ALARPing risk reduction measures: Better quantification for better results

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At Hazards 28, Wood presented an approach for undertaking Cost Benefit Analysis following a MATTE assessment using the CDOIF methodology. EDF Energy operate the UKs entire fleet of nuclear power stations. These stations are all located on the coast and are Lower Tier COMAH establishments. Diesel and various water treatment chemicals pose a MATTE risk at these locations.

Wood have supported EDF Energy in undertaking CDOIF Environmental Risk Assessments across the fleet. Wood and EDF Energy worked together to undertake these assessments for the UK operational nuclear power station fleet in order to prioritise the implementation of further risk reduction measures and demonstrate that environmental risk from these stations has been reduced to ALARP.

This paper presents the approach in general and in particular the ALARP process. It gives real examples of how focused cost-effective changes can reduce environmental risk and the strategic approach taken to determining the most effective options or combination of options. It then presents the lessons learned from a large-scale implementation of this method across the COMAH establishments in the EDF Energy nuclear power station fleet including specific examples of measures, why some measures were determined to be more effective than alternative solutions. The paper also considers the metrics used in describing risk reduction, and how these environmental risk metrics can be best communicated to the various stakeholders involved in the process.

These lessons learned focus around three key themes:

1. How do we define our input values for Environmental ALARP assessments?

2. How do we effectively communicate value and risk to multiple stakeholders for environmental risk?

3. What efficiencies can be gained through looking at similar sites?

Keywords: CDOIF, ALARP, Risk, ERA, CBA

Introduction

Quantification in general terms gives a better understanding of the subject being assessed. In this case, we are trying to quantify the ‘benefits’ associated with reducing environmental risk and the ‘cost’ of making an improvement in order to undertake a sufficiently robust Cost Benefit Analysis (CBA). The methods to establish costs associated with improvements are well understood and thoroughly tested. The question is how effective in a practical sense is the As Low As Reasonably Practicable (ALARP) methodology when used as part of the CDOIF Environmental Risk Assessment (ERA) approach given it has the following key issues to overcome if it is to be useful:

- **Accuracy of frequency data and failure rates** - Numerical uncertainty exists around the frequency data and failure rates (including probability of failures on demand) which should be used. While this is true for all quantified risk assessments, it can introduce significant uncertainty into the assessment. Does the input data give useful output even if it is just a good estimate? This broad issue is not discussed further in this paper but it is part of the context for the discussion.

- **Quantification of benefits** - Numerical uncertainty around the “benefits” of reducing risk. For human health, ALARP demonstrations generally hang around one figure (~£2M) inflated from a figure of £1.34M published by the HSE in 2003 (HSEc, n.d.). However, there is to-date no guidance supported by the regulator for a method of establishing the costs associated with release of a dangerous substance into the environment. This is probably due to the difficulty of quantifying this value as there is such a larger number of variables associated with environmental harm including receptor types, inter-species variability of toxicity, recovery time, breeding cycles and migratory patterns etc.

- **Receptor aggregation** - Inherent in the ERA risk criteria is the definition of risk ‘per receptor per establishment’. The use of aggregation introduces a complexity which is greater than the typical ALARP demonstration associated with human harm. The methodology must provide sensible results for multiple chemicals (each with a range of release scenarios) and multiple receptors. A potential mitigation measure may focus risk reduction on one or two scenarios (e.g. an overfill trip system on a storage tank) or provide protection for a wide range of scenarios (e.g. a site interceptor designed to prevent a MATTE event for the worst-case fuel releases on site). The method must be effective at comparing these options without requiring a disproportionate level of input to complete.

This paper presents the experience of the use of the ALARP process for a series of studies on four nuclear power stations.

Definitions

Several terms are defined here for use throughout this paper:

- Effectiveness – This refers to the benefit (risk reduction) gained relative to the cost of the measure. It does not refer to the probability of the measure functioning correctly i.e. Probability of Failure on Demand (PFD) although this is implicitly considered within the calculation of benefit.
- Risk reduction – A reduction in the frequency of a certain level of consequence occurring as a result of risk reduction measures being implemented, which is presented in terms of frequency reductions in units of y^{-1}.
- Benefit – A reduction in environmental risk as a result of risk reduction measures being implemented, which can be quantified in £.
- Justifiable – This refers to an option where the costs are not grossly disproportionate to the benefits.
- Viable – This refers to an option which is believed by the assessment team to be technically and physically achievable within the constraints of the site and other operating restrictions (including regulatory).

Background

EDF Energy

EDF Energy is part of the EDF group and one of the largest energy companies in the UK producing 20% the UKs electricity. Almost two thirds of this electricity is produced by the eight nuclear power stations around the UK which can generate up to 8.9 GWe.

These stations comprise 7 Advanced Gas-cooled Reactor (AGR) power stations constructed between 1966 – 1988 and a Pressurised Water Reactor (PWR) power station at Sizewell constructed between 1988 – 1995. Two of these stations are located in Scotland, while the remainder are in England. Two of the English stations are located within the same COMAH establishment and are operated as two separate entities. Each of these eight stations is a lower-tier establishment under the COMAH regulations. All these sites are situated on open coastline or large estuaries to provide an adequate supply of cooling water.

