THE ONLY GOOD WASTE IS 'DEAD' WASTE – WASOP, A METHODOLOGY FOR WASTE MINIMISATION WITHIN COMPLEX SYSTEMS

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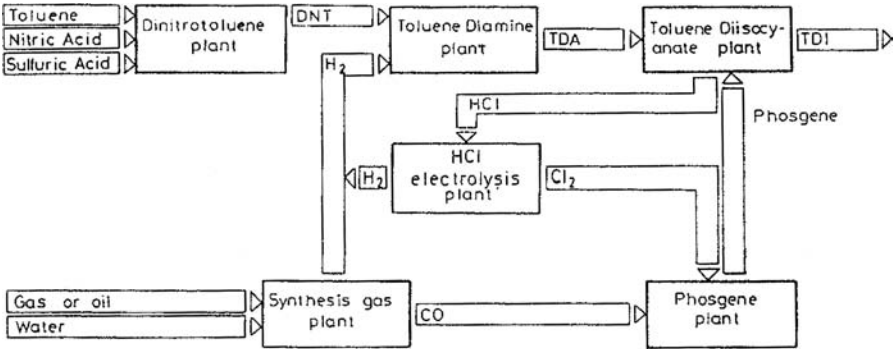
Purpose: The international nuclear community continues to face the challenge of managing both the legacy waste and the new wastes that emerge from ongoing energy production. The UK is in the early stages of proposing a new convention for its nuclear industry, that is: waste minimisation through closely managing the radioactive source which creates the waste. This paper proposes a new technique (called Waste And Source material OPerability Study (WASOP)) for critically analysing a complex, waste-producing system to minimise avoidable waste and thus increase the protection to the public and the environment.
Design/methodology/approach: WASOP critically considers the systemic impact of up and downstream facilities on the minimisation of nuclear waste in a facility. Based on the principles of HAZOP, the technique structures managers' thinking on the impact of mal-operations in interlinking facilities in order to identify preventative actions to reduce the impact on waste of those mal-operations' on other facilities.
Finding: WASOP was tested with a small group of experienced nuclear regulators and was found to support their examination of waste minimisation and help them to work towards developing a plan of action.
Originality/value: Given the newness of this convention, the wider methodology in which WASOP sits is still in development. However, WASOP is believed to have widespread potential application to the minimisation of many other forms of waste, including household and general waste.

Keywords: HAZOP; nuclear; systems thinking; waste management.

INTRODUCTION

The UK's growing concerns over global warming and the limitation of landfill sites are driving a national agenda of recycling and reducing the manufacturing/consumption of items which produce unnecessary waste. This is over and above the business desire to reduce costs by plant integration as shown here for a toluene diisocyanate plant.



Radioactive material has the property of being easily detectable to extremely low levels and, similar to the effects now being exploited in nanotechnology, transfer of radioactive material from a source occurs at a molecular level by direct contact in a process called 'contamination'. This contamination thus generates further radioactive material which may become waste. This process is in addition to the generation of radioactive material caused directly from the fission process. It is an important principle that radioactive material is only truly waste or 'dead waste' when it can only be send to disposal.

The nuclear industry in the UK has legal requirements placed on it with a similar agenda which, put very simply, is to minimise the quantity of nuclear waste that cannot practicably be avoided.

In Practice, the agenda is to reduce the ability of a source material to smear its radioactivity around a nuclear site as it is transported to, and managed in, various facilities which operate to process that source material. The aim is to dispose of, a much reduced quantity of radioactive material through thoughtful approaches to waste minimisation which may include decontamination.

In this context, source material is radioactive material which will contaminate other material in its vicinity with its radioactivity. A waste is material which has become polluted by a source material and needs to be treated or disposed of. Waste, which is transported to other facilities, is itself a source material as it can smear its own radioactivity in downstream facilities.

When contrasting with other types of waste, an unusual feature of nuclear waste is the sensitive handling requirements and often the degradation that may occur due to the storage conditions and length of time it has to be stored, which can span decades. Also unusual is the requirement to manage some source material that is transported across a number of nuclear facilities, constantly smearing radioactivity and so producing wastes in all of: the production of the fuel; the nuclear reactor; short-term storage (around 3–10 years); downstream handling facilities; re-processing plants; long-term storage (over 50 years).

The management of a source material will cross several specialist facilities, potentially across geographically spread sites. Operations in general and the existing stock of radioactive materials in particular, may affect a facility's ability to receive additional stock from up-stream facilities, or deliver stock to downstream facilities. Delays in the sending or receiving of stock can cause the source material to behave in a way that creates more waste than it should under optimal operating conditions. Therefore, the management of source materials across a national nuclear capability is a complex task when problems in one facility can have knock-on effects up and down the supply chain of facilities (and across sites).

Again in simple terms, analysis of waste management must consider the effects of deviations in a system away from the normal operations and the design expectations.

The technique presented in this paper assists operational supervisors/managers of nuclear facilities in systematically analyzing the effects of (mal-)operations in up/downstream facilities on the production of waste in a facility-in-focus. [The technique examines a facility and its interactions with other facilities. From this point on, this facility under focused examination is called the *facility-in-focus*. This distinguishes it from other up/downstream facilities which interact with the facility-in-focus.]

We focus on mal-operations because when a facility is operating within-design it is assumed to have carried out an earlier analysis, perhaps based on use of the waste management hierarchy, and to be producing unavoidable waste (and the technique focuses on avoidable waste).

Conceivably the technique could be applied during design to new processes and facilities builds that are trying to avoid waste production, but that is not the focus of this paper which is to examine potential improvements to an existing system.

A systems thinking approach was taken to develop a technique which could first understand, and then plan to reduce, the effect of mal-operations in interlinking facilities for each significant waste deriving from a source material. What was developed was a structured approach that examines interactions with up/downstream facilities and identifies additional supervisory processes and engineering safeguards.

