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Research Report on Multi-Unit Level 3 PSA – Executive Summary

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ENGINEERING RISK SOLUTIONS

LEVEL 3 MUPSA EXECUTIVE SUMMARY

Due to the commercial content of the report, with proprietary input data being provided by nuclear industry vendors and operators, an extended executive summary has been written for publication. The main report contains the detailed results and proprietary information.

This study investigates the potential consequences of a multi-unit accident. It does not consider the potential frequency of multi-unit accidents. It should be noted that a number of simplifications have been made to support this study. These simplifications do not impact the conclusions; however they do prevent the results being directly comparable to extant safety case submissions.

1 INTRODUCTION

The United Kingdom (UK) Office for Nuclear Regulation (ONR) expects nuclear site licensees to understand the risk posed to the public from offsite releases of radionuclides, including any potentially large releases following accident scenarios. For nuclear reactor operating sites, this expectation is typically met by carrying out a Level 3 Probabilistic Safety Assessment (PSA). This level of PSA models dispersion of radionuclide releases beyond the site boundary, the potential radiological doses amongst the population from shine, inhalation or ingestion of those radionuclides and the consequential deterministic and stochastic health effects.

For economic and operational reasons, it is common for two or more nuclear reactors (units) to be located on the same nuclear licensed site, sometimes with shared systems. There is the potential for multiple units on a site to be affected by a single event such as an earthquake or a loss of offsite power. If core damage ensues from such a multi-unit event, the result may be multiple radionuclide releases close together in time (i.e., within some hours or days).

When assessing the potential health effects to the public of multi-unit releases, one approach has been to sum the consequences of the independent releases from the affected units. The rationale is that such an approach was believed to be conservative. In the most recent update to the ONR Technical Assessment Guide (TAG) for PSA, it is stated that for evaluation of off-site consequences 'Additional consequence analysis may be required to evaluate the consequences of a multi-unit accident. For example, a seismic event may be considered to lead to a release on multiple similar facilities, with a similar or higher frequency than a single unit release, and therefore additional consequence analysis should be performed.' The ONR has commissioned Jacobsen Analytics to investigate whether this guidance is sufficient.

2 METHODOLOGY

This study makes use of the state-of-the-art tools for Level 3 PSA, namely Probabilistic Accident Consequence Evaluation (PACE) v3.3.3 developed by

Public Health England (PHE) and Numerical Atmospheric-dispersion Modelling Environment 3 (NAME3) developed by the UK Met Office. Using these tools, the consequences of multiple simultaneous or staggered releases are compared to the linear sum of single-unit releases using a common metric: the Safety Assessment Principles (SAP) Targets 7 and 9 for individual and societal risk, as well as a number of other metrics. The study also includes a literature review that examines what other work has been carried out internationally on this topic.

A two-step process was followed to investigate the consequences of multi-unit accidents using PACE.

- Step 1: Model a number of single-unit radionuclide releases in PACE to inform the selection of the multi-unit scenarios:
  a) Include a variety of realistic source terms.
  b) Include two representative sites.
  c) Sample from a large number of weather conditions.
  d) All other model variables to be held constant. Choice of model parameters to be justified, where relevant.
  e) Interpret the results and identify which source terms and release locations would provide greatest insights into multi-unit consequences (e.g. scenarios where population close to dose thresholds for early fatalities).
- Step 2: Model a number of multi-unit release scenarios in PACE and determine the SAP Target 7 and 9 values.
  a) Consider both simultaneous and offset multi-unit releases at different sites
  b) As for Step 1, sample from a large number of weather conditions and record model parameter choices.
  c) Compare consequences from multi-unit scenarios modelled in PACE with those obtained by simple addition of the consequences from the single unit scenarios

This study does not consider the frequency of multi-unit accidents. If multi-unit releases could be shown to be very low frequency events, this would impact the importance of any recommendations made in this report, especially where these impact the assessment of compliance with SAP targets for a site. However, the multi-unit release at Fukushima Daichi in 2011 suggests that such events are possible, making it important to understand their potential consequences and how these scale relative to single unit releases.

PACE does not currently allow multiple release locations and so it is assumed the release from both units occurs from the same location. The research discussed in the literature review supports the argument that modelling the release from an average location is a reasonable approximation for stochastic effects. For early fatalities, the approximation begins to break down for doses close to the site boundary if the two units are not in very close proximity (i.e. separate by perhaps 1km), something not typical for UK nuclear licenced sites.

