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PRA based radiation dose estimates around Loviisa NPP in case of a severe reactor accident

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Abstract: There is certain pursuit to reduce the size of emergency planning zones to enable installation of small modular reactors near cities. PRA-based dose estimates may be used in development of emergency response planning and to justify smaller emergency planning zones. To justify acceptable zoning, it needs to be shown, that risk of exceeding certain dose criteria is sufficiently low. In this work PRA based probabilities of exceeding certain dose criteria are developed and presented for Loviisa NPP.

Keywords: Dose Estimation, Emergency Planning Zone, PRA level 2, Source Term

1. INTRODUCTION

Fixed definitions of emergency planning zones (EPZ) for nuclear power plants (NPP) are changing as small modular reactors (SMR) are envisioned to be installed near cities to produce e.g. district heating. One way to demonstrate an acceptable size of the EPZ is to use PRA level 2 to evaluate probability of exceeding certain dose criterion as a function of distance from the NPP.

To justify the smaller size of EPZ it needs to be demonstrated that regulatory requirements for radiation doses at the newly defined precautionary actions zone (PAZ) and urgent protective action planning zone (UPZ) are met. In the United States emergency planning zones have been based on probabilistic approach. The methodology was devised in 1976 by a task force comprised of U.S. Nuclear Regulatory Committee's (NRC) and U.S. Environmental Protection Agency's (EPA) experts – the NUREG-0396 report [1] – and it is still the basis for U.S. emergency planning zoning criteria [2]. As opposed to IAEA's approach of using fixed fractions of volatile fission products assumed to be released, the NUREG-0396 is based on comprehensive PRA level 3 data from the WASH-1400 report or also known as the Rasmussen report [3] (probably the first PRA level 3 analysis of its time). The benefit of PRA based approach is that it takes into account the safety features of the examined NPP. The objective in testing NUREG-0396's methodology with Loviisa NPP's data is to reproduce similar figure as Figure 1.

One reason for exploring a probabilistic methodology is that the result will likely be more optimized compared to a deterministic approach where conservative assumptions are more common. But on the other hand the fact that the methodology require availability of PRA level 2 can be a hinderance if such data is not available in the early phases of the newbuild project, e.g. city land usage planning. If PRA level 2 data is not available early on, a preliminary estimate on EPZ may be assessed using deterministic approaches which can then be verified later on when the PRA level 2 data is available.

Loviisa NPP was chosen to be used to test and demonstrate calculation capabilities. Loviisa NPP is a two unit VVER-440 type power plant located in South-Eastern Finland. The power plant is a unique design of soviet reactor combined with western safety systems and an ice-condenser containment. The NPP started commercial operation in 1977 (unit 1) and 1980 (unit 2). The development of severe accident management (SAM) strategy at Loviisa was started in late 1980's and the installation of SAM systems was finalized in 2003. [4] During the plant lifetime numerous other safety improvements have been implemented as well decreasing risks significantly. [5]

Most relevant earlier work on reproducing NUREG-0396 methodology was conducted on advanced light water reactors (ALWR) by EPRI in 1999. [6] It is evident, that newer ALWR designs provide significantly improved nuclear safety compared to NPPs considered in NUREG-0396 and also Loviisa NPP despite numerous safety improvements at Loviisa over the years.