This paper outlines the technique, called Waste And Source material OPerability study (WASOP).

First WASOP's theoretical underpinnings are introduced as lying in systems thinking and in the *HAZard OPerability Study* (HAZOP) technique. Next the case study is introduced and used to show the application of WASOP to a hypothetical nuclear case. Discussion of the use of WASOP with nuclear inspectors and future developments conclude the paper.

This paper communicates the latest thinking from nuclear regulators on decision making methodology for supporting waste minimisation and will form part of future regulatory guidance.

UNDERPINNINGS OF WASOP

PHILOSOPHICAL UNDERPINNINGS

The philosophy of WASOP is to identify the best portfolio of actions that will severely limit the source materials' generation of avoidable waste resulting from disruptions in the facility-in-focus that are caused by (mal-)operations in its up/downstream facilities. This is a significant departure from the convention of managing nuclear waste that starts by discussing the existing radioactivity and how to deal with that (an approach reported by Hastings et al. (2007), exemplifying the innovation of this new convention).

The new convention proposed here is not waste management – which emphasizes the management of a material once it becomes waste. The convention is to manage the source material to limit it generating avoidable waste in the first place. This departure from an old mindset accommodates the new desires of site managers, politicians and stakeholder groups to deliver environmentally aware solutions through avoiding unnecessary waste production.

Behind the technique also sits the philosophy that we can prevent waste generation by understanding the behaviour of the source material in the facility-in focus, and then design actions to optimally manage that source material. However, understanding the behaviour of the source material in the facility-in focus is done separately to the WASOP, and so is not included in this paper. Though, it is important to note that, much of the information required for a WASOP would be already gathered for a HAZOP.

SYSTEMS THINKING UNDERPINNINGS

Designing actions for effective source material management in a facility, we must consider the up/downstream facilities which affect that management.

WASOP is informed by the principles of System Dynamics (SD) modelling (Forrester 1961). System Dynamics is “a perspective and a set of conceptual tools that enable us to understand the dynamics of complex systems” (pvii) (Sterman 2000).

SD models can represent the subtle relationships between issues through causal loop models which show the issues relevant to a problem (as nodes), and the positive/negative relationships between related issues (in arcs that link related nodes) (Sterman (2000) provides an accessible review). Causal loop models can inform the building of quantitative models of the dynamic relationships between factors in the model which can examine the stock (in our case, the stock of waste), and how that stock varies when other stock items (in our case, the stock of source materials) flow around the system.

Causal loop modelling is appropriate for exploring the concepts which underpin the management of source materials. Such models could be focused at operational levels and the issues they face when managing a source material in a facility (or equally they could be focused on the policy level models of site-wide, or national, strategy).

For WASOP, these models could explore the engineering issues associated with, for example, transporting waste between facilities and quantitative models could predict the additional wastes that are potentially generated.

However, in practice, problem structuring methods (Rosenhead and Mingers 2001), of which SD can be regarded as being, are criticized for being very difficult for novices to independently conduct (Westcombe et al. 2006). Part of the difficulty is in turning expert knowledge about a situation into a structured model which is theoretically and contextually valid.

Thinking about the situation in terms of nodes, arcs, causes, consequences, stocks or flows is not natural for many managers. Granted, SD facilitators could support managers who wish to use SD modelling, allowing modelling novices to benefit from the approach.

However, suitable SD facilitation support is not always as available as general meeting facilitation and so, to have widespread impact on operations in this context, a decision making methodology needs to be not intimidating as well as be easily usable. Also, the simplicity of the decision making process will ensure that the decision outcome is more reliant on the expert knowledge available than it is on the competence of the modellers to structure that knowledge in a certain way.

Despite this, the development of WASOP began with causal loop modelling and the initial development of quantitative models. Through this development it became clear than the highly technical nuclear knowledge involved in this application was not easily able to be modelled in SD terms, and certainly not by a novice modeller working only from an instruction sheet (i.e. without facilitator support).

Furthermore, although they could be developed, the required quantitative inputs to the model were not readily available, resulting in initial models being based solely on expert intuition. As such, it was decided to employ a systems perspective (in adopting the principle of understanding dynamic systems and material stocks and flows) and learn that the models WASOP would rely on had to be as simple as possible. Our approaches employ Sterman's notion (above) of SD being a perspective.

WASOP BUILDING FROM HAZOP

HAZOP is a technique for proactively managing a situation to avoid hazards being realised (Kletz 1997). It was developed in 1960 by researchers at ICI (Kletz 1997, Elliott and Owen 1968) who sought a methodology to rigorously investigate the hazardous effects of deviations from design of operations in processing plants. HAZOP requires experts to pool their knowledge to investigate potential operational weaknesses to allow those weaknesses to be suitably guarded against. Operational weaknesses are explored partly through considering the risk of failure or mal-operation. The technique can consider the smallest detail of piece of equipment to identify the cause and consequence of human, process or material failure (see Kletz (2006) or Redmill (1999) for reviews).

Keywords are used to structure the HAZOP study (for a range of keywords see Tyler et al. (2000)). For example, experts might consider the effects of a flow-pipe carrying NONE, MORE THAN, LESS THAN, HOTTER or COLDER (of) the material for which it was originally designed. Through considering the effects of deviations from design using the keywords, these experts can consider the effects on the integrity of the pipe and the material it carries. A key feature of HAZOP is the systematic approach to evaluating the effect of mal-operations.

The fundamental principles of HAZOP have remained relatively constant since early publications (Kletz 1997) but there have been a number of innovations using the fundamentals of the approach. For example: expert systems can provide analytical support to the process of HAZOP (e.g. Khan and Abbasi (2000) and Chae (1994)); mathematical simulation models have been used to help in training to explore issues around the magnitude of deviation of operating conditions (e.g. Eizenberg et al. (2006)). Also applications of HAZOPs have been extended beyond their original roots, for example: hazards for software and electronic systems that control production operations (Schubach 1997); hazards in business management processes e.g. financial accounts (Pitt 1994); assessing "human reliability and error analysis" (p306) in healthcare (Dhilon 2003).

