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Dose to the population from unit releases of tritium and activation products in EU DEMO

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ABSTRACT

Releases of tritium and activation products may occur during normal operation conditions or during incidents and accidents of the EU DEMO. In particular unit source terms allow to compare the consequences for different materials in a well-defined manor. One gram of tritium in form of HT and HTO as well as six different activated materials identified in DEMO were investigated. For accidental releases, deterministic and probabilistic release scenarios were defined and evaluated with two assessment models. Under normal operation conditions, uniform releases of one gram over one year were assumed. Doses to the most exposed individual in particular at 1 km distance from the source were assessed. Further, concentrations in several key food products were calculated. Tritium in form of HTO dominates all results. For activation products, Tungsten dust and Activation Corrosion Products (ACP) show in most cases highest values, however, clearly below tritium. The simulations demonstrated the importance of the ingestion pathways. Even if doses from accidental releases are generally rather low and far below criteria for early countermeasures, HTO concentrations in food products may exceed limits proposed by the World Health Organisation (WHO) up to several tens of kilometres. For normal operation releases, doses are in the order of one micro Sievert and concentrations in food products below limits from 1 km onwards.

1. Introduction

In the past, >20 years ago, the radiological impact of accidental releases of tritium and activation products from future fusion reactors were investigated in detail (e.g. ITER + SEAFP). In particular site-specific dose assessments for European candidate sites were performed (see e.g. Raskob and Hasemann, 1997 [1], Raskob and Hasemann, 1998 [2], Raskob, Hasemann and Di Pace, 2000 [3]). The main aim was to investigate if potential releases of radionuclides would cause early emergency actions such as evacuation of the public in the vicinity of a site. Within these site-specific calculations it could be proved that the no-evacuation criteria as defined within the ITER project was met by all source terms of the categories 'design basis accidents' (CAT-IV) and 'beyond design basis accidents' (CAT-V). Also, when compared to country specific regulations in Europe it was concluded, that the criteria of any of the potential candidate countries would not be exceeded in case of the non-evacuation target. In addition, further potential emergency actions such as sheltering and relocation were evaluated and only very small areas in the vicinity of a site might be affected by releases of CAT-V (Raskob and Hasemann, 1998 [2]).

In 2021 to 2025, new assessments for potential releases for the next step (DEMO) were performed. This paper focuses on unit releases of tritium and activation products either under accidental or normal operation conditions. These calculations had two objectives, namely the investigation of different materials for DEMO as well as a comparison of deterministic release scenarios and probabilistic ones. In particular the second objective is of high interest in case licensing of potential fusion power plants allows either release scenario. In such a case, typically the conservative method has to be applied.

Two types of doses were considered. The early dose is typically used to estimate the need for early countermeasures such as sheltering and evacuation. The long-term dose is used to estimate the possible total burden to the population. However, as ingestion pathways are always regulated (food above the EU limits cannot be marketed), the long-term dose might be of minor importance but was calculated for completeness.

The following definition was used as defined in former studies (e.g.: Raskob and Hasemann, 1997 [1], Raskob and Hasemann, 1998 [2], Raskob, Hasemann and Di Pace, 2000 [3])

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- Early dose: sum of external and committed internal effective doses (cloudshine, up to 7 days integration time for groundshine, 50 years committed dose from inhalation).
- Long-term dose (ED): sum of external and committed internal effective doses (cloudshine, up to 50 years integration time for groundshine, 50 years committed dose from inhalation, 50 years committed dose from ingestion).

Besides doses to the public, activity concentrations in food products are of interest, in particular if maximum permissible levels will be exceeded.

The paper is structured as follows. Chapter 2 describes the simulation models, input parameters and calculation scenarios, chapter 3 and 4 summaries the results for the accidental and normal operation scenarios, respectively and chapter 5 provides a summary discussion. The final chapter 6 provides an outlook on possible future work activities.

2. Material and methods

This section describes the simulation models, weather data, the scenarios and source terms.

2.1. Simulation models

Calculations for tritium and activation products were performed with separate computer programs. However, they use the same basic input parameters, the identical meteorological data base and sampling scheme as well as a similar atmospheric dispersion model. For the probabilistic assessments, the results of the probabilistic calculations (144 weather sequences with their probability of occurrence, representing the weather conditions in one year) were combined for each individual weather sequence for the final estimation of the percentiles of interest.

2.1.1. Tritium model

The computer program UFOTRI (Raskob, 1990 [4] and Raskob, 1993 [5]) for assessing the consequences of accidental tritium releases was used for the dose assessments. Processes such as the conversion in soil of tritium gas (HT) into tritiated water (HTO), reemission after deposition and the conversion of HTO into organically bound tritium (OBT) are considered. For atmospheric dispersion and deposition calculations (dry and wet) the trajectory model MUSEMET implemented in UFOTRI was used. During the time period of the first few days, all the relevant transfer processes between the compartments of the biosphere (atmosphere, soil, plants, animals) are described dynamically. A first order compartment model calculates the longer-term pathways of tritium in the foodchains. In its newest version all the exchange processes (atmosphere - soil atmosphere - plant) are based on resistance approaches and will be re-evaluated dependent on the prevailing environmental conditions. A simple photosynthetic submodule, which calculates the actual transfer rate of HTO in plant water into organically bound tritium, improved the results for the ingestion pathways.

For normal operation conditions, the computer program NORMTRI is used. It calculates the behaviour of tritium in the environment released into the atmosphere typically over a period of one year (Raskob 1994 [6]). NORMTRI is based on the statistical Gaussian dispersion model ISOLA, which calculates the activity concentration in air near the ground and the ground contamination due to dry and wet deposition at specified locations in a polar grid system (Hübschmann and Raskob, 1990 [7]). ISOLA uses the same weather database as UFOTRI. NORMTRI processes the two chemical forms tritium gas and tritiated water vapour. The conversion of tritium gas into tritiated water followed by its reemission back to the atmosphere as well as the conversion into organically bound tritium is considered. Doses are calculated assuming equilibrium conditions between different compartments of the environment.

2.1.2. Activation product model

Calculations for accidentally released activation products were performed with the version NL/95 of the program system COSYMA, subsystem NL (COSYMA, 1991 [8]) including extended data sets for activation products (Pröhl et al., 1994 [9]). For atmospheric dispersion and deposition calculations (dry and wet) the trajectory model MUSEMET implemented in COSYMA and UFOTRI was used. It was assumed, that the nuclides which appear in aerosol form have a mean diameter of 1 μm AMAD, and the corresponding dry deposition velocity is set to be 1.0E-3 m/s (see Table 1). The doses by ingestion of contaminated foodstuffs are calculated assuming the local production and consumption method that means, all foodstuffs are consumed in the grid element where they are harvested / produced. The foodchain information from the German model ECOSYS has been used in the calculations (Pröhl et al., 1994 [9]).

COSYMA is applied also for normal operation conditions as it contains the ISOLA model for that purpose.

2.2. Weather data

There are two options when assessing the dose to the public. Either deterministic weather conditions or a probabilistic assessment, using weather data for a particular time interval can be used. For our probabilistic calculations, the data used in former assessments for the site of Cadarache was adopted (Raskob and Hasemann, 1992 [10]). However, calculations were performed only for the vegetation period. This shortening of the potential range of weather sequences for the sampling scheme was also used for the calculations of the early dose without ingestion pathways as the early dose appears to differ not dramatically from summer to winter (Raskob and Hasemann, 1992 [10]). A short description of the sampling scheme can be also found in Raskob and

Table 1
Main parameters for the simulations (more on model parameters can be found in Raskob, 1990 [4]).

parameter	value
source term	variable
individual dose for the	Most Exposed Individual
release height	10 m with building wake
building dimensions (h x w)	90 m x 120m
release duration	variable
washout coefficient (w)	w = A*I**B (1/s)
with rain intensity I	in mm/hr
coefficient A (noble gas)	0.0 (hr s/mm)
coefficient B (noble gas)	0.0
coefficient A (aerosol)	8.0 E-05 (hr s/mm)
coefficient B (aerosol)	0.8
coefficient A (HTO)	9.0 E-05 (hr s/mm)
coefficient B (HTO)	0.6
deposition velocity (noble gas)	0.0 m/s
deposition velocity (aerosol)	0.001 m/s
deposition velocity (HTO)	variable, depend on env. conditions
dose conversion factors act. prod.	nuclide dependent
dose conversion factor inhalation HT	1.8 E-15 Sv/Bq
dose conversion factor inhalation HTO	1.8 E-11 Sv/Bq
dose conversion factor ingestion HTO	1.8 E-11 Sv/Bq
dose conversion factor ingestion OBT	4.0 E-11 Sv/Bq
breathing rate	2.66 E-4 m**3/s
skin absorption rate (HTO)	1.60 E-4 m**3/s
ingestion rate veget. (root + grain)	180 kg/year
ingestion rate leafy vegetables	45 kg/year
ingestion rate meat	75 kg/year
ingestion rate milk	110 kg/year
shielding factor	1.0 (potential doses)

Hasemann, 1992 [10].

