ASSESSMENT OF EMERGENCY PLANNING ZONE FOR iPWRs WITHIN THE HORIZON EURATOM SASPAM-SA PROJECT

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ABSTRACT

The Horizon Euratom SASPAM-SA project (Safety Analysis of SMR with PAssive Mitigation strategies – Severe Accidenft) analyzes the applicability of current state-of-the-art severe accident codes against hypothetical generic iPWR designs in the view of the needs of the European licensing processes. In addition to work packages related to code analysis capabilities, current experiments' applicability to iPWRs, and containment analyses, WP6 (on Emergency Planning Zone – EPZ) considers the offsite dispersion and doses caused by radioactive releases from postulated severe accidents, thus representing the last phase of calculations. Twelve partners are working to achieve numerical, quantitative results about the geographic extent of off-site dose consequences, affecting the final decision on EPZ.
Initially, a set of varyingly conservative calculations were performed, based on atmospheric source terms ranging from maximum possible quantities down to smaller release estimates from pure 'expert judgement' or some quite simple analytical work. The codes used included JRODOS, MACCS, HotSpot, RASCAL, GENII and ARANO. The first phase mainly served to test the calculation capabilities of the codes used at the participating institutions.
In the current phase, more refined 'BE' STs produced within WP5 ('Containment') are being used to avoid exceedingly conservative results due to lack of release knowledge, i.e. detailed data about actual nuclide content, activities, temporal release rate trend, effective release height etc.
Generally, it is expected that SMR smaller inventories and longer delays before any atmospheric release might lead to smaller dose consequence footprints than those for existing large LWR plants. That could facilitate the acceptance of SMR plant sites near densely populated areas. Finally, it is expected, at the end of the project, that results from WP6 can be used to understand limits, if any, of the current codes and/or methods and approaches in producing sound and reliable data for EPZ extents of iPWRs.

KEYWORDS
EPZ, Severe Accident, SMR, atmospheric dispersion, offsite doses

1. INTRODUCTION TO WP6 (EPZ)

The Horizon Euratom SASPAM-SA project (Safety Analysis of SMR with PAssive Mitigation strategies – Severe Accident) [1,2,3], coordinated by ENEA (Italy), analyzes the applicability of current state-of-the-art Severe Accident (SA) codes against hypothetical generic integral Pressurized Water Reactor (iPWR) designs in the view of the needs of the European licensing processes. In addition to Work Packages (WP) related to code analysis capabilities [4,5], current experiments' applicability to iPWRs [6], and containment analyses [3], WP6 (Emergency Planning Zone, EPZ), considers the offsite dispersion and doses caused by radioactive releases from postulated SAs, thus representing the last phase of calculations. In order to maximize the knowledge transferability and impacts of the project, two generic design-concepts, characterized by different evolutionary innovations in comparison with larger operating reactor, were selected for analyses.

The overall objective of WP6 is to provide evaluations of size and extension of EPZ for selected SA scenarios, eventually (during latter half of SASPAM-SA project) coupling the results of BE Source Term (ST) codes to radiological consequences tools. One of the most important features of iPWRs is the possibility of their siting near densely populated areas thanks to the (claimed) increased inherent safety, the assumedly lower radiological impact, and possibly reduced size of the region affected by releases (dose consequences footprint). The need to demonstrate these features using quantitative results is addressed by WP6 which attempts to provide a sound basis for the assessment of EPZ. WP6 will produce recommendations on rigorous and justified methodology for iPWR EPZ 'right-sized' determination. However, the size is not necessarily universally the same in all countries due to domestic regulations, for all kinds of plants or for all sites. Furthermore, for the EPZ, SASPAM-SA is strictly considering radiological consequences only ('off-site doses footprint area'), leaving out any possible social, political, logistics etc. factors. It can be postulated that the EPZ cannot be smaller than the area defined by the purely radiological considerations.

The structure of WP6 is the following:
- Task 6.1: Critical review of existing EPZ methodology
- Task 6.2: Preliminary conservative offsite dose assessments
- Task 6.3: Offsite doses & EPZ by Best Estimate (BE) approach
- Task 6.4: Conclusions on iPWR EPZ & recommendations on methodology

This paper considers mainly the first two tasks of WP6, specifically the review of current methodologies (Task 6.1) and the conservative assessments of EPZ (Task 6.2). VTT (Finland) is leading the work in WP6.

