

Control of Nuclear Material Holdup In MOX Fuel Fabrication Plants in Europe

By the members of the ESARDA MOX Working Group

C Xerri, Cogema, France
J Beckers, Belgonucléaire, Belgium
M Boella, Euratom, Luxembourg
B Burrows, BNFL, UK
A Colin, CEA/ISPN/DSMR, France
M Crousilles, Cogema, France
E Haas, Siemens, Germany

R Ingels, Belgonucléaire, Belgium
P Jaunet, MELOX, France
W Koehne, Euratom, Luxembourg
C Koutsoyannopoulos, Euratom, Luxembourg
J Patten, Euratom, Luxembourg
E Pujol CTI, France
W T Stanley, BNFL, UK

1. Introduction

MOX fuel has been produced in Europe for over 30 years using well-established fuel fabrication processes married with mature plutonium management techniques.

European MOX fabrication facilities have evolved from early FBR fuel plants into commercial scale LWR facilities. By the Millennium around half a million mixed oxide fuel rods had been made for thermal reactor fuel corresponding to more than 1000tHM and utilising more than 50t of plutonium. The combined capacity of the current MOX fuel fabrication plants in Europe is over 250tHM/year, all of which is subject, without discrimination, to Euratom Safeguards.

While some protagonists of the nuclear industry suggest that MOX plants are awash with nuclear material, cannot be adequately safeguarded and that material 'stuck in the plant' could conceal clandestine diversion of plutonium, the real situation in Europe is very different: nuclear operators have gone to considerable efforts to deploy effective systems for safety, security and nuclear material control and accountancy, and the safeguards authorities likewise have implemented a hierarchy of safeguards measures enabling them to safeguard MOX plants effectively.

A variety of definitions of material in-process, in-process inventory, holdup or hidden inventory can be found in the published literature (see Appendix). These definitions are not always consistent and can lead to confusion when discussing the concepts involved. This paper will introduce 'definitions' which are consistent with the way that the Euratom Safeguards Office treats nuclear material, especially with respect to access to the material at monthly and annual inventory taking. It describes how work in progress, and in particular material holdup, is controlled, measured and accounted for.

2. What is "holdup"?

2.1 A typical MOX plant

A typical MOX Fuel Fabrication facility is shown in figure 1. At the very simplest level a MOX plant can be thought of as being split into a number of zones. Some of

these zones will be storage areas, where the material is well defined and where safeguards Confinement/Surveillance (C/S) measures can be applied if required, and the remainder will be process areas. All of the material held in the process areas is considered to be in-process material. The actual in-process inventory at any one time will depend on the operational state of the plant.

Given the premise that all material not in store is defined as in-process inventory then next consider the different processes and nuclear materials which they hold.

The rod handling and fuel assembly areas of a MOX plant deal with individual items whose weight and composition have been determined earlier and are therefore dealt with at an item level. The powder and pellet areas of the MOX plant (up to the point the rods are sealed by welding) are bulk handling zones where material is subject to direct measurement by weighing and chemical analysis. It is in these areas that intrinsic measurement uncertainty lie and which determine the material accountancy performance. The ancillary processes dealing with scraps and residues recycling are also bulk handling zones.

Some nuclear materials are clearly and unambiguously identified, for example the engraved serial number on fuel rods. Some materials are in unique containers and have been weighed (and or counted) such as trays or furnace boats of MOX pellets. Therefore material which is truly holdup and "hidden" inventory only occurs in the bulk handling areas.

We can now draw up two definitions:

- **Process areas** are all areas that are not stores.
- **In-process inventory** is the material in the process areas of the plant. It includes all bulk material in process vessels, as well as material in identified containers such as pellets, or fuel pins. Part of the in-process inventory will be made up of material that is considered to be holdup or "hidden" inventory.

To distinguish between holdup and "hidden" inventory, let us have a look at a glove box.

