FORTY-NINE YEARS OF SAFE STORAGE OF RESEARCH REACTOR SPENT FUEL AT ANSTO

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Abstract

ANSTO permanently shut down its 10 MW research reactor (HIFAR) in January 2007 following 49 years of operation. The shutdown followed the earlier closure of a smaller 100 kW research reactor (MOATA) in 1995. The spent fuel resulting from the operation of the HIFAR and MOATA reactors (2281 elements) was stored in wet and dry storage facilities. Of the 2281 spent fuel elements produced only 19 incurred some degree of "damage", either physical or chemical. Until recently (2007) some of these elements were still kept in dry storage, awaiting removal and preparation for final shipment. The damaged fuel elements were then removed from the wet storage ponds, some placed inside special sealed cans, and then deposited in the dry storage holes for long term storage. The management of spent fuel remained a very important aspect of the operation of research reactors for ANSTO. For disposition of UK-origin spent fuel arising from the operation of the HIFAR reactor, ANSTO initially elected to ship the irradiated fuel assemblies to the UKAEA in Dounreay, Scotland. With the closure of Dounreay, alternatives were evaluated, and reprocessing of the spent fuel at the La Hague reprocessing plant was selected as the option for the disposition of ANSTO's UK origin spent fuel. Between 1999 and 2004, a total of 1288 fuel assemblies were sent in four shipments to the La Hague reprocessing plant. For the remaining HIFAR fuel assemblies containing US origin uranium, ANSTO decided to exercise its option to return the fuel assemblies to the USA under the Foreign Research Reactor Spent Nuclear Fuel (FRR SNF) acceptance programme. ANSTO's remaining spent fuel was shipped to the USA in 2006 and 2009 respectively. This paper describes ANSTO's management of its spent fuel inventory.

1. INTRODUCTION

ANSTO has safely operated research reactors for over 50 years (Table I). The longest running research reactor, HIFAR, was a heavy water moderated, light water cooled high neutron flux reactor which operated from 1958–2007. The reactor was powered by 25 MTR type fuel elements and operated at 10 megawatts. Following removal from the reactor core, the spent fuel elements were initially wet stored for a minimum period of 21 months and then transferred to dry storage tubes, mostly under a nitrogen atmosphere. The storage and monitoring methods employed were generally highly successful in ensuring the integrity of the spent fuel elements (SFEs). Of the 2281 fuel elements used, the majority (2262) were maintained in sound condition, with all cladding having total integrity and with no fission products being released.

TABLE I. ANSTO RESEARCH REACTORS

Reactor (power)	Type	Started	Shutdown
HIFAR (10 MW)	DIDO Reactor	1958	2007
MOATA (100 kW)	ARGONAUT	1965	1995
OPAL (20 MW)	Open Pool Light Water	2006	

ANSTO shipped its spent fuel to Dounreay (Scotland) in 1963 and 1996, Savannah River (USA) in 1998, 2006 and 2009 and Cogema (France) in 1999, 2001, 2003 and 2004. In all of the overseas shipments there were only 19 'compromised' elements with some evidence of corrosion. The 19 compromised elements were returned to the USA in the 2009 and final HIFAR spent fuel shipment, after the fuel elements were placed in specific designed over pack canisters, approved by US DOE for reception and storage at Savannah River. The low number of compromised elements demonstrated that the wet and dry storage system used to store the spent fuel during nearly 50 years of reactor operation at ANSTO provided the necessary long term safe storage for the fuel.

2. FUEL TYPES USED

During HIFAR's operating life, a number of different MTR fuel assembly designs were employed, each of which comprised of an enriched uranium-aluminium cast alloy fuel meat (95% volume Al) dispersed in aluminium metal within high purity aluminium cladding [1]. Each assembly consisted of curved rectangular fuel plates, with the fuel meat surrounded by a picture frame and metallurgically bonded between two sheets of Grade 1050 (99.5% Al) aluminium by hot rolling. Each fuel plate was tested at 600°C for 20 minutes [2] and examined for blisters after cooling, to check the integrity of the bond between the meat and cladding. The cladding method prevented the release of uranium and fission products during burnup, and ensured that in the event of a minor breach to the cladding, the only part of the fuel meat exposed to water was directly under the breach. Highly enriched uranium elements (up to 93% ^{235}U) were used until 2005, when HIFAR was converted to use low enriched uranium elements (20% ^{235}U) for the final years of operation.

Figure 1 depicts the variations of fuel types used by HIFAR. There have been three main geometric variations:

- The parallel plate box type (Mark II);
- The annular involute type where the plates form spiral fins between two aluminium cylinders (Mark III);
- Concentric tubular elements consisting of four tubes, each made from three curved plates electron beam welded to form the tube (Mark IV). The figure shows the tubes after cropping the end pieces and held clipped together in preparation for storage or shipment.

For each of the geometric variants, there were several different levels of enrichment, different ^{235}U loading, different country of origin obligations, and after being loaded in the reactor core, they also reached different levels of burnup. All these factors had implications for the subsequent handling, storage, transportation and ultimate disposition of the spent fuel. Table II shows some characteristics of the fuel used in ANSTO's research reactors

3. SAFETY CONSIDERATIONS

Fundamental to the safety of spent fuel storage systems is the maintenance of an accurate detailed record of the location, movements, irradiation history and composition of every individual spent fuel element. Safety assessments and operating procedures must ensure that every conceivable combination of possible fuel variants, enrichments, uranium loadings and burnup is taken into account. This depends on very precise knowledge of the spent fuel being handled in any given operation.

