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Coupling of ASTEC 2.1.1.6 and RASCAL 4.3 Codes to Evaluate the Source Term and the Radiological Consequences of a Loss-of-Cooling Accident at a Spent Fuel Pool

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ABSTRACT

This paper deals with a general methodology to evaluate the Source Term (ST) and the Radiological Consequences (RC) of a Severe Accident (SA) at a Fukushima-like Spent Fuel Pool (SFP) by coupling ASTEC 2.1 and RASCAL 4.3 codes. Essentially, the ST provided by ASTEC is used as input to RASCAL to perform a RC analysis. This methodology was developed as a preparatory study for the Management and Uncertainties in Severe Accident (MUSA) H2020 European Project, coordinated by CIEMAT. Within MUSA project, the laboratory for the Safety of Nuclear Installation of ENEA is involved in the Innovative Management of SFP Accidents Work Package (WP6), coordinates by IRSN. Within WP6, ENEA is committed to perform an analysis on a Fukushima-like SFP with the aim to apply innovative measures on the SFP Severe Accident Management to mitigate the RC of the accident itself. In order to perform the RC studies, the Fukushima-like SFP has been assumed located in one of the Italian cross-border NPP sites. The weather data connected with the radionuclides transport in atmosphere phase are both standard and real hourly meteorological data. The results of the RC for 96 hours of ST release from the SFP in a range of 160 km from the emission point are reported in terms of Total Effective Dose Equivalent (TEDE), I-131 thyroid dose and Cs-137 total ground deposition. The mitigating effect on ST and on RC of the cooling spray system (CSS) actuated with several pH values (i.e., 4,7,10) was also investigated.

1 INTRODUCTION

In the last ten years, following the Fukushima Daiichi Nuclear Power Plant (NPP) accident, there was an increase of the research activities devoted to explore and update the codes capability to calculate the ST [1,2] and the RC [3,4] of Beyond Design Basis Accidents (BDBA) at SFP.

In this perspective, ENEA has developed its own methodology to evaluate the ST and the RC due to a SA at a SFP that can be applied to any nuclear facility. In the second section the methodology used in this study is presented. In the third section the codes used in this work are discussed with the specific parameters and modules used to perform the analyses. In the four section, the results of the application of the ENEA methodology to a Fukushima-like SFP hypothetically located on one of the Italian cross-border sites are presented. In the last section, some considerations on the results and on the planned future work are reported.

2 METHODS AND CALCULATION TOOLS

The methodology presented in this study is capable to perform a RC analysis on any nuclear facilities; it consists of two steps: ST evaluation with the ASTEC code (ASTEC V2, IRSN all rights reserved, [2020]) and RC assessment with the RASCAL code. First, ASTEC is used to calculate and export a ST resulting from a Loss-of-Cooling SA scenario at a Fukushima-like SFP. Second, the ST file is imported in the RASCAL code and the RC consequences are evaluated by means of the Atmospheric Transport module of RASCAL, according to the user-imposed meteorological conditions. The Fukushima-like SFP model, chosen to perform the ASTEC analysis, is an upgraded version of that adopted in the NUGENIA-PLUS AIR-SFP European Project [5] and it will be further developed by ENEA to be used within the MUSA project activities [6]. Two meteorological conditions were investigated: the RASCAL predefined “standard” one, and real 96 hours meteorological data. The 96 hours data were extracted from the history+ Meteoblue online hourly meteo data paid service from a specific geographical point where one of the Italian cross-border NPP is located [7]. Figure 1 presents the flow chart of the proposed methodology.

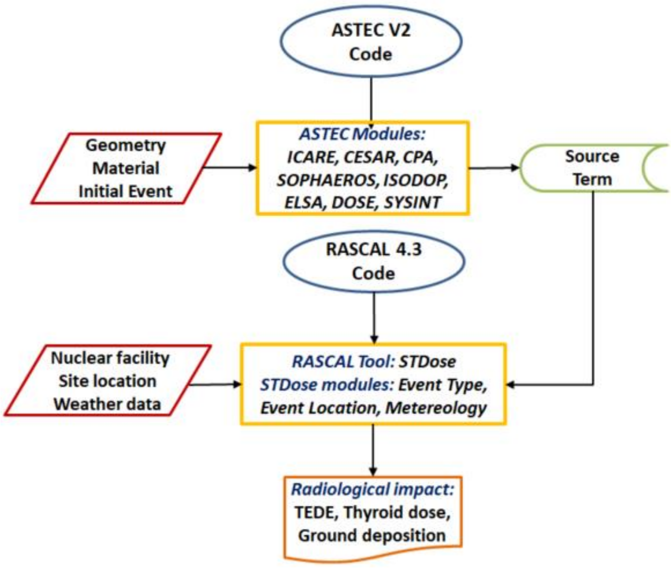

Figure 1: Flow chart of the methodology to evaluate the RC from ASTEC-RASCAL coupling

