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ESTE4Space - SW tool to support safety analyses of space missions with RPS

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Abstract

ESTE4Space is a software tool developed for the purpose of performing radiological consequence assessments for space missions with radioisotope or nuclear reactor power systems onboard. It allows the calculation of potential health risks and effective doses for the population following the inadvertent release of nuclides. ESTE4Space was designed to serve in the planning of future missions and the development of future nuclear power sources. Its functionality was successfully demonstrated on a set of representative accident scenarios related to the launch pad, in-flight neutralization, and accidental re-entry events. Crucial parameters that influence radiological impact include the released isotopes and their amount, the aerodynamic equivalent diameter distribution of the radioactive particles released, and the type of release (continuous, instantaneous, burn-up or intact impact). The radiological impact calculation applies global numerical weather data from ground level up to an altitude of 90 km for atmospheric dispersion and global numerical marine current data for oceanic dispersion. ESTE4Space provides an analysis of radiological consequences for the entire world and also specifically for any area of interest, including the launch site, supporting the safety documentation, which is required for authorization of future space missions with nuclear power sources on board.

1. Introduction

Nuclear power sources (NPS) are essential for current and future space exploration missions. They deliver virtually unlimited power, where energy from a nuclear reaction, either nuclear decay or nuclear fission, replaces conventional energy sources with power densities up to six orders of magnitude greater than is possible with chemical energy. Radioisotope power has been employed as a source of energy in spacecraft systems since 1961, and this technology is expected to play a fundamental role in future deep space and long-duration space exploration missions. Various types of NPS are considered as spacecraft payload, which generate thermal and/or electrical power:

1. Radioisotope Power Systems (RPS) using the thermal power released by the natural decay of radionuclides, such as Am-241 or Pu-238, to produce: a) Heat only - Radioisotope Heater Units (RHU), b) Electrical power via thermoelectric or Stirling engine conversion - Radioisotope Thermoelectric Generator (RTG).
2. Nuclear reactors use fission reactions of fissile radionuclides, such as U-235, to generate electrical or thermal power.

Fission products resulting from the operation of a nuclear reactor include many radiologically significant radionuclides, which need to be taken into account during safety analyses. Similarly, Am-241 and Pu-238 radionuclide sources contain decay products and other isotopes, but their amount and significance are much lower than the significance of Am-241 and Pu-238 themselves. The use of nuclear energy in space must meet specific nuclear safety requirements. Space missions with radioisotope and nuclear reactor power sources must ensure nuclear safety performance level. The potential radiological impacts of possible events must be minimized. Fundamental parts of the safety

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documentation of future space missions with a nuclear source are the assessment of potential of the radiological risk of the whole mission to the local and global human population. This risk must be acceptable for the approval of the mission by the nuclear and space safety authorities. The ESTE4Space tool is designed to fully meet the needs and expectations of the nuclear safety launch approval process.

2. ESTE4Space tool capabilities

The ESTE4Space is a tool for the calculation of radiological consequences resulting from potential accidental events, which can arise during all phases of space missions with nuclear sources, from launch pad to in-orbit operations. These analyses are required in the frame of the nuclear safety launch approval process. The tool integrates several partial modules:

1. Module for source term and trajectories;
2. Module for dispersion in the atmosphere and marine environment;
3. Radiological consequences and risk module;
4. Module for probabilistic analyses.

In addition, ESTE4Space also integrates these important databases:

1. Database of all known spacecraft with nuclear and radioisotope sources already in space and of spacecraft foreseen to be launched in the future;
2. Database of nuclear inventories of all known nuclear and radioisotope sources already in space, in Bq or gram per nuclide, recalculated to the given date;
3. Database with inventories of decay and fission products of potential nuclear and radioisotope sources considered for future missions, mainly based on Am-241, Pu-238, or in case of nuclear reactor, based on U-235, for different assumed reactor-time-in-operation as parameter (e.g. reactor on minimal control power, then after 5/10 years on full power.

The calculated inventories of decay and fission products are used by ESTE4Space to evaluate potential source terms for each identified space object with a radionuclide power source on board. These source terms can then be used by various analyses of radiological consequences and tests. The ESTE4Space system includes functionalities for simulating the launch trajectories, particularly focusing on the radioisotope source ballistic drop trajectories in case of launch or neutralization events, and also on re-entry trajectories (see example in Figure 1). For the safety analysis process, the dispersion and radiological consequences are modeled in ESTE4Space using a deterministic and probabilistic approach. All analyses are based on archived historical meteorological data for the whole planet in the case of global analyses or for the territory of interest in the case of the launch pad. For probabilistic analyses and analyses of re-entry scenarios, a set of at least 2 years of meteorological data is needed. The deterministic approach requires that the initial time of the event specified by the User is the starting time of the release (and the starting time of the dispersion calculation). One sequence of meteorological conditions is used for the calculation. The probabilistic approach stands for hundreds of event initial times that are randomly selected from the historical meteorological data database. Hundreds of sequences of dispersion and radiological impacts are calculated with the same source term at the input. Finally, a statistical analysis of the radiological consequences is performed. The probabilistic approach is crucial for radiological risk analyses for the safety documentation of the mission approval.