The safety objective with the design of spent fuel storage facilities is to ensure that spent fuel will be received, stored and retrieved without undue risk to health and safety, or to the environment. To achieve this objective, the design must incorporate features that will be effective for the lifetime of the facility under normal operating conditions, anticipated operational occurrences and accident conditions. Relevant features include:

- Maintaining sub-criticality;
- Removing spent fuel decay heat;
- Providing for radiation protection;
- Maintaining isolation of radioactive material from the environment.

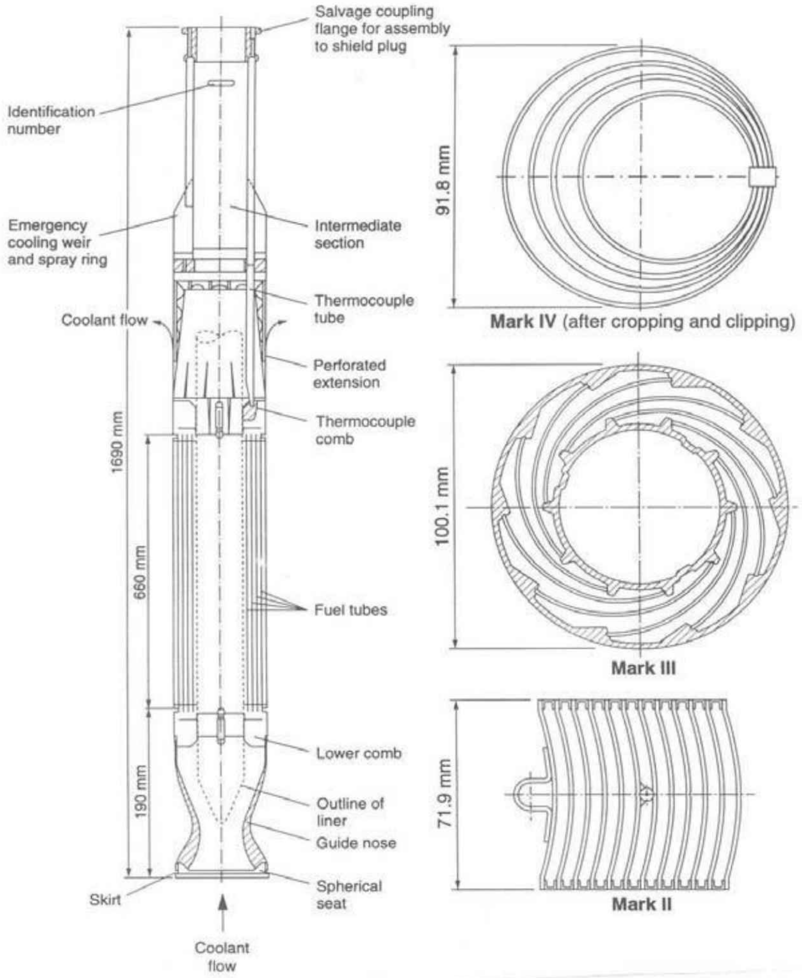

FIG. 1. HIFAR fuel type.

TABLE II. CHARACTERISTICS OF FUEL ELEMENTS USED IN ANSTO'S RESEARCH REACTORS

Reactor	Fuel characteristics
MOATA	60% – 90% HEU fuel assemblies with 12 aluminium clad fuel plates containing about 22–23 g of ^{235}U in an aluminium/uranium alloy
HIFAR	60% – 90% HEU fuel assemblies consisted of a uranium-aluminium alloy in an aluminium matrix with ^{235}U ranging from 115 g to 170 g until 2006. converted to <20% LEU fuel in 2006 until its closure in January 2007
OPAL	<20% LEU fuel consisting of uranium-silicide dispersed in aluminium and clad in aluminium

Whilst fuel cladding has been shown to be capable of retaining its integrity over periods of several decades in storage, very careful attention must be paid to the storage conditions when long term storage is contemplated if unacceptable degradation of the fuel cladding is to be avoided.

4. WET STORAGE

Following the removal of burnt spent fuel elements from HIFAR, they were placed in a sealed storage block, containing de-ionised water, and located within the HIFAR containment building. The initial storage block period is 3–6 months and allows sufficient cooling to occur for the spent fuel to be safely transferred to a larger capacity open pool wet storage facility outside of the HIFAR containment building. The full wet-dry storage cycle is shown in Fig. 2.

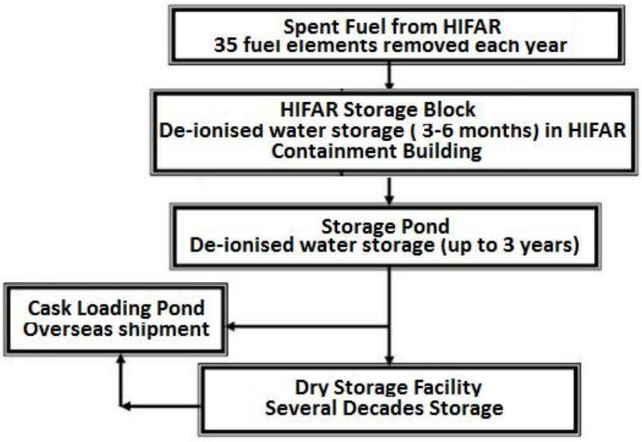

FIG. 2. Wet/Dry Spent Fuel Storage cycle at ANSTO.

Figures 3 and 4 show the ANSTO spent fuel cropping and storage ponds (medium term storage – up to three years), respectively. In the medium term wet storage facility, the spent fuel elements are first cropped, to remove the non-fuel aluminium waste material ends, and then the cropped fuel element is passed through a transfer port (connecting the cropping pond to the storage pond) for medium term wet storage. The storage pond has storage racks that can hold up to 394 spent fuel elements at any time. Both ponds are stainless steel lined, and have a common ion exchange treatment (purification) system, for water circulation and removal of any impurity arising from the spent fuel elements, via corrosion or environmental dust.