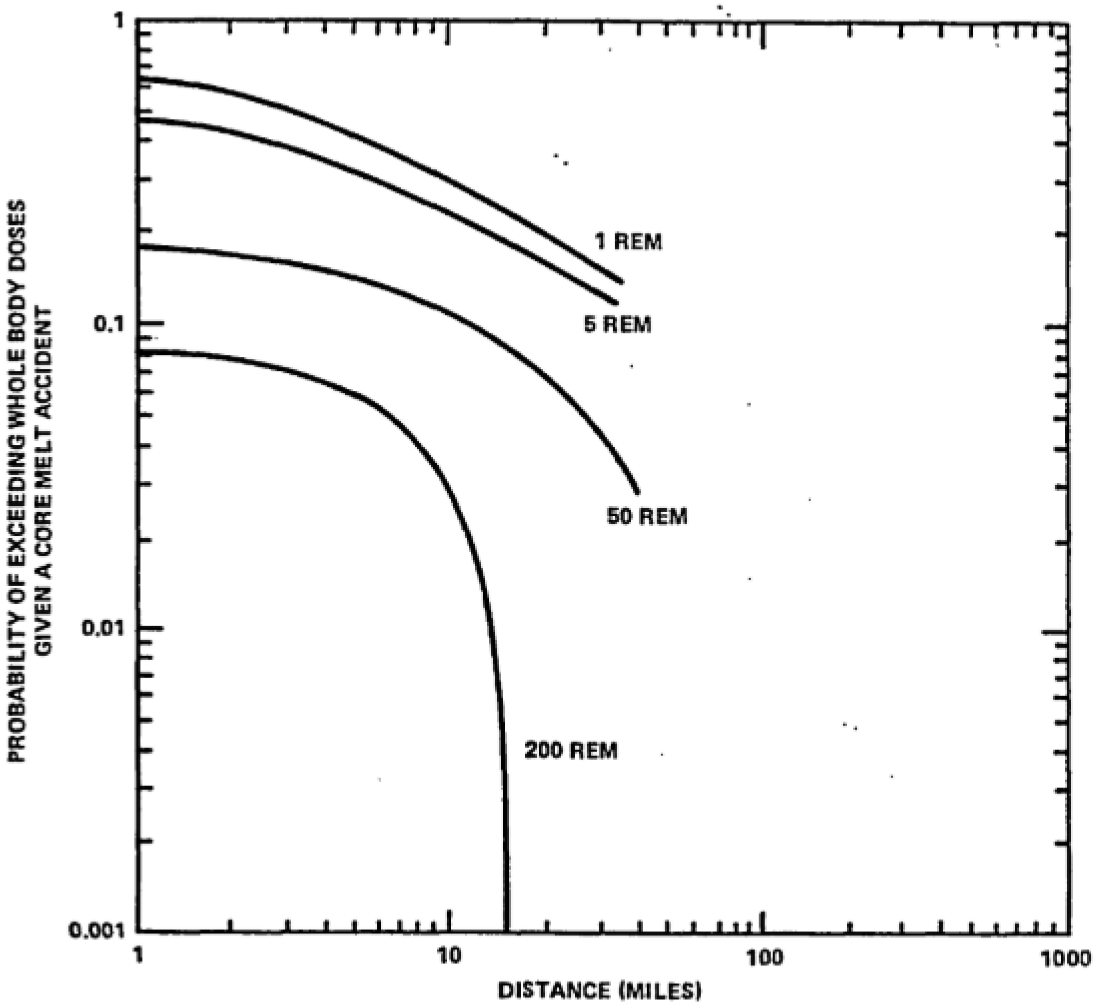

Figure 1. Conditional Probability of Exceeding Whole Body Dose Versus Distance Given a Core Melt Accident taken from NUREG-0396 [1].

2. LOVIISA PRA LEVEL 2

2.1. Scope and Main Results

PRA of Loviisa NPP covers all initiating events including all internal and external hazards on levels 1 and 2. The model is divided into 17 plant operating states covering all plant operating modes. Postulated core damages are divided into 40 plant damage states (PDS), which are used as input for level 2 calculation. Level 1 and 2 PRA models are fully coupled to enable inheritance of equipment failures and plant state from level 1 to level 2 evaluation.

In Loviisa level 2 PRA two main outcomes are evaluated: large release frequency (LRF) and early release frequency (ERF). Large release is defined as 100 TBq of Cs-137 release to the environment. Basically there is no time limit, but generally for small leaks 168 hours since initiating event is used. Early release is defined as such a release within 5 hours since initiating event that would lead to over 10 mSv doses using 48 hour integration time. Definition of early release is described in more detail in [7].

