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Inventories of nuclear power sources used or potentially planned for the orbit

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Abstract

A comprehensive database of existing and planned nuclear power sources aboard spacecraft has been developed to support ESTE4Space, a software tool designed for nuclear safety analysis of space missions utilizing reactor or radionuclide-based power systems. The database includes Radioisotope Thermoelectric Generators, Radioisotope Heater Units, and space nuclear reactors. Publicly available specifications of these sources were used to estimate both current and projected radionuclide inventories, with particular attention to radiologically significant fission products and transuranic elements. These calculated inventories serve as input for defining source terms in numerical simulations aimed at assessing potential radiological impacts and evaluating mitigation strategies.

1. Introduction

The ESTE4Space software tool is aimed at performing potential radiological consequences assessments for space missions with nuclear power sources onboard. The tool was developed within the frame of an ESA-funded project, and its capabilities were successfully demonstrated within this project on a set of potential accident scenarios related to a representative launch pad, in-flight neutralization, and inadvertent re-entry 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 many radiological parameters necessary for the assessment of potential consequences to the population and the environment. The dispersion calculation uses global numerical weather prediction data covering the atmosphere from ground level up to an altitude of 90 km. The numerical weather data are available either as archived data from past years or as current 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 to be a potentially useful tool for emergency applications. This feature is manifested by its capabilities: near real-time connection to spacecraft re-entry services (such as EU-SST) for automatic evaluation of re-entry events, and utilization of a database of inventories of all known space nuclear power sources. The nuclide inventory, coupled with assumptions about the behavior of the nuclear power source during the atmospheric passage (total burn-up during reentry, partial release, intact impact, etc.), determines the source term. The source term is the main input to dispersion modeling and radiological impact assessment.

The database of calculated inventories includes primarily inactive spacecraft in Earth orbit with radioisotopes or nuclear material on board. The database is extended by several missions in preparation, such as radioisotope thermoelectric generator sources based on Am-241. The inventories consist of radionuclides used as a power source (Pu-238, Am-241, or U-235), their decay products, and/or fission products. In the process of inventory calculation, the mission launch date, operation time period, and nuclear source design were considered. The database of nuclear sources contains Radioisotope Thermoelectric Generators (RTGs), Radioisotope Heater Units (RHUs), and nuclear reactors.

2. Inventory of Radioisotope Thermoelectric Generators and Radioisotope Heater Units

The Radioisotope Thermoelectric Generator is a type of power source that utilizes heat generated from the radioactive decay of radionuclides to produce electricity. The decay process releases a significant amount of heat, which is then

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converted into electricity by the thermoelectric modules. RTGs are known for their long operating lifetimes and reliability. Unlike batteries or solar panels, which degrade significantly over time, RTGs can provide continuous power for many years, even decades, without the need for maintenance or refueling.

RTGs have been used extensively in deep space exploration missions where other power sources, such as solar panels, are impractical or insufficient. For example, RTGs have powered numerous deep space probes, including the Voyager, Pioneer, and New Horizons missions. They have also been used in rovers on the surface of Mars, such as the Mars rovers Spirit, Opportunity, and Curiosity. These missions represent potential risk primarily during launch. After leaving the Earth's gravitational well, the probability of return is extremely low.

RTGs were also utilized in several missions with the aim of providing special services for human activities (navigation, communication, meteorological, and intelligence-gathering missions), and they orbited or still orbit the Earth, although they are beyond their lifetime. The list of main RTG sources currently in Earth orbits, as implemented in the database of the SW tool ESTE4Space, is given in Table 1. The inventories in the database of the ESTE4Space system, in Bq, are precalculated for different time horizons after the launch time, and this information is ready to be applied in case of a real future event. Information on RTGs in the ESTE4Space system also includes the launch date, its operational status (current known orbit parameters such as perigee and inclination), mission type, and international identifier number (NORAD ID).

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 [1], in which the Bateman depletion equations are applied. The inventories are calculated up to 1000 years after launch.

