The Latest Thinking of SMRs Impact on the Environment - A Probabilistic Approach

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Abstract: In any SMR design, there is always a level of residual risk of a radiological release following an accident, even with many layers of passive safety. Therefore, the consequences of accidents should be analysed and understood, irrespective of the very low CDF. This paper considers a British study performed at Imperial College London [1], in collaboration with Corporate Risk Associates Ltd. The study considered the consequences to society of a potential accident at an SMR using a Level 3 PSA. The main questions of interest were:
•If radiological release is reduced by a factor of 10, does societal harm reduce by a factor of 10?
•Is this relationship linear? If not, why not?
In the absence of available source term data for SMRs, an assumption of the initial study was that the source term release scales linearly with reactor power output. However, the results suggested a beneficial reduction in deterministic effects (fatalities, doses), no change to stochastic effects (cancer, genetic conditions) and a detrimental impact on Land and Population effects when accidents occur at SMRs as opposed to larger PWRs. The results have been used to scope further work that is currently progressing.
Keywords: PSA, PRA, Level 3 PSA, Emergency Planning, Environmental Impact.

1. INTRODUCTION

Probabilistic Safety Assessment (PSA) is a tool used extensively in the civil nuclear sector to better understand risk and harm arising from accidents. Level 1 PSA analyses the initiating events that can lead to Core (Fuel) Damage, allowing estimation of Core Damage Frequency (CDF) arising from accidents in both the reactor and spent fuel storage facilities. Level 2 PSA analyses propagation of Core Damage to the release of radioactive materials from containment, providing information on source term releases. Level 3 PSA analyses how the source term release from containment affects society – in terms of consequences to society (i.e. human lives, the environment and the economy.)

The current probabilistic approach for many Small Modular Reactor (SMR) vendors appears to have a strong focus on the Level 1 PSA. Analyses suggest very low CDF as a result of the inherent safe design, including extensive passive safety systems. Little effort appears to have been spent to date on Level 2 and 3 PSA for SMRs.

However, there is always a level of residual risk, even with many layers of passive safety. This paper considers a British study performed at Imperial College London [1], in collaboration with Corporate Risk Associates Ltd. The study considered the consequences to society of a potential accident at an SMR using a Level 3 PSA. The main questions of interest were:

- If radiological release is reduced by a factor of 10, does societal harm reduce by a factor on 10?
- Is this relationship linear? If not, why not?

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2. ASSUMPTIONS OF THE STUDY

In the absence of available source term data for SMRs, an assumption of the study was that the source term release scales linearly with reactor power output. Source term data from a severe accident scenario modelled in the UK EPR™ PSA was used for the presented study. The UK EPR™ is a conventional PWR of ~1200MWe.

A number of factors influence source term releases. This includes the design of the fuel, the reactor and other design features such as the containment. In addition, the accident sequence itself will have an impact on the source term release. A large number of SMR vendors are in an early stage of design and have not performed detailed studies, including Level 1 and 2 PSA, to understand potential source term releases from postulated accident scenarios.

Although it is considered that a scaled source term from a conventional PWR is not ideal, in the absence of SMR specific source term data, it does allow the generation of insights as to whether societal harm scales linearly with source term release - a hypothesis which several SMR vendors rely on in terms of a general assumption that an accident at an SMR will have far lower consequences than one at a conventional PWR due to the reduced radioactive inventory.

3. LEVEL 3 PSA SOFTWARE

The Level 3 PSA software used for the estimation of the societal consequences and the environmental impact of a severe accident was PACE (Probabilistic Accident Consequence Evaluation).

PACE is a tool developed by Public Health England (PHE) for performing off-site consequence analyses (Level 3 PSA) for a given release of radioactive material to the atmosphere from a facility. It takes as input, the description of the source term, land usage and population data and a large set of historical meteorological conditions to quantify the ranges of estimated public dose, numbers of health effects, countermeasure requirements and economic costs [2].

