# Towards a simpler and safer nuclear sector: The 2005 THORP Internal Leak

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**Executive summary:** In 2004, a leak of radioactive solution began at the THORP nuclear reprocessing plant due to failure of a single component. The component failure is unremarkable; what is most significant is that the leak progressed for eight months undetected because of an alarm-tolerant culture and inadequate working and monitoring practices.

**Tags:** nuclear, radioactive, reprocessing, energy, Sellafield, alarm-tolerance, monitoring, detection, instrumentation, United Kingdom

## Section 1: Background and introduction

The UK has legally binding commitments to achieve Net Zero by 2050, and realising this ambition will likely require a significant contribution from nuclear energy. Safety is a common concern around nuclear technology, so the UK nuclear sector is heavily regulated. The nuclear sector will probably need to grow quickly and safely in order for the UK to reach its emissions reduction targets, so ensuring that regulation going forward is fit-for-purpose is of paramount importance.

Revisiting the THORP incident from 2005 in this case study will hopefully benefit those outside the nuclear sector who may gain something from the transferable learnings; it should also benefit the new generation entering the sector who, given that 16 years have passed, may not have the details of this incident as part of their consciousness.

### Nuclear reprocessing

Nuclear energy generation exploits the fissile isotope of uranium (U-235) to generate energy and propagate a chain reaction. During operation, not all fissile material within nuclear fuel is utilised. Spent nuclear fuel[1] typically contains approximately:

- 1% plutonium
- 3.5% fission products
- 95.5% uranium, <1% of which is U-235

The reprocessing of spent fuel fulfils two roles: Firstly, it reduces the volume of high level nuclear waste; and secondly it allows for extraction of uranium and plutonium to recycle into new fuel.

In the UK, reprocessing nuclear fuel uses a chemical process known as PUREX (Plutonium Uranium Reduction Extraction) [1] which comprises spent fuel storage, conversion to solution, chemical separation of uranium and plutonium from other elements, conversion to solid oxides, and also treatment of any waste.

The Thermal Oxide Reprocessing Plant (THORP) at Sellafield in Cumbria is the UK's most recent nuclear fuel reprocessing plant, opening in 1994 to handle both domestic and foreign fuel. **Figure 1** provides an overview of the processes which make up the operations at THORP. THORP ceased operation in 2018 in response to reduced reprocessing demand; further spent fuel is now stored on site within storage ponds.

In 2005 a leak of radioactive solution into secondary containment was discovered at THORP. In 1990, the International Atomic Energy Agency (IAEA) developed the International Nuclear and Radiological Event Scale (INES) [2] to help convey the severity of incidents at nuclear installations. The 2005 leak at THORP was classified INES level 3 (out of 7); a serious incident (and near-accident).

## Section 2: Analysis and insights

### The 2005 THORP incident

The part of the process involved in the incident was the first conversion stage. Here, in the Head End plant, spent nuclear fuel is sheared before dissolution in nitric acid, forming a product liquor. The liquor is then centrifuged and the uranium and plutonium content measured before chemical separation begins.

Part of the feed clarification cell, Vessel V2207B, is a 23 m$^3$ Head End accountancy tank, where centrifuged liquor is weighed. Nozzle N5 (**Figure 2**) connected the centrifuges to Vessel V2207B and it was the failure of this nozzle that led to the leak of radioactive liquor.

The operator company, British Nuclear Group Sellafield Limited (BNGSL), learned of the leak on 20 April 2005 and reported

