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ESTE4SPACE: A TOOL FOR SAFETY ANALYSES OF FUTURE SPACE MISSIONS WITH NUCLEAR POWER SOURCE, WITH THE POTENTIAL TO SUPPORT RESPONSE TO REAL EVENTS.

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Abstract

The ESTE4Space is a nuclear safety software tool developed in the frame of an ESA-funded project to provide assessments of possible radiological consequences for space missions with nuclear or radioisotope power sources on board. Its capabilities were demonstrated on a set of potential accident scenarios related to a representative launch pad, in-flight neutralization, and accidental reentry events.

Based on the assumption of the source term, the ESTE4Space models short-term (days) and long-term (years) dispersion of radionuclides in the atmospheric and marine environments and calculates a whole set of radiological impact parameters necessary for the assessment of potential consequences to population and to the environment. Numerical weather prediction data for the entire Earth, from ground level to an altitude of 90 km, are available either as archived data from past years or as current numerical weather prediction data. Similarly, numerical marine current data for the entire planet, as well as archived data, are available for analyzing the radionuclide dispersion in the marine environment. The final task of the analyses performed by the ESTE4Space tool is radiological impact assessment in the territory of interest, which can span any area on the globe, including the surroundings of the launch pad.

The ESTE4Space tool has been developed for direct application in safety analyses of future space missions. It is also designed for use in crisis centers to assess radiological consequences to the biosphere in the event of real emergencies related to past or future missions involving nuclear power systems. In the case of safety analyses, the ESTE4Space tool can be used for probabilistic analyses and probabilistic assessments of radiological consequences. When the probability of event and the probability of consequences are combined, then the total potential health effect risk (in compliance with the requirements of U.S. regulations) or the effective doses of the most exposed inhabitants associated with the worst meteorological situations with a very low occurrence probability (in compliance with requirements of the French regulations) will be the final results provided by the ESTE4Space tool.

In the event of a real accident involving a space mission currently in orbit, a comprehensive database was prepared, containing all known spacecraft and planned future missions equipped with nuclear or radioisotope sources. For each of these spacecrafts, publicly available parameters of the nuclear power source were used to recalculate radionuclide inventories. These calculations were performed for both the current date and any future date to support the operational needs of the ESTE4Space tool.

Keywords: Safety, NPS, radiological consequences, launch approval, space nuclear.

1. Introduction

Nuclear power sources (NPS) are essential for current and future deep-space exploration missions. These systems generate energy through radioactive nuclear decay, as in the case of radioisotope power sources (RPS), or nuclear fission reaction in the case of nuclear reactors. NPS offer power densities significantly higher than those of conventional energy sources, such as solar panels. This technology is expected to play a key role in future deep-space and long-duration space exploration missions. Various types of NPS and RPS are considered as spacecraft payload, including Radioisotope Thermoelectric Generators (RTGs), Radioisotope Heater Units (RHUs), and nuclear reactors.

RTG is a type of RPS that generates electricity by converting heat released from the radioactive decay of radionuclides. RTGs have been widely used in deep space exploration missions, such as the Voyager, Cassini and New Horizons missions, due to their reliability and long operational life. Historically, they have also been employed in several Earth-orbiting missions to provide energy for various services, including navigation and communication. An RHU is a type of RPS whose purpose is to generate a small amount of heat.

Space fission reactors generate heat through controlled chain nuclear fission reactions, which are then converted into electricity using a power conversion system. Unlike terrestrial reactors, these systems are designed to be compact and lightweight. The fission reactors have the potential to provide significantly higher power levels than RTGs and are being considered for future deep-space missions (including crewed missions) to other celestial bodies. They are also considered an energy source for spacecraft propulsion. Examples are the ESA-funded RocketRoll and Alumni projects.

Fission products resulting from the operation of a nuclear reactor include many radiologically significant radionuclides that need to be considered in safety analyses. Similarly, Am-241 and Pu-238 radionuclide sources contain not only radiologically significant amounts of Am-241 and Pu-238, but also their decay products. Space missions utilizing NPS must adhere to strict nuclear safety standards to ensure they do not pose unacceptable radiological risks to human health or the environment. All potential radiological impacts from possible events must be minimized through robust safety measures.

The ESTE4Space software tool is designed to perform analyses of radiological consequences for space missions with NPS on board. The tool was developed within the framework of an ESA-funded project, and its capabilities were demonstrated on a set of hypothetical accident scenarios related to a representative launch pad, in-flight neutralization, and inadvertent reentry events.

The ESTE4Space can perform calculations for both short-term (days) and long-term (years) dispersion of radionuclides released into the environment, and it can calculate various radiological parameters necessary for the assessment of potential consequences to the human population and the environment. The dispersion calculation utilizes global numerical weather prediction data spanning the atmosphere from ground level to an altitude of 90 km. The numerical weather data are available either as archived data from past years or as actual numerical weather prediction data. Similarly, global numerical marine current data are available for analyses of radionuclide dispersion in the marine environment.

