ASNR's approach to introduce countermeasures effects and health consequences assessment of NPP severe accident in PSA

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Abstract: ASNR (previously IRSN) develops Level 2 probabilistic safety assessments (L2 PSAs) for the French pressurized water reactors (PWRs) that provide containment failure modes frequencies and release categories frequencies associated to kinetic and amplitude of releases. These L2 PSAs have been useful to support ASNR reviews of the PWRs severe accident management program implemented by EDF. Since 2008, some individual doses and ground contamination metrics have also been calculated for standard meteorological conditions to facilitate the communication and understanding of the L2 PSA insights. Some complements are currently being developed to model the health consequences and the benefits of protective actions (countermeasures) in order to provide additional informations for emergency preparedness. These L2 PSA are progressively closer to L3 PSA even if weather variations and all details of NPPs environment are not modelled.

The paper presents the general approach and the hypotheses applied to quantify these countermeasures benefits on the committed doses and health consequences.

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1. INTRODUCTION

1.1. Evolution of Accident Consequences Assessments in the ASNR PSA

Level 2 PSAs (L2 PSAs) provide containment failure modes and release categories frequencies associated to kinetic and amplitude of releases. At ASNR, these quantifications rely on several software tools. The probabilistic software KANT [1] is used to model the accident progression event tree (APET), to quantify the accidental sequences frequency and to group releases into large set of categories (around 20 000 for the French PWR L2 PSAs). The amplitude and the kinetics of release (source term) for each release category (RC) are calculated by the very fast-running code MER [2], that takes into account 113 isotopes, includes recent R&D results and uncertainties modeling and is validated by comparison with the European severe accident integral code ASTEC.

To provide a better understanding of the results, ASNR has completed its L2 PSAs with some radiological consequences calculations (individual doses, ground contamination …). Initially, these calculations were performed on a 50 km range with the codes pX (atmospheric dispersion) and ConsX (doses evaluations) of the ASNR Crisis Centre, with standard meteorological conditions (constant wind direction, speed, diffusion and dispersion). Nevertheless, these codes are time consuming for this L2 PSA application and were applied to a limited number of source terms.

To perform these consequences calculations for all RC of its L2 PSAs, ASNR developed the fast-running code MERCOR [2], linked with MER and dedicated to the characterization of both short and long terms radiological consequences (doses, relocation zone, forbidden consumption zone, number of refugees…). MERCOR is based on pre-calculations with pX-ConsX results for pre-defined key distances, population density and standard meteorological conditions. It provides radiological consequences assessments that do not account for variable meteorological conditions but can be applied for all types of facilities (NPPs, SMR, fuel process facilities…).

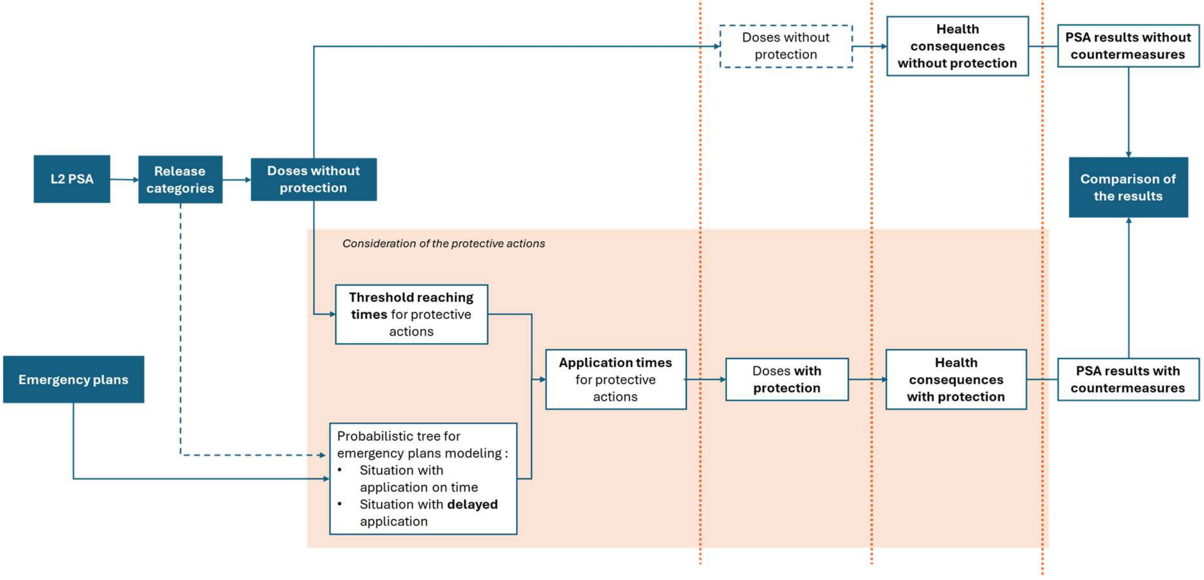
With the objective to provide information on the efficiency of emergency plans based on its PSAs, ASNR is now introducing additional metrics for the health impact of accidents and develops models to account for the efficiency of emergency plans protective actions (countermeasures) in its PSA. The following chapters describe the methodology followed for the modeling of these protective actions.

