Advanced Non-Destructive Assay Systems and Special Instrumentation Requirements for Spent Nuclear Fuel Recycling Facilities - 8032

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ABSTRACT

The safe and efficient operation of the next generation of Spent Nuclear Fuel (SNF) recycling / reprocessing facilities is dependent upon the availability of high performance real time Non-Destructive Assay (NDA) systems at key in-line points. A diverse variety of such special instrument systems have been developed and commissioned at reprocessing plants worldwide over the past fifty years.. The measurement purpose, technique and plant performance for selected key systems have been reviewed. Obsolescence issues and areas for development are identified in the context of the measurements needs of future recycling facilities and their associated waste treatment plants. Areas of concern include (i) Materials Accountancy and Safeguards, (ii) Head End process control and feed envelope verification, (iii) Real-time monitoring at the Product Finishing Stages, (iv) Criticality safety and (v) Radioactive waste characterization.

Common characteristics of the traditional NDA systems in historical recycling facilities are (i) In-house development of bespoke instruments resulting in equipment that if often unique to a given facility and generally not commercially available, (ii) Use of 'novel' techniques – not widely deployed in other applications, (iii) Design features that are tailored to the specific plant requirements of the facility operator, (iv) Systems and software implementation that was not always carried out to modern industry standards and (v) A tendency to be overly complex - refined by on-plant operational usage and experience.

Although these systems were 'validated in use' and are generally fit for purpose, there are a number of potential problems in transferring technology that was developed ten or more years ago to the new build SNF recycling facilities of the future. These issues include (i) Obsolescence of components - particularly with respect to computer hardware and data acquisition electronics, (ii) Availability of Intellectual Property and design drawings and documentation (iii) Lack of compatibility with modern computers, software, data transfer networks, digital protocols and electrical code standards, (iv) Non-compliance with current and future mandatory standards and regulations for nuclear facilities (v) Design focused on measurement and control points that may be specific to the facility process (vi) Lack of utilization of recent technological advances where better performing, less complex and more cost-effective options are now available.

Key radiometric measurement drivers and control points for future recycling facilities have been determined and a review of the adequacy of existing instrumentation has been performed. Areas where recent technology improvements may be more effectively deployed and future technology development may be appropriate are identified.

INTRODUCTION

Many categories of special instrumentation have been developed and commissioned in support of the UK’s nuclear fuel recycling facilities. These system support multi-functionality including process control, safety, accountancy, waste characterization and safeguards.

The application of in-line radiometric technologies to spent nuclear fuel (SNF) recycle plants is well established. The measurement of process materials in-situ eliminates many of the errors, delays and secondary waste arisings associated with off-line analysis and sampling. Instruments such as these that serve several functions in the facility must adhere to the following design criteria:

(i) integration into both the physical plant design and the operational safety case,
(ii) use of mature technologies with robust hardware with high reliability factors,
(iii) use of high integrity software (if applicable) with self-checking to identify faults,
(iv) ability to meet the plant’s performance envelope (range, accuracy, detection limit),
(v) ability to verify and validate critical components of system performance by testing,
(vi) use of feedback from previous generation instrumentation.

Historically, such systems are ‘validated in use’ and as such have proven fit for purpose. However, the transfer of this technology to future generation SNF recycling facilities requires detailed consideration to address issues such as:

(i) Obsolescence of components,
(ii) Availability of Intellectual Property (design drawings and documentation),
(iii) Compatibility with modern computing standards and electrical code standards,
(iv) Compliance with regulations for nuclear facilities,
(v) Applicability of measurement and control points specific to the facility process,
(vi) Recent technological advances in measurement and detection technologies.

SPECIAL INSTRUMENT CATEGORIES

Over 30 types of special instrument systems have been developed and commissioned on the UK's spent fuel recycling plants from the 1970s to present day. Instrumentation has been developed from the first generation equipment installed on the Magnox reprocessing facilities through to the Thermal Oxide Reprocessing Plant (THORP) at Sellafield. Table 1 provides an example of the level of multi-functionality required of these instruments.