For the deterministic cases, also specific assumptions were made. For the first several hours, the initial weather conditions as defined in the scenario was kept to assure that the initial conditions were valid for all distance bands in the first hour of travel. However, for the next 70 h, the weather conditions were made variable. This is important for tritium releases as environmental conditions, in particular the day and night cycle is crucial for the build up of tritium in the crop. A typical weather scenario was taken from the one-year database.

2.3. Model input

In case of a release from a building, the following dimensions were used with a height of 90 m and an average width of 120 m (averaging the length L = 141 m, width W = 98 m of the DEMO tokamak complex [11]). Hourly meteorological data from Cadarache 1991 was used as the basis of the probabilistic assessments. The parameters were adapted as far as possible to those used in former ITER calculations and are listed in the following table.

Additional information for COSYMA databases can be found in the following references

- External dose conversion factor from cloud (Müller and Jacob, 1991) [12]
- External dose conversion factor from ground (Hill et al. 1988) [13]
- Internal dose conversion factor (Phipps et al., 1991) [14]
- Special Fusion related radionuclides (Haywood et al., 1996) [15]

2.4. Deterministic accidental release scenarios and source term composition

Eight unit source terms [16] three stability classes and 4 release heights were defined

- Eight unit source terms of 1 g each.
  - Tritium in form of HTO 1.07E14 Bq (see Table 2).
  - Tritium in form of HT 3.7E14 Bq (see Table 3).
  - Tungsten dust (see Table 4).
  - ACP (see Table 5).
  - $TiBe_{12}$ (see Table 6).
  - LiPb (liquid metal in the water cooled blanket concept) (see Table 7).
  - Eurofer (structure material in the vacuum vessel) (see Table 8).
  - KALOS (advanced ceramic breeder in the helium cooled blanket concept [17] (see Table 9).
- Three different weather conditions.
  - Stability A, no rain, wind speed of 1 m/s (**for elevated releases and near range**).
  - Stability D, rain of 5 mm/h, wind speed of 5 m/s.
  - Stability F, no rain, wind speed of 0.5 m/s.
- Three release heights.
  - 10 m **with** building wake effects.
  - 150 m **without** building wake effects.
  - 150 m **with** building wake effects.

Table 2
Unit release: unit release: total source term for HTO.

HTO source term: 1 *g* released		
Isotope	Specific Activity (Bq/kg)	Activity released (Bq)
HTO	1.07E+17	1.07E+14

Table 3
Unit release: unit release: total source term for HT.

HT gas source term: 1 *g* released		
Isotope	Specific Activity (Bq/kg)	Activity released (Bq)
HT	3.7E+17	3.7E+14

Important to note is that one gram of HT contains 3.7E+14 Bq of tritium, whereas one gram of HTO contains 1.07E+14 Bq, due to larger weight of the molecule. This tritium was treated as if an independent tritium release would be considered and assessed with UFOTRI, however, added up with the other radionuclides for the dose results. The following tables contain the nuclide composition together with the information which of these nuclides were considered for internal and external doses (COSYMA considered) as well as for the ingestion pathways (COSYMA Ingestion considered). Not all nuclides are in the COSYMA nuclide list. However, a study confirmed, that the most important ones were included (Haywood et al., 1996). Nevertheless, the authors recognise the need for further research in the area of tritium cycling in the foodchain to close existing gaps – also if new materials will be considered. The specific activity was defined in the frame of the 5 years project but not published in the open literature so far. The nuclide vector for each material represents the knowledge so far. Possible changes, e.g., tritium might be also present in Tungsten dust or ACP is not considered but will be as soon as information becomes available.

Not all nuclides from the different activation product source terms are in the COSYMA database. When COSYMA was first adopted to Fusion related assessments, only the most important ones were considered for materials at that time (Haywood et al., 1996 [15]). To get a first impression of the possible error – underestimation of the dose - screening calculations were performed with the new JRODOS nuclide database (Ehrhardt at al., 2000 [18]and Yevdin et al., 2010 [19]). Here the results are show for two materials and the three most important exposure pathways, inhalation, groundshine and ingestion. Exposure from the passing cloud is not displayed as its contribution is on average below 2% of the total dose. The screening was performed for the three exposure pathways individually as JRODOS still needs adaptation for the new database. For a unit release of Tungsten dust with the source term defined in Table 4, Fig. 1 shows, that only Ta-180 has a contribution of about 15% to the pathway inhalation. But none of the other missing nuclides are above 1%. Fig. 2 for LiPb with source term from Table 7 shows a different picture. Here Pb-203 contributes to about 50% to the exposure pathway inhalation and with about 20% to ingestion. In this respect, doses for LiPb might be clearly underestimated. For the other four activation product source terms, the contribution of the missing nuclides is negligibly small and only in the order of some percent or less.

The specific activity of one gram of both HT or HTO was set in former studies (Raskob and Hasemann, 1997 [1], Raskob and Hasemann, 1998 [2]) to 3.7E+14 Bq/g. This value was selected to have a one-to-one relation to the tritium inventory of the fusion reactor and immediately be able to demonstrate to the designers the consequences if a fraction of the initial inventory is released to the environment. This assumption was possible as the environmental transport and dose models do not deal with gram but only with Bq. The chemical composition HT or HTO is only used to account for different exchange rates between compartments. Using nowadays computer programs to analyse severe accidents in fusion power plants, the initial inventory as defined as the amount of tritium in terms if T atoms is converted into the two forms HT and HTO, respectively using their molar weights. Using the Avogadro constant and the half-life of tritium, the specific activity of tritium is 3.57E14 Bq/g. Based on the molar weight and assuming that Tritium is present as T_2 in the breeding blanket, a value of 1.07E+14 Bq/g was set for tritium as

Table 4
Unit release: Total source term for AP-tungsten (as dust) with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

AP –Tungsten: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
W 187	3.53E+14	3.53E+11	162	74
W 185	1.64E+14	1.64E+11	161	73
Re 186	1.18E+14	1.18E+11	166	77
W 185m	7.65E+13	7.65E+10		
W 183m	7.28E+13	7.28E+10	160	
W 181	6.30E+13	6.30E+10	159	72
Re 188	6.02E+13	6.02E+10	168	79
Ta 182	1.12E+13	1.12E+10	157	70
Re 184	3.70E+12	3.70E+09	164	75
Ta 180	2.72E+12	2.72E+09		
Ta 183	1.24E+12	1.24E+09	158	71
W 179	7.12E+11	7.12E+08		
Ta 184	1.88E+11	1.88E+08		
Ta 186	1.31E+11	1.31E+08		
Co 60	4.67E+10	4.67E+07	31	25
Na 24	4.30E+10	4.30E+07	4	4
Mn 56	3.92E+12	3.92E+09	21	18
Fe 55	4.32E+12	4.32E+09	23	19

Table 5
Unit release: total source term for ACP, 1 hour release with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

ACP: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
Fe 59	3.01E+11	3.01E+08	24	20
Mn 54	1.04E+12	1.04E+09	20	17
Co 58	1.50E+12	1.50E+09	29	24
Co 57	2.70E+12	2.70E+09	27	23
Co 60	1.43E+12	1.43E+09	31	25
Cr 51	2.12E+12	2.12E+09	16	14
Mn 56	3.00E+13	3.00E+10	21	18
Cu 64	5.16E+12	5.16E+09	37	28
Fe 55	2.09E+13	2.09E+10	23	19
Ni 57	9.20E+10	9.20E+07		

HTO (6 *g*/mol for T_2 and 20 *g*/mol for HTO). In the final chapter we discuss also the assumption, that tritium is present as T in the fusion reactor – which would change again the specific value. To be comparable to previous studies, the specific value for HT was not changed as the transport calculations so far were always performed with HTO. Even conservative, releases of HT are typically not as dose relevant as those of HTO.