The next two subsections describe the calculation tools (ASTEC and RASCAL codes) used to evaluate the ST emitted and the RC on the population of the proposed Fukushima-like SFP SA scenario. In detail, the modules and the values of the main parameters assumed in the two codes will be briefly described.

2.1 ASTEC 2.1 code

The ASTEC 2.1 code [8] (Accident Source Term Evaluation Code), jointly developed until 2015 by the French “Institut de Radioprotection et de Sûreté Nucléaire” (IRSN) and the

German “Gesellschaft für Anlagen und Reaktorsicherheit mbH” (GRS), and developed now only by IRSN, aims at simulating an entire Severe Accident (SA) sequence in nuclear water-cooled reactors from the initiating event through the release of radioactive elements out of the containment. The main uses of ASTEC 2.1 are ST evaluations, accident management studies, and level-2 probabilistic safety assessment (PSA). It features a modular structure where each module is devoted to simulate a specific set of physical phenomena or a specific zone. The modelization of the SFP has involved the following modules: CESAR, CPA, ICARE, ISODOP and SOPHAEROS.

CESAR is dedicated to the thermal hydraulic simulation of the primary and secondary systems; it is a system code, characterized by a two-phase flow model based on a default five equations approach [9]. ICARE is used to simulate the in-vessel core degradation phenomena. It implements mechanical models, processes several chemical reactions and incorporates FPs release. It uses basic geometrical objects able to reproduce most of the internals of the core and the related exchange with the coolant fluid. The core fluid channels complete the meshing and allow thermal-hydraulic calculation [10]. CPA provides a tool based on mechanistic models with the purpose of simulating all the relevant thermal-hydraulic processes and plant states taking place in the containment compartments [11]. SOPHAEROS deals with the chemistry and the transport phenomena of the FPs both in the reactor circuits and in the containment [12]. ISODOP is in charge of calculating FPs decay heat and the isotopes transmutation along the SA sequence [13].

2.1.1 ASTEC model of the Spent Fuel Pool

Figure 2 describes the ASTEC model of the SFP: it is an extension of the model developed by ENEA in the frame of NUGENIA-PLUS AIR-SFP project [14] which was limited to the simulation of thermal hydraulic and core degradation in a Fukushima-like SFP, accommodating 1525 fuel assemblies (FAs) of different cooling time and burnup. In the developed ASTEC model, the 1535 FAs with their racks are divided into 2 groups: the “Hot FAs” which include 548 FAs (21 GWd/MTU) for recently unloaded fuel (i.e., 3.7 months of cooling); and the “Cold FAs” which include 783 FAs (42 GWd/MTU) for the longer stored fuel (i.e., 3.15 years of cooling) plus 204 FAs of fresh fuel (for a total of 987 FAs).

The FAs and racks of the 2 groups are described by ICARE macro-components. The 72 fuel roads of each FA are modelled with a representative cylindrical fuel rod enclosed by the Zr cladding. The Zr water rod, the Zr canister, the steel rack, and the concrete wall of the SFP, are also modelled as ICARE cylindrical structures. Specific ICARE components are dedicated to the simulation of the steel spacer grids. The floor of the pool was modelled with the ICARE structure dedicated to the lower head of the reactor.

The evolution of decay power during the simulated accident transient was computed by ISODOP module and the initial total mass of FPs, assumed in the simulation, is based on the ORIGEN-ARP code [15] calculation of the FPs inventory of recently unloaded and longer stored fuel. The FPs mass was distributed in the Hot and Cold FAs by means of numerical factors, estimated as a function of decay heat computed by ORIGEN-ARP code [15], for recently unloaded and longer stored fuel and adjusted to take into account the presence of the 204 fresh FAs in the Cold FAs group. In such a way, it has been possible to distinguish the thermal behaviour of the two groups of FAs during the simulated accident transient.

