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# Movement of Radioactive Material Sellafield Site

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## Abstract

## Background

The UK nuclear decommissioning priority is to reduce risk and hazard and to deliver the clean-up mission cost effectively. This is particularly relevant at Sellafield where the Legacy Ponds and Silos pose the most significant challenges.

The availability of safe packaging for the movement and storage on the Sellafield site is a key enabler to meet the NDA mission for safe interim storage ahead of its subsequent treatment, packaging and final storage to a Geologic Disposal Facility (GDF). There are a significant number of packages and package design types operating on the Sellafield site. Some packages are licensed to the IAEA regulations for safe transport and others comply only with the Sellafield site specific requirements.

## Introduction

Packages to and from the Sellafield site need to comply with the IAEA regulations for safe transport and must meet the Sellafield site requirements. However, the IAEA regulations do not apply to packages within a licensed site. For on-site safe package operations compliance is required against Sellafield site specific procedures, standards and guidance.

## Package Management System

There are a significant number and types of package transfers routinely undertaken safely on the Sellafield site. The packages range from small (18Kg) hand held sample castles to large complex (100Te) packages some with in-built gamma gates, mechanical interlocks and hoisting drive mechanisms.

The Sellafield Package Management System (SPMS) efficiently manages package operations and includes for asset register, package tracking, operational history and maintenance. The system includes packages used for the on-site movement of radioactive material performed by hand, road and rail.

## Package Safety Substantiation

The way in which safety is assessed for off-site transport operations can differ considerably from that on nuclear licensed sites. The key safety requirement for the latter is to demonstrate that overall risk is as low as reasonably practicable. This requires a holistic view of all the risks associated with operations including criticality, conventional safety, dose uptake and radiological. Package safety engineering substantiation requirements are fully defined for the Sellafield site.

## Introduction

The Sellafield site has been operational since the 1940's, when it was used as a Royal Ordnance factory supporting the war effort. The site is also home to the world's first commercial nuclear power station Calder Hall, which generated electricity from 1956 to 2003. The Sellafield site measures 6 $km^2$ and with over 1,000 nuclear facilities is considered to be one of the largest nuclear sites in Europe, with a most diverse portfolio.

Today, the Sellafield site (Figure 1) is home to a wide range of operations including the decommissioning of redundant buildings, ponds and silos associated with site's early defence work; spent fuel management including Magnox and Oxide fuel reprocessing; and the safe management and storage of low, intermediate level and high level nuclear waste.


**Figure 1 Sellafield site Cumbria**

The safe movement of radioactive material on the Sellafield site using a variety of RAM (radioactive material) transfer packages is a key enabler to reducing the risks and hazards posed by historic facilities and wastes.

The IAEA (International Atomic Energy Agency) Regulations for the Safe Transport of Radioactive Material [1] SSR-6 para 107 (b) states; 'these Regulations do not apply to *Radioactive material* moved within an establishment that is subject to appropriate safety regulations in force in the establishment and where the movement does not involve public roads or railways.'

However, the IAEA Transport Regulations[1] provides a benchmark for safety arrangements for the movement of radioactive material on the Sellafield site in Sellafield Packages (SPs).

## Package Management System

RAM transfer packages operated only on the Sellafield site (SPs) must satisfy Sellafield Ltd specific procedures, standards and guidance. All Sellafield Packages (SPs) must be registered on the Sellafield Package Management System (SPMS) which provides an electronic database and aides co-ordination and control of on-site package movements, including recording of site movements.

The following key functions are performed;

- Unique Identification of all SPs together with the nominated plant owner/operating unit
- Holding references to mandatory documentation for each SP e.g. configuration design information, safety case documents, maintenance requirement/history etc. and
- Control of quarantining arrangements, if required

The on-site transfer of SPs can be by manual means, road and rail. Before a SP can enter service it must go through formal justification and SPMS registration. This process must be followed for first use and any subsequent change of use.

When the appropriate Safety Function Category has been confirmed SPMS can be interrogated for a matching package. Where no suitable packaging exists for the movement, a new or modified design will be required.

All SPs must be justified as providing the required safety functions by the Safety Case Manager (SCM) and the designated Package Design Authority (PDA). The SCM and PDA will determine if the package satisfies key safety criterion e.g. radiation shielding, containment or criticality control and is reliable operations in all relevant plants.

The PDA will endorse design and safety specific information for the proposed movement. The Sellafield Package Maintenance Authority will review the data to confirm it is complete before the package owner can request operational use via the SPMS and On-Site Radioactive Movement Coordinator.

Currently over 950 individual SPs are registered on the SPMS system, ranging from a few kg to over 100t in weight. They can vary in complexity from simple shielded sample carriers to complex interlocked, base opening packages with hoisting mechanisms (Figures 2 to 6).

All SPs align to one of a suite of Model Operational and Maintenance Specifications from which the actual maintenance requirements are developed. SP's must be referenced in the Safety Case for each facility they visit.