The following COMAH dangerous substances are used on the various sites which have the potential to lead to a MATTE. They have been assessed for each station where they are held in sufficient quantities to lead to a MATTE.

- Fuel oil (oil) - Primarily for static combustion plant providing an essential electrical supply for use in the event of a loss of grid connection. Also used for the generation of auxiliary steam, vaporisation of CO_2 and some other heating and ventilation systems in the event that the main steam line supply is unavailable.
- Ammonia (aqueous solution) - Primarily for boiler feed water treatment to avoid acidic conditions thereby minimising corrosion.
- Hydrazine (aqueous solution) - Used as an oxygen scavenger to control concentrations of dissolved oxygen thereby minimising corrosion.
- Sodium hypochlorite (aqueous solution) - Dosed into the incoming cooling water to mitigate efficiency reductions in condenser and circulating water system plant due to biofouling.

CDOIF Environmental Risk Assessment

The Chemicals and Downstream Oil Industries Forum (CDOIF) is a forum group chaired by the HSE and comprises industry representatives and the key regulatory bodies in Great Britain. The CDOIF forum is 'a collaborative venture aimed at delivering health, safety and environmental improvements'. In 2013, the first revision of the forums guidance on *Environmental Risk Tolerability at COMAH Establishments* was published, it was updated to the current V2.0 in 2016.

Despite the plethora of other guidance offered by the forum, the CDOIF name has become synonymous with Environmental Risk Assessments. While these assessments are predominantly undertaken at COMAH establishments, it has also been applied elsewhere.

The CDOIF guidelines give a structured framework for benchmarking environmental risk across receptors and accounting for events of varying magnitude. They further build upon the DETR 1999 guidance. The guidelines have become the de-facto approach to assessing environmental risk and is stated in the Safety Report Assessment Manual as the benchmark standard to be applied for regulating COMAH sites.

ALARP

UK Health and Safety regulation widely applies a principle that risk to people or the environment should be reduced 'as low as reasonably practicable' (ALARP). For COMAH establishments, there is an additional emphasis on demonstrating that these risks have been reduced. This ALARP demonstration takes two main parts:

1. Demonstrate compliance with good practice
2. Demonstrate that further risk reductions are grossly disproportionate to the benefits gained.

Undertaking an ALARP assessment to demonstrate the above usually gives a site the opportunity to review and develop their systems and potentially undertake cost effective risk reduction projects.

The Environmental Risk Assessment process

Overview

As an operator with multiple COMAH establishments, EDF Energy chose to undertake the ERA process in alignment with the approach developed by CDOIF using the same phases detailed in that guidance. Each phase was reported individually at each station so each COMAH establishment will have comparable reports detailing the following phases:

- Phase 1 Part 1 (P1P1) – High-level receptor screening and identification of potential MATTE scenarios
- Phase 1 Part 2 (P1P2) – Detailed failure frequency analysis of station systems with MATTE potential and assessment of risk tolerability
- Phase 2 (P2) – ALARP demonstration including Cost Benefit Analysis of potential additional risk reduction measures.

The work was undertaken on a station by station basis so that one station may be undertaking Phase 1 while another may be in Phase 2. This staggered approach allows a more effective allocation of expert resources and for lessons learned / Competent Authority (CA) feedback to be applied at ensuing stations.

With the support of the CA, a Phase 1 Part 1 report was initially completed for a trial station which rigidly followed the CDOIF guidance and was communicated to the regulator in 2016. Submission of this detailed and conservative assessment demonstrated to the regulator an understanding of the process within EDF Energy. This enabled an informed discussion with the CA to agree a more streamlined bounding case approach for the remainder of fleet stations. Based on the common key characteristics of EDF Energy establishments the trial assessment demonstrated that the screening intention of the CDOIF Phase 1 process could be achieved with a focus on only the most exposed receptor(s) as identified by the consequence assessment. The resultant simplified S-P-R conceptual model was liquid dangerous substances via the surface water drainage network discharged into Surface Water category receptors. Ongoing feedback from the CA has identified further enhancements for incorporation into the Phase 1 report format allowing continual improvement as the project moves through the fleet.

The following overall approach was agreed with the relevant environmental regulators, SEPA and the EA, on behalf of the CA.

Consequence Assessment

A consequence assessment was undertaken by a marine biology specialist as part of the EDF Energy Phase 1 Part 1 assessments. These assessments were undertaken for the bounding CDOIF receptor category, Surface Water, to identify the most exposed receptor(s) specific to that establishment. This was completed using simple modelling techniques appropriate for a screening level assessment accompanied by expert judgement producing a conservative result. The assessment considered what harm/severity values, and therefore CDOIF consequence level, were appropriate for an unmitigated release of the largest single inventory volume for each dangerous substance held on site. The extent of the screening area was conservatively determined on the basis of either insoluble hydrocarbon fuels forming a slick on the surface of a waterbody down to a level well beyond the point at which a continuous thickness would be sustained or soluble ecotoxic materials which will disperse within the water column down to a representative LC50 divided by 3.