The ESTE4Space tool was demonstrated as a tool applicable for safety analyses in both the mission preparation phase as well as the NPS design and engineering phase. Furthermore, several features have been implemented into the ESTE4Space tool, which can aid in its utilization as a decision support system in real emergencies. They include online connection of the ESTE4Space tool to spacecraft reentry services (EU-SST) for automatic evaluation of reentry events, and application of a pre-calculated and updated database of radionuclide inventories of all publicly known nuclear reactors and RPS already launched.

2. ESTE4Space system

The ESTE4Space was designed to be used in events that can occur during all phases of space missions involving nuclear sources, from launch pad to in-orbit operations. These analyses are required in the framework 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.

ESTE4Space includes a database of calculated inventories for all known spacecraft in Earth orbit with radioisotopes or nuclear material on board, as well as potential nuclear and radioisotope sources considered for future missions. The future European RTGs are considering using Am-241 as an energy source.

ESTE4Space uses the calculated inventories of decay and fission products to evaluate potential source terms for each identified spacecraft with an NPS onboard. The ESTE4Space system includes functionalities for simulating ballistic trajectories, particularly focusing on the radioisotope source ballistic drop trajectories in the event of launch or neutralization, as well as reentry trajectories. Additionally, the system has functionalities to simulate a propellant fire event on the launch pad.

For the safety analysis process, the dispersion and radiological consequences are modelled in ESTE4Space using both deterministic and probabilistic approaches. All analyses are based on archived global historical meteorological data for global analyses or for the territory of interest in the case of the launch pad scenario. For probabilistic analyses and reentry scenario analyses, a set of at least 2 years of meteorological data is required. The deterministic approach requires that the initial time of the event specified by the User is the starting time of the radiological release (and of the dispersion calculation). One sequence of meteorological conditions is used for the calculation.

On the other hand, the probabilistic approach stands for hundreds of event initial times that are randomly selected from the historical meteorological data database. Consequently, hundreds of sequences of dispersion calculations and radiological impact calculations are performed with the identical source term at the input. Finally, a statistical analysis of the radiological consequences is performed on the set of simulated results. The probabilistic approach is crucial for radiological risk analyses in the safety documentation for mission approval.

In the next section, the implemented methodology of ESTE4Space is described, spanning from inventory and source term assessment through dispersion calculation to the dose evaluation for the human population. This section is followed by analyses of the implemented inventories and impact assessments.

3. Methodologies

3.1 Source term

The source term in ESTE4Space is represented by the amount of radionuclides released in case of an incident (in Bq or in grams per nuclide), by the spatial distribution of the released activity (including geographical position and altitude), and by the dimensional distribution of particles. These three groups of input parameters are required to define the start of impact calculation, and they are described in the following subsections.

3.1.2 Source term – Inventory and release fraction

The amount of released radionuclides represents the released part of the whole radionuclide inventory of the NPS. The inventory is calculated as the time evolution of the initial inventory. The initial inventory refers to the amount of radionuclides present when the source is fabricated or when it is launched. The initial inventory is a part of the NPS design data, together with other construction information. The time evolution is calculated using specialized software codes. Calculations of the time evolution of inventories are based on the available NPS design data and information of the NPS history or proposed NPS application (launch date, course of operation lifetime, etc).

Importantly, ESTE4Space integrates the following databases:

1. Database of all known spacecraft with nuclear and radioisotope sources already in space and a database 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 nuclear and radioisotope sources considered for future missions, mainly based on Am-241, Pu-238, or, in the case of a nuclear reactor, based on U-235, for different assumed reactor power history as a parameter (e.g., reactor on minimal control power, then after 5 to 10 years on full power).

The released activity depends on the released fractions secondly. They define the portions of the activities that are released from the actual inventory. Its absolute value and temporal distribution depend on the RPS design and the type of event. Some of the events result in instantaneous release (such as an explosion on the launch pad or impact on the surface after intact atmospheric passage), while several events lead to continuous release (such as atmospheric passage of a damaged NPS/RPS).

3.1.3 Source term – Particle size

The dimension of the released particles affects several phenomena considered in impact calculations; therefore, the distribution of particles by size is one of the crucial inputs. In general, the particles form a few classes based on their dimension:

- AED (aerodynamic equivalent diameter) less than 10 µm: Particles are respirable and inhalable. They are dispersed in the atmosphere over large distances, as gravitational settling is effectively absent from their motion. Dry deposition on the ground is due to various surface processes. The particles are assumed to be intercepted by vegetation and can enter the food chain.
- AED between 10-50 µm: Particles are not respirable. They are dispersed in the atmosphere, but gravitational settling is a relevant factor. The larger the particle dimensions, the higher the gravitational settling. The particles 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 and deposited in the close vicinity of the epicenter. Gravitational settlement is dominant. The particles are not assumed to enter the food chain.
- 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 event. They could potentially be gathered and disposed of during the decontamination process of the launch pad after the event.

Information on the distribution of particles by size is expected as an input assumption to dispersion calculations. The implemented default assumed percentage of AED applied in ESTE4Space is based on data reported in [1].

3.1.4 Source term – Spatial distribution

Unlike fixed, land-based nuclear facilities, radionuclide releases during an accident involving a spacecraft with RPS on board typically occur from a moving object. The impact calculation requires the knowledge or the estimate of the ballistic movements of the spacecraft or the spacecraft fragments carrying RPS.