3. Source term and inputs to analyses

The source term in ESTE4Space, the amount of radionuclides released in case of an incident, in Bq per nuclide (or in grams per nuclide), and other parameters such as the initial velocity vector of the fragments, their drag coefficient, etc., can be set or modified by the user. Another parameter of the source term, which is very important for the assessment of radiological consequences, is the initial distribution of particles that are aerosolized and released into the atmosphere by their dimension (AED, aerodynamic equivalent diameter). Information on the distribution of particles by size is expected as an input to dispersion calculations, as follows (the assumed percentage of AED applied in ESTE4Space for scenario demonstration was taken from Los Alamos National Laboratory [5]):

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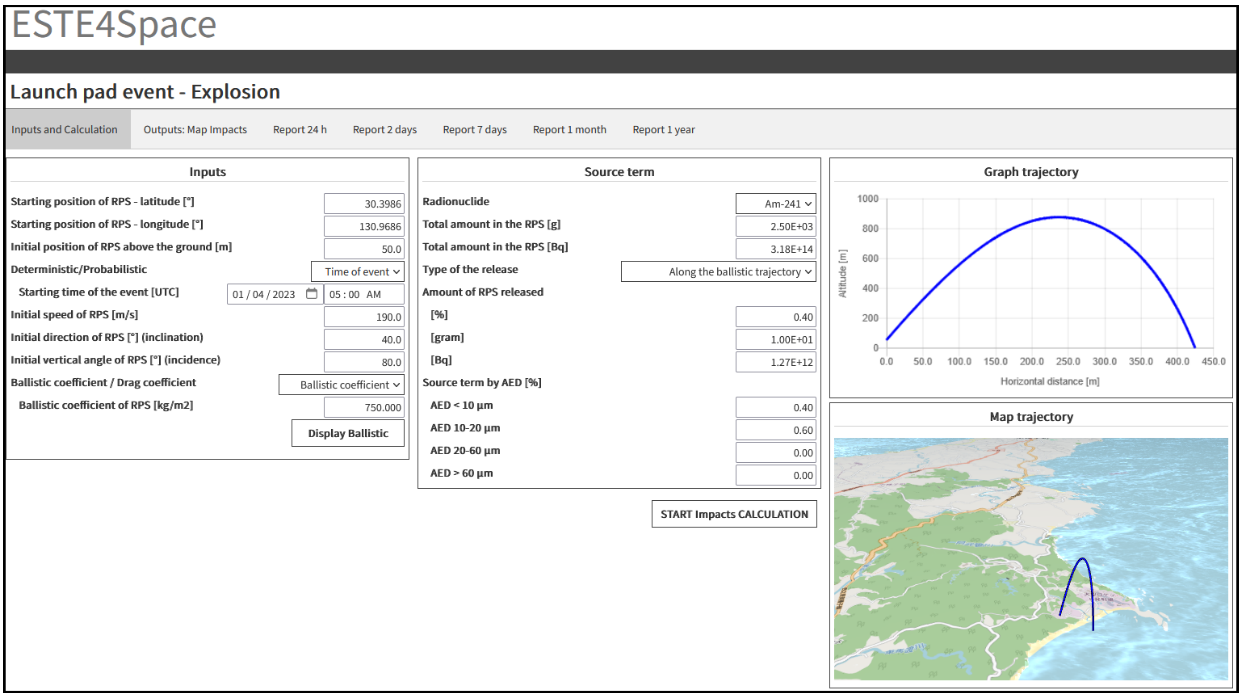
- AED less than 10 µm: Particles are respirable. They are dispersed in the atmosphere over large distances. Dry (and wet) deposition on the ground. Gravitational settling is effectively not present.
- AED between 10-50 µm: Particles are not respirable. They are dispersed in the atmosphere but gravitational settling is relevant. The larger the particle dimensions, the higher the gravitational settling.
- Only particles with AED less than 50 µm are assumed to be intercepted by vegetation and can enter the food chain.
- AED between 50-125 µm: Particles are not respirable. They are settled by gravity, which can cause "hot spots" deposited in the close vicinity of the epicenter. Gravitational settlement is dominant.
- AED greater than 125 µm: Not assumed in the source term. Particles are not subject to dispersion. They are settled by gravity, which can cause "hot spots" deposited in the close vicinity of the epicenter. In the case of Am-241, when, e.g., 1 percent of 2.5 kg is aerosolized and released, the resulting number of particles larger than 125 µm is in the order of 10^4. They will be deposited as hot spots and could potentially be gathered and disposed of in the process of decontamination of the launch pad after the event.

Knowledge or hypothesis about the distribution of particles in the source term is crucial for the estimation of the radiological consequences. The size of the particles affects their transport in the atmosphere, their deposition, their inhalation, and their ability to enter the food chain. In the case of safety analyses of specific missions, the information connected with the source term, including initial distribution of particles in the source term by size, is expected to come to ESTE4Space from other parts of the safety documentation. In addition, ESTE4Space can be used to test various hypotheses and study the influence of various parameters of the source term on the radiological consequences and overall radiation-induced risk to the population.