Each package has a bar code which is scanned on entry and exit from a facility. If an SP has reached the maximum allowed number of uses between maintenance or reached its maintenance due date, this is flagged to the operator by an appropriate message on the hand-held bar code reader. Should a package be used whose status is not 'operational' it will be flagged to the On-Site Radioactive Movement Coordinator where the Sellafield 'Condition Reporting' process is invoked.

The SPMS database does not track or record package payloads. The system gives visibility of SP status, by showing;

- Packages certified as operational
- Packages in maintenance- linked into the plant maintenance systems
- Quarantined packages awaiting authorization
- Packages for decommissioning

Last year the SPMS recorded 13,680 Sellafield Package moves, excluding Transport Package moves and single use RAM package moves.

**Figure 2 Magnox fuel Sellafield Package handling**


**Figure 3 Magnox de-canned fuel Sellafield Packages docked on gamma gates**

**Figure 4 Vitrified waste canister package handling**


**Figure 5 Tungsten hand held container and manual movement fissile material trolley**


**Figure 6 AGR and LWR fuel Sellafield Packages**

## Package Safety Substantiation

The use of SPs on the Sellafield site requires substantiation and plant safety cases to satisfy nuclear site license conditions. The substantiation examines in detail the normal operations and all credible fault conditions.

An engineering assessment produced in the form of a Design Justification Report (DJR) or Design Assessment Report (DAR) confirms that the performance requirements satisfy the safety case criteria. The assessment must take into account all the plants visited by the package and will be incorporated into the relevant plants safety case/s.

A Safety Function is a performance attribute of a structure, system or component which, directly or indirectly, prevents or mitigates nuclear, chemo-toxic or environmental consequences, and is required to achieve an acceptable level of safety. Safety Function Class is a measure of the importance of a Safety Function. The definitions are as follows.

Safety Function Class 1 (SFC1): a Safety Function, which makes a major contribution to radiological safety. A very high degree of confidence is required that the function will be achieved.
Safety Function Class 2 (SFC2): a Safety Function, which makes a significant contribution to radiological safety. A high degree of confidence is required that the function will be achieved.
Safety Function Class 3 (SFC3): a Safety Function, which makes only a minor contribution to radiological safety. A reasonable level of confidence is required that the function will be achieved.
Safety Function Class 0 (SFC): a Safety Function, which makes a slight contribution to radiological safety and does not require substantiation.

The package designer may need to introduce Safety Mechanisms (SM) or Safety Related Equipment (SRE) into his design to allow substantiation against perceived risks, recorded in the Engineering Schedule. SPs are classified according to an assigned safety function class, agreed with plant safety case owners, according to the radiological safety significance of the component (SSC).

Case studies are provided for substantiation of some challenging RAM moves for the following subject areas which are, not exhaustive of the types of substantiation that may be required;

- Containment - aerial and liquor
- Radiation dose
- Criticality
- Explosive atmospheres (hydrogen management)

## Containment

The integrity of containment required is dependent upon the material being transferred, e.g. solids, liquors, powders or gases. This then reflects on;

- Methods of construction
- Seal type and configuration
- Package ventilation methods
- Method of testing and acceptance criteria
- Ability of the package to maintain containment under credible accident conditions, including impact and thermal excursions

The appropriate method of containment can use the ALARP[2] principles (As Low As Reasonably Practicable) involving the designer, operator and plant safety case representatives considering potential dose to operators/public and challenges to the packaging. The level of sealing required is based upon the required SFC rating for containment or the challenge expected by the seal. For SFC 1 rating, where vigorous sealing challenge is expected, two seals are provided allowing for pressure testing. For an SFC2 rating, where mild sealing challenge is expected, a single seal could be adequate. For an SFC3 rating, where minor sealing challenge is expected, machined mating surfaces could be adequate.

Seals, as far as possible, should be designed in such a manner that they are rarely challenged. This can prove problematic, particularly when designing a side or base opening package. Should a single seal be impossible to inspect during operation then the designer could specify a double seal arrangement with an interspace test facility as a means of ‘blind’ inspection.

The use of multiple containment barriers, such as welded Polyvinyl chloride (PVC) bags or tightly lidded liners, may reduce the challenge to the packaging seals whilst maintaining the SFC rating for the package. Substantiation can be provided in conjunction with reference to established Release Fraction Data Base (RFDB), as appropriate.

Case study-Historic fleet of Magnox packages.

Experience with the historic Magnox Sellafield Packages shows the difficulty in continuing to satisfy the initial sealing design intent (Figure 7).