The SFP was radially divided into two concentric main fluid channels: “Pool inner channel” and “Pool outer channel” (Fig. 2). The pool inner channel contains 4 additional fluid sub-channels, housing the 2 groups of FAs with their racks. The two concentric sub-channels indicated as “Hot fuel channel” and “Hot bypass channel” (Fig. 2), deal with the Hot FAs. The first one simulates the fluid in the rods bundle and the second the fluid in the gap between the canister and the rack. The same approach is used for the “Cold fuel channel” and “Cold bypass channel”, dealing with the Cold FAs. The weight of the described channels is based on the number of related assemblies: 548 for the hot channels and 987 for the cold channels.

The 6 SFP fluid channels are connected at the top end with a small CESAR volume, which is used to connect the top part of the pool, with a CPA zone modelling the SFP building. The SFP building zone is connected to an environment zone, imposing atmospheric temperature and pressure. The CPA SFP building model includes lateral, ceiling and bottom walls of the containment, to take into account a series of physical phenomena such as steam condensation and aerosol deposition.

The Zircaloy oxidation by means of steam and air, the creep and burst of the claddings, the dissolution of UO_2 and ZrO_2 by liquid Zirconium as well as the material melting and relocation were modelled. The melting temperature of both UO_2 and ZrO_2 were set between 2550 K (solid) and 2600 K (liquid). Oxidation of U-Zr-O in the relocated materials mixture (MAGMA) is also activated.

The studied accident is a Loss of Cooling without mitigation measures. The simulation starts with a water level which is just at the top of racks, to reduce the computation time.

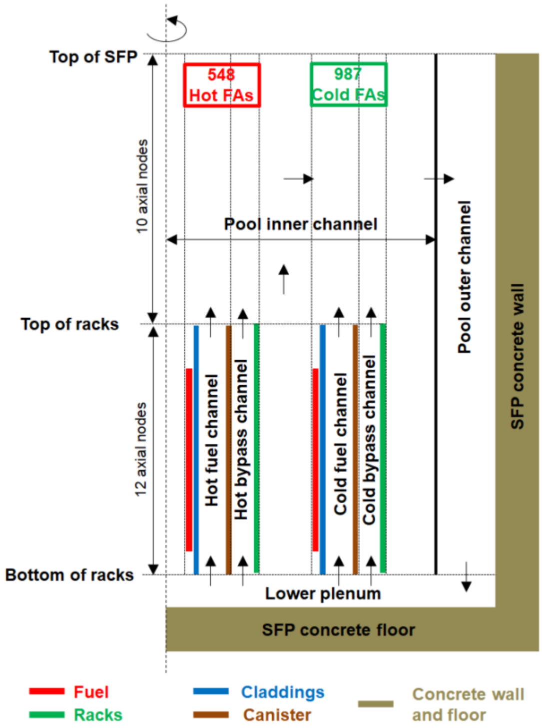

Figure 2: Axial view of the Fukushima-like SFP model – ASTEC code

A CSS was subsequently added to investigate the mitigation effect of the water on ST emission. The CSS was designed to pump the condensed water located at the bottom of the SFP building in recirculation mode. The pH of the sprayed water was imposed by the user. In the calculations the CSS was activated by a water level set point, at about 46 hours after the start of the transient, and kept working until the end of the calculation.

2.2 RASCAL 4.3 code

The Radiological Assessment System Consequences AnaLysis (RASCAL) [4] was developed by U.S. Nuclear Regulatory Commission to provide a tool for the rapid assessment of an incident or accident at any nuclear facility and aid decision making such whether the public should evacuate or shelter in place. RASCAL evaluates time-dependent atmospheric releases (i.e., ST) and dose projection (i.e., RC) from any nuclear facilities that handle nuclear material. The 4.3 version contains new features and revision of several old features (i.e., extension of the domain up to 160 km, increase of the transport time to 96 hours, capability to import and/or merge ST) in response to the lessons learned by the U.S. NRC staff after the events at the Fukushima Daiichi NPP. The main new and revised features are consistent with the possibility to evaluate the RC on Italian territory of a hypothetical SA at one of the nearest SFPs. The modules used for the calculations are described below.

The "Source Term to Dose" (STDose) primary tool was used to evaluate the RC due to the SA scenario. The tool requires the specifications of some parameters in order to evaluate the projected doses to the population; these parameters are given as input to the following subtools: Event Type, Event Location, Source Term, Release path, Meteorology [16].

The "Event Type" sub-module allows to define the source of the radioactive emission; in the case of a SFP Fukushima-like SA, the choice has been SFP.