SNF RECYCLING PLANT PROCESS	**MEASUREMENT AND CONTROL POINT**	**FUNCTIONAL REQUIREMENTS**			
		ACCOUN TANCY	*PROCESS CONTROL*	*CRIT SAFETY*	*WASTE ASSAY*
SNF Storage	Verification of SNF in storage canisters	●			
SNF Transfer	Measurement of water level in dilution vessel		●		
SNF Transfer	Verification of SNF cooling time, enrichment & burnup		●	●	
Acid preparation	Gd poison content in dissolver acid & wash water		●	●	
SNF Shearing	Residual fissile & activity of radionuclides in hulls basket	●	●	●	●
Chemical Separation	Concentration of Pu bearing liquors in pipes & vessels		●	●	
Pu Product	Pu inventory & location throughout finishing line	●	●		
Pu Product	Measurement of Pu mass in product canisters	●			
Pu Product	Product level in hoppers & canisters		●		

Table 1. Examples of Multi-Functional Requirements of Recycling Plant Special Instruments

DESIGN CRITERIA

During plant design the instrumentation needs for the above equipment were addressed and appropriate measurement and detection technologies were selected based on the functional requirements stated above and the resulting performance requirements given in Table 2. The design criteria needed to reflect the fact that the instruments are located at key points in the process with potential restricted man access. Particular attention was paid to maximizing the reliability and robustness of the systems while at the same time meeting the required operational envelope and minimizing the expected down time (e.g. for component replacement and maintenance).

MEASUREMENT PARAMETER	**PERFORMANCE REQUIREMENT**	**RADIOMETRIC METHOD**	**RATIONALE**
Presence of SNF Assemblies Within Canister Channels	Individual channel resolution	Gamma (low res)	Characteristic gamma peaks indicate fuel.
Dilution Vessel Water	Water above a safety level. Two second response time.	Neutron Transmission	Water acts as a moderator. Neutron detector sensitive to thermal neutrons. Rapid go / no go indication.
SNF Cooling Time	± 250d	Passive & Active Neutron, Gamma (high res)	Combined neutron and gamma data required to solve for all three parameters.
SNF Initial Enrichment	± 0.2%		
SNF Burnup	± 0.8 GWd/te		
Gd Concentration	<± 5% (3σ) at 2g/l	Neutron Transmission	Gd absorbs thermal neutrons.
Fissile Content of Hulls	Limit of detection: 6g Pu-239 effective	Passive & Active Neutron, Gamma (high res)	Combined active and passive enables fissile measurement without need to know Cm-244 content.
Radionuclide activity in Hulls	Assay of gamma emitters		
Concentration of Pu	± 10mg/1 at 1g Pu/1 ± 100mg/l at 1g Pu/l	Passive neutron, X-ray Fluorescence	XRF used for in-situ measurement without need for off-line sampling.
Pu inventory in finishing line	± 5% (1σ) on total plant inventory	Passive Neutron	Total neutron counting provides real-time response over wide areas.
Pu mass in product canisters	< ±5% (3σ)	Neutron Coincidence Counting, Gamma (high res)	Gamma required for isotopics. NCC provides Pu-240 effective mass.
Product level in hoppers & canisters	2.5% on fill height	Gamma transmission	Accurate proven level monitoring method

Table 1. Recycling Plant Special Instrument Design Criteria

MONITORING SNF IN THE FEED POND

THORP has two identical Feed Pond Fuel Monitors (FPFMs) shown in Figure 1. These operate in parallel in order to meet the throughput requirements and measure a number of fuel parameters to ensure that only those fuel assemblies within prescribed limits are reprocessed. Thus the instrument provides a go/no-go signal indicating if the fuel is within the plant's acceptance envelope. The limiting parameters relate to the minimum cooling time, maximum burnup and final enrichment U-235 equivalent (originally initial enrichment) for both light water reactor (LWR) and advanced gas cooled reactor (AGR) fuel. The change from an initial enrichment parameter to final enrichment took place in conjunction with a reduction in neutron gadolinium poisoning of the dissolver vessel. The reduction was made possible by the adoption of a burnup credit fuel management regime.

