Assessment of environmental consequences of the normal operations of the ESS facility

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Abstract. As other accelerator based facilities, the European Spallation Source ESS facility will interact with the environment. The Swedish legislation requires a demonstration that the sum of the doses resulting from the exposure of any member of the public to ionizing radiation dose does not exceed the specified limit of 50 µSv/year. A radiological assessment has been produced to provide that demonstration. This evaluation was based upon the actual status of the ESS design. A graded approach was adopted through over the assessment allowing estimating dose for all radionuclides and exposure pathways, but the degree of detail in the assessment depend upon their relative radiological importance. The total dose was obtained making the sum of the contribution of all-important radionuclides treated realistically with that of all screened out radionuclides, derived by means a conservative method.

1. Assessment approach

For the derivation of the release-to-dose-factors and estimation of radionuclide concentrations in the environment, ESS is using PREDO (PREdiction of DOses from normal releases of radionuclides to the environment) methodology.

A graded approach was adopted through over the assessment allowing estimating dose for all radionuclides and exposure pathways, but the degree of detail in the assessment depend upon their relative radiological importance. Firstly, the relative importance of the dose contributions was assessed by comparing doses calculated based on IAEA SRS19 [1] screening approach against predefined dose value of 0.1 µSv/year. In addition, it was required that the sum of the doses of screened out radionuclides is also below the exemption level of 10 µSv/year. In the second step, for all radionuclides previously identified having significant dose contribution, realistic dose factors were derived using dispersion and radio-ecological realistic models.

Finally, the total dose was obtained making the sum of the contribution of all-important radionuclides treated realistically with that of all screened out radionuclides, derived by means the conservative method. The assessment of radiological impacts from releases of radioactive substances to the environment was carried out in two steps: i) estimation of the source term consisting of calculation of activities of radionuclides that can be released annually from the ESS facility and ii) applying dispersion and transport models to calculate radionuclide concentrations in the environment and dose models to calculate doses to reference groups from the population around the site.
The evaluation of exposures to impacted environmental media considers three main pathways: i) airborne releases of radionuclides through ventilation outlets ii) liquid discharges of radionuclides to the sewage system and downstream surface water (rivers and sea), iii) migration of radionuclides with groundwater following activation of the surrounding soil.

2. Releases of radioactive substances to the atmosphere
The releases from the main release point, the main stack, are presents in this work. This is the point of continuous releases from the accelerator tunnel and the target station as well as of periodical short-term releases from the hot cell, occurring during the dismantling and processing of the target system and other obsolete components.

2.1. Source term evaluation
The estimated source term is presented in the following sections, according to the origin of releases.

2.1.1. Tunnel of accelerator. The radionuclide concentrations in the tunnel have been calculated [2] from the radionuclide production yields considering the time evolution of the air inside the tunnel for one air exchange rate [h⁻¹] the baseline parameter of the ventilation circuit. The results of the calculations integrating over 6000 h of continuous operations are provided in figure 1.

![Figure 1. Source term for airborne release during operation. In blue, the effectiveness of the hepa filter (99.97%) is applied for aerosols.](image)

As can be seen in the figure, the source term to the stack takes into consideration the filter effect (blue columns). It was concluded from this analysis that during operation, the ventilation system will extract about 22.6 TBq of air radioactivity per year given mainly by the short lived gases as $^{13}$N, $^{11}$C, $^{14,15}$O and $^{41}$Ar. Therefore the filter effect upon the total released activity is small (less then 2%).

2.1.2. Target station. A detailed analysis of the potential releases to the environment from the main target systems was performed in [3]. Within the Target Station there are four important contributors to radioactive releases in locations where the ventilation system will be implemented: i) helium cooling loop (HeL) of the tungsten (W) target, ii) hot cells (HC) facility , iii) gas-liquid separator (GLS) tanks of the main cooling water circuits and iv) helium within the shielding monolith. In this work only first two components of the source term are addressed.
2.1.2.1 Helium cooling loop (HeL) is the most critical zone where spallation products created within the W target have the potential to be released. Therefore a purification system based on getters was necessary to be inserted into the helium loop. The HeL contains also special filters for W dust that is formed by ablation, see figure 2. The volatiles and dust that will leak from the purified helium through the pipes will be extracted by the ventilation system from the rooms housing the loop. According to the current knowledge, there are three potential mechanisms of radionuclide releases from the target within HeL: i) direct ejection or sputtering due to spallation reactions, i) diffusion and iii) ablation. The species assumed to be released from the W target within the helium loop are almost all spallation products of the W target. The block diagram in figure 3 shows the possible locations where activity can reside, and the ways in which it can move. “Surfaces” is a general term describing any place within the HeL where dust may be plated.