4. Trajectory Calculation

Three possible initiating events with ballistic trajectory movement of RPS or its fragment are implemented in the ESTE4Space system: 1) Event on the launch pad when the object is ejected into the atmosphere (e.g. launch pad explosion); 2) Event during lift-off in the atmosphere (e.g. neutralization); 3) Re-entry of a space object into the atmosphere. The ESTE4Space integrates a common model that calculates the trajectory of objects through the atmosphere for all three event types.



Starting position of RPS - latitude [°]	30.3986
Starting position of RPS - longitude [°]	130.9686
Initial position of RPS above the ground [m]	50.0
Deterministic/Probabilistic	Time of event
Starting time of the event [UTC]	01 / 04 / 2023 05 : 00 AM
Initial speed of RPS [m/s]	190.0
Initial direction of RPS [°] (inclination)	40.0
Initial vertical angle of RPS [°] (incidence)	80.0
Ballistic coefficient / Drag coefficient	Ballistic coefficient
Ballistic coefficient of RPS [kg/m2]	750.000

Radionuclide	Am-241
Total amount in the RPS [g]	2.50E+03
Total amount in the RPS [Bq]	3.18E+14
Type of the release	Along the ballistic trajectory
Amount of RPS released	
[%]	0.40
[gram]	1.00E+01
[Bq]	1.27E+12
Source term by AED [%]	
AED < 10 µm	0.40
AED 10-20 µm	0.60
AED 20-60 µm	0.00
AED > 60 µm	0.00

Figure 1: Specification of launch pad event calculation in ESTE4Space. The left side is the RPS trajectory specification. The source term is input into the center panel, and the visualization of the RPS trajectory is shown on the right side.

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The input parameters for trajectory calculation are (as shown in Figure 1):

- Initial position of the ballistic trajectory: geographical latitude, longitude, and altitude.
- Initial velocity of the ballistic trajectory: speed, angle of direction against the horizontal plane, and inclination of the original satellite trajectory.
- Object properties: mass, area of the object normal to the flow, drag coefficient.

The trajectory is calculated considering two forces, the gravitational force F_g and the air drag force F_d, which act on the object during its passage through the atmosphere:

$$F_g = \kappa \frac{m M_{earth}}{(h + r_{earth})^2} \tag{1}$$

$$F_D = \frac{1}{2} C_D \rho v^2 A = \frac{m}{2 c_b} \rho v^2 \tag{2}$$

Here, m is the mass of the object, M_{earth} is the mass of the Earth, κ is the gravitational constant, h is the altitude of the object, and r_{earth} is the Earth's radius. C_D is the drag coefficient, ρ is the air density (function of altitude), v is the velocity of the object, and A is the area of the object normal to the flow. We also define the ballistic coefficient c_b as a specific coefficient for most satellites. The calculation is performed using the forward Euler method, a Runge-Kutta integrator.

5. Dispersion and transport calculation

The ESTE4Space system performs transport and dispersion of released activity in the atmosphere and in the marine environment as well. For both environments, a specific transport and dispersion model is implemented.

5.1 Atmosphere Dispersion Calculation

The atmospheric dispersion calculation is modeled using the Lagrangian particle model (LPM) method. The particles undergo two main transport mechanisms: they are airborne, i.e., they are transported by the moving air, and they are affected by gravitational force. The significance of the contribution of these processes is determined primarily by the particle size. The motion of the smallest particles is dominated by turbulence and air motion (AED below 10 µm). For these particles the gravitational settling is negligible. On the other hand, the motion of the largest particles is only weakly affected by turbulence and is dominated gravitationally. The size of particles also strongly influences their deposition properties.

Lagrangian particle models simulate a huge number of discrete particles, where each particle carries a specific amount of activity. The i-th component of the position of the particle in the new time step of $t + \Delta t$ is given by:

$$x_i(t + \Delta t) = x_i(t) + U_i \Delta t + \mathrm{d}u_i \tag{3}$$

$$\mathrm{d}u_i = a_i(x, u, t)\mathrm{d}t + b_{ij}(x, u, t)\mathrm{d}W_j \tag{4}$$

U_i is the velocity vector of the mean field at time t and position x, and $\mathrm{d}u_i$ is the turbulent increment, which consists of the drift term and the diffusion term. $\mathrm{d}W_j$ is an incremental component of the Wiener process, which is a Gaussian random variable. In case the particle is in the atmospheric boundary layer (ABL), the drift and diffusion terms are non-trivially parametrized by ABL parameters (e.g., Monin-Obukhov length, friction velocity). For the region above the ABL, the appropriate parameterization of the turbulent increment is given below:

$$\mathrm{d}u_i = \sqrt{D_i / \Delta t}\, \mathrm{d}W_i \tag{5}$$

Here, W_i is the Gaussian random variable with zero mean, and D_i is a diffusivity parameter. In the case of the stratosphere, $D_i = D_z = 0.1\ \mathrm{m^2 s^{-1}}$.[6]·[2] The horizontal component for the stratosphere is set to zero. In the case of the troposphere above the ABL, $D_i = 50\ \mathrm{m^2 s^{-1}}$ [6]. The vertical component is set to zero.

