Provision of NDA Instrumentation for the Control of Operations on Plutonium Finishing and Waste Plants at the Sellafield Nuclear Fuel Reprocessing Facility

KR Whitehouse, CH Orr

BNFL Instruments Ltd, Pelham House, Calderbridge, Cumbria CA20 1DB, England

Abstract

On BNFL's Sellafield site a significant number of major plants are involved in the handling, processing and storage of plutonium in various forms including nitrate, oxide and mixed oxide (MOX). Other plants in operation or under construction treat and prepare for storage, plutonium bearing wastes in the form of plutonium contaminated materials - PCM (transuranic waste - TRU) or low level waste. Concurrently, a number of old plutonium handling plants are being decommissioned. The safety and cost effectiveness of these widely varying operations has been ensured by the development and installation of a wide range of special radiometric instrumentation. These systems based on a range of neutron counting and high resolution gamma spectrometric techniques - singly or in combination - enable BNFL to maintain a detailed and comprehensive picture of the disposition of plutonium within each plant and across the site. This paper provides an overview of the range of plant and waste measurement systems in this context, highlighting the specific roles of the Plutonium Inventory Measurement System (PIMS) for real time accountancy and the Decommissioning In-Situ Plutonium Inventory Monitor (DISPIM) for material control during decommissioning.

Introduction

BNFL operates a large number of discrete plants on its Sellafield site, ranging from storage and dismantling of irradiated fuel assemblies, through reprocessing operations to eventual product finishing and waste management. The control of these operations requires the use of special purpose instrumentation integrated into the fabric of the plant and providing on-line, real-time information regarding the plant operating conditions. Further systems are necessary to ensure that nuclear safety conditions are being adhered to, particularly during the filling of plutonium contaminated material (TRU) waste drums. These instruments become increasingly important during the decommissioning of older plants on the site, where material types and quantities may not be so well characterised.

Each of these measurement situations requires an in-depth knowledge of the plant design, operating conditions and, in the case of decommissioned plants, operating history. This expertise has been developed within the team that has formed the core of a new wholly owned subsidiary, BNFL Instruments Ltd. This team has installed and operated over 150 major radiometric instrument systems on the Sellafield site over the past 20 years. During this period the company has evolved a very close understanding of the concerns and priorities of the operating plants, becoming involved in the initial design of the plant and its processes, commissioning and operation, and the eventual closure, post operations clean out (POCO), decommissioning and dismantling operations.

This experience, coupled with a substantial investment in research and development, has enabled BNFL Instruments Ltd. to tailor new and well proven measurement techniques to meet the requirements of particular plants, and has allowed the company to build up an in-depth expertise in the operation of complex radiometric instrumentation systems within the demanding environments of a nuclear fuel reprocessing facility.

Instrument Design Philosophy

The approach that has been evolved during the successful implementation of so many systems at Sellafield is based on the use - wherever possible- of available, well proven measurement techniques. Where such techniques are inadequate, due for example to new or more challenging measurement requirements, the approach calls for intensive internal research and development following through to the development of new, but equally well proven techniques in a form entirely compatible with their implementation in key plant instrumentation. In this way the risk of disruptions to plant construction, operation and decommissioning programmes can be minimised. Similarly, the use of commercially available components, particularly detectors and electronics hardware, is maximised. This has enabled BNFL Instruments to develop a modular approach to system design, building confidence in the operation of the individual components and therefore the instrument system as a whole.

Many years of commissioning and operations support activities by BNFL Instruments' staff, with additional feedback via the close links established with plant managers has provided the company with an extremely detailed knowledge of systems operation and performance. This feedback has enabled a continuous improvement in system design and operation, ensuring that future generations of systems are simpler to operate in addition to having improved performance, reliability, or operability.

Currently installed systems incorporate a range of techniques including passive total and coincident neutron counting, low and high resolution gamma spectrometry or combinations of these technologies. In particular passive neutron counting techniques have been applied in systems provided for the non-destructive assay of special nuclear material in many quite different process, product or waste streams. More recently, an increasing number of systems have been provided that are based on active measurement techniques using either radioisotope neutron sources or neutron generators.