Task 1 (methodology review) is devoted to the analyses of the methods already available for large Light Water Reactors (LWR) to understand their applicability to iPWR. It included also preparatory work in relation to the following task such as an analysis of the suitability of codes linked to the problem of near range atmospheric dispersion and the effect of nearby buildings.

Task 2 (preliminary / conservative dose calculations) was devoted to develop first estimates of STs relying on publicly available data or conservative hypothesis based on initial inventory evaluated in WP2, and to calculate EPZs using simplified and conservative methods. This provides background technical results to be used as a comparison set for the BE tasks.

2. CRITICAL REVIEW OF THE EXISTING METHODOLOGY FOR EPZ DETERMINATION

The work carried out within Task 6.1 focused on a comprehensive review of the existing methodologies, relevant to the definition of EPZs for integral iPWR. The activities were jointly conducted by ENEA, JRC, LEI, POLIMI, SSTC NRS, TUS, Università di Roma, and VTT, combining expertise from multiple European and international institutions.

The review work included the following subtopics:

- Analysis of the methods already available for large-LWR to understand their applicability to iPWR.
- Preparatory work in relation to the following task such as an analysis of the suitability of codes linked to the problem of near range atmospheric dispersion and the effect of nearby buildings.
- Study of country-specific regulations on EPZ & protective measures, IAEA guidelines on those & outcomes of the SMR Regulators' Forum [13], and outcomes of relevant IAEA CRP projects.
- Analysis of current EPZ approaches (large PWR or other) and their applicability to smaller iPWRs.
- Review of simulation tools and recommendations for suitable, possibly harmonized methods for iPWR SMR EPZ.
- Overview of short range dispersion special approaches & phenomena.
- Consideration of risk-informed methodology for the calculation of the EPZ size for an iPWR SMR.

The activities by WP6 partners included examination of the features of several available dispersion and dose projection tools, including their near-range capability which is important for SMRs, if exceedance of dose limits is only expected in the near-range. Current regulations and methodologies for EPZ were studied to serve as groundwork both for the quantitative calculations and the expected methodology recommendations.

The review of EPZ-related regulations covered e.g. Bulgaria, Finland, Lithuania, Ukraine, and the USA. The implications of the International Atomic Energy Agency (IAEA) and European Union (EU) standards and directives for several EU countries were considered. The codes for release through water volumes (like reactor pool) were SPARC-90 for pool scrubbing and IMPAIR for iodine chemistry and release. For the atmospheric dispersion and dose calculations, e.g. JRODOS, MACCS, HotSpot, or the VTT in-house code ARANO were used.

2.1. Current regulations on EPZ & protective measures

SASPAM-SA WP6 performed a comprehensive review of EPZ[1] regulations and methodologies across multiple countries and international frameworks. In the EU, the bases are directives (Basic Safety Standards 2013/59/Euratom [7] and European Nuclear Safety Directive 2014/87/Euratom [8]) which set overarching goals for emergency management but do not prescribe specific EPZ distances. Instead, member states define zones based on national policies, laws and risk assessments.

Country-specific approaches vary significantly. Belgium mandates evacuation planning within 10 km and sheltering/iodine prophylaxis within 20 km, while Bulgaria uses a tiered system (Precautionary Action Zone[2] – PAZ – 2 km, Urgent Protective Actions Zone[3] – UPZ – conditionally 30 km, and a long-term zone, without fixed outer boundary because its extent is determined by monitoring results and conditions after an event) integrated into the disaster protection legislation. Finland used to prescribe 5 km precautionary and

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[1] **Emergency Planning Zone (EPZ)**: The precautionary action zone (PAZ) and the urgent protective action planning zone (UPZ) [10].

[2] **Precautionary Action Zone (PAZ)**: An area around a facility for which emergency arrangements have been made to take urgent protective actions in the event of a nuclear or radiological emergency to avoid or to minimize severe deterministic effects off the site. Protective actions within this area are to be taken before or shortly after a release of radioactive material or an exposure, on the basis of prevailing conditions at the facility [10].

[3] **Urgent Protective Actions Zone (UPZ)**: An area around a facility for which arrangements have been made to take urgent protective actions in the event of a nuclear or radiological emergency to avert doses off the site in accordance with international safety standards. Protective actions within this area are to be taken on the basis of environmental monitoring — or, as appropriate, prevailing conditions at the facility [10].