Two types of historical weather data are applied. The basic weather data are the numerical weather data from the Global Forecast System (GFS). In the vertical direction, it spans 1000 hPa to 1 Pa, and it has a spatial resolution of 0.25°. The time step of the weather data is 3 hours. The other possible weather data type is monthly averaged

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weather data. ESTE4Space uses ERA5 monthly averaged weather data, generated by ECMWF (European Centre for Medium-Range Weather Forecasts). Its spatial resolution is 0.25°, and it has a global domain. In the vertical direction, the data spans 1000 hPa to 1 hPa. This kind of weather data is intended for long-term calculation since the short-term phenomena are only partially present in it.

5.2 Marine Dispersion Calculation

The transport and diffusion processes of activity in the marine environment are solved using the Lagrangian particle model designed for the marine environment [4]. The turbulent increment is defined as:

$$\mathrm{d}u_1 = \sqrt{12K_h/\Delta t}\, r_0 cos(2\pi r_1) \tag{6}$$

$$\mathrm{d}u_2 = \sqrt{12K_h/\Delta t}\, r_0 sin(2\pi r_1), \tag{7}$$

$$\mathrm{d}u_3 = \sqrt{6K_v/\Delta t}\, r_2 \tag{8}$$

Here, r_0, r_1, and r_2 are random numbers, K_h and K_v are diffusion parameters. The model for dispersion modeling in the marine environment considers three phases: dissolved phase, suspended sediment, and bottom (seabed) sediment. The considered interactions between these phases in our approach are: a) advective transport (as described above), b) diffusion (as described above), c) desorption and adsorption processes, d) radioactive decay (as described for atmospheric LPM), e) burial process on bottom sediment, f) deposition.

To perform marine transport and dispersion calculations in the ESTE4Space system, the system contains a library of historical marine currents for whole calendar years. The library is based on HYCOM data. Its spatial resolution is 0.25°, and consists of 33 distinct levels/depths.The temporal resolution of the marine data is one day.

6. Dose Calculation

The dose calculation in ESTE4Space is based on the following considered pathways: cloud shine exposure, ground shine exposure, committed effective dose by inhalation, including inhalation caused by resuspension of deposited aerosols, and ingestion. The person breathes all the air at a given location. This assumption is also used in the case of the inhalation of radionuclides resuspended back to the air from the ground deposition.

In the case of dose calculation, the particle size plays an important role in the dose by inhalation. Only particles with AED < 10 µm are considered inhalable. The larger particles are considered for other pathways, but only particles with AED < 50 µm are considered to be intercepted by vegetation and transferred or potentially transferred to the food chain.

The model for the calculation of effective dose due to the ingestion of contaminated food is based on the algorithms and procedures described in ECOSYS[3]. Transfer to edible parts of plants is assumed to be performed via direct interception of deposited particles on plants and via root uptake (after deposition on soil). The ingestion dose to humans is caused by the consumption of plants, plant products, and animal products (animals are fed impacted plants). The ingestion model considers the following pathways: 1) Transfer to edible parts of plants is assumed to be performed via direct deposition in plants and root uptake (deposition on soil); and 2) the ingestion dose to humans is caused by direct consumption of plants and by consumption of animal products (animals are fed impacted plants). All foodstuffs defined in the consumption basket based on statistical data are produced at a given location. In the implemented methodology, the following products are considered: leafy vegetables, non-leafy vegetables, fruit, potatoes, cereals, cow milk, goat milk, beef, pork meat, poultry meat, and eggs. For all these products, the activity concentrations up to 1 and 2 years (based on the event type) are calculated and reported.

All doses are calculated for 4 age categories: fetus, children 0 to 5 years old, children 6 to 15 years, and adults (16 years and older). Age-category dependency is present for inhalation rate, consumption basket, inhalation, and ingestion factors. The fetus is exposed as a result of the inhalation of contaminated air by the mother, the food consumption of the mother, and cloudshine and groundshine. The methodology for fetus is based upon ICRP88[1].

In case of modeling marine transport, the activities in fish and crustaceans up to 1 or 2 years are calculated. Both dose calculation models are visualized in the conceptual schemes in Figure 2.

