The Thermal Oxide Reprocessing Plant at Sellafield – Lessons Learned from 10 Years of Hot Operations and their Applicability to the DOE Environmental Management Program

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ABSTRACT

The Thermal Oxide Reprocessing Plant (Thorp) at Sellafield in northwest England is a $4 billion integrated plant that takes irradiated fuel from worldwide Light Water Reactors and UK Gas-Cooled Reactors and separates the uranium and plutonium from the fission products so that the latter can be vitrified and safely stored. The uranium and plutonium are further separated so that the uranium can be recycled as new reactor fuel, either by itself or in combination with the plutonium as Mixed Oxide (MOX) fuel. Thorp concentrates in excess of 99% of the radioactivity in the irradiated fuel into the vitrified waste product and produces a 40-fold reduction in high active waste volume to be stored, in comparison with direct disposal of the fuel.

Thorp incorporates a range of design and operational principles developed over the 50 year history of the Sellafield site. These include the extensive use of no-moving part, no-maintenance equipment in contact with radioactive material, located in shielded "dark cells" where entry is not expected through the life of the plant. These cells are nevertheless provided with comprehensive secondary containment, instruments, washdown and recovery systems, and access for cameras and potentially also for remote repair equipment.

These arrangements were found to be required during an unusual incident identified in early 2005 when approximately 83 m^3 of highly active liquid escaped from primary tank containment into the secondary containment formed by the dark cell and its stainless steel liner. Although a serious incident, the secondary containment and the in-cell design provisions worked exactly as designed and the liquid was recovered by mid 2005 with no releases to the environment and no member of the workforce or public affected. The ability to access and clean dark cells means that repairs are possible and the large capital asset is thus protected. The enquiry that followed this incident identified issues with carry-through of late design changes into operations and with the training and mindset of the operators, the latter leading to a later than ideal identification of the loss of primary containment.

This paper describes Thorp, its design and operational principles, its performance over the last 10 years and provides details of the loss of containment incident. It draws lessons from this incident and looks at how these could be applied to assist the current DOE Environmental Management (EM) program and its large waste treatment plants at Hanford and Savannah River.

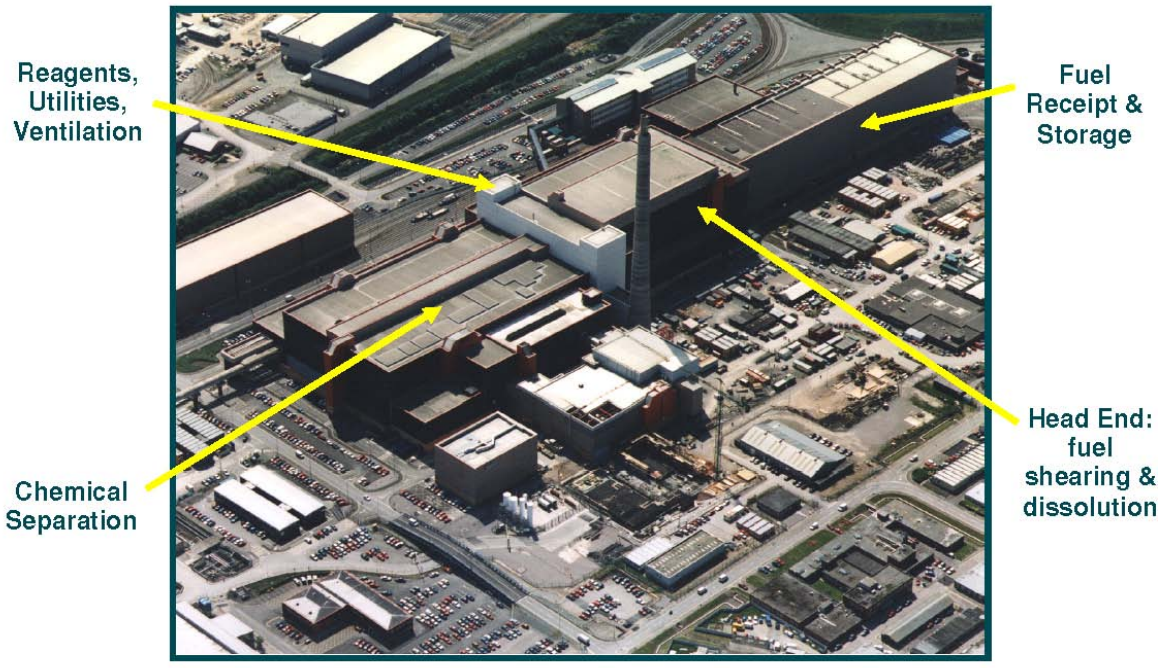
INTRODUCTION

British Nuclear Fuels plc (BNFL), British Nuclear Group and associated companies have provided uranium purification and enrichment, new nuclear fuel production, nuclear materials transport, irradiated

nuclear fuel recycling and nuclear waste management services to the United Kingdom nuclear industry for more than 50 years. These services have been progressively extended over the last 30 years to cover European and Japanese Light Water Reactors. The companies have bases in the UK at Chester (enrichment), Preston (fuel manufacture), Daresbury (Head Office), Warrington (design and transport), and at Sellafield in Cumbria (irradiated nuclear fuel recycling and waste management). Sellafield is the major UK nuclear site and it has two working spent nuclear fuel recycling plants, a Mixed Oxide Fuel (MOX) fabrication plant, fuel storage basins, three HL waste vitrification plants, three intermediate level waste cement grout encapsulation plants, a floc-based transuranic (TRU) removal plant, an ion exchange cesium removal plant and a wide range of legacy defense-related plants and nuclear reactors under decommissioning.

During the 1980's and 1990's, BNFL used the recycling and waste management expertise obtained from its Magnox uranium metal reprocessing plant to develop and build the Thermal Oxide Reprocessing Plant (Thorp)(Figure 1). Thorp recycles uranium oxide fuel from Light Water Reactors in Europe and Japan and from the UK Advanced Gas-Cooled Reactors. The facility has a $20 billion order book to recycle some 7000 tonne of irradiated fuel from Japanese, European and UK based nuclear power utilities, and has a maximum capacity of 5 tonne of fuel per day. It commenced hot operation in 1994 and has so far recycled over 5700 tonne of irradiated fuel. Recycling of irradiated nuclear fuel reduces significantly the volume of waste that needs to be encapsulated and stored, in comparison with the volume of the irradiated fuel elements. It also allows the approximately 95% of the weight of the irradiated fuel that is unused uranium to be re-used as new fuel. The improved "salt-free" chemical flowsheet used by Thorp also enables both high active and medium active liquid waste streams to be directed to the high active (HA) vitrification plants, thus concentrating almost all the waste radioactivity into the vitrified product.