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., commanded neutralization); 3) Reentry 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.

The trajectory is calculated considering the gravitational force F_g and the air drag force F_d, both acting during the atmospheric passage of the object:

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

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

M_{earth} is the mass of the Earth, κ is the gravitational constant, ρ is the air density (function of altitude), and r_{earth} is the Earth's radius. The forces depend on the instant velocity v of the object and the instant altitude h of the object. The parameters specifying the object itself are the object mass m, the drag coefficient C_D, the area A as the area of the object normal to the flow, and the ballistic coefficient c_b. All these objects' parameters are basic, inevitable input parameters for trajectory calculation. Additional input parameters include the object's initial position (geographical latitude, longitude, and altitude) and its initial velocity (speed, angle of direction against the horizontal plane, and inclination of the original satellite trajectory). The trajectory, as a solution to the dynamic system of both forces, is calculated using the forward Euler method, a Runge-Kutta integrator.

A special release type is an incident when the radioactive source is exposed to propellant fire on the launch pad. In that case, the spatial distribution of the released activity is calculated using a plume rise model, which provides the estimated plume rise height, calculated for each particle size.

3.2 Atmospheric dispersion calculation

The atmospheric dispersion calculation is modelled 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 primarily determined 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 by gravitational settling. 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 + Δt is given by:

$$x_i(t + \Delta t) = x_i(t) + U_i \Delta t + du_i \quad (3)$$

$$du_i = a_i(x, u, t)dt + b_{ij}(x, u, t)dW_j \quad (4)$$

U_i is the velocity vector of the mean field at time t and position x, and dui is the turbulent increment, which consists of the drift term and the diffusion term. dW_j is an incremental component of the Wiener process, which is a Gaussian random variable. If 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 as:

$$du_i = \sqrt{D_i/\Delta t}\, dW_j \quad (5)$$

Here, W_j is the Gaussian random variable with zero mean, and D_i is a diffusivity parameter. In the case of the stratosphere, the vertical component of D is equal to 0.1 m^2s^{-1} [2,3]. The horizontal components for the stratosphere are set to zero. In the case of the troposphere above the ABL, the horizontal components of D are set to 50 m^2s^{-1} [2]. The vertical component of D is set to zero.

Two types of historical weather data are used. The basic weather data, applied in ESTE4Space, are the numerical weather data from the Global Forecast System (GFS). In the vertical direction, it spans from 1000 hPa to 1 Pa levels, with 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 weather data. ESTE4Space uses ERA5 monthly-averaged weather data, generated by ECMWF (European Centre for Medium-Range Weather Forecasts). Its spatial resolution is also 0.25°, and it spans the global domain. In the vertical direction, the data spans from 1000 hPa to 1 hPa levels. This type of weather data is intended for long-term dispersion calculations, as short-term phenomena are only partially represented in it.

3.3 Marine dispersion calculation

The radionuclide transport and diffusion processes in the marine environment are modeled using the Lagrangian particle model specifically designed for this environment [4]. The turbulent increment (derived from Equation 5) is defined as

$$du_1 = \sqrt{12K_h/\Delta t}\, r_0 \cos(2\pi r_1) \quad (6)$$

$$du_2 = \sqrt{12K_h/\Delta t}\, r_0 \sin(2\pi r_1) \quad (7)$$
$$du_3 = \sqrt{6K_v/\Delta t}\, r_2 \quad (8)$$

Here, r_0, r_1, and r_2 are random numbers, while K_h and K_v are diffusion parameters, as described in [4]. The marine transport model considers three phases: dissolved phase, suspended sediment, and bottom (seabed) sediment. These phases are considered to interact with each other via: a) advective transport (i.e., transport due to mean marine current), b) diffusion (as described above), c) desorption and adsorption processes, d) radioactive decay, e) deposition on the bottom, f) burial process on bottom sediment.

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 global HYCOM data. Its spatial resolution is 0.25°, and 33 distinct levels/depths are applied. The temporal resolution of the marine data is one day.

3.4 Dose calculation

The conceptual model of activity transport in ESTE4Space considers the atmospheric transport of radionuclides, their deposition on terrain, resuspension into the air, and subsequent passage to the biosphere (where they are taken up by plants and animals). The dose calculation encompasses all these transport components and is based on the following pathways: cloudshine exposure, committed effective dose by inhalation, groundshine exposure, including inhalation caused by the resuspension of deposited aerosols, and ingestion. The considered conceptual model is visualized in Figure 1.

The calculated doses are age-dependent. Four age categories are considered: fetus, children (0 to 5 years old), children (6 to 15 years old), and adults (16 years and older). Age-category dependency is evident in human habits and characteristics, including, for example, breathing rate, consumption basket, inhalation factors, and ingestion factors. In the case of the fetus, the exposure is a result of the inhalation of contaminated air by the mother, the food consumption of the mother, and cloud shine and ground shine. The methodology for fetus is based upon [5].