2.5. Probabilistic accidental release scenarios and source term composition

For the probabilistic scenarios, three unit source terms were considered. Also for the deterministic ones, the three release heights were adapted. The release duration was set to one hour. The composition of the materials is identical to the ones for the deterministic cases.

- Three unit source terms of 1 g each.
  - ○ Tritium in form of HTO.
  - ○ ACP.
  - ○ Tungsten dust.
- Three release heights.
  - ○ 10 m with building wake effects.
  - ○ 150 m without building wake effects.
  - ○ 150 m with building wake effects.

The nuclide composition is identical to the ones for the deterministic cases.

2.6. Normal operation scenarios and source term composition

For normal operation releases, seven unit release source terms were considered. It has to be noted, that the amount of tritium releases was identical for HT and HTO – differing from the accidental release scenario. This was assumed to have a direct relation of the release into the environment to the tritium inventory as so far detailed transport calculation for normal operation conditions are not available. For the other materials, the source term as defined for accidental releases was also applied here.

- Seven unit source terms of 1 g each.
  - ○ Tritium in form of HTO 3.57E14 Bq.
  - ○ Tritium in form of HT 3.57E14 Bq.
  - ○ ACP.
  - ○ Tungsten dust.
  - ○ LiPb.
  - ○ $TiBe_{12}$.
  - ○ Eurofer.
- Two release heights.
  - ○ 10 m **with** building wake effects.
  - ○ 150 m **without** building wake effects.

Table 6
Unit release: Total source term for $TiBe_{12}$ (as dust), 1 h release, with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

$TiBe_{12}$: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
H-3	4.50E+12	4.50E+09	UFOTRI	UFOTRI
Sc- 46	4.90E+11	4.90E+08	11	9
Sc- 47	5.97E+11	5.97E+08	12	10
Sc- 48	1.73E+12	1.73E+09	13	11
Ca-45	3.52E+11	3.52E+08		
Mn- 56	5.07E+10	5.07E+07	21	
Co- 60	2.69E+10	2.69E+07	31	25
Kr- 85	4.83E+06	4.83E+03	44	
I −131	6.25E+08	6.25E+05	114	
Xe-133	1.23E+09	1.23E+06	121	
Pu-238	1.05E+07	1.05E+04	182	86
Pu-239	3.75E+06	3.75E+03	183	87
Pu-240	1.80E+06	1.80E+03	184	88
Pu-241	9.10E+08	9.10E+05	185	89
Am-241	5.44E+06	5.44E+03	187	91
Cm-242	2.01E+08	2.01E+05	191	

Table 7
Unit release: Total source term for LiPb (as dust), 1 h release, with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

LiPb: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
H-3	1.06E+13	1.06E+10	UFOTRI	UFOTRI
Pb-203	3.95E+11	3.95E+08		
Pb-208	1.88E+11	1.88E +08		
Pb-204m	4.60E+10	4.60E+07		
Po-210	1.36E+08	1.36E+05	173	84
Bi-210	2.98E+08	2.98E+05		
W −187	1.28E+10	1.28E+07	162	74
Na- 24	1.30E+09	1.30E+06	4	4
Mn- 54	7.31E+08	7.31E+05	20	17
Co- 58	5.04E+08	5.04E+05	29	24
Ti-202	1.11E+09	1.11E+06		
Ag-110m	7.72E+07	7.72E+04	89	51

Table 8
Unit release: Total source term for KALOS (as dust), 1 hour release, with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

KALOS: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
H-3	6.66E+14	6.66E+11	UFOTRI	UFOTRI
Sc- 48	7.56E+11	7.56E+08	13	11
Sc- 47	2.60E+11	2.60E +08	12	10
Sc- 46	2.06E+11	2.06E +08	11	9
Ca-45	1.56E+11	1.56E+08		
Ar-29	1.78E+07	1.78E+04		
Au-198	4.63E+10	4.63E+07		
Ar-37	2.17E+08	2.17E+05		

3. Results for accidental release scenarios

Potential doses to the population (early dose and ED) are provided for the distance of 1 km. This distance was also selected in former assessments (e.g. Raskob and Hasemann, 1997 [1]). For all scenarios the tables in the following chapters contain the results for the release of 1 g for the three atmospheric stability conditions (A = unstable, D = neutral, F stable) and three release heights, two of them including building wake effects with an initial broadening of the plume.

The assessments provided show the dose for the Most Exposed Individual (MEI) for all distance bands. The MEI at one distance is independent from any other MEI at different distance bands in particular for the probabilistic calculations which consider 144 weather scenarios together with their probability of occurrence during the year. This means, that for example the weather sequence resulting in the highest dose for 1 km might be not the same as for 2 km.

Besides dose results, also concentration in food products were calculated. We concentrate here on leafy vegetables as this is often the most contaminated one assuming direct deposition to the leaves. We also assumed, that the release has occurred in summer and all food products were contaminated before harvesting.

It has to be noted, that time dependent concentrations in food products will be only available for tritium releases. For activation products, the maximum concentration in food products – independent of its time of appearance is provided. The reason for this is the fact, that COSYMA does not provide such time dependent concentrations in its

Table 9
Unit release: Total source term for Eurofer (as dust), 1 h release, with the nuclide number of COSYMA for external irradiation, inhalation (COSYMA) and ingestion (COSYMA -Ingestion).

Eurofer: 1 *g* released				
	Specific Activity (Bq/kg)	Activity released (Bq)	COSYMA considered	COSYMA Ingestion considered
Cr- 51	9.50E+11	9.50E+08	16	14
V-52	6.93E+11	6.93E+08		
Mn- 54	7.42E+11	7.42E+08	20	17
Mn- 56	7.34E+12	7.34E+09	21	
Fe- 55	6.95E+12	6.95E+09	23	19
Co- 60	3.34E+10	3.34E+07	31	25
Sb-124	4.53E+10	4.53E+07	92	
As-76	3.72E+11	3.72E+08		
Sb-122	2.05E+11	2.05E+08		
Sb-124	4.53E+10	4.53E +07		
Ta-182	5.32E+11	5.32E+08	157	70
Ta-183	1.30E+11	1.30E+08	158	71
W −185	2.09E+11	2.09E+08	161	73
W −187	2.79E+12	2.79E+09	162	74
Re-186	1.53E+11	1.53E+08	166	77
Re-188	4.63E+11	4.63E+08	168	79

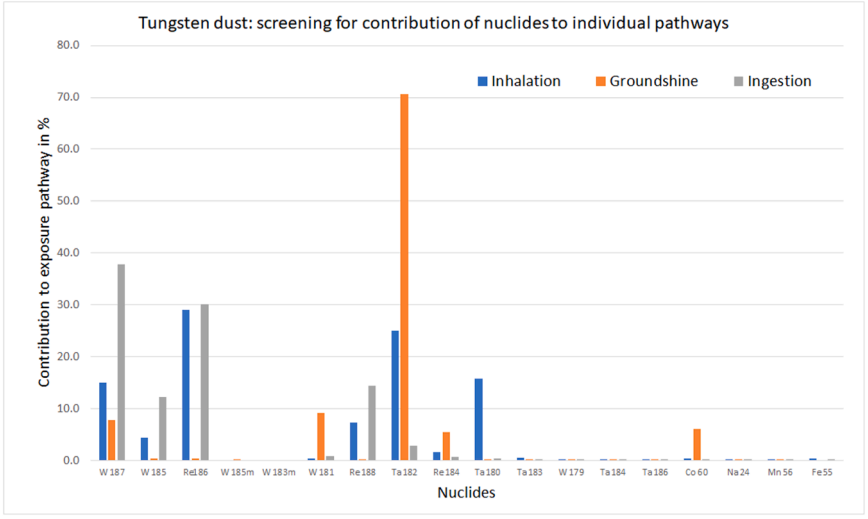

Fig. 1. Contribution of all Tungsten dust nuclides for the three exposure pathways inhalation, groundshine and ingestion.