In association with Thorp, a range of waste treatment and clean-up plants have been developed, designed and built on the Sellafield site. These reduce discharges to the environment of radioactive materials and allow for safe long-term storage of radioactive waste. Thorp and the other new plants on the Sellafield site together form a safe and environmentally satisfactory means of treating and dispositioning irradiated nuclear reactor fuel.



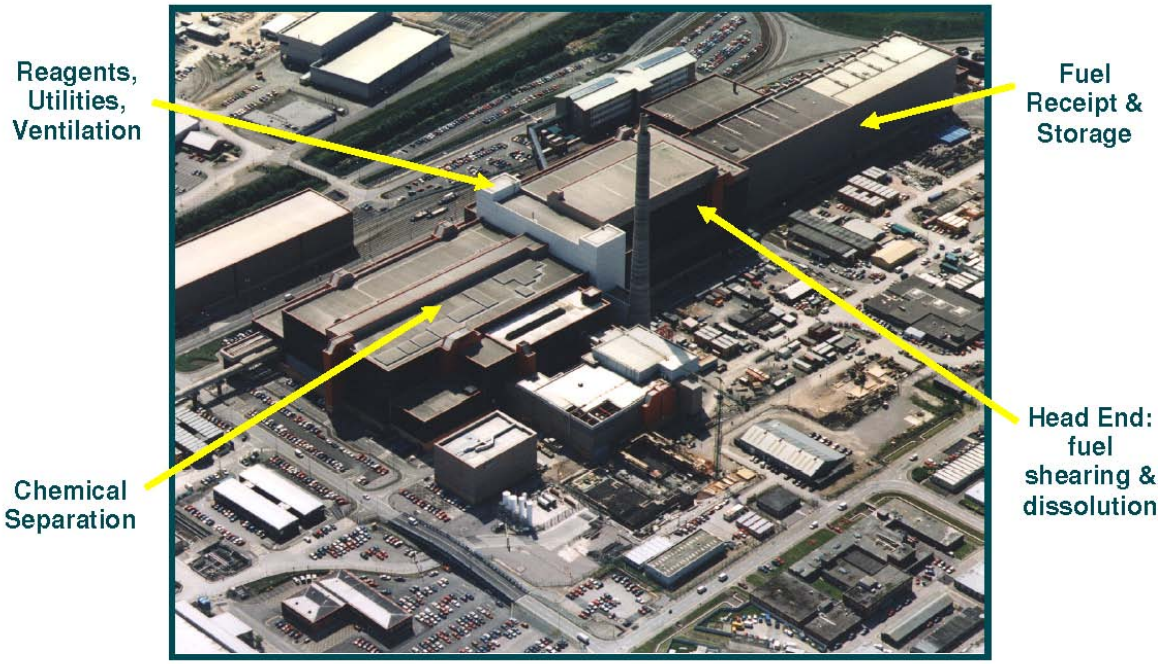


Fig. 1. The Thermal Oxide Reprocessing Plant at Sellafield

Recently, Thorp has experienced a problem with the fracture of a pipeline within the radioactively shielded parts of the plant. No radioactive material was lost from the plant secondary containment and all has been safely recovered into primary containment. Nevertheless, Thorp will be shut down for a period while the lessons learned from this incident are assimilated and the plant is remotely repaired. This paper describes the Thorp processes and the principles on which the plant was designed. It examines the operating experience with Thorp and looks at how this experience can be applied to waste cleanup plants being constructed under the US Department of Energy (USDOE) Environmental Management (EM) program.

NOMENCLATURE

BNFL	British Nuclear Fuels plc, parent company of British Nuclear Group
BNG America	British Nuclear Group's US-based subsidiary
DF	Decontamination Factor
DCS	Distributed Control System (computer plant monitoring & control)
USDOE	United States Department of Energy
EM	USDOE Environmental Management program
HA	High Active (high radioactivity)
IAEA	International Atomic Energy Agency
LA	Low Active (radioactivity)
MA	Medium Active (radioactivity)
Magnox	Magnesium-aluminum alloy used for uranium metal fuel cans
MBA	Material Balance Area (for nuclear materials accountancy)
MOX	Mixed Oxide Plant (uranium/plutonium fuel)
MWD	MegaWatt-days
NDA	(UK) Nuclear Decommissioning Authority
te	tonne: metric ton (1000kg)
PIT	Physical Inventory Take (for nuclear materials accountancy)
PJM	Pulse Jet Mixer, an air operated fluidic tank agitation system

PP	Plutonium Purification
PUREX	Plutonium-Uranium Extraction
SRD	Shipper-Receiver Difference (accountancy measurement)
Thorp	Thermal Oxide Reprocessing Plant
TRU	Transuranic elements
USDOE	U.S. Department of Energy
UP	Uranium Purification
WTP	Waste Treatment Plant (at Hanford)

THORP OVERVIEW

The Thermal Oxide Reprocessing Plant at the Sellafield, U.K. nuclear site is a $4 billion integrated plant with all stages of reprocessing and conversion of the uranium and plutonium products to oxide powder under one roof (Figure 2). The plant is designed to process 5 tonne per day of fuel irradiated up to 40,000MWD/tonne and a minimum 5 years out-of-reactor cooling time. The fuel irradiation capability is being progressively extended as operating experience is gained, so that now fuel irradiations up to 48,000 MWD/tonne can be handled.

Development testing and design for Thorp started in the late 1970s and the start of construction followed in 1985. Construction was completed to schedule and budget in 1992 [1]. Commissioning of the plant started in late 1991 and the first radioactive fuel was sheared and dissolved in early 1994 [2]. Radioactive operation of the chemical separation processes followed in early 1995 and the plant was granted its full routine operating license by the UK Nuclear Installations Inspectorate in mid 1997.

Receipt and Storage

Thorp Receipt and Storage receives irradiated fuel from the customer, removes it from its shielded transport flasks under water in the Receipt "Pond" or Basin, and places fuel element assemblies into temporary storage containers. Thorp operates under full civil nuclear materials accountancy and safeguards controls, and at this point the fuel element uranium and plutonium content is calculated from reactor irradiation records to provide an input "book" value.