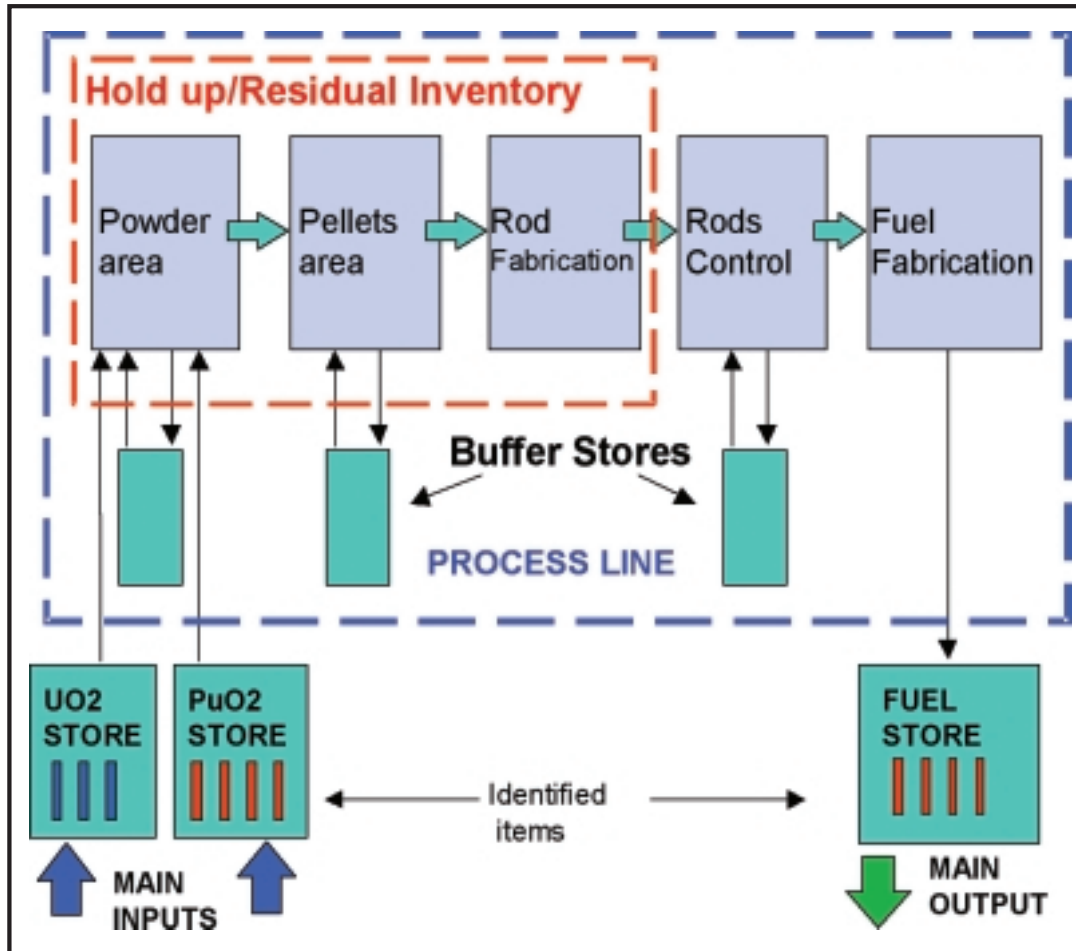


Figure 1 – A typical MOX plant

2.2 A glove box at a glance

Consider as an example a simple glove box (see Figure 2) which contains a piece of plant equipment such as a pellet crusher. Trays of pellets of known weight enter the glove box, the pellets are tipped into the grinder and the resultant powder leaves the glove box in containers that are also weighed. A forced ventilation system is attached to the glove box and any airborne dust that may arise as a result of the crushing operation will be collected on filters.

During normal operation of the glove box, all material would be considered as belonging to the in-process inventory of the glove box.

During inactive commissioning an assessment of the amount of material that remains in the crusher, after it has been ‘emptied’, can be made. This reaches equilibrium within a very short time and thereafter remains approximately constant.

This material constitutes the holdup; the quantity is reasonably well known but cannot be directly measured. It remains in the crusher until it is deliberately removed, either for the Interim Inventory Verification (IIV) or, more likely, at Physical Inventory Taking (PIT) /Physical Inventory Verification (PIV).

There will be material on glove box surfaces, on the filters in the glove-box ventilation system and possibly on associated pipe-work. The material on the filters will nor-

mally form the majority of this inventory until such time as the filters are removed for disposal and/or an appropriate measurement is made. This material, which can be recovered during cleaning or maintenance operations, is part of the holdup (although the quantity is difficult to assess apart from feedback from experience). The remaining material in the pipe-work and glove box faces will form part of the “hidden” inventory and will be recovered eventually during the decommissioning and/or dismantling of the equipment or of the plant.