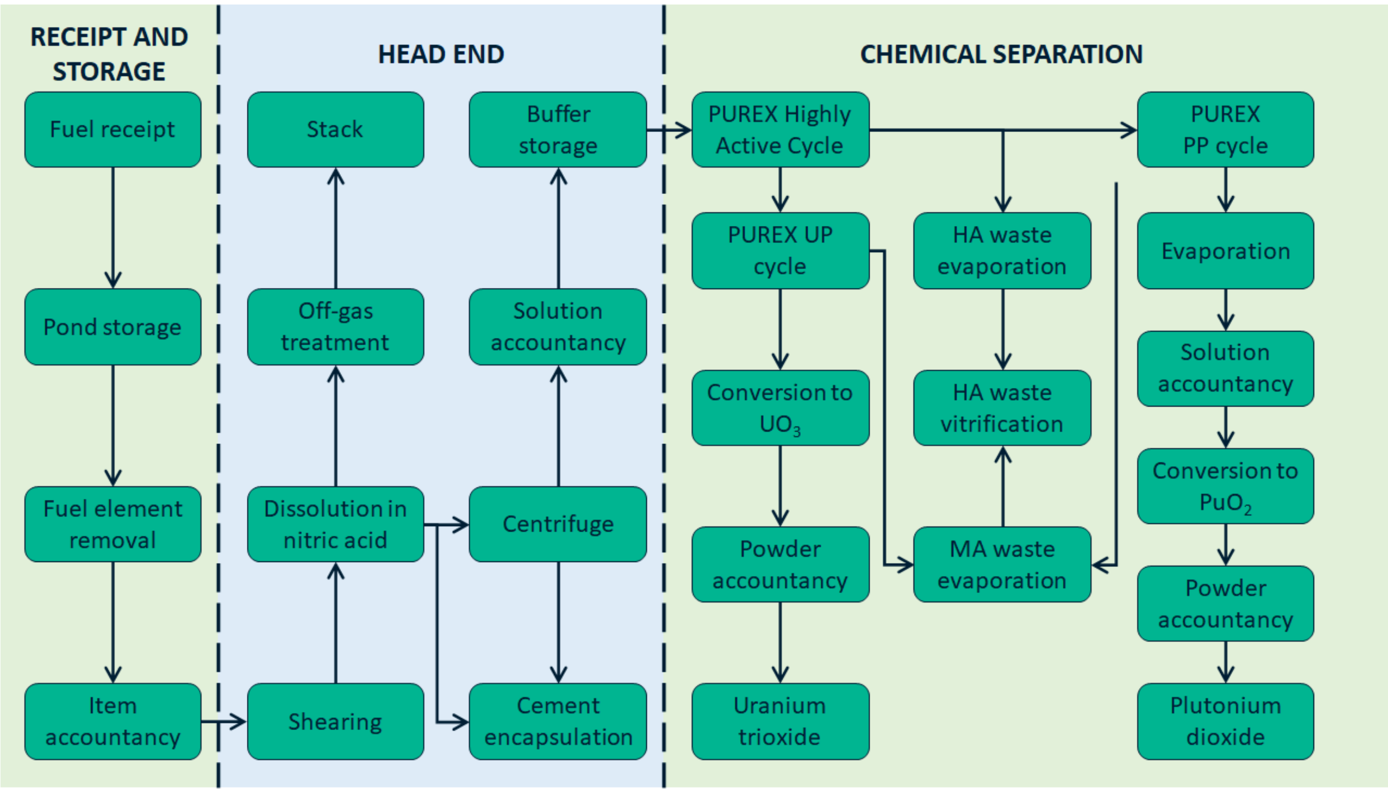


Figure 1: Overview of the THORP processes. The Head End plant was where the events which caused the THORP incident took place. In the Head End plant, spent nuclear fuel is sheared before dissolution in nitric acid, forming a product liquor. The liquor is then centrifuged and the uranium and plutonium content measured before chemical separation begins. A nozzle connecting a centrifuge to an accountancy tank failed, resulting in the leak of dissolver liquor. (Source: adapted from [8])

it to the UK Health and Safety Executive (HSE). This was, however, at least eight months after the leak had started, by which point 83,000 litres of dissolver liquor had leaked onto the floor of the feed clarification cell. This volume of dissolver liquor contained 22 tonnes of uranium and 160 kg of plutonium. The volume of leaked liquor was 3.5 times that of the capacity of the intended destination accountancy tank. Remote camera investigation after locating the leak revealed that the corrosive liquor had damaged the support frame steelwork.