Head End

In the Head End, the fuel element assemblies are sheared into 2 inch (5cm) lengths via a vertically operating shear blade, to cut through the zircaloy or stainless steel cladding of the individual fuel elements and expose the uranium oxide powder and fission products. The cut pieces fall by gravity into perforated-walled baskets within one of three dissolvers, and nitric acid is used to dissolve the uranium, plutonium and fission products. The dissolver off-gases are treated with a range of scrubbers to remove radioactive and chemical contaminants before they are released to the stack. When dissolution is complete, the zircaloy or stainless steel cladding "hulls" are removed in the basket for washing and cement grout encapsulation. The dissolver solution is sent to one of two centrifuges to remove remaining small particle size undissolved fuel and cladding components. These solids are periodically washed from the centrifuge walls and sent to cement grout encapsulation.

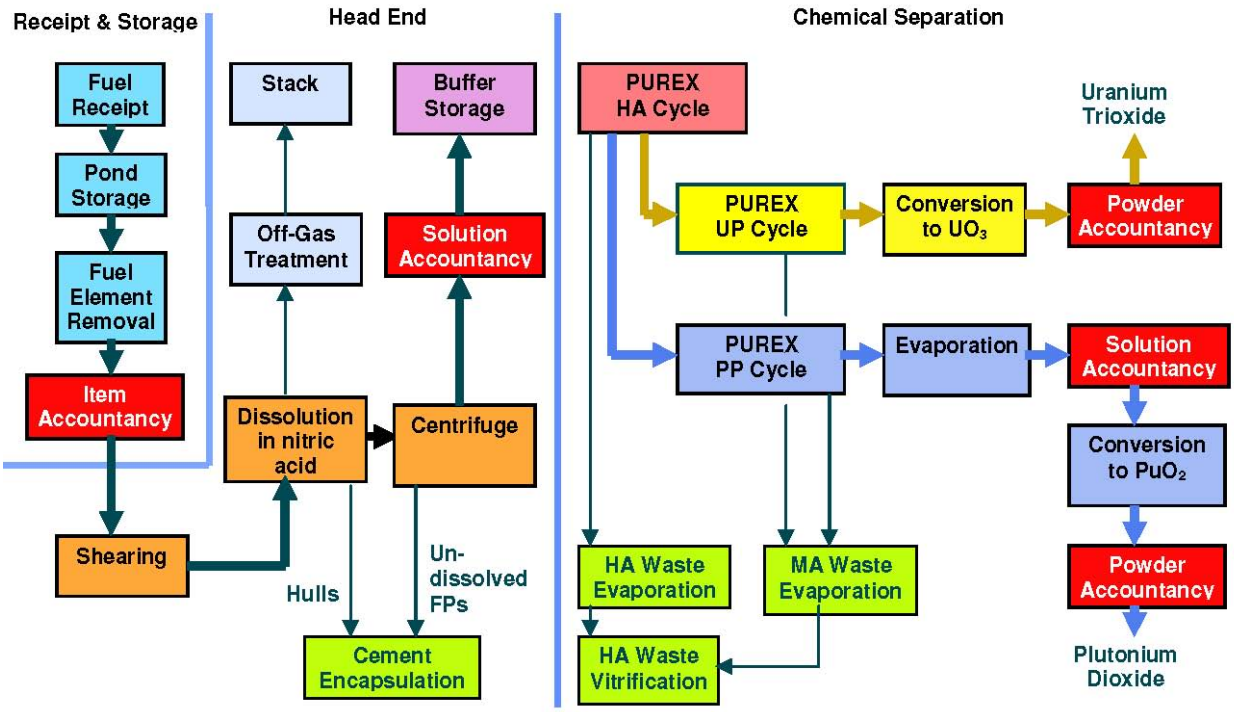


Fig. 2. Overview of Thorp processes

The clarified dissolver solution moves to one of two Accountancy Tanks, where the solution is homogenized, sampled and weighed so that its uranium and plutonium content can be accurately measured. This is the first "solution accountancy" step, and the uranium and plutonium amounts measured here form the basis of the civil nuclear materials accountancy through the rest of Thorp. To provide the necessary accuracy for these measurements, it was found necessary to weigh the entire tanks to provide, in conjunction with the sampled density, a sufficiently accurate total volume measurement. This is achieved by suspending the tanks on load cells located outside the radiation shielding.

Chemical Separation

Chemical Separation is decoupled from Head End by a series of buffer tanks and, from these, the dissolver solution is fed to the Highly Active (HA) separation cycle. This is a modified PUREX solvent extraction process, using tri-butyl phosphate in kerosene as the solvent. Almost all the fission products are removed from the uranium and plutonium in the high active (HA) cycle waste from the first solvent extraction contactor and are sent to evaporation and vitrification. Because stainless steel equipment is used throughout, there is no need to neutralize this waste with sodium hydroxide and so there is no excess sodium to remove prior to vitrification. The uranium and plutonium are separated in the second part of the HA cycle by chemically reducing the plutonium from the 4-valent to the 3-valent oxidation state, using 4-valent uranyl nitrate solution as the reducing reagent. This reagent is "salt-free"; unlike other reducing agents that have been used in PUREX it does not add any "foreign" cations or anions to the process that would restrict or complicate the subsequent waste treatments.

Final purification of the uranium and plutonium streams is achieved in single purification separation cycles (UP and PP) by careful control of the chemistry and the oxidation states of the contaminants neptunium and ruthenium, again using salt-free reagents [3]. This is in contrast to "traditional" PUREX flowsheets that require two separation cycles each to achieve the required uranium and plutonium product purities. Thus not only are these medium active (MA) wastes from the purification cycles minimized, but also because they are salt-free, they can be routed to HA waste evaporation and

vitrification along with the HA cycle waste.

The purified plutonium nitrate and uranyl nitrate solutions are converted to oxide powders by oxalate precipitation and thermal denitration processes respectively, go through further accountancy stages and are then dispatched for storage or the manufacture of new mixed oxide fuel at an adjacent facility.

THORP DESIGN AND OPERATIONAL PRINCIPLES

Thorp was designed, commissioned and operated by BNFL plc during the period when it was owneroperator of the Sellafield Site. Since April 2005, the plant's ownership has transferred to the UK Nuclear Decommissioning Authority (NDA), and British Nuclear Group (formed from BNFL) has the contract to operate the Sellafield site, including Thorp. As with all nuclear plants, the priority driver for the design and operation of Thorp was to ensure the safety and protection of the workforce, public and the environment. In addition the owner-operator approach placed significant emphasis on two other major drivers for the plant design and operation:

- Minimization of lifetime costs for the plant mission, and hence maximization of profitability
- Protection of the financial investment in the plant.