20 km planning zones, supported by STUK regulations and detailed rescue plans, but shifted to a flexible scheme with the STUK Emergency Decree Y/2/2024 [12]. France in 2019 expanded its EPZ for sheltering and iodine pills from 10 km to 20 km to improve public preparedness. Other European nations (Czech Republic, Hungary, Lithuania, Slovakia, Slovenia, Spain) adopt similar concentric-zone models, typically ranging from 3–5 km for immediate actions to 30 km or more for extended measures, often aligned with IAEA guidance. Ukraine is in the process of harmonizing national rules with EU and IAEA standards.

Internationally, Canada applies flexible, case-by-case EPZ sizing, while the U.S. has shifted to a performance-based, risk-informed approach for SMRs and new technologies, formalized in updated NRC regulations (final new rule 2023). This method considers accident scenario likelihoods, together with the STs, potentially reducing EPZs to very small distances for advanced designs.

Overall, trends indicate some movement towards risk-informed, site-specific EPZ sizing, especially for SMRs, balancing safety, practicality, and societal factors. For example, the UK Nuclear Regulatory Review by Fingleton, 2025 [11], strongly emphasizes simplification of regulations together with management and proportionality of risks. Protective actions, such as evacuation, sheltering, iodine prophylaxis, and food restrictions, are most universally planned based on dose criteria and operational intervention levels.

2.2. Future development – Finland example

Finland's regulations are evolving related to SMRs, starting with the determination of EPZ (consisting of PAZ and UPZ). STUK emphasizes that SMR safety should be assessed case by case, as their lower power and passive safety features can reduce risks compared to traditional nuclear power plants. This flexibility may allow SMRs to be located closer to urban areas, provided safety is demonstrated.

A major legislative reform is underway, but EPZ rules were updated earlier through STUK Regulation Y/2/2024 (effective February 2024) [12] to support urban planning. Previously fixed EPZ distances — PAZ at 5 km and UPZ at 20 km — are now flexible, based on dose criteria. For PAZ, radiation dose outside the zone must remain below 1 Sv within 10 hours. Inside PAZ, efficient precautionary evacuation is planned to prevent early deterministic health effects. Outside UPZ, dose remaining below 10 mSv within 48 hours is required, to not necessitate sheltering indoors there. Licensees must demonstrate compliance using realistic SA scenarios, though probabilistic risk assessment is not required. SASPAM-SA WP6 is facing the same fundamental problem: How to choose the accident scenarios for EPZ determination purposes? However, a further step towards risk-informed approach may be expected with the recent STUK information that the accident and release scenario for UPZ may be less severe than that for PAZ. The approach prioritizes safety performance regarding emergency preparedness rather than prescribing reactor design / technology, actually so aligning with IAEA EP&R high-level guidelines and STUK emergency regulations ('VAL' guides).

2.3. IAEA and the SMR Regulators' Forum

WP6 outlined IAEA guidelines for emergency preparedness and response planning, with protective measures for nuclear facilities, which are not yet specifically focusing on SMRs. The IAEA defines five Emergency Preparedness Categories (EPC), with Category I posing the highest offsite health risks. SMRs generally fall between Categories I–III, suggesting potential for reduced emergency planning compared to large LWRs, though enhanced safety needs to be demonstrated.

Key standards include GSR Part 7 (2015; possibly to be updated) [10], which sets 26 requirements for preparedness and response, covering hazard assessment, protective actions, public communication, and medical response [10]. It applies to all reactor types, including small or next-generation designs. Supporting documents such as EPR-NPP-PPA (2013) [9] provide practical guidance on protective actions and EPZ sizing, though currently presented methods remain deterministic and rather simplified, often based on worst-case scenarios.

The IAEA recommends concentric EPZ zones called PAZ near the plant for immediate measures once release is expected and UPZ for rapid protective actions. Post-Fukushima, recommended planning area increased significantly, with Extended Planning Distances (EPD)[4] up to 100 km and Ingestion and Commodities Planning Distance (ICPD)[5] up to 300 km.