Water is pumped from the cropping pond, passed through filters, a fully sealed UV treatment system (for disinfection) and an ion exchange unit, before returning to the cropping pond. An overflow pipe connects the storage pond to the cropping pond. The pond water circulation system includes cartridge filters for removal of particulates and ion-exchange resin beds for removal of dissolved ions.

FIG. 3. Spent Fuel Cropping Pond.

FIG. 4. Spent Fuel Storage Pond.

Cropped spent fuel elements are transferred to the adjacent storage pond via an underwater connecting gate transfer port as highlighted in yellow arrows in Figs 3 and 4.

5. DRY STORAGE

Just as the water quality must be controlled and monitored to preserve spent fuel in wet storage, the condition of the storage atmosphere in dry storage must also be carefully controlled and monitored. The dry facility should be designed and operated so as to minimize the possibility for water (moisture) to enter the facility. From our experience at ANSTO the issue of radiolytic ionisation and chemical reactions in the moist air have been shown to produce oxides of nitrogen in the atmosphere. When dissolved in any free water these lead to weak solutions of nitric and nitrous acids which attack aluminium cladding aggressively. In the absence of water no such attack has been seen even though some oxides of nitrogen must be present in the dry atmosphere. Therefore, provision should be made to detect and remove any water that inadvertently enters the facility and to maintain the humidity of the atmosphere at very low levels. The atmosphere is usually dry air. The recommended practice is to replace the air with dry nitrogen or inert gas (Argon) which further limits the potential for radiolysis reactions.

ANSTO's Dry Storage Facility (Figs 5 and 6) is a typical vault type dry storage and was one of the earliest such storages built. It consists of fifty stainless steel tubes, each one about 16 m long and placed in holes drilled into sandstone bedrock. Two spent fuel elements are placed in transfer canisters (stainless steel) and the canisters lowered into the holes. Each storage hole takes eleven canisters for a total capacity of the store being 1100 spent fuel elements or approximately 30 years of HIFAR operations.

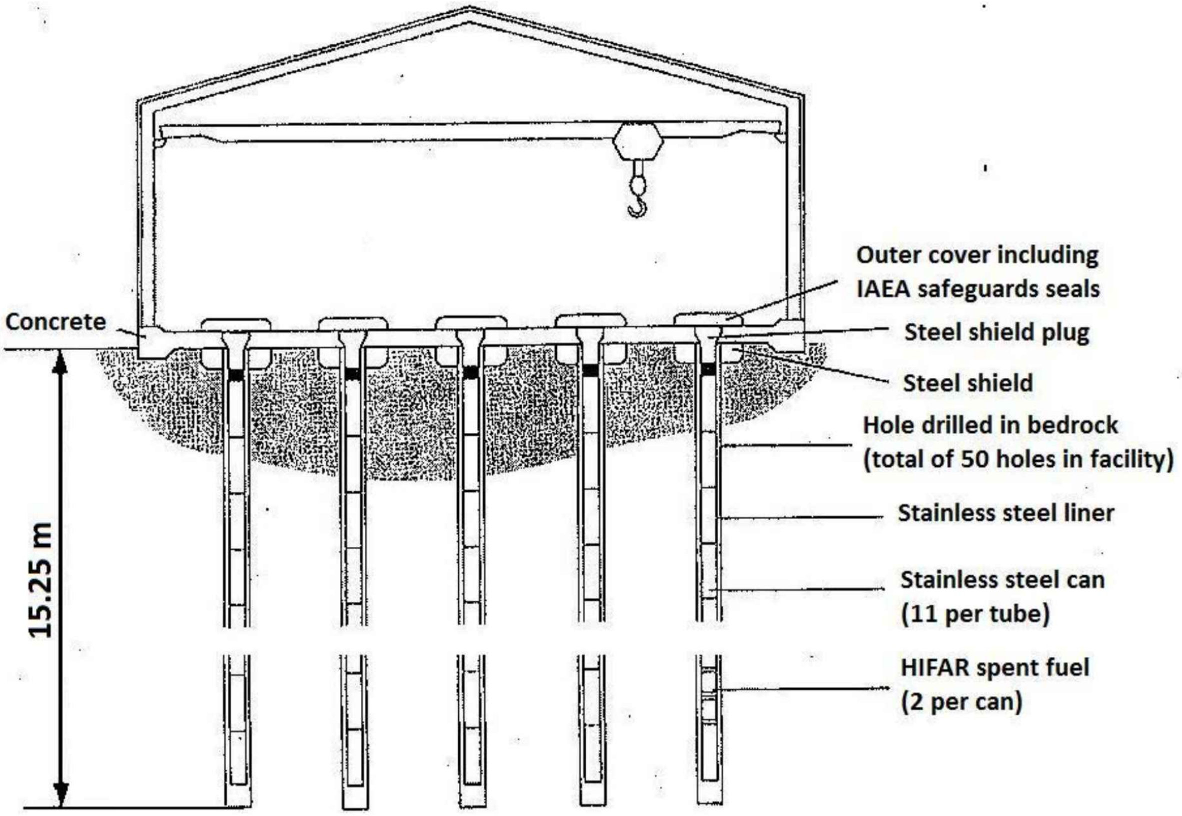

FIG. 5. Schematic of ANSTO's Dry Storage Facility.

FIG. 6. External view of ANSTO's Dry Storage Facility.

The transfer of spent fuel elements between the wet and dry storage facilities is carried out using a shielded spent fuel general purpose transfer flask, shown on the right side of Figure 7. On the left side of Fig. 7 is shown the medium term wet storage pond, used for loading spent fuel assemblies into overseas shipment casks, and for extraction of spent fuel elements using the general purpose transfer flask.