Table 1: RTG sources with Pu-238 currently in Earth orbit - basic information in database of ESTE4Space (example) [2]

Power Source	**Spacecraft**	**Launch Year**	**Activity 1 year after launch [Bq]**	**Activity 50 years year after launch [Bq]**
SNAP-3B7	TRANSIT 4A	1961	5.0E+13	3.2E+13
SNAP-3B	TRANSIT 4B	1961	5.0E+13	3.2E+13
SNAP-9A	TRANSIT 5BN-1	1963	5.4E+14	3.5E+14
SNAP-9A	TRANSIT 5BN-2	1963	5.4E+14	3.5E+14
SNAP-19B2	NIMBUS III	1969	1.2E+15	7.6E+14
TRANSIT-RTG	TRIAD-01-1X	1972	9.1E+14	5.8E+14
MHW-RTG	LES 8	1976	5.8E+15	3.7E+15
MHW-RTG	LES 9	1976	5.8E+15	3.7E+15

In the case of RTGs and RHUs, the nuclear source is based on the radioactive decay of radionuclides available during the time of manufacture of the nuclear source. The most common are nuclear sources based on Pu-238, which has a long half-life and emits alpha particles as it decays. The half-life of Pu-238 is 87.8 years, enabling to manufacture of a stable, continuous source. Another radionuclide is Po-210, applied in Soviet lunar missions, e.g., Cosmos 90 or Lunokhod moon rover. Due to its short half-life (183 days), it can be used only for short-duration space missions. Another radioisotope is Am-241, planned for ESA missions. Its half-life of 432 years enables the preparation of a stable, long-lasting source.

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 nuclides. The initial isotopic composition can vary depending on the source (fission products) from which the Pu-238 was originally extracted, that is, the composition at the time of manufacture. For Pu-238 RTGs, case-by-case information on the initial isotopic composition of the source is considered for calculation, taken from [3]. A typical radioisotope composition of Pu-238 RTGs at the time of manufacture and the pre-launch time is given in Table 2. 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.

An example of the time evolution of the isotopic inventory is shown in Figure 1 for the GPHS-RTG (general-purpose heat source - radioisotope thermoelectric generator). This type of RTG was utilized in Galileo (2 of such sources), Ulysses (1), Cassini-Huygens (3), and New Horizons (1) missions. The total activity of the Ulysses mission [4] was 4.9 PBq, corresponding to a total weight of Pu of 9.1 kg. The most dominant isotope is Pu-238. At the time of manufacture, the second most dominant component was Pu-241, which was slowly replaced by Am-241 during the subsequent decades.

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Table 2: Typical isotopic composition of plutonium source at the time of manufacture as applied in the database of inventories of ESTE4Space [2]

Fuel Composition	Mass [%]	Half-Life [years]	Activity [%]
Pu-236	6×10^{-8}	2.851	0.00
Pu-238	72.33	87.7	98.84
Pu-239	11.83	24 131	0.06
Pu-240	1.70	6 569	0.03
Pu-241	0.09	14.1	0.74
Pu-242	0.04	375 800	0.33
Impurities	2.11	N/A	N/A
Oxygen	11.9	N/A	N/A

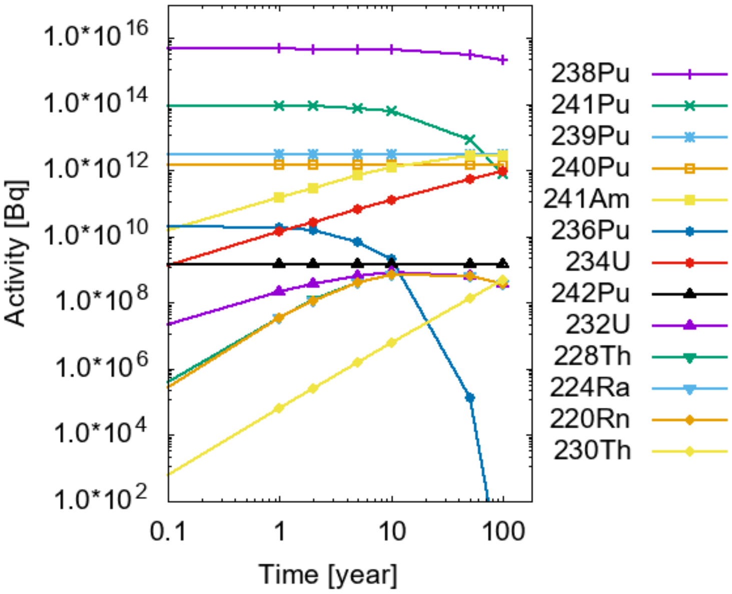

Figure 1: Calculated inventory of GPHS-RTG with Pu-238 (in the unit of Bq) as a function of time. Time 0 is the time of the production of the Pu-238 source.