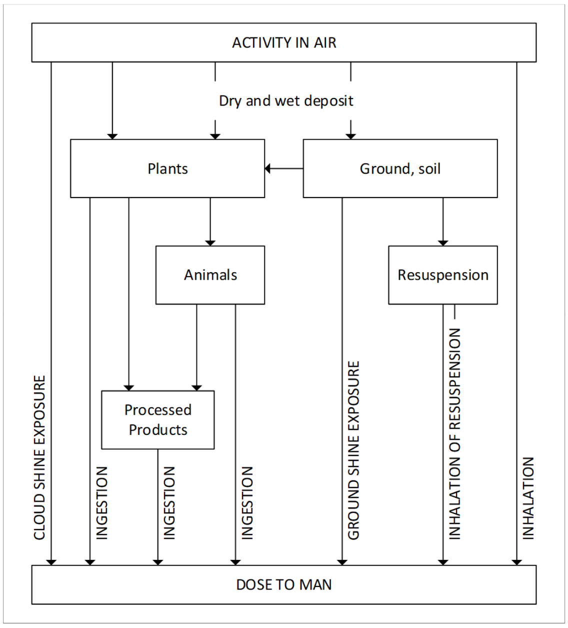
The particle size significantly affects individual pathways. Particles with AED < 10 µm are considered inhalable, and only they contribute to the dose by inhalation. In case of interception on vegetation and potential transfer to the food chain, only particles with AED < 50 µm are considered. The doses by ground shine and cloud shine are without particle size limits.

The model for the calculation of effective dose due to the ingestion of contaminated food is based on the algorithms and procedures described in [6]. The ingestion dose to humans is caused by the consumption of plant products and animal products. The ingestion model considers the transfer to edible parts of plants, which occurs via direct deposition on plants and through root uptake (following deposition on soil), as well as the feeding of animals by impacted plants. The ingestion dose to humans is caused by direct consumption of plants and by consumption of animal products. 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's milk, goat's milk, beef, pork, poultry meat, and eggs. For all these products, the activity concentrations are calculated and reported up to 1 and 2 years (based on the event type).

The person is always assumed to be localized in a single location. I.e., a person breathes the air at a given location, with the originally airborne activity as well as radionuclides resuspended back into the air from the ground deposition. That person is also assumed to consume locally produced foods.

The marine part of the implemented dose model consists of the activity calculation in fish and crustaceans, up to 1 or 2 years, depending on the event scenario. The marine dose calculation model is visualized in the conceptual scheme in Figure 2.

Fig. 1. Conceptual model of ESTE4Space: Basic scheme for the calculation of dose to inhabitant by all



exposition pathways

3.5 Event types and settings for impacts calculation

ESTE4Space includes several modules to calculate the radiological impact. Each module covers a specific accidental spacecraft event involving the release of radionuclides into the environment, as outlined in the following subsections.

3.5.1 Explosion on launch pad

An explosion event of the rocket propellant during on-ground operations (on the launch pad) or immediately after launch, when the radioactive power source (its casket) is damaged, could result in the release of radioactive material. Potentially, the power source is hit by a high-speed rocket fragment or gains momentum during the explosion and is shot away along a ballistic trajectory.

For the launch pad explosion event, the ESTE4Space system requires input data on the radioactive power source trajectory and the specification of the release type. The spatial distribution of the released activity is determined using the calculated ballistic trajectory of the RPS movement after launch. The ballistic trajectory calculation is based on the initial velocity and position of RPS. Furthermore, an assumption regarding the release type is required (release during the explosion, during RPS's ballistic flight, or during impact on the ground). Finally, the specification of the released activity is required, including the total amount and its percentage distribution according to the particle size. The module for launch pad explosion, applying all these data, generates the initial distribution of Lagrangian particles for atmospheric transport and dispersion.

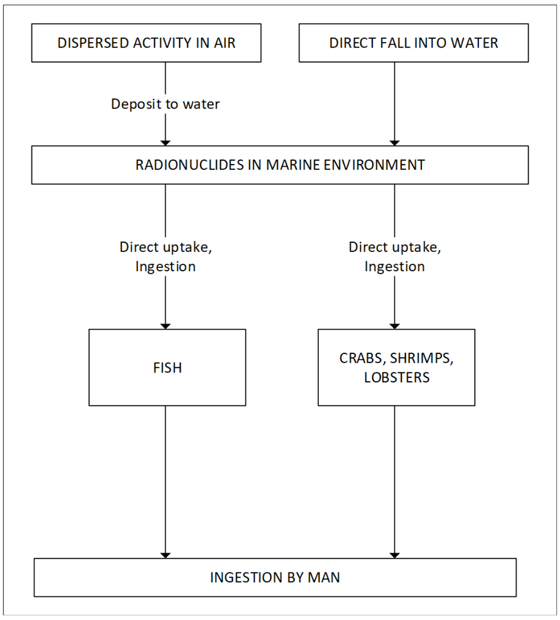


Fig. 2. Conceptual model of ESTE4Space: Basic scheme for the calculation of ingestion doses due to activity in the marine environment.