Figure 2. Schematic view of the helium cooling loop of the tungsten target.

Figure 3. Compartment model for developing the analytic expressions governing radioactivity releases from the helium cooling loop.

Analytical solutions to the differential equations developed based on this compartment model governing radionuclide turnover in the system as well as the parameters values used in the calculations are provided in [3]. The obtained source term amounts at 6.32E+11 Bq. It contains more than 1050 radionuclides, which were grouped according to their properties: gases, volatiles, semi-volatiles and particulates or metalloids. It was found, for example, that the annual release of the iodine isotopes is 1.4E+09 Bq, while of the noble gases is 6.6E+09 Bq.

2.1.2.2 Hot cells (HC) facility is the potential origin of the following releases to the environment arising during the processing:

1. Tungsten (W) dust (pasted-up on the surfaces of the structures and pipes) that can be spread and arise during the cutting process;
2. Stainless steel dust arising from machining of the obsolete components (target shaft and shroud, moderator reflector twister, pipes, plugs, others).

The ventilation system associated to HC has at least two levels of hepa filtration: i) local and ii) at the stack. In the present estimates credit is taken for at least one level of filtration. It was assumed that all W dust accumulated on the surfaces (see figure 3) during five years of irradiation will be spread within the processing HC and released via ventilation system to the stack. Firstly, the accumulated activity at
the end of the 5th annual run was estimated and thereafter the annual release to the environment, considering a continuous uniform dismantling over two months, was derived. The annual release of the W dust is about 3.1E+7 Bq for the worse case, when only the first level of the ventilation filtration located at the HC level is accounted for. Annual release is about 9.2E+3 Bq when considering also the effectiveness of the second level of hepa filtration at the stack. The annual release is completed by adding tritium assumed to be released from both W target bricks and W dust during dismantling, about 2.6E+11 Bq. It is further assumed that other gases and volatiles in the W dust stay attached and behave as dust.

The radioactive inventory of the stainless steel dust (SS dust) produced in the HC during cutting the shaft and the shroud of the target system was calculated in two steps. Firstly, the radioactive inventory of each of the items, the shroud and the shaft, to be cut within the HC was calculated. Secondly, the amount of SS dust that might arise during the cutting process was estimated. And finally, the annual release was derived as above using the maximum of SS dust that can be produced during processing. The estimated release of the SS dust is 4.6E+08 Bq in case if only one filtration level is accounted and 1.4E+05 Bq if subsequent filtration at the stack is also accounted for. The source term accounts for 2.0E+08 Bq of tritium, assumed to be released from the SS dust. The remaining tritium in the SS dust is assumed to stay attached and behave as dust.

2.2. Doses from releases to the atmosphere

2.2.1. Screening study for releases from the main stack. From calculations with the IAEA screening models [1] conservative release-to-dose-factors were obtained for all radionuclides that can be potentially released from the main stack. These release-to-dose-factors were then multiplied by the total releases from the main stack, to obtain a conservative estimation of the annual dose from each released radionuclide. Both continuous and short-term releases were included in the in the release rate used for the screening. It was found that only for 16 radionuclides the screening doses were above the screening criteria of 0.1 μSv/y. Consequently they were further treated by means realistic models. The total screening dose from these 16 radionuclides is about 25 μSv/y. The total screening dose rate of the remaining radionuclides that were screened out is 0.54 μSv/y.

2.2.2. Dose estimates for continuous releases from the main stack. The following dose exposure pathways were considered in the realistic models for atmospheric releases: i) immersion in the plume; ii) exposure to deposited radionuclides; iii) ingestion of food from a garden plot; iv) ingestion of crops from a cropland area; v) ingestion of meat and milk; vi) ingestion of forest food; vii) ingestion of water and viii) ingestion of freshwater food. The realistic doses were calculated for representative land use objects: residential areas, croplands, pasturelands, forests, Kävlinge river subcatchment area and discharges to surface waters: the Källby sewage treatment plant and the part of Höje river which flows downstream Källby plant. Three age groups were considered: Infant, Child and Adult. In the following, results are presented for averaged Adult and the other groups are treated in the uncertainty analysis. Two cases of release rates were considered for the estimation of the annual doses:

1. Pessimistic estimate of the release rate. This is the most pessimistic case, assuming the maximum that the facility can potentially release to the environment. It means no credit is given to the filtration equipment (all hepa filters are down) at the main stack. Only the clean-up and abatement equipment located inside the buildings are considered in function. This source term would never be approached during normal operation.