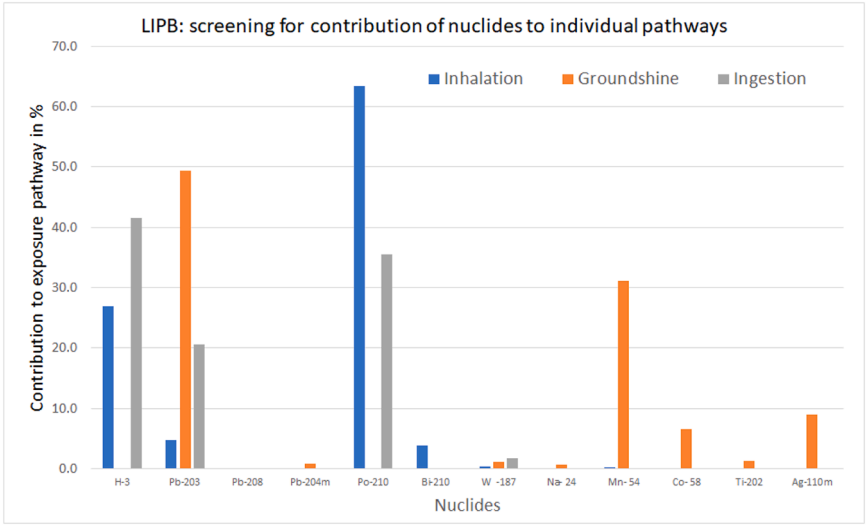

Fig. 2. Contribution of all LiPb nuclides for the three exposure pathways inhalation, groundshine and ingestion.

present version. However, distance dependent maximum concentrations were calculated.

For activation products, concentrations in food products were calculated for three nuclide groups – if available in the nuclide composition. Caesium group, representing all radionuclides with a half live of 10 days and longer, iodine group, representing all iodine isotopes and alphas, representing all alpha emitters. Typically, the caesium group is most important and will be presented in this paper. Maximum concentrations are provided in Euratom, 2016 and can be seen in Fig. 3 [20]. For tritium the concentrations are 10,000 Bq/kg, proposed by the Food and Agriculture Organisation of the United Nations (FAO) (https://www.fao.org/3/j2262e/j2262e24.htm). Maximum permissible levels of other radionuclides are shown in Fig. 3.

Concentrations in food products – here leafy vegetables ("Lveg") are reported for two release heights (10 m = "ground" and 150 m without building wake = "150_nB") and the three stability classes A, D and F, as indicated in the figures further down.

For probabilistic simulations no concentrations in food products are available as these were not foreseen in the original design of the codes.

The following shows results for all releases, however, figures are presented only for typical examples. Results are also shown in some tables later on - Tables 11 and 12.

3.1. HTO 1 g deterministic and probabilistic

The maximum dose is obtained for the probabilistic case followed by the stable atmospheric condition F, in particular for the ED (see Fig. 4). The elevated releases typically result in lower doses at 1 km. Without initial plume broadening, unstable atmospheric conditions may cause higher doses compared to stable one as the plume reaches the ground earlier. The neutral case with precipitation does not play a significant role for an HTO release but will be more important for activation products.

The ground level release shows the highest concentrations being about 40 days above the food intervention level of 1.0E4 Bg/kg fresh weight (see Fig. 5). Elevated Releases show much lower values and are hardly above the limit. Other food products show similar results.

Concentrations of HTO in leafy vegetables are above the limit up to about 30 km for some cases and up to 10 km for all release scenarios (see Fig. 6).

Table 10
Dose in mSv for distance of 1 km from release point for a release of 1 g of HT0 or HT over one year.

Release height	Release duration 1 year			
	HTO		HT	
	Early dose	ED	Early dose	ED
10 m with buildings	4.96E-03	1.49E-02	5.57E-05	6.18E-04
150 m	2.28E-04	1.60E-03	2.70E-06	4.94E-05

3.2. HT 1 g deterministic

For licensing applications, the regulatory body, as was the case for ITER, requests conservative assumptions, in particular that tritium is released as HTO. However, for comparison, also some cases were considered for an HT release. In general, one has to state, that doses from HT releases are caused from HTO that is converted in the soil from deposited HT. This HTO is either reemitted to the atmosphere (early dose) and/or taken up by the crops via roots or leaves (ingestion). For our scenarios, the reemission is very conservative, as the wind direction and speed remain exactly constant for many hours – rather unlikely in real weather conditions. Further, the amount released for one gram is >3 times higher compared to the one for HTO.

As for HTO, doses from the stable atmospheric case are highest for both, the early dose and ED. Elevated releases show lowest doses. Doses in general are at least one order of magnitude lower and the result of reemission of HTO – for numbers see Table 11. Ground level releases dominate the concentrations at 1 km with stability F as highest case. For about 50 days, concentrations are higher than the limits- For all other cases, concentrations are higher for only some days or generally below (all elevated releases). As for doses, concentration in food products are typically at least one order of magnitude lower – see Table 12 for I km results. Distance dependent concentration fall below the limit at several kilometres for all scenarios. Only the ground level release under stable atmospheric conditions show values above the limit up to 8 km.

3.3. ACP 1 g deterministic and probabilistic

The ground level release with stable stratification and rain result in highest values for the early dose and ED (see Fig. 7). The results from the probabilistic scenarios are close to the deterministic ones. In general, elevated releases show lower doses at 1 km distance.

The concentrations of long-lived radionuclides in leafy vegetables

Isotope group/Food group	Food (Bq/kg) (1)			
	Infant food (2)	Dairy produce (3)	Other food except minor food (4)	Liquid food (5)
Sum of isotopes of strontium, notably Sr-90	75	125	750	125
Sum of isotopes of iodine, notably I-131	150	500	2 000	500
Sum of alpha-emitting isotopes of plutonium and transplutonium elements, notably Pu-239 and Am-241	1	20	80	20
Sum of all other nuclides of half-life greater than 10 days, notably Cs-134 and Cs-137 (6)	400	1 000	1 250	1 000

(1) The level applicable to concentrated or dried products is calculated on the basis of the reconstituted product as ready for consumption. Member States may make recommendations concerning the diluting conditions in order to ensure that the maximum permitted levels laid down in this Regulation are observed.
(2) Infant food is defined as food intended for the feeding of infants during the first 12 months of life which meets, in itself, the nutritional requirements of this category of persons and is put up for retail sale in packages which are clearly identified and labelled as such.
(3) Dairy produce is defined as products falling within the following CN codes including, where appropriate, any adjustments which might subsequently be made to them: 0401 and 0402 (except 0402 29 11).
(4) Minor food and the corresponding levels to be applied to them are set out in Annex II.
(5) Liquid food is defined as products falling within heading 2009 and Chapter 22 of the Combined Nomenclature. Values are calculated taking into account consumption of tap-water and the same values could be applied to drinking water supplies at the discretion of competent authorities in Member States.
(6) Carbon-14, tritium and potassium-40 are not included in this group.

Fig. 3. Maximum permitted levels of radioactive contamination of food products.

Table 11
Summary of doses at 1 km in mSv for selected 1 hr release scenarios (*1 g HT contains roughly 4 times more tritium compared to HTO) – only deterministic results.

Source term of 1 *g*	ACP	BeTi	Tungsten dust	Eurofer	KALOS	LiPb	HT (g)*	HTO (g)*
Early dose: ground level release								
Stability A, 10 m with building	1.70E-04	2.83E-05	9.80E-04	3.50E-05	1.04E-05	4.20E-05	1.60E-04	**5.90E-03**
Stability D, rain, 10 m with building	7.90E-04	2.80E-04	5.80E-03	2.00E-04	1.21E-04	4.59E-05	8.30E-05	**6.60E-03**
Stability F, 10 m with building	3.40E-03	5.85E-04	2.10E-02	7.20E-04	2.13E-04	8.29E-04	1.30E-03	**1.20E-01**
Early dose: elevated release with buildings								
Stability A, 150 m with building	1.30E-04	2.22E-05	7.90E-04	2.90E-05	8.33E-06	3.43E-05	1.20E-04	**4.90E-03**
Stability D, rain, 150 m with building	3.90E-04	1.40E-04	**2.90E-03**	1.00E-04	6.02E-05	1.60E-05	2.70E-05	2.30E-03
Stability F, 150 m with building	6.70E-04	1.11E-04	4.00E-03	1.40E-04	4.18E-05	1.78E-04	2.30E-04	**2.50E-02**
ED with ingestion: ground level release								
Stability A, 10 m with building	4.10E-03	1.32E-04	5.00E-03	5.50E-04	3.62E-05	2.64E-04	7.20E-03	**4.10E-02**
Stability D, rain, 10 m with building	**1.10E-01**	3.10E-03	**1.10E-01**	1.40E-02	7.29E-04	6.04E-04	6.50E-03	8.70E-02
Stability F, 10 m with building	8.90E-02	2.92E-03	1.10E-01	1.20E-02	7.30E-04	2.55E-03	1.30E-01	**3.90E-01**
ED with ingestion: elevated release with buildings								
Stability A, 150 m with building	3.30E-03	8.21E-05	4.00E-03	4.40E-04	2.94E-05	2.14E-04	5.80E-03	**3.30E-02**
Stability D, rain, 150 m with building	5.40E-02	1.60E-03	**5.90E-02**	7.20E-03	3.73E-04	2.16E-04	2.20E-03	3.00E-02
Stability F, 150 m with building	1.70E-02	5.64E-04	2.10E-02	2.30E-03	1.38E-04	5.35E-04	2.70E-02	**8.00E-02**

Table 12
Summary of concentrations for leafy vegetables and milk at 1 km in Bq/kg for selected 1 hr release scenarios (*1 g HT contains roughly 4 times more tritium compared to HTO)– only deterministic results.

