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Accident scenarios of the TRIGA Mark II reactor in Vienna

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ABSTRACT

The safety report of the TRIGA Mark II reactor in Vienna includes three accident scenarios and their deterministic dose consequences to the environment. The destruction of the cladding of the most activated fuel element, the destruction of all fuel elements and a plane crash were considered scenarios in that report. The calculations were made in 1978 with the software program named STRISK. In this paper, the program package PC Cosyma was applied on the TRIGA Mark II reactor in Vienna and the deterministic consequences of the scenarios to the environment were updated. The fission product inventories of all fuel elements were calculated with ORIGEN2. To get meteorological data of the atmospheric condition around the release area, a weather station was installed. The release parameters were taken from the safety report or were replaced by worst case parameters. This paper focuses on two accident scenarios: the destruction of the cladding of the fuel element with the highest activity content and the case of a large plane crash. The current accident scenarios show good agreement with the calculations from 1978, hence no technical modifications in the safety report of the TRIGA reactor Vienna were necessary. Even in the very worst case scenario – complete destruction of all fuel elements in a large plane crash – the expected doses in the Atominstitut's neighborhood remain moderate.

1. Introduction

Simulations of accident scenarios are important to assess the possible hazards in case of an accident with any nuclear facility. Possible accident scenarios of the only operating Austrian nuclear facility, the Atominstitut's TRIGA Mark II research reactor in Vienna are topics of this paper. For TRIGA reactors, some possible accident scenarios have been investigated in the past (Glumac et al., 1997; Hawley and Kathren, 1982; Margeanu et al., 2008). The safety report of the Vienna reactor includes three accident scenarios and their deterministic dose consequences to the environment, namely the destruction of the cladding of the most activated fuel element, the destruction of all fuel elements and a plane crash were considered scenarios in that report. The calculations were made in 1978 with the computer program STRISK (Strubegger, 1978) and needed to be verified and, if necessary, updated to the current state of the art. Although the safety report includes three different scenarios, we will discuss the two most interesting scenarios here: first, the damage of the cladding of the fuel element with the highest activity concentration (one of the less severe accident scenarios) and the crash of a large plane followed by complete destruction of the reactor core and the reactor hall (the worst case scenario) (Haydn, 2009).

The current core of the Atominstitut's TRIGA reactor consists of 83 fuel elements which are arranged in 5 annular circles around the central irradiation tube: 54 fuel elements of the type *102*; 21 fuel elements of the type *104*; and 8 fuel elements of the type *110*. The fuel elements have 3.75 cm in diameter and 72 cm in length; the cladding is either aluminum Al-1100 F (type *102*) or type 304 stainless steel (types *104* and *110*). Each fuel element consists of three cyclinders of uranium–zirconium hydride fuel, which is responsible for the inherent safety of TRIGA reactors. The uranium content in the fuel is 8.5 wt% U with a ^{235}U enrichment of 19.75% (types *102* and *104*) and 70% (type *110*), respectively. For an image of the reactor core configuration and a simplified scheme of a fuel element, see Khan et al. (2010).

2. Methods

The program system PC Cosyma Version 2.01 (Jones et al., 1996; National Radiological Protection Board, 1995) was used to assess the off-site consequences of an accidental release of radioactive substances into the atmosphere. In this paper the effective dose (ICRP-60) after one day and after 50 years of the two scenarios are considered. The evaluations were made deterministically, which means that the atmosphere was assumed as temporally stable. The program's atmospheric condition E was used, which means a stable atmosphere. Standard values for mixing layer height (320 m), wind profile exponent (p = 0.44) and sigma coefficients were used for calculation. A list of used depo-

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Table 1
Used deposition parameters in the program PC Cosyma 2.01.

Aerosols	Dry deposition velocity [m/s]	0.001
	Dry deposition correction factor	1
	Wet deposition coefficient a	8.0E-05
	Wet deposition coefficient b	0.8
Elementary bound iodine	Dry deposition velocity [m/s]	0.01
	Dry deposition correction factor	1
	Wet deposition coefficient a	8.0E-05
	Wet deposition coefficient b	0.6
Organically bound iodine	Dry deposition velocity [m/s]	5.0E-004
	Dry deposition correction factor	1
	Wet deposition coefficient a	8.0E-07
	Wet deposition coefficient b	0.6

sition parameters (standard values of PC Cosyma) is given in Table 1.