16 regular release categories are used. They represent various sizes of leaks from the containment including evaluation of washing aerosols from the containment air by using spray system and failures leading to loss of containment integrity at different stages of the accident (hydrogen explosions, reactor pressure vessel failure, long-term over-pressurization of the containment). Containment event tree is presented in Figure 2. After failures which clearly lead to large release, no further branches are included in the event tree. Regarding source term this is considered mostly conservative assumption.

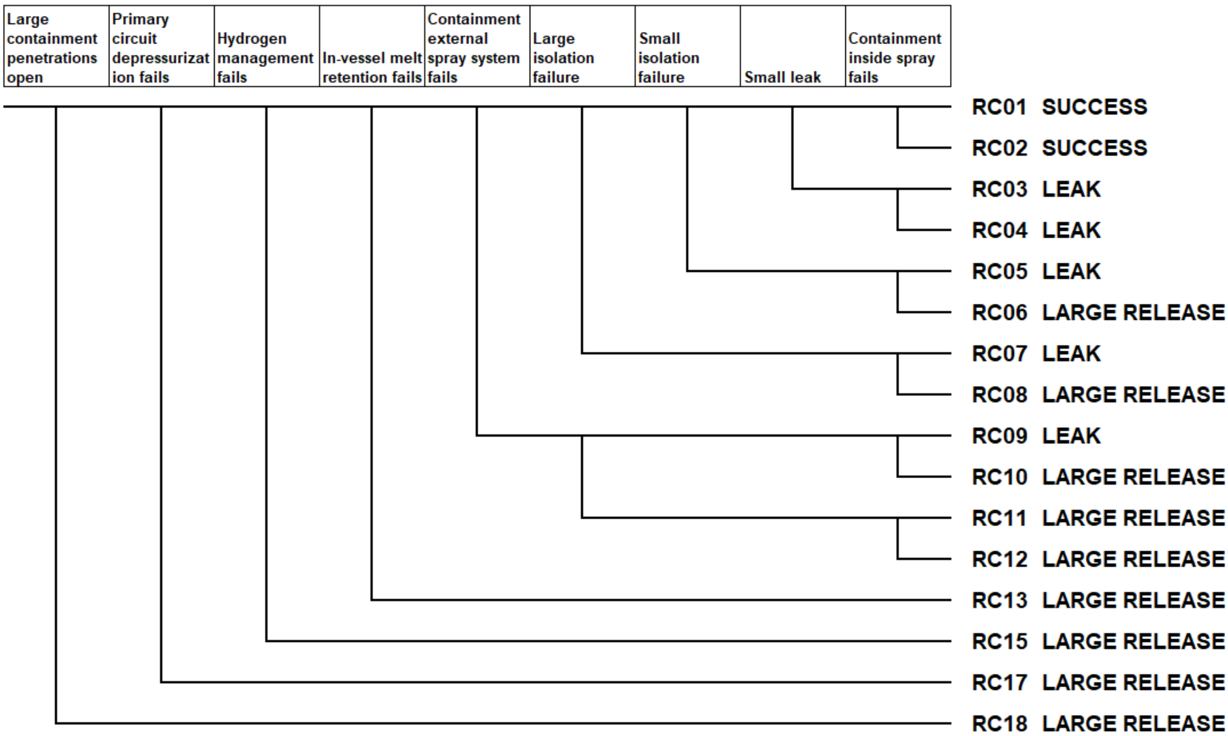

Figure 2. Containment Event Tree of Loviisa NPP

In addition to containment event tree, a special release category is used for PDS, which are hard to analyze with containment event tree and engineering judgment is used to give rough estimate of the outcome of severe accident management. Such scenarios include e.g. reactivity accidents and pressurized thermal shocks. Success probability of severe accident management in these accident scenarios is generally very low and many of them are assumed to lead always to a large release.

Main results of PRA level 2 for Loviisa 1 are presented in Figure 3. SAM systems are adequately designed against many internal initiating events and hazards during power operation. External initiating events (weather, seismic) pose challenges to SAM systems as well as shutdown states, when SAM systems may be out of service due to maintenance.

