STUK

STUK-YTO-TR 173 December 2000

SPENT FUEL VERIFICATION OPTIONS FOR FINAL REPOSITORY SAFEGUARDS IN FINLAND

A study on verification methods, their feasibility and safety aspects

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STUK • SÄTEILYTURVAKESKUS • STRÅLSÄKERHETSCENTRALEN
RADIATION AND NUCLEAR SAFETY AUTHORITY

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ISBN 951-712-426-0
ISSN 0785-9325

Oy Edita Ab, Helsinki 2000

HAUTAMÄKI Johanna, TIITTA Antero (VTT Chemical Technology). Spent fuel verification options for final repository safeguards in Finland. A study on verification methods, their feasibility and safety aspects. STUK-YTO-TR 173. Helsinki 2000. 29 pp + Annex 1 pp.

ISBN 951-712-426-0
ISSN 0785-9325

Keywords: back end of fuel cycle, final disposal, NDA, safeguards, spent fuel

ABSTRACT

The verification possibilities of the spent fuel assemblies from the Olkiluoto and Loviisa NPPs and the fuel rods from the research reactor of VTT are contemplated in this report. The spent fuel assemblies have to be verified at the partial defect level before the final disposal into the geologic repository. The rods from the research reactor may be verified at the gross defect level.

Developing a measurement system for partial defect verification is a complicated and time-consuming task. The Passive High Energy Gamma Emission Tomography and the Fork Detector combined with Gamma Spectrometry are the most potential measurement principles to be developed for this purpose.

The whole verification process has to be planned to be as slick as possible. An early start in the planning of the verification and developing the measurement devices is important in order to enable a smooth integration of the verification measurements into the conditioning and disposal process.

The IAEA and Euratom have not yet concluded the safeguards criteria for the final disposal. E.g. criteria connected to the selection of the best place to perform the verification measurements have not yet been concluded. Options for the verification places have been considered in this report. One option for a verification measurement place is the intermediate storage. The other option is the encapsulation plant. Crucial viewpoints are such as which one offers the best practical possibilities to perform the measurements effectively and which would be the better place in the safeguards point of view. Verification measurements may be needed both in the intermediate storages and in the encapsulation plant.

In this report also the integrity of the fuel assemblies after wet intermediate storage period is assessed, because the assemblies have to stand the handling operations of the verification measurements.

HAUTAMÄKI Johanna, TIITTA Antero (VTT Kemiantekniikka). Loppusijoituksen safeguards-valvontaan liittyvät läytetyn polttoaineen verifiointivaihtoehdot Suomessa. Tutkimus verifiointimenetelmistä, niiden toteutettavuudesta ja turvallisuusnäkökohdista. STUK-YTO-TR 173. Helsinki 2000. 29 s. + liite 1 s.

ISBN 951-712-426-0
ISSN 0785-9325

Avainsanat: polttoainekierto, loppusijoitus, NDA, safeguards, käytetty polttoaine

TIIVISTELMÄ

Tässä raportissa tarkastellaan Olkiluodon ja Loviisan ydinvoimalaitosten käytettyjen polttoainenippujen ja VTT:n tutkimusreaktorin polttoainesauvojen verifiointimahdollisuuksia. Käytetyt polttoaineniput täytyy verifioida partial defect -tasolla ennen loppusijoitusta maan alle. Tutkimusreaktorista tulleet sauvat voidaan verifioida gross defect -tasolla.

Mittaussysteemin kehittäminen partial defect -verifiointia varten on monimutkainen ja aikaa vievä tehtävä. Todennäköisimmät ehdokkaat menetelmiksi, jotka voidaan kehittää tähän tarkoitukseen, ovat passiivinen gammaemissiotomografia sekä fork-detektori täydennettynä gammaspektrometrisella mittauksella.

Koko verifiointiprosessi täytyy suunnitella mahdollisimman sujuvaksi. Verifiointimittauksen suunnittelun ja mittalaitteen kehityksen aloittaminen tarpeeksi ajoissa on tärkeää, jotta verifiointimittaukset onnistutaan sujuvasti yhdistämään kapselointi- ja loppusijoitusprosessiin.

IAEA ja Euratom eivät vielä ole päättäneet loppusijoituksen safeguardskriteereitä. Esimerkiksi parhaan verifiointipaikan valintaan liittyviä kriteereitä ei vielä ole päätetty. Mahdollisia verifiointipaikkoja on tarkasteltu tässä raportissa. Yksi vaihtoehto on välivarasto ja toinen mahdollisuus on kapselointilaitos. Ratkaisevia näkökohtia ovat sellaiset asiat kuten, kummassa ovat parhaat käytännön mahdollisuudet suorittaa mittaukset tehokkaasti ja kumpi on parempi paikka safeguards-valvonnan kannalta. Verifiointimittauksia saatetaan myös tarvita sekä välivarastoissa että kapselointilaitoksella.

Tässä raportissa tarkastellaan myös polttoainenippujen kuntoa märän välivarastointijakson jälkeen, koska nippujen täytyy kestää verifiointimittausten käsittelytoimenpiteet.

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1 INTRODUCTION

There are two nuclear power utilities in Finland at present. The Olkiluoto nuclear power plant consists of two BWR reactors, whereas the Loviisa nuclear power plant has two reactors of VVER 440 type. In addition, VTT Chemical Technology has a research reactor, FiR 1, of Triga Mk II type in Espoo.

Approximately 75 tonnes of spent fuel are annually removed from the reactors of the Olkiluoto and Loviisa NPPs and stored in wet storage facilities at the power plants. A total inventory of some 2600 tonnes of spent fuel will accumulate during the projected 40 years of operation of the Finnish reactor units.

Finland is among the first countries in the world to adopt the final disposal of spent fuel in industrial scale. Over 15 years, the Olkiluoto nuclear power plant has made domestic arrangements like site selection, technical plans and safety assessments for the final disposal of spent fuel based on the 1983 decision-in-principle by the State Council. The Loviisa nuclear power plant returned spent fuel to the Russian fuel supplier until 1996, when the Finnish nuclear legislation prohibited export of nuclear waste. After this, the power utilities decided to co-operate in the management of spent fuel. They established a waste management company Posiva for the planning and later implementation of the final disposal in the Finnish bedrock.

In May 1999, Posiva submitted an application for a decision-in-principle to the State Council about the siting of the final repository near the Olkiluoto power plant in Eurajoki. The decision-in-principle on the location of the final repository is to be made by the end of 2000. Detailed investigations will be performed in 2000–2010 and the construction of the encapsulation plant will take place in 2010–2020. The disposal of spent fuel will start in 2020.

In order to ensure nondiversion of nuclear material, final disposal of spent fuel gives rise to demands for new safeguards approaches. Spent fuel conditioning plants and geologic repositories are new facility types, where IAEA has not previously applied safeguards. Presently, the criteria for the nuclear material accountancy and control are being drafted.

The aim of this report is to give a basis for further work in specifying a safeguards verification measurement system for spent fuel assemblies and rods before they enter the final repository in Finland. The report considers the safeguards process at the back-end of the fuel cycle and pertinent verification methods. Important aspects are the verification levels of the methods and possible risks to the spent fuel due to verification activities.

2 SAFEGUARDS MEASURES AT THE BACK-END OF THE FUEL CYCLE

The safeguards system failed to reveal the secret nuclear weapon programme of Iraq. Owing to this, the safeguards system is being reformed. The objective is to give credible assurance of the non-diversion of the declared nuclear material and of the absence of undeclared nuclear material or activities. The new safeguards system based on INFCIRC/540 [1] is going to be integrated with the old system based on INFCIRC/153 [2]. The integrated safeguards system considers a state as a whole. IAEA collects diverse information on the nuclear activities from the state and other sources e.g. satellites. If necessary, it makes additional inspections and has a wide access to take environmental samples. The mechanical and systematic inspections, which were characteristic of the old system, are reduced in the integrated safeguards system.