Thresholds

The first step of P1P2 was to determine upper and lower bound quantities for each of the substances which P1P1 indicated could lead to MATTE releases. Conservative assumptions were employed to give a robust manner to screen release scenarios of varying size. This was done via a simplistic linear extrapolation of affected area and mass released. A simplified example is given below.

> Aqueous sodium hypochlorite solution is stored on site with a maximum inventory of 50 te. If a release of 50 te can affect 50 ha of coastal (littoral/sub-littoral) habitat in the marine receptor for 1-10 years, this represents a MATTE B. If 1 te is needed to cause a MATTE level of harm over 1 ha, then it follows that any release over 2 te will represent a MATTE scenario (based upon a 2 ha threshold for severe). Accordingly, a 20 te release represents the boundary between severe and major (MATTE A & MATTE B) in this scenario.

This calculation was undertaken for each of the substances at each station and removed the need for detailed consequence assessment of every possible release scenario.

Frequency

The second element of the P1P2 assessment is the frequency assessment. A general HAZID had previously been undertaken on these systems prior to the consequence assessment. A quantified approach to frequency assessment was undertaken on the basis of engineering drawings considering static and temporary equipment failure as well as operational failure modes such as overfilling or incorrect delivery. The HAZID was used as the basis of to identify possible failure mechanisms, but these were expanded and developed to capture all potential release scenarios based on failure rate mechanisms and the resultant available data. The base failure rate and probability data was drawn from industry data sources, HSE guidance, data from supply chain and EDF Energy’s own records.

The detailed frequency assessment determines the unmitigated and mitigated event frequencies considering the PFD of the safeguards that are in place for each release scenario including the volume released. It also considers partial safeguards such as tertiary containment systems which may be reduce the MATTE level but not be capable of entirely eliminating it.

Risk

The final element of the P1P2 assessment is the risk integration and tolerability assessment. The risk is determined by applying the release thresholds for each MATTE level / substance to each scenario and summing the frequency of the relevant scenarios to determine the aggregated risk. The aggregated risk can be compared against the criteria in the CDOIF guidance which are plotted on the risk matrix below.

This example matrix shows the unmitigated event frequency (UEF) and mitigated event frequency (MEF) for two different receptor types at two MATTE levels.

Figure 1 – Station 2 MATTE Risk Matrix (after Phase 1 studies)

	Frequency per establishment per receptor per year						
Frequency at which CDOIF consequence level is equalled or exceeded	$< 10^{-7}$	10^{-7} - 10^{-6}	10^{-6} - 10^{-5}	10^{-5} - 10^{-4}	10^{-4} - 10^{-3}	10^{-3} - 10^{-2}	$> 10^{-2}$
D - MATTE							
C - MATTE	**Broadly Acceptable**			**TifALARP** MEF (Marine)		**Intolerable**	UEF (Marine)
B - MATTE				MEF (Marine)			UEF (Marine)
A - MATTE				MEF (Marine)	MEF (Ramsar)		UEF (Marine) UEF (Ramsar)
Sub - MATTE	Tolerability not considered by CDOIF						

For some stations over 100 different release scenarios were assessed. Those with a significant contribution to the risk were identified enabling the site and the ALARP process (Phase 2) to focus in the areas of highest risk.

The ALARP process

The P2 ALARP process was undertaken in two parts.

Firstly, for each system identified as having a scenario which significantly contributes to the environmental risk, an assessment against recommended good practice (standards and codes) was undertaken. This started by reviewing the HSE COMAH Technical Measures to determine which were applicable to the system scenarios which have a MATTE risk. When the appropriate Technical Measures had been identified, a gap analysis was carried about between current EDF Energy operation / arrangements and the latest codes and standards. This generates a list of actions and a preliminary list of improvement options.

Secondly, the options are then reviewed in a team workshop for viability and, using a cost benefit analysis approach, to identify options which need to be assessed further. The workshop used order of magnitude cost estimates and it was recognised that due to the complexity of the site and constraints of the nuclear safety case, each potential option may not ultimately be feasible due to a problem that the workshop team had not considered. For example, given that MATTE scenarios often impact the drainage systems, these can have complex impacts that require detailed engineering studies.

Further assessment is then undertaken after the workshop to identify the most effective option or combination of options to reduce the risk to ALARP. Sometimes this results in further action to validate CAPEX estimates or constructability and operability studies.

The cost benefit analysis uses a ball park CAPEX estimate provided by the workshop team to compare against the Maximum Justifiable Spend (MJS) for the risk reduction gained. Where the CAPEX is less than 150% of the MJS, these are screened in for further assessment. 150% is used to allow for uncertainty in the initial CAPEX figures. During the further assessment stage, these CAPEX estimates are refined, and the uncertainty factor mitigated.