3.5.2 Fire on launch pad

A severe rocket propellant fire during on-ground operations or immediately after the launch, when the radioactive power source falls into the fire and is exposed to high-temperature conditions, leads to a potential cladding degradation and release of radioactive material. In such a situation, the released radionuclides are transported away by the rising fire plume into the atmosphere.

ESTE4Space uses the plume rise model [7] to evaluate the buoyancy flux, based on either the fire temperature or the heat rate generated by the fire. The output is the estimated plume rise height, calculated for each particle size, considering the current local weather conditions (wind data). The calculated plume trajectory determines the initial particle distribution, which, together with the total amount of released activity, is the input into atmospheric transport and dispersion modeling using LPM.

3.5.3 Events between liftoff and leaving the Earth's atmosphere

Events occurring after leaving the ground (lift-off) and before entering outer space represent a category with specific threats of releasing radioactive material into the environment. The most threatening event is an (accidental or controlled) explosion of the rocket, leading to damage to the RPS and a subsequent 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 an explosion.

Regarding the explosion after leaving the launch pad, the inputs for this type of event include 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.

3.5.4 Reentry

The last event type considered is the reentry of a spacecraft. The event specification consists of analogous input data as in the previous cases, but it reflects the particulars of reentry events. The required input data for trajectory calculation (and thus spatial distribution of the source term) are from the reentry location, altitude, reentry velocity, and direction. Weather data is defined up to the 1 Pa pressure level (approximately 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.

The release types are extended by the possibility of modelling a burnup in the atmosphere, 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 reentry point up to the determined point at the specific altitude.

3.5.5 Settings for event types

Each event type is very specific with its release conditions, such as its height above the terrain and external conditions causing the release (burnup or launch fire). The duration of the relevant atmospheric transport and the expected impacted area are also determined by these conditions. Due to these circumstances, each event type has its own particular setting of impact calculation. The launch event and the following atmospheric dispersion, since they are happening close to ground or on the ground, have a short duration. The impacted area is expected to be in the vicinity of the launch pad, with lateral geographic distances considered up to 100 km. The other extreme situation is a reentry event. In case of high-altitude burnup, the atmospheric transport can be expected to take longer, on a timescale of one year; therefore, the calculation domain has to be global, and the transport simulated duration is 1 or 2 years. A summary of characteristics of impacts calculation for all event types is summarized in Table 1.

Table 1. Characteristics of impacts calculation - atmosphere

	Launch Pad	After lift-off	Reentry local	Reentry global
Atmospheric transport	7 days	30 days	1 year	1 year
Spatial domain	400 km	800 km	400 km	Earth
Maximal resolution	200 m	300 m	200 m	0.5°
Resolution type	Gradual	Gradual	Gradual	Uniform
Ingestion	1 year	1 year	2 years	2 years
Marine transport	1 year	1 year	2 years	2 years

Impact calculation can be approached in a probabilistic and a deterministic manner. A deterministic calculation uses one specific weather condition defined by the date and time of the considered event. A probabilistic calculation performs many separate deterministic calculations inside the given time interval (e.g., in a calendar year), and it is finalized by a statistical analysis 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.

The deterministic type of calculation in ESTE4Space is available for all event types. Probabilistic calculations can be performed for both launch pad event types (fire and explosion on the launch pad).

4. Results and discussions

4.1 Inventory calculation

The list of main RTG sources currently in Earth orbits, as implemented in the database of the ESTE4Space is given in Table 2. The inventories are precalculated for different time horizons after the launch time, and this data is ready to be used in case of a real event in the future.

The inventory calculation is based on the initial isotopic composition of RTG, and the time evolution of inventory follows the decay chains of the present radionuclides. The calculation was performed using the SERPENT code [8], in which the Bateman depletion equations are applied. The inventories are calculated for up to 1000 years after launch.

In the case of Pu-238-based RTGs, the nuclear source is not isotopically pure Pu-238, but it also contains other isotopes of Pu and other relevant contaminating nuclides. The initial isotopic composition can vary depending on the source (fission products) from which the Pu-238 was originally extracted (an example is in [9]). Although the construction of the plutonium RTG is based on the physical properties of the Pu-238 isotopes, the impact calculation in case of release to the environment has to include all present radioisotopes.

Table 2. RTG sources with Pu-238 currently in Earth orbit - basic information in the database of ESTE4Space

Power Source	Launch Year	Activity 1y after launch	Activity in the year 2025
SNAP-3B7	1961	5.0E+13	2.9E+13
SNAP-3B	1961	5.0E+13	2.9E+13
SNAP-9A	1963	5.4E+14	3.2E+14
SNAP-9A	1963	5.4E+14	3.2E+14
SNAP-19B2	1969	1.2E+15	7.3E+14
TRANSIT-RTG	1972	9.1E+14	5.7E+14
MHW-RTG	1976	5.8E+15	3.7E+15
MHW-RTG	1976	5.8E+15	3.7E+15

Controlled nuclear fission reactions are able to provide heat with significantly higher power levels than RTGs. Historically, several reactor designs have been used to generate power in space. The known nuclear reactors currently in Earth's orbit are listed in Table 3. The list consists of three types: SNAP-10A, TOPAZ-1 reactor, and BUK-type reactor (3 of 31 launched BUK reactors reentered the atmosphere). The list also includes publicly available and known data on these nuclear reactors. All reactors used highly enriched U-235 as fuel, with a core fuel mass of up to 50 kg. They typically produced thermal power on the order of 100 kW, which is an order of magnitude higher than the thermal power produced using RTGs in the CASSINI mission.