The "Event Location" sub-module has the function to locate in space the SFP and to define all the necessary SFP data in order to evaluate the Activity Inventory. Despite the SFP data are not necessary for a calculation which involves an externally imported ST, it was necessary to use this module to locate in space the user-defined wheater data. The procedure adopted to estimate the Event Location involves the use of the s.c. *surrogate NPP* (plant already available in RASCAL 4.3 database of U.S. plants and which differs from the real plant only in terms of actual power and actual core average burnup) [3,17]. In practice, this means to find among the U.S. fleet a BWR-4 Mark-1 plant which could be used to mock-up the Fukushima-Daiichi NPP unit 4 which contains the SFP under SA conditions. The plant chosen for the analysis is Cooper NPP, a U.S. BWR-4 Mark-1 NPP currently in operation.

The "Source Term" module allows to characterize the time-dependent ST for a SFP accident on the basis of the type of storage (i.e., pool or dry). It includes three sub-modules: uncovered fuel, damage assembly underwater and cask release. The analysis was performed without setting the submodule parameters because the ST was imported from ASTEC. The ST resolution was set up on a radionuclide emission value every 15 minutes.

The "Release Path" module defines the release conditions: release height, release timings (i.e. fuel uncovered, start/end of release), pathway conditions (i.e. with or without filtering), number of fuel damaged, percentage of fuel rods damage, etc. No Release Path conditions were set because they were previously defined in ASTEC to obtain the ST.

The "Meteorology module" allows to estimate the distribution of the radionuclide into atmosphere during the SA event. The RASCAL 4.3 2-D Gaussian puff model (i.e., TADPUFF) was used to evaluate the radionuclides distribution at up to 160 km from the release point for which temporal and spatial variations in meteorological condition are not negligible; the model domain consists of a Cartesian square grid with 41x41 receptor nodes uniformly distributed through the domain itself [18]. The radionuclide atmospheric transport time on the environment was set to 96 hours.

2.2.1 RASCAL model of the meteorological data

The starting date of the ST emission was chosen on the basis of a preliminary conservative analysis of the radiological impact on Italian territory of a hypothetical SA at one of the cross-border NPPs using the French Eulerian atmospheric dispersion code ldX, owned by IRSN [19]. The analysis with ldX assumed a "puff" (i.e., 24 hours of constant emission) release of I-131 (i.e., 1.0E+17 Bq) for a transport time of 4 days using an operational meteorological dataset provided by Météo France and available in a range of ten years (i.e., 2002-11) on the so-called ARPEGE domain.

In this study, two different meteorological dataset were imposed. Table 1 reports the first set of RASCAL constant standard meteorological data.

Table 1: Standard meteorological dataset

Values of the standard weather parameters				
Time [dd/mm/yyyy]	Class Stability	Wind speed [m/s]	Precipitation [mm/h]	Temperature [°C]
25-29/12/2002	D	2.9	No	21

Table 2 reports a fraction of the second dataset of hourly meteo data extracted from the on-line history+ Meteoblue paid data service [7].

Table 2: Actual hourly meteorological dataset

Values of the hourly weather parameters						
Time [yyyy-mm-dd Thh:mm:ss]	Class Stability	Wind speed [m/s]		Wind direction	Precipitation	Temperature
		Average [45 min]	Gust [15 min]	[degree]	[mm/h]	[°C]
2002-12-25 T21:00:00	D	3.34	4.60	65.14	0	-0.83
2002-12-25 T22:00:00	D	3.31	4.50	63.43	0.1	-0.89
2002-12-25 T23:00:00	D	3.11	4.90	61.61	0.1	-0.94
…	…	…	…	…	…	…
2002-12-29 T19:00:00	E	1.73	4.30	170.13	0	6.40
2002-12-29 T20:00:00	F	1.71	5.10	184.97	0	2.27
2002-12-29 T21:00:00	E	1.86	4.70	186.84	0	1.79

The stability class was evaluated using wind speed, solar radiation and cloud cover hourly data according to *Pasquill-Gifford* classification [20]. The wind speed for each hourly meteo data was set by means of two values: average wind for the first 45 minutes and gust wind for the second 15 minutes. Figures 3-4 report the wind rose and the wind velocity distribution within 96 hours from the emission date (i.e., 25-12-2002).