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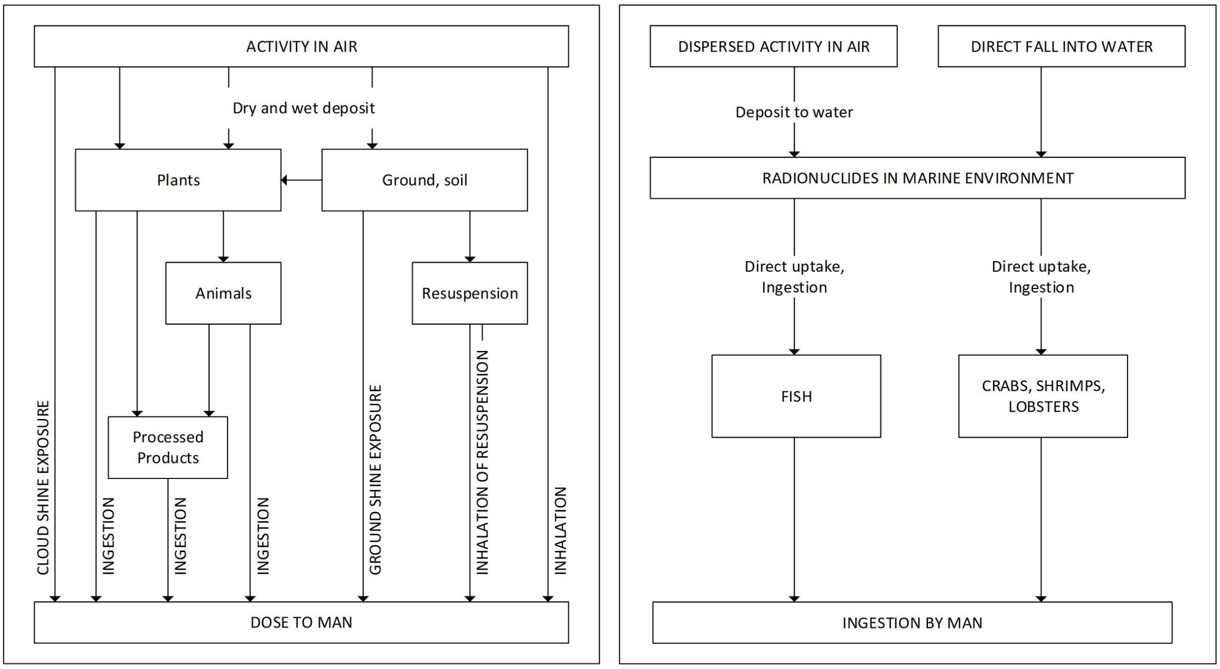

Figure 2: Conceptual models of ESTE4Space: Basic scheme for the calculation of dose to inhabitant by all exposition pathways (left scheme), and calculation of ingestion doses due to activity in the marine environment (right scheme).

7. Event types and examples of radiological consequences analyses

An accidental event with the release of radioactive material into the environment could happen during any stage when the spacecraft is moving in the Earth's atmosphere; therefore, we can define three general accident types: accidents occurring on the launch pad (before the launch itself or in the very early stage of the launch), accidents occurring after launch but before leaving the atmosphere, and finally reentry events when the spacecraft is reentering from space into the Earth atmosphere. Each type has several specific features; therefore, the ESTE4Space system has separate modules to deal with each type of event.

Crucial assumptions about the source term: Inventory of the RPS (Am-241, Pu-238 or reactor core inventory by nuclides, in Bq or grams); The assumption about the amount of the inventory aerosolized and vaporized (total source term, in Bq or grams); The assumption about the release mode (continuously along the ballistic trajectory, at the beginning of the ballistic trajectory, burnt at an altitude between 60–40 km, intact impact); The assumption about the dimensions of particles aerosolized (AED).

7.1 Launch pad events: Explosion and Fire

Two types of launch pad events are considered. Both of them are based on a specific basic initiating event leading to the release of radioactive material on the launch pad - explosion and fire on the launch pad.

The explosion event is an event during on-ground operations (on the launch pad) or immediately after the launch, when a severe explosion of the rocket propellant occurs, leading to damage to the radioactive power source (its casket) and to the release of radioactive material into the environment. Potentially, the power source is hit or gains momentum during the explosion and is shot away along a ballistic trajectory.

As input for the launch pad explosion scenario, the ESTE4Space system requires input data of the radioactive power source trajectory and specification of the release type. The calculation of spatial distribution of the released activity includes 1) determination of RPS movement after the explosion (i.e. ballistic trajectory calculation based on initial velocity and position), and 2) an assumption for release type is required (release during the explosion, or during RPS's ballistic flight or during the impact on ground). Further, the specification of the released activity is required, including the total amount and its percentage distribution according to the particle size.

A fire event is an event during on-ground operations (on the launch pad) or immediately after the launch, when a severe fire occurs that involves the rocket propellant. The radioactive power source is assumed to fall into the fire and be exposed to high-temperature conditions, with its potential cladding degradation and release of radioactive material.

The radioactive material is transported away by the rising fire plume into the atmosphere.

The system applies the plume rise model [7] to evaluate the buoyancy flux based on either fire temperature or heat rate generated in the fire. The output is the estimated plume rise height, calculated for each particle size considered and taking into account present weather conditions. Finally, the output of the plume rise model is an input into atmospheric transport and dispersion modeling using LPM.

The definition of the source term requires specifications of the fire (i.e., specifying the fire temperature or the released energy during the fire). These inputs, together with local wind data are applied to calculate the plume rise height for each particle size. Finally, the source term is fully defined by the total amount of released activity and its percentage distribution according to the particle size.

For launch pad events, the ESTE4Space system calculates radiological impacts on a specific local calculation domain centered on the launch pad location and covering a region with a size of 200 km. A similar calculation domain is used for marine dispersion calculation. The air concentration is calculated for 7 days. The deposition on the terrain and the marine concentration are modeled for up to 1 year. Activity in agricultural products and dose by ingestion are modeled up to 1 year.

The launch pad event can be approached either in a probabilistic or a deterministic manner. A deterministic calculation means the use of one specific weather condition defined by the date and time of the considered event. On the other hand, a probabilistic calculation performs many separate deterministic calculations inside the given time interval (e.g. in a calendar year). In the final step of the probabilistic calculation, statistical analysis is performed on the set of separate radiological impact calculations. The outputs are mean values, 95 percentiles, and maxima for given distances from the event location.