Furthermore, it is expected that a new generation of space nuclear power sources will be considered as an energy source for spacecraft propulsion, with orders of magnitude higher thermal energy output. Examples are the ESA-funded RocketRoll and Alumni projects. The database of potential nuclear inventories of the RocketRoll reactor, calculated under various operational conditions, is also prepared in the SW tool ESTE4Space and is ready to use for the needs of safety analyses.

Table 3. Space fission reactors in Earth orbit - basic information in the database of ESTE4Space

Project	SNAP-10A	BUK	TOPAZ-1

Country	USA	USSR	USSR
Development status	Flight test	31 Flights	2 Flights
Timescale	1965	1970-88	1987
Uranium enrichment [%]	93	>90	96
Core loading of U-235 [kg]	4.3	30	12
Thermal power [kW]	35	<100	150
Design operation years	1	1	0.9
Actual operation years	0.1	0.5	0.96

Reactor inventories at various time horizons after the end of the fission reaction, for the needs of the ESTE4Space database, were calculated using the SERPENT code [8] and the MCNP code [10]. For comparison, the Origen SCALE code was used as well. The reactors were modeled in 2D mode in the case of SERPENT and SCALE. A 3D approach was taken for the calculation in MCNP. A comparison of the three calculation codes is shown in Table 4. The comparison is performed for COSMOS 1176 (with a BUK-type reactor, which launched in 1980 and was in operation for 134 days). The differences are on the level of a few percent for the fission products with high activities. The differences grow for some fission products with low activity and some transuranic isotopes. The differences here are up to 45 percent in a few cases. The differences mainly arise from the reactors being modeled in various codes.

Nuclear reactor inventories are calculated up to 1000 years after launch. Impact calculations within the ESTE4Space system consider 35 radionuclides, including the most relevant fission products and transuranic isotopes.

Table 4. Comparison of the calculated inventories (in Bq) 1 year after the end of the mission of COSMOS 1176 performed by various codes.

Isotope	MCNP	Serpent	SCALE
Ce-144	1.9E+13	1.9E+13	2.0E+13
Pm-147	4.8E+12	4.8E+12	5.1E+12
Ru-106	1.9E+12	2.0E+12	1.7E+12
Cs-137	1.6E+12	1.6E+12	1.6E+12
Sr-89	7.6E+11	7.7E+11	8.2E+11
Kr-85	1.9E+11	2.0E+11	2.0E+11
Eu-155	5.8E+10	5.7E+10	5.3E+10
U-235	2.2E+09	2.0E+09	2.2E+09
Cs-134	9.1E+08	1.5E+09	4.3E+08
Pu-239	3.5E+08	3.1E+08	3.2E+08
Eu-154	3.5E+07	2.7E+07	1.8E+07
Zr-93	3.2E+07	3.2E+07	3.4E+07
Sn-126	7.7E+06	5.6E+06	2.8E+06
I-129	4.2E+05	4.4E+05	3.6E+05
Np-237	1.8E+05	1.8E+05	1.7E+05
Pu-240	7.4E+04	2.9E+04	3.3E+04

4.2 Reentry of orbiting object

he ESTE4Space system contains a database of inventories of all orbiting NPS/RPSs. In case of a reentry event, the start of impact calculation requires the data about reentry in the atmosphere, including the reentry altitude, location, and velocity vector, the air drag properties of the NPS/RPS, and the assumed release type. While the reentry information is primarily covered by a reentry service, the release type (including particle size distribution, fraction of inventory released, and type of release) depends on further input and expertise of the users.

The performance of impact calculation using ESTE4Space for reentry of an orbiting object is demonstrated on a hypothetical reentry of COSMOS-1249, with NORAD ID 12551. The spacecraft was launched on the 5th of March 1981, and the reactor was in operation for 105 days. The deactivated reactor was boosted into the graveyard orbit (at an approximate altitude of 930 km). Its calculated inventories 1 year and 50 years after the end of its mission are given in Table 5. For comparison, the estimated amount of Cs-137 released into the environment during the Fukushima accident was on the level of 10 PBq (1.0E+16 Bq), i.e., approximately 4 orders of magnitude larger than is present in the whole inventory of COSMOS-1249.

In the hypothetical reentry scenario, the reentry was assumed near the Atlantic coast of Africa, and the calculated impact point was in the region of the Kalahari Desert. The passage through the atmosphere is shown in the lower right corner of Figure 3. In addition, the assumption of a continuous release of the total spacecraft inventory along the whole atmospheric passage is made. The event was set to the current year (2025), so the source term is almost identical to the inventory after 50 years, as is shown in Table 5. The calculated impacts are shown on the deposits of Cs-137 on the terrain 30 days after the event, in Figure 3. This kind of event can lead to contamination up to the level of 1 Bq/m^2 near the impact point, without considering large hot particles and debris. In the figure, the projection of the trajectory on the surface is partially visible in the calculated deposit as a result of the presence of large particles in the source term. The atmospheric transport and dispersion are performed using the ESTE4Space Lagrangian particle model with global numerical weather data covering the atmosphere up to the altitude of 90 km (these altitudes are considered as the beginning of the reentry).