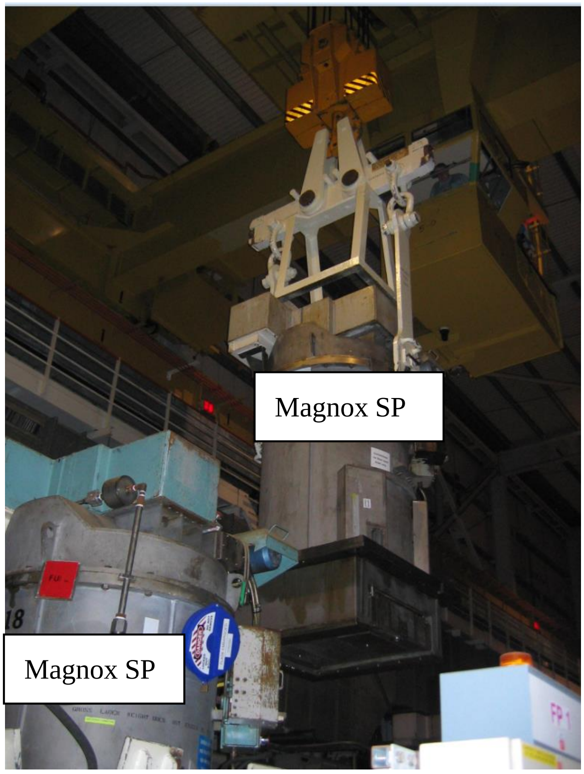



**Figure 7 Historic Magnox Sellafield Packages**

Designed to contain solids and liquid in the form of Magnox uranium fuel element rods or de-canned Magnox swarf and water, this function is carried out adequately under normal conditions. The package internal containers provide the primary containment under normal operations. The respective outer packaging provides the secondary containment function for bulk materials.

The design intent was for the square seal plate with a circular sealing feature housing an elastomeric seal to provide liquor sealing for the base of the package. However, with continued use, contamination issues and environmental restrictions it is not always possible to adequately undertake routine maintenance or decontamination of the package door areas and seals.

An under-slung stainless steel external carrier (Figure 8) attaches to the base of the package providing an enclosure. This forms part of the package configuration and enables the capture of potential drips of liquor. The external carrier to package base enclosure boundary is not challenged during normal operations. The existing plant safety cases have been reviewed and the safety function and performance requirements are not significantly undermined by not providing the initial design intent of package door sealing. The continued use of theses historic packages supports the accelerated risk and hazard reduction requirements of the Sellafield site.


**Figure 8 Package base residual liquor retention carrier**

## Radiation dose

The IAEA Transport Regulations[1] provides a benchmark for Sellafield Package arrangements for the safe movement of radioactive material. The threshold radiation dose rate limits set for the movement of Sellafield Packages is typically <2mSv/h at contact and <0.1mSv/h at 2m. The need to further optimise dose rates for high package operability may reduce new package surface design target dose rate to 7.5 µSv/h.

For normal operations the designer must ensure the threshold radiation levels are not exceeded and also satisfy the lowest targets of the plants to be serviced. The shielding safety function required following an accident differs depending on the safety function classification assigned, which in turn is dependent on the potential consequences of failure and the degree of confidence required in the function being achieved. The accident shielding performance requirements for the various safety function classifications therefore differ, not only in their inherent shielding performance, but in their ability to withstand accidental damage.

The following case studies show a flexible, holistic ALARP[2] approach used for shielding of RAM movements;

- Unshielded skip movements were justified on the basis of pre-planned operational control/ contingencies and resulting accelerated inventory removal.
- The package design (Self Shielded Box SSB) considered its whole life cycle in particular its final storage location to determine the optimum design.

## Case study-Metal fuel skip retrieval

Up to April 2011, no metal fuel had been retrieved and exported from the storage pond for over 47 years. The fuel was in the pond, in packages, and in skips, that could not be handled by other facility. A pilot project was successfully delivered in 2011 using very little new equipment to retrieve metal fuel, and prove export route from storage pond to the required facility. The lessons learned were taken forward to enable the remaining bulk fuel to be retrieved & exported.

To demonstrate that the proposed direct route is ALARP[2], alternative export methods were reviewed and discounted. Fully loaded with metal fuel the skip(s) (Figure 9) were successfully transferred out of deep pond and moved across the facility to be loaded in to a Sellafield Package for movement across the site.


**Figure 9 Retrieved skip loading into a Sellafield Package**

Possible breakdown scenarios and a recovery strategy were in place with all personnel excluded from the area during the transfer. Pre-installed recovery systems and local shielding ensured access was available should it be required. Hold points and measurements were put in place to confirm bounding assumptions during the lift from the pond.

Key Benefits;

- Early removal of active inventory from plant approaching end of life
- Small number of movements between two fixed points with exclusion zones constrained within the area under that facilities control
- Removing corroding bulk metal fuel will enable pond water activity to be lowered and effluent discharges to be reduced (predominantly Cs137 and Sr90 from metal fuel corrosion)
- Removal of metal fuel is a key enabler to dewatering the pond
- Remove criticality hazard

## Case study-SSB Package

There is a safety driver to remove pond solids unsuited to reprocessing. Sellafield propose to export fuel from its current pond location to the Interim Storage Facility (ISF) using packages (referred to as metal Self Shielded Boxes SSB) which can be stacked in an array within shield walls but with an unshielded roof (Figure 10).

**Figure 10 Concepts Interim Storage Facility and SSB**

The design is driven by the dose rate emergent from the top face of such an array and the impact of sky-shine scatter. Local shielding around lid bolting stations can become a better focus for dose reduction than over-shielding the SSB. The shielding requirement for the SSB is optimised based on the storage requirement of the ISF. This is supported by calculations given the activity distribution and storage plan to show insensitive to the activity variation or the presence of hydrogen vents in the lid locally constrained only by the 2mSv/h limit.