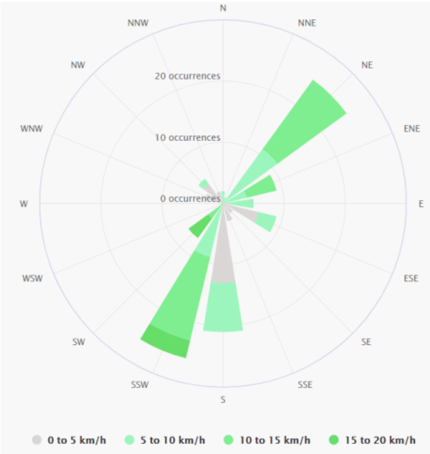

Figure 3: Wind rose, Meteoblue data

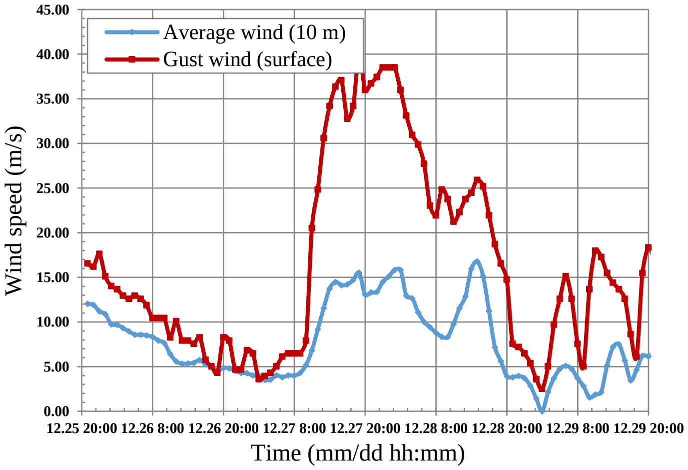

Figure 4: Average and gust wind, Meteoblue data

According to the Meteoblue service definition for which the wind rose displays the direction from which the wind blows, the prevailing winds directions come from NE, S and SSW and account for up to 70% of the total wind directions; the highest wind speed values come from NE and SW with an average values of 0.5 ÷ 5.0 m/s. The difference between gust and average wind in the overall time frame is between a factor 1 and 10 (Fig. 4).

RASCAL 4.3 takes into account the horizontal and vertical radionuclide spread with distance from the emission point by means of dispersion parameters (i.e., σ_y, σ_z) which are function of the following variables: friction velocity, mixing layer height, plume height, Monin-Obukhov length and Coriolis factor. The functional relationship with the dispersion parameters of the previously mentioned variables varies according to the stability class [21].

Dry deposition is evaluated as the product of a deposition velocity and radionuclide concentration; the deposition velocity is in turn evaluated on the basis of meteo conditions (i.e., stability class), surface roughness (i.e., friction velocity) and wind speed. Typical values of deposition velocity are between 0.0021 and 0.016 m/s for reactive gases, between 0.0031 and 0.0090 m/s for particles and between 0.0014 and 0.0072 for vapour (i.e., I_2) [22].

Wet deposition is assessed using different models for particles and gases. In particular, for particles the wet deposition rate is calculated as the product of a washout coefficient and the overall particles deposition as precipitation falls through the full extent of the plume. The washout coefficient is a function of precipitation type, intensity and, to a limited extent, temperature; typical washout coefficient values are between 0.25 (light rain) and 0.3 (moderate snow). Wet deposition rate for gases is instead evaluated as a product of a solubility coefficient and the rain/snow precipitation rate, assuming that the concentration of gases in the air and in the precipitation are in equilibrium; typical wet deposition velocity are between $2.8 \cdot 10^{-5}$ (light rain) and $4.2 \cdot 10^{-4}$ (moderate snow) [18].

RASCAL 4.3 assumes null dry and wet deposition for nonreactive (CH_3I) and noble gases (Krypton). It also assumes that the atmospheric iodine is made up of: 25% particles, 30% vapour (i.e., I_2) and 45% organic form (i.e., CH_3I). This speciation contributes to the deposition of iodine and to the inhalation doses if ICRP 60/72 dose coefficient are selected, while it does not enter into inhalations doses if ICRP 26/30 dose factors are applied [21].

3 RESULTS AND DISCUSSION

The first set of results is the ST generated by ASTEC code. Figure 5 shows the time-dependent ST produced from a series of radionuclides (RNs) released from the SFP since the start of release into atmosphere (i.e., 7200 min) for 96 hours of emission time.