The innovation presented in this paper is not in strengthening HAZOP, but it is in addressing the gap of waste minimisation through the structured approach which HAZOP brings to hazard minimisation.

Other techniques have utilised the HAZOP approach in a similar fashion e.g. ENVOP (Isalsk). However the focus has always been end result/objective driven. As indicated earlier the approach presented here aims, by analysing the system using the understanding of the fundamentals, to retain simplicity and allow the outcome to be unconstrained.

HAZOP structures the analyses of the system to take the experts through a decomposition of the complexity of the system. Through decomposing the complexity, the method aims to allow the complexity of source material behaviour and waste production to be better understood. The importance of providing useful techniques for understanding complex systems is illustrated by Lawley (1973) (quoted in Schubach (1997) p303) who asserts that "[HAZOP] is based on the supposition that most problems are missed because the system is complex rather than because of a lack of knowledge on the part of the design team". In alignment with this approach of decomposing complexity to understand it, WASOP in our nuclear context decomposes two aspects of facilities:

1) The system of facilities which collectively process a source material.
   System decomposition aims to identify transportations of source materials and materials that may become wastes or carry waste between facilities in order to appreciate the potential for smearing radioactivity across the site, as well as to understand which facilities depend on each other and may trigger operational consequences if there are mal-operations in the system. Importantly, only one level up/downstream is considered for the facility-in-focus – further up/downstream is considered when those other facilities are the facility-in-focus. System decomposition might be accessible from a site wiring diagram and so WASOP can effectively use existing documentation.
2) The interrogation of each source material transportation between facilities using keywords (see Table 1 for a summary of potential WASOP keywords).
   Keyword decomposition aims to take a structured approach to thinking through the widest range of possible consequences for a facility-in-focus, if mal-operations occur in up/downstream facilities. Although different applications may require a careful selection of alternative keywords, an illustrative list of keywords include considering the effects of:

   – *Nothing* being transported between the facility-in-focus and the up/downstream facility.
   – *More than* normal being transported between the facility-in-focus and the up/downstream facility.
   – *Less than* normal being transported between the facility-in-focus and the up/downstream facility.

Table 1. Potential keywords for the WASOP

– Nothing
– More than
– Less than
– Part of
– Other material (as well as the designed material)
– Other material (instead of the designed material)
– Reversing

– *Part of* the material (e.g. half-empty containers) being transported between the facility-in-focus and the up/downstream facility.
– *Other material (as well as the designed material)* being transported between the facility-in-focus and the up/downstream facility.
– *Other material (instead of the designed material)* being transported between the facility-in-focus and the up/downstream facility.
– Material *reversing* through this transportation route between the facility-in-focus and the up/downstream facility.

Some important issues which assist in the smooth running of the WASOP (many of which resonate with HAZOP) include:

– Before the WASOP, select a source material and facility-in-focus in which the source material is managed.
– Select a group of experts who can best inform the WASOP. These experts should bring the required depth and breadth of knowledge when considering the source material being managed in the facility-in-focus. In particular, they will bring sufficient knowledge of the chemical behaviour of the source material in various conditions of management and the operating conditions in the facility-in-focus and up/downstream facilities.
– A chair/facilitator should lead the group through the WASOP. They are responsible for providing the group with content support, that is encouraging the group to rigorously consider issues (and actions) as well as accurately capturing the detail of the discussion. They will also provide process support, that is ensuring the group understand the process, make progress through keywords, and attending to the social process of group working (Schwarz 2002).
– The group will need to identify the major wastes which emerge during the management of this source material, the system of up/downstream facilities which serve the facility-in-focus, and the keywords to be used for their application.
– Brainstorming and other techniques can be used to encourage the group to think laterally about the range of concerning issues using these keywords for this source material in this facility-in-focus.

- For each concerning issue, identify actions which can alleviate the concern or reduce the likelihood of the system producing avoidable waste.
- Document all issues and actions as appropriate to form a suitable audit trail.

The paper now moves to explain the context for the development of WASOP before discussing its application to the management of a source material in the nuclear industry.

CASE STUDY

THE CONTEXT

The production of waste is an inevitable feature of many production processes, often resulting in the need to dispose of that waste. Recognising this, the joint regulators of the nuclear industry (HSE's Nuclear Installations Inspectorate (NII), Environment Agency (EA) and Scottish Environmental Protection Agency (SEPA)) have delivered guidance on how the licensee can discharge its responsibilities for the management of radioactive waste (HSE, 2007). This has also reinforced the importance of the Nuclear Site License in this management as it is a legal contract that includes requirements on the licensee to manage all nuclear matter on its site and to minimise its radioactive waste. The disposal of this radioactive waste is governed by the Radiological Substances Act 1993 (RSA 1993). The extent of the waste management involved in the industry is highlighted in the Nuclear Decommissioning Authority's recent Strategy (NDA, 2006) which shows that the repository for low level radioactive waste is becoming full, thus requiring alternative approaches for that band of radioactive waste (in which waste minimisation is central).

A feature of this accumulated guidance is the clarification that radioactive waste management is a fundamental part of the safety case for a facility. This means that, when managing radioactive waste, there is a legal requirement on a licensee to demonstrate how they would manage radioactive waste (HSE, 2007). Best practice would indicate that the safety case for our context of the management of radioactive waste should include the adoption of the following principles:

- Auditable – so the waste, and its handling, can be tracked.
- Transparent – to avoid accusations of hiding nuclear material and to improve understanding.
- Clear – to avoid confusion and misinterpretation of the characteristics of the waste.
- Strategic and Planned – to demonstrate that the production of waste from the management of nuclear matter has been considered both locally and as part of an integrated site, or national, strategy.
- Managed – taking an operational view of facility conditions including deterioration.
- Optimised and minimised – to challenge management to deliver good practice.
- Integrated – to identify interdependencies with other nuclear facilities and matter.
- Delivered – a practical demonstration of operational compliance with that is the safety case.