The implications of this design concept on operators handling and transporting the SSB, and possible construction workers overlooking the store, were considered against annual dose limits, envisaged dose management controls and ALARP[2] in the decommissioning context.

Key Benefits;

- The aim is to efficiently empty the pond in a timely manner
- Standardised and simple SSB design since many SSBs would be required
- ALARP[2] judgments of the overall risk profile
- Truly limiting dose levels need to be considered, but storing a single ‘hot’ SSB in the middle of the array, may be better than overdesigning all and rejecting the concept

## Criticality

All SPs carrying fissile material must be subjected to a Criticality assessment[3]. Internal Sellafield Ltd safety practice guides detail the requirements for both routine and non-routine movement of fissile material. Only a small fraction of packages handling active materials (including waste etc.) are likely to be exempt from criticality assessment. SPs that are assigned criticality normal operation safety functions are likely to have different additional performance requirements, such as;

- Spacing within the package for normal operations to maintain minimum distance between any inventory being transported
- Minimum spacing between packages for normal operations
- The potential for the degradation of materials (e.g. from heat, radiation damage, fire) to affect reflection conditions within a package or neutron interaction within or between packages
- All criticality based requirements are included in the Engineering Schedule, prepared by the safety team in conjunction with the engineering team

The Sellafield Ltd mission of risk and hazard reduction is very much linked to cost of that delivery. The EA (Environmental Agency), ONR (Office for Nuclear Regulation) and NDA (Nuclear Decommissioning Authority) have expressed expectations that Sellafield demonstrates ‘doing the right thing’ and ‘doing the thing right’. The challenge to overly pessimistic safety assessment assumptions is consistent with that expectation and ALARP [2] principles.

## Case study-Challenge to overly pessimistic criticality safety assessment - AGR slotted can container

The Thorp (Thermal Oxide Reprocessing Facility) is primarily used for temporary storage of AGR (Advanced Gas cooled Reactor) fuel in skips and Light Water Reactor fuel (LWR) in Multi Element Bottles (MEB) prior to reprocessing. The AGR interim storage project aims to develop the capability of the facility from short-term storage for reprocessing business to interim storage >75yrs.

A new over 18t container design (Figure 11 AGR slotted can container) has been developed to increase the storage capacity of the AGR fuel in Thorp.

Current containers (Figure 12) would not be able to store the planned fuel receipts of approx. 6000t uranium and to maximise storage would require over 1,800 20 capacity AGR slotted can skips at significant costs. These containers use BSS (boronated stainless steel) for the compartment walls as a neutron poison.