Source term of 1 *g*	ACP	BeTi	Tungsten dust	Eurofer	KALOS	LiPb	HT (g)*	HTO (g)*
Leafy vegetables: ground level release								
Stability A, 10 m with building	1.031E+02	1.780E+00	5.638E+02	3.211E+01	7.084E-01	4.513E-03	2.06E+04	**1.99E+05**
Stability D, rain, 10 m with building	2.750E+03	4.747E+01	1.503E+04	8.563E+02	1.889E+01	4.239E-03	7.47E+03	**8.81E+05**
Stability F, 10 m with building	2.257E+03	3.895E+01	1.234E+04	7.027E+02	1.550E+01	9.874E-02	2.47E+05	**2.33E+06**
Leafy vegetables: elevated release with buildings								
Stability A, 150 m with building	3.009E-01	1.430E+00	4.530E+02	2.580E+01	5.692E-01	3.626E-03	1.57E+04	**1.57E+05**
Stability D, rain, 150 m with building	1.425E+03	2.460E+01	7.792E+03	4.438E+02	9.790E+00	6.236E-02	2.33E+03	**3.00E+05**
Stability F, 150 m with building	4.362E+02	7.527E+00	2.384E+03	1.358E+02	2.996E+00	1.908E-02	4.77E+04	**4.81E+05**
Milk: ground level release								
Stability A, 10 m with building	3.745E-01	1.441E-03	1.743E+01	9.949E-02	2.816E-04	3.548E-05	7.38E+03	**3.98E+04**
Stability D, rain, 10 m with building	9.987E+00	3.843E-02	4.648E+02	2.653E+00	7.509E-03	9.460E-04	2.17E+03	**6.68E+04**
Stability F, 10 m with building	8.196E+00	3.154E-02	3.814E+02	2.177E+00	6.162E-03	7.762E-04	7.68E+04	**4.63E+05**
Milk: elevated release with buildings								
Stability A, 150 m with building	8.287E+01	1.158E-03	1.400E+01	7.993E-02	2.262E-04	2.850E-05	5.77E+03	**3.12E+04**
Stability D, rain, 150 m with building	5.176E+00	1.992E-02	2.409E+02	1.375E+00	3.892E-03	4.902E-04	7.03E+02	**2.13E+04**
Stability F, 150 m with building	1.584E+00	6.094E-03	7.371E+01	4.207E-01	1.191E-03	1.500E-04	1.52E+04	**9.56E+04**

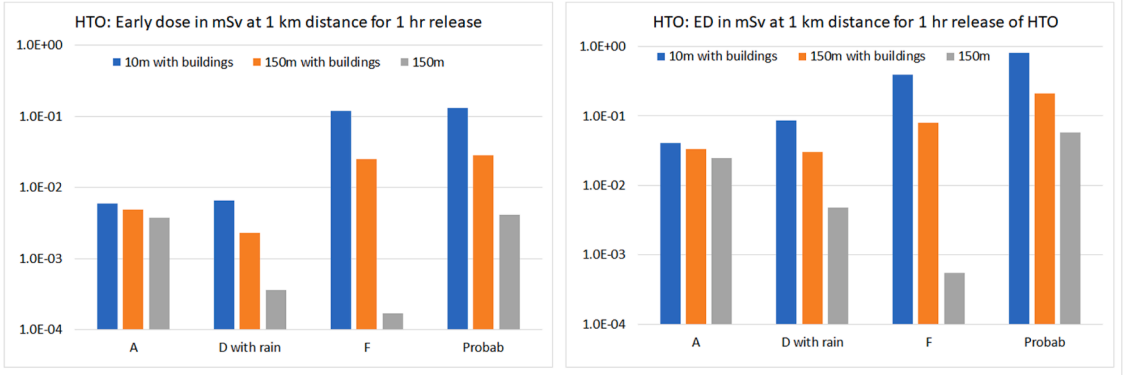

Fig. 4. Early dose and ED in mSv at 1 km distance from 1 hr release of HTO – deterministic and probabilistic.

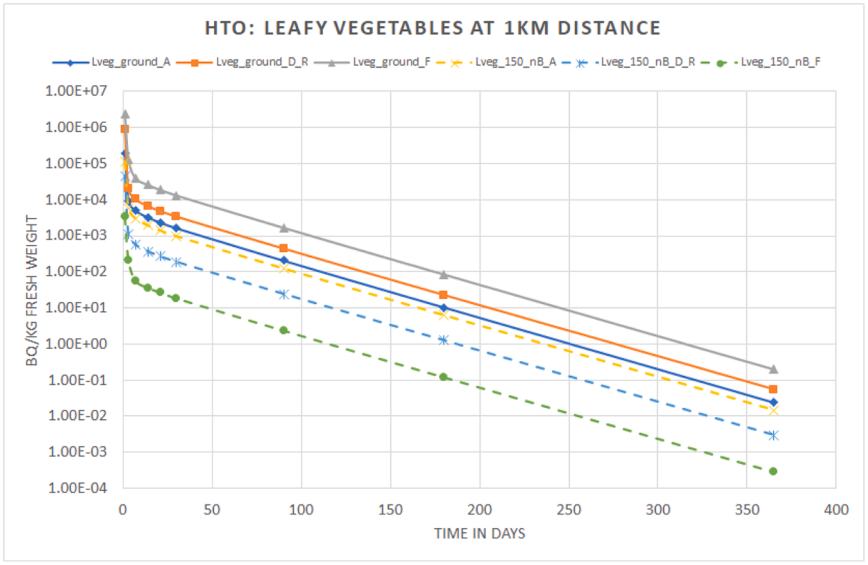

Fig. 5. Time dependent concentration of HTO in leafy vegetables at 1 km distance for ground level (line) and elevated releases (dotted line) and the three stability classes from 1 hr release of HTO - deterministic.

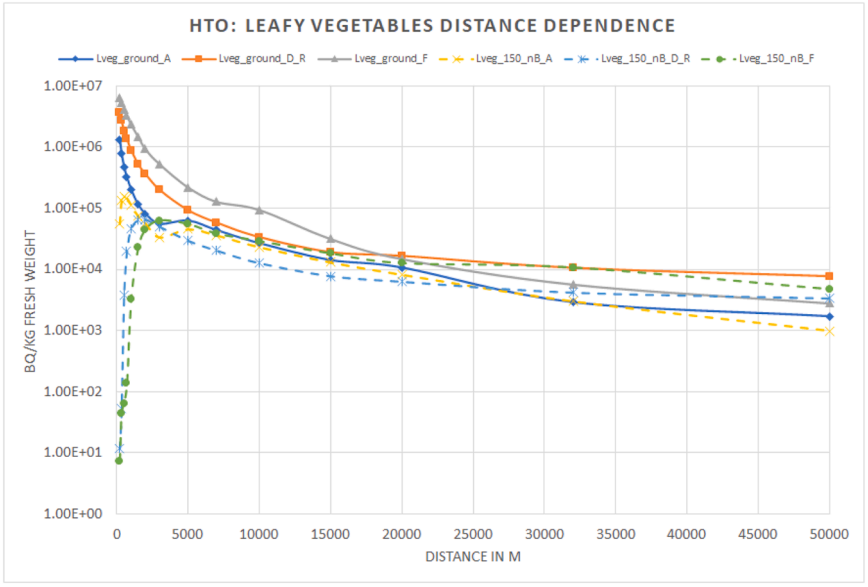

Fig. 6. Distance dependent concentration of HTO in leafy vegetables for ground level (line) and elevated releases (dotted line) and the three stability classes from 1 hr release of HTO - deterministic.