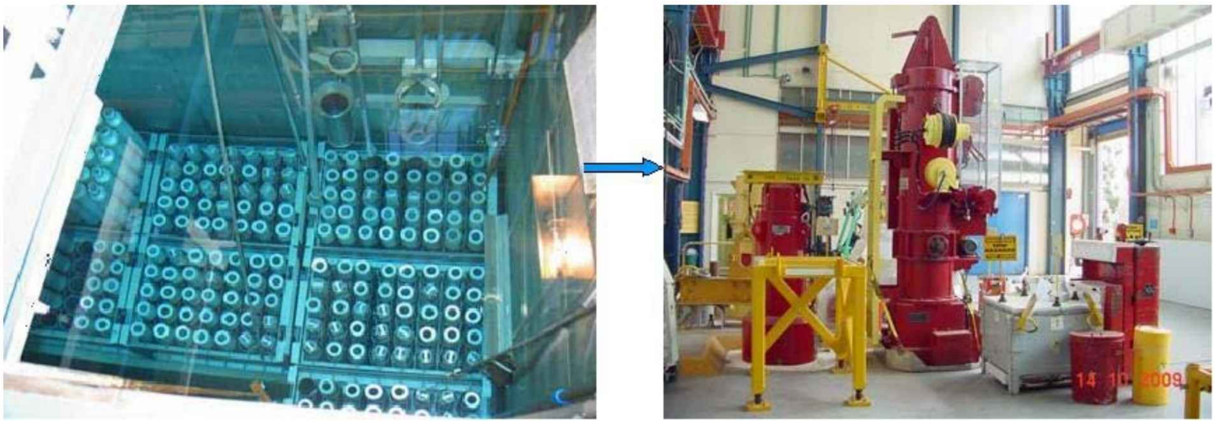

FIG. 7. Medium term wet storage pond (left), and a general purpose transfer flask (right).

6. MONITORING CONTROLS IN WET AND DRY STORAGE FACILITIES

6.1. Wet storage

For aluminium-clad research reactor fuel the predominant type of corrosion occurring is pitting corrosion which can lead to direct exposure of the fuel meat to water. In wet storage, pitting corrosion is promoted by poor water chemistry which includes too high or too low pH, high conductivity or high chlorine ion concentration which can all lead to the onset of corrosion. Other factors promoting corrosion are stagnant water which allows buildup of ions or conductivity in crevices, surface impurities on the cladding and contact with dissimilar metals (galvanic corrosion). The presence of biological films on the cladding has also been reported to increase corrosion.

To prevent the occurrence of aluminium cladding corrosion in wet storage it is recommended that the pool water be frequently (or continuously) circulated through an ion exchange column and filter. At ANSTO the chemical control is implemented through pumping the pond water through a bed of ion-exchange resin that removes virtually all the dissolved ions. Any particulate material is removed in the cartridge filters, which are located before the ion exchange resin beds. In addition to the removal of solids in suspension and ions, UV light is used to control biological activity in the water. The parameters for control of the water condition are listed below in Table III. The parameters are monitored through analysis of water samples taken at least monthly. During flask movement operations involving spent fuel, samples are measured more frequently.

TABLE III: THE DESIGNATED RANGES AND MINIMUM TESTING FREQUENCIES FOR CHEMICAL PARAMETERS IN WET STORAGE PONDS

Parameter	Normal Range	Notification Level	Minimum Frequency
pH	5 – 8	<5 – >8	Weekly
Conductivity µS/cm	1 – 10	> 20	Weekly
Gross α activity, Bq/mL	<0.02	>0.02	Weekly
Gross β activity, Bq/mL	<0.50	>1.0	Weekly

Where activities outside the normal range are measured, follow up γ spec measurements are initiated. If fission products are suspected a determination of ^{137}Cs leaking rate should be the most sensitive indicator [3]. Where the conductivity or activity (α, β) is above the normal operating range, the ion exchange column may need replacing. In this instance, samples from the Ion Exchange Column return are analysed to determine the effectiveness of the resin bed.

It is common that no firm limit is imposed on the radioactive content of the pond water but rather an “action level” is established which, if reached, requires an investigation and corrective action to be taken. This action level is generally well below any level that would represent a direct radiation hazard to operating personnel. The action level is established at a value that ensures a good measure of integrity of the fuel and the proper operation of the pond water cleanup system. For example, at ANSTO for the fuel storage and loading cask ponds the normal operating levels of radioactivity are in the range of 50 Bq/L to several hundreds of Bq/L depending on the frequency of spent fuel movements in the ponds. The action level is established at 1000 Bq/L. These are very low levels compared with some other spent fuel ponds overseas. For example, in the Receiving Basin for Off-site Fuels (RBOF) of Savannah River Site, the normal steady-state basin activity level is about 4,000 Bq/L [3], and the normal operating levels in the power reactor fuel storage ponds at La Hague, France and the CLAB Facility, Sweden are 12 000 Bq/L and 10 000 Bq/L respectively [4] Ongoing monitoring of the wet storage ponds is routinely carried out at ANSTO. Figures 8 and 9 provide the results over the past 14 years. The spikes in alpha and beta activity during 2002 resulted in the breach of the fuel meat of one spent fuel element during routine cropping operations, when the spent fuel element has its metal waste ends cut off with in-pool circular saws. The investigation of the event led to the root cause being the non-placement of an end stopper on the cropping saw mechanism. This led to non-alignment of the cropping saw blades resulting in the saws partially cutting though the fuel meat and releasing fission product (swarf) into the pond water.

Figure 10 shows the setup of the cropping pond saw cutting equipment with the missing spacer.