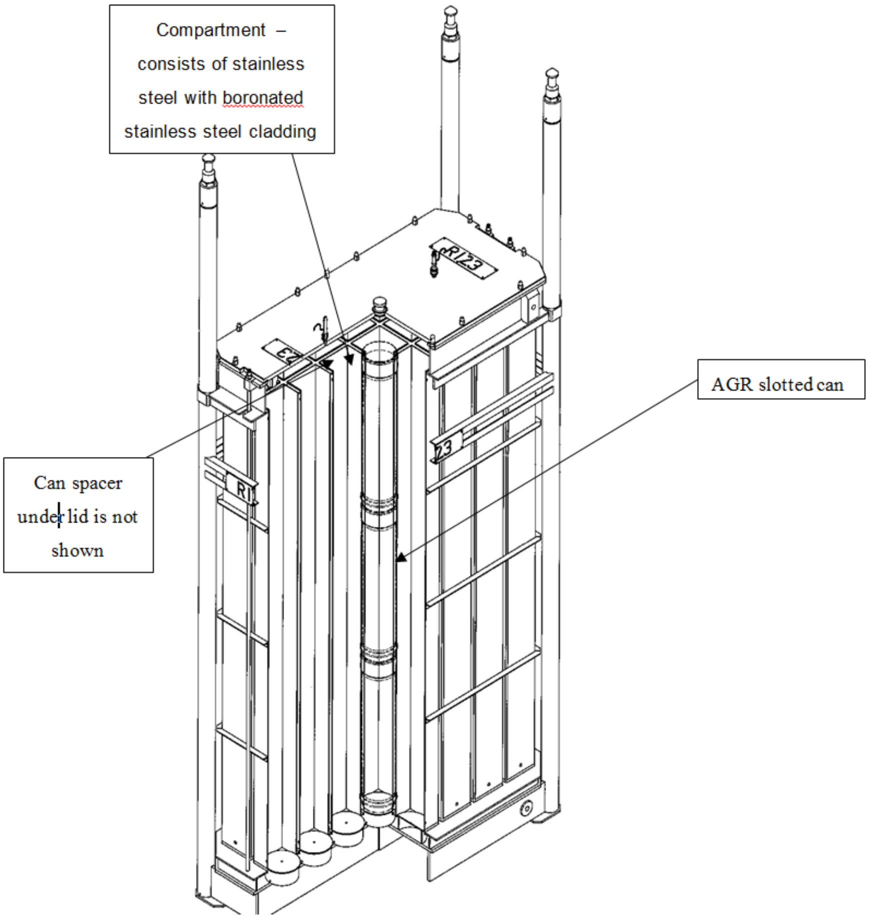



**Figure 11 High capacity AGR slotted can container – in pond transfer and storage**

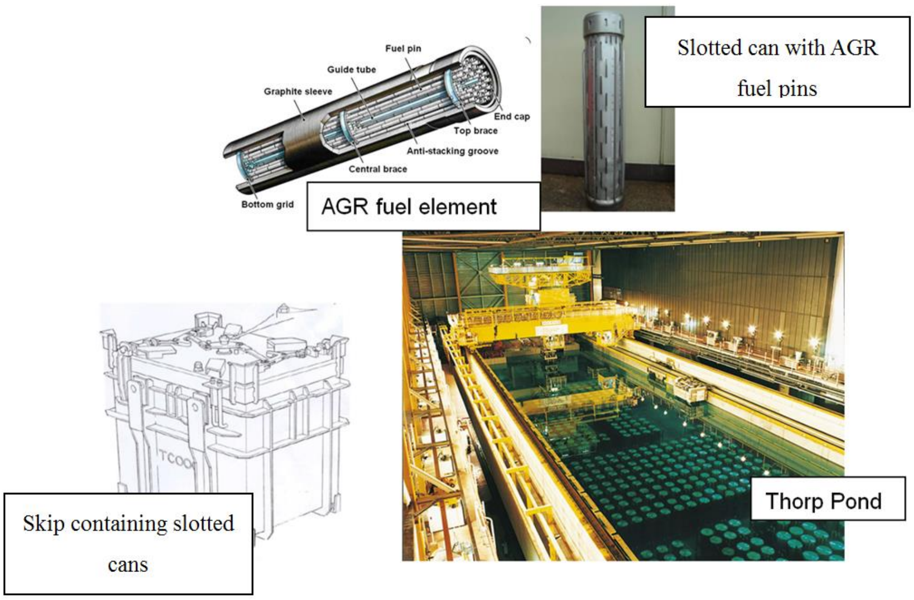
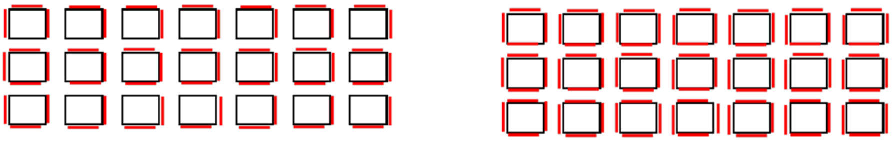



**Figure 12 Consolidation of AGR fuel transfer to Thorp**

Criticality hazards arising from key fault sequences associated with fuel storage and handling have been modelled. For several fault sequences it is shown that a criticality cannot occur because of the deterministically safe design of the AGR slotted can container. These sequences are scenarios by which the geometry of the fuel pins changes and therefore may increase the criticality risk. The following key fault scenarios were identified from the criticality hazard analysis for the container;

- Impact damage causes gap closure
- Single failed can, pins spill out into compartment
- Topple causing gap closure & fuel breakup – slurry in container lid space
- Topple of container causes gap closure & fuel breakup – slurry in cans
- Loss of pond water or container raised out of water

A key feature of the original AGR slotted can container design was the use of 84 BSS (Figure 13). This was based on the initial criticality assessment which assumed that all the fuel was at the maximum initial U235 enrichment for or all fault scenarios. A review of assumptions within the criticality assessment was performed to see if less onerous assumptions could be justified and the BSS reduced.



52 sheet arrangement 84 sheet arrangement

**Figure 13 Design options for BSS sheets**

Further criticality models were run to investigate the number of BSS sheets required for the bounding limits of gap closure, residual fuel enrichment and number of pins per slotted can, taking into account less onerous data provided by reviews of engineering, inventory records and operational experience.

There are some fault sequences for the container without any BSS, which are not criticality safe when modelled using the reactor maximum initial U235 enrichment, but which could be justified using a lower but still conservative residual enrichment of AGR fuel arisings (i.e. accounting for reduction in the fissile content resulting from irradiation).

In order to validate the declared U235 residual enrichment data, measurements made as the fuel was fed to be reprocessed were compared against the declared data for the campaigns studied (Figure 14). A review of the residual enrichment data from recent AGR fuel reprocessing campaigns, representing 1000teU of fuel, gives confidence that the lower U235 residual enrichment figure for assessment is appropriate. This is on the basis that the maximum element residual enrichment was even lower including +3σ uncertainty.

The average residual enrichment data of campaign, declared compared against measured, shows a good x = y relationship. However, it is recognised that the end of life reactor fuel may be above this value.