The SMR Regulators' Forum (2015–2018) [13] addressed challenges in applying EPZ concepts to SMRs, advocating a graded, site-specific approach that considers design features and possible accident scenarios with smaller inventories, passive safety features and possibly slower accident progression. While smaller EPZs for SMRs are possible, current IAEA methodologies are mainly those for large reactors, lacking adaptation for SMR-specific safety innovations. Future guidance should integrate lessons from modern studies, emphasizing optimization and justification principles.

2.4. IAEA CRP projects

WP6 reviewed results from two IAEA Coordinated Research Projects (CRPs) focused on EPZs for SMRs. The earlier CRP (I25001, 2010) [14] examined small reactors without on-site refueling, producing TECDOC-1652 [15], which addressed reactor characteristics and emergency planning, proposing a methodology to redefine EPZs using Probabilistic Risk Assessment (PRA) and deterministic dose evaluations. The approach aimed to reduce EPZ size for innovative SMRs while maintaining safety level.

The later CRP (I31029, 2018–2021) [16] involved participants from 12 countries, aiming to establish technical bases for EPZ sizing for SMRs, particularly relevant for urban or industrial heat applications. Objectives included:

1. defining criteria for EPR based on SMR safety features (e.g. smaller STs, enhanced safety systems),
2. developing methodologies linking SMR design to offsite arrangements, and
3. contributing to future IAEA guidance on EPZ determination.

Research focused on modelling radioactive inventories, STs, and off-site dose assessments to compare against national and international protective action levels. While most participants calculated reference accident cases for specific SMR designs, broader methodological discussions also occurred. A TECDOC summarizing these findings is still pending publication.

2.5. Different safety approaches: risk-informed, generic vs. specific etc.

WP6 also discussed the characterization and classification of various methodologies for determining EPZs for nuclear installations, particularly with regard to their applicability for SMRs. Two main categories can be described as generic and specific. Generic approaches apply fixed distances based on conservative assumptions without considering plant-specific details, relying on bounding calculations for STs and atmospheric dispersion. These methods are simple and widely used but often overly conservative and

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[4] **Extended Planning Distances (EPD)**: The extended planning distance is the distance within which arrangements at the preparedness stage (before an emergency) need to be made to monitor the dose rates from deposition [9].

[5] **Ingestion And Commodities Planning Distance (ICPD)**: distance at which urgent restrictions are placed on the consumption and distribution of local produce, wild-grown products (e.g. mushrooms and game), milk from grazing animals or rainwater that need to be implemented before or shortly after a release in order to: (a) significantly reduce the risk of an increase in the thyroid cancer incidence due to radiation induced cases, and (b) to reduce doses in excess of the generic criteria given in Table 23 of [9].

misaligned with smaller inventories and advanced safety features of modern SMR designs. Specific methodologies, by contrast, incorporate plant-specific safety analyses, accident scenarios, and plant PRA, offering tailored EPZs that reflect actual design and safety features. Within specific approaches, deterministic methods use bounding SA scenarios, while probabilistic methods employ Level 2 PRA results to estimate accident frequencies together with consequences. Hybrid or risk-informed approaches combine deterministic dose calculations with probabilistic insights to balance conservatism and practicality.

WP6 also attempted to classify some national and international EPZ practices, including IAEA guidelines, UK's REPPIR 2019 [17] framework, and examples from France, Belgium, Slovakia and the Netherlands. Probabilistic and mixed approaches can significantly reduce EPZ size, potentially to site boundaries, by leveraging SMR safety features. However, these methods are computationally demanding and require regulatory maturity and ultimately, for best acceptance, harmonized probability thresholds across jurisdictions. WP6 work includes a SWOT analysis for deterministic (see Table I), probabilistic, and mixed approaches, highlighting trade-offs in implementation complexity, exploitation of SMR inherent safety features, conservatism, and alignment with EU and global practices. While deterministic methods remain straightforward and widely understood, probabilistic and mixed approaches, though challenging, offer opportunities for optimized EPZs and broader SMR deployment, provided harmonization and technical capability are achieved.