At the further assessment stage, each screened in option was assessed to determine the most effective combination of options to determine how to achieve the lowest risk for the lowest cost. Although it should be noted that HSE guidance dictates that to achieve ALARP the greatest absolute risk reduction must be implemented to reach ALARP, rather than the most cost-effective (HSE, 2001).

Maximum Justifiable Spend (MJS)

The maximum justifiable spend for a risk reduction option is calculated to be the sum of the benefit gained at each MATTE level after applying a disproportion factor (DF). MJS is option specific, although it will be the same value for options which give the same risk reduction.

MJS is calculated using the formula below where x= MATTE A, MATTE B, MATTE C, MATTE D

$$MJS = \sum_{MATTE\ A}^{MATTE\ D} VPM_x \times\ DF_x \times \Delta F_x \times Remaining\ life\ of\ facility \qquad 1$$

Where:

DF is the disproportion factor at that MATTE level and is derived using the formulas described in (Davy, 2018).

VPM is Value of Preventing a MATTE at that MATTE level

ΔF is the risk reduction at that MATTE level

CAPEX Costs

It should be noted that the CAPEX figures for risk reduction measures on EDF Energy sites can be higher than would be anticipated in some industries. This reflects the fact that the cost of execution of projects on nuclear power stations can be high due to a combination of factors including site security / access requirements and the level of demonstration required to comply with the obligations of a nuclear safety case. A number of the systems are defined as safety critical in the site management system as a result of their nuclear safety case/site license implications and as such modifications receive an appropriately high level of scrutiny.

EDF Energy has chosen not to include operating costs within the assessment. These are harder to estimate and likely to be small in comparison to the CAPEX costs and therefore can be accommodated within the accuracy of the CAPEX estimate.

Key learning points from each station

Station 1

Station context

At Station 1, the Marine receptor was identified as being the most exposed CDOIF receptor type. The station held fuel oil, ammonia, sodium hypochlorite and hydrazine in quantities that could lead to a MATTE. The risk to groundwater was determined to be broadly acceptable. The risk to the marine receptor was dominated by sodium hypochlorite and fuel oil, and the aggregated risk fell within the TIfALARP region. Two release scenarios represent over 70% of the MATTE risk at the station, with the top seven scenarios contributing 94% of all MATTE risk at the station. These small number of scenarios were the focus of the ALARP assessment.

ALARP Process

The cost benefit analysis considered the potential improvements which could reduce the risk from the largest seven risk contributing scenarios which came from the fuel oil and hypochlorite systems. Initially 46 potential improvement options were screened by the team which led to 12 of these being taken for more detailed feasibility/effectiveness assessment.

At this station, there were four viable options for the gas oil systems and eight viable options for the sodium hypochlorite system. Of these options, it was evident that the implementation of at least one measure on each system would be justified as both systems have substantial risk contributions but there were no options which were able to reduce the risk of both sodium hypochlorite and fuel oil. This meant there was no interdependency between the two best options selected.

Upon further assessment, it was apparent that Option 4 was the most effective solution for fuel oil. An oil on water alarm in the surface water discharge chamber which provided £124k of benefit for £50k investment and was also favoured for ease of installation.

It is noted that by implementing Option 4 on the fuel oil system, this may reduce the justifiable spend on any further improvements on either system. While Option 4 is not directly connected to the hypochlorite scenarios, they are indirectly linked through the DF. If there is a sufficient reduction in aggregated risk, the DF applied to the remaining MJS will be reduced. This will lead to a step-change in the MJS, as the DF calculation works on an integer coefficient rather than a continuous scale. In this case, implementing Option 4 renders one of the eight hypochlorite options grossly disproportionate.

A number of the remaining sodium hypochlorite risk reduction options are broadly similar in terms of their effectiveness. However, it is noted that one option (Option 46) reduces the risk from the system to Broadly Acceptable levels. The HSE guidance states '*The option, or combination of options which achieves the lowest level of residual risk should be implemented, provided grossly disproportionate costs are not incurred*'. So while Option 46 is not the most effective in terms of risk reduction and CAPEX, neither is it grossly disproportionate and therefore it is recommended for implementation.

Lessons learned

For an establishment, where the risk is dominated by a few scenarios across different systems, it is possible that the viable potential risk reduction measures will be independent. Such that implementation of one measure does not drastically alter the attractiveness of options on the other system. In this case, it made all the options less favourable by a similar proportion but it rendered one option grossly disproportionate. However, it does not drastically alter the other options, it is therefore important to understand where the risk is coming from to justify further spending on risk reduction measures. In this case, presenting the risk and justifiable spend separately by system allows the stakeholders to understand the maximum viable cost of additional improvement options to each system and to select justifiable options that achieve the lowest residual risk in line with the HSE guidance.

Station 2

Station context

At Station 2, there were two relevant receptors, the marine receptor and a Ramsar site located within and adjacent to the marine receptor. The station held fuel oil, ammonia and hydrazine in quantities that could lead to a MATTE. For the marine receptor, at MATTE A, the risk was split evenly between fuel oils and hydrazine while at higher MATTE levels, the risk was dominated by hydrazine release scenarios.