PACE incorporates both a Gaussian dispersion model and the UK Met Office NAME III [3] Lagrangian particle model which uses hourly numerical weather prediction (NWP) data. PACE is embedded within the ArcGIS™ Geographic Information System software enabling high-quality map output to be produced.

PACE is used to estimate the probability distributions of consequences [4] such as:

- Individual doses from exposure to radioactive material in the air and on the ground as well as collective doses from ingestion of contaminated food.
- Numbers of health effects both fatal and non-fatal arising from exposure.
- Costs of health effects, disruption in agriculture, industry and society.

4. METHODOLOGY

4.1. Input Data

4.1.1. Source Term

The source term likely to arise from a single severe accident event was used scaled to different power outputs at: 100%, 80%, 60%, 40%, 20%, 10% and 5%. The severe accident event was conservatively chosen as one of the most onerous in terms of a release for an EPR™, a conventional PWR of ~1200MWe; a Large Interfacing Loss of Coolant Accident (LOCA).

The source term for the chosen event is publically available in the Level 2 PSA report published as part of the UK EPR™ pre-construction safety report [5] which lists a "Large interfacing system LOCA without fission product scrubbing (RC802A)" as the most severe accident sequence.

Due to limitations in the Level 3 PSA PACE Software, the source term file cannot exceed more than a total of 30 radionuclides. The Level 3 PSA PACE Software considers the daughters of the radionuclides. Therefore, the limitation of 30 also includes the daughters of the released nuclides (initialized with a 0 value). As the original source term contains over 30 products, prioritisation was required.

The prioritisation method utilised removed the isotopes that held the smallest dosage as well as those that were known to have less significant impacts (compared to other radionuclides present). An example of this is the removal of Kr-85, whose dosage is two magnitudes lower than the other radioisotopes present as well as having a relatively small known impact. Furthermore, isotopes and daughters that are known to have significant impacts are prioritized regardless of their dose. As Am-241, I-131, Cs-137 and Sr-90 contribute significant environmental and health impacts [6] these nuclides are prioritized. The limited source term for the 100% power output can be found in Table 1.

Table 1: Reduced Source Term Including Daughters

Isotope	**Release (Bq)**
Am-241	0
Ba-137m	0
Ba-140	3.46E+18
Ce-144	2.81E+17
Cs-134	6.57E+17
Cs-135	0
Cs-137	4.38E+17
I-131	4.30E+18
I-132	6.22E+18
I-133	8.73E+18
I-134	9.61E+18
I-135	8.14E+18
La-140	5.20E+16
Np-237	0
Pr-144	0

Isotope	**Release (Bq)**
Pr-144m	0
Pu-238	5.10E+14
Pu-241	2.98E+16
Rh103m	0
Rh-106	0
Ru-103	5.01E+18
Ru-106	1.71E+18
Sr-90	5.36E+16
Te-132	6.06E+18
U-234	0
Xe-131m	0
Xe-133	9.25E+18
Xe-135	3.00E+18
Xe-135m	0
Y-90	2.45E+15

4.1.2. Meteorological Data

A key component in a Level 3 PSA is the atmospheric dispersion of the source term. The PACE tool allows the advantage of using a Monte Carlo Lagrangian model. The Met Office's Numerical Atmospheric dispersion Modelling Environment (NAME) is incorporated within the PACE software to model a broad range of atmospheric dispersion events. NAME uses NWP meteorology data. The model imposes no limitation to the duration of pollutant release or time of simulation. Thus, it is possible to predict the dispersion of radionuclides over vast distances [3].

The advantage of using the NAME dispersion model is that no assumptions need to be made for the shape of the plume distribution, unlike what is required in Gaussian models. NAME is a Lagrangian particle model which resolves dispersion via tracking of the model particles through the atmosphere. The particle's motion within the model is determined via wind conditions varying through space and time. Furthermore, the design allows for random motion which reflects the presence of atmospheric turbulence in the particle's motion through the atmosphere [3].