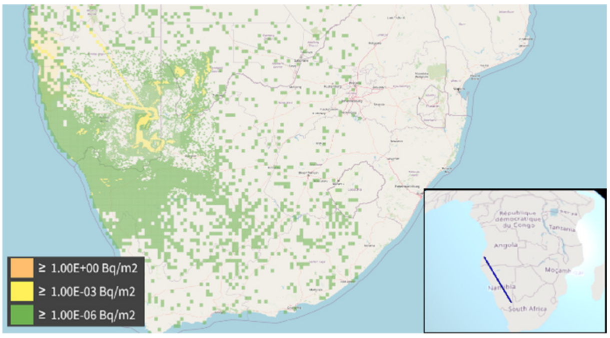


Fig. 3. Deposit of Cs-137 on the terrain in 30 days after a hypothetical reentry of COSMOS 1249. Calculation performed on the local domain.

Table 5. Inventory of the BUK reactor of COSMOS-1249, in Becquerel

Isotope	Activity 1 year after the end of the mission	Activity in the year 2025
Kr-85	1.6E+11	9.8E+09
Sr-90	1.2E+12	4.4E+11
Sr-89	7.4E+11	«
Y-90	1.2E+12	4.4E+11
Nb-95	5.8E+12	«
Ru-103	1.4E+11	«
Ru-106	1.4E+12	«
Te129m	1.7E+09	«
I-129	2.8E+05	2.8E+05
I-131	2.0E+00	«
Cs-134	2.6E+08	1.5E+02
Cs-135	1.8E+07	1.8E+07
Cs-137	1.3E+12	4.7E+11
Ba-140	4.7E+05	«
La-140	5.4E+05	«
Ce-141	7.0E+10	«
U-234	8.4E+06	8.4E+06
U-235	2.2E+09	2.2E+09
U-238	3.7E+07	3.7E+07
Pu-238	2.4E+05	1.7E+05
Pu-239	2.5E+08	2.5E+08
Pu-241	1.8E+02	2.2E+01
Am-241	3.2E-01	5.3E+00

4.3 Effect of particle sizes

Many parameters and circumstances can significantly influence the resulting radiological impact, such as the type of event and the prevailing weather conditions. This subsection focuses on analyzing the effect of particle size on radiological dispersion and deposition. The distribution of released particle sizes is determined by a combination of the RPS's structural characteristics (e.g., encapsulation) and specific conditions present during the accident. We considered a hypothetical launch pad explosion. The spacecraft is assumed to carry an Am-241 RTG onboard. The RPS is damaged during the explosion, and a release of Am-241 occurs. In Figures 4 and 5, the calculated deposits of Am-241 are shown for two different release scenarios. In the case of Figure 4, all particles considered in the source term are smaller than < 10 µm. The deposit is localized not only in the launch pad area, but also a low-level contamination is present outside of the 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 5, 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 prevailing effect of the gravitational settling on the considered large particles. The deposit level is higher in that case, but the dose by inhalation is practically negligible due to the irrespirability of these large particles, and the area of the impacted arable land is very small.

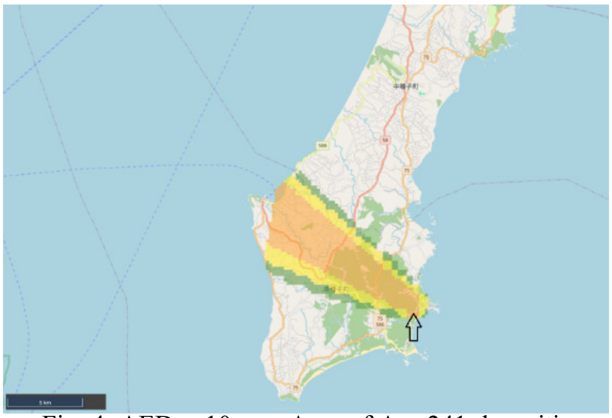


Fig. 4. AED < 10 µm. Area of Am-241 deposition on the terrain in case of a hypothetical explosion on the launch pad. All assumed released particles in the source term are of the AED < 10 µm. The arrow shows the location of the event. The launch pad site was chosen as hypothetical and random.

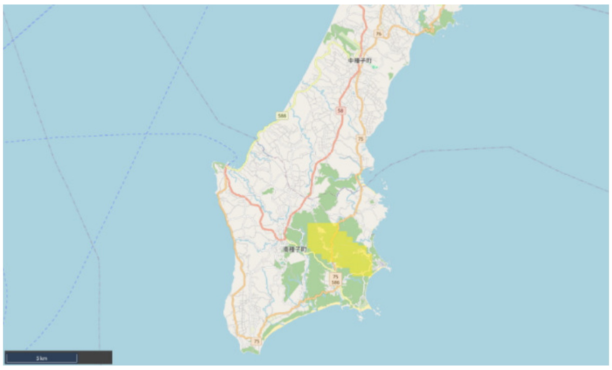


Fig. 5. AED > 60 µm. Area of Am-241 deposition on the terrain in case of hypothetical explosion on launch pad. All assumed released particles in the source term are of the size AED > 60 µm.