Table I. SWOT Analysis for the Deterministic Approach (ENEA)

	Strengths +	**Weaknesses -**
Internal Factors	• Easy to implement (no need for PSA-2) • Easy to check and verify • Well known and established	• Not exploiting, in ST use, the inherent safety features of some SMRs • Over-conservative in results
	Opportunities +	**Threats -**
External Factors	• Depends only on Intervention Levels, which should be harmonized in EU • Easy to implement in different EU countries, even in those with lower background in PSA	• Results not supportive of SMR non-electric uses • Not aligned with USA, UK or Canada practice • Considered too much old-fashioned? • Perhaps not reaching the goal of EPZ harmonization in EU for a given design

2.6. SMR-specific dispersion and exposure considerations

If expecting to find exceedance of dose limits in SMR cases nearer to the plant than currently typical for large LWRs, it is more important than before to have physically realistic modelling of atmospheric dispersion in the near-field, with still a lot of influence from ST parameters and possible building etc. obstacles. For larger plants, such distances have been included in the EPZ anyway. Some particularities of near-field dispersion that were identified in WP6 work can be listed as follows:

- Many SMR designs locate the reactor underground, or at least the size of the building is smaller than for large NPPs. Possibly the initial heat content is smaller. These factors will make the effective release height smaller, meaning a more concentrated radioactive cloud in the nearby areas. Furthermore, the possible offsite adverse effects are inherently located more pronouncedly in the

nearby areas only, because of the small source. Potential siting near population centres makes it very important to study those near-field effects in great detail.
- Building wake: Turbulent eddies around buildings provide more initial spread.
- Stack-tip downwash (buildings and other structures causing downwards transfer of activity concentrations)
- Cloud rise (plume rise): Initial upward momentum and heat content make the release rise higher than stack height right at the starting point. Even when iPWR plants are not expected to have tall stacks, the effect may not be negligible, depending on how the release enters the atmosphere.
- Near-field dispersion parameters: Weather mast measurements may be more reliable near the source than NWP (numerical weather prediction) model, but more masts than one single would make the data even more reliable and complete.
- Very narrow plume: It takes some time for the release to spread in the lateral and vertical directions, and when e.g. using the Gaussian model, choice of appropriate parameters is very important.
- Urban / industrial terrain: Terrain roughness may decrease wind speeds locally and induce turbulence. Furthermore, spread directions may favour street 'canyons' etc.

In many dose pathways (exposure modes), there are potentially some specific considerations to perform an accurate assessment of doses, originating specifically from the siting and small size of SMR plants:
- Cloudshine: In many codes, the so-called 'semi-infinite uniform' approximation of the radioactive cloud is used. Then the radiation source is a uniformly distributed concentration [18] in a half-space (or practically, a half-sphere). With SMR plants, we are interested in the close surroundings, and it is important to consider the cloudshine source in all of its possible physical reality / realizations: In some cases, a long, narrow plume extending as such relatively far (even several kilometers) from the source (cf. the LINCON code used to generate cloud gamma dose conversion coefficients for ARANO). In urban environment, big buildings may provide considerable shielding effect against external radiation.
- Groundshine: In population centers and in industrial settings, deposition will not accumulate only on ground surface and vegetation, but to a relatively large extent also on the surfaces of buildings. They will become an additional source of radiation. Their decontamination is usually laborious. On the other, buildings provide some shielding for more faraway radiation source.
- Inhalation: In urban environment, with a large population in a large number of buildings, the inhalation dose caused by inhaled radionuclides indoors is a particularly important consideration. Air-tightness and ventilation systems of the buildings determine how much activity will be inhaled indoors. Depending on the systems, it may be possible to considerably reduce the internal dose commitment.
- Ingestion: Traditionally, and with regard to usually defined representative person, the conservative assumption of all consumed foodstuff being produced locally, very near the target population, has been used. However, this is seldom true in today's world, where foodstuff are routinely transported over great distances before being offered to consumers. It is even less true for SMR surrounding environment which may be urban or industrial, and in any case the area affected by significant deposition is expected to be smaller.

3. OFFSITE DOSE ASSESSMENTS BEFORE CONTAINMENT CALCULATIONS

In the SASPAM-SA project, two hypothetical generic iPWR designs were defined to be considered in detail in all WPs and phases of the project:
- Design 1: A generic iPWR characterized by a submerged containment and electric power of about 60 MWe;
- Design 2: A generic iPWR characterized by the use of several passive safety systems, a dry containment and an electric power of about 300 MWe.