A hypothetical launch pad explosion is considered for visualization of the launch pad module of the ESTE4Space. The spacecraft is carrying an RTG based on Am-241. The RPS is damaged during the explosion, and a release of Am-241 occurs. The follow-on impacts depend on several conditions. Here, we analyzed the size of released Am-241 particles. In Figures 3 and 4, the calculated deposits of Am-241 are shown for two different release scenarios. In the case of Figure 3, all particles considered in the source term are smaller than < 10 μm. The deposit is localized not only in the launch pad area, but it is on a low level outside the launch pad area. The level of contamination and boundaries of the impacted area are dependent on the amount of release and meteorological conditions. In case of Figure 4, all considered particles in the source term are larger than > 60 μm. The impacted area is only within the launch pad area because of the intensive effect of the gravitational fall on the considered large particles.

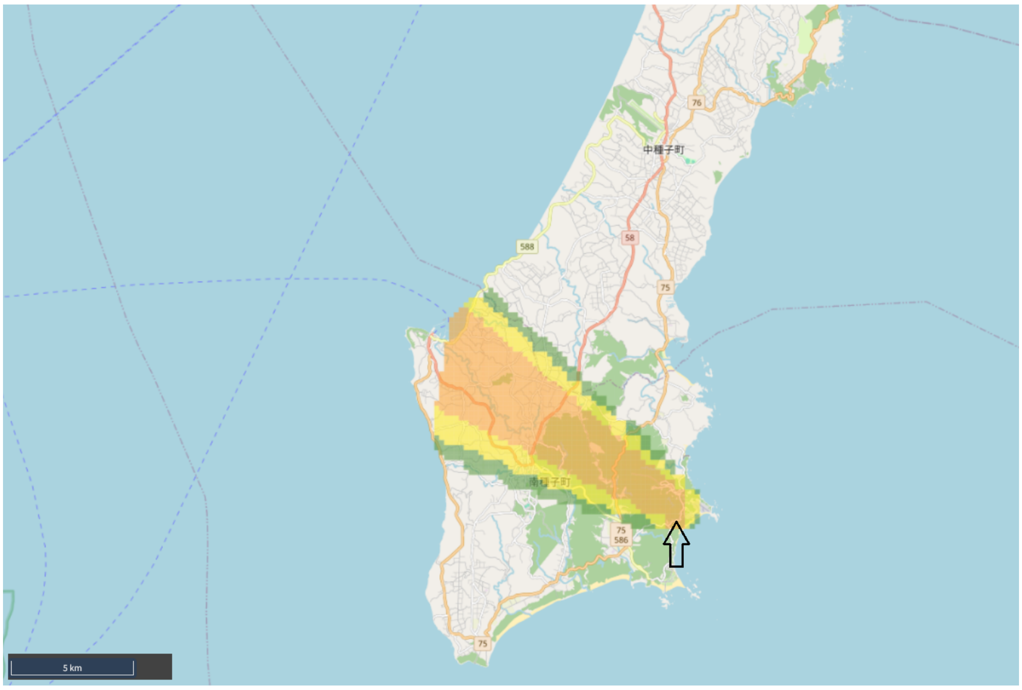

Figure 3: AED < 10 μm. Area of Am-241 deposition on the terrain in case of a hypothetical explosion on the launch pad. All assumed released particles in the source term are of the size AED < 10 μm. The arrow shows the location of the event. The launch pad was chosen as hypothetical and anonymous.

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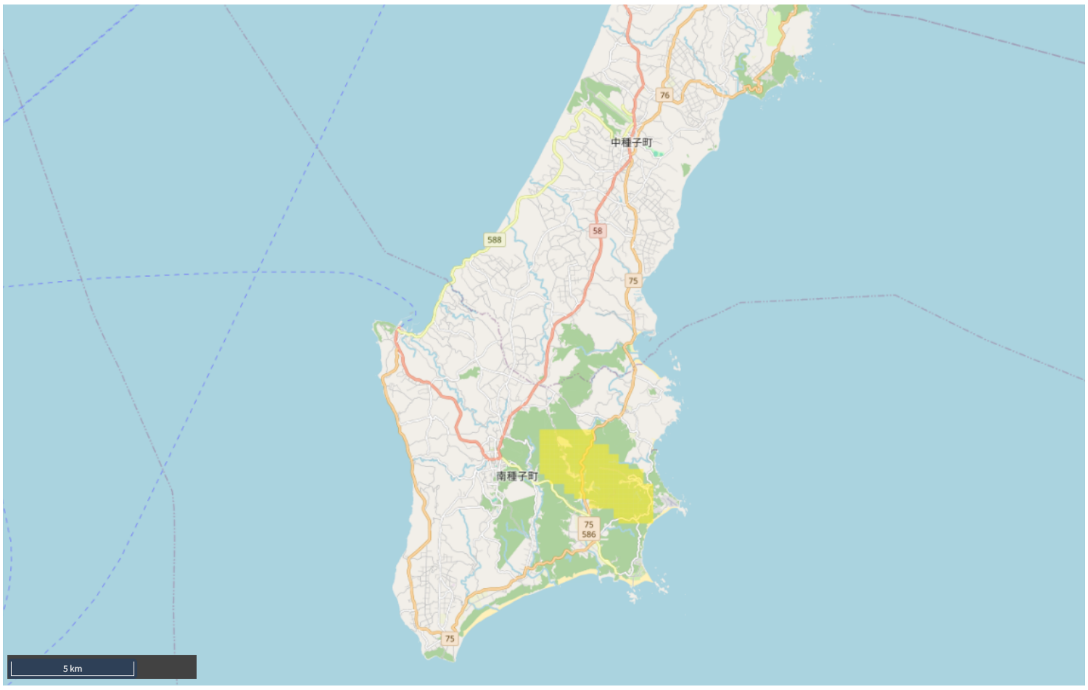