While Ramsar sites are designated wetlands, the particular feature which was identified in P1P1 to be exposed to MATTE level harm were seasonal fish populations which further reduced the likelihood of an impact at this location. The risk posed to the Ramsar site is extremely small only just over Broadly Acceptable so the contribution to the justifiable spend in risk reduction is insignificant.

ALARP Process

When looking at potential improvements, as there was already extremely low risk to the Ramsar receptor, there was a maximum justifiable spend of only approx. £50 to reduce the risk of all scenarios affecting the Ramsar to Broadly Acceptable levels. In this case, the review focused on any improvements in operational practice as the cost of physical upgrades would be grossly disproportionate and not justified.

The cost benefit analysis considered the potential improvements to fuel oil and hydrazine systems and computed these against the risk reduction to the marine receptor. Initially 56 improvement options were screened by the team which led to 10 of these being taken for more detailed feasibility / effectiveness assessment.

At this station, there were two viable options for the fuel oil systems and eight viable options which could reduce the risk from the hydrazine system. Of these options, it was evident that the implementation of more than one measure would be justified. However, this brings the additional complication of interdependence, where the implementation of one option drastically reduces the risk reduction gained if then a second option affecting the same scenarios were to be implemented.

Options 38 and 48 both reduce the risk of a MATTE by reducing the frequency of the same scenario, a leak from a specific section of hydrazine pipework. These two options were flagged during the ALARP workshop as delivering the highest risk reduction for the lowest cost. However once one of the measures is implemented, the residual risk has changed substantially, such that an option that previously could have justified >£300k of CAPEX will now only deliver <£10k in benefit. This is illustrated below.

Table 1 - Station 2 Comparison of Options 38 and 48

Option No.	Description	CAPEX	Standalone		If other measure already implemented	
			Risk Reduction	**MJS**	**Risk Reduction**	**MJS**
38	Double walled pipework	£25k	2.88E-5	£389k	3.17E-7	£4.3k
48	Secondary containment around pipework	£10k	3.17E-5	£428k	2.88E-7	£3.8k

An assessment was then undertaken on the fuel oil systems to determine which options provided the greatest reduction. Option 7 was selected as giving the greatest risk reduction as well as the most cost-effective. Following the initial selection of Options 7 and 48, there was still a maximum justifiable spend of up to £172k on the hydrazine system. Options 35, 36, 37, 41, 42 and 52 remained justifiable with CAPEXs ranging from £5-50k. Of these remaining options, Options 41 and 42 and Options 35 and 36 were both mutually exclusive pairs similar to Options 38 and 48 above.

However, as two substantial risk reduction measures have already been selected, the residual risk is already much reduced. Therefore, the MJS should be recalculated to ensure that only justifiable options which are not grossly disproportionate remain in consideration. As the remaining Options are independent of the release scenarios which have already been mitigated, the absolute risk reduction of the remaining options are unchanged, so only the change in DF needs to be reconsidered. Based on the station initial aggregated risk, the DFs for MATTE A, B and C were 1, 5 and 9. After the implementation of Options 7 and 48 these factors are reduced to 1, 3 and 7.

While Options 41 and 42 are mutually exclusive, previously there was no obvious choice between them. Option 42 delivered a greater risk reduction but at a much greater cost such that selecting it without considering the other combinations may not be the most favourable solution, as Option 41 in combination with another option may deliver a greater risk reduction for less cost. However, once we revise the cost benefit analysis, it becomes obvious which option should be selected as Option 42 becomes grossly disproportionate once Options 7 and 48 are 'implemented'.

A revised Cost Benefit Analysis of these two options is shown below.

Table 2 - Station 2 Comparison of Options 41 and 42

Option.	Description	CAPEX	Initial MJS	Revised MJS	Grossly Disproportionate
41	Replace plastic IBCs with steel	£10 k	£34 k	£23 k	No
42	Use of dedicated delivery vehicle	£50 k	£61 k	£41 k	Yes

Only one other option remains justifiable after the implementation of Options 7 and 48, and that is Option 52. After the implementation of Options 7, 41 and 48, it still delivers £13k of benefit for ~£5k CAPEX. All further options assessed are now grossly disproportionate.

Based on this, these four Options (7, 48, 41 & 52) were recommended as the most effective solution. They deliver the lowest level of risk for options which are not grossly disproportionate. As no further options have been identified which are not grossly disproportionate, then the risk is demonstrated to be ALARP.

For the four Options, the benefit can be quantified as £643k of risk reduction for an estimated investment of ~£60k.

Lessons learned

For an establishment, where a few scenarios dominate the risk, it is likely that viable potential risk reduction measures will overlap. However once one of the measures is implemented, the risk profile has changed substantially, so that risk reductions measures that are favourable when considered in isolation may not be justifiable in combination. It is important therefore to ensure that all measures justifiable in isolation are screened in for further assessment as the most effective combination of measures might not be that which is a combination of the most individually effective measures. However, there is no necessity to screen in measures which aren't justifiable in isolation as implementation of any risk reduction can only reduce the effectiveness of other measures.