Continuing the regulatory focus on using decision making methodology to further support operations, the HSE commissioned a project to help design a methodology for delivering waste minimisation at the UK's nuclear sites. At the time of writing, that project is in the process of developing, testing and evaluating a wider methodology, part of which is the WASOP technique reported here. Integral to the development of WASOP, in mid-2007 a day-long workshop was run involving four HSE/NII inspectors and two EA nuclear regulator inspectors with the aim of testing the technique and gaining feedback on its continual development. The case study material presented below is taken from the preparation for that workshop. Feedback from the inspectors on the utility of the technique is presented.

The paper now moves to introduce the waste that is being managed in a hypothetical 'system' and then use WASOP to show how waste minimisation can be analysed.

THE SOURCE MATERIAL AND ITS WASTE

In this example, the source material is spent nuclear fuel as fuel pins. Associated with this source material is a can which holds the fuel pins, a skip which holds several cans. Sludge which is inside the skip is associated with primarily the fuel but can spread to the can and skip and the water which surrounds all of the other components.

Put simply for the sake of illustration of the WASOP technique, wastes which potentially arise from association with the fuel pin include: the can which is disposed of downstream and is a consequence of the original process design; the skip which can be reused following decontamination; the sludge which contains radioactive particulates and the water surrounding the system. Other wastes are produced e.g. buildings and skip handling equipment, but these are unavoidable in this type of operation and so are outwith the scope of WASOP.

THE SYSTEM

Figure 1 shows the hypothetical system which is used to illustrate the WASOP technique. The facility-in-focus is the Fuel Pond and the upstream facility is PF1 while the downstream is PF2. The other boxes in the diagram represent extended parts of the system, but these are not immediately up/downstream from the facility-in-focus, so would be analysed when PF1 is the facility-in-focus. The WASOP keywords are be applied to each transportation route identified in Figure 1 i.e. 1–3b.

To explain Figure 1, several fuel pins are housed in a can which is housed in a skip. These are transported from PF1 to the Fuel Pond along transportation Route 1. When the skip (containing the can and fuel pins) arrives into the Fuel Pond it is flushed of water to remove the radioactive water which would contaminate the pond. The skip (still containing the can and fuel pins) is placed under fresh water in a pond container, and then moved to a location in the pond where it is cooled for several years in short-term storage. The pond container holding the skip is then removed from the pond and the skip (and its contents) is removed from the pond container and transported along Route 2 to PF2. In PF2 the fuel pin and the can are removed from the skip and processed. The skip is washed in PF2 and

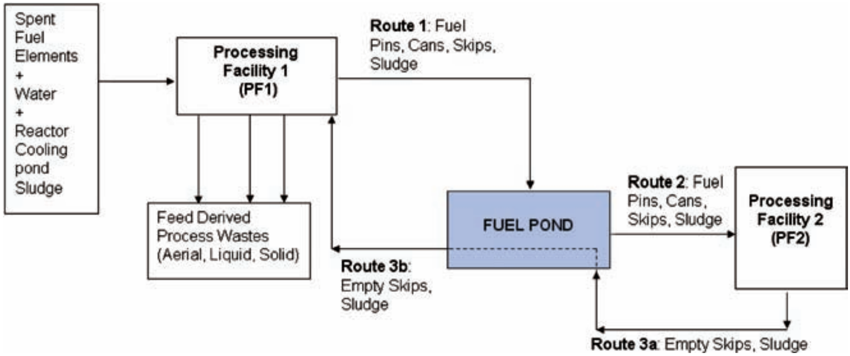


Figure 1. Nuclear material transportations between facilities (with the Fuel Pond as our facility-in-focus)

returned to PF1 along transportation Route 3 (a&b) where it is filled with another can that contains fuel pins. The breaking of Route 3 signifies that the only route for the skip to be transported back to PF1 is physically through the Fuel Pond where it is sometimes stored temporarily if Route 3b or PF1 is blocked. We add this break in route as it nicely complicates the system's dynamics for illustration.

Also able to be stored in the Fuel Pond is non-skipped fuel, albeit temporary storage. This can enter from PF2 through Route 3a. After storage it leaves through Route 2 to PF2. One 'unit' of non-skipped fuel is larger than one skip and so takes up considerably more space in the Fuel Pond.

APPLICATION OF WASOP

Table 2 illustrates a range of possible concerning effects of mal-operations in PF1 and PF2 and the transportation Routes 1-3b on the operation of the Fuel Pond with respect to the skips alone. Empty cells indicate that there are no concerning effects, either because the scenario is impossible, or beneficial.

It is assumed that the maloperation indicated by the WASOP word only occurs within the route being examined. All other routes are expected to be operating to normal flowsheet/capacity, Table 2, and importantly the discussion which informed its content, raised the following main issues:

Beyond the production of unavoidable waste, this system produces avoidable waste, excess empty skips, a main cause of which is a stagnation of full skips (in pond containers, but for simplicity this will be referred to only as skips) in the Fuel Pond. In part, this stagnation can result from either:

– empty skips blocking transportation Route 2 to PF2. This is partly caused by PF1 being unable to accept more empty skips and so the empty skips being temporarily stored in the Fuel Pond.