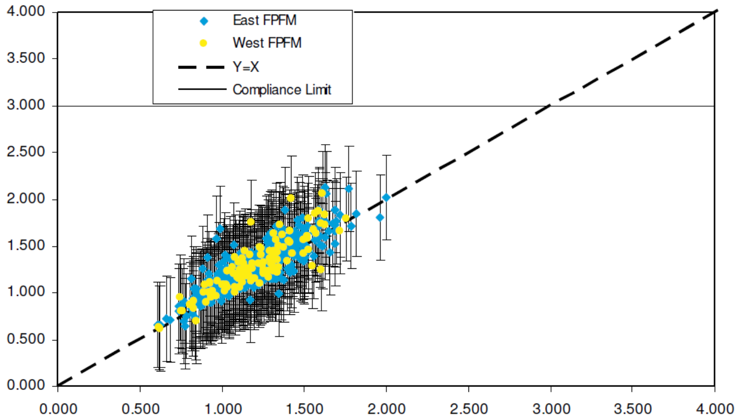



**Figure 14 AGR fuel measured vs declared U235 residual enrichment**

A review of the U235 residual enrichment values of AGR fuel received and the likely trends in U235 residual enrichment in the future justify a suitably conservative and bounding figure to use for the criticality assessment of the AGR slotted can container without BSS. Benefits gained from BSS removal included a £21.5m savings for total container requirements, ease of fabrication, reduced lead time, avoided reliance on limited number of producers and thermal advantage to fuel tubes by avoiding potential air/water gap insulation.

Two designs are produced- A design without BSS for vast majority of containers and a design with BSS for some containers expected for end of reactor life fuels, expected circa 2035. Appropriate human factor controls added over and above existing arrangements to distinguish between the two designs.

## Hydrogen management

The IAEA Transport Regulations[1] Para 662 states, ‘A package shall not include a pressure relief system from the containment system that would allow the release of radioactive material to the environment under the conditions of the tests’. This may not be possible for hydrogen generating waste transported in base opening Sellafield Packages with integral hoists that are free venting.

## Case study- Magnox swarf waste Sellafield Package

A new over 50t Sellafield Package (Figure 15) is designed for the transfer of Intermediate level waste (ILW) from the Magnox swarf storage facility[4] for interim storage, in 3m3 boxes, on the Sellafield site. Magnox swarf storage facility is one of the site’s four historic pond and silo facilities waiting decommissioning. The waste will in time be conditioned and suitable packaged for transport to the UK’s GDF for long term storage.

The hydrogen challenge associated with the new waste SP mainly arises from Magnox corrosion but is also influenced by a number of additional factors including the presence of uranium corrosion products. The swarf then undergoes a process which results in the release of gaseous hydrogen. Magnox (magnesium non-oxidising) is an alloy mainly of magnesium with small amounts of aluminum and other metals used in cladding unenriched uranium metal fuel. Magnox swarf is stored underwater.

Magnox alloys will corrode if left in water for long periods to produce hydrogen.

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \text{ hydrogen evolution}$$

Uranium hydride may be formed in very specific circumstances where uranium metal comes into contact with water, by reaction of the metal with hydrogen formed by corrosion of the uranium.

$$U + 2H_2O \rightarrow UO_2 + 2H_2 \text{ hydrogen evolution}$$

$$U + 1.5H_2 \rightarrow UH_3 \text{ uranium hydride}$$

Uranium hydride can be pyrophoric, reacting very vigorously with atmospheric oxygen. If further water is present, uranium hydride can also produce hydrogen.

$$UH_3 + 2H_2O \rightarrow UO_2 + 3.5H_2 \text{ hydrogen evolution}$$

The impact is a potential for a waste fire and hydrogen evolution. In order to address these issues the reference hydrogen generation rate challenge of $1m^3/h$ was developed as a strategic assumption.

This challenge impacted the complexity of the package design. The reference design at the time of the pyrophoric challenge being identified was a passively ventilating design based on hydrogen release from loaded skip of $< 1m^3/h$.

The potential fire risk of the passive package design was considered to be negligible on the basis of insignificant risks of containing uranium hydride. However, the loaded skip is water filled.

The designer has options for hydrogen management in Sellafield Packages;

- Use of fixed internal $H_2$ gettering devices
- Free venting via engineered filters
- Free venting via engineered openings in the package lid and
- Inerted packages with external passive autocatalytic re-combiner (PAR) unit

Where the hydrogen generation rate challenge is significantly beyond the capabilities of an air based package design (passive package) in terms of managing hydrogen below the Low Flammable Limit (LFL, <4% v/v hydrogen) an actively engineered package design may provide the internals of the package with an inert atmosphere. However, the requirement to vent hydrogen may conflict with the packages ability to maintain containment. Conventional safety risk is considered within ALARP[2] principles. The development of the Magnox swarf waste SP considered actively engineered package features to inert the package using a PAR unit. The key features of the actively engineered package included nitrogen inerting system, sealing test system, PAR unit, skip water-fill feature and a number of monitoring /sensory equipment (Figure 15).