It is also essential to ensure that the change in risk is calculated accurately considering the interdependencies of scenarios when selecting a combination of measures to implement to ensure that risk benefits are not 'double-counted'. It is further important to ensure that when options are selected and sequential options are being considered, the benefits are reassessed to confirm that they are still justifiable after other risk reduction measures have already been implemented.

Station 3

Station context

At Station 3, the main receptor was the marine environment. The station held only fuel oil in quantities that could lead to a MATTE. The risk at MATTE A was very close to the broadly acceptable threshold, it was dominated by releases from an extensive pipework run on one of the smaller fuel oil systems. At higher MATTE levels, the risk was spread evenly over a relatively large number of scenarios.

ALARP Process

The ALARP workshop initially identified 33 potential options which could be implemented on the fuel oil system. Following the workshop and CBA, four of these were identified as viable and justifiable and taken forward by the team for further assessment.

As the risk was fairly evenly distributed, none of the options focused on only a single scenario. Two focussed on the largest fuel oil system, and the other two were 'global' measures which affected almost all of the potential fuel oil releases. This presented a similar issue to Station 2 where the options were not independent, however as the overall site risk was lower, it was unlikely that multiple large-scale measures would be justifiable. In this case, a simpler risk evaluation was used based upon site wide MJS.

Initially, the MJS for reducing the whole site to Broadly Acceptable levels was initially calculated to be ~£180k. For the purposes of screening, each measure was presented with their CAPEX, benefit and the remaining MJS for reducing the entire site to Broadly Acceptable levels. This is demonstrated below.

Table 3 - Station 3 Assessment of Options

Option No.	Description	CAPEX	Benefit	Remaining MJS
2	Alarm on bulk tanks	£50k	£109k	£70k
3	Sump level alarm	£40k	£141k	£38k
7	Oil on Water alarm	£50k	£170k	£10k
8	Oil on Water trip	£70k	£173k	£7k

Three of the four measures have substantial enough benefits that all other options become unjustifiable. However, the cost benefit analysis indicates that options 3, 7 and 8 are broadly equivalent in terms of effectiveness but that one of them should be implemented. At this stage these options were taken forward for further evaluation to determine which was the most favourable in terms of operability, constructability and to refine the CAPEX estimates.

Lessons learned

For an establishment, where no scenarios dominate the risk, 'global' solutions or those targeting whole systems are likely to be the most effective. While these options can be expensive, they may target a large number of risk contributors and ultimately justify that the risk is ALARP without further measures. However, with these global measures, there is increased potential for operability issues or feasibility issues on a site with limited space where new facilities can be built. These must be factored in when making final decisions.

Station 4

Station context

At Station 4, the most exposed CDOIF receptor type was again identified as being the Marine environment. The station held fuel oil, and hydrazine in quantities that could lead to a MATTE. The risk was dominated by fuel oil with 97% of risk at MATTE A, 75% at MATTE B and 100% at MATTE C. However, the risk within each substance was evenly spread across a large number of scenarios and systems.

Prior to this assessment and for other reasons, initial consideration had been given to installation of a large outfall separator by the station. Several versions of this were examined in detail during this study.

ALARP Process

The cost benefit analysis considered the potential improvements to fuel oil and hydrazine systems. 48 improvement options were screened by the team which led to six of these being taken for more detailed feasibility/effectiveness assessment. At this station, there were five viable options for the gas oil systems and one viable option which could reduce the risk from the hydrazine systems.

Three of these options that were initially thought to be extremely effective were variants on the outfall separator proposed by site. However, given the extremely high CAPEX costs of modifying the outfall of an operational nuclear power station, they were all shown to be grossly disproportionate for the reduction in MATTE risk. The site had an MJS to reduce all MATTE risk to Broadly Acceptable of ~£410k and the cheapest option had a CAPEX of £750k.

Of the remaining options, the two gas oil solutions were mutually exclusive as implementing Option 2 reduced the benefit of Option 3 by an order of magnitude, such that it was unjustifiable. Option 2 was a solution on one of the large fuel oil systems, while Option 3 addressed one scenario on that same system. The remaining hydrazine option (Option 47) was independent from the fuel oil options and implementation was justified.

For comparison, the three possible combinations are shown below.

Table 4 - Station 4 Comparison of Option combinations

Options	Total CAPEX	Benefit
2 & 47	£85k	£265k
3 & 47	£40k	£71k
2, 3 & 47	£105k	£266k

All of the combinations are justifiable in isolation, although as can be seen by the table above, Options 2 and 47 gives the most effective risk reduction. The additional implementation of Option 3 gives less than £2k in additional benefit for an extra £20k of spend (clearly not justifiable). In this case, the combination of options which results in the lowest residual risk is also the most cost-effective.

Lessons learned

For this establishment, where no scenarios substantially dominate the risk, global solutions are likely to be more effective. This station illustrates an example where a scenario specific solution and system-wide option were compared. When considered in isolation, both are justifiable but considered in conjunction, Option 3 is grossly disproportionate.