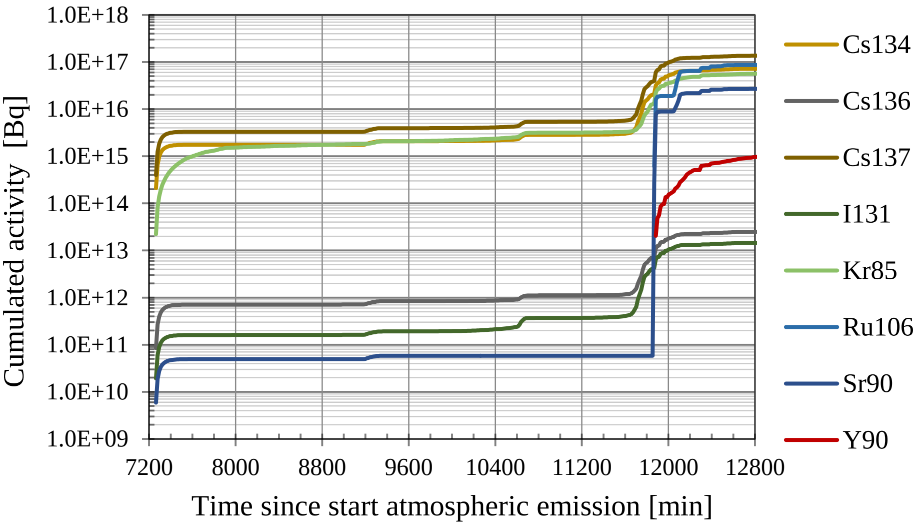

Figure 5: ST emitted from SFP during a Loss-of-Coolant accident scenario – ASTEC code

The RNs list (i.e., Cs-134, Cs-136, Cs-137, I-131, Kr-85, Pu-238, Ru-106, Sr-90, Y-90) is the list of radionuclides with the greatest radiological impact potentially emitted from a SFP as assessed by IRSN and ENEA within the MUSA Project activities. Figure 5 reports the contribution to the ST of all radionuclide included in the RNs list with the exclusion of Pu-238 for which ASTEC provides the first release in atmosphere only after 10 days from the start of the SA event at the SFP, time for which it is reasonable to assume that all the necessary emergency response countermeasures have been implemented. Figure 5 also shows that the most important radionuclides release occurs between 73 and 83 hours after the start of atmospheric emission and that all the radiologically important RNs reach a saturation value ten hours before the end of the RASCAL 4.3 calculation. However, Y-90 presents a residual activity of 4.4E+16 Bq until the end of the imposed ASTEC simulation; this activity could be potentially released before the adoption of emergency countermeasures. Nevertheless, ENEA contribution on the RNs list assessment found that Y-90 is a contributor for groundshine exposition mode only with, in addition, a negligible weight (<1%) compared to the other radiological relevant radionuclides.

The second set of results is the evaluation of the mitigation effect of the CSS actuated with several pH values on the ST generated by each of radionuclides belonging to the RNs list. Figures 6 reports the reduction effect due to the activation of the CSS for several pH values on I-131, being in the ASTEC modelling the other radionuclides included in RN list are not affected by the pH of the water [12]. Figure 6 accounts for a decrease of the I-131 activity released as water pH increases; this phenomenon essentially depends on the pH-related behaviour of two chemical reactions involved in the water phase chemistry: the increase of I_2 hydrolysis and of the HOI disproportionation as the pH value increase [23, 24].