The Finnish approach to the back end of the fuel cycle is represented schematically in Figure 1. The fuel assemblies are stored in the reactor building for 1–3 years before they are transferred to the interim storage. The safeguards measures before the final disposal concern fuel, which is in stationary state in the reactor building and in the interim storage. When the final disposal begins, the spent nuclear fuel flow will be safeguarded. The knowledge about individual fuel

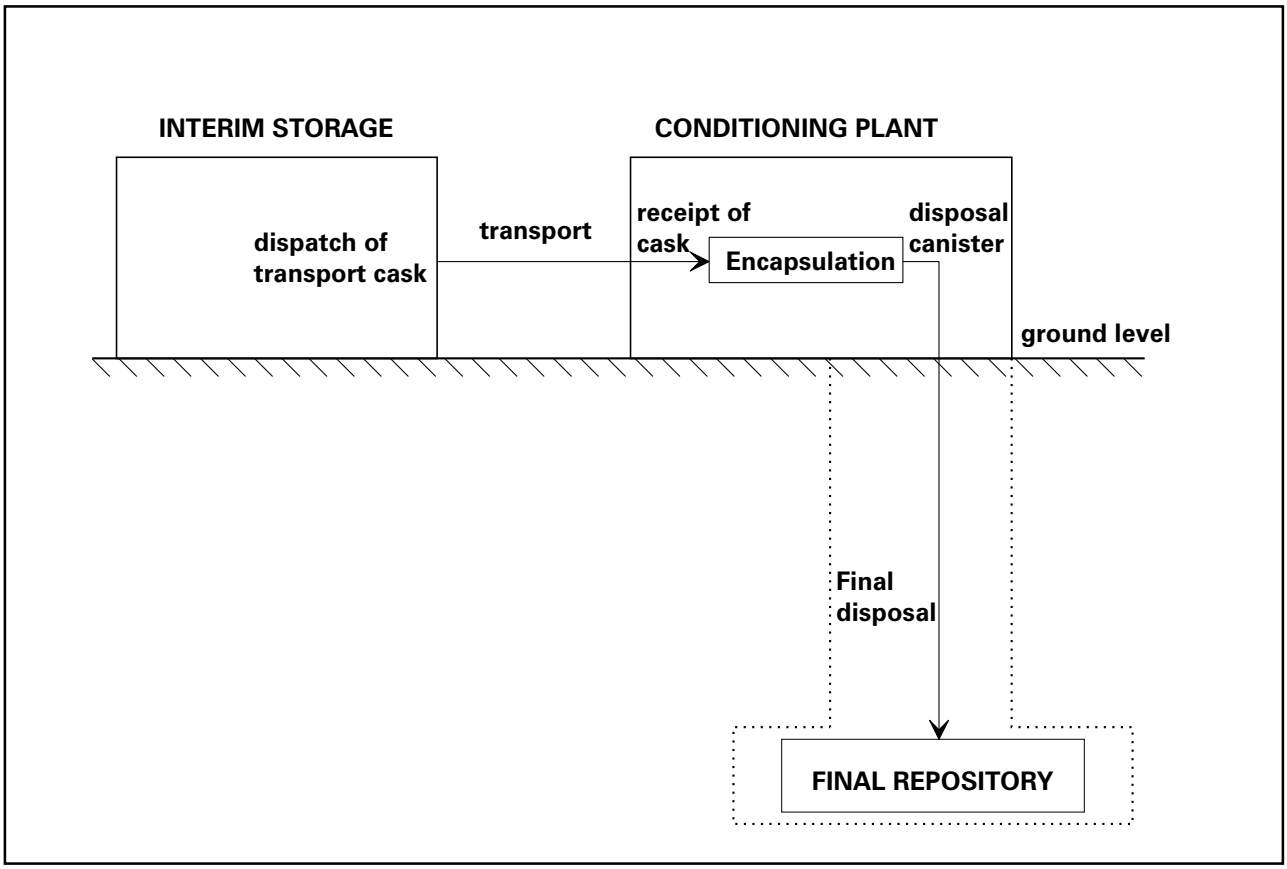

Figure 1. *The back end of the fuel cycle in Finland.*

assemblies decreases towards the end of the fuel cycle.

The safeguards measures for the conditioning plant, operating repository and closed repository are described in sections 2.1, 2.2 and 2.3 based on the reports of the SAGOR Programme [3, 4, 5].

2.1 Conditioning plant

The last possible place to verify individual spent fuel assemblies and rods is the conditioning plant. The spent fuel assemblies and rods lose their identity in the conditioning process. The new item is a disposal canister. After this point, the continuity-of-knowledge of the material flow is mainly maintained by containment and surveillance (C/S) measures.

Nuclear material accountancy (NMA) verification establishes and tracks knowledge about the quantity of nuclear material present at the facility. These measures include reviewing records, counting items, checking item identification (where possible) and making nondestructive assay (NDA) verification measurements (where feasible). The design information verification (DIV) assures that the facility design and operation are as declared and that the applied safeguards approach addresses all diversion concerns. In order to increase the efficiency, the safeguards approach will include unannounced random inspections, authentication of site monitoring systems data and remote monitoring measures.

2.2 Operating repository

Spent fuel will arrive in sealed disposal canisters at the repository. The safeguards objective is to maintain the continuity of knowledge on all canisters. Any diversion of the spent fuel should be detected and the absence of underground reprocessing should be confirmed.

The safeguards strategy is based primarily on the maintenance of the continuity-of-knowledge. To verify the flow of the canisters, the recommended safeguards approach is to use item counting supported by a reliable and comprehensive C/S system above the ground. The C/S measures should ensure that undeclared items neither leave nor enter the underground area. The C/S system will be comprised of an integrated system of motion and radiation detectors, optical surveillance and seals. These will be designed for independent operation and remote monitoring to minimise the presence of inspectors at the site.

DIV demonstrates that the construction and operation of the repository fully meet the declared design of the facility. DIV is recommended as the primary safeguards measure underground to detect the presence of undeclared excavations and activities. The main instrument is visual observation. Additionally, DIV would include e.g. geophysical methods.

Environmental monitoring will be done underground and on the surface, especially at the outlets of ventilation shafts of possible adjacent excavations. This monitoring is likely to be effective should a clandestine reprocessing plant be operated in the repository or in an adjacent mine.

Satellite surveillance may be useful to monitor the surface of the repository site. For example, large equipment, which could be used for drilling undeclared boreholes, could be detected.

2.3 Closed repository

Diversion of spent fuel can only take place by excavation after closure of the repository. The important locations for detecting mining activities are the entrance of the original shaft, the surrounding area on the surface above the repository and adjacent mines, tunnels or caves.

The suggested safeguards measures include unannounced random visual inspections by inspector, geophysical monitoring, satellite or aerial monitoring and seismic monitoring. Visual inspection could be the most effective way to detect undeclared activities at the original shaft or at adjacent mines or caves. Satellite monitoring could be the most useful safeguards measure for surface area inspection. Passive seismic monitoring could be continuously used to detect the possible seismic signals created by mining activities. Geophysical monitoring techniques could be used during on-site inspections. Furthermore, environmental sampling and information analysis could be applied. Remote transmission of data would reduce costs and enable an early detection of undeclared activities.

3 SAFEGUARDS REQUIREMENTS

Safeguards requirements are approached in this section based on the reports of the SAGOR programme [3, 6].

Diversion of a significant quantity of nuclear material from spent light-water reactor fuel requires diversion of spent fuel casks, canisters, assemblies, cans, rods or pellets. Diversion could occur, while the spent fuel item is being transferred, in storage, undergoing conditioning or emplaced in the repository. Diverted spent fuel could be processed at a clandestine reprocessing facility (whose detection is the goal of the Strengthened Safeguards System) or used as undeclared feed in a declared reprocessing facility. This concern is addressed by the safeguards measures implemented at reprocessing facilities. Separated nuclear material could be used in the manufacture of a nuclear explosive device.

3.1 Safeguards objectives

The current safeguards criteria contain safeguards measures for spent fuel storage and handling operations at reactors, reprocessing facilities and storage facilities. However, safeguards approaches are required for new facility types i.e. spent fuel conditioning plants and geological repositories, where IAEA has not previously applied safeguards. Owing to that, safeguards criteria for the back-end of the fuel cycle are under development.

Concerning the final disposal of spent fuel in geologic repositories, the objective of the safeguards is to assure with a high degree of confidence that the nuclear material contained in spent fuel is as declared, is emplaced and remains within the repository. Safeguards actions for the geologic repository continue until the state declares that it is removing the nuclear material or safeguards are no longer implemented anywhere. The specific safeguards objective for a conditioning plant is to provide a high level of assurance that the quantity of nuclear material, which is contained in the spent fuel and received by the conditioning facility, leaves the facility in the declared disposal containers.

3.2 NDA verification measurements

Spent fuel is expected to arrive at the conditioning facility either as unverified items or as items verified at the gross defect level in casks under single C/S. In some cases, spent fuel may arrive having been previously verified at the partial defect level. The requirement for partial defect tests applies to irradiated fuel assemblies, which can be dismantled at the facility. According to the IAEA's safeguards criteria, a partial defect of a spent fuel assembly means that one half or more of the irradiated rods of an assembly is replaced or missing. A gross defect means that a whole assembly is replaced with a dummy or the assembly is missing. Presently, safeguards criteria for non-destructive assay (NDA) verification measurements for the back-end of the fuel cycle are being drafted by the IAEA and Euratom.