1.2. General Approach for Protective Actions Consideration in ASNR PSAs

The first step of ASNR's methodology is the modeling of the zoning and timing of the protective actions (sheltering, stable iodine intake and evacuation) as defined in the French emergency plans (§3). A probabilistic tree is then built and coupled with the L2 PSA APET[1]. Each sequence generated corresponds to a specific timeline of implementation of the protective actions and depends on the accident configuration (outputs from the L2 PSA). Furthermore, dose-reduction effects of the protective actions are quantified and correlatively the reduction of deterministic and stochastic health consequences of the accident. Deterministic effects are evaluated as the risk of early fatality due to acute radiation injury for the two organs representing the predominant risk (lung, red bone marrow). Stochastic effects of radiation exposure are evaluated as the excess risk of developing cancer for 4 radiation sensitive organs (thyroid, lung, red bone marrow, breast). Deterministic and stochastic effects are calculated with and without countermeasures application.

Figure 1 summarizes this methodology.

Figure 1: General approach for health consequences assessment in ASNR PSA



2. INPUT DATA AND ASSUMPTIONS

For health consequences assessment, several assumptions have been made by ASNR. The following table synthesizes them as well as the input data necessary.

Table 1: Input data and assumptions for health consequences evaluations

Population	The population is represented by 3 different ages and 2 genders (Women/Men), corresponding to 6 representative categories: • 1-year-old infants (W/M); • 10-year-old children (W/M); • adults (over 14-year-old) (W/M). The density of population is considered to be homogeneous around the NPP (French average density).

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[1] Accident progression event tree.

Organs evaluated	The following radio-sensitive organs are considered: - thyroid; - lung; - red bone marrow; - breast.
Meteorological data	A single standardized meteorological condition is considered, according to Doury's model [3] with a fixed wind direction, a low diffusion, a constant wind speed of $2m.s^{-1}$, and a dispersion factor of 5.
Exposure pathways considered	The following exposure pathways are considered in the assessment: - cloud (external exposure); - ground (external exposure); - inhalation (internal contamination). Doses by ingestion are not considered in the model described in this article but will be taken into account (for post-accident consequences assessment).
Time evolutions for doses (evaluation without protection - standard meteorological conditions)	In the wind axis, the following consequences are evaluated (at distances 1km, 3km, 5km, 7km, 9km, 15km, 25km, 35km and 45km): - organ equivalent dose evolution; - effective dose evolution (whole body). Outside the wind axis, consequences are evaluated thanks to a dose profile (relationship to determine dose depending on the angle as a function of the dose in the wind axis at angles ranging from -80 degrees to 80 degrees in 20-degree increments).
Dose contribution ratios (evaluation without protection - standard meteorological conditions)	The following ratios are considered: - ratios between the dose received from radionuclides in either gas or aerosol form and the total received dose; - ratios between the dose received from either iodine aerosols or other aerosols and the total received dose from radionuclides in aerosol form.
Times for reaching dose thresholds for protective actions (evaluation without protection - standard meteorological conditions)	The dose thresholds considered in the PSA are the following: - for sheltering: effective dose of 10mSv; - for stable iodine intake: thyroid equivalent dose of 50mSv; - for evacuation: effective dose of 50mSv.