Table 2. Using the WASOP keywords for the Fuel Pond

	Route 1	Route 2	Route 3a and 3b
	The concerning effects of ... PF1 to Fuel Pond on the management of Fuel Pins in Fuel Pond	The concerning effects of ... Fuel Pond to FP2 on the management of Fuel Pins in Fuel Pond	The concerning effects of ... PF2 to Fuel Pond to FP1 on the management of Fuel Pins in Fuel Pond
No skips being transported along the transport route	• PF1 becomes blocked and so a bulid up of empty skips in Fuel Pond, eventually meaning that Fuel Pond is unable to receive from PF2, and from PF1 when it restarts	• Build up of full skips in Fuel Pond, eventually means the Fuel Pond is unable to receive from PF1, and from PF2 when it restarts • Stagnation and problems on restart if Fuel Pond feed-out is at capacity • Longer residence time in Fuel Pond, and so more contamination and degradation of materials	• Build up of empty skips in PF2 or Fuel Pond, eventually meaning that no empty skips in PF1 to be filled
More than normal skips being transported along the transport route	• Starve PF1 of empty skips (as they are not available to return to PF1), so temptation to order more skips causing more skips to clog the system and to eventually dispose of • Build up of skips in Fuel Pond, unless sending more to PF2 • Potentially longer residence time in Fuel Pond due to FP2 not processing at 'more than' rate (and so more contamination and		

Less than normal skips being transported along the transport route	• Build up of full skips in PF1 and build up of empty skips in Fuel Pond (which are unable to move along Route 3b due to space restrictions in PF1) – gridlock will result	• Build up of full skips in Fuel Pond, eventually meaning that Fuel Pond is unable to receive from PF1 • Longer residence time in Fuel Pond, and so more contamination and degradation of materials	• PF2 becomes blocked • Fuel Pond cannot send full skips to PF2, so soon will not be able to receive from PF1 • This block the entire system- but easier to move things in PF2, if turn off PF1 supply
Part filled skips being transported along the transport route	• Lots of part-filled skips will take up valuable space in Fuel Pond – inefficient use of space	• Build up of full skips in Fuel Pond as focus on processing part-filled skips	• Build up of empty skips in Fuel Pond as quicker to process part-filled skip in PF2, so faster turnaround of empty skip to send back to Fuel Pond
Other materials (as well as skips) being transported along the transport route		• For non-skips being stored in Fuel Pond (from PF2) – possible blockage of Route 3a and 2 if non-skips become dislodged during transportation when being returned to PF2	• For non-skips being stored in Fuel Pond (from PF2) – possible blockage of Route 3a if non-skips become dislodged during transportation on being sent to Fuel Pond • Takes up valuable space in Fuel Pond thereby reducing number of skips able to be stored

– PF2 being unable to accept full skips due to being off-line (which conceivably could happen for a period of several years in the nuclear industry).
– the Fuel Pond being congested with skips which are delaying and preventing the safe movement of skips inside the pond.

If, for one of these reasons, skips have a longer residence time in the Fuel Pond then they degrade by becoming more contaminated, more difficult to handle and decontaminate. This degradation can result in the loss of a skip from the reuse cycle which must be disposed of thus creating additional unforeseen waste.

It is possible that this unforeseen consequence may not have been recognised in the provision of waste disposal routings leading to the empty skip and pond container being left in the pond causing the loss of pond capacity or loss of shielding if containers were to be stacked vertically. Increased residence time in the pond may then lead to further contamination of that skip/pond container combination creating an even greater waste disposal problem.

For waste management in the Fuel Pond there is the issue of decontaminating, or disposing of: pond water; HEPA filters which catch aerial releases; degraded skips; damaged pond containers; degraded physical infrastructure from higher levels of pond water contamination, which is outwith the focus of this discussion. This waste is in addition to the processing of the source material when it arrives at PF2, and the complications which arise if the skip's structure is compromised.

From the analysis, there are two findings which we will use to illustrate the technique (there are more findings, but space prohibits an exhaustive discussion which would only repeat causes of the found consequences). First, there is a strong tendency for the Fuel Pond to become congested with skips. In part, the systems characteristics which result in congestion include:

– Sending 'more than normal' number of full skips from PF1 along Route 1.
– Sending 'normal' or 'more than normal' number of full skips from PF1 along Route 1 when there is a blockage from the Fuel Pond along Route 2.
– Sending 'no' or 'less than normal' number of full skips from PF1 along Route 1, meaning that PF1 can receive less empty skips along Route 3b (and so must be stored in the Fuel Pond). This is due to space restrictions in PF1 which can only accommodate a few skips at any one time.
– Sending 'no' or 'less than normal' number of full skips to PF2 along Route 2, eventually resulting in it causing restrictions on receiving full skips from PF1.
– Sending 'no' or 'less than normal' number of empty skips to PF1 along Route 3b, as this will congest the number of empty skips in the Fuel Pond.
– Sending 'part filled' skips from PF1 will lead to inefficiencies in the occupation of space in the Fuel Pond, requiring more skips to take the material from PF1 and be stored in Fuel Pond.
– 'Other wastes, as well as skips' being accepted from PF2 which take up space in Fuel Pond.

These issues that one may expect to discover in a tightly coupled system of this sort. The extensions of these points are three interesting findings which would become WASOP actions:

- Transporting full skips from the Fuel Pond to PF2 should be highly prioritized; else material will degrade in the pond. Degradation has many consequences for: pond contamination levels; processing the degraded material once it has been retrieved; reusing skips which have become too badly degraded; reusing pond containers which are too contaminated.
- If there is any hindrance in this system concerning the movement of full skips out the Fuel Pond, then operational supervisors in the Fuel Pond and PF1 and even PF2 should be prepared to stop all flows of skips into the Fuel Pond until the situation is rectified. This would aim to not further complicate the moving of skips in the Fuel Pond and ensure that materials are not degrading in the pond and creating waste any longer than absolutely necessary. However there may be circumstances where such an action would have consequences outside the facility-in-focus and its local network which highlights the importance of carrying out the WALARP step separately from WASOP.
- Operational supervisors should explore the possibility of decoupling the Fuel Pond from PF1 using a buffer store, perhaps by building a more penetrating decontamination facility to wash empty skips so that they can be safely stored outside (or at another facility) during times of congestion in the Fuel Pond. This will reduce the reliance on the Fuel Pond being the store for empty skips and containers, allowing it to store full skips from PF1, especially useful if PF2 is off-line for a considerable period.