These three drivers led BNFL to adopt the following design and operating principles for Thorp:

Equipment Design Principles

The general design principles for Thorp were developed from the 50 years of experience that BNFL and its associated companies have had with designing, building and operating nuclear plants at the Sellafield site. They are summarized in Table I and, with their emphasis on no-maintenance equipment and shielded no-entry "dark cells", it can be seen that they differ in some respects from the design principles that have evolved at the US nuclear sites. All Sellafield radioactive plants have been designed using these principles, and experience of operating the plants over the last 50 years has been excellent. Only limited intervention for repair of equipment has been necessary, and the pulse jet mixers, air lifts, fluidic pumps, steam ejectors and air bubblers ("pneumercators" for level and density measurement) in particular have stood out as totally maintenance-free devices.

Where intervention has been required to deal with moving mechanical equipment, this has normally been achieved remotely using the access hatches provided in the dark cells to introduce lighting, cameras, remote manipulators and remote repair equipment. On the few occasions where personnel entry to certain cells has proved essential, this has been facilitated by the lack of radioactive contamination in the cell itself. It is usually only necessary to wash out the in-cell tanks and pipes thoroughly to reduce radiation levels to acceptable levels. This contrasts with a typical "canyon" arrangement where intentional remote removal of the connectors or "jumpers" between plant items through the life of the plant to allow equipment renewal inevitably leads to spillage of radioactive liquids and permanent contamination of the canyon floor and walls.

Table I. Thorp Design Principles

	Commentary
Process plant in contact with radioactivity is designed to need no maintenance through the life of the plant.	•Equipment with no moving parts is used. •Air lifts and fluidic pumps are used to pump liquids [3]. •Fluidic Pulse Jet Mixers (PJM) are used instead of mechanical stirrers to agitate and homogenize liquids [3]. •Compressed air devices are used for level and density measurement (air bubblers or "pneumercators"). •All-welded stainless steel piping and vessels with full radiography are used.
Radioactive shielding is designed on the expectation of no routine entry during life of plant.	•Shielded process "cells" used (referred to as "dark cells") with no routine entry points. •Cells lined throughout with stainless steel or, as a minimum, lined to the highest liquid level reached if the largest tank leaked completely.
In-cell inspection and remote repair is nevertheless provided, even in dark cells.	•Hatches are provided in the cell roof through which cameras and lights can be introduced. •Remote inspection and repair equipment that can be inserted through the ports is designed and its use practiced.
Where mechanical equipment is essential in-cell, the design allows for out-cell maintenance of moving parts.	•Motors and gearboxes mounted out-cell, with through-wall drives. •Temperature probes mounted in pockets to allow renewal from outside cell. •Specially designed valves and pumps that can be removed from in-cell housings into shielded containers
The design is based on the expectation of no equipment failures or leaks but nevertheless provides for detection and recovery.	•All cells have low point sumps with level detection and sampling facilities. •All cells have steam ejectors to allow them to be emptied. •All cells have wash-down rings, both at the sump and at the top of the stainless steel lining.
Where removal of in-cell equipment is likely to be necessary during the life of the plant, the design allows for the removal of only the moving parts.	•In-cell equipment such as cross-flow filter elements are designed to be retrievable from their in-cell housings through a "gamma-gate" on the cell roof into a shielded flask that is removed to a maintenance facility. •This system is more flexible than the traditional crane and canyon approach.

Process Design Principles and Targets

- Thorp is built on an existing nuclear site alongside the Magnox Reprocessing Plant. A major design target for Thorp was that it should contribute no more than 10% of the Site Limit for activity in discharged liquid wastes from the Sellafield site. In practice this target has been readily achieved, with total alpha activity discharges at 0.1 to 0.7%, and beta at 0.23 to 0.33% of the Site Limit.
- Fuel shearing and leaching is used rather than chemical dissolution of the fuel can and contents. This significantly reduces the volume of liquid waste produced and simplifies HA vitrification processes.
- Batch rather than continuous dissolution is adopted to allow full nuclear material accountancy of each batch before it is fed to Chemical Separation. Each batch of fuel "hulls" is also monitored for undissolved fuel before sending it to cement grout encapsulation.
- Feed clarification by centrifuge is employed because of the significant amount of undissolvable fission products in high irradiation oxide fuel.
- "Salt-free" chemical reagents are used that do not restrict the ability to concentrate and vitrify the waste streams. This reduces to a minimum the waste handling needs of the plant and the impact on the environment.
- Operator radiation dose is minimized by limiting the extent, size and complexity of process equipment in contact with radioactive material and by the use of dark cells and maintenance-free

equipment wherever possible. The modified PUREX flowsheet helps achieve the former by requiring only three cycles of solvent extraction rather than the traditional four or five. The use of fluidic pumps and agitators allows a significant amount of mechanical equipment to be eliminated.

Operational Principles

Thorp is designed to be operated without routine observation of the interior of the dark cells and with no routine operator presence local to the cells. Instead the plant is controlled and monitored by a range of instruments, a series of alarms and a Distributed Control System (DCS) that allows the operator to observe and operate all in-cell and out-cell equipment remotely via a series of interactive computer screens depicting the plant. All alarms are indicated on the DCS screens, safety critical alarms are duplicated by hardwired systems connected to traditional annunciators.

- Liquid flows are generally measured from the air or steam flow supplied to, or frequency of cycling of, the fluidic devices [3]. This avoids the need for flowmeters that would require maintenance. Where mechanical "paddle wheel" pumps are used, the speed of rotation of the through-wall drive is used to measure flow.
- Liquid levels and densities are monitored by air bubblers (pneumercators), and the DCS tracks rising and falling levels in dispatching and receiving tanks. The only maintenance that these devices require is periodic re-calibration of the out-cell pressure transducer and air supply system, plus measures, such a humidifying the air, that reduce the possibility of blockage of the pneumercator pipe within the cell.
- Liquid transfer routes are set up via "diverters" rather than conventional valves. A diverter is essentially a small, vented, header tank with several compartments leading to different outlets. A "spout" for the incoming feed liquid can be rotated via a through-wall drive and stepper motor to direct the incoming liquid to the desired compartment. Proximity switches on the stepper motor provide feedback to the DCS to show how the spout is positioned.
- Sampling and sentencing for process control is used at hold points in the process before the contents of a tank can be pumped to the next stage. An autosampling system [4] and pneumatic tube sample transfer to the Analytical Laboratory is used to aid in rapid analysis turn-round time and to avoid manual handling of radioactive samples.
- Although there is no expectation of leaks into dark cells, the sumps are maintained "wet" with a few liters of acid, so that a positive readout from the sump pneumercators is continuously present. Any change in this reading is a cause for operator investigation.
- Dark cell sump contents are routinely sampled and analyzed, with any unusual results triggering further investigation.