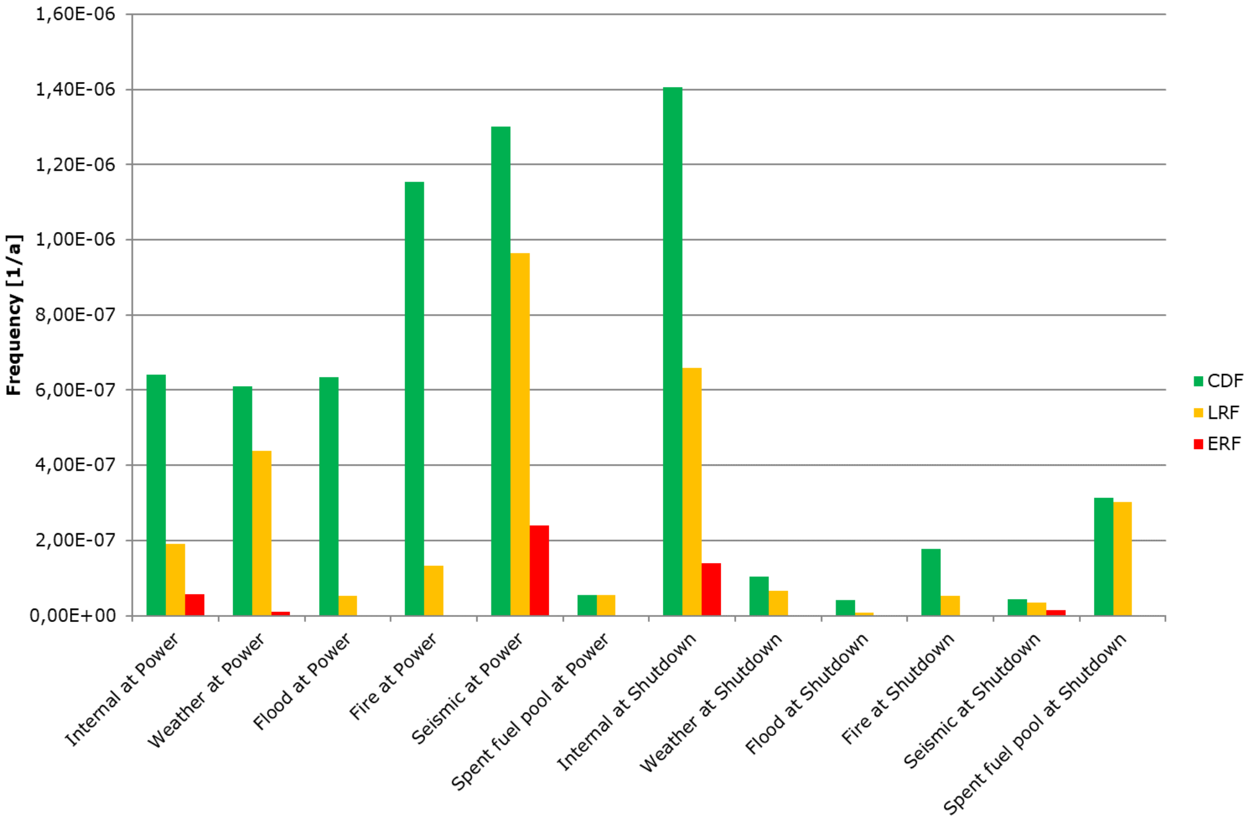

Figure 3. Core Damage, Large Release and Early Release Frequencies in Various Initiating Event Groups at Loviisa NPP Unit 1

2.2 Source Term Calculation

The source term in Loviisa PRA level 2 is estimated with in-house developed SaTu software. [8] SaTu software estimates the released radioactive materials as a function of time based on user inputs like timing of core uncovery, primary circuit leak size, containment pressure development and leak size, status of ice-condenser and so on. SaTu software was initially built to be used by emergency response organization of Loviisa NPP to be used to predict and estimate source term and its time development during emergencies. Later SaTu was modified for PRA level 2 purposes. In PRA mode release fractions are calculated for 10 fission product groups during the first week since the initiating event.