Two examples of the use of basic neutron counting techniques are the Plutonium Inventory Measurement System (PIMS) and the Decommissioning In-Situ Plutonium Inventory Monitor (DISPIM). The development of these systems has been described in some detail in earlier technical papers. [1, 2, 3]

PIMS systems are currently installed within three plutonium finishing lines on the Sellafield complex. These applications include the Magnox plutonium oxide finishing plant (FL5), a plutonium metal finishing line (now shut down) and the newly constructed product finishing line within the THORP plant. A further system is being designed for installation into the Sellafield Mixed Oxide Fuel Fabrication Plant (SMP) currently under construction on the Sellafield site.

Three DISPIM systems have already been provided for decommissioning operations at Sellafield. These systems are being used in an ongoing programme of monitoring and characterisation in which some 200 items of plant and equipment have been measured, both before and after dismantling. These range from cut up sections of pipe, through to whole gloveboxes, 200 litre waste drums (55 gallon barrels), and, in certain cases, whole waste crates (boxes). Forward programmes of decommissioning will result in a dramatic increase in the use of DISPIM at Sellafield as more plant reaches the end of its useful life.

The Plutonium Inventory Measurement System (PIMS)

The PIMS system developed by BNFL Instruments Ltd. is an installed, non-intrusive NDA measurement system capable of determining the quantity and distribution of plutonium process materials throughout an operating plant. This information provides the operators with a near real time indication of the distribution of plutonium in the plant, allowing early identification of plant abnormalities, such as blockage occurrence, spillages, etc. The PIMS data is also used for materials accountancy of the plant and, in a limited number of circumstances, for nuclear safety control of the plant operations. The PIMS installed within the THORP Product Finishing Line (TPFL) has also generated a significant amount of interest within the International Safeguards community, to the extent that the mass estimates produced are automatically reproduced at a Euratom monitoring station within THORP.

Figure 1 shows a block diagram of the PIMS. The PIMS comprises a number of boron trifluoride neutron proportional counters, generally mounted within polyethylene/cadmium moderator modules, positioned at strategic locations throughout the plant. The system measures the total neutron count rate and mathematically unfolds these count rate responses to calculate the neutron emission from each process area. The neutron detector modules are positioned either singularly or in arrays surrounding the process vessels of interest. Pulses from each detector are processed by a dedicated internally designed head amplifier. The data processing electronics have also been designed and assembled by BNFL Instruments and comprise a number of standard commercially available electronics modules in addition to proprietary electronics systems.

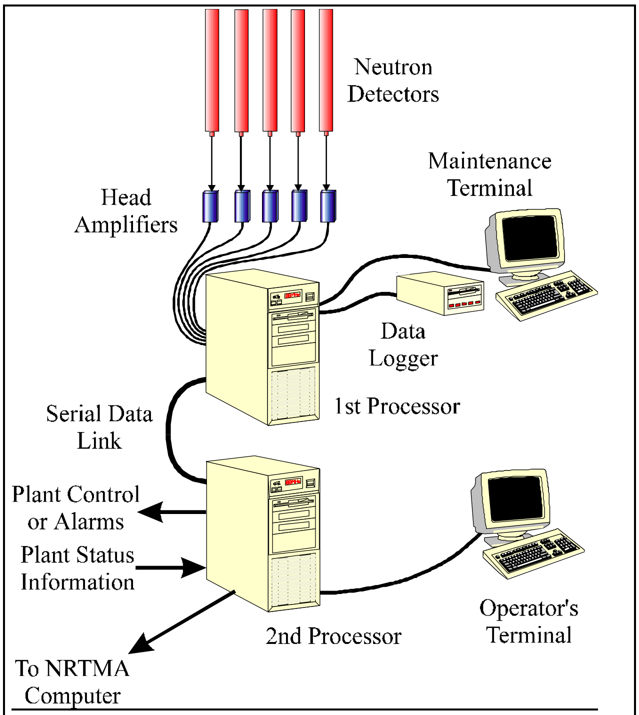

Figure 1 - PIMS Block Diagram

Much of the accuracy of the PIMS operation relies on the positioning of the detectors relative to the plant process line. Typically, the PIMS comprises between 30 and 100 detector modules positioned around the process vessels and gloveboxes throughout the plant. Each vessel / glovebox is modelled, either experimentally or using Monte Carlo neutronics codes to determine the optimum locations of the neutron detectors. The criteria for siting the detectors are:

- to maximise the detection efficiency of the detector (or array) to the process area being monitored;
- to minimise any system response variation over the process area being monitored, due to different source positions;
- to minimise the detection efficiency of the detector (array) to adjacent areas of plant;
- to avoid dead-time problems due to excessive count rates.

In order to meet each of these criteria it is essential that the PIMS is integrated into the plant design at an early stage, enabling the optimum detector locations to be incorporated into the plant design.

Figure 2 shows a simplified sketch of a plant layout including the main process vessels, and identifies the typical positions of the neutron detectors that form the PIMS.

Many of the neutron detectors have been installed within polyethylene / cadmium moderating modules in order to harden their response to epithermal and fast neutrons. This biasing of the detectors to higher energy neutrons reduces the sensitivity to adjacent process areas as neutrons from material in these areas are more probably thermalised prior to arrival at the detectors and be absorbed in the outer layer of cadmium.

Ideally, the module would only be sensitive to neutrons above 1 MeV in order to minimise the detection efficiency to adjacent process areas. This optimum module design has been determined using both computer based and experimental modelling work. This design comprised a 50 mm (2") thick polyethylene sleeve around the neutron detector tube, surrounded by a 0.5 mm (0.02") cadmium sheath. This module is then wrapped in heat shrink polyvinylchloride.

In the case of the most recent installation it was not possible to achieve this ideal situation due to restrictions on the space envelopes imposed by the

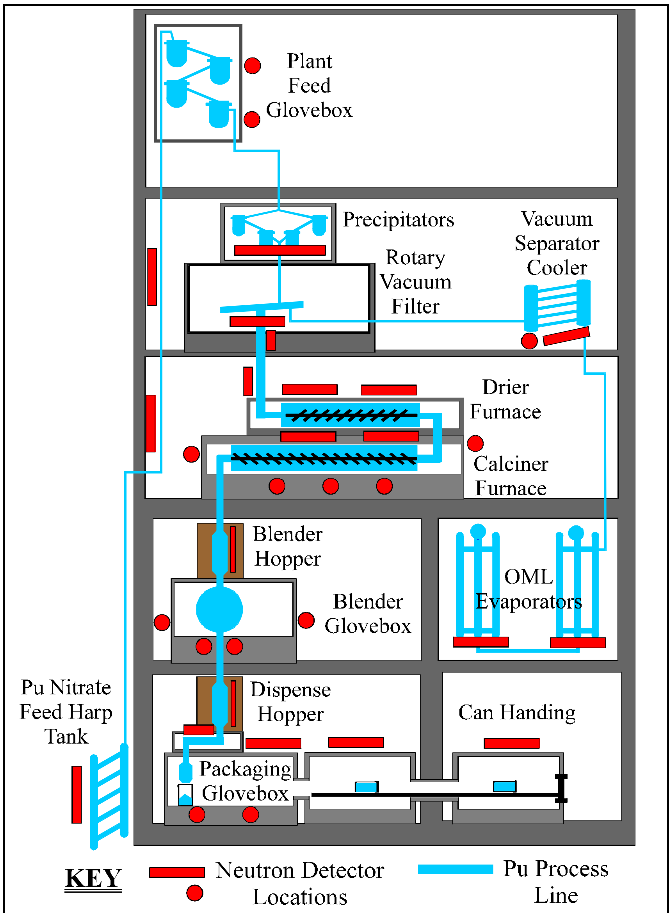

Figure 2 - Typical PIMS Detector Locations on a Plutonium Finishing Facility

plant design. The chosen detector module design is similar to the optimum module but has a polyethylene wall thickness of only 25 mm (1”). This gives an optimum detection response within the 10 eV to 1 MeV energy range making the system sensitive to fast and epithermal neutrons.