6.2 Dry storage

The aim of monitoring the spent fuel in dry storage is to detect for moisture and humidity probes. A well sealed, dry storage compartment should maintain relative humidity below 20% and humidity above 50% is an indication of a poor seal. Where dry nitrogen or inert gas is used as the normal storage atmosphere (as at ANSTO) the two possibilities can be distinguished by means of a concurrent oxygen probe measurement. High humidity and oxygen suggest air leakage into the storage. High humidity and oxygen (<5%) suggest the seals are working but water has been inadvertently introduced into the storage.

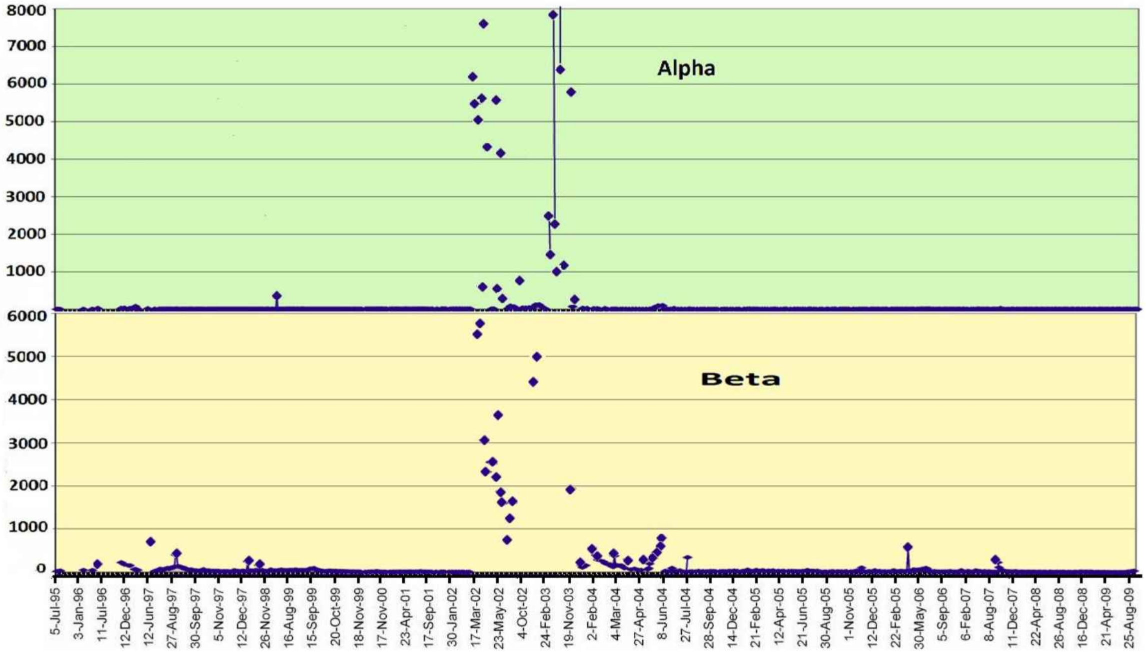

FIG. 8. Alpha and Beta levels (KBq/m3) for B23 cropping pond.

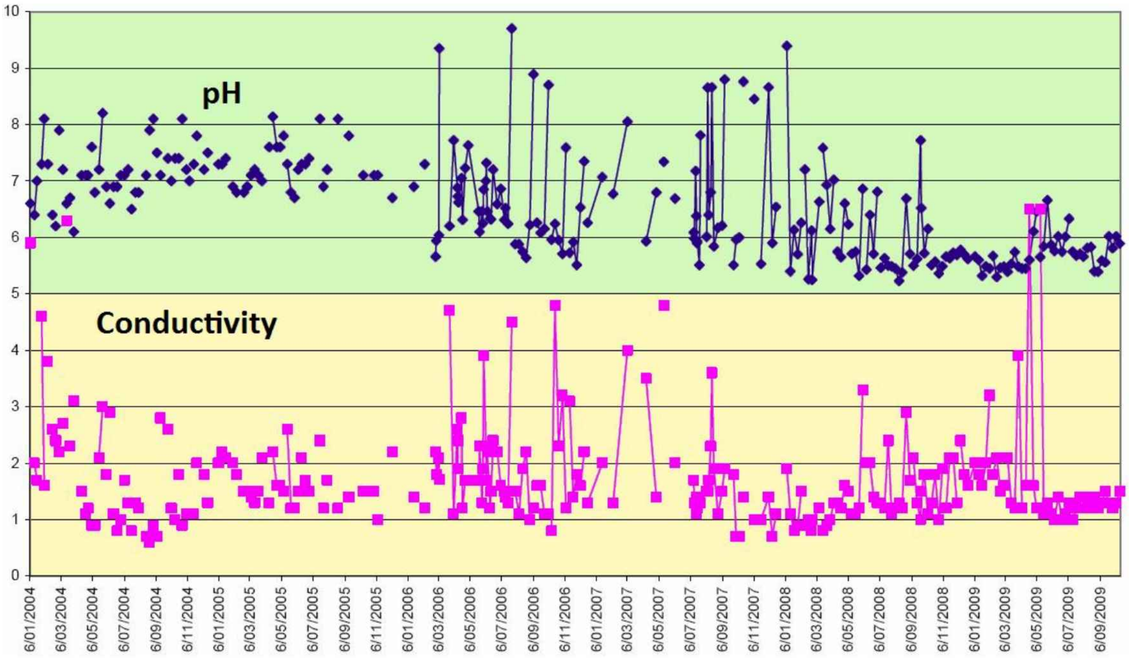

FIG. 9. pH and conductivity levels for B23 cropping pond.