This also demonstrates the value of better quantification as the three options evaluating different size outfall separators were positively promoted initially as they would allow the risk to be reduced by the largest amount. The largest of the options would allow the risk to be reduced to Broadly Acceptable levels across the whole site when installed in conjunction with Option 47. However, quantification of the costs and benefits determined these to be grossly disproportionate and allowed more effective solutions to be adopted. The options selected deliver £265k of benefit for £85k CAPEX as opposed to £410k benefits for a CAPEX of £1.52m.

It should however be noted that the CBA only indicates that the cost of the outfall separator is grossly disproportionate to the benefit gained in terms of MATTE risk reduction. It cannot indicate that you should not install one. There may be other external drivers for such a project which if quantifiable could be factored into the assessment or override the ALARP considerations.

Summary

A similar approach has been employed across all four stations, the method has been tailored in each case to the specific differences of that station, whether it be the number of receptors or the interdependency of the options being assessed.

The following table provides a high-level summary of the data involved in these assessments. It shows how the process works on a macro level – starting with a detailed frequency/risk assessment, generating a large number of options and whittling these down to a small number of targeted and effective options for implementation to achieve ALARP at the lowest possible cost.

The risk values are colour coded to indicate Broadly Acceptable, Tolerable If ALARP or Intolerable.

Table 5 - Summary of Phase 2 assessment outcomes

	Station 1	**Station 2**	**Station 3**	**Station 4**
Number of Chemicals studied	2	3	1	2
Number of Receptors studied	1	2	1	1
Initial Overall Risk:				
MATTE A-D	2.63E-04	8.95E-05	6.57E-05	1.13E-03
MATTE B-D	2.43E-04	7.25E-05	2.88E-05	1.14E-04
MATTE C-D	-	5.84E-05	1.73E-05	2.34E-05
Improvement options generated	46	56	27	48
Number of options to progress *	12 further assessment 2 to be developed for implementation	10 further assessment 4 to be developed for implementation	4 further assessment 1 to be developed for implementation	6 further assessment 2 to be developed for implementation
Cost of proposed measures*	£130k	£60k	£70k	£85k
Final Overall Risk				
MATTE A-D	3.92E-05	4.73E-05	6.57E-05	3.41E-04
MATTE B-D	3.52E-05	3.04E-05	2.46E-05	6.73E-05
MATTE C-D	-	1.62E-05	4.01E-07	1.24E-05

*The proposed measures are those which were proposed as the most effective options from the assessment, these will then be subject to further feasibility analysis by EDF Energy’s engineering teams for implementation.

Lessons Learned – Key themes

How do we define our input values for Environmental ALARP assessments?

Value of Preventing a MATTE

The Value of Preventing a MATTE (VPM) is the cost that should be borne by the duty-holder to prevent a specific MATTE consequence level from occurring. In practice, this is applied as reducing the likelihood that this event will occur from 1 (i.e. certain to happen every year) down to Broadly Acceptable levels.

However, the valuation of the environment is one of the key unknowns within the Cost Benefit Analysis. It is the least easily quantifiable of the criteria which influence the outcome. This is because we are trying to monetise the benefit gained by a wide spectrum of possible events not occurring and the complexity of those environmental systems which could be affected.

The environment has no intrinsic concept of value, any valuation of the environment is a subjective valuation placed on it by societal judgement. As discussed in a previous paper (Davy, 2018), there are many factors that can be accounted for when determining the benefit of a reduced risk.

Development economists use various methods to determine this value for cost benefit analysis of infrastructure projects and central government investment decisions. Some of these models are based upon stated preferences, revealed preferences or market values but the focus tends to be on macro-economic factors and these are difficult to scale for a proportionate CDOIF assessment.

In other cases, specific studies have been undertaken examining the likely costs as a result of environmental major accidents or historic land contamination (English Partnerships, 2008) (OPOL and Oil & Gas UK, 2012).

For all of the EDF stations, the marine receptor is the most exposed and most sensitive. After careful consideration and benchmarking, values of £1m, £10m and £100m were selected to represent the cost of MATTE A, MATTE B and MATTE C. This represents a valuation of £50k-500k per ha of affected area.

These values were deemed to be reasonably representative of the likely costs of an incident at an EDF Energy nuclear power station considering spill response, environmental remediation, regulatory enforcement action and other related costs. It also aligns to the examples given in Appendix 3 of All Measures Necessary (COMAH Competent Authority, 2016). They were specifically chosen to be a factor of 10 apart to ensure that the link between the tolerability of the risk (as defined in CDOIF) and the benefit of reducing it, is consistent.

Sensitivity analyses were undertaken using values that were half of the proposed values and five times higher i.e. £0.5m and £5m for MATTE A. In most cases, even when substantially increasing the VPM values, it does not drastically alter the results of the assessment. Taking Station 3 below as an example, increasing the VPM by a factor of 5 leads to 4 additional options being screened in for assessment, however, the final conclusion remains. i.e. that there remains a single option which can be implemented to reach ALARP. However, if higher VPM values are used, it will justify spending more in total (if it is required) to reach ALARP.