NAME also incorporates realistic physical attributes that pollutant particles display. Particles are capable of having individual characteristics, for example particles can represent compounds or chemicals such as a radionuclide present in the source term. Additionally, the model also allows particles to be removed by several processes [3]:

- Fallout due to gravity,
- Impaction with surfaces
- Washout, where the pollutant is ’swept out’ by falling precipitation
- "Rainout" where the contaminant is absorbed directly into cloud droplets as they form.

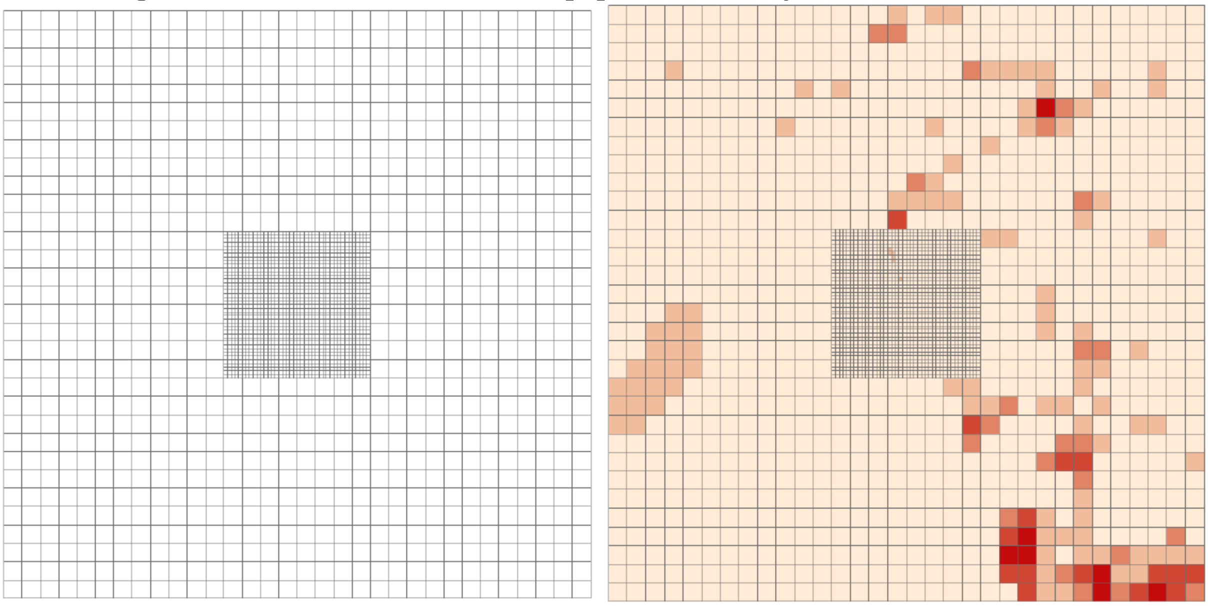
4.2. Analysis Settings

4.2.1. Pre-processing stage

The pre-processing stage is used to perform two tasks. Firstly, it is used to specify a nested grid area at the location in which the PACE analysis will be conducted. Secondly, for the nested grid the process inputs all necessary spatial data for each grid square such as population, meat production and vegetable production. PACE uses a substantial amount of input spatial data. However, the default PACE run set provided includes the spatial data needed for a complete run over the UK.

The pre-processing stage allows the use of up to 4 nested grids. The inner nested grids give results over smaller areas than the outer grid nests and can have a higher resolution thereby giving more precise results. The use of an inner nested grid is used to model more precisely the area near the release point. The size of the grid and number of squares affect the computational power/time required. Hence, the grid size needs to be large enough to reduce truncation of results yet not too large as to unnecessarily increase computational times. Thus, based on the US planning approach [7] an outer grid of length 160km (approximately 50 mile radius) and an inner nested grid of length 40 km are used. An example of the resulting grid can be seen in Figure 1.