Figure 4: AED > 60 µm. Area of Am-241 deposition on the terrain in case of a hypothetical explosion on the launch pad. All assumed released particles in the source term are of the size AED > 60 µm.

7.2 Events between lift-off and leaving the Earth's atmosphere

A category of events with specific threats of a release of radioactive material into the environment represents accidents after the lift-off, before entering outer space. The most threatening and potential event is an explosion of the rocket leading to damage to the RPS, with a following impact on the Earth's surface. One specific event type is the intended neutralization of the rocket, and another is a rocket failure leading to the explosion.

The inputs for after-launch events consist of the trajectory of the radioactive power source, the type of release, and the source term. Three release types are considered: release along the entire ballistic trajectory of RPS, release at the event location (that is, at the moment of the explosion), and release at the impact point on the terrain. The trajectory of the RPS is calculated using its initial location, initial velocity vector, and air drag properties. Its final ballistic trajectory in the atmosphere is calculated as described in the section Trajectory Evaluation. The source term specification again requires the total amount of released activity and its percentage distribution according to the particle size.

This phase of rocket flight is still well located in the vicinity of the launch pad (from a global view). Therefore, a local calculation domain centered in the launch pad location and covering the region with a size on the level of 500 - 1000 km is used for radiological impact assessments. The air concentration of nuclides is calculated for up to 7 days, and the deposition on the terrain and the marine concentration are modeled for up to 1 year. Activity in agricultural products and dose by ingestion is modeled up to 1 year.

7.3 Re-entry

The third event type considered is the re-entry of a spacecraft. The event specification consists of analogous input data as in the previous cases, but is tailored for the re-entry event. The trajectory and impact calculations are performed from the re-entry point; thus, the input data include: re-entry location and altitude, re-entry velocity, and direction. Weather data is defined up to the 1 Pa pressure level (about 80 - 90 km above the Earth's surface). This height is also considered the maximum release height, and the calculation of atmospheric dispersion is limited to this altitude.

There are two considered atmospheric calculation domains. The global domain, which covers the entire Earth and enables a review of complete global radiological impacts, represents the first possibility. The other option is a local domain with a dimension on the level of 500 km. It enables a high-resolution review of impacts in the specific region of interest. The atmospheric dispersion is modeled up to 1 year. The marine transport is modeled for up to 2 years on the global calculation domain. Activity in agricultural products and dose by ingestion are modeled for up to

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2 years. The release types are extended by the possibility of modeling a burn-up, as an additional release type besides the three basic release types described for the previous events. A burn event means a trajectory in the atmosphere from the re-entry point up to a specified endpoint at a specific altitude. The source term is fully defined by the total amount of released activity and its percentage distribution according to the particle size.

Re-entry events can be assumed not only in analyses for future missions. Today, there is a large group of RPSs orbiting Earth, such as TRANSIT 4A with SNAP-3B7 RPS and nuclear reactors (BUK and TOPAZ types of soviet reactors in the COSMOS and PLASMA spacecraft). The ESTE4Space system has a built-in database of all Earth-orbiting RPSs. It includes their calculated actual inventories and their mission information (launch info, operation parameters). This database allows impact calculations and analyses of re-entry events for the existing space missions.

An example of re-entry event is considered for visualization of radiological impact calculation in Figure 5. The event is assumed to be in New South Wales (Australia). Figure 5 shows the calculated time evolution of the deposition of Am-241 on the terrain. The source term (amount of Am-241 released) was chosen as hypothetical example. The release with a whole spectrum of particle sizes was assumed along the re-entry trajectory and with impact on the Earth's surface. Naturally, the highest radiological impact is in the vicinity of the impact point, where the particular situation is affected by the impact description. Within 1 year, a low-level deposit can be expected in the southern hemisphere.