Nuclear Material Accountancy Principles

Thorp is licensed as a civil nuclear plant and it is designed and operated to meet all the accountancy, inspection and instrumentation requirements of the International Atomic Energy Agency (IAEA) and its European Union equivalent, Euratom. These agencies have a continuous presence on Thorp and have their own independent instruments, sampling and analysis arrangements for measuring nuclear material.

Each main part of Thorp is designated a "Material Balance Area" (MBA), and the quantity of all nuclear material entering or leaving an MBA is recorded so as to provide a continuous "book" record of the nuclear material content of Thorp at any time. Typical MBAs are Receipt and Storage, Head End, Chemical Separation, Plutonium Dioxide production, Uranium Trioxide production. Periodically, Thorp is shut down and the nuclear material within each MBA is physically measured so it can be compared with the book value. The two figures must match within an uncertainty band derived from the summation of the accuracies of the individual measurements. Such "Physical Inventory Takes" (PITs) are carried out at least every six months and typically after every fuel reprocessing campaign for a particular customer.

PERFORMANCE OF THORP

Thorp performance has been excellent over its 10 years of operation, with uranium and plutonium product qualities well within the specifications. The plant has operated at throughputs ranging from 3 to 5 tonne uranium per day and the chemical separation plant in particular has been consistently chemically and hydraulically stable. With the exception noted later in this paper, the Head End plant has operated reliably to shear, dissolve, clarify and condition the irradiated fuel for chemical separation. During the ten years of operation there has been no loss of radioactivity from the plant, nor has there been any permanent contamination spread to any out-cell area. Thorp process worker radiation doses are comparable with those of the office staff on the Sellafield site. For a plant that has processed over 6.15 E10 GBq (1.66 billion Ci) of radioactivity over its 10 years of operation, this is a significant achievement.

Purification of Uranium and Plutonium from Fission Products

Tables II and III show typical overall Decontamination Factors (DFs) for fission products, neptunium, uranium and plutonium through to the uranium and plutonium products.

These tables demonstrate the excellent performance of the solvent extraction plant. Fission product DFs in the HA cycle have been consistently better than the flowsheet expectation. Across the whole plant to the UO3 and PuO2 products, the achieved DFs for fission products and other radioactive contaminants have also been higher than design prediction, resulting in products well within International (ASTM) Specifications for new fuel manufacture. Uranium and plutonium losses to Thorp waste streams typically amount to no more than 0.19% and 0.22% respectively, so that Thorp is shown to be an efficient recycling process for these valuable sources of energy.

The overall neptunium DF for the UO3 product is seen to be higher than the already large flowsheet expectation. This shows the effectiveness of the specially developed single cycle flowsheet [5] for the simultaneous removal of neptunium and plutonium in the UP Cycle.

Table II. Comparison of Observed Contaminant DFs with Flowsheet
(Whole Plant to UO3 Product)

Contaminant	Required Flowsheet DF	Observed DF to UO_3 Product
Tc-99	4.0 E3	8.17 E3 to 2.21 E5
Ru-106	8.7 E5	4.32 E6 to 5.91 E8
Cs-134 + Cs-137	6.5 E8	5.66 E9 to 2.36 E10
Ce-144 + Eu-144 + Eu-145	3.3 E7	9.36 E5 to 5.65 E8
Np-237	1.5 E4	3.31 E4 to 2.90 E5
Plutonium (all isotopes)	5.0 E6	8.60 E6 to 1.22 E10

DF is $\frac{\text{Amount of Contaminant in Feed per g of Uranium}}{\text{Amount of Contaminant in Product per g Uranium}}$

An apparent exception to the excellent decontamination is the Ce-144/Eu-144/Eu-145 DF to the UO_3 product. However, the content of these species in the fuel feed to the plant has been lower than the reference flowsheet because of longer than 5 year cooling of most of the fuel feed. This leads to analytical limit-of-detection restrictions for the low levels that are therefore present in the uranyl nitrate product.

Table III. Comparison of Observed Contaminant DFs with Flowsheet (Whole Plant to Plutonium Nitrate and PuO2 Products)

Contaminant	Required Flowsheet DF	Observed Average DF to Plutonium Nitrate Product	Observed DF to PuO_2 Product
All fission products	2.8 E8	-	3.37 E 8 to 7.06 E 8
Tc-99	1.0 E2	1.00 E2	-
Ru-106	3.2 E5	1.04 E6	-
Cs-134 +Cs-137	5.0 E6	1.31 E8	-
Ce-144 + Eu144 + Eu-145	3.7 E6	2.10 E7	-
Np-237	4.5 E1	6.60 E1	-
Uranium (to nitrate)	4.2 E3	4.62 E4	-
Uranium (to PuO_2)	2.1 E5	-	5.80 E 6 to 5.55 E 8

DF is $\frac{\text{Amount of Contaminant in Feed per g of Plutonium}}{\text{Amount of Contaminant in Product per g of Plutonium}}$

Separation of Uranium and Plutonium

Table IV shows typical uranium-plutonium separation performance achieved in Thorp and it can be seen that the removal of plutonium from the uranium product has been an order of magnitude higher than the design requirement. This separation step, using salt-free reagents and in the presence of significant amounts of the fission product Tc-99, is not without difficulty and was the subject of intensive R&D testwork [6,7] when the Thorp flowsheet was under development.

This degree of separation allows the uranium to be readily recycled as new fuel. The purified plutonium can be used in new MOX fuel, alternatively it can potentially be mixed back with the fission product waste stream and vitrified to permanently isolate it.

Table IV. Comparison of Observed U-Pu Separation Performance with Flowsheet

	Required Flowsheet DF	Observed DF
Removal of Pu from U product[a]	3.3 E3	1.4 E 4 to 6.5 E4
Removal of U from Pu product[b]	2.1 E3	4.5 E 3 to 8.4 E4

a:. DF is $\frac{\text{Amount of Pu in feed per g of U}}{\text{Amount of Pu in U product per g of U}}$

b: DF is $\frac{\text{Amount of U in feed per g of Pu}}{\text{Amount of U in Pu product per g of Pu}}$

Waste Streams from Thorp

Table V shows some typical volumes and radioactive contents of the High Active (HA), Medium Active (MA) and LA Active (LA) waste streams from Thorp. It can be seen that in excess of 99 % of all radioactivity in the original irradiated fuel is concentrated into the very small volume (0.064 m /tonne fuel reprocessed) of the vitrified waste product, suitable for long term safe storage either on the Sellafield site or at a national repository. In comparison with the 2.5 m^3 volume of a typical 20 element skip containing a tonne of irradiated fuel, this represents a very substantial 40-fold reduction in volume of high active waste to be stored.