Figure 1: Blank Grid and Grid with population density shown for a location



4.2.2. Dispersion

For each radionuclide, the NAME tool predicts the hourly integrated concentration of activity in the air, the cloud gamma dose and the deposition of activity on the ground. This process is performed for every grid square specified in the pre-processing stage. The procedure is repeated for all meteorological sequences. The sequences are spread across the year and hence simulate releases at multiple points throughout the year. Varying the sequences across the year is vital to account for several seasonal and extreme weather events. The following parameters were used to allocate sequences:

- Temporal Domain: 30 hours
- Number of Cycles: 100
- Cycle Length: 58 hours
- Number of Particles per hour: 1500

The temporal domain field stores the maximum time period used by the NAME model per sequence. At the end of the period, all particles used by the NAME model are removed. Particles can be removed prior to this if they are deposited, their activity decayed or if they leave the spatial domain defined in the pre-processing stage. It is vital to set the temporal domain value large enough to minimise the dose truncation from all pathways. As the interest of impact is on a national scale, temporal domains of 24 hours (or more) are appropriate, according to the PACE user manual [8].

The cycle length represents the time between the start and end of each sequence. The cycle length is set larger than the temporal domain to allow contiguous sequences to be independent of each other. Additionally, the cycle length ensures that a good variation of daily times is used, and thus a range of different meteorological daily conditions are present. The value of the cycle length should not be a multiple of 6 or 8 as to avoid specific times being overly repeated.

The number of particles per hour represents the number of particles that will be used in the NAME calculations for each hour of release. Selecting a greater number of particles tends to give more reliable and less noisy results. However, this will also increase the processing time significantly. To determine a suitable value a convergence study of a test area is recommended, a value of a few thousand is usually acceptable according to the PACE user manual [8].

5. RESULTS

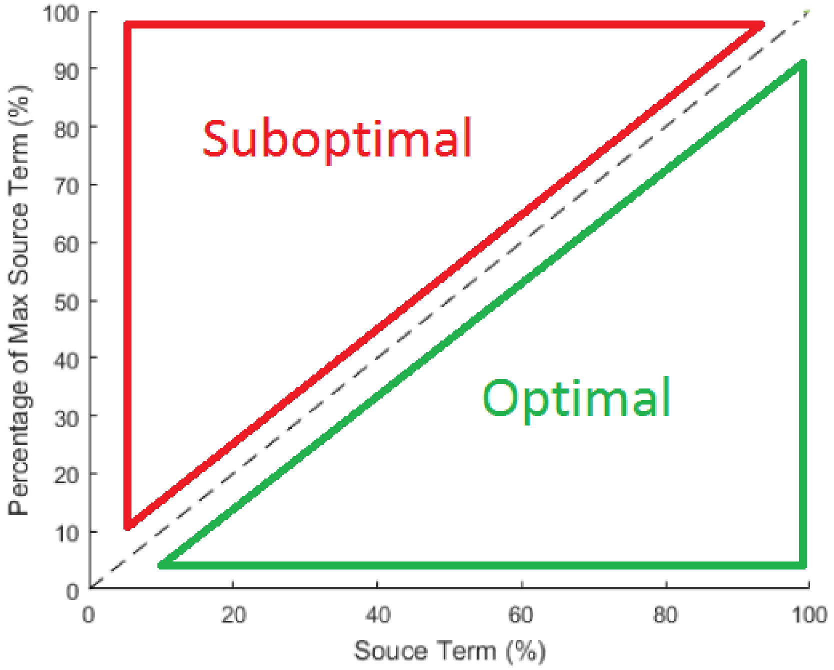
The PACE run carries out the probabilistic calculations for the given release across outlined meteorological sequences. The PACE run performs the processing of data from the pre-processing stage and the atmospheric dispersion results from the NAME model to produce results for each element of the nested grid area. Five sites around the UK were studied in the project. In order not to raise concern, the sites remain anonymised. The generated output consists of a large quantity of end points for every grid square; an example of an endpoint is "mortality count due to skin burn". It is worth noting that the endpoints will only be produced in grid squares where there is land, hence a plume may appear to end when it reaches the coast. The end points are categorized as follows:

- Environmental activity.
- Health effects.
- Dosage.
- Economic costs.