Of all radionuclides produced in a nuclear reactor, only noble gases and halogens are regarded as volatile enough to be released into the atmosphere in so significant amounts that the they become dose relevant. Only nuclides with half-lives longer than 14.1 min were considered. In this work, only one release phase is used with a release duration of one hour and no external or internal thermal energy contribution was assumed (0 MW). For this reason, less volatile radionuclides such as radiocesium, have not been taken into account. Cesium isotopes are released in significant amounts only from a hot environment, e.g. in the thermally destroyed Chernobyl reactor.

The fission product inventories of all fuel elements were obtained in the ORIGEN2 (Ludwig, 2002), where the inventory of each fuel element was evaluated for a reactor operation from March 9, 1962, until June 30, 2009. After the destruction of a fuel element's cladding, only a fraction of the whole inventory is released. To define the fraction of the released noble gases and halogens, the formula $w_i = e_i \cdot f_i \cdot g_i$ was used, where e_i defines the fraction of fission products, which migrate into the gap between fuel and fuel element cladding and was empirically found by General Atomics with a value of 1.5×10^{-3} percent. f_i defines the fraction of the fission products, which migrate from the gap between fuel and fuel element cladding into the water tank. g_i defines the fraction of fission products, which are released from the water tank to the ventilation system or into the atmosphere. In the following, index N is used for noble gases and the index H is used for halogens.

The received dose outdoors is higher than the received dose in a protected location (building) because of shielding effects. For a list of the used shielding effects, see Table 2. All scenarios were calculated within 5 km from the release point. The lattice is partitioned into 64 sectors and 25 circles.

Both noble gases krypton and xenon fission products are equally considered in this study. Noble gases are chemically inert and neither retained by water in the reactor tank nor by particle filters in the ventillation system. The only halogen considered in the calculation was iodine. The fact that iodine has a biological function (the production of thyroidal hormone) and that it is stored as an essential element in the thyroid gland makes it especially dose relevant. Further, iodine and iodine compounds are more volatile than bromine (compounds) or the lighter halogens. Radiobromine fission products are very short-lived or have a relatively small fission yield (Br-83: $T_{½} = 2.40$ h, cumulative fission yield: 5.36E-01; Br-84: $T_{½} = 31.8$ min, cumulative fission yield: 9.85E-01). Due to all these facts any contribution by bromine was ignored in this study. In PC Cosyma, isotopes of iodine are partitioned into three chemical forms. These are organically bound iodine (e.g. CH_3–I and higher organic compounds), elementary bound iodine (I_2) and any iodine in aerosol form, including anionic iodine such as iodide (I^-) and iodate (IO_3^-). The presence of organic compounds stemming from a purely inorganic fuel (uranium–zirconium hydride) may be surprising at first glance. It can be explained by the graphite reflector inside the fuel element (see Khan et al. (2010) for a graphical sketch of the TRIGA fuel elements), which undoubtly acts as the carbon source for the formation of organic molecules. In any case, it was assumed that 92% of the released iodine was organically bound, 4% was elementary bound iodine and 4% was in aerosol form (the latter are summarized under the term "other chemical form").

Table 2
Used shielding parameters in the program PC Cosyma 2.01.

Cloud radiation	1
Ground radiation	1
Inhalation	1
Re-suspension	1
Deposition on skin and clothes	1

Table 3
Volatile fission product inventory of fuel element No. 10075.