2. Realistic estimate of the release rate. In this case all abatement equipment works optimally, including the filtration system.

Annual Dose (Sv/y) to the Average Adult and contributions to the annual dose from different radionuclides for the two analysed release cases are given in Table 1.
Table 1. Annual effective dose to the reference Averaged Man. Results from linac, Target Station-helium cooling loop and hot cells.

| Component                        | Released Activity (Bq/y) | Effective dose (µSv/y) |
|----------------------------------|--------------------------|------------------------|
|                                  | Screening approach       | Realistic approach     |
|                                  | Pessimistic release      | Optimal release        |
|                                  | Pessimistic release      | Optimal release        |
| Linac                            | 2.26E+13 2.25E+13 1.16E+01 | 1.02E+01 5.44E-01     |
|                                  | H3                       | 6.24E+11 6.24E+11 1.08E+00 | 1.08E+00 5.60E-03 |
|                                  | 1.35E+09 1.35E+09 1.20E+01 | 1.20E+01 5.57E-02     |
|                                  | Other halogens           | 5.94E+07 5.94E+07 1.98E-03 | 1.98E-03 1.98E-03 |
|                                  | 6.24E+11 6.24E+11 1.08E+00 | 1.08E+00 5.60E-03     |
|                                  | Iodine                   | 5.94E+07 5.94E+07 1.20E+01 | 1.20E+01 5.57E-02 |
|                                  | 6.60E+09 6.60E+09 1.28E-03 | 1.28E-03 1.28E-03     |
|                                  | Gases (O, N, CO)         | 7.33E+03 7.33E+03 7.53E-09 | 7.53E-09 3.83E-09 |
|                                  | Noble gases              | 2.72E+05 8.17E+01 9.20E-04 | 9.20E-04 |
|                                  | Metaloids_1              | 5.29E+07 1.59E+04 2.06E-01 | 2.06E-01 6.20E-05 |
|                                  | Metaloids_2              | 6.60E+08 6.60E+08 7.44E-01 | 7.44E-01 5.71E-04 |
|                                  | Total target             | 6.32E+11 6.32E+11 1.33E+01 | 1.33E+01 6.47E-02 |
|                                  | Total at stack           | 2.33E+13 2.31E+13 2.49E+01 | 2.49E+01 6.79E-01 |
|                                  | 2.39E+13 2.37E+13 2.37E+13 | 2.37E+13 2.37E+13 2.37E+13 |
| Continuous release               |                          |                        |
| Short term release               |                          |                        |
| Dismantling in the Hot Cells     |                          |                        |
| W dust                           | 6.24E+11 6.24E+11 1.26E+00 | 1.08E+00 3.47E-02     |
| Total                            | 6.24E+11 6.24E+11 1.26E+00 | 1.08E+00 3.47E-02     |
| TOTAL each 5 years               | 2.39E+13 2.37E+13 2.37E+13 | 2.37E+13 2.37E+13 2.37E+13 |

The total annual effective dose obtained for both variants are below 1 µSv/year and is dominated by N-13, C-11, Ar-41, O-15, I-125 and H-3, see figure 4. The reduction effect of the filtration system on the total doses from continuous releases is marginal, since the total doses are dominated by radionuclides that are released in gas form and are therefore not retained in the filters.

2.2.3. Dose estimates for short term releases from the main stack. For short term releases, the release-to-dose-factors were calculated using a repeating pulse as release rate. The pulse was defined as a constant release of length 2/12 y and amplitude 12/2 Bq/y occurring repeatedly every 5th year. In this way, the release rate corresponds to 1 Bq of released activity during the release period. release-to-dose-factors were calculated the following two-month-long release periods: January and February, March and April, May and June, July and August, September and October, November and December. Interception of deposited radionuclides onto plant surfaces was assumed for all release periods except those occurring in the winter (January and February, November and December).
Table 1 contains the maximum annual doses corresponding to the period September-October and contributions from the two analysed release cases. The total dose from short term releases from the main stack is small in comparison to the contribution from continuous releases. The reduction effect of the filtration system on the total doses from short term releases from the main stack is negligible, since the total doses are dominated by releases of H-3 occurring during dismantling of the obsolete target. While for the dust, which is retained in the filters the effect is about three orders of magnitude.