The vessel was originally poisoned on the assumption that the dissolved fuel was enriched to its initial enrichment rather than its final enrichment as recognized under the burnup credit revision. As a result the Gd usage has been reduced by approximately 50% giving considerable cost savings and benefits to the vitrified waste stream product quality.

The FPFMs each use a 15% efficiency High Purity Germanium (HPGe) detector, and five fission chamber neutron detectors that are split into two modules arranged at 90 degrees to each other. A neutron source transfer system, controlled by the FPFM, moves a Cf-252 source between exposed and shielded positions to allow active and passive neutron measurements. Prior to each assay, measurement control is implemented by an automated standardization routine. Once the fuel assembly has been transferred to the measurement position, assays are performed at four measurement heights as the fuel rotates.

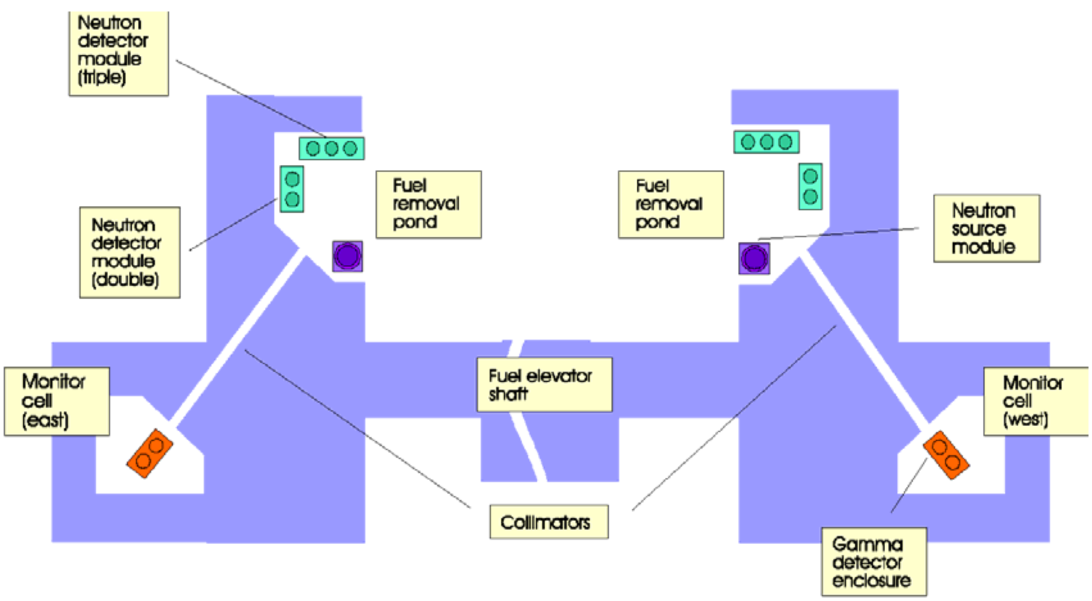

Figure 1. THORP Feed Pond Fuel Monitors

A combination of three techniques is used to characterize the fuel. Cooling time is determined by High Resolution Gamma Spectrometry (HRGS) using fission product gamma activity ratios. Burnup is determined using a combination of HRGS and passive neutron data. Initial enrichment is calculated from a combination of the final enrichment and measured burnup. Final enrichment is determined by a combination of the measured burnup and a neutron multiplication parameter determined from the active neutron measurements using the external Cf-252 neutron interrogation source. The only operator declared input that is required is the fuel type e.g Pressurized Water Reator (PWR) or Advanced Gas Cooled Reactor (AGR).

Over two decades of plant operation, thousands of assemblies have been successfully measured. Figure 2 indicates the results of a cross-comparison between operator declared and measured burn-up. Good agreement was achieved, providing validation of the methods used.