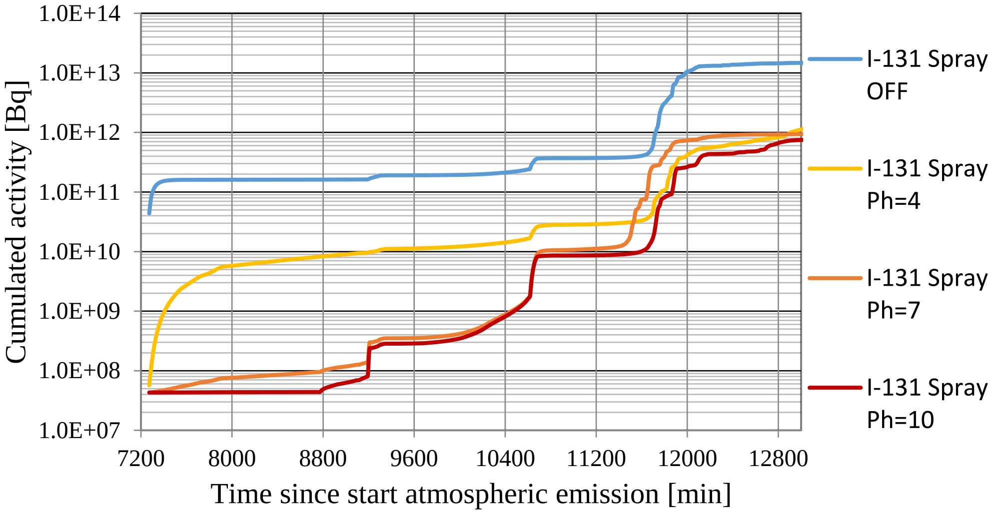

Figure 6: I-131 ST for several mitigation conditions (Spray: OFF/ON, pH: 4,7,10)

The third set of results is the RC due to the atmospheric transport of the evaluated ST with real, site-related hourly meteorological dataset. Figures 7-9 report both TEDE, thyroid dose and Cs-137 total ground deposition distribution maps for the most conservative SA scenario (i.e., Sprays not activated). An intercomparison of the distribution maps achieved with the RASCAL 4.3 standard Meteorology data is also reported.

The maps reveal that the SE-SSE is the direction of the most impacted zone according to the direction from which the wind blow (i.e., 300-350 rad) in the time-frame (i.e., 73–87 hours) of the maximum radiological emission (Fig. 3). In general, a significant impact of different metereological conditions and ST emission time on both the atmospheric distribution of the dose and the total ground deposition was noticed. For this particular scenario, the actual meteo data chosen reduce the radionuclides spread into the atmosphere from more than 160 km to about 100 km with respect to the application of the standard meteorological dataset.