3. EMERGENCY PLANS MODELING

3.1. French Crisis Organization

In the event of an NPP core melt accident, emergency plans would be applied to protect the population. According to the French crisis organization, these protective actions would be initiated within a radius of 20km around the NPP:

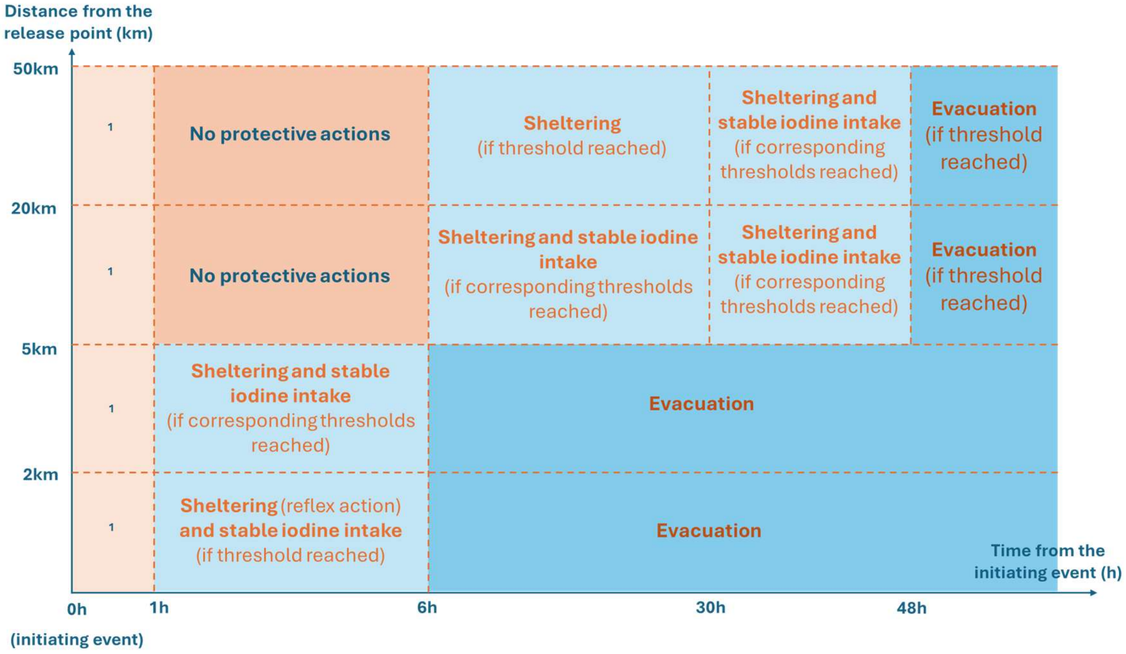
- within 20km: population can be subjected to sheltering, stable iodine intake and evacuation, depending on the decisions made by the different actors of the French crisis organization and on the release kinetic and amplitude ;
- within 5km: population would be evacuated on the order of the regional Prefect if core melt can occur within 10 hours ;
- within 2km: population can be sheltered promptly (sirens, automatic calling system) if immediate releases are foreseen after the initiating event .

3.2. Modeling Principles

For the purposes of the PSAs, the French crisis organization plans, are modelized through a “baseline emergency plan”.

This modeling considers characteristic times (1h, 6h, 30h, 48h) chosen through crisis exercises feedback. Furthermore, the zone of interest is extended from 20km to 50km. Figure 2 summarizes the conditions of application of the different protective actions, depending on time, distance and reaching of doses thresholds (see table 1).

Figure 2: ASNR’s baseline modeling of the French crisis organization emergency plans



[1] No core melt accidents starts less than 1h after the initiating event in the scenarios considered

