak at 208 keV (Pu-241). Excessive scattering of gamma-radiation in water can however negatively affect the measurements, if the detector is not well collimated or is not close enough to the assembly. Another possible disturbing factor is the proximity of spent fuel assemblies which could obscure the entire gamma spectrum. A neutron gross counter (He-3-tube) is being considered to be added to complement the gamma measurement.

A more sophisticated and powerful method suitable for gross and partial defects tests is based on the well known neutron coincidence counting technique and realized in the Under Water Neutron Coincidence Counter (UWCC) [2,3]. The detector consists of a solid polyethylene body with two polyethylene fingers and the distance between the fingers is suitable for either a PWR or a BWR size assembly. Each finger contains two high sensitivity He-3 tubes. The body is fixed at the bottom of a long rigid watertight pipe. Through this pipe neutron signal cables come to a standard neutron coincidence shift register electronics (JSR-12). The device is capable to determine the axial density of even plutonium isotopes ("Pu-240eff"), which could be transformed into the total plutonium density, provided the isotopic composition is known (normally it is verified at the fuel assembly fabrication plant). The measurement accuracy with appropriate calibration is about 2-3%.

4.2 Spent LWR Type MOX Assembly Verification

A gross defects test for the normal LEU LWR type assemblies is usually performed by the Improved Cerenkov Viewing Device (ICVD) from the spent fuel pond bridge. The method is fast, non-intrusive and well established. It is not applicable, however, for MOX spent fuel, as it is not capable to distinguish between MOX and standard LEU spent fuel assemblies. The only easy indicator to detect the difference between spent LEU and MOX fuel assemblies is the neutron emission rate, which is significantly (factor of 10) higher for MOX assemblies, when the irradiation history of both types of assemblies is comparable. One of the standard safeguards techniques for LWR spent fuel assembly verification is the fork detector (FDET), which is used if ICVD application is not possible (very long cooling time, bad water transparency), or some additional information is required,

The FDET detector mechanical construction is the same as the mentioned above UWCC , but He-3 tubes are substituted by fission chambers. The He-3 tubes are too sensitive to high gamma radiation fields. Also, the FDET contains one ionization chamber to monitor the gross gamma activity of the verified assembly. Thus the FDET detects two spent fuel attributes: neutrons (arising mainly from Cm-242 and Cm-244 isotopes) and gammas (mainly from fission and activation products). A part of the attribute (gross defect) test, the FDET detector is capable to provide a consistency check with operator declared burn up and cooling time.

The FDET is able to distinguish between MOX and LEU spent-fuel assemblies by neutron count rate comparison, unless the irradiation history of MOX and LEU assemblies is completely different. A one-cycle MOX assembly produces approximately the same amount of neutrons as a standard LEU assembly of three irradiation cycles. If it is the case, the gross gamma activity measurement helps, because a 3-cycle LEU assembly produces significantly higher gamma radiation than a l-cycle MOX assembly.

However even a combination of both neutron and gross gamma measurements fails to distinguish MOX and LEU assemblies, when the cooling time is short, because with short cooling time (a few weeks) the gross gamma emission does not reflect the whole irradiation history, but only the last weeks of operation. The solution has been found through introduction of spectrometric (instead of gross) gamma measurements [4,4], using miniature spectrometric CsZnTe detector. It was experimentally shown, that such a detector, if adequately shielded and collimated, is capable to detect quantitatively the 662 keV peak from Cs-137 even for short cooling times. Because of a very long decay time, the Cs-137 fission product activity is proportional to the burn up, which obviously is much higher for a 3-cycle LEU assembly than for a l-cycle MOX assembly. At present the method and device are in the process of development (Reference 4). A partial defect test for a spent fuel assembly is formulated as a confirmation that no more than 50% of fuel is removed from the assembly with a confidence level of 3σ. This requirement does not look strong, however, it is not a straight forward task for any kind of spent fuel. At present a number of possible solutions are under consideration. One of them could be based again on the combination of neutron and gamma spectrometry measurements. Assuming that the neutron emission is proportional to the amount of fuel and is a power function of the burn up, and on the other side, the Cs-134/Cs-137 activity ratio, after correction for irradiation history and cooling time, is linearly proportional to the burn up and presumably does not depend on the amount of pins removed from the assembly, the calibration curve N = F (Cs-137/Cs-134) could be created for any given type of fuel. This approach is under investigation. A second approach is the development of under water tomography of spent fuel assemblies [ref. 5] into a practical method which can potentially detect the removal of single rods in a measurement time of less than 30 min.

5. Experience achieved

In order to judge the effects of the efforts undertaken we should differentiate between detection goal attainment at all (quantity component) and timely detection goal attainment (timeliness component).
The timeliness goal for fresh MOX fuel is very demanding and seldom attained whenever a primary C/S measure failed to be conclusive and fresh MOX spent fuel must be re-verified. Priority is given to attaining the quantity component.

- It is agreed that MOX assemblies which will be shipped to a reactor which is under safeguards will be submitted to safeguards already prior to shipment (i.e. from MOX fuel fabrication plants in nuclear weapon states). They will be verified at the fabrication and shipped under seal.

- At a reactor of type II the operator was reluctant, on safety grounds, to accept the installation of underwater surveillance for the open core during refuelling.

- At one large BWR a good resolution of the open core surveillance was impossible to achieve. The core pond is too deep to maintain the continuity of knowledge on the small BWR MOX fuel assemblies in the large deep core pit with about 700 assemblies positions. An alternative approach implemented for indirect confirmation (survey of canalgate) that the declared number of MOX assemblies was loaded into the core was partially accepted; due the operational needs, to remove core fuel assemblies from the core to the dismantling station, does not assure that no unirradiated MOX assemblies were returning back from the core (fig. 4).