We can now precise the definitions of holdup and "hidden" inventory:

- **Holdup** refers to material that remains in the process area of the plant when the plant has been run down. The amount of material in holdup can be assessed, but may not be directly measurable. This material is recoverable as a result of the periodical thorough cleaning of the plant, including routine filter changing.
- **"Hidden" inventory** refers to material that remains in the plant in small quantities after the periodical thorough cleaning and which cannot normally be estimated or measured. This material is only recoverable as a result of dismantling of whole or parts of the plants, e.g. glove box or pipe-work.

2.3 The inventory of plutonium in a MOX plant

MOX fuel generally has total plutonium content of 4 to 10 percent, dependant on the fissile content of the plutoni-

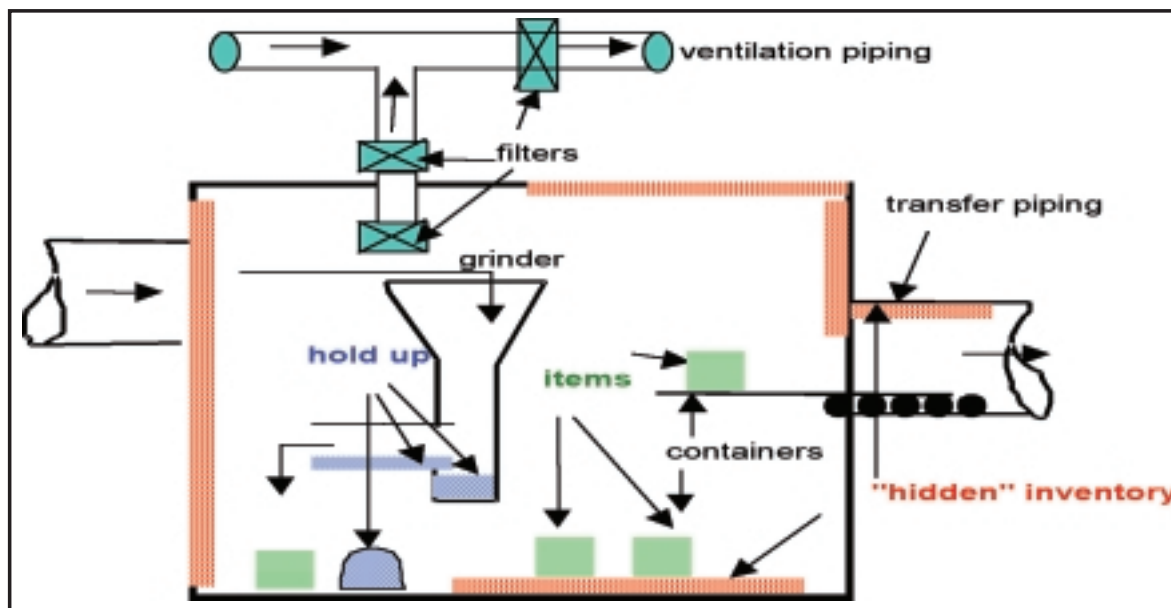


Figure 2 – A glove box at a glance

um. MOX fuel designs call for rods with different plutonium concentrations (up to three in PWR and six in BWR). MOX rods can include some uranium only pellets and a MOX assembly may also contain some uranium only rods. In large plants, high throughputs are obtained by having a number of parallel process lines and this together with the variations of fuel designs and plutonium concentrations lead to significant plutonium stocks.

As described above, front-end stocks of plutonium oxide or nitrate and back end stocks of finished fuel elements in storage are not part of the in-process inventory. Likewise, true in-process inventory does not include intermediate stocks of finished pellets and fuel rods held in secure stores under strict item control.

The table below gives a typical breakdown of inventory in stores and in-process. At Physical Inventory Taking, in process inventory is only made of holdup and "hidden" inventory, and is located in glove boxes.

	During normal operation	At Physical Inventory Taking
In stores	90%	99.8%
In process equipment	10%	0.2%

Table 1 – distribution of plutonium inventory

2.4 Holdup and material balance

A material balance cycle starts and finishes with a Physical Inventory Taking (PIT) and is roughly an annual cycle. At PIT the aim is to make all material available to be accounted for in the material accounts and to be verified (PIV) by the safeguards authorities. There should be very little material in the plant not in measurable containers; that which is not is the holdup and "hidden" inventory.