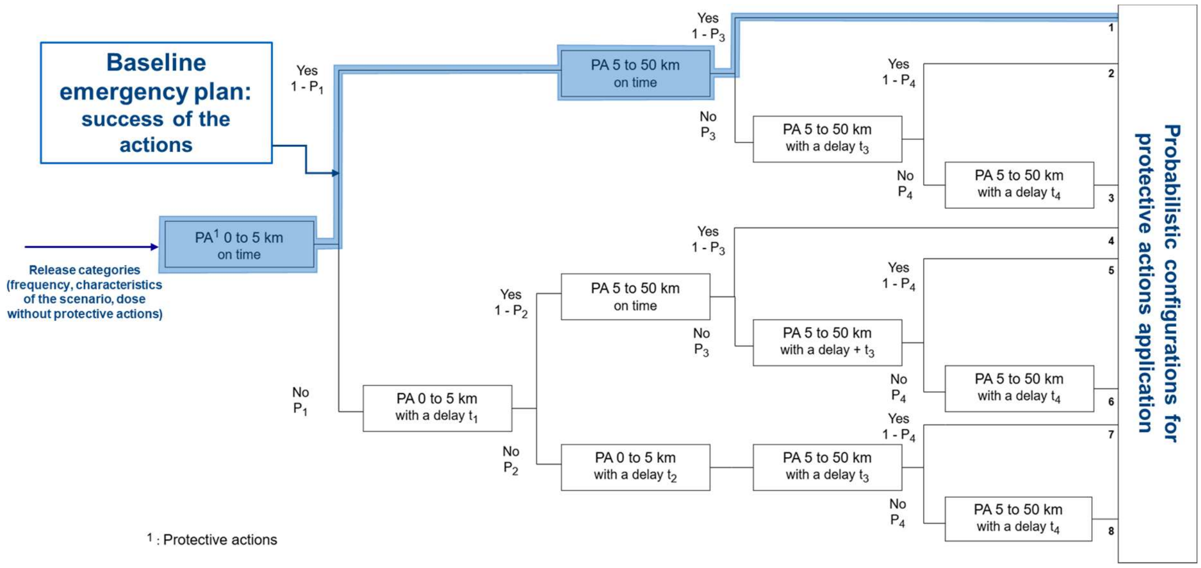
To take into account potential delays in the decision (due to the public authorities, operators, etc.), a probabilistic tree is defined. The geographical modeling of the emergency plans is simplified in two zones: from 0 to 5km and from 5 to 50km, to separate the emergency zone (where short-term actions may be needed) from the zone where later actions can be acceptable. The probabilistic tree proposes 8 timing modeling: the baseline configuration (application of the emergency plans) and seven configurations with delays that represent possible errors in the diagnosis/prognosis method of the crisis organization or communication difficulties.

Figure 3 represents these 8 configurations and highlights, in blue, the baseline configuration:

- for actions that would not be correlated to the reaching of dose thresholds, the wording “on time” refers to the following times : 1h for sheltering within 2km, 6h for evacuation within 5 km;
- for actions that would depend on the reaching of dose thresholds (stable iodine intake, sheltering over 2km, evacuation over 5 km), the wording “on time” refers to the application of the protective action as soon as both dose threshold and baseline emergency plan time are reached. This approach is conservative in terms of received dose.

To cover the cases when the emergency plans are not applied on-time, probabilities of failure P_1 to P_4 (and the associated delays t_1 to t_4) will be defined through the statistical analysis of crisis exercises feedbacks and in function of the characteristics of the scenario (late or early releases, severity, complexity, etc.) transmitted from the L2 PSA.

Figure 3: Probabilistic tree for the time of protective actions application



4. QUANTIFICATION OF THE PROTECTIVE ACTIONS EFFECTS

4.1. Definition of Protection Factors

Dose reduction effects from stable iodine intake and sheltering are evaluated as protection factors, defined as the ratio between the dose with the protective action and the dose without (see equation 1):

$$PF_i(t) = \frac{D_{with\, i}(t)}{D_{without\, i}(t)} \tag{1}$$

Where i represents the considered protective action (*sii* for stable iodine intake and *sh* for sheltering). The dose with protective action is then expressed as a function of the protection factor and the dose without protection.

4.2. Stable Iodine Intake

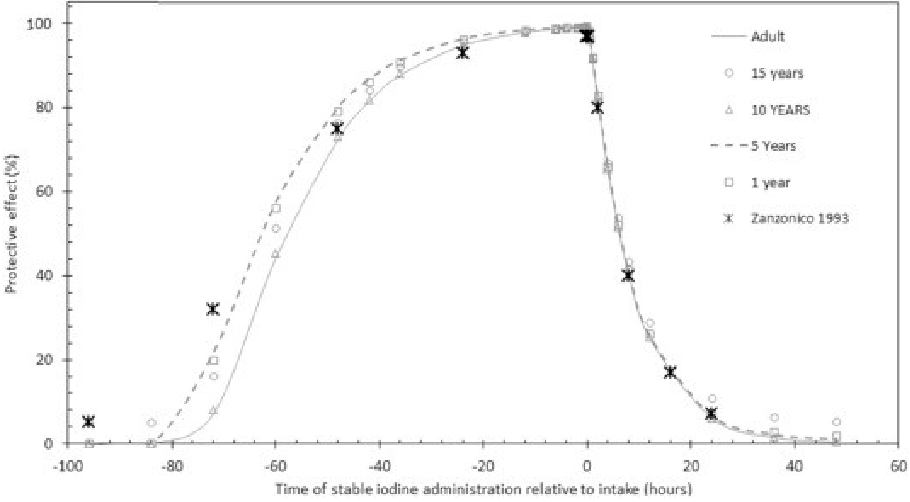
Stable iodine intake is a protective action that can reduce the radiological consequences of contamination by iodine inhalation to the thyroid. For other organs, other radionuclides and other exposure pathways, this action is ineffective and the protection factor is constant and equal to 1 (which signifies the absence of protection).