The process of producing the simple additive consequences (step 2c above) is by linear combination of the single unit consequence percentile curves to generate a predicted multi-unit curve. The detailed procedure followed is to sum the consequence values (i.e., the total number of fatalities with CM) at each percentile from the two single unit scenarios, across the whole percentile range. This process of constructing a new percentile curve by linear combination of the single unit curves can be applied for all the risk metrics presented in this report, though as indicated below, it is only necessary to actually construct the predicted curve in the case of the Target 9 metric, due to the different nature of this metric.

For the SAP Target 9 probability, a new, predicted, value for the multi-unit case can be derived by identifying the new percentile value (on the constructed curve) for which 100 deaths occur. The constructed curve has to be explicitly created to do this.

For mean numbers of deterministic and total fatalities, the mean values from the single unit analyses can be summed directly. For a mean value, this direct sum is identical to the result that would be obtained by constructing a predicted fatalities-percentile curve and calculating the mean across that curve. This is due to the properties of the mean value, which allow a short-cut calculation to be performed.

As Target 7 is a mean value, the values from the single unit cases scenarios are simply added together for the simple additive scenarios. As above, this works because of the properties of the mean value and the short-cut calculation route is valid.

It is noted that the approach described above differs from some previous analyses for the Target 9 metric. These previous analyses simply multiplied by two all consequence values including Target 9.

In addition to investigating multi-unit effects, some discussion is provided on the effect of including a low dose threshold (in the mSv range) on the total long term cancer fatalities consequences, particularly when the number of fatalities is dominated by stochastic effects. Although the linear no-threshold model is currently used to calculate cancer fatalities, it is possible that a threshold model could be introduced in the future as advances in radiological consequence understanding are made.

The release source terms used for the single and multi-unit analyses were provided by the ONR. The source terms include a representative source term developed by the ONR for SAP Target 9 studies, as well as source terms provided by reactor designers and site licensees. For some source terms, nuclides with a very low contribution to dose were excluded to improve PACE model run times. PACE performs a simple dose calculation as part of the source term module to allow nuclide prioritisation. Two locations were considered, a site in the south west and a site on the east coast.

The multi-unit cases represent simultaneous and staggered releases of radionuclides using the same source terms as were used for the single-unit cases. The chosen cases were selected to include releases from both locations.

3 CONCLUSIONS

This study has investigated the consequences of multi-unit releases using the offsite consequence analysis software PACE.

Six single unit source terms were selected from data provided by the ONR representing various core damage and spent fuel pool accidents with a range of magnitudes and release properties.

Based on the results from the single unit runs, a series of multi-unit source terms were developed and calculated. Six of the multi-unit combinations assumed simultaneous release. Increasing the time offset between releases was analysed for a particular source term at the east coast site, with 6, 12 and 24 hour offsets used in addition to simultaneous release.

The results from the multi-unit cases were then compared to the linear combination of the constituent single unit source term results. This approach was to give insight into how the consequences from multi-unit releases may differ from single unit releases. The potential for this linear combination approach to accurately predict key risk metrics was assessed.

This study has shown the complex nature of radiological consequence analysis, particularly when considering time offset between multi-unit releases. Release location, source term, atmospheric conditions, population distribution and countermeasures interact to produce distributions for the consequences analysed in this study. A time offset can have a significant impact on the shape of these distributions as different weather conditions prevail at the time of each release, dispersing plumes over wider areas.

The findings are summarised below.

3.1 SAP METRICS

The key SAP risk metrics assessed in this report are Target 7 for individual risk of death for the most at risk person and Target 9 for the probability of 100 eventual fatalities.

3.1.1 Target 7

The individual risk of fatality is calculated within the PACE software. The maximum risk is identified from each met sequence and the mean of all these maximum values is used as the Target 7 value. Note that PACE includes the stochastic risk as part of the individual risk of fatality.

For the simple additive cases, the Target 7 values from the single unit cases were added together. This was then compared to the multi-unit result.

- A simple additive approach tends to overpredict the Target 7 risk for cases with a high risk (i.e. when both contributing source terms result in deterministic deaths) and underpredict the Target 7 risk when combining single unit releases with a low risk (below 0.01). It is a good approximation when combining source terms with a moderate Target 7 risk. This behaviour is as expected when combining risk factors between the values 0 and 1.