Each of these also contains a further category that includes countermeasures that can be taken. However, in the interest of reducing computational expense, countermeasures were not considered in the project. This is because countermeasures vary based on emergency plans set in place and is not a measure of consequence directly. Countermeasures are more of a reaction to an event and are a derivative to how harm scales with source term size. The environmental activity represents a time-integrated concentration of activity in air and ground deposition. The health effect endpoints represent both stochastic and deterministic health effects. The dosage end points represent both long term and short term pathways. The short-term pathways include internal exposure to inhaled radioactivity from the plume, external exposure to radioactivity in the plume and deposited activity on skin and clothes. The long-term pathways include external exposure to radioactivity deposited in the environment, internal exposure to inhaled re-suspended radioactivity and ingested contaminated food substances. The economics end point outputs a cost based on the health effects that occur.

All results normalize the endpoints about the 100% source term value to examine the effect a varying source term has. Additionally, a linear y=x dotted line is added as a threshold to determine the data points that display an optimal or suboptimal result. If the core damage frequency is taken to be constant; data points on the XY line indicate the maximum consequence value allowable to justify a smaller source term/power output. Data points that are shown to be above the XY dotted line display suboptimal cases as the reduction in the value of harm are disproportionate to the reduction of source term size. The suboptimal cases require that the smaller reactors possess an inherently lower damage frequency to be justified. Conversely, data points below the XY line indicate optimal cases. A more graphic description of this is presented in Figure 2:

Figure 2: Graphical Description of the interpretation of the Results



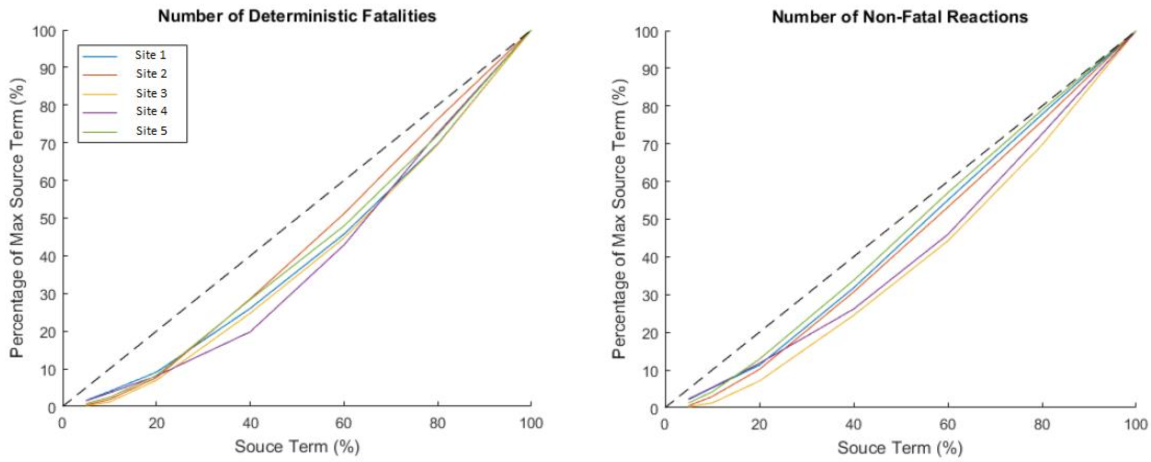
5.1. Deterministic Effects

The severity of deterministic health effects is dependent on the effective dose an individual receives and are assumed to have a threshold level below which no effect is seen. Parameters of the deterministic effects calculations used by PACE are as follows:

- Cataracts
- Mental retardation
- Skin burns
- Lung function impairment
- Hypothyroidism
- Pulmonary syndrome
- Haematopoietic syndrome
- Gastro-intestinal syndrome
- Pre-natal/neo-natal death

As the threshold dosage varies between different health effects the results displayed are the summations of individual effects. For most health effects the number of incidents is calculated by applying the risk to the whole population in the grid square whereas some health effects are only applicable to a specific portion of the population e.g. pregnant women. The combination of multiple health conditions makes it difficult to predict or explain the entire deterministic effect. As multiple fatal conditions exist, double counting of deaths is possible. This is due to the fact that the software does not assume that one health effect will reduce the population who could contract another. Therefore, it is possible that the total number of deaths summed over all deterministic effects may be slightly overestimated, though the trend displayed will largely remain unaffected. Figure 3 presents the deterministic effects; fatal and non-fatal.