The results of realistic dose calculations for airborne releases of radionuclides from the main stack show that annual doses to members of the public are well below the Swedish regulatory constraint of 100 µSv/year and even below the exemption level of 10 µSv/year.

3. Discharge to the sewage system
All radioactive wastewater produced during the operation (run cycles and maintenance) will be sent to the waste facility (via pipes or tanks) for treatment. If the activity levels of the radionuclides in the treated wastewater meet the requirements, then the waste water can be discharged to the sewage plant in Lund. Radionuclides potentially contained in the wastewater originate from: i) activation of the water, and ii) contamination of water with corrosion products and dust. The breakdown of radionuclides with potential to be released to the sewer system from the waste facility is given in [5]. Radionuclides from the ESS facility discharged to surfaces waters are assumed to be directly received by the Källby sewage treatment plant. After treatment, the water is released to the downstream freshwater receptor Höje river. Further downstream, the marine basin (Lomma bay) is considered the final receptor of the discharges.

The assessment accounts for exposure to 1) workers in the sewage plant that are exposed to radionuclides in the non-treated water or sewage sludge and 2) the general public exposed, either directly (through consumption) or indirectly (though use of water for irrigation or for feeding cattle). Workers in the Källby sewage treatment plant are assumed to be exposed by: i) external irradiation from radionuclides in the water or sludge and ii) from internal exposure though inhalation of re-suspended radionuclides and inadvertent ingestion of sludge.

The general public is assumed to be exposed to radionuclides by the following exposure pathways: i) ingestion of freshwater and freshwater food from the Höje river, ii) ingestion of marine food from the

![Figure 4. Main stack continuous release. Total annual effective dose and contribution of the dominant 16 radionuclides (80%).]
Lomma bay, iii) Marine activities in the Lomma bay (boating, swimming and sunbathing), iv) exposure to radionuclides accumulated on the ground as result of irrigation with water from the Höje river, v) ingestion of irrigated garden foods, vi) ingestion of meat and milk from cattle consuming contaminated water. Because quantification of the wastewater discharge rates from the waste facility outlet was not available the dose calculations could not be carried out. Therefore, for all identified radionuclides realistic release-to-dose-factors were derived using the models described in [6]. The realistic release-to-dose-factors were further used to derive discharged limits (reference discharge levels) for each radionuclide that could be potentially discharged to the sewage system. In deriving these limits, all potential exposures of sewage workers and the general public have been taken into account by dividing the assumed dose target 10µSv/y with the maximum of the Release-to-Dose-Factor for workers and general public. Reference [4] provides the obtained values of the reference discharge limits.

4. Migration of contaminants with the groundwater

4.1. Source term evaluation
The estimation of the source term of radionuclides generated by activation of the soil surrounding the accelerator tunnel is presented in [7]. This report derives detailed earth activation levels around the linac tunnel providing the results along the entire length of the machine. From all radionuclides derived in the soil only 11 were considered and justified as representative and used further as source term in the assessment: H-3, Be-7, Na-22, Na-24, P-32, S-35, Ca-45, Sc-46, Mn-54, Fe-55, Zn-65.

4.2. Groundwater modelling
The assessment of doses to reference persons from activation of soil and groundwater was carried out in two steps: i) groundwater flow modeling using MODFLOW code and ii) radionuclide transport modeling by means the NORMALYSA model library, see details about modelling in [8]. The groundwater flow model assumes steady state groundwater flow regime. Specific geological layers of the surrounding area and the associated hydrogeological and hydraulic parameters were used to create the 2D groundwater model of the flow from the tunnel to a well located at 300 m distance. The radionuclide transport is based on water fluxes and flow rates calculated in the step 1. The conceptual model of the radionuclide transport from linac to the well is shown in figure 5.

![Figure 5](image_url). Conceptual model of radionuclide transport process to groundwater from the linac tunnel.
This model accounts for production of radionuclides in a sequence of soil layers surrounding the tunnel with a total thickness of 6 m. Radionuclide transport in the unsaturated and saturated soil zone was modeled using the advection-dispersion transport equation accounting for sorption described by $kd$ model (linear reversible sorption). Transport calculations were carried out for the higher mobility radionuclides, namely: H-3, Na-22 and S-35. These higher risk radionuclides were selected from the list of 11 spallation products in the course of a previous screening radionuclide transport analyses.