- The Target 7 value was seen to decrease with time offset. This was due to increased dispersion leading to lower individual doses close to the release and potentially an increase in the area impacted by countermeasure implementation. Whilst an individual is more likely to receive a small dose than for a simultaneous release, they are less likely to receive a high dose. This relationship is dependent on the interaction between the statistical variability of the local weather conditions and the source term released. In the scenarios studied in this report, the interaction between these factors resulted in a lower mean value overall when time offset is increased. This is supported by findings from other studies identified in the literature review.

3.1.2 Target 9

The Target 9 metric is obtained from the percentile distribution of total fatalities with countermeasures in place. From this, the probability of 100 fatalities can be identified.

- Directly adding the Target 9 values from two single unit scenarios is a conservative predictor of Target 9 probability for a multi-unit scenario that includes those same two source terms. However, such a simple technique has clear limitations given the Target 9 metric is a value between 0 and 1. An improved technique is therefore proposed, this being described in the next item.

- An improved technique of predicting the Target 9 value from single unit results was applied in this study. This technique uses a linear combination of the single unit consequence-percentile curves for total fatalities with countermeasures, to enable the multi-unit Target 9 value to be re-evaluated from the resulting curve. This linear combination approach provides a good approximation for multi-unit Target 9 probability for scenarios with simultaneous releases.

- The linear combination was a good approximation for the Target 9 probability for the 0 and 6 hour offset cases but underpredicted the probability for the 12 and 24 hour offset cases, by 8% and 19% respectively. The higher Target 9 probability occurs because there is an increased likelihood of weather conditions resulting in around 100 deaths, which is a relatively low consequence for this source term. This is due to increased variability of the wind direction and other weather conditions over the duration of the release. The same trend was seen for the probability of 1000 deaths for the case studied, although the underprediction was lower at 6% and 11% for the 12 and 24 hour offset cases respectively. A source term which results in lower consequences than that studied in this report may show different behaviour for the Target 9 metric. Similarly, a metric evaluating the probability of some higher number of fatalities (e.g. probability of 10,000 deaths) will likely show a decrease rather than an increase with time offset; it is highly dependent on the release properties and the release location due to the interaction of factors such as population distribution and weather conditions as well as the release magnitude.

- All the scenarios studied in this report considered either combinations of source terms with very different release magnitudes (so one of the releases was very dominant) or a combination of two identical source terms. It is possible that a combination of two source terms with similar magnitudes but very different release durations may show similar non-linear behaviour for the Target 9 metric as for the time offset cases, but this was not investigated in this study.

- Target 9 is insensitive if either of the component releases already leads to a Target 9 value of 1 (i.e. if at least one of the single unit releases is very large) as Target 9 cannot exceed a value of 1.

3.2 DETERMINISTIC FATALITIES

- A linear combination accurately predicts mean deterministic deaths if only one out of the two source terms leads to deterministic deaths when released on its own (as a single-unit scenario).

- A linear combination was found to underpredict the mean number of deterministic deaths when both single unit source terms cause deterministic deaths as a single-unit release, for the cases of this type studied in this report. This is due to the use of the threshold risk model for deterministic fatalities, leading to super-linear behaviour and cliff-edge effects. This underprediction was found to be 17% without countermeasures and 57% with countermeasures.

- The use of countermeasures, which also have an implementation threshold and are limited by distance, magnifies the super-linear impacts for the multi-unit scenario based on two single unit releases that individually lead to deterministic fatalities.

- Deterministic consequences were found to occur at further distances from the release for multi-unit releases compared to the single unit release.

- When a time offset is introduced between releases, the likelihood of small numbers of deterministic fatalities is seen to (generally) increase with time offset but the mean and the consequences at the higher end of the distribution curve decrease. This was due to the increased likelihood of the weather resulting in a small dose above the threshold to a larger area of the population but a lower likelihood of higher doses due to the increased dispersion. This behaviour is complex and is expected to be highly dependent on the interaction between the time offset, release progression and release location.

3.3 STOCHASTIC FATALITIES

- The simple additive approach provides a very good approximation for the total number of fatalities for simultaneous releases.

- The impact of the time offset on the consequences was seen to vary over the percentile distribution curve. At lower percentiles, a higher offset tended to result in higher consequences due to increased likelihood of more individuals receiving a dose, whereas at higher percentiles a smaller offset appeared to result in higher consequences due to a concentrated plume over a highly populated area. The nature of the relationship between offset and consequence is likely highly dependent on release location and locally prevailing weather conditions, including any periodic variation in those conditions.

- As discussed in the literature review, another study performed in the US described this complex behaviour as showing synergistic effects between the timing offset and other contributing factors.