All but a tiny amount of the remaining activity is contained in the cement encapsulate, which occupies less than 0.6 m^3/tonne of fuel reprocessed, is also satisfactory for long term storage and represents another volume reduction with respect to unprocessed irradiated fuel.

Table V. Volumes and Activities of Thorp Waste Streams

	Final Conditioned Volume m^3/te Fuel	Alpha Activity GBq/te Fuel	Beta-Gamma Activity GBq/te Fuel	% of Total Activity
Vitrified high/medium active liquid waste	0.0640	5.90E04	1.00E07	99.0387
Cement encapsulated Head End medium active waste	0.5122	2.18E02	9.76E04	0.9597
Cement encapsulated floc from treating low active salt-containing wastes	0.0394	3.13E00	1.63E02	1.63E-03
Discharged low level liquid waste	N/A	3.79E-02	3.51E-01	3.81E-06

The discharged low level waste activity amounts to about 3.8E-6 % of the total activity in the irradiated fuel. For the period 1997 through 2004, Table VI shows the main constituents of these activity discharges as a percentage of the Sellafield Site annual discharge limits and of the site actual annual discharges. It can be seen that, in general, the discharges form a small fraction of the site discharge limits and are well within the design target of less than 10%. An exception to this is I-129 but even with this difficult fission product, Thorp discharges are no more than 25% of the site limit.

Table VI. Liquid Effluent Discharges from Thorp Head End & Chemical Separation

Contaminant	Average Annual Discharge of Activity as Percentage of Site Limit (%SL) and Actual Site Discharge (%SD)					
	1994 -1999		2000 -2002		2003 -2004	
	%SL	%SD	%SL	%SD	%SL	%SD
Total alpha activity	0.08	0.38	0.31	1.51	0.71	2.13
Total beta activity	0.33	1.11	0.32	1.32	0.23	1.20
H-3	0.00	0.03	0.00	0.03	0.00	0.02
C-14	1.03	3.85	1.08	2.72	1.55	1.96
Co-60	7.66	83.90	7.31	85.52	3.30	70.20
Sr-90	0.05	0.11	0.10	0.22	0.27	0.79
Zr-95 + Nb-95	0.50	10.68	0.57	19.77	0.32	11.16
Tc-99	0.01	0.01	0.02	0.03	0.01	0.04
Ru-106	0.16	2.32	0.16	2.66	0.16	1.65
I-129	13.09	56.17	24.27	80.42	21.12	69.89
Cs-134	0.37	6.90	0.33	5.98	0.27	4.51
Cs-137	1.07	8.38	0.89	8.64	0.52	4.98
Ce-144	0.49	5.58	0.88	9.41	0.36	3.38
Pu total alpha	0.14	0.58	0.40	1.57	0.88	1.98
Pu-241	0.08	0.59	0.30	1.58	0.66	2.05
Am-241	0.25	1.19	0.20	1.79	0.21	1.41
Uranium all isotopes	2.02	4.02	0.08	0.35	0.04	0.19

OPERATING EXPERIENCE WITH THORP

Apart from the normal repairs and replacements commonly required for any large scale chemical processing plant over a ten year period, Thorp has operated generally trouble-free over its current 10 year operating period. It was designed for a 25 year lifetime so that once the baseload 7000 tonne of fuel has been reprocessed there is the possibility of further post-baseload reprocessing contracts. The revenue stream from Thorp is an important contributor to paying for the cost of decommissioning and clean-up of the legacy plants on the Sellafield site and so there is every incentive to maximize this income so as to limit dependence on UK government funding from tax revenues.

However, in April 2005 a serious fault was identified within the Head End Accountancy Tank dark cell, where it was found by camera inspection that approximately 83m3 of clarified dissolver product solution had accumulated in the stainless steel lined cell, within the secondary containment but outside the primary tank containment. No radioactivity escaped to the environment and the secondary containment formed by the stainless steel lining performed exactly as designed to contain the liquid safely. There were no aerial releases of radioactivity. The built-in steam ejectors were subsequently used to recover the liquid to another tank and this was accomplished, and the cell liner washed down, by June 2005. This incident has been under intensive investigation since that time and following is an account of the cause, location, detection, remedial actions and restoration work that will be carried out, together with a summary of lessons learned and their applicability to other nuclear plants.

Cause and Location of the Incident

The cause of the leak from the primary containment was found to be a fracture in one of the liquid feed lines to one of the two Accountancy Tanks in the Head End plant. The fracture occurred just above the feed line weld to the top of the Accountancy Tank. The cause of the fracture has been positively ascribed to metal fatigue, caused by oscillations in the suspended tank due to operation of the Pulse Jet Mixers (PJMs).

As noted earlier, the two Head End Accountancy Tanks are unique in being suspended from load cells located on the cell roof so that they can be weighed to provide accurate accountancy figures for their plutonium and uranium content. There are four load cells per tank and each tank is suspended by four stainless steel rods that attach to suspension collars on the tanks and pass through seals in the dark cell top to connect to the load cells (Figure 3). All pipe connections to these tanks have extended unsupported lengths close to the tanks so as not to interfere with the load cell measurements. The feed pipe that fractured had the shortest of these unsupported lengths.

The Accountancy Tanks are enclosed within a steel spaceframe and, for calibration purposes, the tanks can be lowered off the load cells to rest on this frame. The design intent is to operate the tanks normally in the suspended mode, and the operating instructions reflect this.

The PJMs installed in the Accountancy Tanks ensure thorough homogenization of the tank contents. They are intended to be operated for a period of 3 hours prior to sampling and weighing the tank when an accountancy measurement is required. A typical installation of PJM tubes in a tank is shown in Figure 4. Such an installation may have five or six PJM tubes located around the periphery of the tank, with open jets at the base of each tube. A vacuum produced by an air ejector is used to draw tank liquid into each tube and then compressed air is applied to drive the liquid out through the jet, creating a swirling motion across the base of the tank and up through its contents. A control system prevents "overblow" so that no air enters the tank. The PJM tubes are timed to eject liquid sequentially, both to obtain efficient tank mixing and to avoid a single large pressure pulse in the motive air ventilation system.