Figure 3: Normalized number of Deterministic Effects; Fatal and Non-Fatal



Overall the deterministic measures of harm and consequences are shown to largely be in favour of reducing source term size. This can be said as the normalised results indicate that a reduction in source term results in a disproportionate and beneficial reduction in consequences. The underlying cause of this trend can be linked to the threshold system these effects operate on. As source term is reduced, the dosage received is reduced below threshold values, leading to a non-linear reduction in likely health effects.

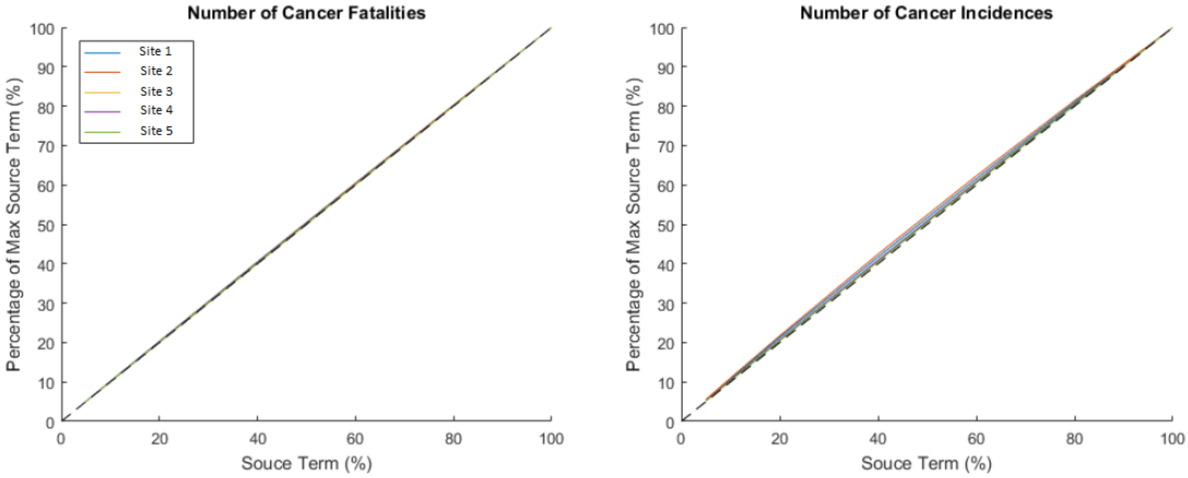
5.2. Stochastic Effects

PACE calculates the risks, incidents and fatalities of cancers in the following organs and also the risk and incidents of hereditary effects:

- Bone marrow
- Bone surface
- Breast
- Lung
- Colon
- Liver
- Pancreas
- Thyroid
- Skin
- Remainder

Due to the nature of stochastic effects, it is expected that a linear trend between source term and harm will be exhibited. This is because the probability of a stochastic health effect occurring is dependent on both the radiation dose that an individual is exposed to, and their risk factor. These effects can occur from low does and do not have threshold values. Therefore, with these properties it is possible to determine the risk of a stochastic effect directly from the dose received. Figure 4 presents the stochastic effects both fatal and non-fatal.