3. Inventory of Nuclear Reactors

Space fission reactors use controlled nuclear fission reactions to generate heat, which is then converted to electricity using a power conversion system. They are typically compact and lightweight compared to terrestrial reactors because of their optimization for the constraints of space missions. 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.

The space fission reactors represent a promising technology for enabling ambitious space exploration missions, offering high power output, reliability, and independence from solar energy constraints. It is expected that a new generation of power sources will orbit Earth and beyond. They are considered an energy source for spacecraft propulsion. Examples are the ESA-funded RocketRoll and Alumni projects. The database of potential nuclear inventories of the RocketRoll reactor, calculated under various circumstances, is also prepared in the SW tool ESTE4Space and is ready to use for the needs of various safety analyses.

In the history of the application of nuclear reactors in space, there have been several reactor designs. The nuclear reactors applied in real missions and still in Earth orbits are listed in Table 3. The list consists of three types: SNAP-10A, TOPAZ-1 reactor, and BUK-type reactor (3 of 31 BUK reactors re-entered 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.

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Table 3: Space fission reactors in Earth orbit - basic information in 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 [1] and the MCNP code [5]. 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 applied for the calculation in MCNP. The visualization of the BUK type, as modeled in MCNP, is given in Figure 2. 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 ESTE4-Space system consider 35 radionuclides, including the most relevant fission products and transuranic isotopes.

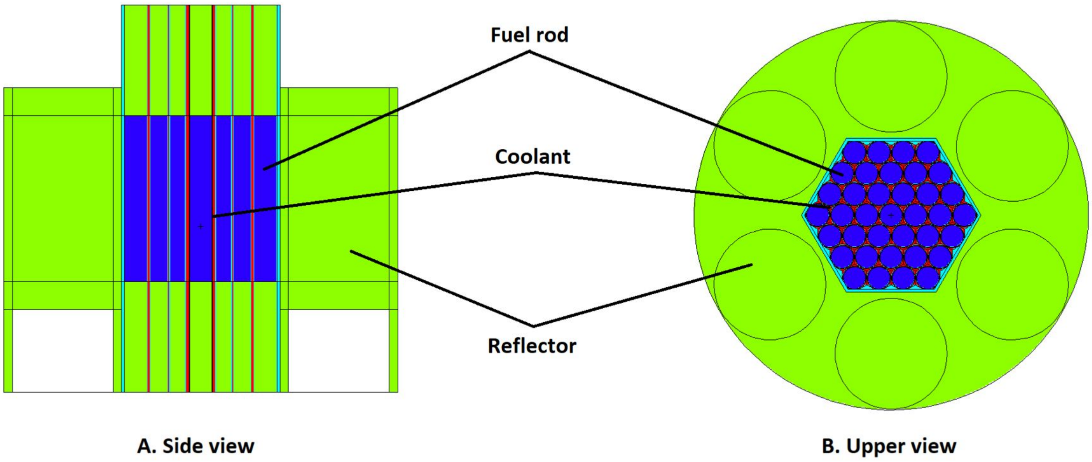

Figure 2: Model of BUK reactor [6] as modeled in MCNP. The fuel rods are shown in blue, the Be reflector in green, and the NaK coolant in red.

In the future, it can be assumed that a new generation of power sources will orbit Earth and beyond. They are considered an energy source for spacecraft propulsion. Examples are the ESA-funded RocketRoll and Alumni projects.

4. Calculation of impacts in ESTE4Space

The ESTE4Space system contains a database of inventories of all orbiting RPSs. In case of a re-entry event of an object from this catalog, the start of impact calculation requires defining the altitude, location, and velocity vector of the re-entry in the atmosphere, the air drag properties of the RPS, and the assumed release type (particle size distribution, fraction of inventory released, type of release). While the re-entry information is primarily covered by a re-entry service, the release type depends on further input and expertise of the users.