PJMs are efficient and effective mixing devices and avoid any moving mechanical parts in contact with radioactivity or anywhere within the dark cell. They have been used successfully at Sellafield for over 30 years without a single in-cell failure. It was recognized however, in the initial design of the suspended Accountancy Tanks, that the oscillating movement that sequential PJM tube discharge imposes on a tank

would not in this case be absorbed and damped out by the usual rigid tank mounting. Because of this, design calculations were made of the oscillatory movements and these showed that, with a full tank and the intended 3 hr period of agitation prior to sampling, oscillation of the tank would

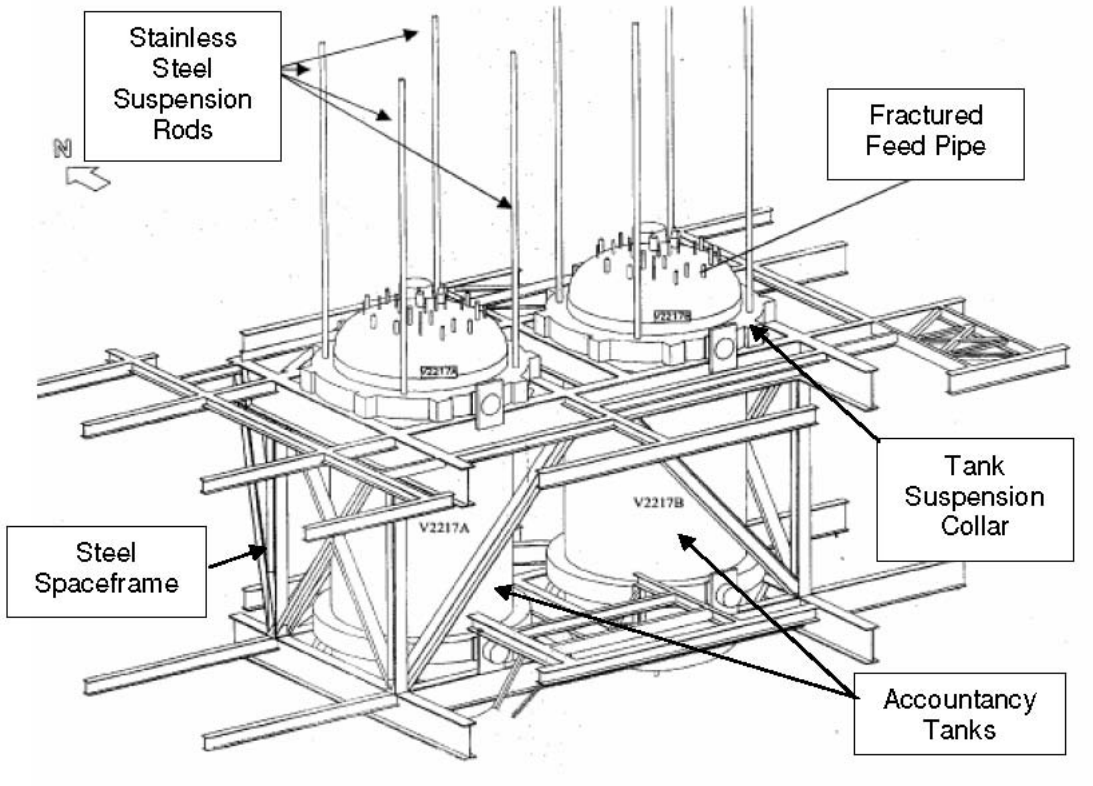


Fig. 3. The suspended accountancy tanks in Thorp head end

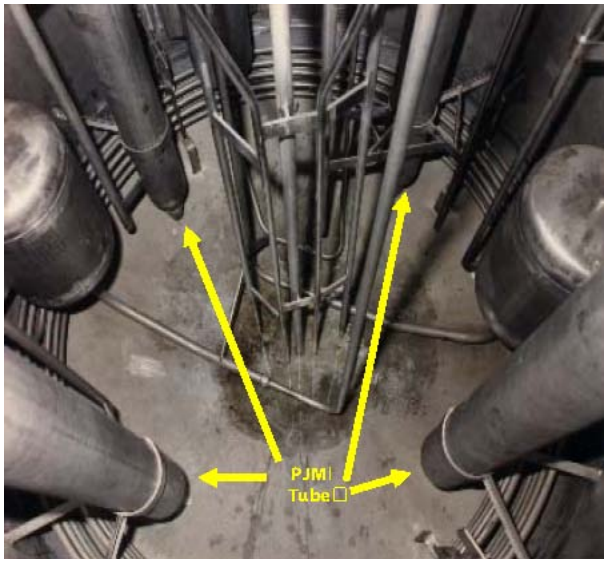


Fig. 4. Arrangement of PJM tubes in a typical tank

be minimal and would not lead to any fatigue problems. As an additional precaution, restraint blocks were fixed to the steel spaceframe that would interact with the tank collars and would also prevent any

more than the smallest oscillatory movement.

However, late in the design process, when commissioning had already commenced, the restraint blocks were removed because of concerns that they would transmit unacceptable loads to the dark cell walls in a seismic event. This change was assessed as acceptable because of the calculations that showed only minimal tank movement when a full tank was agitated for the standard 3 hour period. Unfortunately, however, the crucial importance of these restrictions on agitation was not emphasized in the system operating instructions. From 1996 onwards, the plant operators agitated the tanks for increasingly longer periods and did so with partially filled tanks, where the agitation energy is dissipated into a smaller mass of liquid and thus causes greater tank oscillation. This change in agitation regime was made to investigate whether the accuracy and repeatability of plutonium and uranium accountancy measurements could be improved by more intense and longer tank agitation.

Subsequent calculations have shown that over the operating period from 1996, the number of cycles of movement, and magnitude of oscillation undergone by the pipe that fractured, is within the range that would be expected to cause a fatigue fracture. The root cause of the fracture was thus a failure to modify operating instructions to emphasize the restrictions on agitation when a late design change was made. Had this design change been made within the main design period, or during normal operations, standard procedures would have enforced a formal appraisal of operating implications.

Detection of the Incident

The camera inspection of the Accountancy Tank dark cell was triggered by accountancy measurements comparing the book value of uranium and plutonium received into Head End (calculated by item accountancy and reactor fuel irradiation records), and the amounts of these materials measured in the accountancy tanks by weighing, sampling and analysis. During early 2005, this "Shipper-Receiver Difference" (SRD) indicated an increasing negative trend outside the normal uncertainty band. Although initially attributed to calculational errors, by late March rechecks and further accountancy measurements had shown that the unusual SRD was real.