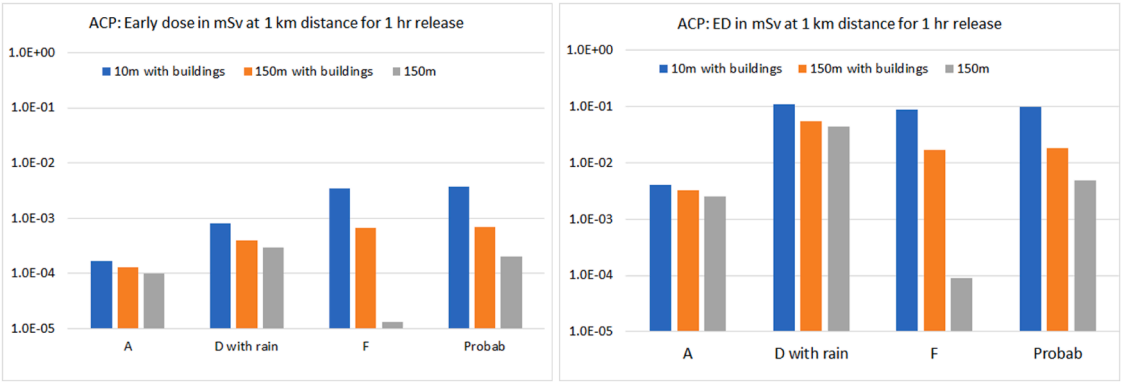

Fig. 7. Early dose and ED in mSv at 1 km distance from 1 hr release of ACP – deterministic and probabilistic.

from an ACP release are below the limits from about 5 km onwards (see Fig. 8). The scenarios with neutral stratification and rain show highest values up to 20 km; further down, the stable case is the highest. Concentrations in other food products are always lower than that in leafy vegetables.

3.4. Tungsten dust 1 g deterministic and probabilistic

Doses are very similar to ACP. The ground level releases dominate the doses for a unit release of Tungsten dust. In particular stability class F and the probabilistic one are highest for the early dose whereas also the neutral case with rain is similar to the two mentioned before. Lowest values are found for the unstable case.

Concentrations are highest for the ground level release heights and in general some factors higher than ACP (for 1 km see Table 12). Stable and rain cases show similar concentrations with the rain case dominating up to 20 km. Elevated releases show lower values, however, the rain case is close to the 10 m release cases. This due to the fact, that precipitations moves the radionuclides from the plume to soil and from there will be taken up by the rood system and appear in the food product. Concentrations drop below the limits from 10 km onwards. Concentrations in other food products are always lower than that in leafy vegetables.

3.5. $TiBe_{12}$ dust 1 g deterministic

The early dose from a unit release of $TiBe_{12}$ is dominated by the stable ground level release. For the ED, the stable and neutral case with rain are similar for a ground level release. Also the elevated releases for the case with rain show high values for the ED. This is caused by precipitation that moves the radionuclides to the ground much more effectively than dry deposition. Furthermore, dose from ground is high due to radionuclides with a high dose conversion factor for ground shine. Even if dependency is similar to ACP, doses are at least one order of magnitude lower at 1 km distance.

For the release of $TiBe_{12}$, concentrations of radionuclides from all groups are well below the limits for all distances and scenarios. This is the same for all the other food products.

3.6. Eurofer 1 g deterministic

As for $TiBe_{12}$, the stable ground level scenario is the highest for the early dose in case of a unit release of Eurofer. The ED is similar for the ground level release with rain and the stable one. Also the case with rain show high ED values at higher release scenarios. Doses are slightly higher than for $TiBe_{12}$ but much lower than ACP or Tungsten dust.

Concentrations for long lived radionuclides from the release of Eurofer are highest for ground level releases, but they drop below the limits from 1 km onwards. For other food products, limits are not reached at any distance from the release point.

3.7. KALOS 1 g deterministic

The doses for a unit release of KALOS behave similar to the other dusts. For the early dose, the stable case shows the highest value, whereas for the ED, the case with rain is the highest, however nearly identical to the stable one. The rain case shows also high doses for elevated releases. Doses are the lowest one for all activated materials (see Table 11).

As before, concentrations for long lived radionuclides from the release of KALOS are highest for ground level releases, but they are below the limits for all distances. This is the same for all the other food products.

3.8. LiPb 1 g deterministic

The doses from the unit release of LiPb show a different behaviour than reported before. Here, the stable case is the highest for the early dose and the ED. The rain case is not so dominant which is the result of radionuclides with a rather low dose conversion factor for ground shine. However, doses are in general low and do not reach 1.0E-3 mSv for the early dose and 2.5E-3 mSv for the ED.

Concentrations for long lived radionuclides from the release of LiPb are highest for ground level releases, but they below the limits for all distances. This is the same for all the other food products.

4. Results for normal operation release scenarios

For normal operation, doses for the MEI at 1 km distance as well as concentrations in food products are presented here. It has to be noted, that NORMTRI, applied for tritium, and COSYMA do not consider building wake effects under normal operation conditions, if the release point is above the building height. Therefore, results for 150 m with and

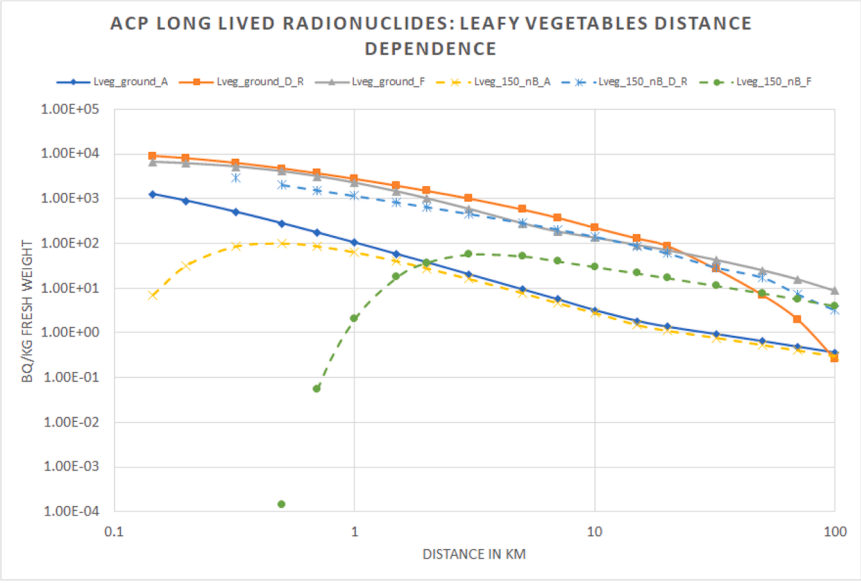

Fig. 8. Distance dependent concentration of the caesium group in leafy vegetables for ground level (line) and elevated releases (dotted line) and the three stability classes from 1 hr release of ACP - deterministic.

without buildings are identical and thus only two results are reported: 10 m with building wake and 150 m without building wake.

4.1. Dose results

Doses are reported for tritium and activation products. However, for activation products, not all individual dust components will be presented. For a detailed table of dose results for activation products, please take a look into the results sections.

4.1.1. Tritium

The doses from 10 m release with building effects are highest for a HTO release of 1 g in a year (see Table 10). Differences between the early dose and the ED with ingestion is roughly a factor of 4 to 7, dependent on the scenario. Doses range clearly below 1 mSv/year. For HT, values are more than one order magnitude lower for the early dose and ED.

4.1.2. Activation products

For activation products, one can distinguish two groups. ACP and Tungsten show highest values with about 1.0E-3 mSv for the ED and about one order of magnitude lower value for the early dose. Elevated releases reduce the numbers for one additional order of magnitude – see Table 13.

Doses for $TiBe_{12}$, Eurofer and LiPb are at least one order of magnitude lower. Thus, only releases of a large amount of material from these activation products would reach the 1 mSv value per year.

4.2. Concentrations in food products

As for the doses, time and distance dependent results are only shown exemplarily, in particular for HTO. Individual results at 1 km distance are presented in Table 14.