Additionally, changing the VPM has no effect on the order of prioritisation as it affects all scenarios equally. All the MJS values go up proportionately, so would justify spending more in total, but the frequency reduction remains the same. The option or combination that should be selected remains that which gives you the greatest frequency reduction (i.e. lowest residual risk) subject to them not being grossly disproportionate.

How do we effectively communicate value and risk to multiple stakeholders for environmental risk?

While all of the stations above are assessed against the same basic premise (*'is the station ALARP?'*), the specifics of each station are different. The frame of reference for the stakeholders to the ALARP assessment also vary widely. The accountant needs to know how much these measures will cost, the regulator may care more for the residual risk and the assumptions used to justify gross disproportion, while the study itself hinges on the accurate quantification of costs and benefits. How this is communicated to stakeholders is important, especially to stakeholders who are not risk specialists. For most people, a unit of £ is more accessible than a unit of y^{-1}.

Drawing on the maxim, that 'everything should be as simple as it can be, but no simpler' in some cases, a simplistic metric can be applied. As seen at Station 3, once it was determined which options were justifiable, the only metric presented was the sequential MJS. 'If I do this, how much more do I need to spend?'. This allows you to find the options which are effective enough on their own that the site does not need to implement further risk reductions. It communicates this in simple terms that lay-people can understand, e.g. you only need consider further options under £50k.

However, for other stations, the picture is more complex. Where a station may require more than two options to be implemented to reach ALARP, there are considerations about the effectiveness of the individual measures within that combination. For example, if there are three options and Option 1 is the most individually effective, it is possible that the most effective combination for reaching the lowest residual risk (i.e. achieving ALARP) is the implementation of Options 2 & 3. In these cases, it is possible to present the various combinations with their combined CAPEX and benefits, which provides a simplified approach to visualising the difference between the various combinations as those with the highest benefit values will have achieved the greatest risk reduction / lowest residual risk as shown in the Station 4 example above. Taking lowest residual risk as the primary driver, will in some cases force sites to select combination of options which is not the most cost-effective, but the test of gross disproportion always ensures that they will be a net benefit.

What efficiencies can be gained through looking at multiple stations?

There are various efficiencies that can be gained by evaluating multiple stations.

Firstly, while the stations were built at different times they have broadly similar systems in many regards and comply with the same internal EDF Energy standards and procedures. This generally means a similar standard of protection has been applied across the fleet. Some of the UK stations are also 'sister stations' where they were designed and built in parallel meaning the assessment from one station can be more easily adapted for considering another.

Secondly, some of the core technical decisions for the CDOIF risk and ALARP assessments affect all the stations and have been made centrally to ensure that the process is consistent across the fleet. One of these is the decision to use the same VPM values across the whole fleet and the same minimum MATTE thresholds for the marine receptor at each station.

Thirdly, the first assessment becomes the template for the rest. This expedites the process and also makes the information gathering process more efficient while still being tailored to each station.

Finally, data has been shared between the stations to inform the assessment. A lot of the data gathered during the course of the assessment has been applicable across the fleet. Eight stations with between 23 and 42 years operational experience provides a substantial dataset for accident records, failure rates and frequency inputs.

Conclusions

The ALARP process works. It requires a detailed frequency assessment for releases in combination with threshold consequence values and understanding of environmental harm pathways. The process described above works because it allows different options to be prioritised against each other and against other combinations of options. This is true for all VPM values unless the ratio of the VPM value A:B:C (1:10:100) changes, i.e. if the operator wished to apply a scale aversion factor, the process would still function but the options could be in a different order of preference.

This approach has been iteratively developed as we have faced different challenges on the different stations. This has gained multiple benefits including the sharing of ideas regarding risk reduction. It has ensured that the methodology is robust and is suitable for application across varying stations. This process has also been the subject of ongoing discussion with the CA with the overall approach agreed back in 2016. The process has been tweaked following feedback on the submitted Phase 1 reports.

Our experience is that it gives a clear output which can be understood by those who are not Technical Safety specialists. It can provide either a prioritisation of measures or selection of combination of measures which provide the greatest risk reduction for the lowest CAPEX i.e. the combination of options which leave the lowest residual risk.

However, there are intricacies which need careful attention when calculating the benefit of multiple options based upon the interdependencies of safeguards. In a scenario where multiple materials, multiple options, or multiple receptors are involved, the calculation is further complicated but still effective and potentially more valuable.

The outputs of these assessments can and should be tailored to ease decision making depending on the nature of the best solution for that site. In a case where there are a large number of interdependent options, metrics to determine the most effective solution can be used. On a site, where a single large solution should be implemented, then a simple benefit value calculation may suffice. This form of scalable quantification can ease decision making by answering the right questions, it can allow the assessment team to overlook the complexity and choose the most effective solution to deliver the lowest risk.

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