Second, in times when PF1 lacks empty skips to fill, there may be a temptation to acquire more skips to transport material into the Fuel Pond. In part, the system's characteristics which drive this temptation include:

- Sending 'more than normal' number of full skips from PF1, resulting in a lack of empty skips available in PF1 due to there being insufficient storage of empty skips in PF1.
- Sending 'part filled' skips from PF1. This reduces the amount of material being sent from PF1 per skip, thus requiring additional skips.
- Sending 'no' or 'less than normal' number of empty skips to PF1 from the Fuel Pond. This may arise if the Fuel Pond is congested and unable to move the empty skips in a timely manner, or if the Fuel Pond receives 'less than normal' skips from PF2.
- When 'less than normal' empty skips are being sent from FP2 to Fuel Pond (i.e. a store of empty skips are building up in FP2), FP1 may view that the skips are far down the system and will take a long time to be transported to them.

The extensions of these points are two interesting findings which involve the Fuel Pond and which, again, would become WASOP actions:

- Do not purchase more empty skips when PF1 requires them. There are enough skips in the system and buying more will only further clog up the system with additional (perhaps, half-full) skips. Also, for waste minimisation, the negative consequence of acquiring more skips is that more will need to be disposed of eventually. Instead of purchasing more, operational supervisors should locate the skips that are in the process and all should work on facilitating their movement to PF1. Thus enhanced communication channels between the facilities need to be encouraged.

– Build a buffer into PF1 so that the transportation of skips from PF1 is disconnected from the delivery of empty skips from the Fuel Pond.

DISCUSSION

This discussion centres on three issues. First, we discuss how WASOP sits within a wider methodology. Then, we discuss lessons learned from using WASOP during the workshop with six nuclear inspectors. Finally, we discuss opportunities for future research.

ANALYSING THE WIDER SYSTEM

By analysing the systemic effects of mal-operations in other facilities, WASOP ignores the effect of mal-operations within the facility-in-focus on the propensity to generate avoidable waste internally. Obviously a systems approach to analysing waste minimisation needs to consider all sources of waste generation in the system and so there is a requirement to consider that waste produced inside the facility. WASOP cannot help here, but WASOP does sit comfortably inside a broader method which examines these issues.

Just as HAZOP sits within the wider methodology of HAZAN (Hazard Analysis) (Kletz, 2006), WASOP sits within a wider methodology of WASAN (Waste And Source material ANalysis) (see Table 3). WASAN is a methodology which aims to derive a set of optimal conditions for managing source materials to reduce the generation of waste. Other components of WASAN are designed to interrogate waste minimisation within the facility-in-focus as well as eventually discriminate between potential actions.

Very briefly, to show context but not to fully explain the broader methodology, WASAN begins with the 'Waste And Source material Identification' which defines the scope of the system being analysed and identifies key components which are central to the analyses, for example, the nature of the source material and how it reacts in different storage conditions. Based on a shared group understanding of the source material and the facility, WASAN then examines operations inside the facility-in-focus. A Waste and Source material Management Hierarchy is used to explore ways in which waste inside the facility-in-focus can be, for example, minimised, reused or treated to ensure that which is eventually disposed of is of a reduced quantity and radioactivity than might otherwise be the case. This is the opportunity to analyse waste minimisation inside the facility-in-focus. WASOP follows next. Then the rank and sentence phase begins where the actions are considered as a portfolio of interacting actions that jointly contribute to the minimisation of waste in the system. The selection of actions is informed by making Waste As Low As Reasonably Practicable (WALARP) – knowing that some waste is inevitable, but identifying where effort is best placed to avoid

Table 3. The WASAN Methodology

'WASAN' for Fuel Pond 1
Waste And Source Material Analysis
A methodology for deriving a set of optimal conditions for managing source materials to reduce the generation of wastes

	Scope of analysis	'Internal to' facility management	'External to' facility management	Rank and sentence consolidation phase	Programme and delivery phase
What do we want to do?	To identify and understand source materials, their behaviour and the wastes which derive from them	To minimise waste generation by identifying management and engineering safeguards for the source material	To reduce the effect of (mal-)operations in interlinking facilities, for each of the significant wastes deriving from a source material	To highlight significant issues in the management of the source material by consolidating issues across the WASMAH and WASOP	To create a work programme to deliver the actions identified through the WALARP
How do we use this?	By identifying how to manage the source material both within, and external to, the faclity either by engineering in safeguards or setting up management processes	By using a structured approach to identify all reasonably forseeable methods for source material management within the facility	By using a structured approach that examines interactions with up/downstream facilities and identifies additional management processes and engineering safeguards	By ranking and sentencing the consolidated issues using relevant criteria (e.g. waste reduction significance, cost, timescale) to produce a set of source material management actions	The programme and its underpinning evidence from the WASAN is the deliverable for waste management under the safety case and is the input to a discharge authorisation
The name of the step	WASID Waste And Source material Identification	WASMAH Waste And Source material Management Hierarchy	WASOP Waste And Source material Operability Study	WALARP Waste As Low As Reasonably Practicable	WASP Waste And Source material Programme

unnecesary waste. The actions are then structured into a Waste And Source material Programme (WASP) to ensure they are prioritised in work programmes.

We present the details of the wider WASAN methodology to reinforce that a systems approach should not only examine one part of the system at the exclusion of other, critical parts (Forrester, 1961). A wider methodology beyond WASOP does exist, but space and its continuing development prevent a detailed presentation of the entire methodology at this stage although these will be described in future publications.