	Activity [Bq]		Activity [Bq]
Kr-83m	5.91×10^{10}	I-133	7.44×10^{11}
Kr-85m	1.39×10^{11}	I-134	8.40×10^{11}
Kr-85	2.22×10^{10}	I-135	6.93×10^{11}
Kr-87	2.81×10^{11}	Xe-131m	3.56×10^{9}
Kr-88	3.97×10^{11}	Xe-133m	2.18×10^{10}
I-129	7.47×10^{4}	Xe-133	7.45×10^{11}
I-130	7.16×10^{8}	Xe-135m	1.26×10^{11}
I-131	3.21×10^{11}	Xe135	7.03×10^{11}
I-132	4.77×10^{11}	Xe-138	6.87×10^{11}

3. Results and discussion

3.1. Scenario 1 – damage of the fuel element with highest activity content

In scenario 1, it was assumed that the building was still intact. The dimensions of the building were assumed as follows: height 20 m, width 20 m and the release height was also assumed to be 20 m, which, by and large, coincides with the dimensions of the Atominstitut's reactor hall. The fission product inventory of the fuel element with the highest activity content was evaluated with ORIGEN (Khan, 2010) and is tabulated in Table 3 (only nuclides, which were considered in PC Cosyma).

For e_N, f_N and g_N, the same assumptions were used as in the safety report (Atominstitut, 2006). e_N is the empirically found parameter provided by General Atomics and describes the amount of noble gases, which reach the gap between fuel and fuel element cladding. It was assumed that 100% of the noble gases were released from the gap between fuel and fuel element cladding into the water tank. Further was assumed that all noble gases from the water tank were released to the ventilation system and finally to the atmosphere.

For e_H, f_H and g_H, again, the same assumptions were used as in the safety report (Atominstitut, 2006). e_H is the empirically found parameter from General Atomics and describes the amount of halogens, which reach the gap between fuel and fuel element cladding. It was assumed that 50% of all halogens were released from the gap between fuel and fuel element cladding into the water tank. It was assumed that 10% of all halogens in the water tank were in form of organic compounds and were released to the ventilation system. Further was assumed that 1% of the remaining halogens in the water tank (which had another chemical form) were released to the ventilation system. Table 4 gives a list of the release fractions for noble gases, organically bound halogens, halogens in other chemical form and the total release fractions are presented.

For the present calculations, a Pasquill stability class E and a wind speed of 1 m/s was used as a worst case atmospheric con-