It is generally considered that each spent fuel item to be loaded into disposal canisters should be subjected to a verification measurement at the partial defect level in advance of the final packaging operation. Verification of the nuclear material content of the spent fuel should occur at that point where the spent fuel can be most effectively measured. This measurement can take place at the intermediate fuel storage or at the conditioning plant.

It is desirable to implement an optimum combination of NDA and C/S actions. The optimum

solution can vary from facility to facility depending on specific design. The grade of the measurement requirements, e.g. gross or partial defect, and remeasurements can depend substantially on the applied C/S measures. For example, if confidence can be achieved through C/S that no fuel rods or assemblies have been diverted after the assembly was verified at the appropriate level, then no further measurements are required. It is advisable that the highest grade verification measurement is applied to the spent fuel as late as possible in the process as this may place less demand on the C/S system up to that point and decrease the possibility of loss of continuity of knowledge. For approaches, which have this measurement early in the process, it would be prudent to have at least gross defect measurement at some later step in the process, preferably as close as possible to loading spent fuel into the disposal container. If the C/S system could confirm that all rods or assemblies have gone into disposal containers, there would be no need to verify the waste streams, though it may be prudent to do so should there be anomalies generated from the C/S system.

The fuel assemblies become difficult to access when they are placed in a disposal canister. Once closed and sealed, canisters shall not be reopened for reverification of the nuclear material content. For safety reasons, reopening of canisters can not be excluded. When spent fuel is emplaced in the repository, it will no longer be accessible for direct safeguards verification.

3.3 Continuity of knowledge

Continuity of knowledge is currently maintained through the application of C/S measures. A dual C/S system uses two independent surveillance or monitoring systems that are based on different principles such that there is no common failure or defeat mode for both systems. The dual C/S system provides assurance that a diversion of nuclear material would be detected and that continuity of knowledge would not be lost unless a diversion occurred. As advanced surveillance and monitoring systems are developed and implemented the role of dual C/S in safeguards approaches may change. However, the objective that a high degree assurance of maintaining the continuity of knowledge must be preserved.

Maintaining the continuity of knowledge of the contents of a disposal canister and of the repository is critical to the safeguards approach for the final disposal of spent fuel. If the continuity of knowledge of the presence of the spent fuel is lost and the nuclear material presence can not be re-established because of inaccessibility, a high degree of assurance about detection of the undeclared processing of spent fuel should be required.

4 INTEGRITY OF FUEL ASSEMBLIES AFTER WET INTERMEDIATE STORAGE

Minimising and controlling radioactivity releases to the pond water and to the environment are the main considerations in the wet storage technology. The key factors are the durability of fuel cladding and fuel material in water. Furthermore, the corrosion resistance of the underlying fuel material is not an issue, if the cladding is highly durable and it is not mechanically damaged. [7]

4.1 Objectives of fuel design

The fuel structure shall be designed in such a way that it is not damaged during operation. The fuel bundles must maintain their integrity in all operational conditions and in postulated accidents. They have to endure the respective loading so that the reactor shutdown and cooling are not endangered. The fuel design shall be such that, after normal usage, it endures long-term storage and handling connected to disposal. [8]

4.2 Durability of Zircaloy cladding

Fuels clad with zirconium alloys represent the dominant fuel type in wet storage [7]. The fuel cladding alloys are Zircaloy 2 in Olkiluoto BWR reactors and Zr-1% Nb in Loviisa VVER reactors. Both power plants use uranium fuel in the form of UO_2 pellets. [9,10]

Based on a series of hot cell examinations after wet storage periods from 5 to 27 years, Zr alloys are highly durable cladding materials in wet storage. Results of the examinations are supported by laboratory data, by specific observations during fuel shipments and other fuel handling operations and by visual surveillance by storage pond operators for periods approaching 30 years. Results of data and experience support a conclusion that wet storage of fuel with Zr alloy cladding will be acceptable for periods in the range of 50 to 100 years. It is important to continue to evaluate evidence regarding performance of zirconium alloys as wet storage periods increase and as design and service characteristics of the fuel assemblies change. [7]

For example, fuel with Zircaloy cladding from the Shippingport reactor has been examined after wet storage of 20 years. Results were compared with investigation results of the rods of the same assembly, which were received 20 years earlier. No significant change was observed in the oxide thickness of the cladding, in the hydrogen content or distribution of the cladding, in the mechanical strength or ductility of the cladding, in the cladding ovality or dimensions, in the fission gas release fractions or in the rod appearance. There was no evidence of active corrosion.

Reactor-formed zirconium oxide, ZrO_2, develops on zirconium alloys during aqueous corrosion. Zirconium oxide is highly resistant to a wide range of aggressive chemicals at low temperatures. For example, fuel with Zircaloy cladding was investigated after 27 years of storage in aggressive water chemistry (up to 760 ppm chloride). According to video inspections and pond radioactivity monitoring, Zircaloy clad fuel survived without evidence of degradation. The oxide films on Zircaloy clad are typically scratched in fuel handling, particularly when fuel rods are withdrawn from the assembly spacers. However, bare Zircaloy reforms a thin oxide layer, which has high resistance to aqueous corrosion at low temperatures.

Indirect evidence of the durability of Zircaloy cladding has been received from fuel handling operations. Rod consolidation involves mechanical removal of all the fuel rods from the fuel assembly hardware, which normally maintains the rod-to-rod spacing, and placing the fuel rods into a closely packed array in a fuel assembly shaped

canister. Videotapes of the rods at West Valley, Battelle Columbus Laboratories, Idaho National Engineering Laboratory (INEL), Test Area North (TAN) and Millstone-2 and observations at TAN provide a qualitative indication that the rod consolidation operation generally does not appear to result in significant damage to the fuel cladding. Quantitative data on the effects of rod consolidation on fuel rods were also collected at TAN. Longitudinal burnish lines or scratches were visible in most rods, but they did not appear to have affected the rod integrity. Lines had been generated, when the crud or oxide layer was penetrated as the rod was pulled or pushed through fuel assembly spacer grids.

Scratches or mars on the fuel cladding that extend into underlying metal (Zircaloy) could be of concern should those fuel rods later come into direct contact with aluminium (e.g. in storage racks or canisters) during subsequent storage in impure water. There is potential for galvanic coupling, which could result in accelerated hydriding of Zircaloy under certain conditions. Such conditions are not likely to develop in commercial storage ponds. [11]

Rods with failed cladding have been exposed to withdrawal forces from fuel assembly spacers during consolidation. Some rods with collapsed cladding were reformed to a circular cross section and loaded into the canister (U.S. Tool & Die and Rochester Gas and Electric). This indicates considerable residual ductility. According to INEL, Virginia Power and Florida Power and Light, fuel rods have been found to be flexible and some mishandling would be tolerable. Also severely bowed fuel rods have been successfully consolidated (Westinghouse Electric Corporation and Northern States Power).

Examination of the condition of the spent fuel assemblies will be done every ten years at the Loviisa NPP. The first follow-up study will be performed in 2005. In each follow-up study a few assemblies will be picked up for investigation. [12]

The service of the fuel assemblies is controlled in the Olkiluoto reactors every year during the revision period. Some assemblies, which have been discharged from the reactor or which will be loaded into the reactor for the next irradiation period, are inspected. There is also a control program for the condition of the spent fuel assemblies. The last inspection was performed in 1997 and the next will be in 2002. After the year 2002, the inspections will be conducted every ten years. [13]

4.3 Damage mechanisms

Large gamma exposures have minimal effects on the microstructure of metals. Neutron irradiation generally increases the strength and decreases the ductility of metals. The consequences, which would emerge during post-irradiation handling and storage, are not evident. The decrease of ductility may be strong enough to considerably reduce low temperature impact strength of the fuel assemblies, which have high burnups. The radiation-induced loss of ductility is exacerbated by hydrogen cracking in the zirconium alloys. Zirconium alloys absorb a fraction of the hydrogen released by the following reaction during irradiation in the reactor:

$$Zr + 2H_2O = ZrO_2 + 4H (or\ 2H_2)$$

Because corrosion rates are extremely low at wet storage temperatures, further hydrogen uptake is not expected. Some high burnup PWR fuel claddings have been reported to have hydrogen contents above 600 ppm. Combined with reduced ductility due to irradiation, this suggests low impact strength in the low temperature (< 50°C) wet storage regime. Marked decreases in ductility of Zircaloy cladding have been measured for high burnup assemblies. Because of this, impacts should be avoided when handling fuel assemblies or rods, which have high burnup. Cases involving dropping of fuel assemblies have occurred during post-irradiation handling. The consequences of mechanical impacts were minimal, but the dropped assemblies have had low or moderate burnups. Due to decrease of low temperature impact strength, similar events with high burnup assemblies may result in more significant consequences. [7] This is the problem of the assemblies of old types. Concerning the assemblies of new types, the emerging evidence suggests that improvements in cladding metallurgy and reactor coolant control are resulting in lower hydrogen absorption in high burnup fuel cladding.