Material that is known to be in certain locations and is defined as holdup should be reduced to the minimum possible, such as by replacing filters before a PIT/PIV when it can be done without adversely impacting operation of the plant, and has to be accounted for at PIT/PIV. This would most probably be by estimates established during commissioning trials or from later plant experience. The material is included in the physical inventory and is not part of the Material Unaccounted For (MUF).

As far as the "hidden" inventory is concerned, it should be reduced to a level as low as possible and the operator can take appropriate actions when possible. "Hidden" inventory which remains will automatically become a component of the MUF that is established at the end of the Material Balance Period (MBP). It will only be recoverable when the plant, or parts of it, is decommissioned.

Two different MUF components can thus be distinguished: the difference between the input and output due to the measurement uncertainties and any "hidden" inventory which may be present in the plant. The MUF (including its "hidden" inventory component) is written off from the books each year. If the component due to the measurement uncertainties has a mean of zero then the Cumulated MUF (CUMUF) should be a measure of the "hidden" inventory, which remains in the plant.

3. The Control of holdup in MOX plant

3.1 Design features of the plant to minimise holdup

Among other things, MOX fuel fabrication plant and more specifically plutonium plant processes are designed to protect operators from radiation exposure, to prevent criticality events and to meet ionising radiation regulations and also to ensure a high degree of quality control.

Taking into account safety and radioprotection leads to high containment standards consisting of multiple barriers, and emergency breach protection systems. Such measures in effect make plutonium much less accessible both to the operator (diversion more difficult) and to the inspector (calling for tailored safeguard approach). It also translates into several other measures such as:

- Confining plutonium materials to airtight glove boxes, under constant under-pressure;
- Locating glove boxes within fire proof zones with tight barriers;
- Increased automation to give hands-off, remote operation;
- Compact equipment, close process connections;
- Regular and more efficient glove box cleaning to reduce material deposits;
- Optimised maintenance to reduce dose uptake;
- Minimised waste streams.

As far as quality control is concerned, it requires extensive control and tracking features that are also beneficial to nuclear materials accountancy and can be of direct benefit to the safeguards authorities:

- control over homogeneity and plutonium concentrations and therefore extensive efforts to minimise holdup;
- 'bar' coding of containers and components to allow automatic identification of the products either in store or as they are transferred within the plant;
- fully computerised data capture and tracking for product traceability;
- automated inspection (e.g. pellet surface, end cap weld integrity, etc.);
- sophisticated handling and transport systems;
- the introduction of statistical process control and planning techniques.

3.2 Design features of glove boxes to minimise holdup

Focusing on glove boxes, a key equipment of the bulk handling part of a MOX fabrication plant, some technological features can participate in reducing the "hidden" inventory. New glove boxes only use stainless steel and lead glass for their construction, and their internal shape is optimised for plutonium recuperation: hence the "hidden" inventory can be kept relatively low. Holdup in process vessels is also dependent on the smoothness of the stainless steel surfaces in the silos, blenders, homogenisers and other process equipment and the free flowing characteristics of the powders.

Glove box extract systems employ high airflow venting through a primary outlet HEPA (High Efficiency Particle Arrester) filter to the vent ducting. This outlet filter traps most of the possible contamination. Ventilation ducting usually terminates at a single or double HEPA filter bank.

3.3 Control of holdup during plant operation

On one hand, routine cleaning procedures are carried out during tooling-up between different production campaigns and also after each change of Pu-enrichment. It allows keeping the amount of holdup and "hidden" inventory at a low level. On the other hand, the constant monitor-

ing of accountancy balances gives an indication of the level of holdup and "hidden" inventory. Because of these two features, special Non Destructive Assay measurement for the determination of holdup and "hidden" inventories is not required.

However, since gamma and neutron dose rate measurements are done for radiation protection monitoring at selected points in the process area, they are additionally used to give adequate warning of any apparent increase of holdup and "hidden" inventories. Those measurements are done at each glove box, at each working place and at all locations known to give higher dose rates.

The regularity of cleaning keeps the holdup and "hidden" inventory relatively low and avoids build-up to any "saturation level". Warnings from the radiation monitoring or from the accounting system give rise to additional cleaning measures. An additional thorough cleaning is also required for the annual PIT to minimise holdup and "hidden" inventories and to make those materials available for physical verification; for the same reason, in so far as possible, some maintenance operations such as filter replacement are scheduled before annual PIT.