Once the detectors have been positioned in their optimum locations it is necessary to calibrate the system. The calibration involves moving an intense isotopic neutron source, usually ^{252}Cf, throughout the plant process line. The sensitivity of each detector to this “point” source in each of the calibration positions is accurately measured and used to build a calibration matrix, defining the response of each detector to neutron emitting material within each process area being monitored. The calibration matrix is used to interpret the count rate data from the detectors and to estimate the neutron emission from, and hence the plutonium mass in, each of the areas. The matrix solution technique uses an iterative weighted least squares technique to estimate the plutonium mass (and its associated measurement uncertainty) in each process area.

A comparison of the PIMS total plant estimates with the plant book accountancy figures for the system installed in FL5 shows that the PIMS estimates are typically within ± 10% of the materials accountancy figures. The predicted performance based on the system calibration was significantly worse than this (typically 30 - 40%). This overestimation of errors is thought to be due to the efficiency variations encountered in the point source calibration caused by the large range of possible source positions in some areas. Also, the source positions used during the calibration must not fully represent the actual weighted distribution of plutonium in the plant. Additional detectors or refined detector locations may have improved the error analysis but this was not possible due to access restrictions around the process areas

Total plant mass estimates from the PIMS installed in the metal plutonium finishing plant were also typically within 10 - 15% of the true plant mass. This is a remarkable performance considering the range of masses and chemical compositions (oxide, fluoride and metal) present in close proximity within a very compact plant.

Improvements to the design and calibration philosophy employed on the THORP system have reduced the predicted errors to approximately 10 - 20%. The system performs on-line monitoring of the plant feeds to identify changes of isotopic composition, and monitors this new feed batch as it progresses through the plant. Changes in plant status are also monitored through the use of proximity switches, rotation sensors, etc. This provides the PIMS with the information it requires to characterise the plutonium contained in every glovebox and process vessel throughout the whole of the THORP finishing plant.

Initial testing of the system using point sources has indicated that the on-line measurements should be well within the predicted error ranges. A comparison between the PIMS estimates and book accountancy figures for THORP will provide the basis for a future performance report once sufficient operational data has been acquired.

On-going development of the PIMS includes overcoming the specific problems posed by the design of the Sellafield MOX Plant. The compact nature of the plant and the large throughput of material cause specific difficulties with neutron multiplication effects not encountered on the previous systems. A development program has been set up to investigate and overcome these problems, possibly by redesign of the detector modules or their locations, or by utilising computer modelling techniques to characterise multiplication effects within the plant.

Further development is underway to investigate the integration of PIMS with other radiometric and non-radiometric instrument systems in order to provide a link within a full plant control and safeguards strategy.

The Decommissioning In-Situ Plutonium Inventory Monitor (DISPIM)

The utilisation of simple neutron detector modules has been extended from the PIMS concept to provide a versatile and highly flexible monitoring system for the in-situ measurement of residual plutonium in large plant items prior to decommissioning. This system is the Decommissioning In-Situ Plutonium Inventory Monitor or “DISPIM”. An example of the plant items measured using the DISPIM equipment would be redundant gloveboxes.

The DISPIM comprises a number of neutron detectors enclosed within polyethylene / cadmium moderating modules similar in design to those used in the PIMS. Modifications to the PIMS module design have been made, however, to tailor it to the specific needs of decommissioning measurements. Helium-3 (^3He) neutron detectors are used in order to increase the detection efficiency to a level that will support neutron coincidence measurements. Additionally, the detector module design has been modified to ruggedise the system: the detector being held in place within the module using a spring and O-ring system for physical protection and the module being fitted with handles for transport and location around the item to be measured. The weight of each module is approximately 20 kg (44 lb.) enabling handling by persons operating within access areas requiring full PVC suits.