For example, the clad thickness of VVER 440

fuel is about 0.63 mm and the clad thickness of ATRIUM 9 fuel is about 0.665 mm [9]. The oxides that form on zirconium alloy fuel rods during reactor service vary in thickness from about 3 µm to 5 µm for low burnup rods and at the ends of the rods to nearly 200 µm on high burnup rods. Oxide thicknesses up to 200 µm have reduced typical PWR cladding thickness by approximately 20 %. No additional significant loss of thickness is anticipated during wet storage. Thick oxides (> 60 µm) are sometimes observed to spall during reactor service. Further spallation in wet storage is not likely unless impacts occur. [7]

4.4 Damaged rods

A worldwide survey of spent fuel storage experience indicated that 70 % of operators store failed LWR fuel in the same way as intact fuel and the rest 30 % store failed fuel in canisters. [7] At the Olkiluoto nuclear power plant the leaking rods are extracted from the fuel assembly and hermetically encapsuled into a shielding pipe. The pipe is positioned into a fuel assembly shaped rod rack. [14] The Loviisa nuclear power plant has returned the leaking assemblies to the Russian fuel supplier until 1996. After this, the leaking assemblies have been stored in the same way as the undamaged assemblies in the storage rack. If necessary, the leaking assemblies can be encapsulated into hermetic bottles. This option has not been used yet. [15]

Because the likelihood of rod breakage is potentially higher with fuel rods with large cladding defects, these fuel assemblies represent a biased sample. Few of the rods broken during handling have required special handling or storage considerations. [11]

Damaged fuel rods have been investigated and two important results emerge from these examinations. Defects in Zr alloy fuel cladding have not been observed to enlarge during wet storage in about 10 years' period. There is also systematic evidence that uranium oxide exposed to cladding defects does not dissolve detectably over periods of several years should it be in contact with the storage pond water, either deionized or borated. Laboratory leaching studies of irradiated uranium oxide fuel with burnups up to 54 MWd/kg have been performed at 25 °C. According to these studies, exposed fuel will contribute to the radioactive inventory in the pond water. However, low temperatures and small exposed pellet areas limit releases to amounts, which are readily removed by the cleanup systems of the pond. [7]

Eighteen intact and ten defective PWR fuel rods with Zircaloy cladding were investigated during wet storage in the spent fuel pond of the Obrigheim nuclear power plant. The rods were inspected using visual inspections, profilometrical testing, eddy current testing and oxide thickness measurements four times in a seven-year period. There was no detectable change in the rod parameters. During handling and measuring the mechanical straining and stressing of a single fuel rod is higher than that of a defective fuel rod fixed in a fuel assembly. [16]

Many fuel shipment campaigns provide additional evidence based on visual observations, that wet storage does not degrade reactor-induced cladding defects and that cladding defects do not preclude the rigors of handling and shipping [7]. For example, decommissioning of a major spent-fuel pond of the Western New York Nuclear Service Center has contained shipment of fuel assemblies. Satisfactory handling and shipping characteristics of the fuel after extended wet storage confirm the prior experience, suggesting that Zircaloy-clad fuel does not degrade significantly during interim wet storage. Numerous assemblies in the inventory were known to have cladding defects. They were stored uncanned without substantial effects on pond operations, fuel handling, shipment or rod consolidation. [11]

4.5 Crud effects

Crud layers generally overlay the oxide films on fuel that has been in reactor service. The crud layers are posed of radioactive corrosion products from the reactor circuits. The composition of the layers differs depending on the reactor circuit materials and on the water chemistry in the reactor coolant systems. [7] According to the investigations made at the Olkiluoto NPP, the amount of the crud depends on the water chemistry of the primary circuit and the irradiation time, not substantially on the burnup of the assemblies [17].

The crud is carried by the reactor coolant and it deposits on fuel rod surfaces. When fuel assem-

blies are discharged after reactor service, the crud layers are carried on the fuel rod surfaces into the wet storage facilities. Crud thicknesses vary from about 50 µm to almost zero. The thickest layers generally relate to reactors with oxygenated coolants. However, recent improvements in water purity and chemistry control have minimised crud deposition. [7]

The behaviour of the crud layers during wet storage may have significance in future. There is evidence, that crud layers, which have originally been tenacious upon discharge from reactor, may soak loose from the fuel rods during long periods of wet storage. For example, there have been indications of crud loosening for both BWR and PWR fuels, which have had storage periods from 12 to 18 years in the West Valley storage pond. Impacts of crud loosening should be anticipated both in shipments and in transfers to dry storage during future handling of fuels having long periods of wet storage. Crud may contaminate the verification measurement device.

4.6 Investigations made at the Olkiluoto NPP

The mechanical integrity and the appearance and surface quality of different components of the spent fuel assemblies have been in focus of visual inspections made at the Olkiluoto NPP. Especially, the corrosion and crud of the rods, the differential growth and deflection of the rods, the fastening of springs and screws, the position of spacer grids and the possible damages originating from deterioration or vibrations have been the concern in the visual inspections. The results of the inspections have mainly been as expected. An exception has been the ABB Atom LK2-claddings of SVEA assemblies. Their corrosion has been quite intense in the locations of the spacer grids, especially concerning the locations of the lowest spacer grids. This has been taken into consideration in the operational limits of SVEA assemblies. The features of these claddings have been improved since the delivery of 1995. According to the visual inspections of leaking assemblies, there have been leaking assemblies whose damages have been caused by debris fretting. [17]

4.7 Handling and inspection systems

The fuel handling and inspection systems shall be so designed that, during handling and inspections, criticality is prevented, adequate cooling and radiation protection is ensured and the potential for fuel failure is extremely low. Handling and inspection measures shall be so planned that they do not compromise the integrity of storage pools or fuel. Transfer of heavy objects shall be avoided above the fuel and above locations where, if dropped, they might endanger safety-significant components. The layer of water ensuring radiation protection shall be maintained adequate also after a single failure. Also the gripping devices shall be so designed that loss of grip is prevented by two independent ways and that the devices fail safely if their power supply is lost. The components and parts of components in contact with pool water shall be designed to resist contamination, and they must be decontaminable. [18]

5 TECHNICAL ASPECTS IN IMPLEMENTATION OF VERIFICATION

Spent fuel items loaded into disposal canisters should be subjected to a verification measurement at the partial defect level in advance of the final packaging operation [3]. So far, IAEA and Euratom have not concluded the safeguards criteria. E.g. what would be the best place to perform the verification measurements for the final disposal of spent fuel assemblies have not been concluded yet. Possible candidates for places where these measurements could take place are spent fuel storage ponds in the intermediate storages of the Olkiluoto and Loviisa power plants. The other candidate is the encapsulation plant. The advantages and disadvantages of the intermediate storage or the encapsulation plant as a place for verification measurements are compared in this chapter. Also the verification measurement of the FiR 1 research reactor fuel is considered.

5.1 Verification in interim storages

Many measurement campaigns have been conducted in the Olkiluoto and Loviisa KPA stores. If verification of spent fuel is conducted in a spent fuel storage pond of an interim storage the measurements could be performed in water. Water absorbs radiation and gives radiation protection for the persons involved in measurements. Radiation from other assemblies does not disturb the measurements due to good radiation shielding of water. Measurements have been performed in the evacuation pond where there are no other spent fuel assemblies but the one under measurement. However, the situation may be different at the time when the final disposal of spent fuel starts.

One benefit in the arrangement of the verification measurements at the partial defect level in the interim fuel storages is that there is a lot of experience in performing spent fuel measurements under water. Measurement devices have to be waterproof and because of liquid nitrogen cooling, using HPGe detectors is impossible in most devices. On the other hand, the resolution of cadmium-zinc-telluride (CZT) detectors has improved to such an extent that they can replace the more difficult to use HPGe detectors in many spent fuel gamma spectroscopic measurements. An important characteristic of CZT detectors is their room temperature operation.

5.1.1 Verification in Olkiluoto KPA store

There may be spent fuel or other items stored in the evacuation pond in the Olkiluoto KPA store, see Figure 2 [14]. One benefit is that the evacuation pond is quite large. The transfer cask is placed apart from the evacuation pond. There is a fuel handling machine for lifting and transferring single spent fuel assemblies in the storage. In order to ensure good radiation shielding, there should be enough water between the verification measurement point and the spent fuel assemblies stored in the evacuation pond.