Due to fast calculation time of SaTu a large number of source term analysis have been conducted. Currently source term calculation at Loviisa covers almost 300 combinations of plant damage states and release categories. The source term calculation covers over 99 % of core damage frequency excluding fuel damage in in-containment spent fuel pool. To achieve this, cutoff frequency of 1E-9 /a is used for combinations of plant operating states, plant damage states and release categories. Additionally source term calculation includes several accident scenarios, which have been significant in the past, but due to plant modifications and improved modelling their frequency has been reduced below current cutoff frequency.

Probability distribution for frequency as a function of release fraction is presented for cesium in Figure 4. The probability distribution has clearly two peaks. One peak represents success scenarios, in which release to the environment is relatively small. Another peak occurs at large releases in which containment integrity is lost and significant fraction of volatile fission products is released to the environment. Releases with small leaks from the containment fitting in between these two peaks represent only a minor share of the total core damage frequency.

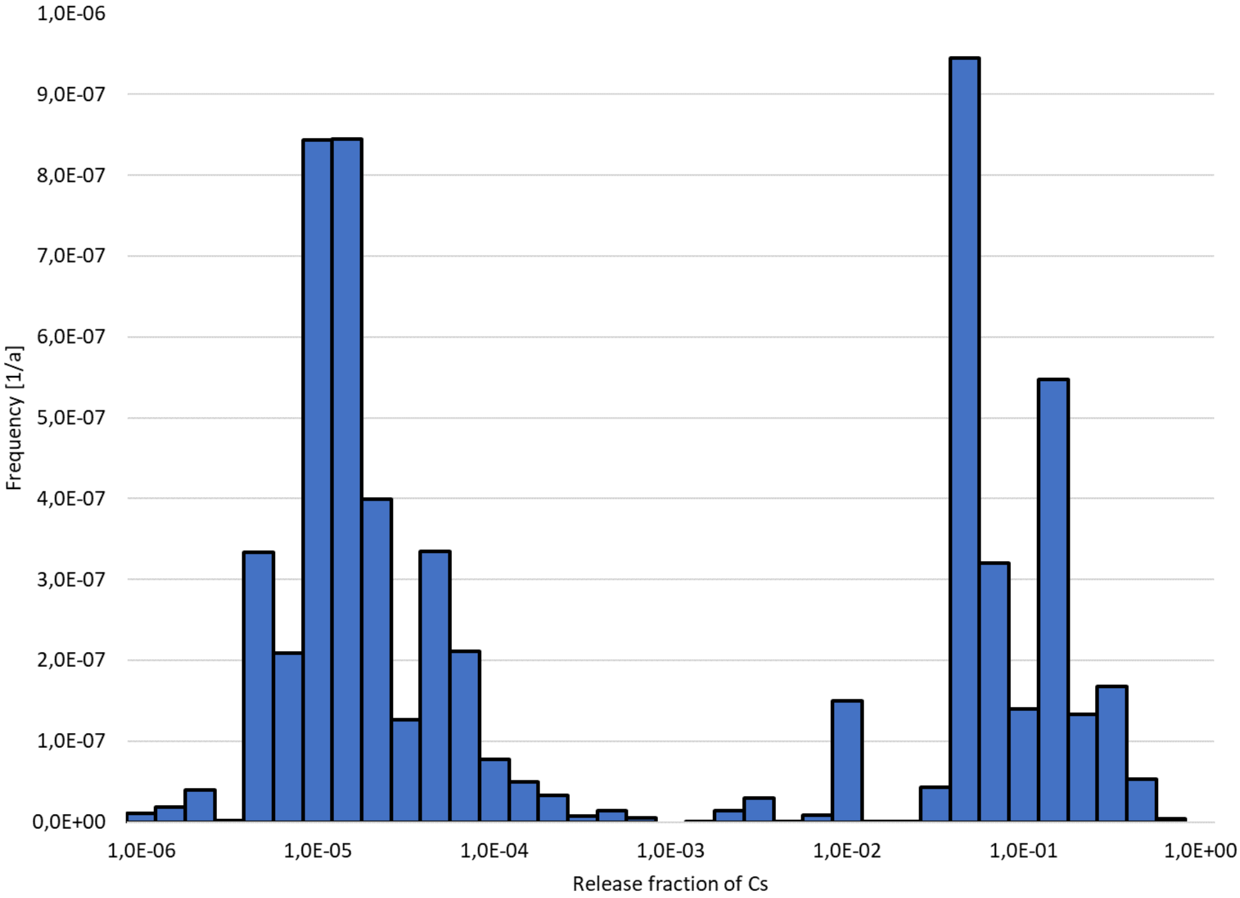

Figure 4. Frequency histogram of cesium release fraction to the environment

3. DOSE ESTIMATION

Tuulet software is used in Finland for licensing dose analysis and annual reporting of doses from normal operation. The development of Tuulet was started in the beginning of 1990s and it has been developed significantly further since. Tuulet calculates the probability distribution of doses in 12 sectors at different distances based on a Gaussian dispersion model and measured weather data at the NPP.