Several SASPAM-SA project partners working in WP6 (ENEA, JRC, KIT, KTH, LEI, POLIMI, SSTC NRS, TUS, UNIROMA, VTT) selected one of the designs to study with regard to potential atmospheric radioactive releases and offsite doses. In the conservative phase of the project, detailed SA code calculations of the phenomena in reactor core and containment were in most cases not used.

Each partner had the freedom to select representative accident scenarios to study, including both Design Basis Accidents (DBAs) and SAs. The selection of scenarios common to the project was defined by WP2 and had various postulated breaks in piping, malfunctions of valves and failures of safety systems. The scenarios enable performing varied assessments of radionuclide behaviour and containment performance, which is the topic of WP5. The diversity of cases ensured that the study so far captured a broad spectrum of released amounts of radionuclides. The selection of scenarios is crucially important for EPZ determination purposes. In WP6, it was concluded that some consideration should be paid to the probabilities of the scenarios, in order to not use e.g. only extremely unlikely cases to calculate the dose consequence footprint areas.

STs are affected by assumed fuel burnup, which was available from WP2 for 20 to 60 MWd/kg in steps of 2.5 MWd/kgU; higher burnup means more accumulation of long-lived isotopes. From WP2, there was the inventory of 304 nuclides available [19]. Fractions of inventory released to the atmosphere usually depend on nuclide chemical group. The atmospheric release may happen at temporally variable release rates. Simple offsite dose codes typically only accept a uniform rate; more sophisticated codes can use any temporal evolution. Obviously, released amounts of activity have a very big and direct effect on off-site doses, the exact effect depending on nuclide. For final phases of SASPAM-SA, the releases will come from WP5 results. In previous studies it was typically found that the biggest uncertainty in offsite doses (and so also in the EPZ sizing) is coming from the (poor) knowledge of the ST, while also other, subsequent uncertainties do exist.

The preliminary / conservative analyses by WP6 partners considered a broad range of input parameters, like the variability in ST evaluations. Fuel burnup values ranged from 15 to 60 MWd/kgU, representing conditions from early to extended core reloading. Radionuclide inventories used included 2 – 71 species, mostly ensuring coverage of key fission products and activation products relevant to safety assessments. Atmospheric release fractions were highly dependent on chosen scenario and expert judgement by partner, spanning from fraction 1e-5 to whole inventory, depending on nuclide, reflecting both conservative (or even extremely conservative) SA release assumptions and more realistic ones, and also more probable design-basis accident conditions. These ranges provided a good readiness basis for evaluating containment performance and radiological consequences under diverse accident scenarios.

As an example of the initial conservative phase of WP6, the atmospheric source term used in the LEI analyses was developed by applying a simplified large PWR methodology consistent with U.S. NRC RG 1.183 [20] and with the source term evaluation approaches discussed by Mitrakos, 2022 [21]. In this LEI specific approach, a prompt LOCA driven release without delay was assumed, using standard PWR release fractions for noble gases, iodines, and aerosols. Radionuclide behaviour in the containment was calculated through a time dependent balance of release, decay, deposition, and a conservative leakage rate of 0.65 % d^{-1}. This methodology produced nuclide specific released fractions like in Fig. 1 below.