All leaked material from the failed nozzle was contained within the feed clarification cell and returned to the primary containment during the recovery operation in May 2005. No injuries resulted from the incident and no leak of material from the secondary containment occurred. THORP was closed following the incident and was granted permission to restart operations in January 2007, 20 months after the discovery of the leak. BNGSL pleaded guilty to breaches of site licence conditions and was fined £500,000.

### Criticality risk

The major safety concern in accidents involving fissile material is the potential for a criticality accident; that is, an unintentional uncontrolled nuclear fission chain reaction. Criticality accidents require a greater than critical mass of fissile material arranged in a specific geometry and can lead to the release of fatal radiation doses and, in some cases, serious mechanical damage [3].

The criticality safety case for the feed clarification cells covered multiple accident conditions, though a major leak was considered unlikely. Given the scale and duration of the leak, the regulator concluded that "the effectiveness of some of the measures in place to prevent criticality could not be guaranteed." [4].

### The "cause" of the leak

Mechanically, the cause of the shearing of Nozzle N5 from its vessel was attributed to fatigue failure from repeated and continued oscillation of the accountancy tank, which is suspended to allow for weighing of the vessel.

Normal operation of the accountancy tank involves blending the dissolver liquor within it using a pulse jet and, as a consequence, the agitated contents initiate motion of the tank. This movement was accommodated in the original design of the cell with a restraining mechanism, but a modification to the operation of the vessel in 1997 removed the restraint, enabling the failure.

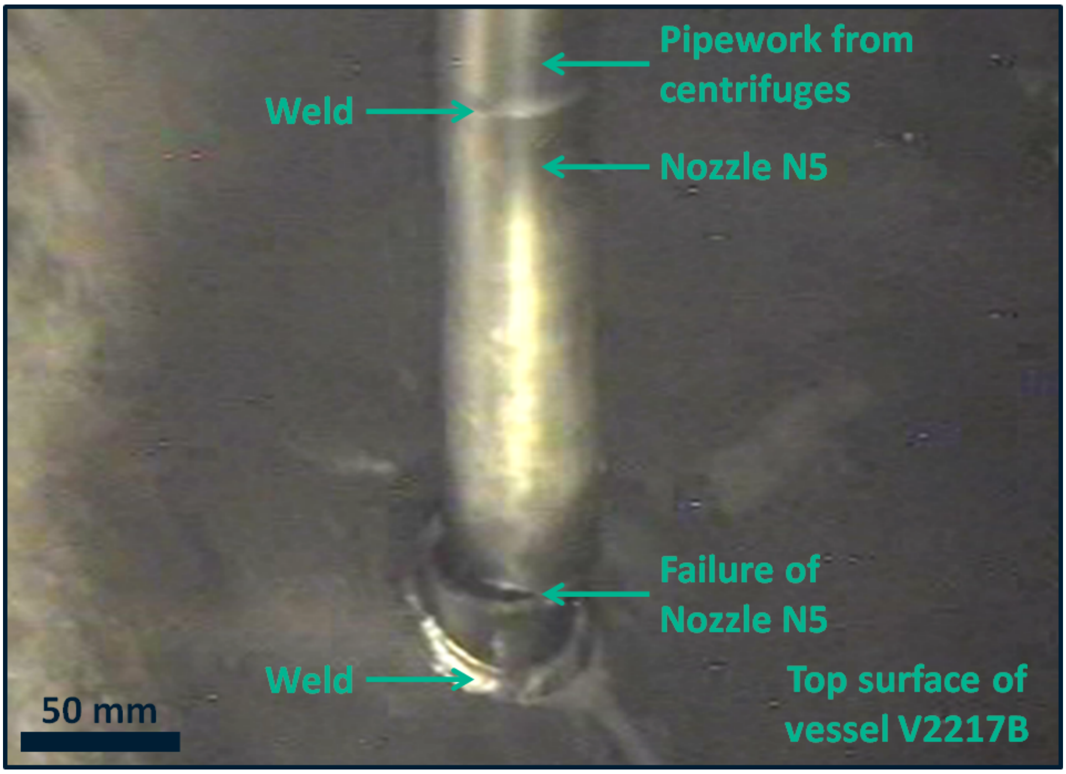


Figure 2: Image showing the severance of Nozzle N5 from the accountancy tank into which the dissolver liquor should have fed. (Source: adapted from [4])

The failure of the system, however, goes beyond the failure of a single component. Leaks are to be expected when handling fluids; the ultimate failure of the system was not that the leak occurred, but that it went undetected for at least eight months.