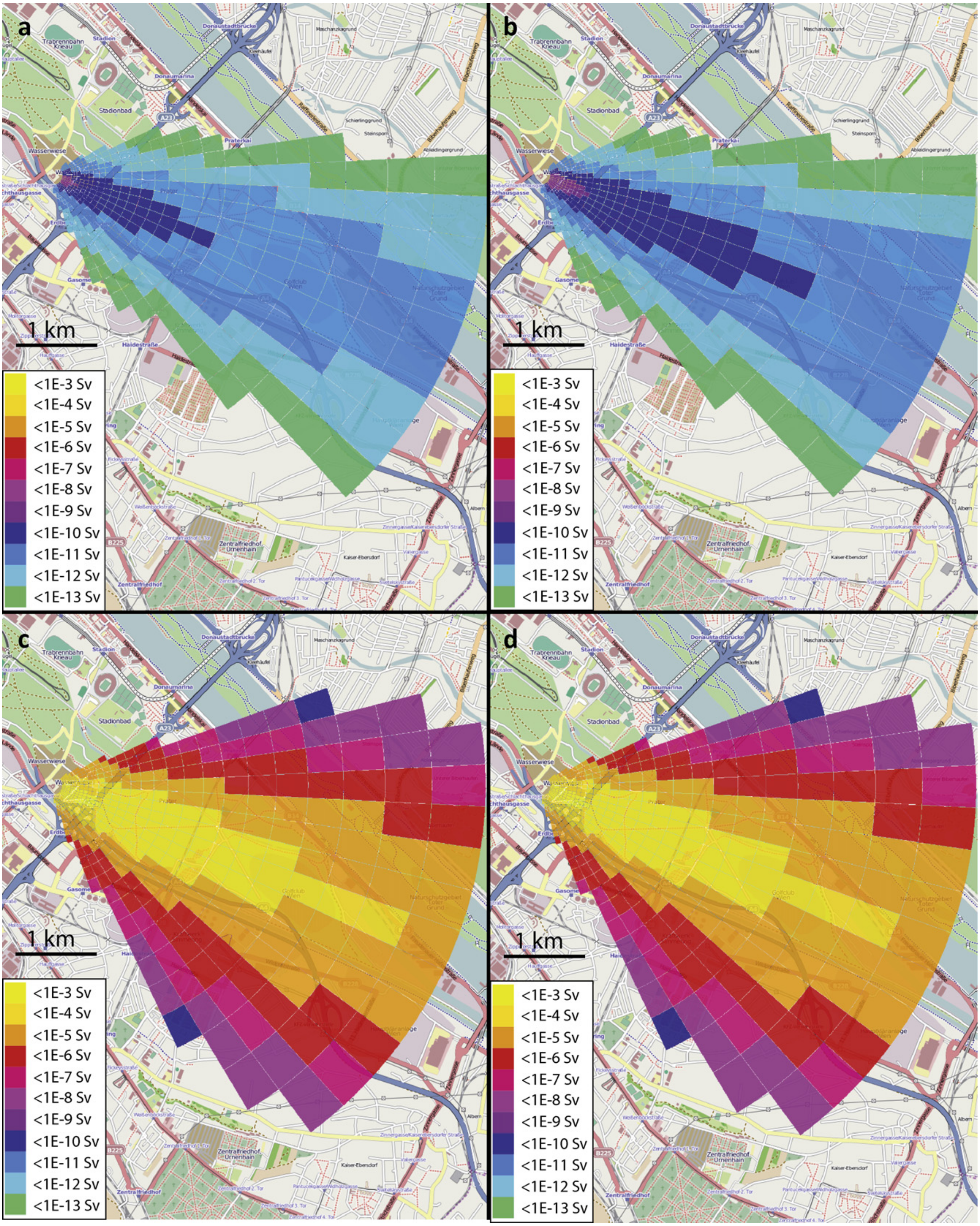

Fig. 1. Graphical illustrations of the doses calculated in the accident scenarios of this paper maximum effective doses obtained after 1 day (a) and after 50 years (b) in scenario 1 (damage of a single fuel element). Maximum effective doses obtained after 1 day (c) and after 50 years (d) in scenario 2 (destruction of the entire reactor core in a large airplane crash).

Table 4
Release fractions of scenario 1 (single fuel element damage with the highest activity content).

	Noble gases	Organically bound halogens	Halogens in other chemical form
e	1.5×10^{-5}	1.5×10^{-5}	1.5×10^{-5}
f	1	0.5	0.5
g	1	0.1	0.009
w	1.5×10^{-5}	7.5×10^{-7}	6.75×10^{-8}

dition. According to the typical weather conditions obtained by measurements of the institute's weather station, a wind direction from WNW and no rain were chosen for the calculations. The dose is evaluated in an area within 5 km distance from the release point (Atominstitut).

Fig. 1 graphically illustrates the results of the effective dose calculations in all scenarios presented herein. The maximum effective dose (ICRP-60) in Sv after one day has a value of 2.51×10^{-10} Sv and lies in wind direction close to the release point. Exterior the radius of 0.31 km the dose is less than 1×10^{-10} Sv and exterior the radius of 1.98 km the dose is less than 1×10^{-11} Sv (see Fig. 1a).

After 50 years, the maximum effective dose (ICRP-60) increases to a value of max. 7.73×10^{-10} Sv in wind direction next to the release point. Exterior the radius of 0.60 km the dose is less than 1×10^{-10} Sv and exterior the radius of 3.36 km the dose is less than 1×10^{-11} Sv (see Fig. 1b).

3.2. *Scenario 2 – case of a large plane crash (worst case scenario)*

In the second scenario, the effects of a large plane crash were investigated. It was assumed that the building was fully destroyed. The height of the building was assumed to be 1 m, the width 20 m and the release height 1 m. The fission product inventory of the whole reactor core (summed over all fuel elements) is presented in Table 5 (which includes only nuclides that were considered in the calculation).