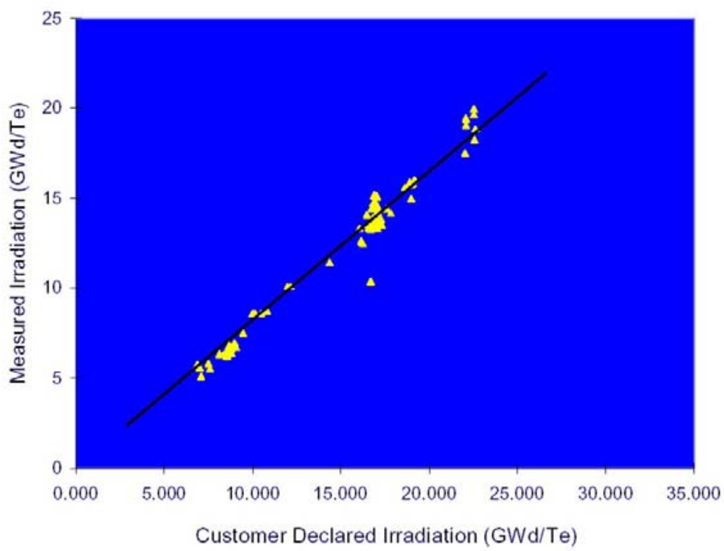

Figure 2. Comparison of Measured and Declared Burnup (Irradiation) for THORP Feed Pond Fuel Monitors

HULLS MONITORING

The THORP plant receives and reprocesses several thousand tons of spent light water reactor (LWR) and advanced gas cooled reactor (AGR) fuel. After dissolution of sheared fuel, the resulting pieces of empty fuel cladding (hulls) are measured by the Hulls Monitor (Figure 3) prior to encapsulation and eventual disposal. Hulls Monitor measurements are required to (i) assure criticality safety of the hulls during subsequent handling in THORP and the Waste Encapsulation Plant, (ii) provide process control data on the leach efficiency to permit sentencing of each hulls batch, (iii) determine the residual masses of U-235, total plutonium and fissile plutonium in the hulls for materials accountancy and Safeguards purposes, (iv) provide an activity inventory for compliance with Intermediate Level Waste contractual agreements and anticipated repository acceptance criteria [1,2].