### Leak detection systems

The feed clarification cell was designed as a secondary containment in the event of any leak and is capable of holding 250 m$^3$ of fluid (ie the cell was at one third full capacity when the leak was discovered). Sumps within the cell, where leaked solution would accumulate, are fitted with pneumercators which measure the depths of any leaked fluid present and sound alarms when operating outside of intended conditions.

The sump pneumercators require a residual depth of acid within the sump to operate effectively, and 'low' alarms indicate if the acid needs replenishing. 'High' alarms indicate that the depth is too high and therefore suggest a leak of dissolver liquor into a sump.

In addition to the pneumercators, THORP operational arrangements dictated that samples were to be taken from the sumps for analysis every three months. Detection of uranium within the samples would indicate the presence of a leak of dissolver liquor.

### End-of-campaign stocktake discrepancies

The leak which began in or before August 2004 went undetected by these leak detection systems and it was only when accountancy discrepancies were noticed in end-of-campaign figures that an investigation was initiated and the leak discovered. The accountancy figures rely on sampling results and complex calculations which can take over a month to produce after the end of a campaign. This was responsible for the delay between the start of the leak and discrepancies appearing on the books.

It should be noted that the accountancy process was not intended to contribute to plant monitoring; its role was to ensure that international non-proliferation commitments are being met.

### Uranium sampling

The presence of uranium within the samples collected quarterly from the sump would have indicated the presence of a leak into the feed clarification cell.

According to records, difficulties in obtaining samples from the buffer sump led to several unsuccessful collections, as far back as 1995. Requests for samples were routinely made and failed collections reported, but no action was taken. The lack of successful routine sampling was not deemed a priority, with collecting operational samples to continue processing taking precedence.

Between November 2003 and April 2005, only one successful buffer sump sample was collected, in

August 2004, which measured the presence of 50 g of uranium per litre. Samples taken from elsewhere in the cell in Q4 2004 and Q1 2005 also showed a presence of uranium.

This limited sampling should still have been enough to suggest the presence of a leak. Confusion between teams as to which team was responsible for this monitoring and data analysis inhibited the response, as did the inability of potential monitoring staff to use the data interpretation software due to lack of training.

### Leak instrumentation and maintenance

Even after the discovery of the leak, with 83 $m^3$ of dissolver product liquor present within the feed clarification cell, the relevant pneumercator was still not recording high liquid levels. The error was caused by a stuck float within the sump pneumercator and it was later discovered that simply tapping the tube containing the float caused the device to measure accurately.

Maintenance instructions omitted the necessity to check the float (which would eventually become stuck), focusing instead on calibration and pressure responses. As such, no proof of correct operation of the instrument as a whole was required during maintenance. Checking historical instrument data for inconsistencies also did not form part of the maintenance process.

The absence of comprehensively detailed maintenance instructions meant that effective maintenance relied more on the skill of the staff. The use of non-specialist staff for maintenance reduced the ability to identify problems with instrumentation.

The investigation also raised questions regarding logging job requests and their role in best practice. Maintenance of instruments was carried out following direct verbal requests, without being routed through management. Staff suggested that this practice had become common practice following reductions in employees.

### Alarm-tolerant culture

During the following investigation, the pneumercator in question had been in 'low' alarm modes for 85% of its operating period since 2000. This was attributed to the difficulty involved in adding acid to the sump, and in achieving the correct sump depth so as to not trigger either the 'low' or 'high' level alarms.

The safety case for the feed clarification cell did not recognise a 'low' sump alarm as significant, unlike a 'high' alarm. Instruments were operating routinely under 'low' alarm status.