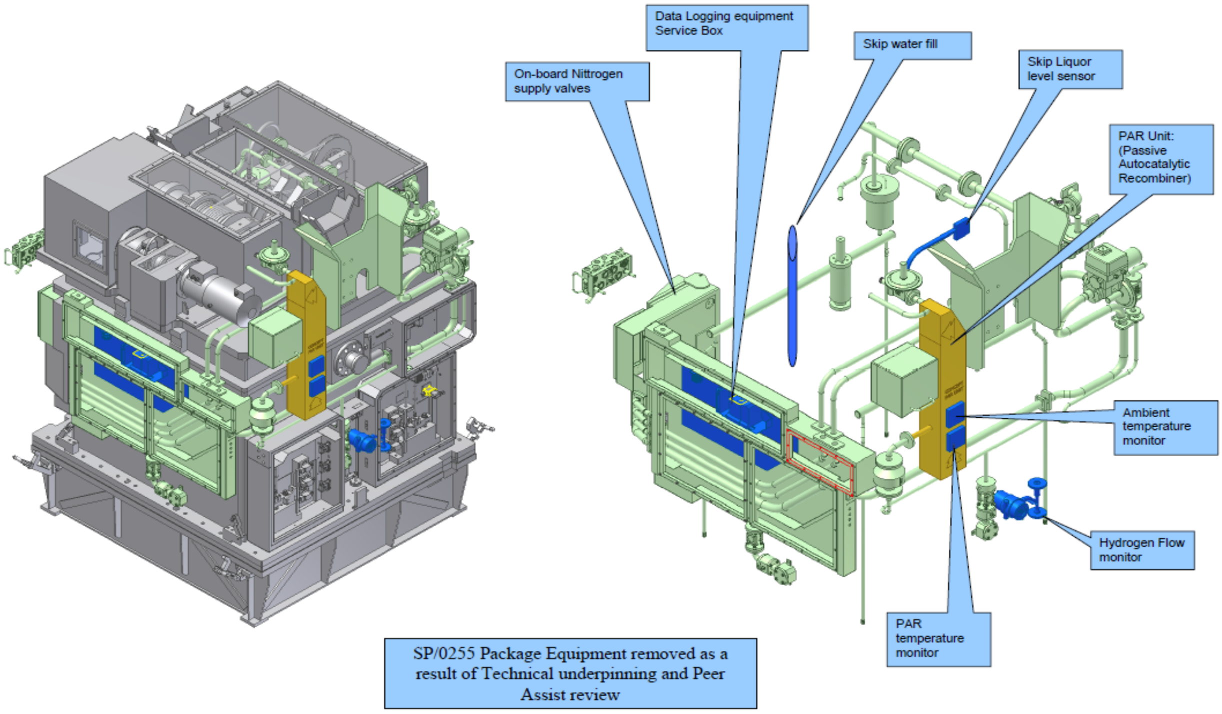



**Figure 15 Magnox swarf waste inerted package features**

Between 2009 and 2013 confidence increased in the number of skips whose hydrogen generation rates could be underpinned to well below $1m^3/h$. Figure 16 summarises the distribution of chronic hydrogen generation rates and associated cumulative relative frequency. The output provides good confidence that a significantly lower hydrogen generation rate of <1litre/h basis can be supported.

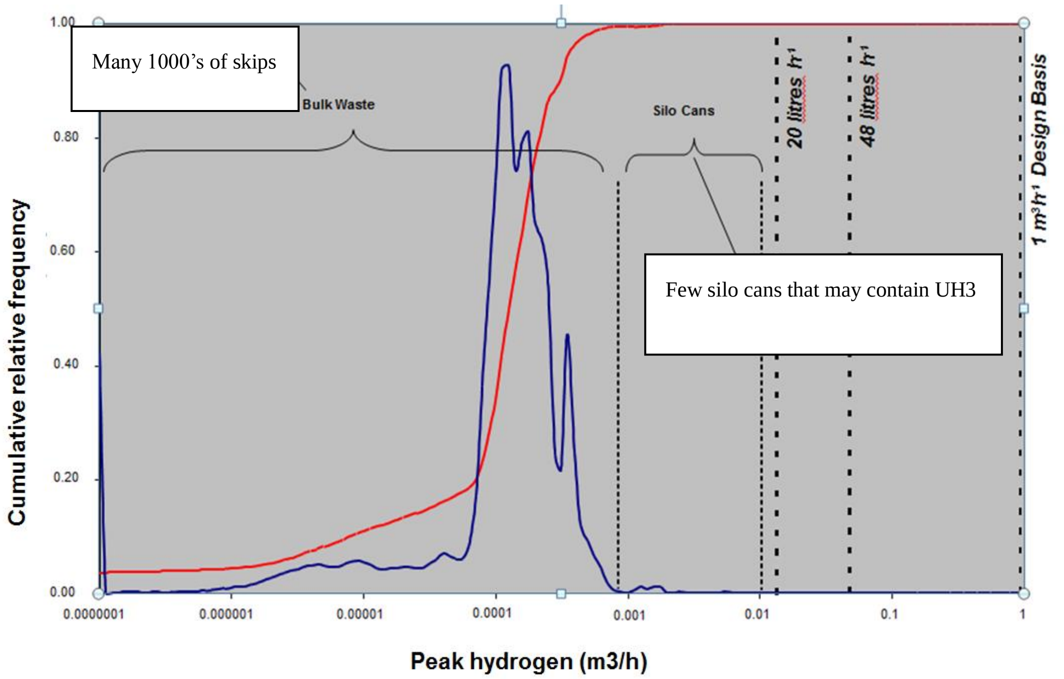



**Figure 16 Hydrogen generation rates**

The justification for not providing inerted package features was made avoiding package complexity which would impact reliability and availability for continuous use. The following features and equipment were removed from the package; On-board nitrogen supply valves, Data logging equipment services box, Skip water fill, Skip liquor-level sensor, PAR unit, Ambient temperature monitor, Hydrogen flow monitor and, PAR temperature monitor.