For e_N, f_N and g_N as well as e_H, f_H and g_H, the same assumptions were used as in the safety report (Atominstitut, 2006). Again, e_N describes the amount of noble gases, which reach the gap between fuel and fuel element cladding; in this scenario, it has the value 1. This reflects the assumption that all noble gases reach the gap between fuel and fuel element cladding (complete pulverization of the fuel meat). Further was assumed that 100% of all noble gases were released from the gap between fuel and fuel element cladding into the water tank and all noble gases from the water tank were released into the atmosphere.

Again, e_H is the parameter empirically found by General Atomics and describes the amount of halogens, which reach the gap between fuel and fuel element cladding. In the safety report (Atominstitut, 2006) it was assumed that 100% of all halogens were released from the gap between fuel and fuel element cladding into the water tank. It was assumed that 100% of all halogens in the water tank were released into the atmosphere. Further was

Table 5
Whole reactor inventory of volatile fission products.

	Activity [Bq]		Activity [Bq]
Kr-83m	3.82×10^{12}	I-133	4.83×10^{13}
Kr-85m	9.00×10^{12}	I-134	5.45×10^{13}
Kr-85	1.67×10^{12}	I-135	4.49×10^{13}
Kr-87	1.82×10^{13}	Xe-131m	2.30×10^{11}
Kr-88	2.57×10^{13}	Xe-133m	1.41×10^{12}
I-129	8.78×10^{6}	Xe-133	4.83×10^{13}
I-130	6.57×10^{10}	Xe-135m	8.19×10^{12}
I-131	2.08×10^{13}	Xe135	4.59×10^{13}
I-132	3.10×10^{13}	Xe-138	4.45×10^{13}

Table 6
Release fractions of scenario 2 (large airplane crash, complete destruction of the reactor).

	Noble gases	Organically bound halogens	Halogens in other chemical form
e	1	1.5×10^{-5}	1.5×10^{-5}
f	1	1	1
g	1	0.1	0.9
w	1	1.5×10^{-6}	1.35×10^{-5}

assumed that 10% of all halogens were bound in organic molecules and the rest was in other form (50% of the latter was elementary bound iodine and 50% was iodine in aerosol form). The values from the safety report (Atominstitut, 2006) were hence taken for the present calculations as well. Since in this scenario, the entire fuel meat is destroyed, also iodine is liberated, which had not been in contact with the graphite reflector until the time of the accident. Thus the relative fraction of organically bound iodine decreases in this scenario. Table 6 presents a list of release fractions for organically bound halogens, halogens in other chemical form and noble gases.

For these calculations, again Pasquill stability class E, wind direction from WNW, a wind speed of 1 m/s and no rain were used as worst case atmospheric conditions. The effective dose is evaluated in an area within 5 km distance from the release point (Atominstitut), too.

The maximum effective dose (ICRP-60) after one day has a value of max. 3.72×10^{-4} Sv and lies in wind direction close to the release point. Exterior the radius of 0.60 km the dose is less than 1×10^{-4} Sv and exterior the radius of 4.38 km the dose is less than 1×10^{-5} Sv (Fig. 1c). After 50 years, the maximum effective dose marginally increases to max. 3.74×10^{-4} Sv. This is even less than the previously estimated maximum dose of 2.7×10^{-3} Sv (Atominstitut, 2006; Strubegger, 1978). However, both values are yet in the same order of magnitude. Exterior the radius of 0.60 km, according to present calculations, the dose is less than 1×10^{-4} Sv and exterior the radius of 4.38 km the dose is less than 1×10^{-5} Sv (Fig. 1d).

From these values, one can see that even in the worst case scenario, dose effects in the neighborhood of the Atominstitut will remain moderate. In summary, the accident scenarios were consistent with the previous calculations from 1978 (Strubegger, 1978).

4. Conclusions

The current calculation of the accident scenarios of the TRIGA reactor Vienna are in satisfactory agreement with the calculations from 1978, hence no technical modifications in the safety report of the TRIGA reactor Vienna were necessary. Even in the very worst case scenario – complete destruction of all fuel elements in a large plane crash – the expected effective doses in the Atominstitut's neighborhood remain moderate and require no large-scale evacuation of the population.

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