In this section, an example of impact calculation using ESTE4Space is described - a hypothetical re-entry of COSMOS-1249, with NORAD ID 12551. The object was launched on 5.3.1981 and was in operation for 105 days.

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

Isotope	**MCNP**	**Serpent**	**SCALE**	**St. deviation/mean**
Ce-144	1.9E+13	1.9E+13	2.0E+13	0.03
Pm-147	4.8E+12	4.8E+12	5.1E+12	0.03
Ru-106	1.9E+12	2.0E+12	1.7E+12	0.05
Cs-137	1.6E+12	1.6E+12	1.6E+12	0.02
Sr-89	7.6E+11	7.7E+11	8.2E+11	0.03
Kr-85	1.9E+11	2.0E+11	2.0E+11	0.02
Eu-155	5.8E+10	5.7E+10	5.3E+10	0.03
U-235	2.2E+09	2.0E+09	2.2E+09	0.04
Cs-134	9.1E+08	1.5E+09	4.3E+08	0.46
Pu-239	3.5E+08	3.1E+08	3.2E+08	0.04
Eu-154	3.5E+07	2.7E+07	1.8E+07	0.27
Zr-93	3.2E+07	3.2E+07	3.4E+07	0.02
Sn-126	7.7E+06	5.6E+06	2.8E+06	0.38
I-129	4.2E+05	4.4E+05	3.6E+05	0.09
Np-237	1.8E+05	1.8E+05	1.7E+05	0.02
Pu-240	7.4E+04	2.9E+04	3.3E+04	0.44

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 re-entry scenario, the re-entry 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 Figures 3 and 4. 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, so the source term is almost identical to the inventory after 50 years from Table 5. The calculated impacts are shown on the deposits of Cs-137 on the terrain 30 days after the event. Figure 3 shows the deposit on the global scale and Figure 4 on a local scale with higher resolution. 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. The atmospheric transport and dispersion are performed using the ESTE4Space Lagrangian particle model by applying global numerical weather data covering the atmosphere up to the altitude of 80-90 km (these altitudes are considered as the start of the re-entry).

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

Isotope	**Activity 1 year**	**Activity 50 years**	**Isotope**	**Activity 1 year**	**Activity 50 years**	**Isotope**	**Activity 1 year**	**Activity 50 years**
Kr-85	1.6E+11	6.7E+09	I-129	2.8E+05	2.8E+05	U-234	8.4E+06	8.4E+06
Sr-90	1.2E+12	3.7E+11	I-131	2.0E+00	«	U-234	8.4E+06	8.4E+06
Sr-89	7.4E+11	«	Cs-134	2.6E+08	1.8E+01	U-235	2.2E+09	2.2E+09
Y-90	1.2E+12	3.7E+11	Cs-135	1.8E+07	1.8E+07	U-238	3.7E+07	3.7E+07
Nb-95	5.8E+12	«	Cs-137	1.3E+12	4.1E+11	Pu-238	2.4E+05	1.6E+05
Ru-103	1.4E+11	«	Ba-140	4.7E+05	«	Pu-239	2.5E+08	2.5E+08
Ru-106	1.4E+12	«	La-140	5.4E+05	«	Pu-241	1.8E+02	1.7E+01
Te129m	1.7E+09	«	Ce-141	7.0E+10	«	Am-241	3.2E-01	5.4E+00

*« lower than 1E-02 Bq

5. Summary

ESTE4Space is a system for modeling radiological impacts connected with events and accidents of space missions with radioactive or nuclear sources onboard. An important part of the ESTE4Space is a database of existing and planned-to-be-launched nuclear sources. This database includes Radioisotope Thermoelectric Generators, Radioisotope Heater