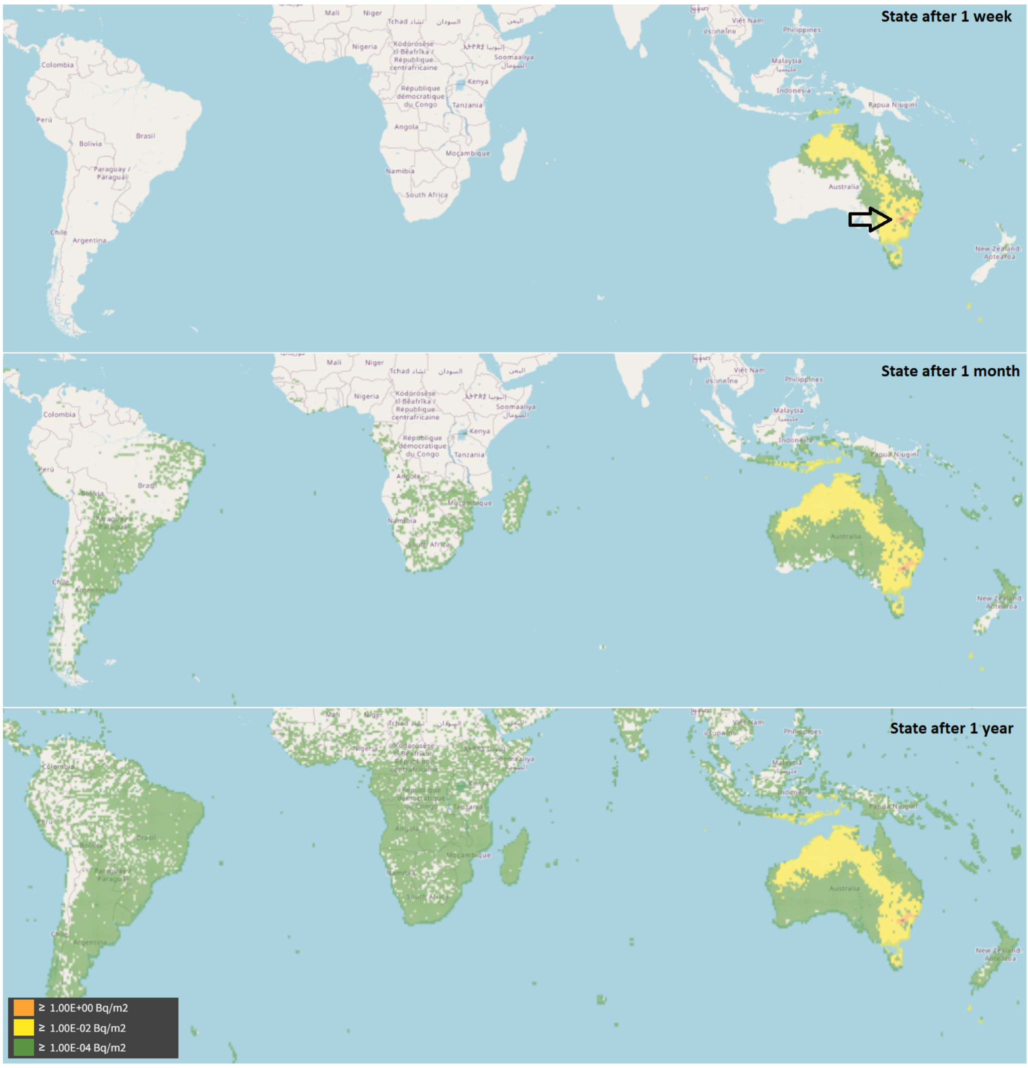

Figure 5: Calculated deposit on land after a hypothetical re-entry of a spacecraft with an Am-241 RPS on board, in various times after the event. The arrow in the upper part shows the re-entry and impact location of the spacecraft.

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8. Discussion and Summary

ESTE4Space is the tool to support the safety analysis of space missions with RPS. Its main task is to be used and to provide results of analyses for safety reports in the nuclear safety launch approval process for the assessment of effective doses to the most exposed population (in compliance with the French regulations) and health-effect risk (in compliance with the US regulations). The main focus is on providing the tool for safety analysis and reports, which are necessary for the approval of a spacecraft mission by relevant authorities. In the future, the ESTE4Space can be potentially used as a tool for real emergency response, including analysis of radiological consequences in case of real emergencies.

Based on ESTE4Space analyses and calculations, the most important pathway of potential exposure of inhabitants in case of a launch accident or re-entry accident is internal exposure by inhalation of airborne aerosols dispersed in the near-above-ground level of the atmosphere. This exposition pathway can hardly be eliminated with protective measures. Another potentially significantly harmful pathway is the ingestion of contaminated foodstuffs. However, this pathway can be eliminated or limited by the application of protection measures. Therefore, the most important is the inhalation pathway.

Information on the potential release of radioactive aerosols by their particle size distribution (AED) is a critical input for analysis of radiological consequences. These data should accompany the encapsulated radioisotope or nuclear source provided for the given spacecraft mission. The source manufacturer should experimentally study the behavior of the given encapsulated source under accident conditions and should provide the results of these experiments as input to the safety analysis.

The analyses and calculations performed by ESTE4Space highlighted several critical assumptions that are crucial in determining radiological consequences:

- Percentage of Am-241 released.
- Distribution of vaporized and aerosolized particles by dimensions (AED). Larger AEDs correlate with lower radiological consequences, emphasizing that a key objective during an event should be the fragmentation of RPS into larger particles.
- The mode of release (continuously along the ballistic trajectory, at the beginning of the ballistic trajectory, burnt at an altitude between 60 km and 40 km, intact impact).

9. Acknowledgments

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