Two scenarios of radionuclides leaching from the activated soil around the linac tunnel to the subsurface were analyzed:

1. Scenario 1 assumes an impermeable soil cover (or membrane), situated on top of the tunnel, which will fail after the end of operations of the accelerator (at the 40th year), leading to leaching of the accumulated nuclides in the activated soil to groundwater;

2. Scenario 2 assumes that there is no protective cover present, and a chronic release occurs through the operation life time of the facility (40 years).

Radionuclide concentrations in well water (Bq/m$^3$) for the reference case obtained for the two scenarios considered are presented in Table 2.

Table 2. Maximum radionuclide activity concentrations (Bq/m$^3$) in the water of the well for the two scenarios considered.

| Radionuclide | Scenario #1 | Scenario #2 |
|--------------|-------------|-------------|
|              | Reference $kd^*$ | Conservative $kd^{**}$ | Reference $kd^*$ | Conservative $kd^{**}$ |
| $^3$H       | 3.57E+04    | 3.57E+04    | 1.67E+04    | 1.67E+04    |
| $^{22}$Na   | 1.45E-32    | 2.91E-11    | 1.28E-31    | 2.01E-10    |
| $^{35}$S    | 1.21E-88    | 1.10E-43    | 2.19E-87    | 1.75E-42    |

*$kd$ provided in [8]  
**$kd (= Reference Kd/10)$

The results for both scenarios show that doses will be formed practically 100% by tritium. Transport of other radionuclides to the well is delayed by sorption, and their predicted concentrations in well water are negligible. The results of modeling show that tritium concentrations in well water are approximately one order of magnitude below the admissible level of 100 Bq/L.

4.3. Dose estimates

Uses of the well water for drinking and irrigation of a garden plot were considered in the dose calculations. The models described in [6] were used in the dose estimations. Annual doses (Sv/y) from exposures to groundwater contaminated by activation are shown in Table 3.

Table 3. Annual dose rate ($\mu$Sv/y) from exposures to groundwater from linac tunnel area. Values are given for a representative Average Adult.

| Radionuclide | Scenario #1 | Scenario #2 |
|--------------|-------------|-------------|
|              | Ingestion of water | Total | Ingestion of water | Total |
| $^3$H       | 2.42E-01    | 2.45E-01    | 1.13E-01    | 1.15E-01    |
| $^{22}$Na   | 1.74E-35    | 3.22E-35    | 1.54E-40    | 1.54E-34    |
| $^{35}$S    | 3.51E-92    | 6.50E-92    | 6.34E-92    | 1.30E-34    |
| Total       | 2.42E-01    | 2.45E-01    | 1.13E-01    | 1.15E-01    |
Values are given for a representative adult with average habit. The estimated doses are the highest for the scenario of accumulation of radionuclides and below 1 $\mu$Sv/year, considering the use of well water for drinking and irrigation of a garden plot.

5. Summary and conclusion
Maximum annual dose for continuous release to the main stack from linac tunnel and helium coolant loop is less than 1 $\mu$Sv/y and the major contribution (80%) is given: N-13, C-11, Ar-41, O-15, H-3, I-125, Cl-38,39, P-32, Be-7, S-35, W-185, Hf-172, Co-60, Mn-54 and Co-58. Maximum annual dose for short term release to the main stack is less than 0.1 $\mu$Sv/y and the major contribution is given by H-3 release during dismantling. The source term to the waste facility outlet is not known therefore derived activity limits where derived for all 72 radionuclide with potential of discharging into the sewage system. Maximum annual dose due to the migration of the contaminant with the groundwater is less than 1 $\mu$Sv/y and is due to the drinking water contaminated with $^3$H.

Actual results of realistic dose calculations for airborne releases of radionuclides from the main stack show that annual doses to the public are well below the regulatory constraint of 100 $\mu$Sv/y and even below the exemption level of 10 $\mu$Sv/y.

Obtained results shall be completed with remaining contributors.

This report is conceived according the knowledge that ESS staff has in this stage of the project. The current data are estimations subjected to evolution and update.

An environment monitoring program was defined and it will be implemented gradually during the commissioning of the ESS facility.

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