5.1.2 Verification in Loviisa KPA store

There are two spent fuel storages, storage 1 and storage 2, in the Loviisa KPA store, see Figure 3. The spent fuel assemblies are stored in the transfer baskets in storage 1. Each basket accommodates 30 assemblies. There is no fuel handling machine for lifting and transferring individual assemblies in storage 1. Instead, there is a crane for handling transfer baskets. When the fuel is removed from the storage, a transfer cask is placed in the evacuation pond. The transfer basket containing the spent fuel assemblies is moved into the transfer cask. Transfer of individual assemblies is impossible. Owing to this, the verification measurements can not be conducted in storage 1. [15]

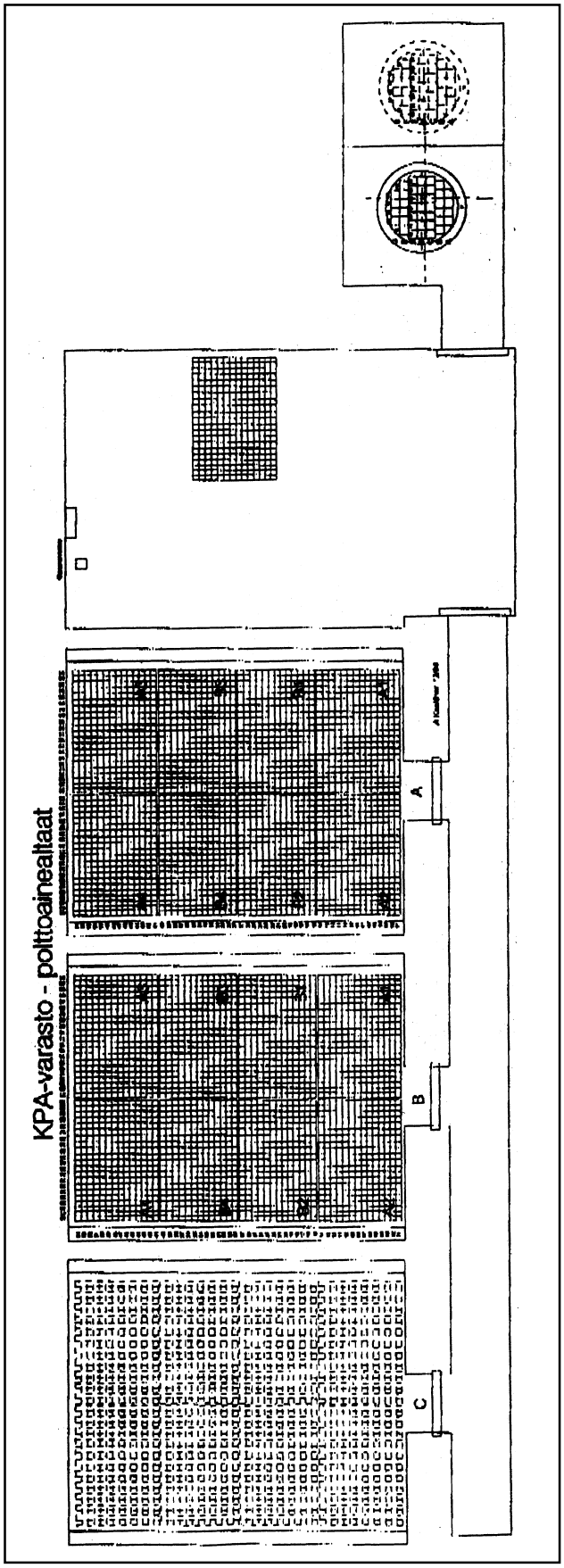

Figure 2. *Layout of the Olkiluoto KPA store: transfer basket, evacuation pond and storage ponds A, B and C.*

The fuel assemblies are stored in racks in storage 2. There is a fuel handling machine for transfer of single assemblies. There will be nothing stored in the evacuation pond at the time when the final disposal starts. The transfer basket and cask are in the evacuation pond for transportation. The evacuation pond is quite small. There are two options to load the transfer cask, when the fuel assemblies are moved out of the storage. One option is that the assemblies are first placed into the transfer basket. When the basket is full, it is lifted into the transfer cask. In this case, the basket and cask need their own space in the evacuation pond and there is no room for the verification measurement system. The other option is that the basket is placed as empty into the cask. After this, the assemblies could be transferred one by one into the basket inside the cask. In this case, there could be enough room for the measurement system despite the fact that the evacuation pond is quite small. In order to ensure enough radiation shielding, the measurement position should be as far as possible from the assemblies that have already been packaged into the transfer cask. [15]

In the Olkiluoto KPA store and in storage 2 of the Loviisa KPA store, the verification measurement could, in principle, be performed when a spent fuel assembly is moved from the storage rack to the transfer cask. Owing to this, no additional movement of assemblies would be required. In addition, water attenuates impacts should accidents or mishandling of spent fuel assemblies or rods happen, e.g. dropping of an assembly.

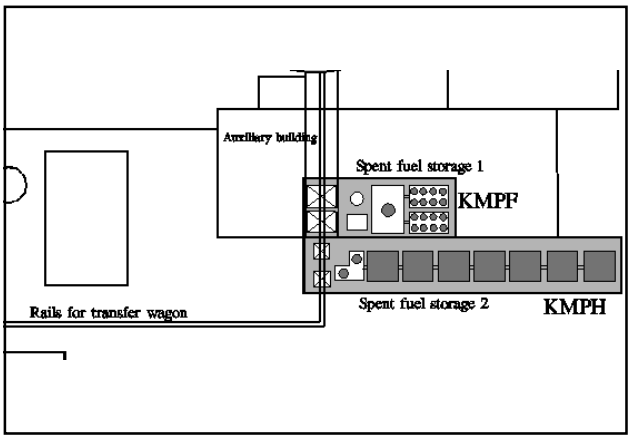

Figure 3. *Layout of the Loviisa KPA store: Two storage ponds and an evacuation pond in storage 1, seven storage ponds and an evacuation pond in storage 2.*

Storage 1 of the Loviisa KPA store has features that prevent the verification measurements of individual assemblies.

A transfer cask containing assemblies could, in principle, be transferred from storage 1 to storage 2, but it is very inconvenient and time-consuming, and is not a normal procedure at the Loviisa NPP.

The arrangement of a complete verification measurement system at the partial defect level in the Finnish interim storages is impractical.

5.1.3 Other safeguards aspects

Concerning the phases before spent fuel is packaged into disposal canisters, the verification measurements at the partial defect level in the intermediate storages are performed in a very early phase. The continuity of knowledge should be preserved at the defined level during transport to the encapsulation plant until a new item, a spent fuel disposal canister, is constructed, see Figure 4. This would require that e.g. dual C/S measures should be applied instead of single C/S measures. Reverification for partial defect would be necessary at the conditioning plant, if the continuity of knowledge on the cask has not been maintained during transport from the intermediate storage to the conditioning plant. The partial defect reverification of the cask could be possible, if a cask with a verified loading is measured to get a "baseline" for the cask before the shipment to the conditioning plant. Subsequent measurements of the same cask could be compared with the "baseline" to verify no change in the nuclear material content of the cask. The measurement device in the intermediate storage and the measurement device in the conditioning plant have to be intercalibrated. At present there is no validated method to implement this measurement at the level able to detect one missing assembly of a full cask.

The risk of losing the continuity of knowledge during transport will concern especially the spent