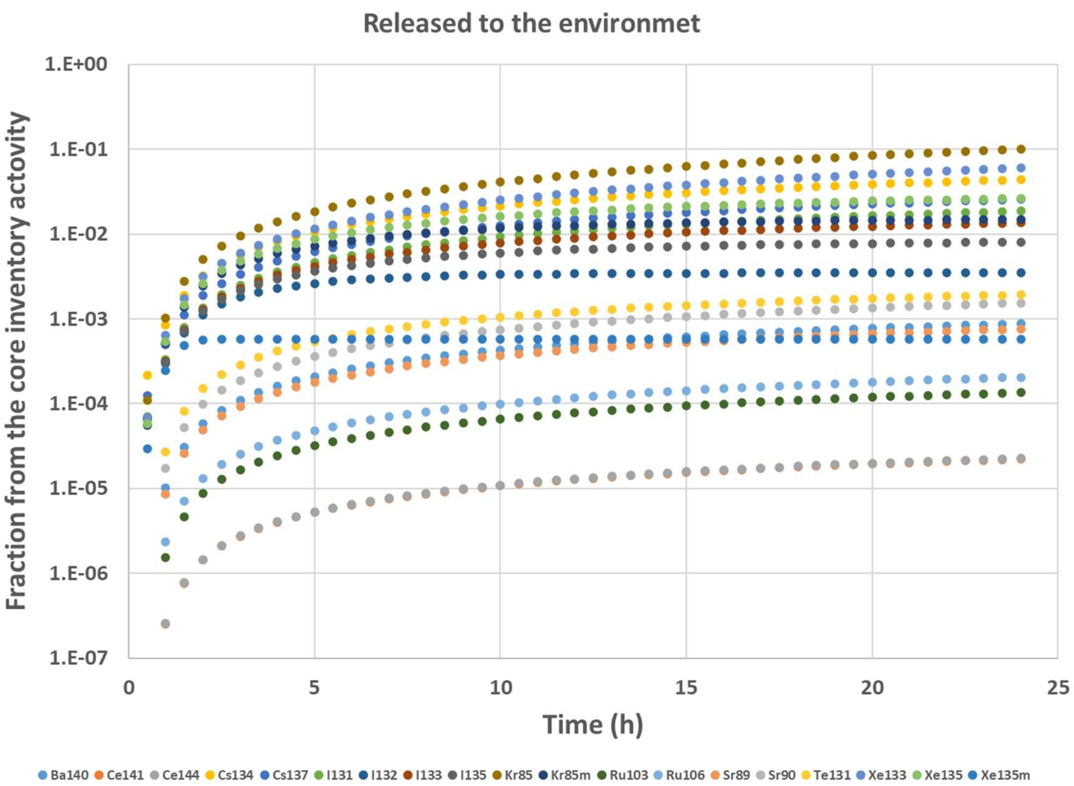

Figure 1. Nuclide-specific cumulative released fractions to the environment of the core inventory of Design-2. A sample case from the initial conservative phase approach by LEI, to illustrate some of the source term features needed for the subsequent atmospheric dispersion modelling.

In addition to released amounts of activity, STs must be described by also a number of other release parameters, like effective release height (or distribution on various atmospheric transport starting heights), and release duration, with possible temporal variations of nuclide-specific release rates. Effective release height is typically defined by height of stack or containment breach hole, increased by the effect of plume rise by momentum and buoyancy. Several off-site dose codes use the inventories at reactor shutdown time, corrected by the so-called delay time (time for radioactive chain decay and various other decontaminating processes between shutdown and start of atmospheric release). Decay inherently continues also during release duration and atmospheric dispersion. All the mentioned release parameters have a major effect on off-site doses; their increase leads to doses decreasing).

The modelling of atmospheric ST in WP6 incorporated a wide range of temporal and spatial release parameters, reflecting different assumptions on possible accident progression. Release delay times varied from the unrealistic zero to more than one day, depending on assumptions made about containment integrity and safety systems response. Effective release heights ranged from ground level for containment bypass or venting scenarios to more than 100 m for stack discharges with cloud rise, influencing the subsequent atmospheric dispersion patterns. Release durations spanned from rapid emissions lasting for one hour to prolonged releases over several days, corresponding to severe accident conditions with only a gradual leakage. These variations represent coverage of potential off-site radiological consequences on many levels of severity.

Assumed iPWR site in WP6 could be anything from operating NPP site to proposed newbuild site and a completely hypothetical one. The partners mostly selected representative locations within their countries, typically existing nuclear sites or candidate SMR deployment areas, while also ensuring realistic dispersion and population data. Off-site doses generally depend on site-specific environment and weather conditions. As the source of weather data, both Numerical Weather Prediction (NWP) reanalysis (data assimilation of past prediction data with observations) and site mast measurements were used, with the size of the data set chosen according to the needs of deterministic or statistical study. For near field calculations (as expectedly most interesting and typical for small iPWR), local weather mast measurements may be better representative than numerical data with large grid cells. Meteorological inputs for WP6 work were obtained from national weather services, site-specific historical datasets, or publicly available databases such as ERA5 reanalysis, providing wind speed, direction, temperature, and stability classes (one point or 3D) for dispersion modelling.