The air based package design (Figure 17) incorporates filters to meet the current hydrogen performance requirements for normal and fault cases;

- Normal case - hydrogen concentration levels <1.0 %v/v for chronic hydrogen rates significantly < $1m^3/h$.
- Fault case- hydrogen concentration levels <4.0 %v/v LFL for infrequent acute release of approximately twice the volume generated in an hour using the normal rate.

The package hoist enclosure may incorporate pressure relief panels to reduce the overpressure against potential fault scenario of hydrogen explosion.

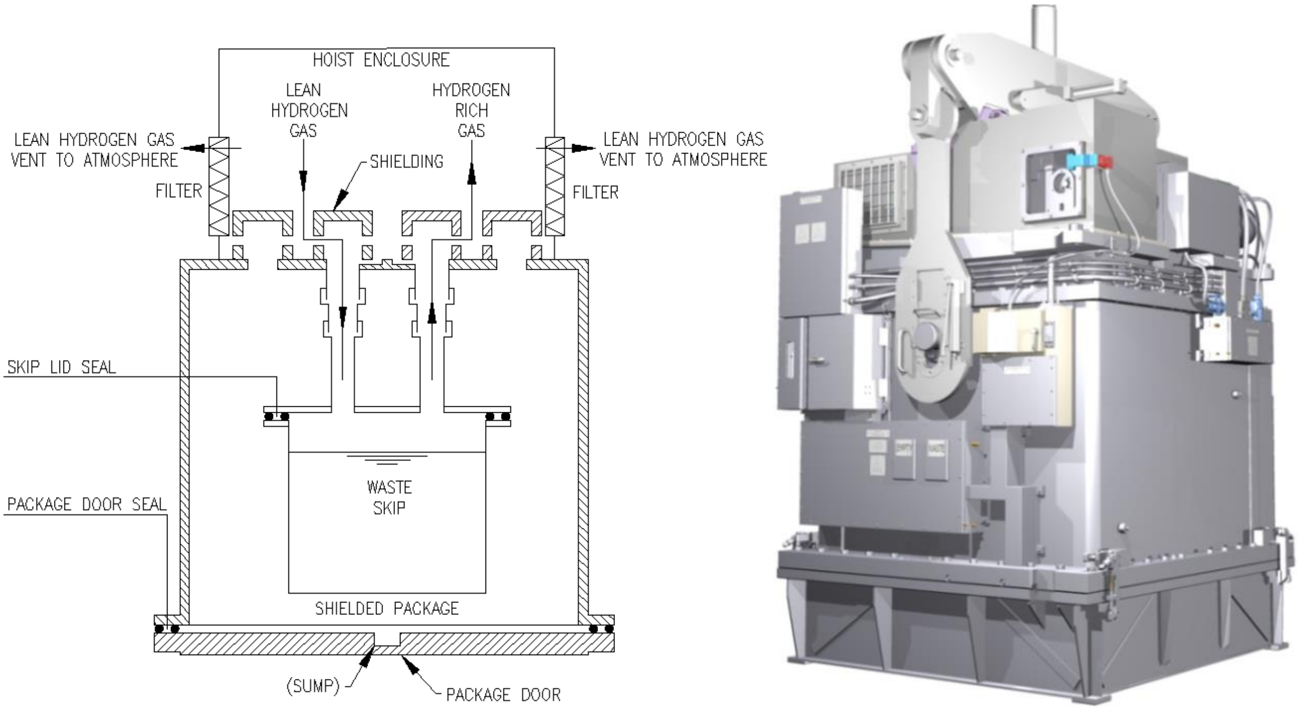



**Figure 17 Magnox swarf waste air based Sellafield Package –hydrogen management**

Natural buoyancy flow ensures hydrogen is driven from the skip to the hoist enclosure, through two hydrogen vents, where it diffuses through the filters. The package includes connections for purging if needed.

## Conclusions

The IAEA Transport Regulations[1] provides a benchmark for the safe movement of radioactive material in Sellafield Packages (SPs). This is considered within a flexible, holistic approach and within the context of ALARP[2] principles. Compliance is required against Sellafield Ltd specific procedures, standards and guidance. All SPs are registered on the Sellafield Package Management System (SPMS). The successful operation of over 13500 SP moves per year provides high confidence in Sellafield Ltd.'s safety management arrangements. Case studies are provided for substantiation of some challenging radioactive material movements undertaken on the Sellafield site.

## Acknowledgments

The author thanks the many Sellafield Ltd colleagues for their support.

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