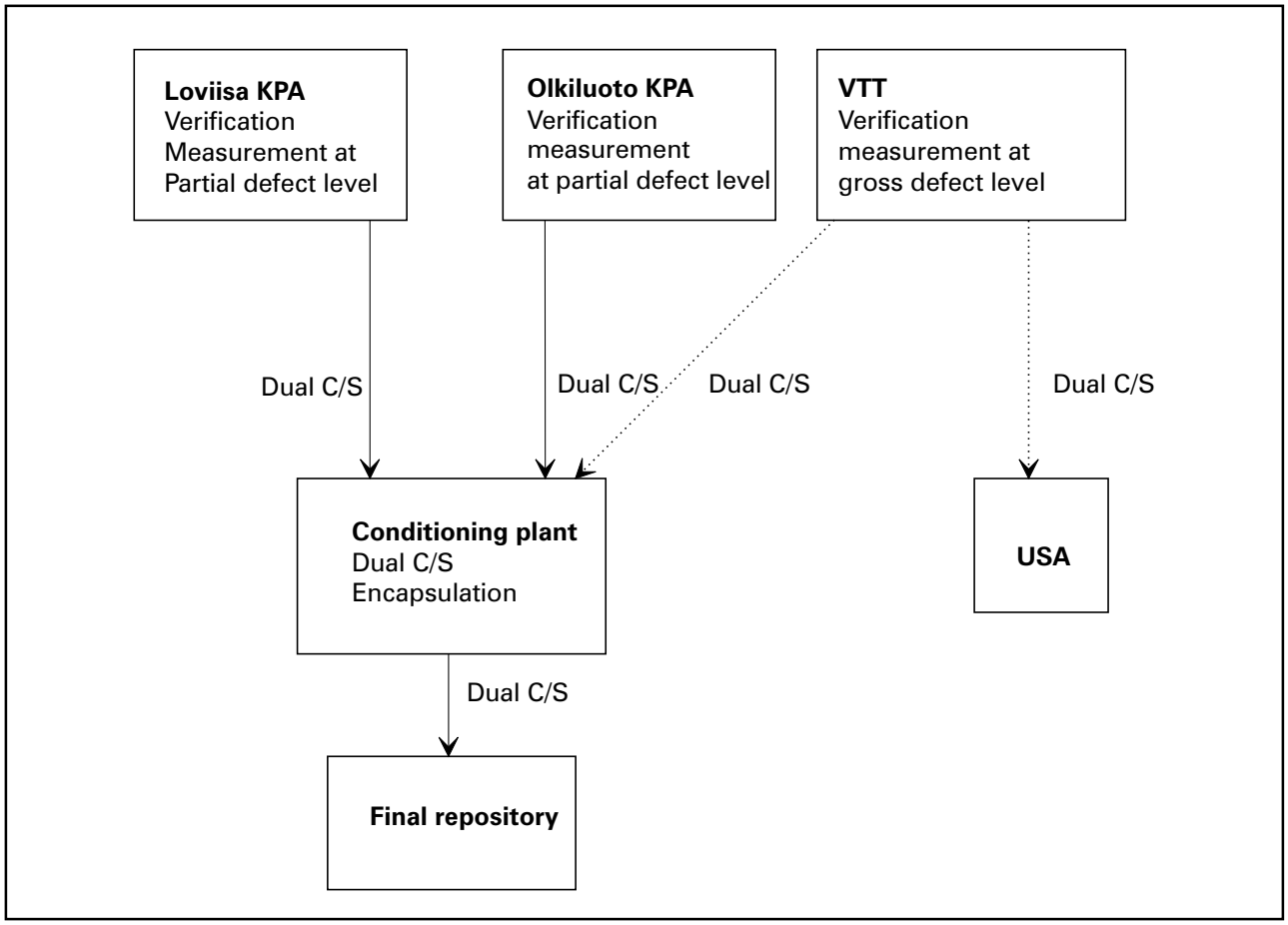

Figure 4. *A block scheme on the option of performing the verification at the partial defect level in the KPA stores of the Olkiluoto and Loviisa NPPs and at the VTT. The dotted lines represent alternative back-end options of the VTT reactor fuel.*

fuel transported from Loviisa, if the repository is built in Eurajoki, see Figure 5. It is possible that the continuity of knowledge is lost during the long way, e.g. due to a transportation accident. The transportation could be managed by sea or by land. If the final disposal of the spent fuel of Loviisa NPP takes 20 years, 40 tonnes of spent fuel would be transported annually. This amount of spent fuel would fit into 12 transfer casks similar to those used for returning fuel to the Russia. This would annually require 12 railway wagons, 12 special transports by road or 1–2 sea transports.

5.2 Verification at conditioning plant

It would be convenient to conduct the verification measurement at the partial defect level in the encapsulation plant, because verification would take place just before the spent fuel assemblies enter into the disposal canister in the hot cell. If the verification measurement were performed in the hot cell of the encapsulation plant, it would place less demand for the C/S system up to this point, see Figure 6. In this case, the measurements would obviously be performed in air.

The hot cell is the only place inside the encapsulation plant, where assemblies are moved individually. The current plans include a shielded measurement position embedded in the floor of the hot cell. [19] The specific requirements of the measurement position have not yet been taken into consideration. The final design of the measurement position depends on the specifc characteristics of the verification measurement system.

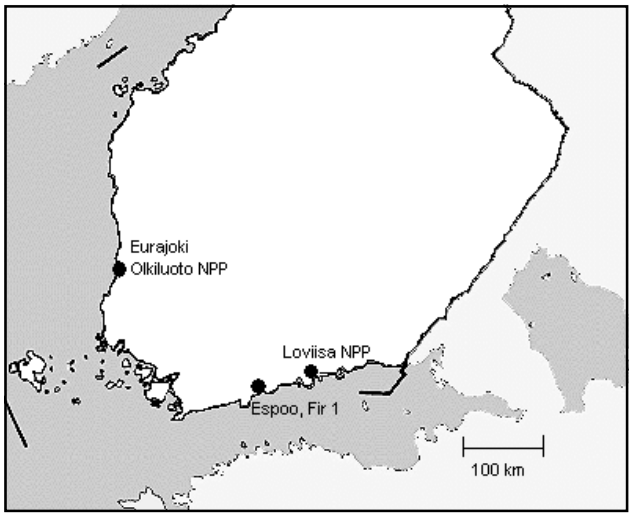

Figure 5. *Locations of the nuclear reactors and potential final repository site in Finland.*

Every assembly is identified by reading the fuel ID code and verified for cooling time and burnup data during the encapsulation. The identification and verification are important factors also in the viewpoint of safety, because the thermal load of the disposal canisters is restricted. The fuel is assumed to be transported dry. Provisions for wet transport are made. There are autoclaves in the design of the encapsulation plant originally intended for drying spent fuel assemblies after wet transportation. In the case of dry transportation, autoclaves would not be needed for drying. One option is that the room allocated for autoclaves could be used for the verification measurements. [19] The room needed for the verification measurement system can not be banked on this.

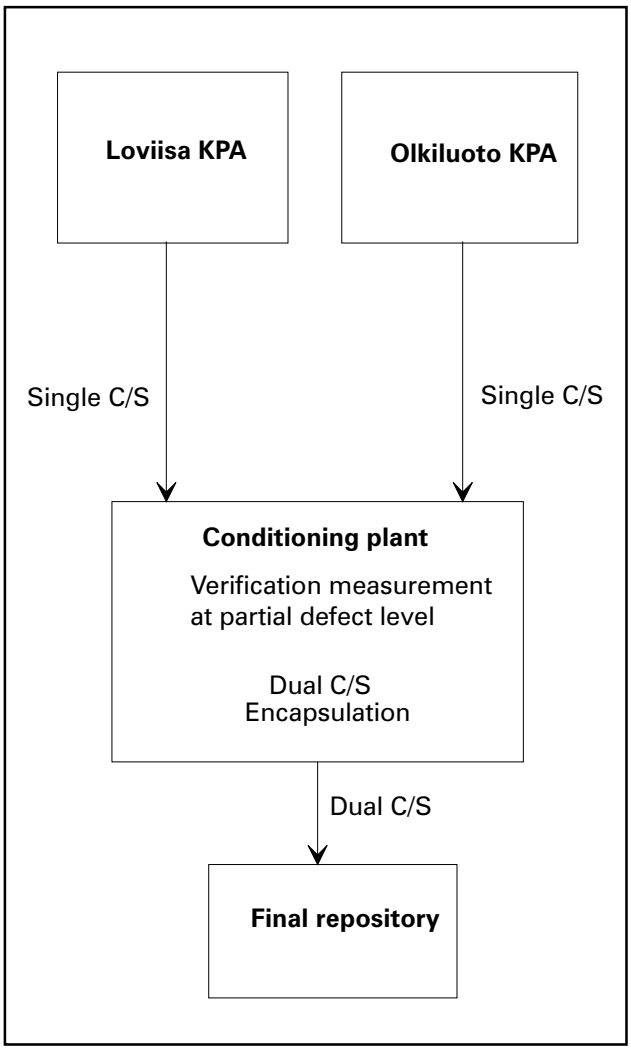

Figure 6. *A block scheme concerning the option to perform the verification measurements at partial defect level in the conditioning plant.*

If the partial defect verification measurements are performed in the encapsulation plant, it has to be taken into consideration in the design of the encapsulation plant

In case of accidents or mishandling, possible damages to the fuel assemblies are more severe in air than in water. Measurements performed in air are technically more demanding as compared to measurements performed under water and there is very little experience on measurements in air. It is important to keep in mind, that the measurement position needs to be shielded, since otherwise radiation in the hot cell from other assemblies in transport casks and canisters could disturb the measurement. The measurement devices do not have to be waterproof. Because of this, it is possible to use HPGe detectors, which need liquid nitrogen cooling. On the other hand, HPGe detectors may be not the optimum solution for the gamma spectrometric measurements.