In France, stable iodine distribution campaigns concern a 20km-radius around NPPs so that affected populations already have tablets in their possession as a precautionary measure (in practice, only a fraction of the concerned population has immediate access to stable iodine tablets; a sensitivity study is planned to cover this topic, see section 6).

The stable iodine ingestion saturates the thyroid gland and prevents the fixation of radioactive iodine in the organ. However, this intake's efficiency is strongly time-dependent, as demonstrated by figure 4. This figure is from D. Broggio's assessment of iodine efficiency [4] and represents the time evolution of the protective effect (PE) for stable iodine intake for several population categories.

The protection factor (PF) for the population categories of interest in ASNR's health consequences assessment is then obtained with the expression $PE_{sii} = 1 - PF_{sii}$[2].

Figure 4: Protective effect for stable iodine intake [4]



Indeed, the efficiency of the stable iodine intake depends on the time of intake compared to the time of the exposure. An intake of stable iodine few hours before the exposition can reduce the dose received to the thyroid by over 95%.

Moreover, the modeling presented by figure 4 is based on calculations for a punctual exposure, whereas NPP core melt accidents lead to continuous releases, and thus continuous exposures. To take into account such a specificity, the time interval of interest (from the initial event to the evaluation) is divided into n smaller equal intervals. Then, to account for the stable iodine's impact, the dose $D_{with\ sii}$ is evaluated as the sum of the dose $D_{without\ sii}(t_k \rightarrow t_{k+1})$ received at each time step (where k is an integer between 0 and n-1), multiplied by the corresponding protection factor $PF_{sii}(\frac{t_k+t_{k+1}}{2})$ (assessed at the middle of the k^th^ interval):

$$D_{with\ sii}(t_0 \rightarrow t_n) = \sum_{k=0}^{n-1} D_{without\ sii}(t_k \rightarrow t_{k+1}) \times PF_{sii}(\frac{t_k+t_{k+1}}{2}) \qquad (2)$$

4.3. Sheltering

Sheltering is a protective action which consists of shielding the affected populations inside buildings, reducing the radiological consequences for each exposure pathway and organ. Sheltering dose-reduction effects are presented as protection factors, defined separately for each exposure pathway.

Inhalation

For inhalation, it is evaluated by the resolution of the following differential equation, for different groups of radionuclides:

$$\frac{dC}{dt} = \lambda_t \times f \times C_0(t) - \lambda_t \times C(t) - \lambda_d \times C(t) - \lambda_r \times C(t) \qquad (3)$$

Where:

- $C(t)$ is the concentration inside of the housing;
- $C_0(t)$ is the one outside;
- λ_t is the air renewal rate of the housing;
- f is the filtration factor (disregarded here: $f = 1$);
- λ_d is the deposition rate for aerosols inside the housing;

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[2] Therefore, when the protective effect is maximal, the protection factor is minimal.

- λ_r is the decay constant (neglected here: for PWR accidents, the released radionuclides which contribute the most to the received dose have half-lives superior to 1 day. Therefore, corresponding decay constants are much lower than the order of magnitude for deposition or air renewal rates).

The protection factor is then obtained by resolving the differential equation (3) for a constant concentration outside the housing ($C_0(t) = C_0$ at the target point, which is an acceptable approximation as the expression obtained allows to quantify appropriately the protection factor for the large variety of scenarios[3]).