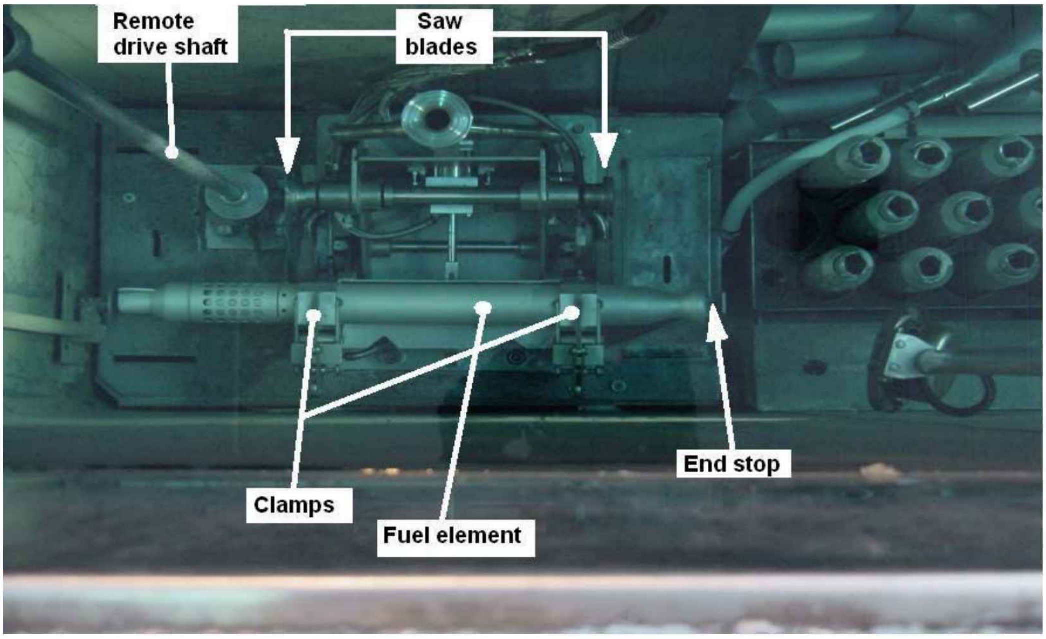

FIG. 10. Cropping pond saw with end stop spacer missing.

Radioactivity checks can be made by measuring the beta-emitting gaseous fission product krypton-85. Experience at ANSTO shows that the detection limit for this test is around 0.15 MBq/m^3. However krypton-85 is not considered a sensitive early warning sign of the onset of a corrosion problem in research reactor fuel dry storage. It can be considered more useful as a backup measure in the sense that a negative result gives confidence that no major problem has already developed in storage. The more reliable measure is provided by the combination of humidity measurements and a regular programme of using randomly selected fuel elements for visual inspection. Figure 11 shows the dry nitrogen purging and a filling unit used on the dry storage facility at ANSTO.

FIG. 11. Dry nitrogen purging of dry storage holes.

6.3 Hot cell inspection of spent fuel

As indicated in Section 6.2 a more reliable measure of spent fuel integrity testing is provided by a regular programme of using randomly selected fuel elements for visual inspection. At ANSTO random inspection of spent fuel from wet and dry is carried out in dedicated hot cells.

The hot cells have been extensively used to carry out physical non-destructive testing of ANSTO's spent fuel inventory over the past 50 years. As mentioned earlier, of the 2281 spent fuel elements produced during the operation of the HIFAR reactor only 19 elements were considered as being affected by some degree of corrosion during the storage period. These "compromised "spent fuel elements were assessed in the hot cells, as illustrated in Fig. 12.