5.3 Verification measurement of leaking assemblies and rejected rods

Leaking assemblies and rejected fuel rods are packed into hermetically sealed capsules at the NPP site before transport to the conditioning plant. The capsules can be handled in the same manner as the intact fuel assemblies. [20] The leaking rods are also stored in hermetic capsules at the Olkiluoto NPP [14]. The leaking assemblies are stored in the same way as intact assemblies at the Loviisa NPP. There is an option to package and store leaking assemblies in hermetic capsules. When leaking assemblies were returned to Russia, they were packaged into hermetic capsules before transportation. [15]

Leaking assemblies packaged into hermetically sealed capsules are special cases in the verification measurements. All special cases should be identified and verified at the partial defect level already in the intermediate storages. A standard verification measurement system may not be suitable for verification measurements of special cases. A measurement system should be devised, which would be designated particularly for the verification of the special cases. The verification device for special cases could be portable. After the special cases have been verified in the intermediate storage and transported to the encapsulation plant, the same device could be used to verify no change in their nuclear material content.

Hermetic capsules are disposed of in specially manufactured canisters, which have an enlarged position. The sealed capsules will not be opened in the encapsulation plant. [20] Because of this, the verification measurement of leaking assemblies and rejected fuel rods at the partial defect level has to be performed without opening the capsule in the conditioning plant.

If an assembly starts leaking during the transportation to the encapsulation plant or inside the encapsulation plant, it would be an advantage, if the assembly were already verified in the interim storage. Verification measurement of leaking assembly at partial defect level may be more problematic to perform in the encapsulation plant. The leaking assembly will be placed normally in a canister. The ventilation and decontamination systems in the hot cell shall have enough capacity to filter the releases from a certain fraction of leaking fuel rods to keep the radiation exposure for employees and the public well under the safety limits.

5.4 Verification of FiR 1 research reactor fuel

The spent nuclear fuel rods from the FiR 1 reactor of the VTT will be either transported to the USA or disposed of in the same final repository as the power reactor fuel in Finland, see figure 4. The transportation option to the USA is valid only if the FiR 1 reactor is closed before May 2006. [21]

Because the fuel of the FiR 1 reactor is inside separate encapsulated rods, it can not be taken out without breaking the rods. The verification measurement of the fuel rods could be performed at gross defect level. In order to ensure that the fuel rods have maintained their integrity, also a visual inspection of the rods should be performed. The initial enrichment of the fuel is high (20 %) as compared to the power reactor fuel. The high enrichment increases their susceptibility to diversion.

If the spent fuel rods of the FiR 1 reactor are disposed of in the final repository in Finland, they may be packaged into a few BWR assembly

shaped cassettes at the VTT in Espoo. In this case, the rods should be verified at the VTT before packaging, because these cassettes shall not be reopened, see Figure 4. They would be encapsulated into the BWR disposal canisters in the conditioning plant.

It is a long way from the VTT in Espoo to Eurajoki, see Figure 5. In order to maintain the continuity of knowledge during transport, it could require that dual C/S measures should be applied. The partial defect measurement of a cassette will be required at the conditioning plant, if the continuity of knowledge has not been maintained during transport. The measurement could be implemented, if each cassette with a verified loading is measured to get a “baseline” for the cassette at the VTT. Subsequent measurement of the same cassette could be compared with the “baseline” to verify no change in the nuclear material content of the cassette at the conditioning plant. One and the same transportable measurement device at the VTT and at the conditioning plant could be used.

6 MEASUREMENT SYSTEM FOR PARTIAL DEFECT

The non-destructive assay (NDA) techniques have a firm place in the verification applications. Compared to destructive assay (DA), NDA causes less intrusiveness, less radioactive waste production and lower contamination risk.

NDA techniques are based on the measurements of radiation emitted from the samples. This radiation is emitted spontaneously or induced from outside. Neutron and gamma radiation is detected.

6.1 Non-destructive measurement methods and instruments

The verification measurements of the spent fuel assemblies and rods at the partial defect level can be performed either under water or in air, see table 1. Assemblies or rods are generally transferred from their storage racks to the measurement. There are instruments, which are in use and instruments or methods, which are under development.

The Spent Fuel Attribute Tester (SFAT) and the Gamma Burnup Verification device (GBUV) are used by the Finnish Authority for gross defect and burnup verification in the Olkiluoto and Loviisa KPA stores. GBUV has been installed in the Olkiluoto KPA store. The Cerenkov Viewing Device (CVD) is used by the IAEA for gross defect verification. More information about the methods listed in Table I can be found in references 22 and 23.

6.2 Potential NDA methods for partial defect verification

All instruments and methods listed in Table I satisfy the gross defect requirement. There is no validated device available for routine partial defect measurements. There is even no common idea of the most suitable verification method at the partial defect level. The most promising NDA methods, which have the potential to be developed for this purpose, are the High Energy Gamma Emission Tomography and the Fork detector combined with a CdZnTe detector (Upgraded Fork detector). These methods are considered in this chapter. Also such an everyday method like weighing should not be forgotten. Weighing of an assembly would reveal e.g. missing rods.

It is important to keep in mind, that developing a measurement device for partial defect verification purposes is a long-term project. Evolving the methods by building test devices, making test measurements and developing the analysis of the measurement data is a very demanding and time consuming process. The user interface of the completed verification system has to be constructed operator friendly i.e. easy to use. Owing to this, the development of the verification device has to be conducted concurrently with the process planning of the back-end of the fuel cycle.

6.2.1 High-Energy Gamma Emission Tomography Device

A Passive High-Energy Gamma Emission Tomography Device is capable of partial defect verification on rod level. It reconstructs a 2-D activity cross section map of an assembly from the measured radiation profiles. Measurements can be performed either in water or in air. No operator declared information on burnup, cooling time or irradiation history is needed. [24] However, the Passive High-Energy Gamma Emission Tomography device has limited power in performing burnup verification measurements.

Partial defect verification of an irradiated BWR assembly by gamma emission tomography requires about 1 hour of measurement time, if each

Table I. *Verification methods and devices. [22,23]*

Device/method	Fuel movement needed	Measurements performed	
		in water	in air
SFAT		X	
Gamma Taucher		X	
CVD		X	
Upgraded Fork	X	X	
BUD/CONSULHA	X	X	
PYTHON	X	X	
SMOPY	X	X	
NAJA	X	X	
FPFM	X	X	
GBUV	X	X	
Passive High Energy Gamma Emission Tomography	X	X	X
CANDU Fuel Monitor	X	X	
Spent Fuel Identification System	X	X	
Californium Shuffler	X	X	
Passive Neutron Multiplicity Counting	X		X
Active ^{124}Sb-Be Epithermal Neutron Method	X		X
^{252}Cf-Source-Driven-Noise measurements	X		X
The Synchronous Active Neutron Detection method	X		X
LSDTS	X		X

fuel rod has to be detected using an array of 10 CdTe detectors with a 2 mm sampling interval. In order to scan one side of an assembly (318 mm), the detector array has to be moved stepwise 15 times. The assembly has to be rotated 48 times with 7.5 degrees intervals. High-resolution images are received with a device, which has these parameters. The measurement of one assembly requires many measures for the operator. For practical detection of a missing rod a lower resolution image is enough. Such an image could be achieved by an array of 50 detectors with 4 mm spacing between them. Also the scanned linear length could be decreased to about 200 mm. This kind of detector system would not need linear movement of the detector system. Only rotation of the assembly would be needed. The measurement time could be reduced to 3–4 minutes for BWR assemblies using suitable means of rotating the assembly. However, the measurement head becomes heavier and more expensive, when the number of detectors is increased. Further improvement is possible if the objective is not to reveal missing of just a single rod (less than 2 % of material) but rather missing of several rods. As good sensitivity as for BWR assemblies can be achieved for PWR assemblies by measuring the double number of views as for a BWR assembly. Four times longer measurement time is needed for a PWR assembly as compared to a BWR assembly. About 12–16 minutes measurement time could be achieved for PWR assemblies.

The integral of gamma intensities above a certain threshold energy level is detected in tomography measurements. The device could be enhanced by measuring a complete gamma spectrum in addition to the gamma integral. The gamma spectroscopic measurement would reveal if the gamma integral includes beyond the fission products other isotopes, which might originate e.g. from irradiated dummy rods.

6.2.2 Upgraded Fork Detector

A conventional Fork Detector can be combined with a CdZnTe detector to make an Upgraded Fork Detector. Passive total neutron count, total gamma and gamma spectroscopic measurements

are performed simultaneously. Model calculations made with the programs PYVO or SAS2H/ORIGEN-S are exploited in the analysis of the measurement data. Measurements are performed in water. [25]

The Upgraded Fork Detector has potential for partial defect verification. As a matter of fact, it has been found that BWR assemblies of ABB SVEA-64 type can be separated from assemblies of type ABB 8×8-1 and Siemens 9×9-1. This separation is possible if the assemblies are measured at four sides with 90 degrees rotation to even up possible azimuthal asymmetry. In addition, it should be possible to distinguish the assemblies of Siemens ATRIUM type which contain also part length fuel rods from the assemblies with all rods full length. However, this has not yet been experimentally established.