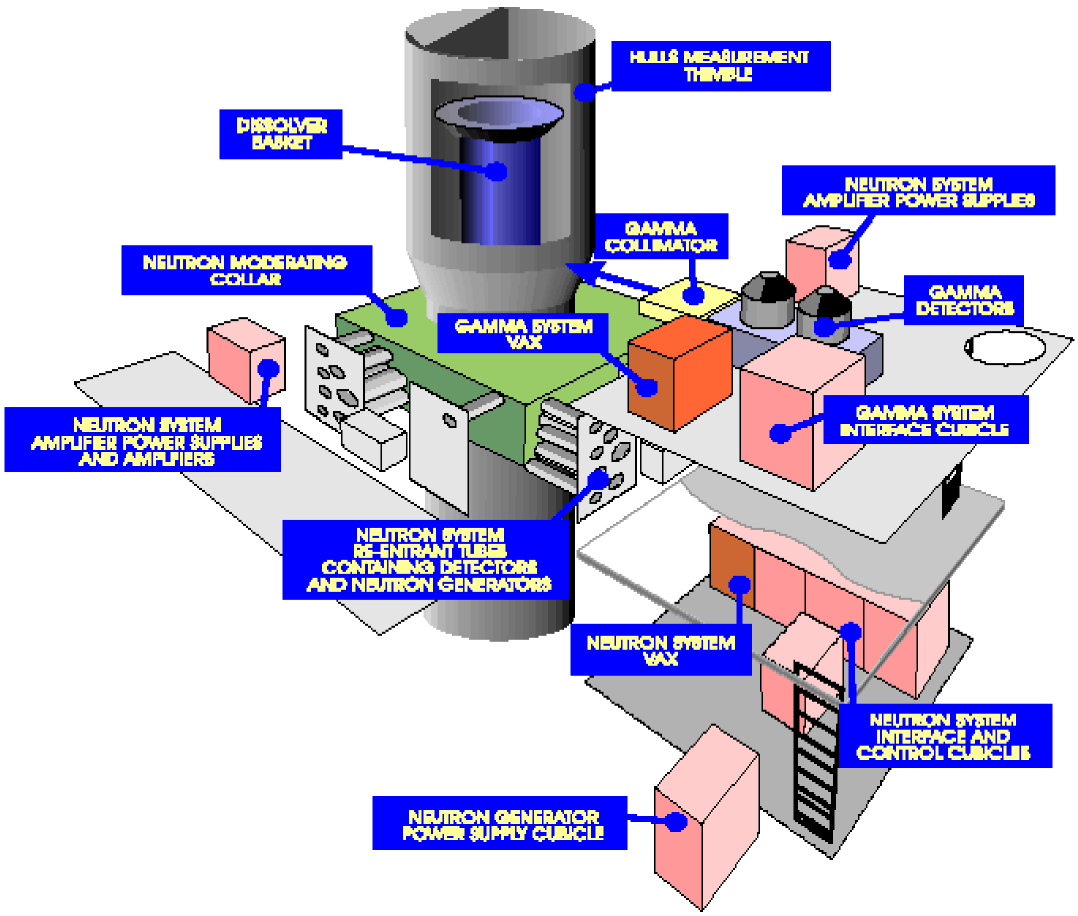

Figure 3. Schematic of Hulls Monitor

The Hulls Monitor uses three radiometric techniques: Differential Die Away (DDA) active neutron measurement, passive neutron measurement and HRGS. The DDA determines the residual fissile content of the hulls. The passive neutron emission rate is used in conjunction with the fissile mass from DDA and with the initial enrichment and cooling time (from measurements of the spent fuel prior to its shearing and dissolution in the Feed Pond Fuel Monitor) to determine the residual uranium mass, the Cm2-44 activity, total Pu activity, total U activity, total alpha activity, U-235 mass, fissile Pu mass and total Pu mass. The HRGS measurement is used to determine the activity of measurable gamma emitting fission products and activation products present in the hulls [1].

The operation of the Hulls Monitor was demonstrated during commissioning to Euratom Safeguard inspectors. This involved the independent verification of the fissile content of the Hulls Monitor un-irradiated UO_2 fissile standards using a Euratom owned and operated Active Well Coincidence Counter and the subsequent “blind” measurement of a range of these fissile standards in measurement configurations specified by the inspectors. Additionally, during the reprocessing of the initial hulls batches in THORP, replicate measurements were conducted to characterize random errors, to demonstrate absence of systematic bias from neutron generator output, and to assess sources of total measurement uncertainty (TMU) such as distribution of hulls, residual background contamination and matrix effects [1].

CONCLUSIONS

The control of operations in SNF recycle plants, and the monitoring of special nuclear material within those plants, gives rise to a variety of requirements for assay of radionuclides and plant process monitoring. Many of the subsequent performance requirements these can only be satisfactorily met by the provision of on-line special instrumentation.

The operational lifetime costs of such special instrumentation has been justified by the benefits resulting from their use. The close and continuing dialogue between the instrument supplier, the plant designer, the safeguards / regulatory authorities and the plant operator, is invaluable in maximising this benefit. By definition, these instruments are located at key points in the process, therefore particular attention was paid to the design and construction of such instruments to maximise reliability and minimise down time.

In addition to the mission critical measurement and control issues relating to plant design and processing of materials it is important that, where possible, the plant instrumentation provides characterization data for the waste product to meet regulatory requirements relating to interim storage and ultimate disposal. Experience with historical recycling facilities, were such consideration was not included in the design, has demonstrated the level of complexity involved in extracting compliant data on legacy waste steams [3].

The THORP plant in the UK required considerable system development to meet its special instrumentation needs. The resulting mature measurement and detection technologies are widely applicable in the design and development of new SNF recycling plants. Experience gained in commissioning and several decades of system operation will prove beneficial in extending the technologies to the fabrication of future facilities.

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