- Although the linear no threshold model is currently the preferred model when calculating stochastic deaths, any change to the approach could also have implications for how multi-unit consequences scale from single unit consequences. Investigations of the results generated in this study suggested if a dose threshold model were to be applied, a linear combination of single unit results may underpredict the total number of fatalities. In other words, introduction of a threshold could lead to stochastic fatalities scaling analogously to deterministic fatalities.

3.4 RECOMMENDATIONS

The current guidance in the PSA TAG states that 'Additional consequence analysis may be required to evaluate the consequences of a multi-unit accident.'

The findings presented above show that a simple additive approach is a good approximation of the risks and consequences in many cases. However, certain multi-unit cases require more analysis in order to fully understand the potential consequences, particularly in cases where deterministic fatalities are predicted. There may therefore be a need for additional analyses to ensure ALARP requirements are met. The following recommendations aim to provide clarity on where additional analysis should focus.

Recommendation 1:

- The accuracy and usefulness of the Target 9 metric can be improved on by using a linear combination rather than a simple addition of the probabilities. Therefore, estimates of multi-unit Target 9 probabilities should be derived from linear combinations of the single unit total number of fatalities with countermeasures distributions. Though usually conservative, simply adding the two single unit Target 9 probability values produces less accurate estimates than the linear combination of distributions.

Recommendation 2:

- The simple additive approach may underpredict mean deterministic fatalities, especially when countermeasures are modelled. Therefore, further analysis is required to ensure potential deterministic consequences are fully understood for the multi-unit releases. This further analysis should focus on scenarios where deterministic fatalities are expected and could be limited to an appropriate area near to the plant, to reduce calculation times when running software such as PACE. Such analysis could inform decisions on emergency procedures for multi-unit releases, for example the size of the extended emergency planning zone and the extent of sheltering and evacuation. In addition, including analysis of deterministic fatalities close to the plant would provide a more accurate calculation of the Target 7 risk for multi-unit scenarios.

Recommendation 3:

- The simple linear combination approach may underpredict the Target 9 probability in the case of non-simultaneous release or for two source terms of similar magnitude with very different durations. This suggests that sensitivity calculations should be performed to understand the potential impact on Target 9 for a range of time offsets. Sensitivity studies should focus on those multi-unit releases that are expected to contribute most to the total Target 9 risk.

Recommendation 4:

- The sensitivity of the Target 9 metric to time offset was seen to be heavily dependent on the interaction between the local weather, population distribution and the release properties. For large releases, a similar metric looking at the probability of a higher number of fatalities (such as 1000 fatalities) may also show super-linear behaviour. This should be considered when performing the Target 9 calculations set out in Recommendation 3. The guidance currently in TAG 45 states that 'The severity of a large release is also a consideration: clearly an accident that causes 1000 deaths is less acceptable than one that 100 deaths if both occur with the same frequency.' In addition to the probability of 100 deaths, multi-unit time offset sensitivity studies should quantify probabilities of higher numbers of fatalities (e.g. probability of 1000 deaths).

It is believed that implementing the above recommendations would lead to an improved understanding of multi-unit risk without placing an unreasonable burden of effort on designers and site licensees.

3.5 FURTHER WORK

The number of calculations undertaken in this report were limited due to available time and resources. Only one case combined two single unit events that each resulted in deterministic fatalities. In addition, only one set of calculations were performed to analyse the impact of time offset. Additional work would be beneficial in these areas, in order to develop the understanding and further refine the recommendations above.

Further Work Recommendation 1:

- Undertake further calculations which combine two, different, single unit releases which each result in deterministic fatalities. Perform sensitivity calculations on various countermeasure assumptions, such as the size of the implementation zone to understand the impact on the multi-unit results compared to the single unit releases.

Further Work Recommendation 2:

- Repeat the time offset calculations performed in this report at the south western site location to investigate any difference in findings due to the different weather conditions and population distribution of the alternative site.

Further Work Recommendation 3:

- Undertake further analysis of offset time with a range of release categories to understand how the relationship between the magnitude and timing of the release impacts the time offset findings. In order to narrow the focus of the sensitivity studies recommended above, a deeper understanding of the potential synergistic effects between these factors is required.

Further Work Recommendation 4:

- Undertake additional calculations of deterministic fatalities using the new version of PACE, which allows simultaneous releases from different locations. This would provide validation (or not) of the assumption that releases from units situated on the same site can be modelled from a single releases point with limited impact on the results.

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