Alarms from all areas of the plant (not just local alarms) are displayed on the plant's distributed control system. As further alarms activated, existing alarms would be pushed down the list, making them harder to observe and thus long-standing alarms would reduce in priority.

### The 1998 THORP leak

This was not the first such leak during the operation of THORP. In 1998, events similar to those in 2005 occurred, when eroded pipework in the dissolver cell resulted in a leak into the sump.

An internal investigation followed, which provided 28 recommendations, most concerning sump monitoring, sampling and the pneumercators. No formal record was kept as to what extent the 28 recommendations had been implemented. Given the similarity between the two incidents, it is likely that proper implementation of the 1998 recommendations would have prevented the more serious incident of 2005.

## Section 3: Discussion and transferable learnings

The THORP safety case stated that any leaks of dissolver product liquor in the feed clarification cell would be detected within a few days. In fact, when such a leak did happen it took over eight months to detect, and through a process never intended to be used for plant monitoring.

The cause of the leak was modification to the accounting vessel which did not consider the detrimental impact this would have on the connecting pipework, ultimately causing a guillotine failure on Nozzle N5. Full assessment of the impact of any design changes should have been carried out, with consideration paid to understanding the original design before any modifications were carried out. The importance of second-order thinking eloquently described by G.K. Chesterton with his heuristic fence[2] applies as much in engineering as it does to policy decisions.

The lack of appreciation of the restraint apparatus and its subsequent removal constituted an unconscious design change, made during maintenance cycles, and was therefore beyond the scope of the normal change control procedures that usually exist for design. Design changes feature in the stories of many major accidents; the incident at THORP is one further example.

Even combined with the difficulties of sampling from the buffer sump and accurately adding the correct volume of acid, these design flaws did not cause the THORP incident. The incident, and particularly its severity, resulted from the human and organisational failings which allowed the leak to continue for over eight months.

Numerous failures are evident, all within the management and task and technical layers (ie none within the governance layer) [5, Fig. 5]. The running failure theme of the incident is that of human-system interaction [5, p. 89]; operators' understanding of the system was continually at odds with the true system state.

The confusion between teams as to who was responsible for the monitoring and data analysis of samples taken from sumps prevented the identification of 50 g/l of uranium present, and by consequence, the existence of a leak. Having no single owner [5, p. 89] of tasks may also have led to staff being improperly trained in the use of the relevant data interpretation software. Clearly defining roles would have helped ensure tasks were fully carried out and separating the alarms displayed on the distributed control system into those relevant to each area of the plant would have kept them on display and maintained their priority status.

Most failings resulted from management and/or operators not following protocols that had been put in place. Two clear exceptions to this were that no proof of correct overall operation was required during routine pneumercator maintenance and that checking historical instrument data for inconsistencies did not form part of the maintenance process. Inclusion of these two tasks within the maintenance process would have identified the ineffectiveness of the flawed pneumercator.

Lean organisational operation [5, p. 96], shedding excess capability to preserve the minimum required to carry out business operations makes enterprises less resilient. Inadequately retraining surplus electricians as instrument maintenance staff ensured that they were ill-placed to compensate for the sub-optimal protocols mentioned above. Dedicated instrument personnel might have identified that there was a problem with instruments over a long time period.

Competing objectives [5, p. 90] sacrificed a focus on obtaining successful routine sampling, in favour of the collection of operational samples, while the significance of 'high' alarms within the safety case over 'low' alarms contributed heavily to alarm tolerance. The safety case was inadequate with regards to 'low' alarms so their significance was not understood by supervisors.

The remaining failures all exist at the managerial level and can be grouped into three principal areas:

1. Alarm tolerance

The culture of the Head End plant was to routinely allow instruments to operate continuously under alarm. Pneumercator alarms were distinguished between 'low' and 'high', with 'low' alarms not deemed urgent enough to warrant investigation to resolve the fault. The pneumercator at fault in this incident had been in 'low' alarm modes for 85% of its operating period over the preceding four years. The extent of this demonstrates that the problem was systemic, and not the fault of single individuals.