The Upgraded Fork Detector is also suitable for burnup verification. A reference curve is needed in the actual partial defect or burnup verification measurements. The use of operator declared data is inevitable in order to calculate the necessary corrections to the measured neutron and gamma data. The parameters needed are the evacuation date from reactor, the burnup and the initial enrichment values, the irradiation time and the possible off-reactor cycles.

When an assembly is rotated between the measurements, it has to be drawn out from the measurement position and then rotated. One measurement takes typically 100 s. The time needed for four measurements and rotating the assembly is about 10–12 minutes in the case of BWR assemblies.

The Upgraded Fork Detector could be further developed for the burnup verification measurements by constructing many measurement heads one above the other. In this way, the average burnup representing the whole assembly could be obtained by one measurement. The measurement would even up the differences in axial burnup profiles of the assemblies.

6.3 Verification measurement process

The verification measurements of spent fuel should not unduly increase the workload of the operator. The operations performed by the operator, e.g. rotation or vertical movement of an assembly, during the verification measurement should be as minimal and as simple as possible. In order to minimise the costs, the working hours spent to the verification measurements should be minimised. For example, more measurement time is needed, if the measurement method requires that assemblies have to be rotated or moved in the vertical direction. Also the accident probability in the fuel handling increases, when more operations are needed to perform one verification measurement.

The verification measurement could be a continuous process or a batch process. If the verification measurements are performed continuously in the conditioning plant, the measurement system should be integrated into the conditioning process. The measurement device should be an automated device with unattended operation. The measurement data should be saved and transferred on-line to the inspecting organisation. It should be assured that the data transfer is done without tampering. The verification measurements should be performed in a particular verification gate. The assemblies and rods should be packaged into the disposal canisters after passing through the gate. It is important that this gate would be the only route to the disposal canister. This would ensure that every assembly is measured. The result of the automated measurement should be clear, e.g. “OK” for non-defected assemblies or “not OK” for potentially defected assemblies. A spent fuel assembly passes the verification gate only when it has been verified as “OK”. A potentially defected “not OK” assembly must not pass the gate. Instead, it should be put aside and verified by other means later. Owing to this, there should be a special storage for the assemblies, which have not passed the automated verification. In the encapsulation plant, this kind of storage could be e.g. a particular transport cask assigned for this purpose. The return of potentially defected assemblies back to the interim storage may not be allowed.

If the verification measurements are performed in the intermediate storage, the measurement system should be integrated into the process of transferring the assemblies into the transfer cask. The potentially defected assemblies could be stored e.g. in the rack in the storage pond. This

rack should be designated for these potentially defected assemblies.

If the verification measurement is a batch process, an automated and unattended verification device would not be needed. Instead, an inspector should attend the verification measurements. In this case, a large number of assemblies or rods should be verified in one go. Fuel is to be transported on the average in two casks once a month from the intermediate storages of the Olkiluoto and Loviisa NPPs [19]. If the verification measurements are performed in the storages, an inspector should come to control the measurements once a month. The verification measurements of the fuel rods from the FiR 1 research reactor will obviously be a batch process, if the measurements are performed at the VTT.

According to the IAEA safeguards policy, the safeguards verification system should have the capability of functioning, as far as practicable, in automated, unattended and remote data transmission modes. [26]

A failure of the C/S system has to be avoided by all means, because the continuity of knowledge might be difficult to re-establish. Therefore, the use of fault-tolerant, diverse and redundant systems is mandatory. [27]

7 CONCLUSION

It is generally considered that all spent fuel items to be loaded into the disposal canisters should be subjected to verification measurement at the partial defect level in advance of the packaging into the final disposal canisters. The verification measurement of the fuel rods from the FiR 1 research reactor may be performed at the gross defect level.

Concerning the integrity of the spent fuel assemblies, Zr alloys are highly durable cladding materials. Marked decreases in ductility of Zircaloy cladding have been measured for high burnup assemblies. The loss of ductility is exacerbated by hydrogen cracking. This suggests low impact strength in the low temperature wet storage regime. Because of this, impacts should be avoided when handling fuel assemblies or rods, which have high burnup. In general, all normal handling operations made by dedicated fuel handling tools should be harmless to the fuel.

It is considered that there should be no reason to limit the verification measurements due to their possible risk to the fuel integrity.

At present there is no method or device, which could readily be applied for partial defect level verification at the back-end of the fuel cycle. At the moment the most potential devices, which could be developed for the partial defect verification purposes, are the Passive High-Energy Gamma Emission Tomography device and the Upgraded Fork detector. It is important to understand that developing such a device into an operative level is a demanding and time-consuming project.

The planning of the whole safeguards verification process is essential. In order to minimise the costs, the verification measurements of spent fuel should take as little time as possible. A balance should be found between the effectivity, the speed of the measurements and the investments necessary to implement the desired level of assurance. The operator interface of the measurement device should be simple.

Both for economical and safety reasons, the fuel handling operations needed during a single measurement should be minimised. The verification measurement could be a continuous or a batch process. If it is continuous, the measurement system should be integrated into the conditioning process. The measurement device should be automated with unattended operation. If the verification measurement is a batch process, an automated and unattended verification device would not be needed. Instead, the inspector should attend the verification measurements. In this case, a large number of assemblies or rods should be verified in one go.

To summarise, the whole verification measurement process should be slick. The first key factor is that all assemblies or rods are measured. The second key factor is that only the assemblies, which have been verified to be non-defected, are passed to disposal. This necessitates that there should be a special storage for potentially defected assemblies. These assemblies have to be verified with some other, yet unspecified device.

So far, IAEA and Euratom have not concluded about safeguards criteria e.g. what would be the best place to perform the verification measurements for the final disposal of spent fuel assemblies in the safeguards point of view. Possible candidates are the intermediate storages in the Olkiluoto and Loviisa NPPs and in the VTT. The other candidate is the encapsulation plant. The opinions expressed so far by the representatives of the regulatory organisations support strongly the placement of the verification measurement as close as possible to the phase where the fuel items lose their identity.

There are two main standpoints, as the verifi-

cation place is considered. On one hand, where are the best practical possibilities to perform the measurements effectively, on the other hand, what is the best place in the safeguards point of view. It stresses more demands for the C/S system to maintain the continuity of knowledge at the defined level, if no verification capability is installed in the encapsulation plant and the verification measurements are performed only in the intermediate storages. Re-verification for partial defect is needed in the encapsulation plant, if the continuity of knowledge has not been maintained on the cask during transport from intermediate storages to the encapsulation plant. The continuity of knowledge after the last verification is easier to maintain, if the verification measurements were performed in the encapsulation plant. It is also important to notice that if the verification measurements are performed in the encapsulation plant, it has to be taken into consideration in the planning of the plant in an early phase.

The considerations above and those performed in section 5 lead to a conclusion that it would be advisable to install the final verification system of the individual fuel assemblies at the partial defect level in the encapsulation plant.

The safeguards verification measurement of the spent fuel assemblies from the Olkiluoto and Loviisa NPPs should be integrated in the fuel encapsulation process and it should operate in unattended and automated mode.

Due to many unsolved problems pointed out in this report it is proposed that a research programme should be started aimed at developing the methods, equipment and systems, which could be used for the verification measurements to be seen necessary for the back-end of the fuel cycle in Finland. This programme should be conducted in parallel with the research programme aiming at the achievement of the readiness to apply the construction licence for the encapsulation plant. A first proposal for such a programme is drafted in the Annex.

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ANNEX PROPOSAL FOR A VERIFICATION RESEARCH PROGRAMME FOR THE BACK END OF THE FUEL CYCLE

1 Development of the Upgraded Fork method

- validated method for BWR and VVER assemblies
- transportable prototype device
- licensed verification device and procedure especially for verification of non-standard fuel items

2 Development of the high energy gamma emission tomography

- validated method for BWR and VVER assemblies
- transportable prototype device

3 Choice of the method as the basis of the partial defect verification

- comparison of methods 1 and 2
- choice of the method for the encapsulation plant, either 1, 2 or combination of both

4 Development of a device, which could be integrated into the back-end process of the fuel cycle

- development of a non-transportable device, which optimises the effectiveness, data collection efficiency and cost
- development of a data collection and transfer system with authentication of the data

5 Development of a verification device for the transport cask at the partial defect level

- need of this device to be discussed

6 Development of a verification device for the final disposal canister at the partial defect level

- need of this device to be discussed

7 Design of a complete verification system

- based on the methods chosen in 1–3 and
- the devices and systems developed in 1,2 and 4–6