The residual plutonium content of redundant plant items is often not well characterised, particularly in terms of its isotopic and chemical composition or its location within the internal volume of the plant item. The configuration of the system must be chosen to account for all possible material types and locations within the plant item being measured. In order to achieve sufficient detection efficiency for successful neutron coincidence measurements a number of DISPIM detector modules are configured around each item as uniformly as the plant arrangement will allow. Typically 12 modules are used around small to medium sized plant items but this can be increased to a (current) maximum of 30 detectors. This flexibility allows the system to be completely reconfigured to suit specific vessel or glovebox sizes. One DISPIM system has been reconfigured to operate as a temporary crate (box) counter, measuring waste boxes that range in size up to a maximum of 2m x 2m x 2m (6.5' x 6.5' x 6.5').

Figure 3 shows a block diagram of the DISPIM system, illustrating the common design principles shared with the PIMS. Figure 4 shows a photograph of the DISPIM in position around a glovebox shell during decommissioning.

The calibration of each DISPIM arrangement for the measurement of a particular plant item is performed using the “add a source” method. This is achieved by locating a californium-252 (^{252}Cf) isotopic neutron source at, or close to, the possible locations of residual plutonium within the item, and determining the increase in system response for each source location. As the system is primarily used for nuclear safety and clean out evaluation it selects both the lowest and mean detection sensitivities within the item in order to ensure “worst case” and “most probable” estimates of the plutonium content of the vessel. In

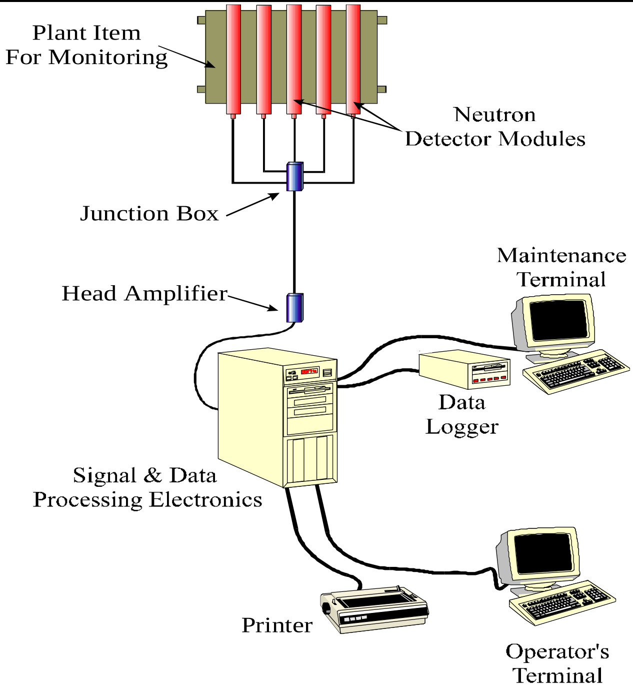

Figure 3 - DISPIM Block Diagram

certain circumstances it may be impractical to calibrate the system by introducing the neutron source. In these cases it is possible to calculate the system sensitivity using Monte Carlo based computer modelling codes such as MCNP. Extra computer models are constructed to allow validation of the numerical methods against actual measurement data.

Using the DISPIM it is possible to achieve minimum detectable quantities of a few grams of