Finding ways to address the alarms would have been far preferable to tolerating their continued operation. With so many continuous alarms signalling, it was left to the supervisor to assess what was most pressing, resulting in a competency gap from the unmanageable complexity [5, p. 90].

2. Inadequate record-keeping

Requests for sump samples were routinely made and their many failed collections were reported. Despite this, no action was taken. In addition, maintenance of instruments was carried out following direct verbal request, without being routed through management. With no paper trail of written requests and reports, no systematic check of plant conditions could be carried out.

Formalised checking regimes would have potentially enabled managers to spot trends of dysfunctional instrumentation within the plant and act accordingly.

3. Failure to learn from previous incidents

Perhaps most worrying was the similar, but less severe, incident in the Head End plant in 1998. Although the resulting internal investigation issued 28 recommendations, there was no formal record of the extent of implementation. The investigation following the 2005 incident stated that proper implementation of the 1998 recommendations would have prevented the more serious incident of 2005. It is important to ensure that the lessons from the 2005 incident have been learned and the recommendations continue to be followed.

### Effects on the site

In response to the post-incident investigation by the HSE, THORP implemented a range of changes to safety culture:

- An updated plant safety case
- Staff knowledge development workshops
- Operating experience and training
- Organisational reviews for leadership roles
- An increased focus on nuclear safety.

One of the benefits of revisiting the 2005 THORP incident more than 16 years later is that it is possible to see whether the learnings from the incident are still being applied and feature in current staff training. While THORP closed in 2018, much nuclear work continues elsewhere around the Sellafield site, and it is here that the generic lessons can still be applied.

The lessons from the 2005 THORP incident are reportedly being kept alive across the site and the learnings feature throughout the site's culture as Learning from Experience.

Robust hazard and fault identification is essential to any demonstration of safety and forms part of the management systems and processes, contributes to the Safety Case and to any subsequent Periodic Safety Review.

A range of activities and studies are applied to identify hazards, with the approach selected dependant on the size of the project or task. Examples include Hazard and Operability Studies, Failure Modes and Effects Analyses as well as plant walk-downs, task analyses and revisiting previous studies. Importantly, Learning from Experience is specifically identified in all nuclear industry management systems.

The UK nuclear industry is closely regulated by Government's Office for Nuclear Regulation and has robust oversight from nuclear safety and security committees; while industrial bodies such as the Safety Directors Forum provide insight into wider learning and their Good Practice Guides draw upon and share Learning from Experience across the sector. Certification bodies, such as Lloyd's Register and the World Association of Nuclear Operators (WANO), have their own independent mechanisms incorporating Learning from Experience which contribute to broadening safety culture. Following the 2005 incident, the THORP team instigated daily nuclear safety calls; the forerunner to the daily fleet call which forms part of WANO best practice.

More recently, the industry has made a distinction between leadership and management. Sellafield Ltd has recently released a revised Nuclear Professionalism Standards and Expectations document [6] which aims to provide clarity of purpose for the site. The document prioritises 'how to think' rather than solely prescribing safety and engineering processes that identify 'what to do' under rigidly specific circumstances.

Leadership and project academies have their curriculum built upon Learning from Experience and focus on case studies, such as the THORP incident of 2005, to provoke reflection on the past and stimulate thinking on how this might impact the nuclear site in the future.

Too often, Learning from Experience leads to straightforward modification of procedures, rather than any deeper cultural change. However, THORP operated without incident for the 13 years up until the closure of the plant in 2018. If the experience from the 2005 incident led to real change in attitudes and culture, driven from the top of the organisation, then this can be considered a successful Learning from Experience model.

With new growth expected in the UK nuclear sector in the coming decades, the safety lessons from incidents such as that at THORP in 2005 must continue to feed into future nuclear safety culture, long after the plants where the incidents took place cease to operate.

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## Endnotes

1. From a typical light water reactor.
2. Chesterton's Fence [7], he describes, "was not set up by somnambulists who built it in their sleep". He insists that before removing a structure that at first seems useless, one must first establish the *full* purpose of the structure; and only then can it be safely removed without fear of unexpected consequences.

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