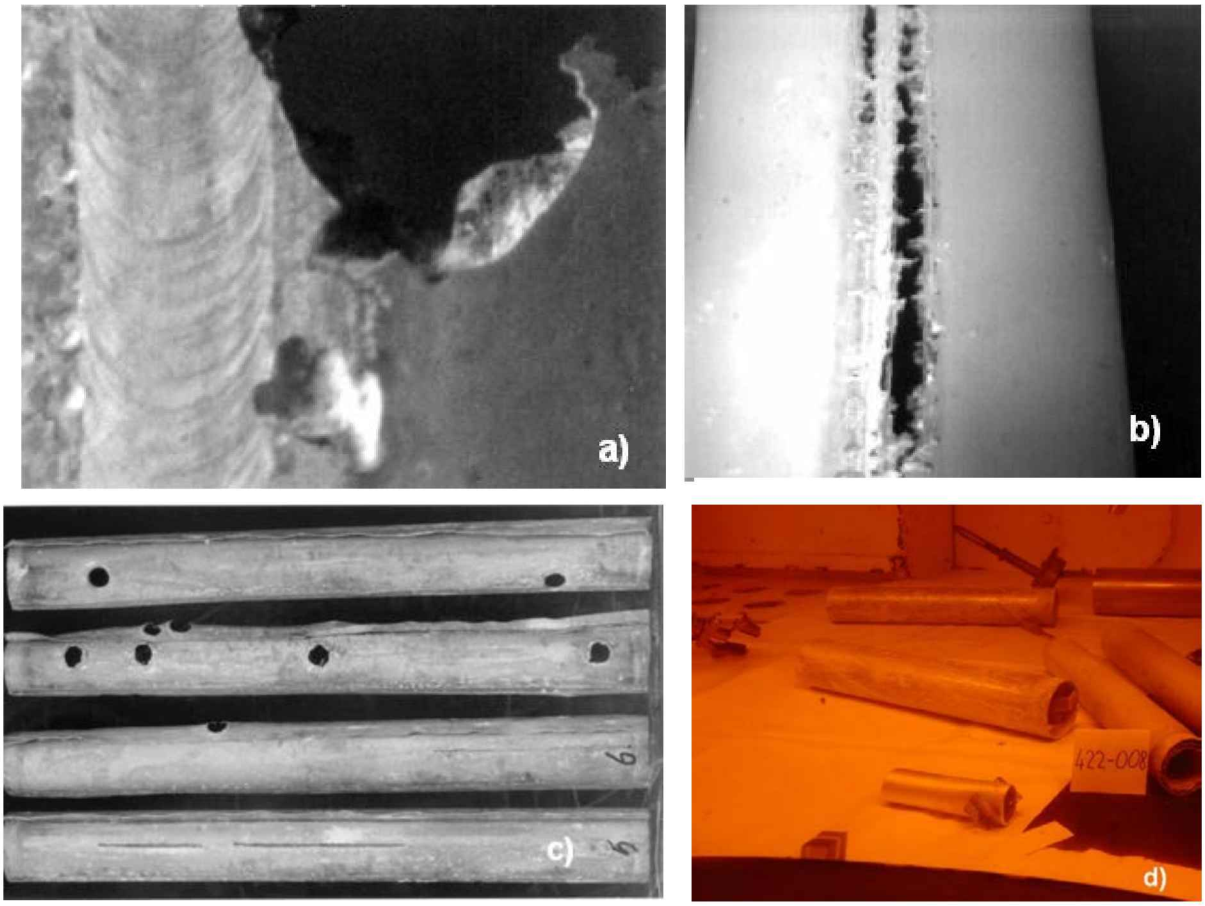

FIG. 12. (a) The corner of the fuel meat has been exposed at the top of a plate from assembly; (b) Extensive pitting corrosion in the non-fuel section, resulting in compromised structural integrity; (c) Punched plates (not corrosion but holes physically made to sample the fuel meat; (d) Spent fuel undergoing inspection in hot cell.

7. SPENT FUEL SHIPMENTS

In April 2009 ANSTO shipped its 9th and final spent fuel shipment to the USA (Table IV). The final shipment resulted in all of the spent fuel produced from the operation of the HIFAR and MOATA research reactors to being shipped overseas for reprocessing or as part of the Foreign Research Reactor (FRR) Spent Nuclear Fuel (SNF) Acceptance Programme. As mentioned earlier the successful shipment of the spent fuel (2281 spent fuel elements) can be attributed to the effective storage and monitoring programme at ANSTO over the past 50 years.

TABLE IV. ANSTO SPENT FUEL SHIPMENTS

Year	Quantity	Destination
1963	150	Dounreay (UK)
1996	114	Dounreay (UK)
1998	240	Savannah River (USA)
1999	308	Cogema (France)
2001	360	Cogema (France)
2003	344	Cogema (France)
2004	276	Cogema (France)
2006	330	Savannah River (USA)
2009	159	Savannah River (USA)
Total of Spent Fuel Elements shipped	2281	

For the loading operation, a cask loading/buffer storage pond, shown in Fig. 13, and previously in the left side of Fig. 7, was used.

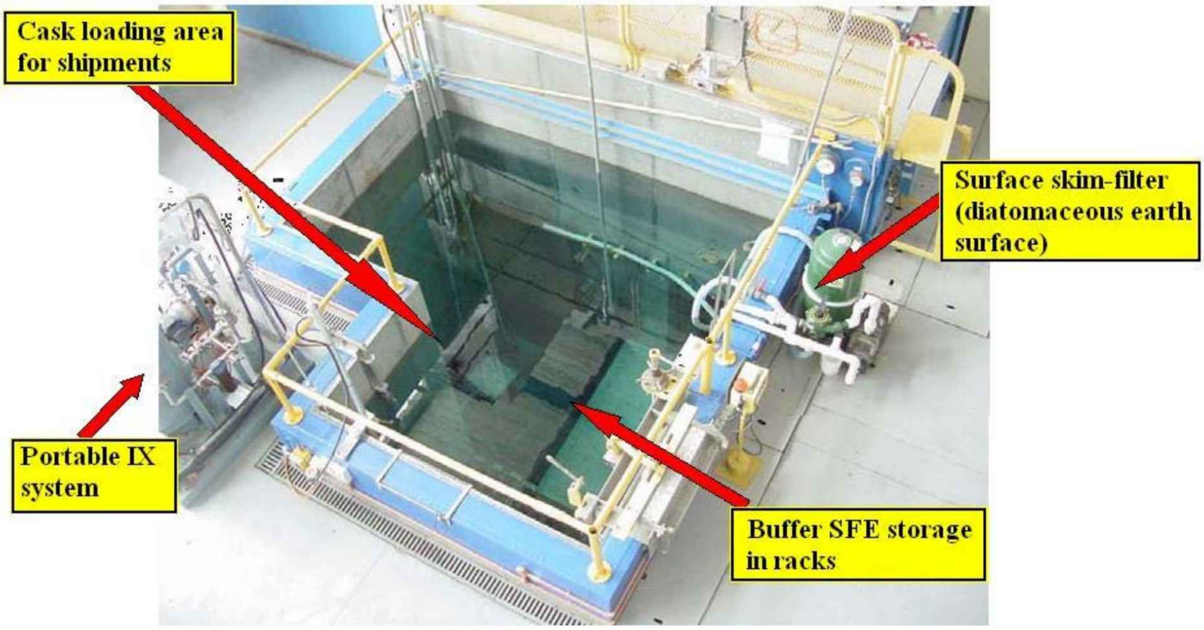

FIG. 13 Cask Loading/ Storage pond.

Figures 14 to 16 provide practical evidence of the preparation for the spent fuel shipments using both wet and dry cask loading systems.

FIG. 14. (a) Preparation for spent fuel shipment: wet loading; (b) drying; (c) inspection; (d) cask loaded and ready for shipment.