Figure 4: Normalized number of Stochastic Effects, Fatal and Non-Fatal



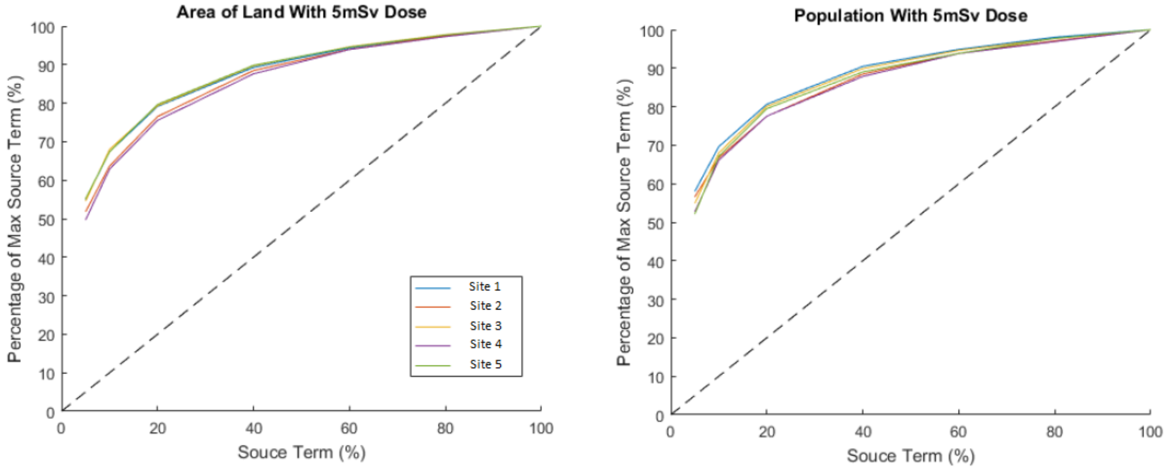
As these stochastic effects can be directly calculated from the dosage received, the linear trend that the average dosage the population receives will also maintain a linear trend. Overall, it is clear from the results that a reduction of source term has no relative benefit or cost in the regards of stochastic consequences. The reason for this trend can be attributed to the mechanism stochastic effects operate within and thus the reduction of source term results in a reduction in dosage which leads to a linear fall in the relevant measures.

PACE incorporates a linear non threshold model to calculate the results of stochastic effects. This model assumes that the long term cancer risk is directly proportional to the dosage received. Therefore, this model causes the stochastic effects to vary linearly with source term size. However, the accuracy of this model has been questioned by a large proportion of the scientific community and is especially doubted at low radiation dosages [9]. Therefore this adds some uncertainty to trends found in the study especially in regards to lower source term sizes.

5.3. Emergency Planning Zones

A common measure to represent the extension of the Emergency Planning Zones in the UK is the area of land that is affected by a 5mSv dosage following a within design basis accident. Furthermore, the radius of this field also represents the minimum radius required by the UK Office for Nuclear Regulation (ONR) to produce a Detailed Emergency Planning Zone (DEPZ) [10]). The UK government defines a nuclear emergency as "an effective dose of 5 mSv in the period of one year immediately following the radiation emergency" [11]. Figure 5 presents the normalized number of Area and Population with a 5mSv dose to inform on the characterisation of the DEPZ.