REFLECTIONS FROM USING WASOP

At the end of the workshop with the inspectors, we encouraged them to critique WASOP to reflect on potential improvements and future applications. From this, the importance of a range of issues emerged. First, there was strong agreement in the group that the WASOP process was successful in taking them systematically through the issues. Other comments are presented below:

Process of the WASOP:

- Have a chair/facilitator who is effective. Examples of the importance of this are that many times the group tried to explore the upstream when we were discussing downstream, or external issues when we were focusing on internal issues. While those issues can be logged, discussion of them should be held at the appropriate time in the methodology, so that a structured discussion can cover all issues in sufficient detail. Failure to chair effectively may result in whole issues being overlooked because of the complexity of the system being analysed and the lack of structure to the discussion.
- The experts should be able to share their knowledge to the development of the issues and have that knowledge accurately logged. A facilitator can help here in providing a process which supports the sharing of knowledge, partly through ensuring the sharing of airtime across participants. In our workshop a public projection screen was used so that every member of the group could see the record being made of key points, thus allowing them to feel ownership of the record. A rough copy can be printed out for them before they leave the room.
- When the group become familiar with the process then they should be able to move through it rapidly. It is significant that total novices to the method were able to complete two transportation routes to a facility-in-focus to an appropriate level of detail in about 60 minutes (a similar depth as contained in Table 2). If there is a need to streamline the process further then one could decide on which were the significant waste streams and focus mainly on those. An important issues is that WASOP needs to be appropriate for the user, and thus the inputs should be appropriate to the outcome (i.e. that it is not too much of a drain for resources given the outcome/benefit). In this, there is a need to ensure that the analysis does not expand out of control, providing marginal additional benefit.
- Participants should be reassured if they find commonalities across the WASOP discussion (e.g. the same issues arising from upstream and downstream plants). Commonalities show concentration – serving to validate the importance of issues and reinforce the need for action.

The source material:

- Ensure that everyone understands what is the source material, the nature of its management in the facility-in-focus, and general knowledge about up/down stream facilities. This is a fundamental issue which should not be assumed just because the experience of the participants. There may subtle, but important, differences in the perception of the source material, and so a common view needs to be built at the beginning (in the WASID).
- There may be situations when the group are unclear on what is the source material e.g. when the source material is smeared all around every part of the system. The advice here is to tightly define the facility-in-focus and the source material, systemically focusing on major wastes one at a time.

Actions:

- Discussion needs to examine the issues in enough rigor and appropriate breadth to ensure that important issues are not marginalized, but that irrelevant issues do not take prominence. To accomplish this the facilitator may need to remind the group that their task is to identify actions for the WASP and ask them to ground conversation in pursuit of that aim.
- While the WASP is important, the actions that emerge do not need to be restricted to what is currently feasible. Actions which may appear infeasible to some, could be actionable by others. Hence, the WASP action may be a feasibility study.
- Resulting from the workshop could be a list of actions which is impractical because it contains too many issues to simultaneously pursue. Hence, evaluation of the actions is necessary. WALARP aims to bring the set down to a manageable number of complementary actions which can be implemented in this system for maximum effect. The important point here is that WALARP is done near the very end, advocating that evaluation is not done during the WASOP. The process should be action generation (stage A) and then evaluation (stage B), not constantly iterating between these stages at will. Actions should be evaluated as a portfolio of systemic actions which can only be done near the end of WASAN.
- In our workshop the participants felt it important to steer away from identifying new bandages for old problems. Bandages do not solve the problem – they only cover the problem up with a temporary fix. Instead, they aimed to discover genuine actions which will have a positive lasting impact on waste minimisation and improving the fundamentals of the waste producing system.
- What is right for one facility might not be right for the wider system. For example, deciding to change operational relations between an upstream plant and a facility-in-focus might appear sensible for that relationship, but it might be problematic for facilities further upstream. This is not to say that the WASOP is not useful, but that actions need to be considered in a wider context and operating environment. This is a major issue in the site-wide utility of WASOP and WASAN.

The inspectors also fed back their belief in a strong potential for applying WASOP beyond nuclear, for example, new building of operational plants, environmental waste management, household waste. The topic of 'polluter pays' has resonance far beyond nuclear, and WASOP might contribute in the minimisation of waste and pollution.

The strength of WASOP for nuclear is partly in its affinity to HAZOP, which is widely respected and understood. Hence, these inspectors were familiar with HAZOP and were already comfortable with the notion of structuring analyses through keywords and systematically analysing a system through structured decomposition of interactions. Due to its simplicity in modelling approach, even for those who are not familiar with HAZOP (for example academic colleagues we have discussed this with) are able to understand the method of analyses, allowing them to devote their attention to the content of what is discussed and the conclusions which are being reached. The same might not be said for other methods which take a more complex diagrammatic modelling approach, requiring a steep learning curve on the process of analysis, as well as the content being discussed.

FUTURE WORK

There is an extensive programme of future work planned, including: further testing of WASOP and WASAN in nuclear and other context; continual reflection on the methodology and development in alignment with good decision making practice.

A key area of future work is to more firmly ground and evaluate WASOP and WASAN in the wider family of existing decision making approaches. For example, subtle lessons from other methods (e.g. failure mode and effects analysis (Stamatis, 1995) or fault tree analysis (Vesely et al., 1981; Toola, 1992)) might help to further strengthen the method.

Beyond WASOP, we will strengthen WALARP as currently this is an underdeveloped part of the methodology. We have considered taking a multi-attribute decision analysis approach to evaluating actions (French et al., 2007; Belton and Stewart, 2002) which is very popular in nuclear (Bertsch, 2007). However, this could require a considerable amount of analysis during a workshop which might over-engineer the methodology at this stage. Also for the same reason we have steered away from analytical hierarchy process (AHP) (Brent et al., 2007), but we might be able to select relevant parts of AHP, if not the entire method. Another method which is popular in nuclear is best practicable environmental option (EA/SEPA, 2004) which may offer lessons to option evaluation.