In order to solve the problems currently still preventing attainment of the quantity component at the type II reactors and large BWR, action has been initiated leaving 3 options to be followed:

a) Human surveillance of the open core

Inspectors present during the whole period of MOX loading observe the loading of the fresh MOX and keep the knowledge of MOX position in the core to confirm that MOX assemblies are not moved out of the core.

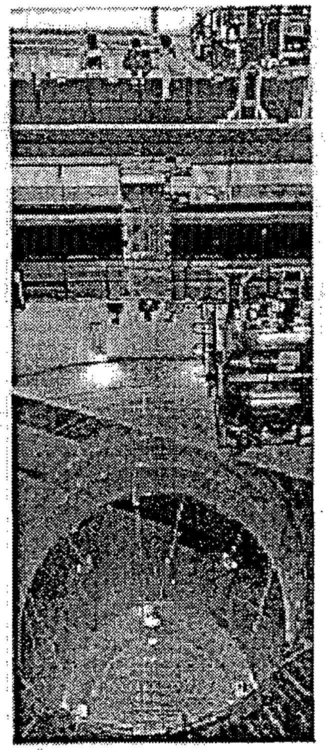


Fig. 4
BWR with deep core pond

If possible, an agreement should be made with the operator that MOX is loaded at the end of the campaign to reduce the otherwise very high inspection effort.

b) Open Core Camera

This requires positioning of a relatively large number of surveillance cameras, including underwater cameras looking into the reactor core. These arrangements should ensure that the movement of a MOX assembly can be followed during the surveillance review from the storage position to the dedicated position in the core. It should also be possible to confirm that MOX is not moved back from the core to the pond. The interpretation of surveillance records might be difficult for type II reactors (involvement of two bridges and the presence of a channel gate where an assembly may be hidden).

c) “Combined approach”
Cameras are installed for observation of the water surfaces in the pond and reactor area and for observation of the movement of MOX assemblies from the storage position to the channel gate. Before the loading starts the inventory of the pond is established. Upon completion of loading and sealing/fixing the channel gate, the core control is performed and the pond inventory is verified (including verification of fresh assemblies and of any dummies in the pond). These measures confirm the loading of MOX into the core by difference.

6. Needs for further Research and Development (R&D)

In the area of Containment and Surveillance (C/S) remote monitoring techniques will be considered for already installed C/S equipment to reduce the necessary number of inspections for timeliness purposes, in particular if MOX fuel is stored for longer periods and to facilitate timely re-verification in case of inconclusive C/S results. In addition new C/S measures are currently being investigated for spent MOX fuel safeguards measures. These include:

a) An unattended gate monitor in the transfer channel for monitoring the flow of MOX assemblies between the spent fuel pond and the reactor core. The Gate Monitor is an integration of NDA equipment and new generation digital surveillance-instrumentation on an adequate platform to perform front-end triggering and back-end review of the collected data. A support programme task will be defined for the development activities. Investigations are carried out about the feasibility of gate monitor in the transfer channel for ensuring that no unirradiated MOX assemblies were returning back from the core. Special He-3 tube detectors, radiation resistent, are being tested for this purpose. The main users will be reactors of type II and BWR using MOX fuel.

b) Underwater surveillance equipment utilizing the existing and authenticated digital surveillance technology will need to be developed and tested. Remote monitoring fresh MOX fuel is on storage will reduce the number of inspections for timeliness purposes, it also facilitates the detection of inconclusive C/S for timely re-verification.

c) Improved sealing methods have been identified as a need for better MOX safeguards measures. Therefore the feasibility of an ultra-sonic seal for fuel assemblies should be further investigated. An existing task of the EURATOM Support Programme should be further sponsored by other Support Programmes to assure timely success.

Regarding the large BWRs investigations are carried about the feasibility to lower down new, particularly small, underwater cameras into the reactor pit for better view of the open core during refuelling.

A method is being developed to re-verify MOX fuel assemblies loaded to the core after the next irradiation cycle when a surveillance failure happens during or shortly after core loading. It is based on the use of neutron yield measurements and ratio of Cs-137/134 (gamma spectrometry) using CdTe miniature detectors.

7. Conclusion

From the previous discussion, it can be understood that the Safeguards measures for MOX LWR assemblies is still an on-going and developing field in safeguards. A good deal of work has been done and effective measures exists as a result, but the complete and effective safeguarding of MOX assemblies requires further development.

REFERENCES

[1] ARLT, R., "User Requirements and Specifications of Fresh MOX Assembly Tester (FMAT), IAEA, (1998).

[2] NELSON, A.J., BOSLER G.E., AUGUSTON, R.H., COWDER L.R., "Underwater Measurement of a 15x15 MOX PWR Type Fuel Assembly", LANL, NM 87545, ISPO-3 16, (1990).

[3] CARCHON, R., MANDOKI, R., BAETEN, P., BRUGGEMAN, M., KULIKOV, Y., CHERRADI, I., DE BAERE, P., MENLOVE, H., ECCLESTON, G., "Measurement of Fresh MOX-LWR Type Fuel Assemblies under Water, SCK-CEN, BLG-766, May (1998).

[4] ARENAS CARRASCO, J., CHERRADI, I., HEINONEN, O., LEBRUN, A., BIGNAN, G., MAKIL, H., SZABO, J.L., VAUBAILLON, S., "Development of method for irradiated MOX assemblies using non-destructive assay", ESARDA, Sevilla, Spain, May (1998).

LEVAI, F., TIKKINEN, J., TARVAINEN, M., ARLT, R., "Feasibility of computed tomography in partial defect detection of spent BWR fuel" STUK- A 197, October 1990, FIN, (1990).