The effect of particle size distribution can also be visualized in a reentry event. We considered a reentry to the atmosphere from a transfer orbit; therefore, the ballistic trajectory is very steep (unlike the reentry from low-Earth orbit). The source term (amount of Am-241 released) was chosen as a hypothetical example. The release with a whole spectrum of particle sizes was assumed along the reentry trajectory and with impact on the Earth's surface. The assumed percentage of AED considered in this scenario was taken from [1]. The event is assumed to be in the atmosphere above New South Wales (Australia). In the second example, we assumed that only particles with AED < 10 µm are present in the source term. Figure 6 shows the calculated time-integrated concentration (TIC) on the ground surface of Am-241 for AED < 10 µm (inhalable particles) after 1 month following the event. This variable is applied for the calculation of the internal dose via inhalation. Within 1 month, a low-level TIC of Am-241 can be expected in the southern hemisphere. The upper part corresponds to the case when only particles with AED < 10 µm are present in the source term, and the bottom part is for the case when a composition of particle sizes is assumed according to [1]. The colours represent areas where three various levels of TIC are exceeded. In general, the impacted areas have very similar geographical distributions; nevertheless, there are some significant differences. The maximal value of TIC of Am-241 in the ground layer for inhalable particles is almost an order of magnitude larger in the second variant of release. The area where TIC of Am-241 in the ground layer for inhalable particles is larger than a set value is approximately 3 to 10 times larger in the case of the release only with AED < 10 µm. The ratio of area sizes increases by increasing the analysed level of TIC.

In both analysed events - the hypothetical launch pad scenario and reentry event - the particle size distribution plays a significant role in determining the resulting radiological impacts.

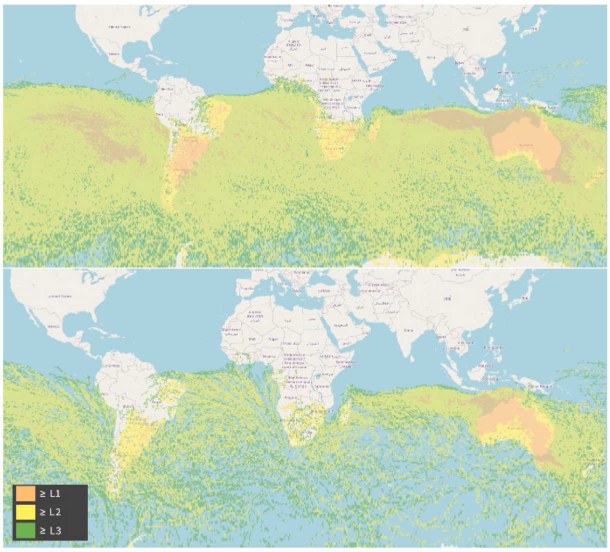


Fig. 6. Calculated time-integrated concentration (TIC) of Am-241 for AED < 10 µm after 1 month following the event in the surface ground. The upper part corresponds to the case when only particles with AED < 10 µm are present, and the bottom part is for the case when a composition of particles sizes is assumed according to [1]. The colours represent areas where three various levels of TIC are exceeded.

5. Conclusions

ESTE4Space is a new tool to support the nuclear safety analysis of space missions with NPS. Its primary role is to conduct analyses for nuclear safety reports during the launch approval process, assessing effective doses to the most exposed population in accordance with French regulations, as well as evaluating health-effect risks in compliance with US regulations. In the future, ESTE4Space could also serve as a valuable tool for emergency response, including the analysis of radiological consequences during real emergencies. ESTE4Space is capable of straightforward integration of any new NPS type.

The main components of the ESTE4Space that enable analyses for impact calculations related to space missions are the in-built Lagrangian particle models for atmospheric and marine dispersion, a module for generating source terms covering events from the launch pad accident up to reentry events, and the implemented dose calculation model containing the most important pathways of potential exposure of inhabitants. The exposition pathway with the largest impact is the internal irradiation by inhalation. Another potentially significant exposure pathway is ingestion of contaminated foodstuffs.

For radiological impact analysis purposes, the particle size distribution (AED) is a critical input to ESTE4Space. These data should accompany the safety report of the manufactured encapsulated radioisotope or nuclear source designated for the given spacecraft mission. The source manufacturer should experimentally study the behaviour of the given encapsulated source under accident conditions and should provide the results of these experiments as input to the safety analysis.

ESTE4Space includes a database of existing and planned nuclear sources. This database contains RTGs as well as nuclear reactors. An essential component of the database is the calculated present-day and projected future nuclear inventories of nuclear power sources. The methodologies used for inventory calculations within the database are described, and a hypothetical reentry event was analyzed to demonstrate the application of the pre-calculated inventory and to illustrate the qualitative results of the radiological impact calculation.

Acknowledgements

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