Perhaps a more radical development would be to reconsider the methodology in the light of a life cycle assessment approach (Alexander et al., 2000), by focusing on the lifetime smearing of the source material from conception to disposal.

The range of potential areas for future work is vast because this methodology is brand new and we do not discount anything regarding it continual improvement. Testing and evaluation with users will help us to ensure that all improvements align with the users' needs, and not simply development for the sake of it.

CONCLUSIONS

We have presented a new method for analysing Waste and Source material Operability, that is, the proactive avoidance or minimisation of waste resulting from mal-operations elsewhere in the system having impact on waste production in a facility-in-focus.

The philosophy behind the method is that a closer management of up/down stream facilities which interact with a facility-in-focus should aim to prevent fluctuations in their operations having a negative (waste producing) effect on the facility-in-focus. However, to accomplish this requires detailed knowledge of the type of mal-operations which might happen up/down stream, and their systemic effects on the facility-in-focus operations. WASOP structures such an analysis through encouraging experts to collaborate on dissecting the relationships between a facility-in-focus and its interacting facilities.

We, and the inspectors who tested the method, believe that this method is applicable to a wide range of waste producing systems. One feature of our present application is that waste can only be derived from operations associated with the handling and storage of nuclear matter – and this might not be the case in all waste-producing contexts. However, WASOP has potential applicability where the aim is to manage the source of waste and move towards a philosophy of the minimisation of waste generation. Future work will seek to test our belief, and we constantly search for alternative contexts (in energy and beyond) in which to apply this methodology.

APPENDIX – INSTRUCTIONS FOR CONDUCTING A WASOP

The facility-in-focus does not operate in isolation of other facilities. A WASOP looks at up/downstream facilities and explores their impact on the facility-in-focus.

1. Select: a source material; a facility-in-focus; a group of experts to conduct the analysis; a facilitator to manage the process and content.
2. Identify the major wastes which emerge from the source material.
3. Define the material transportations between the facility-in-focus and its up/downstream facilities i.e. facility interactions. Above these are defmed in Figure 1. It is important to note:
   – Only consider 'first-level' interaction (facilities interacting with the facility-in-focus), not 'second-level' interactions (facilities which interact with facilities which interact with the facility-in-focus).
   – Identify separately any wastes which have independent transportations to facilities or interactions between facilities. For example, in Figure 1, 'Fuel pins, cans, skips, sludge' represents all the major wastes contained in a skip. We would not treat these as separate wastes because they are dependent on one another, in that the skip always contain fuel pins, a can and sludge when moving from PFl to Fuel Pond. 'Feed derived process waste' however, is independent from 'Fuel pins, cans, skips, sludge' as it can leave the PFl without considering the movement of 'Fuel pins, cans, skips, sludge'. This analysis should separately consider the wastes which independently move between facilities.
4. Using a selection of appropriate WASOP keywords, systematically analyse each material transportation to explore the effect of mal-operations in up/downstream facilities on the operational performance of the facility-in-focus, for example:
   a. *Nothing* being transported between the facility-in-focus and the up/downstream facility.

b. *More than* normal being transported between the facility-in-focus and the up/downstream facility.
c. *Less than* normal being transported between the facility-in-focus and the up/downstream facility.
d. *Part of* the material being transported between the facility-in-focus and the up/downstream facility.
e. *Other material (as well as normal material)* being transported between the facility-in-focus and the up/downstream facility.
f. *Other material (instead of normal material)* being transported between the facility-in-focus and the up/downstream facility.
g. Material reversing through this transportation route between the facility-in-focus and the up/downstream facility.

It is important to note:

– Some keywords will not be appropriate for certain transportations.
– If an up/downstream facility has more than one interaction with the facility-in-focus (e.g. two types of source material independently being moved between facilities) then each interaction should have its own keyword analysis.

5. Review and validate the issues which have emerged through the WASOP. This review should: consolidate the discussion; identify issues which may require special highlighting and consideration; add issues which may be missing. The result from this activity will be confidence that the list exhaustively represents the breadth issues which require attention.
6. Identify at least one potential action to address each issue identified through the WASOP.
   a. if there is more than one action, then record all actions.
   b. if the group cannot identify any solution to an issue, then the action would be to find potential solution(s).
   c. some may be implemented in the facility-in-focus to allow it to reduce the effect of disruptions in the feed from upstream, or to downstream, facilities.
   d. some may be implemented in an upstream facility to allow it to reduce disruptions in its feed to the facility-in-focus.
   e. some may be implemented in a downstream facility to allow it to reduce disruptions in its acceptance of feed from the facility-in-focus.
7. Rank and sentence the actions into a plan of deliverable actions which will ensure waste is as low as reasonably practicable (WALARP). This can be achieved through a number of approaches, for example:
   a. Split actions into two sorts (to encourage discussion of the relative merits of the actions, not it is to identify a work programme).
      i. lesser actions, so-called because they require less resources (not because they necessarily have less effect). Lesser actions may be: less contentious; require little resource; require little preparatory work; implemented quickly.

   ii. major actions because they require major amounts of resources and/or preparation. Major actions may be: contentious; require large amounts of resource; require substantial preparatory work; those which involve length implementation.

b. conduct a full-scale multi-attribute decision analysis of the actions. Use the rating of each action against a range of measures to discuss the actions and build understanding of which are emerging as being 'good'.
c. Place all the actions on an effort/impact grid to identify how actions compare on these measures. Actions which require little effort compared to their impact are ones which have a good return and might be considered closely. Actions which have large effort compared to impact might have lower priority.

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