4.2.1. Tritium

The following shows the concentrations of HTO in leafy vegetables and meat. The two are examples for the maximum (leafy vegetables) and average (meat) concentrations of tritium in key food products over the year. Results are displayed in Bq/kg fresh weight.

Fig. 9 shows that the 1.0E4 Bq/kg recommended by the WHO for stopping consumption is only exceeded for meat very close to the site. From 300 m onwards, concentrations are below that value.

For leafy vegetables, that value is reached at around 500 m (see Fig. 9). In general, concentrations beyond 1 km are always below that food restriction limit. However, there might exist national recommendations that are below the one from WHO.

It should be also noted, that NORMTRI assumes equilibrium conditions between all compartments. However, due to the changing wind directions equilibrium is not reached and thus all other food products are below leafy vegetables which is close to the HTO in air humidity.

Concentrations in food products from a release of tritium gas HT follow the same distance dependence, however are lower by more than one order of magnitude compared to the HTO release.

4.2.2. Activation products

For all activated materials, the dependency is similar as for tritium. Leafy vegetables are highest and the other food products are lower by about one order of magnitude. Exemplarily pork, representing meat, and leafy vegetables are presented. Concentrations of long lived radionuclides are always highest in the food product.

ACP shows a value of <100 Bq/kg fresh weight at 1 km distance as maximum for leafy vegetables, pork and thus other food products are much lower.

Concentrations of long lived radionuclides from the unit release of Tungsten dust shows highest values for leafy vegetables. The values in general are slightly higher compared to ACP but follow the same trend.

Concentrations in food products from a release of $TiBe_{12}$ are much lower compared to ACP and Tungsten dust for at least 2 orders of magnitude. Further, concentrations in meat is low as is the case also for the other food products.

Concentrations in food products from a release of Eurofer are between $TiBe_{12}$and ACP.

Concentrations in food products from the unit release of LiPb are lowest and do not reach even 0.1 Bq/ kg at any distance.

5. Discussion and summary

Table 11 provides a summary of the early dose and ED with ingestion for the distance of 1 km for the selected one hour release scenarios. The table summarises the 10 m and 150 m releases with building influence. HTO shows typically the highest early doses from all release scenarios. Second for the early dose is Tungsten dust. Only for the case with rain, Tungsten dust is the highest for the elevated release.

This dependency is similar for the ED with ingestion. HTO is the highest for all cases without rain. In case of rain, Tungsten dust and ACP are also the highest.

The difference between the early dose and the ED with ingestion depends on the scenario. For cases without rain, differences between the two dose categories are in the order of one magnitude and often lower. In case of rain, the difference is much larger as the precipitation deposits large amounts of activation products to the soil and they can enter the foodchain via root uptake. The differences between the early dose and the ED in case of HT is typically always larger than one order of magnitude. This is the result from the conversion of HT into HTO which at the end dominates the dose.

The probabilistic calculations demonstrated, that the results (95% percentile) are comparable to the highest deterministic scenarios. In this respect, specific deterministic and probabilistic scenarios provide similar conservative dose results. This is in particular important as it might reduce the effort in computation if both methods are applicable.

For concentrations at 1 km distance, the picture is much simpler (Table 12). Concentrations of tritium are always highest, independent of the release scenario and food product. Tritium concentrations from HTO are always higher compared to those from activated product releases. For the different activated materials, concentrations from Tungsten dust are highest, followed by ACP`s. As for all food products, highest concentrations can be found in leafy vegetables due to direct deposition (large leaf area index) and root uptake (fast growing plant).

The distance dependence is important for the unit release of tritium in the form of HTO. Here the maximum permissible level of 1.0E4 Bq/kg fresh weight is exceeded for several 10 km, dependent on the release

Table 13
Summary of doses at 1 km in mSv for normal operation releases (different to accidental releases, the specific activity of HT and HTO was set to 3.57E14 Bq/g).

Source term of 1 g in one year	ACP	$TiBe_{12}$	Tungsten dust	Eurofer	LiPb	HT	HTO
Early dose							
Release height 10 m with building	5.70E-05	1.21E-05	3.30E-04	1.20E-05	4.37E-07	5.57E-05	**4.96E-03**
Release height150 m	4.40E-06	1.00E-06	2.60E-05	9.70E-07	3.13E-08	2.70E-06	**2.28E-04**
ED with ingestion							
Release height10 m with building	1.30E-03	5.42E-05	1.70E-03	1.60E-04	1.84E-06	6.18E-04	**1.49E-02**
Release height150 m	1.90E-04	6.62E-06	2.20E-04	2.40E-05	2.02E-07	4.94E-05	**1.60E-03**

Table 14
Summary of concentrations for leafy vegetables, pork meat, grain products and milk at 1 km in Bq/kg for normal operation releases (different to accidental releases, the specific activity of HT and HTO was set to 3.57E14 Bq/g).

Source term of 1 g in one year	ACP	$TiBe_{12}$	Tungsten dust	Eurofer	LiPb	HT (g)*	HTO (g)
Leafy vegetables							
Release height 10 m with building	3.920E+01	6.760E-01	2.430E+02	1.220E+01	1.710E-03	1.16E+02	**3.51E+03**
Release height150 m with building	5.310E+00	9.160E-02	3.130E+01	1.650E+00	3.970E-05	9.25E+00	**3.67E+02**
Pork meat							
Release height10 m with building	1.170E-01	1.710E-05	7.310E+00	4.510E-02	2.060E-06	2.17E+01	**6.97E+02**
Release height150 m with building	2.150E-02	3.130E-06	1.340E+00	8.260E-03	1.300E-08	1.50E+00	**7.11E+01**
Grain products							
Release height10 m with building	5.160E+00	1.100E-02	1.760E+01	1.520E+00	1.700E-04	1.89E+01	**5.71E+02**
Release height150 m with building	9.460E-01	2.010E-03	3.230E+00	2.780E-01	5.470E-07	1.70E+00	**5.97E+01**
Milk							
Release height10 m with building	7.680E-02	2.960E-04	3.580E+00	2.040E-02	7.280E-06	3.00E+01	**9.45E+02**
Release height150 m with building	1.410E-02	5.420E-05	6.560E-01	3.740E-03	2.070E-07	2.37E+00	**9.71E+01**

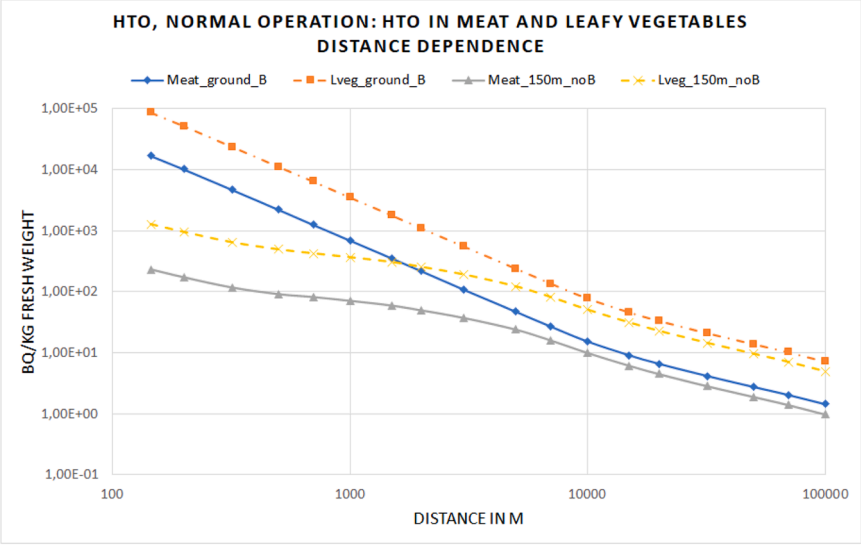

Fig. 9. Distance dependent concentration of HTO in meat (full line) and leafy vegetables (dotted line) in Bq/kg as average over one year for a release of 1 g HTO in one year.

scenario. The time dependency shows that in the worst case, the maximum permissible level is exceeded for roughly 2 months at 1 km distance. This is not the case for any of the dust materials. Here maximum permissible levels are hardly reached or exceeded at 1 km distance.