The code tools of WP6 implement physical models for atmospheric dispersion and off-site dose projection. They typically have a large number of possibly user-tunable parameters, like dry deposition velocity, washout coefficient, dose and dose rate conversion factors, shielding factors, breathing rates etc. Partners used their chosen set of dose criteria, i.e. limits of projected (or averted) dose, above which actions should be implemented to reduce doses to people. When using statistical / long-term weather data, also confidence levels are chosen, meaning the fractile (percentile), e.g. 95 %, of all values such that the dose was lower (or EPZ smaller) in 95 % of all cases, called P95 in short. In WP6 so far, the partners used a mix of established calculation tools for ST and dispersion modelling, including RODOS, MACCS, RASCAL, GENII, HotSpot, ARANO, and as well as some in-house / national methodologies. As for the radiation dose criteria, evaluations were based on standard IAEA or national regulatory limits for public exposure, typically expressed in terms of e.g. effective dose (mSv) for short-term health effects. With statistical weather, meteorological sampling applied percentile-based confidence levels, most commonly 95%, to ensure conservative enough estimates of doses under varying atmospheric conditions.

4. CONCLUSIONS

Generally SASPAM-SA WP6 on iPWR EPZ was, even in the conservative assessments phase, able to demonstrate that the EPZ for iPWR could potentially be reduced from that of large LWRs. Conservative and deterministic assessment of off-site doses is basically usable also for SMRs. Also the IAEA SMR Regulators' Forum Pilot project report [13] concludes about EPZ that '*the IAEA safety requirements and methodology for determining the EPZ size are effective in establishing an emergency preparedness and planning program*'. After the conservative assessments phase of SASPAM-SA WP6, the calculations using a BE ST will show if further reduction of iPWR EPZ seems feasible. This will depend on assumed mitigative strategies to reduce the emissions from the containment to outside atmosphere. If only very near-range doses turn out to be decisive for EPZ size, then probably some improvements to near-field dispersion and dose models would be recommended.

A possibly justifiable way to further reduce the iPWR EPZ size (even with conservative STs) is to replace the so far most used deterministic worst-case methodology, to a risk-informed approach. This is however outside the scope of the present SASPAM-SA project, in lack of the full spectrum of STs and their associated probabilities from PSA level 2. For future projects, some knowledge of the order of magnitude of Design Extension Condition (DEC)-A and DEC-B frequencies / probabilities could be useful. Some nuclear regulators are considering or going to consider a risk-informed methodology, meaning to take into account also the probabilities of accident sequences and the associated offsite consequences, not only their magnitudes.

In future projects, creating an EPZ database for DEC-A and DEC-B can be recommended. The US 'traditional' EPZ distances (10 / 50 miles) originate in part as kind of generalization of the results of the influential WASH-1400 study (1975) [22] where several NPPs and also SA sequences for them were considered. Likewise for the EPZ determination of present iPWR (and other SMRs) it would be beneficial that several plant types and SA releases be considered. Also, there is no one single ‘correct’ off-site consequence code that calculates the most reliable results. To draw conclusions that are useful for regulators and operators willing to site their plant, it would be good to have much more results than just single plant type – single accident scenario – single ST – single approach to EPZ calculation.

Co-location of SMRs presents many cases: colocation of several modules / units, siting reactor(s) in a populated city, or reactor(s) in industrial area (like oil refinery, hydrogen production, fertilizers, steel, etc). There are events like common cause failure, or e.g. industrial accident affecting nuclear plant, or nuclear radioactive release affecting the industry, thus also the possibility of simultaneous conventional and nuclear emergency. Too high dose rates and contamination may slow down emergency management efforts. Also there are some new considerations to calculate dispersion, deposition and external / internal doses when accidents happens in built environment. Those would be good to study more in more detail.

NOMENCLATURE

BE	Best Estimate
CRP	Coordinated Research Project
DBA	Design Basis Accident
DEC	Design Extension Conditions
EDP	Extended Planning Distances
EPC	Emergency Preparedness Categories
EPZ	Emergency Planning Zone
EU	European Union
IAEA	International Atomic Energy Agency
ICPD	Ingestion And Commodities Planning Distance
iPWR	Integral Pressurized Water Reactor
LWR	Light Water Reactors
NPP	Nuclear Power Plant
PAZ	Precautionary Action Zone
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
SA	Severe Accident
SASPAM-SA	Safety Analysis of SMR with PAssive Mitigation strategies – Severe Accident
SMR	Small Modular Reactor
ST	Source Term
UPZ	Urgent Protective Actions Zone
WP	Work Packages

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