FIG. 15. (a) Preparation of spent fuel shipment using dry loading cask (basket in pond; (b) shielded sleeve; (c), basket removal system; (d) dry loading cask being set up for loading.

FIG. 16. Spent fuel shipment ready for transport to dock.

8. ILW RETURN FROM REPROCESSING

The Australian Government, through ANSTO, has contractual agreements in place for the reprocessing of research reactor spent fuel in the United Kingdom and France and the subsequent return of reprocessing residues in flasks as shown in Fig. 17. At the time of entering into these contracts, it was assumed that the Australian Government would have a licensed intermediate level waste (ILW) storage facility in operation before the scheduled return of the ILW reprocessed wastes.

The current lack of a licensed ILW storage facility in Australia and the absence of firm plans to site and license a facility prior to the scheduled return of the ILW residues are of major concern to ANSTO.

Under the contractual agreements, ANSTO must provide details for the repatriation of residues by the end of 2010. These details necessarily include the return destination in Australia — a facility that is appropriately designed and licensed for operation.

The complexity of the return logistics and the lengthy national and international regulatory approval process requires that detailed planning and cost estimation be carried out in the near future. In order to progress that planning, it is necessary for ANSTO to have a suitable backup option for the receipt of ILW residues. The only backup option that is compatible with the tight time schedule is to construct and licence an interim ILW storage facility at ANSTO. This interim storage facility would operate only until such time that the national ILW storage facility is constructed and licensed for reception and storage of these wastes.

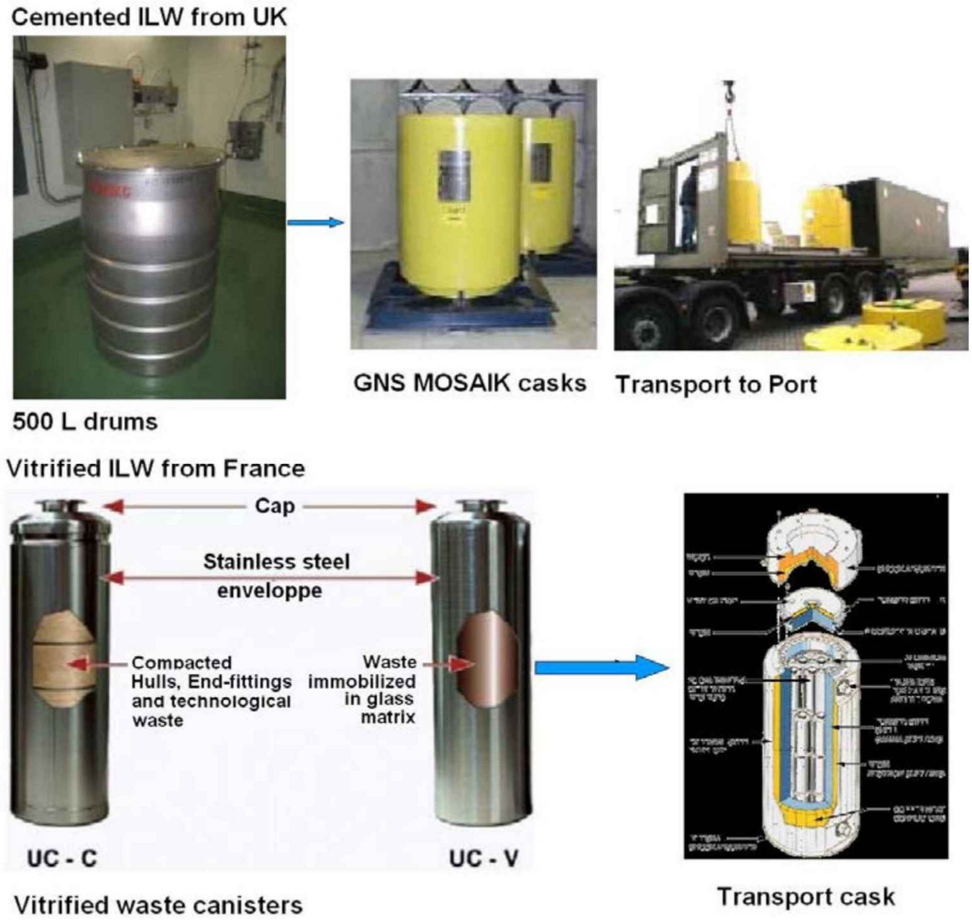

FIG. 17. Reprocessed ILW packages and transport casks for cemented ILW from Dounreay (top) and vitrified ILW canisters from France.

9. OPAL SPENT FUEL MANAGEMENT

OPAL, the new Australian research reactor, is a 20 MW open pool, heavy water reflected and light water cooled reactor, which started operation in August 2007. OPAL generates a nominal 36 spent fuel elements per year and operates typically in cycles of 30–35 days, followed by a short refuelling outage to remove two or three spent fuel elements, that are replaced with new fuel elements. Figure 18 shows the OPAL Reactor Service Pool (front) and the reflector vessel (core) in the background.

The service pool has a nominal storage capacity for 10 years of OPAL operation (up to 360 spent fuel elements), and under the current OPAL operating license, the storage of spent fuel is restricted to the OPAL Service Pool (wet storage). ANSTO's current plan is to send two shipments of OPAL spent fuel to the USA, as part of the Foreign Research Reactor Spent Nuclear Fuel Acceptance Programme. The programme is scheduled to accept fuel discharged from eligible reactors before May 2016, to be received in the USA by May 2019. After the expiration of the programme, ANSTO will send its used research reactor spent fuel overseas for reprocessing, with ultimate return of reprocessing wastes to Australia.

FIG. 18. OPAL reactor service pool (rectangular pond) showing the storage racks for spent fuel.

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