Table 13 provides a summary of the early dose and ED with ingestion for the distance of 1 km for normal operation release scenarios. The table summarises the 10 m releases with building influence and the one of 150 m without building influence. HTO shows typically the highest early doses from all release scenarios. Second for the early dose is Tungsten Dust. In general, doses are below 1 mSv, except for HTO. This dependency is similar for the ED with ingestion. HTO is the highest for all cases, followed by Tungsten dust, and then ACP. The difference between the early dose and the ED with ingestion depends on the nuclide composition. It can range between a factor of five (e.g. ACP and HTO) and twenty for Tungsten dust.

For concentrations released under normal operations, the picture is similar (Table 14). Concentrations of tritium are always the highest, independent of the release scenario and food product. Tritium concentrations from HTO are always higher compared to those from activated product releases. For the different activated materials, concentrations from Tungsten dust are highest, followed by ACP. As for all food products, highest concentrations can be found in leafy vegetables due to direct deposition (large leaf area index) and root uptake (fast growing plant).

This paper presents results from deterministic and probabilistic simulations of releases from tritium and activation products. Results can be used for DEMO design planning of the next step. This information can help to limit the maximum amount of tritium and activation products to be released in accidental or normal operation conditions. As the design is still under debate, the amount of activity that can be mobilised from the given inventory can still be adjusted aiming for the operation of potential fusion power plants. In this respect, doses for early countermeasures, or areas where the maximum permissible levels for food products are exceeded should be minimised to gain acceptance of this technology by the public.

In the following, we will discuss possible release limits for early countermeasures such as sheltering (10 mSv) and evacuation (50 mSv). Table 15 provides a summary for HTO the dominating radionuclide. We provide three values, the first one for a specific activity of 1.07E14 – as used primarily in this study – and a second one of 5.37E13 assuming T_2 or DT as initial condition, respectively. The third value represents the amount of tritium as part of the inventory. This third value allows a direct comparison of the fraction of the inventory to be released to initiate early countermeasures. We also partly indicate the amount of Bq released in the text as this amount is independent for any tritium composition.

Considering worst-case release conditions(F and 10 m release height), the dose is 0.12 mSv (0.06) per gram at 1 km distance for HTO. This would allow a release of 83 g (166 g) of HTO or about 8000 TBq or

Table 15
Summary of the amount of tritium needed to trigger sheltering (10 mSv) or evacuation (50 mSv) for two specific activities of HTO and the fraction of the tritium inventroy – early countermeasures do not consider ingestion.

Weather	Release height	mSv/g	HTO in g needed for		Tritium inventory in g released, needed for	
			Sheltering (10 mSv)	Evacuation (50 mSv)	Sheltering (10 mSv)	Evacuation (50 mSv)
A	10	5.90E-03*	1.7E+03	8.5E+03	5.1E+02	2.5E+03
		2.95E-03**	3.4E+03	1.7E+04		
D	10	6.60E-03*	1.5E+03	7.6E+03	4.5E+02	2.3E+03
		3.30E-03**	3.0E+03	1.5E+04		
F	10	1.20E-01*	8.3E+01	4.2E+02	2.5E+01	1.2E+02
		6.00E-02**	1.7E+02	8.3E+02		
A	150	4.90E-03*	2.0E+03	1.0E+04	6.1E+02	3.1E+03
		2.45E-03**	4.1E+03	2.0E+04		
D	150	2.30E-03*	4.3E+03	2.2E+04	1.3E+03	6.5E+03
		1.15E-03**	8.7E+03	4.3E+04		
F	150	2.50E-02*	4.0E+02	2.0E+03	1.2E+02	6.0E+02
		1.25E-02**	8.0E+02	4.0E+03		

* Specific activity of 1 g of HTO 1.07E+14 (based on initial tritium in form of T_2).
** Specific activity of 1 g of HTO 5.37E+13 (based on initial tritium in form of DT).

25 g of the tritium inventory– if no other material is released. In case of Tungsten dust, the unit dose is 0.021 mSv per gram at 1 km distance. This amounts to a possible release of about 470 *g* before 10 mSv at 1 km are exceeded. In case of releases of several of these materials together, the numbers have to be adjusted accordingly. If a release via a stack (Table 11 and Table 15) can be assumed for accidental conditions, the maximum amount of tritium and activation products might be increased by about a factor of five before the 10 mSv is reached.

However, concentrations in leafy vegetables for example (see Table 12) are exceeded at 1 km distance for a much smaller release of about 0.043 *g* (4.6 TBq) of HTO under worst case accidental conditions. For Tungsten dust and leafy vegetables, the possible amount is reduced to about 0.08 *g* for accidental conditions. Assuming a release from a stack of 150 m, the maximum amount that could be released is higher by roughly a factor of five for HTO and a factor of two for Tungsten dust.

Under normal operation conditions (see Table 13), up to 7 *g* of HTO (7 g of the tritium inventory as the specific activity of HTO was set equal to specific activity of tritium as T) could be released before a dose of 0,1 mSv in a year (reference for ITER, see Baojie et al. 219 [21]) would be exceeded at 1 km distance. For activated materials, the amount is roughly a factor of 10 higher. However, these results need further discussion. First, the specific activity for HT and HTO need revision – the Bq released is the important information – and second, possible releases due to maintenance activities might be performed in a much smaller time period and thus reducing the possible amount that is still acceptable. For food products (see Table 14), a release of 3 *g* of HTO per year (1071 TBq per year or 3 g of the tritium inventory) under normal operation conditions would exceed 10,000 Bq/kg in leafy vegetables at 1 km distance and thus would be not acceptable. In this respect, concentration limits in food products are also more sensitive under normal operation conditions – as was also the case for accidents. The release target of JET with 40 GBq per day (14.6 TBq per year) under normal operation conditions is much below the possible 3 *g* target for food products.

This work is in line with assessments performed by Karajgikar et al. (2023) [22] that discussed the influence of release and environmental conditions. She concluded that a higher stack and unstable conditions minimised the dose to the public. This was also found here, however, in case of licensing, mostly worst-case conditions have to be applied. For Demo, a stack height of 150 m or higher is strongly recommended to increase possible release targets as indicated above.

Nevertheless, the unit release scenarios described here are the first step in assessing the burden to the population from a potential fusion power plant. They can be used to scale simple release scenarios to obtain an overview on the potential consequences. The missing nuclides do not affect results significantly, in particular for the most dominating activation product materials such as ACP and Tungsten dust. However, for detailed assessments, potential releases of DEMO need to be identified following the design development and the related events. Scenario specific releases, based on the simulation of the behaviour of radionuclides in the fusion power plant following an incident or accident are thus the important next step.

A final point to be mentioned is the fact that the activity of HTO released in gram cannot be directly linked to an inventory as the specific activity of HTO differs from the specific activity of the tritium inventory. To solve possible confusion with the specific activity of HT or HTO, releases should be provided no longer in gram but purely in Bq as in the case in Fission. The environmental transport and dose models do not consider gram but only Bq and the chemical form. In this respect the fraction of the inventory released can be used as information to plant designers without any further explanation and conversion.

6. Outlook

COSYMA, UFOTRI and NORMTRI are the standard simulation models for dose assessments in the frame of ITER and DEMO and were rated high in international studies (see e.g. BIOMOVS IIa [23], 1996, BIOMOVS IIb [24], 1996, IAEA-BIOMASS-3 [25], 2003, Raskob, 2007 [26]). However, even if the mathematical models for dose assessment and concentrations in food products might be appropriate, the atmospheric dispersion models in the three codes are no longer state of the art. These models use Gaussian atmospheric transport and dispersion models that are nowadays replaced by e.g. particle models. Such models are part of modern decision support systems used for emergency management applications in case of releases from nuclear power plants.

The authors acknowledge that the current approaches require an update with respect to atmospheric transport and dispersion modelling. Therefore, an activity has started to integrate the tritium specific functionalities into the decision support system JRODOS (Ehrhardt at al., 2000 [18]and Yevdin et al., 2010 [19]). This will also assure, that missing nuclides are available for the assessments. A prototype is foreseen for 2026, however, the final version is scheduled for a later date. This new JRODOS version will combine functionalities for fission and fusion applications and will be unique for decision making in both communities.

CRediT authorship contribution statement

Wolfgang Raskob: Writing – original draft, Investigation. **Irmgard Hasemann:** Writing – review & editing, Data curation. **Thomas Schichtel:** Supervision, Project administration, Formal analysis. **Sadeeb Ottenburger:** Writing – review & editing, Funding acquisition.

Declaration of competing interest

There is no competing interest

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Data availability

Data will be made available on request.

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