The cell inspection and Board of Enquiry that followed the detection of the leak identified some evidence that a small leak had started some time in mid to late 2004 and had become much larger in early 2005 as the pipe fractured completely. The opportunity therefore existed for the plant operators to detect this smaller leak via the dark cell sump level detectors and the routine sump samples for several months before they did so. The question therefore arose as to why they did not. The Board of Enquiry studied this in some depth and concluded:

- There was a "new plant" mindset and the operating team considered a leak from primary containment to be so unlikely that any indications that suggest such a leak must have other explanations.
- The sump level detector in the accountancy tank cell had been giving a falsely low reading due to low air flow and a problematic pressure transducer for some months. Not enough urgency had been placed on repair because of the new plant mindset; there was thought to be no likelihood of a change in sump level to measure.
- The operating instructions unfortunately reinforced the new plant mindset by referring to leaks from the primary containment as highly unlikely events.
- Samples had been automatically taken from the sump by the autosampling system. Although most of these showed no uranium or plutonium, three were found to indicate the presence of these species when the records were studied post-event. The operators had not noted these results, chiefly because the volume of information that they were required to deal with had caused them to be obscured.
- DCS records of transfers from the Centrifuge Product Tank to the Accountancy Tank, when examined during the enquiry, showed increasing discrepancies between volumes of liquid dispatched and those received. However, such records were not routinely accessed by the operators and would only have

shown a noticeable discrepancy after the leak became large, which was close to when it was discovered by the accountancy tank measurements.

Remedial Actions and Restoration work

The remedial actions following discovery of the leak have been well planned and successful:

- Immediately following the discovery of the leak the plant was shut down. This could be done in a planned and orderly manner because of the presence of buffer tanks between key parts of the plant. Thus the plant was left in a status that will facilitate restart.
- The escaped liquid was sampled using the in-cell systems and fully characterized.
- The liquid was removed from the cell using the built-in steam ejectors and sent to the undamaged accountancy tank and then on to the Head End -Chemical Separation buffer tanks where it can be stored safely for long periods.
- The built-in washdown rings were used to wash out the cell, and the contents were ejected to the Plant Wash tanks. These tanks allow recycle of this wash liquid to suitable treatment processes within the plant.
- Further camera inspections were carried out to confirm the clean state of the cell, to inspect the damage more closely and to start to plan the repair action.

British Nuclear Group has now prepared a range of detailed repair options for the Accountancy Tank Cell and is discussing these with the UK Nuclear Regulator and the NDA. Options range from remote welding repair to the damaged feed line through isolation of the tank with the damaged line and future sole use of the remaining undamaged accountancy tank.

THORP LESSONS LEARNED AND APPLICATION TO THE EM PROGRAM

- Thorp has operated successfully for over 10 years, and has shown that reprocessing and recycling is an environmentally satisfactory method of reducing significantly the volume for long term repository storage of HA waste from irradiated nuclear fuel.
- Such successful operation can produce a sense of false security in the operating team that must be recognized and steps taken to guard against it.
- Design changes made late in the design process, and particularly once commissioning has started, have the potential to escape formal procedures to ensure operations arrangements take them into account.
- There are formal procedures in place to prevent operational changes made once the plant is in routine operation adversely impacting design intent. However, these can become ineffective if restrictions on operations imposed by the design are not prominently recorded in the operating instructions.
- Thorp design principles produce dark cells with a very low probability of a leak from primary containment. Nevertheless, the means of containment and recovery of such a leak, together with methods of inspection and repair, was provided in every dark cell. These provisions proved to be essential in the containment of, and recovery from, the Accountancy Cell incident.
- The accountancy tank cell was stainless steel lined to a level enclosing a volume well in excess of a single Accountancy Tank. This proved essential to contain a leak not from the tank itself but from a feed pipe.
- The secondary containment design principles and provisions have therefore proved themselves in practice, have ensured that there was no radioactive release to the environment and have provided a

relatively straightforward recovery operation.

- These design principles and measures have protected a very large capital asset from becoming permanently inoperable due to an event that was considered to be highly unlikely.
- Further protection of the asset can be achieved by paying even more attention to operating procedures and operator training, especially after the commissioning and early operating period is over.
- Further protection of the asset can also be achieved by providing a routinely-available in-cell visual inspection capability. The current availability of radiation-hardened cameras facilitates this for new plants.
- The USDOE EM program is currently engaged in building first-of-a-kind "flagship" waste treatment plants such as Hanford's WTP and the Salt Waste Processing Facility at the Savannah River site. These plants represent a very large capital investment and nothing of similar scale or complexity has been built at US nuclear sites for at least 10 yrs. Indeed no similar chemical processing facilities have been built at US nuclear sites since the 1950s. There are a number of lessons learned from the Thorp incident that are likely to provide valuable inputs to the EM program:
- The new US plants are being built under commercial contracts and there will not necessarily be the same long-term operability drivers and provisions as there were for the owner-operator designed Thorp.
- Savings in capital costs by, for example, limiting dark cell access or reducing cell lining and instrumentation are likely to be of increased attraction under a commercial contract but may lead to an inoperable plant in the future if an unlikely event happens.
- Carry-over of late design changes into revised operating instructions is likely to be even more difficult than experienced by owner-operator BNFL, when different companies have the contracts for construction and operation.
- The "new plant" operator mindset may well be an issue with these flagship US plants and needs to be taken into consideration so that it can be guarded against.

It is noted therefore that Thorp's design and operating experience represents a valuable resource against which to measure the EM program's projects.

CONCLUSIONS

Thorp has proved to be a highly successful plant over its 10 years of operation. It has demonstrated that reprocessing and recycling of irradiated nuclear fuel provides a significant reduction in the volume of HA waste that needs to be long-term stored in a repository, when compared with direct disposal of the irradiated fuel elements. Careful flowsheet design limits the amount of chemical processing required, reduces the number of waste streams and enables all but the lowest radioactivity streams to be concentrated into the HA vitrified waste.

Thorp design principles make extensive use of no-moving part, no-maintenance equipment in dark cells that have no routine access arrangements. Nevertheless, the design allows for highly unlikely faults, and provides the means to contain leaks within these dark cells, detect their presence and recover them safely. These secondary containment provisions were tested by the leak of HA liquid into secondary containment that was identified in Spring 2005, and found to work well. No radioactivity was lost to the environment and no worker or member of the public was affected. The liquid was safely recovered into primary containment. Access to the cell for inspection and repair is possible so the Thorp capital asset is protected.

The subsequent enquiry recommended improvements to procedures that ensure carry-through of late design changes into operating arrangements, and required that a means must be found to continuously

combat a "new plant" operator mindset that rejects indications of leaks and other unlikely events as being too improbable to be true. The provision of routinely available in-cell camera inspection equipment is recognized as both desirable and feasible for future plants

The design, performance and operational lessons from Thorp are likely to provide an important input to the current waste plant program of DOE EM.

ACKNOWLEDGEMENT

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