Tuulet calculates external dose and doses from ingestion and inhalation. The integration period of the dose calculation in this work is 7 days as the focus is to evaluate the need for protective measures in early phase of an accident. Ingestion is excluded from consideration as its effect on doses is very low during such short integration period and limitations on local food consumption are assumed to be imposed in case of a severe reactor accident.

The calculation is done for 10 and 50 mSv doses based on US protective actions guides (PAG), 500 mSv (early illness) and 2 Sv (early injury), because same limits were used in NUREG-0396. If similar methodology to define EPZ would be used in Europe, other criteria may be more applicable.

Variation in doses is caused by included weather data. Three years of weather data is used. The release is divided into 1 hour long sequences and weather conditions for each sequential release is assumed to be the same as weather conditions at the NPP during the hour in question. This gives relatively good estimation of the doses close to the NPP (within 20 km), but further away it imposes significant uncertainty to the overall results and conservatism to the maximum results as weather conditions may be different or change during the release spreading further. In general long-term releases result in lower doses compared to shorter releases of same overall magnitude, as radioactive substances are more likely to disperse into many directions due to changing weather.

Probability of exceeding certain dose criterion for each accident scenario is presented in Figure 5. It needs to be kept in mind that at the larger distances the Gaussian dispersion model assuming plume release into one direction based on weather data at the NPP is considerably conservative.