For a specific radionuclide, the resolution of the differential equation (3) provides the following expression of the protection factor:

$$PF_{sh}(t) = k \times (1 + \frac{1}{mt}) \times (e^{-mt} - 1) \qquad (4)$$

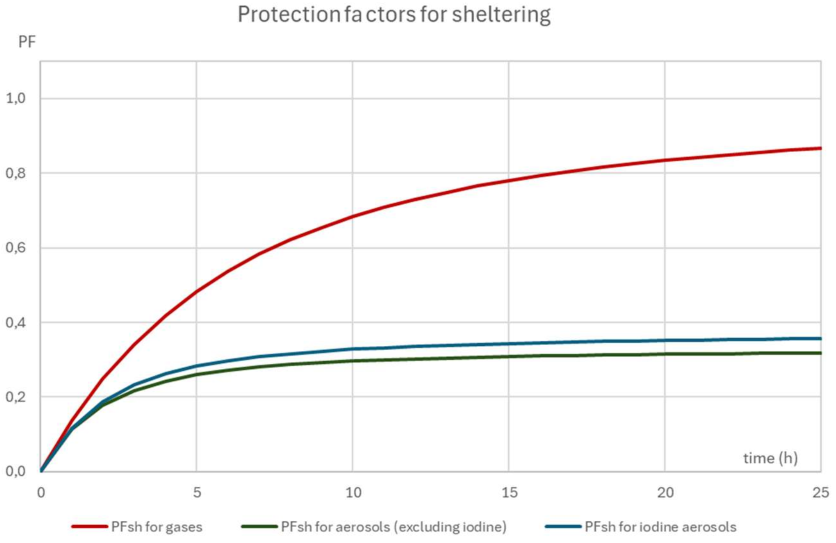
Where:

- $k = \frac{\lambda_t}{\lambda_t + \lambda_d}$
- $m = \lambda_t + \lambda_d$

Regarding the 113 radionuclides considered in MER and MERCOR, the model simplifies the protective actions effects assessment by grouping them into three categories: gas, iodine in aerosol form and other aerosols. The protection factor is evaluated with the equation (4) for each category by assessing the mean deposition rates (for a specific radionuclide, the rate λ_d is obtained from experimental values [5]). This approach allows an accurate representation of the different kinetics of sedimentation.

Figure 5 illustrates an example of the evolution of the sheltering protection factor during an accident, for the three categories of radionuclides.

Figure 5: Protection factors for sheltering



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[3] To consider the specificity of each scenario, an incremental concentration model could be used (multi-linear extrapolation of the dose profiles) to solve the differential equation. For a specific radionuclide, $PF_{Sh}(t)$ can be calculated as (for shielding at t=0): $\int_0^t C\,(t).RF.DC.dt$ / $\int_0^t C_o\,(t).RF.DC.dt$ where RF is the respiratory flow and DC the inhalation dose coefficient of the radionuclide.

Cloud and ground dose

The respective protection factors are defined as constants and obtained as follows:

- For cloud dose reduction effects, Monte Carlo simulations allow the estimation of the protection factor. Results show little variation in the parameter value (between 0.08 and 0.14) and therefore:

$$PF_{sh}(t) = 0.1 \tag{5}$$

- For ground dose reduction effects, the protection factor depends on the aerosol deposition inside the building. The factor is time-dependent; however, low value variations and calculation complexity justify the use of a constant value:

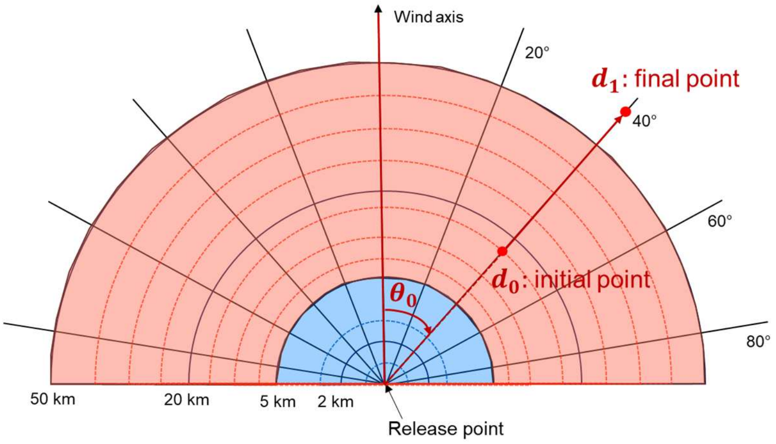
$$PF_{sh}(t) = 0.05 \tag{6}$$

4.4. Evacuation

As opposed to the previous protective actions (sheltering and stable iodine intake), the dose reduction from the evacuation of a zone is not evaluated as a protection factor in the dose calculation. It is rather expressed as an additional term: the dose is evaluated (with stable iodine intake and sheltering effects if applicable) from the initiating event to the evacuation and then summed with the one received from the start of the evacuation to its end (only with stable iodine intake effects if applicable).