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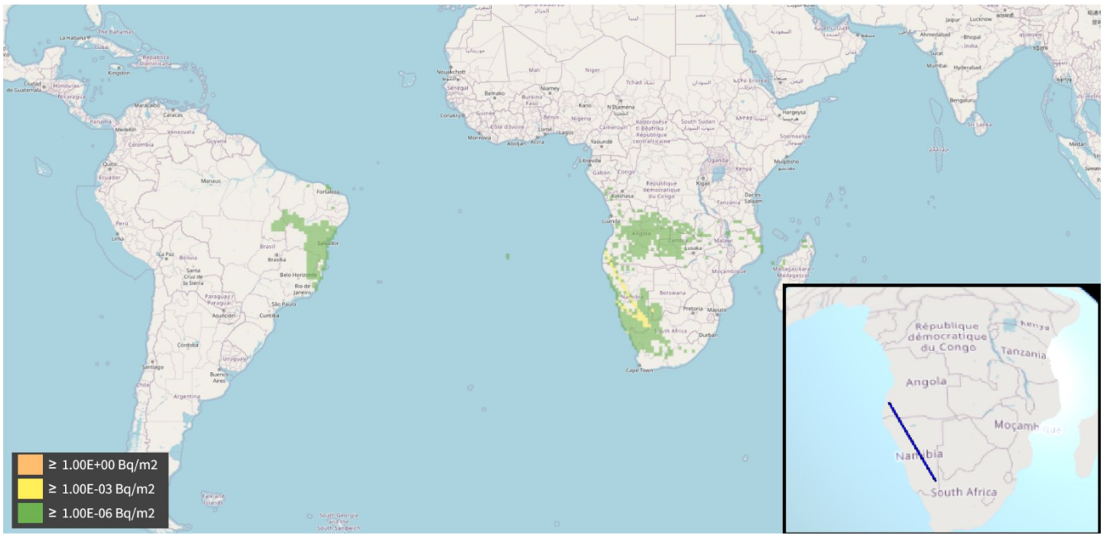

Figure 3: Deposit of Cs-137 on the terrain in 30 days after a hypothetical re-entry of COSMOS 1249. Calculation performed on the global domain.

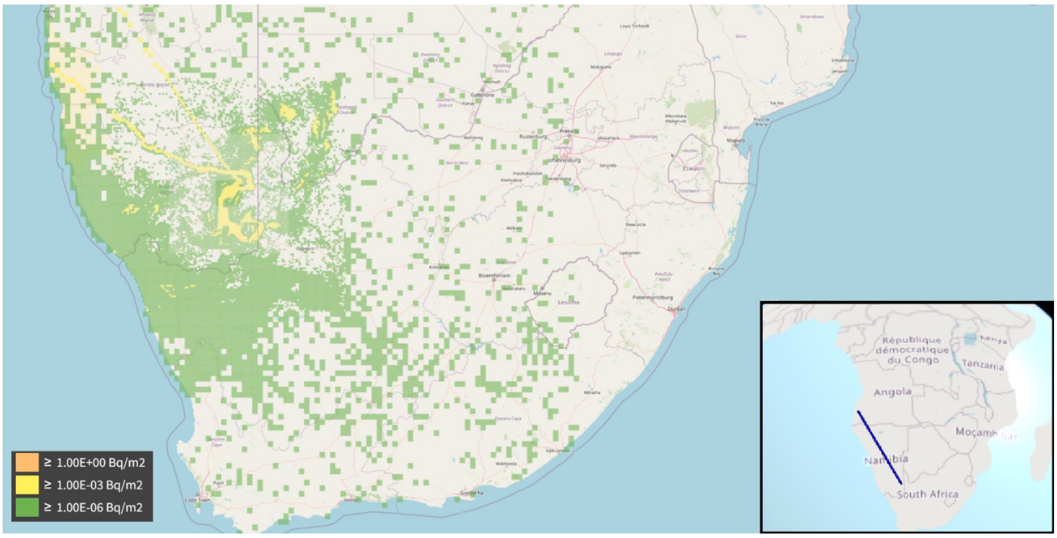

Figure 4: Deposit of Cs-137 on the terrain in 30 days after a hypothetical re-entry of COSMOS 1249. Calculation performed on the local domain.

Units, and nuclear reactors. An essential part of the database is the relevant calculated present-day and future nuclear inventories of nuclear sources. In the article, a hypothetical re-entry event was presented, where the precalculated inventory was used, and the results of the impact calculation were demonstrated.

6. Acknowledgments

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