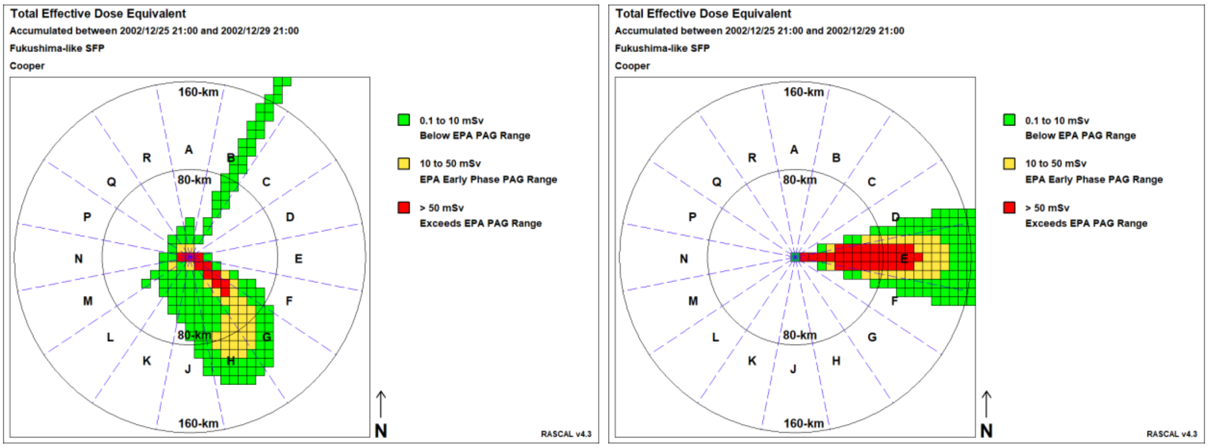

Figure 7: TEDE maps for actual (left) and standard (right) meteo data

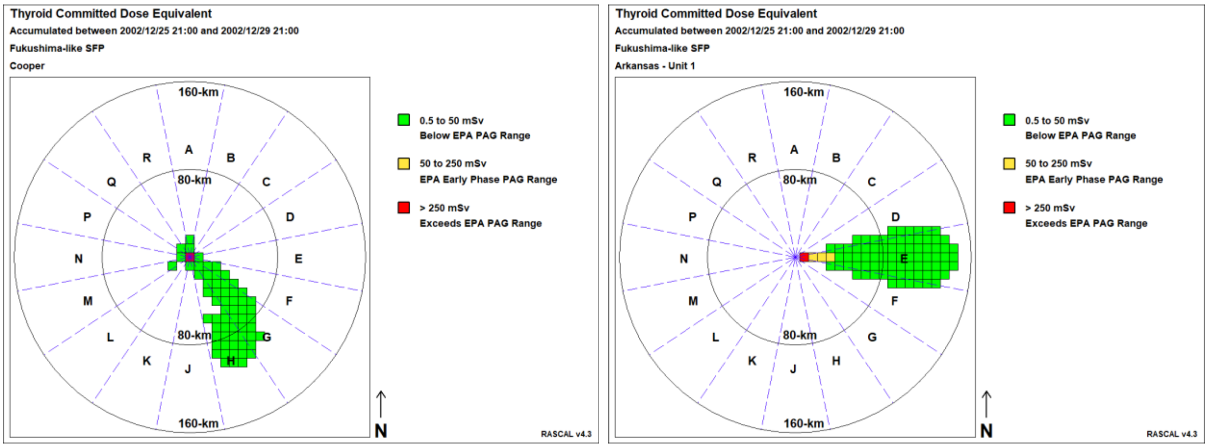

Figure 8: I-131 Thyroid dose maps for actual (left) and standard (right) meteo data

Figures 7-8 report a legend with a dose range split according to early phase criteria of the Protection Action Guide (PAG) implemented by U.S. Emergency Protection Agency (EPA) [25]. For the specific SA scenario and meteo data implemented in this study, RASCAL 4.3 foresees the adoption of some early phase protective actions (i.e., sheltering-in-place or evacuation of the public) in the SE-SSE directions up to a distance of 100 km from the emission point. Figure 9 reports the distribution maps of the Cs-137 total ground deposition both for standard (right) and 96 hours actual (left) meteo data.

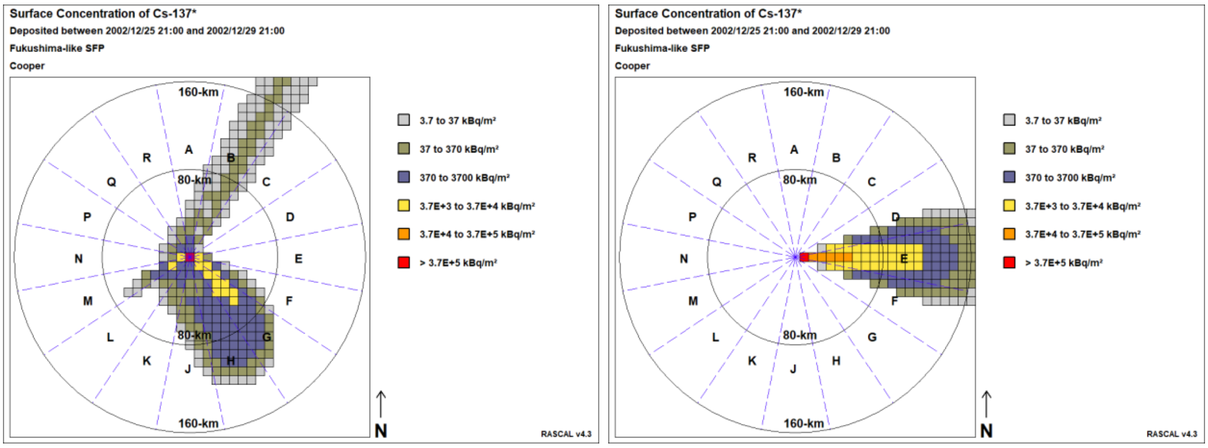

Figure 9: Cs-137 Ground deposition maps for standard (right) and actual (left) meteo data

4 CONCLUSION

In this paper, a general methodology to evaluate the ST and the RC due to a hypothetical SA scenario at a Fukushima-like SFP was proposed. This methodology allows to make a more precise evaluation of the RC with respect to the use of a stand-alone radiological impact assessment code because it combines a code specifically designed to estimate the ST during a SA (i.e., ASTEC) with a validated and widely used fast-running code for radiological consequences analysis (i.e., RASCAL). The preliminary application of this methodology on an Italian cross-border site, where it is hypothesised that a Fukushima-like SFP is allocated, has highlighted the relevant impact of ST emission time and meteo dataset on the spatial dose distribution. If countermeasures actions are activated and/or effective to stop the SFP release three days before the emission start, the adoption of a classical mitigation strategy (i.e., spray system) has revealed that a basic environment seems to be the best choice to reduce the RC resulting from the major contributors to the dose (i.e., I-131), being I-131 the only radionuclide, among the major contributors, to be affected by pH water value in the ASTEC modelization. In the future this methodology will be applied to an European SFP really placed in one of the Italian cross-border NPP site, together with actual roughness and morphology data of the site itself and with time-dependent weather data on more than one point of the geographical domain.

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