Evacuation reduces the dose received by distancing an individual from the source of the releases, since radiological consequences decrease with distance. It occurs in a straight direct path to the furthest distance from the release point achievable (straight line at the same angle with the wind axis as the starting point), as shown on figure 6.

Figure 6: Evacuation organization depending on the initial point



A simplified mathematical model has been developed to quantify the dose received during evacuation. Its expression is a decreasing power law as follows (dose variation in time is neglected here over the dose decrease with distance, the dose rate is only evaluated at t_0):

$$D_{evac} = DR_{tot}(d_0, \theta_0, t_0) \times \frac{d_0}{v(1-n)}\left[\left(\frac{d_1}{d_0}\right)^{1-n} - 1\right] \tag{7}$$

Where:

- $DR_{tot}(d_0, \theta_0, t_0)$ is the dose rate at the initial point d_0, at an initial angle with the wind axis θ_0 and at the time of evacuation t_0 (see Figure 6);
- d_1 is the distance reached at the end of the evacuation (after this point is reached, the dose rate is assumed to be negligible and no more considered);
- v is the constant evacuation speed;

- n is the coefficient of the decreasing power law along the evacuation pathway. It is fixed at a value of 2.

4.5. Synthesis

The model assesses the effectiveness of protective actions by expressing the received dose with protection as a function of:

- the dose without protection;
- the distance from the release point and angle with the wind axis;
- the last moment of the evaluation (the dose evaluated is the dose received between the initiating event and the considered time);
- the protection factors (for sheltering and stable iodine intake) and additional terms (for evacuation) that quantify protective actions impacts;
- the dose contribution ratios for categories of radionuclides (gas, iodine aerosols and other aerosols).

The algorithm evaluates the dose received from each radionuclide categories during incremental time intervals (as mentioned in 4.2). For each time increment, the dose is calculated by combining the different dose reduction effects according to the specific configuration of the accident scenario. The dose received during the complete duration of the evaluation is equal to the sum of the doses received during each of these intervals.

The doses obtained as a result are then used to estimate the health consequences with dose-effects relationships.

5. HEALTH CONSEQUENCES ASSESSMENT

5.1. Deterministic Effects

Deterministic effects are evaluated as the risk of early fatality from acute radiation injury to the lungs or red bone marrow. The following method follows the approach described in ANVS's guide on L3 PSA [6], which stems from NUREG's report on health effects models for NPP accident consequence analysis [7].

This risk of early fatality is expressed according to a hazard function defined by a 2-parameter Weibull distribution. This hazard function defines the cumulative distribution function H in relation to the organ weighted absorbed dose D, the median lethal dose LD_{50}, the shape parameter for the organ v_{org} and the organ threshold dose T_{org} (which corresponds to the dose value for a mortality risk of about 1%):

$$For\ D > T_{org},\ H = ln(2)\left(\frac{D}{LD_{50}}\right)^{v_{org}} \tag{8}$$

The risk r of early fatality from acute radiation injury to an organ of interest is equal to:

$$For\ D > T_{org}, r = 1 - \exp(-H) = 1 - exp\left[-ln(2)\left(\frac{D}{LD_{50}}\right)^{v_{org}}\right] \tag{9}$$

However, if the dose threshold for the organ has not been exceeded, the mortality rate is 0:

$$For\ D < T_{org}, r = 0 \tag{10}$$

For lungs and red bone marrow, the Weibull parameters are as follows:

Table 2: Weibull parameters for mortality evaluation

Organ	Median lethal dose (Gy-eq)	Shape parameter	Threshold dose (Gy-eq)
Lungs	10	7	5.5
Red bone marrow	4	5	1.75

A multi-organ mortality risk expression is then defined by summing both cumulative effect functions. This multi-organ model is the one used in this health consequences assessment to accurately determine the deterministic risk for non-uniform exposures (due to the inhalation exposure pathway for NPP accidents).