3.4 Holdup evaluation

MOX fuel fabrication is a discontinuous, "batch" process and each production batch (material from the same origin, e.g. from a mixing process) can be individually balanced and followed from process step to process step, from glove box to glove box, from "accounting position" to "accounting position". A running balance of the expected inventory is recorded for each "accounting position", subdivided into cans, boats, trays etc. for each production batch. Routine cleaning is performed between each production campaign.

The differences between input/output-data of each accounting position are allocated to special batches. Following collection and measurement of sweepings from the glove box then the difference is split into two special batches, one for sweepings and one for material holdup (still in the process equipment). If in addition the actual process equipment is thoroughly cleaned then any remaining difference is regarded as "hidden inventory". The determination of the "holdup" and "hidden inventories" is primarily based on weight measurements but is affected by arising of Plutonium Contaminated Materials (PCM). PCM is primarily in the form of organic waste and in the filters, which are measured by NDA methods. Following waste transfers and thorough cleaning the accounts are reset to zero. Of course there would still be some nuclear material present in the form of firmly sticking deposits in the glove box system, which is kept in check by the continuous dose rate measurements and by monitoring the cumulative MUF account.

Periodical cleaning therefore is an important measure on the one hand for the reduction of the holdup and inventory and on the other hand for the adjustment of the book accounts.

3.5 Specific safeguards measures

In modern plants where processes are difficult or impossible to access, early consultation between the oper-

ator and the safeguards authorities is vital. During design verification activities the safeguards authorities can gain assurance that there are no undeclared features/access routes. During commissioning the operator's measurement systems and process operations are verified and process norms established for use in future process monitoring. Any holdup values established at this time can be verified by the inspectors.

In some plants, where production can be stopped on a regular basis, the safeguards approach is based on a monthly Short Inventory Verification (SIV). The operator then ensures that the majority of the material is moved into measurable locations, thus reducing in-process inventory to holdup and hidden inventory. In continuously operating plants, a safeguards approach based on frequent inventory verification of a running process has been adopted by Euratom. This requires the in-process inventory to be measured using methods that are as unobtrusive as possible.

4. Plant specific experience

This section will provide some examples based on actual operation and experience of European plants. Obviously, it is not intended here to be comprehensive on all features of each of these plants, whether these features are common to all plants or specific to a plant or a process, and the illustrations given below shall not be understood as the only features of those plants.

4.1 The Belgonucléaire MOX plant: holdup management for PIT

Production procedures require regular cleaning of production equipment and/or glove boxes. Different levels of cleanings are applied, depending on the purpose: change of Pu-enrichment within a campaign, change of production campaign, and once per year for the PIT.

At the time of the PIT, specific actions are applied:

- all powders and pellets are collected in cans or trays, which can be weighted or measured with NDA methods;
- the scrap material is transferred to storage room after measurement;
- the process equipment that could contain MOX powder or MOX pellet is emptied and cleaned as far as reasonably possible (thorough cleaning).

For instance, a prolonged emptying procedure is applied to the ball mills in order to minimise the remaining holdup quantity (usually, less than 25g of MOX powder), which is then recorded on the Physical Inventory Listing (PIL) as part of the dust estimate of the process area concerned. Likewise, remaining powder after emptying grinding devices (including filters and dust collectors) is recorded on the PIL as part of the dust estimate of the process area concerned. Other process equipment does not usually contain any MOX powder after emptying and cleaning.

The powder transport container are also emptied and weighted; if it is not completely empty, the container is listed on the PIL.

The outlet filters of the glove boxes are measured with a portable neutron device, and Pu amounts are deduced based on a calibration curve.

In the glove boxes, dust sweepings are collected, weighted and measured with NDA methods.

While those are specific measures performed at PIT time, preventive measures are permanently applied, such as splitting the process area in working-units for which balances are drawn in a continuous way (in-out), continuous control of the quantities in-out of the blenders and the ball-mills, or traceability of batches.

As a result of those preventive measures and PIT specific actions, the holdup and "hidden" inventory can be minimised, and experience shows that it remains at a constant level over the years.

4.2 The MELOX plant: combining plant design and pro-active material management

As in other MOX plants, the holdup and "hidden" inventory will derive from the use of powders (handling, dosage, milling, homogenisation), the pellets handling (drop of pellet), and the pellet grinding (grinding dust).