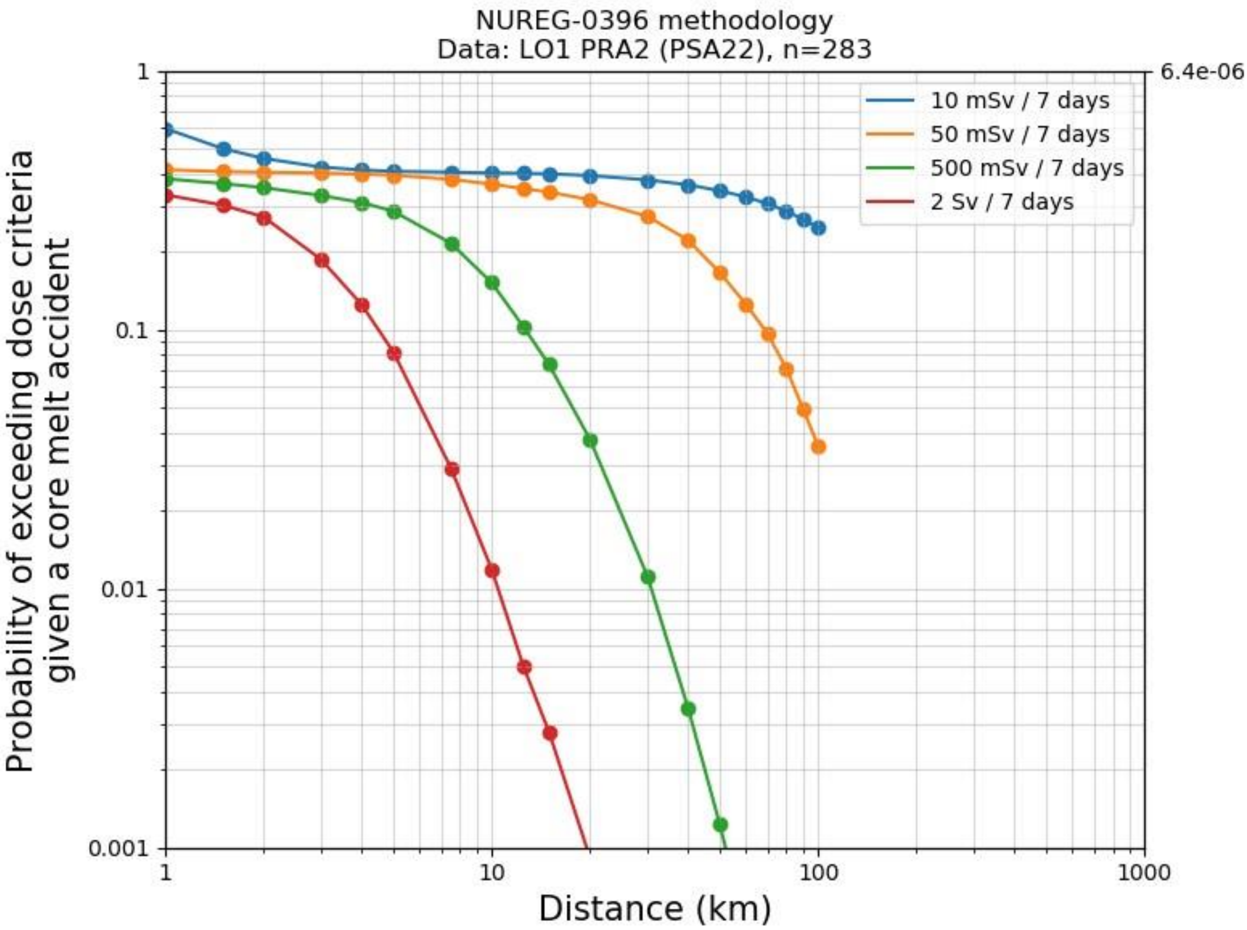

Figure 5. Conditional probability of Exceeding Certain Dose Criteria as a Function of Distance in Case of a Severe Accident at Loviisa NPP

4. DISCUSSION AND CONCLUSIONS

Results per core melt accident at Loviisa NPP are of the same order of magnitude as the results for even older NPPs in NUREG-0396 [1]. However, in NUREG-0396 CDF is evaluated at 5E-05 /a per unit compared to 6.4E-06 /a per unit at Loviisa. In Loviisa a lot of time and effort has been invested to reduce risks especially regarding CDF and the most important remaining core damage scenarios are such, in which external events pose substantial challenges on the safety systems including SAM systems. Therefore in large part of the remaining accident scenarios cliff-edge effect results in reduced success rate of severe accident management leading to large releases.

Despite some conservatism in source term calculation, one interesting find is the two-peaked release distribution of release size. If initiating event does not affect the SAM systems then the releases of radioactive materials to the environment are rather low. On the other hand initiating events in large part of the remaining core damage scenarios challenge SAM systems as well and result in relatively high large release frequency. Improvement of SAM system protection against external events could lead to significant reduction in LRF/CDF-ratio, but on the other hand with same money similar improvement can often be achieved in core damage frequency leading to worse LRF/CDF-ratio but to similar overall reduction of LRF and additional reduction of CDF.

Future work on Loviisa NPP dose calculation will include reduction of conservatism especially in source term calculation. In many aspects best-estimate approach has been used in level 1 and 2 PRA model development, event probabilities and calculation of CDF and LRF. However, source term calculation is considered to be more conservative especially in shutdown states.

Further studies on the EPZ methodology development could include applying the methodology for generation 3+ NPP designs especially considering that in EPRI report the results for ALWR were significantly lower and seeing that Loviisa NPP originates from the same time period as NUREG-0396.

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