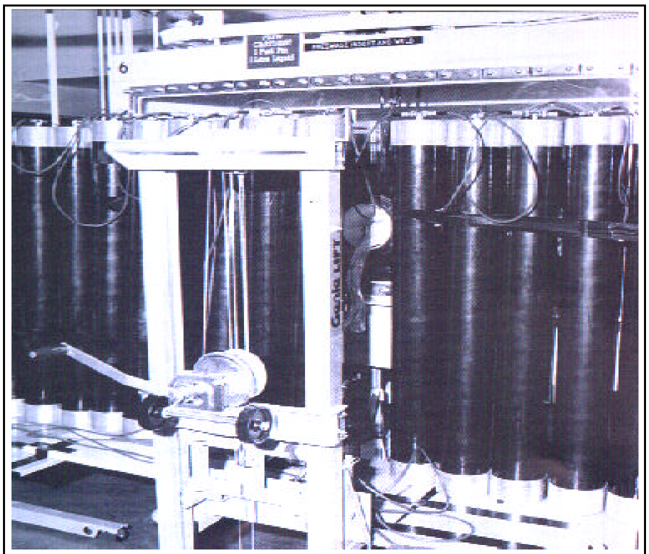

Figure 4 - DISPIM in Position Around Glovebox Shell

plutonium for a typical glovebox within a plant environment using a count time of approximately 4 hours. The total measurement uncertainty predicted by the system is of the order of 30 - 50%. Although this initially appears to be a large measurement uncertainty it should be noted that the DISPIM is often implemented in the high neutron backgrounds of plutonium facilities and, as the items are measured in-situ, it is generally not possible to acquire a representative background measurement. The system is also pessimistically calibrated to meet specific nuclear safety requirements. Measurements are performed following post operational clean out (POCO) procedures, ensuring that the items routinely contain no more than a few tens of grams of plutonium. As such a possible 50% error on this figure will not cause operational difficulties during the follow-up decommissioning operations. Such accurate measurements are achieved by the package and drum assay systems also provided by BNFL Instruments Ltd.

Additionally, the DISPIM only provides the initial in-situ measurement in a monitoring programme that includes further assay once the plant item is removed and size reduced. It is not necessary for the system to provide the level of accuracy and precision required for the definitive materials accountancy purposes.

To date over 150 plant items (many are gloveboxes) have been assayed successfully using the DISPIM. This extensive operational experience - as part of large decommissioning programmes - has already led to refinements to the system and calibration procedures. However, future development of the DISPIM system will concentrate on two aspects of the system design. It is necessary to further reduce the weight of the system, possibly by moving to smaller ^{3}He detectors. This will enhance the system's handling capabilities but may also improve the measurement conditions as modules may be positioned in areas that would have previously been inaccessible. The second area being investigated is that of improved module detection efficiency. This will become increasingly important if the size of the detector modules is reduced, and may eventually lead to some degree of information regarding the distribution of plutonium throughout the plant item..

Conclusions

The PIMS and DISPIM systems demonstrate how simple neutron counting techniques can be tailored to suit two very different measurement requirements encountered during the routine operation of the Sellafield site. The requirements discussed are by no means unique to British Nuclear Fuels' operations at Sellafield. The construction of irradiated fuel reprocessing and MOX fuel fabrication plants, particularly in the Far East, presents an increasing number of safeguards and process control requirements that could be met by the installation of PIMS. Conversely, decommissioning, dismantling and clean up of historic liabilities within Western Europe and the United States of America provide specific measurement requirements ideally suited to DISPIM and associated instrumentation (package monitors, piece monitors, drum monitors, and crate (box) monitors).

The systems described within this paper have been in full time operation on BNFL's Sellafield site since the early 1980's. This, together with similar experience on other radiometric assay systems, has produced a unique combination of radiometric, engineering and operational plant support skills that enable laboratory based radiometric measurement techniques to be ruggedised and integrated into the design, operation and decommissioning of full scale industrial plant.

References

1. Special Radiometric Measurement Systems on THORP : Can Contents Monitor (CCM) and Plutonium Inventory Measurement System (PIMS).
JP Ronaldson and **KR Whitehouse**
ESARDA International Workshop on Passive Neutron Counting 1993 (Pages 92 - 114). EUR 15102 EN / 1993.

2. Total Neutron Counting Plutonium Inventory Measurement Systems and Their Application to Near Real Time Materials Accountancy.
I Driscall, CH Orr, GH Fox, and **KR Whitehouse**
Journal of the Institute of Nuclear Materials Management (JNMM) Volume XVI Number 4 (Pages 26 - 29), July 1988.

3. Plutonium Measurements During Decommissioning Operations
S Buck, JP Ronaldson and **A Colqhoun**
Waste Management '90, Tucson, Arizona
Waste Reprocessing, Transportation, Storage and Disposal: Technical Programmes and Public Education Volume II - High Level and Low Level Waste Technologies (Pages 797 - 805), February 1990.