In order to limit "hidden" inventory and to track holdup, active measures are implemented. For instance, containers are identified and weighed at the entry and the exit of each production station; the data are sent and processed in the Material Information System (MIS) to determine the material undergoing processing in each production station and detecting any drift. In the powder processing areas, the quantity of material entering and leaving each line is measured and compared to determine the quantity remaining in the line. Dealing with pellet handling, the mass of each container entering a processing station is compared with the mass known when leaving the previous processing station, in order to detect pellets dropping between two stations.

This complements preventive measures incorporated at the design stage. For instance, every docking station for jar drainage or filling is equipped with a cyclone system to prevent dissemination of powder during powder transfers, and jars are equipped with plugs during transfer between stations. A cyclone system is also used in the pellet grinding glove boxes to recover the material in dust pots; and pre-filtration of the extraction from those glove boxes prevents the deposit of dusts in the ventilation ducts. In addition, all glove-boxes and their attachments use stainless steel to facilitate cleaning.

In addition, specific operational actions are taken to minimise the holdup and the "hidden" inventory while participating in product quality and reduction of workers radiological exposition. Regular cleaning is one of those measures: cleaning is performed routinely when the Pu content has to be changed in a given campaign and between campaigns, during the annual inventory, and also during specific maintenance operations. Cleaning operations can also be triggered by the results of regular irradiation measurements performed by the "Radiation Protection and Environment section" of the plant at several points (filters, hoppers in glove boxes, ...).

All those measures, whether design or operation, ensure a minimised quantity of holdup and "hidden" inventory. Holdup and "hidden" inventory are evaluated with a good accuracy by feed back, and by measurement whenever possible. They are then recorded in material balance for each production station, and the MIS can track it in each production station as well as in the entire plant.

4.3 The Siemens MOX Facility: feed back of holdup quantification

4.3.1 Handling weight data

The Siemens 2 plant was designed for automatic data capture from identification and weighing systems in all areas which transfer items in "containers" (e.g. trays, boats etc.). In the Powder Treatment Area the transfer data was to be read manually from the weighing systems after having completed a transfer. The accounting system would therefore reflect the results after the completion of transfers. "Dynamic" readings from the continuous weighing systems would be recorded via a "Monitoring System" and used "only" for a plausibility check of the data booked in the accounting system.

Holdup amounts found to lie within the uncertainty of the measurement systems would not be recorded in the accounting system, only significant amounts would be recorded. However even differences that lie within the measurement uncertainties could be evaluated over a longer period of time, if the differences proved to be systematic.

4.3.2 Some holdup levels

- **Ball Mills** - The "machine holdup" was on average about 200g of MOX powder. If the material balance in the mill was higher then mill operation was continued, until this level of run out was reached.
- **Blenders** - For a 200kg blender a constant "machine holdup" lay between 300g and 800g of powder. Before each change of enrichment, the blender was cleaned to avoid inhomogeneities in the final product.
- **Filters** - All exchanged filters in the upstream of the Mixer glove box between 1988 and 1991 (183 filters) from the first step glove box HEPA filter were measured before disposal. The Pu-content of the filters amounted to 504g, e.g. approximately 15kg of MOX powder. The next filter in the down stream ventilation system was found to be normally free of nuclear material or only slightly contaminated. The 15kg of MOX Powder was about 30% - 50% of the amount of material on the filters, the rest was removed mechanically before transfer to waste.
- **The Pneumatic Transport System** - trials with a Pneumatic powder transport system show the receiving station has a constant "holdup inventory" of about 100g, whereas the sending station appears optically to be clean, as long as dry, flowing powder is used. The holdup in the feed pipes depends on the type of the material (Mix, Mastermix, UO₂ etc.) and can amount to 1 - 5g per meter of the system as such.

4.4 The Sellafield MOX Plant: prevention is better than a cure

SMP employs the Short Binderless process which is a rapid forced milling system which has short material dwell

times and a compact design, thus minimising the amount of material being processed in order to achieve the desired throughput. The process is arranged in vertical towers. These towers are all individually monitored by near real time accountancy software that employs the continually occurring inventory data to assess statistically the holdup and cumulative differences between tower inputs and output.