Figure 5: Normalized number of Area and Population with a 5mSv Dose



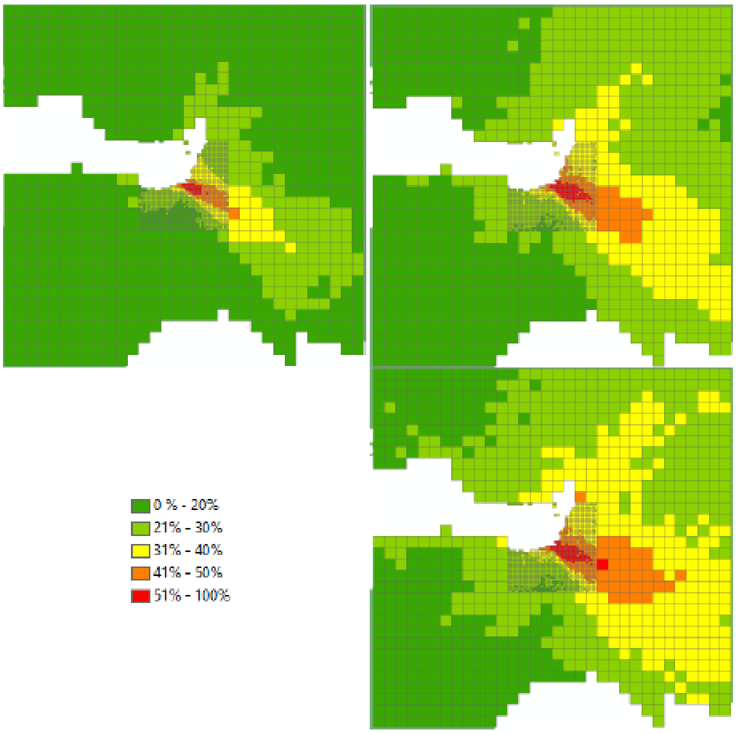
The results indicate that the area of land and population size receiving above a 5mSv dose threshold scale non-linearly with source term size. The results indicate that at the 5mSv level, reducing source term is a sub-optimal method to reduce the 5mSv planning zone. The non-linear trend displayed exists because even at the 5% source term size there is still a considerable amount of material released and thus will disperse across a wide area before diluting to below a 5mSv dosage. Furthermore, the DEPZ works on a threshold mechanism similar to deterministic effects hence leading to nonlinear drops in health effects as the threshold value is crossed. It is noted here that the onerous nature of the source term selected, which would occur following a very low frequency initiating event, is likely to have a large impact on this result and it is subject to further studies being performed currently.

5.4. Probabilistic Contour Plots

As there are 100 met sequences per simulation, it is possible to create percentile maps within the PACE software. This allows the visualization of the area of land that is likely to be susceptible to consequences. Furthermore, the contour maps allow an insight into the spread of plume for various levels of source terms.

The plots also provide a better understanding concerning DEPZ size. The 5mSv value is a relatively low value in severe accidents, such as the one considered in the study, and thus it may not be appropriate or feasible to evacuate all areas that may receive a 5mSv dose. Hence the plots provide an indication into which directions are more prominent and should be evacuated in a severe accident; this may reduce the casualties that undoubtedly occur from panic during an emergency evacuation [12]. However, it is also worth noting that the purpose of this study is not to advise any action into changing the current regulations and the plots are presented to observe the change in the plume spread for varying source terms. Figure 6 presents a probabilistic contour plot which expresses the probability of receiving ≥ 5mSv at one of the locations studied for 5%, 40% and 100% source term.

Figure 6: Probability Contour Plot – Probability of Receiving ≥ 5mSv for 5%, 40% and 100% Source Term



6. CONCLUSIONS

To conclude, the project finds the relation between source term size and resulting consequences to display both aspects of linearity and non-linearity. In particular, deterministic effects show a non-linear trend in favouring the reduction of source term size. Whereas, the detailed emergency planning zone regulation based on the threshold dose of 5mSv, is shown to have a non-linear trend in favour of larger source term sizing. These findings are in regards to a low frequency and severe loss of cooling accident sequence, one which arguably the 5mSv DEPZ is not orientated towards. It was also found that stochastic effects, due to their non-threshold mechanism, display a linear scaling with source term size.

Additionally, motivated by the UK's recent interest in SMR technology the project attempted to analyse their effect on the environment. It was found that based on the reduction of source term size SMRs have potential to reduce deterministic effects. Although, in cases where multiple SMRs are deployed at a single location these benefits are quickly overshadowed by the need to investigate core damage frequency of SMRs. As the project did not concern itself with Level 1 PSAs, it is unable to conclude whether or not SMRs are viable for the replacement of conventional nuclear power plants by itself, but does go some way as to better understanding how harm may scale with source term release.

The project has led to a number of items for further consideration, some of which are progressing at the time of writing. These include:

- Re-performing the study using source term data for early SMR designs, including Molten Salt reactors;
- Re-performing the study using less onerous 'power scaled' PWR source terms;
- Investigating sensitivity to the threshold value that could be used for DEPZ (5mSv assumed in the study);
- Investigating the effect of Level 3 PSA variables such as weather data set and grid size on analysis and results.

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