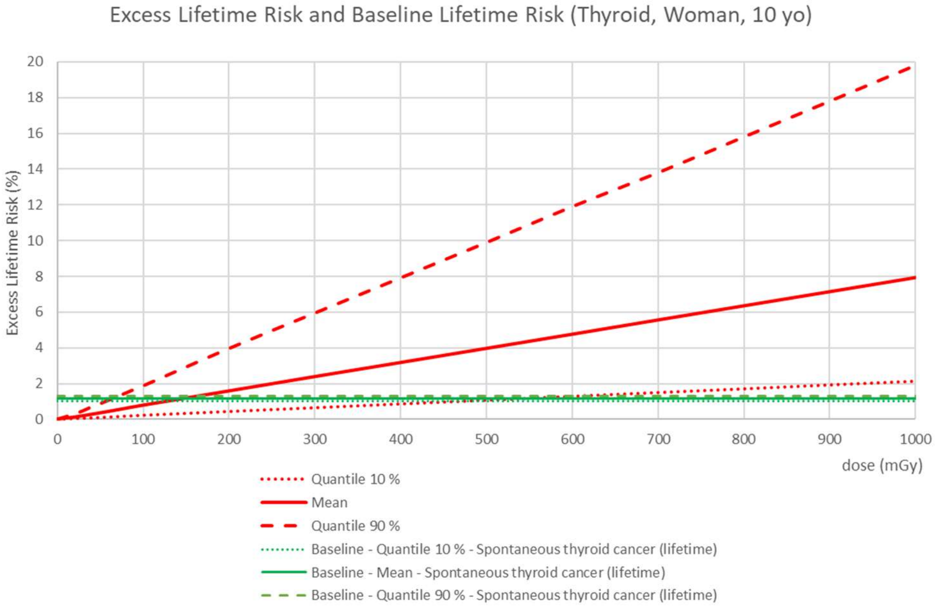
The deterministic risk is evaluated for each pre-defined geographical sector (sectors are defined with the discretized distances / angles, see table 1) and multiplied by the population density in order to assess the number of deaths linked to a specific configuration.

5.2. Stochastic Effects

Stochastic effects are evaluated as the lifetime risk of developing radiation-induced cancer for the four radio-sensitive organs mentioned in table 1 (lungs, breasts, red bone marrow and thyroid). Such risk is quantified with the American software RadRAT (National Cancer Institute) [8] using both the doses which consider the dose reduction effects from protective actions, as well as the ones which do not for comparison purposes. This software was developed with the risk models presented by the BEIR VII 2006 report [9] for the organs of interest and includes age-dependent and gender-dependent evaluations. Therefore, ASNR's health consequences assessment focuses on the three different population categories mentioned in table 1: 1-year-old infants, 10-year-old children and adults over 14 years old (the risk is proportionally weighted for ages over 14 since the lifetime risk decreases with age).

Figure 7 illustrates the excess lifetime risks for 10-year-old girls, calculated with RadRAT using French population data.

Figure 7: Excess lifetime risk of developing radiation-induced cancers



Similarly to the deterministic evaluation, the risk is multiplied by the population density for each geographical sector (excluding potential deterministic deaths) to estimate the number of people who will develop cancers as the result of the radiological exposure over their lifetime.

6. PERSPECTIVES AND CONCLUSION

ASNR's health consequences assessment for NPP PSA, described in this article, is currently being developed with the software KANT. It will take into account the benefit of protective actions implemented by the national crisis organization.

Once this development has been completed, sensitivity studies will be conducted in order to determine which parameters are the most influent in the model and how they affect the results. For example, one of those sensitivity studies will consist of introducing more variations in the chronology of protective actions defined in the emergency plans modeling (see figure 2). For example, it is planned to evaluate the impact of an evacuation 70h after the initiating event rather than 48h for the 5 to 50km zone. Another example will be the consideration of the limited availability of stable iodine tablets for the 20km radius around the NPP, by varying the proportion of people having access to a tablet. A sensitivity study on the positive impact of FFP masks (filtering facepiece) on the reduction of the dose will also be conducted.

Quantification of PSA with this health consequences assessment will provide information on the efficiency of emergency plans.

In a further step, the ASNR PSA will include local meteorological variations as well as site-specific population distribution, which will require further development based on tools available at the ASNR crisis center for environmental dispersion.

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