Like any MOX plant the activity that tends to generate the most dust tends to be the grinding of pellets. In SMP grinding again occurs in enclosed equipment with dust being removed by force by a high power extract system. This collects material grinding dust onto a re-usable pulsed filter. The pulse blow back force removes material from the filter into a sealed collection vessel, which is weighed and transferred to the residue, recycle system.

All process operations up to the transfer of pellets from boats to trays are to be conducted automatically without manual intervention. A combination of material tracking, direct in-line weighing and process sequence control give the plant a high probability of detecting individual pellet losses.

The plant safety case included a large number of hazard operability and analysis studies (HAZOPS and HAZANS), which have covered the issue of glove boxes and equipment design to prevent unwanted accumulations and to provide a deterministically criticality safe processes (either by plant geometry or capacity limitations). These studies also identified all areas with potential for material to collect and as a consequence engineered the design so that these materials migrate and collect in known places with special collection and retrieval systems.

Conclusions

Modern MOX fabrication plants allow for a highly efficient accounting and safeguarding of nuclear material, from the design stage up to day to day operation. The design of the plant and of the glove boxes are meant to reduce loss of nuclear material and therefore to reduce material unaccounted for. During operation, control of nuclear material is enhanced by monitoring and regular cleaning and maintenance of the plant: such operations lead to the routine recovery and measurement of most of the material which did not make its way into a MOX pellet.

At PIT/PIV time, holdup can be assessed and is therefore accounted for, while "hidden" inventory is recorded into the MUF because it cannot normally be measured or estimated. Even in the MUF, "hidden" inventory is under control: this small quantity of nuclear material is in the plant and is recovered as a result of dismantling of the plant or parts of the plant (glove boxes, ..).

On one hand, the operators of MOX fabrication plants are dedicated to reducing to the minimum the "hidden" inventory and to providing the best information to assess holdup when it cannot be directly measured; on the other hand the safeguards authorities are implementing a hierarchy of safeguards measures and their inspectors have gained an in-depth knowledge of the plants. Combining those factors enables the safeguards authorities to give safeguards assurances for MOX plants.

APPENDIX: Some Reference Definitions United States Nuclear Regulatory Commission

Regulation 10 CRF part 70 Licensing of SNM

70.51 Material in process means any SNM possessed by the licensee except in unopened receipts, sealed sources and ultimate product maintained under tamper safing.

NUREG/BR-0096 Instructions and Guidance for Completing Physical Inventory Summary Reports, October 1992

IN-PROCESS HOLDUP - Process related SM or SNM that has not been drained from its processing equipment at the time of physical inventory. The quantity of any in-process holdup must be included in the physical inventory determination. [NOTE: The term "in-process holdup" should not be confused with the term "residual holdup".]

RESIDUAL HOLDUP - Any SM or SNM that remains within processing equipment (including ventilation filters and ductwork) after system drain down and/or clean out. If, at the time of physical inventory, the total quantity of residual holdup is significant, such holdup must be measured (or estimated on the basis of partial measurements and engineering calculations) and included in the physical inventory listing.

NUREG/CR-5550, LA-UR-90-732 Passive Non-destructive Assay of Nuclear Materials

NUCLEAR MATERIAL HOLDUP - The term "holdup" refers to the accumulation of nuclear material inside the processing equipment of nuclear facilities. Other common terms for such material are "hidden inventory", "normal operating loss", and "in-process inventory". The choice of terminology depends in part on the application or point of view. For example, the nuclear material that remains in the facility after the runout of all bulk products may be called "in-process inventory". The material that remains after thorough brushing, wiping, acid leaching, and rinsing may be called "fixed holdup".

Because of the high economic value of nuclear material and the need to ensure radiation safety and criticality safety and to safeguard against theft or diversion, it is important to minimize holdup, to measure or model its magnitudes, and to remove it.

IAEA Safeguards Glossary (IAEA/SG/INF/1, Rev.1, 1987, latest version)

Art. 58: HOLDUP - nuclear material deposits remaining after shutdown of a plant in and about process equipment, interconnecting piping, adjacent work areas. For plants in operation the holdup is the amount of nuclear material contained in the process.

Art. 174: MUF observed value - the value stated by the operator, based on the closing of a material balance for a given period. Whether or not diversion has occurred, the MUF for bulk material will normally be different from zero owing to holdup in process equipment and unmeasured losses.