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Management of the radioactive waste and emissions within the European Spallation Source facility

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Abstract. The European Spallation Source (ESS) is the European common effort in designing and building a next generation large-scale user facility for studies of the structure and dynamics of materials. The schematic layout of the ESS facility is based on a linear driver (linac) directing proton pulses (5 MW of 2 GeV) of 2.86 ms length at 14 Hz onto a tungsten target where neutrons are produced via spallation reactions. Furthermore the neutrons will be moderated to thermal and cold energies by water and liquid hydrogen. These thermal and cold neutrons will be transported by 22 beamlines to the scattering instruments, mainly used for neutron scattering research. This paper reports the status of the waste management plan of the ESS facility and the radiological consequences of the discharge of the radioactive gaseous waste into the environment. Estimations of types and quantities of waste that the ESS project will generate at different stages: commission, operation, and decommissioning were derived using: i) Monte Carlo calculations ii) scaling the activity from the operational experience of the existing spallation sources. Associated waste treatment/conditioning options and final disposal route were further analyzed in order to define the waste type and packet descriptions in agreement with Swedish regulations and policy. Particular attention was devoted to the highly activated components of the target station and its surroundings. First estimates of the radioactive waste water to be produced during ESS operations and solutions for its handling will be provided. An overview of the different aspects of the tritium management in ESS facility will be given. Finally, the source term for atmospheric releases and the radiological assessment of the dose to the critical group will be reported.

Introduction

The development of the waste management plan is an iterative process based on the actual status of the project and consultations with the organizations involved in waste treatment, conditioning, transport and disposal, as well as with the regulator. This paper provides a preliminary waste management plan based on the actual status of the European Spallation Source (ESS) project [1]. The main goals of the ESS waste management plan are: i) to establish the major objectives of the waste management process, ii) to provide estimates of the total ESS waste volumes to be generated, iii) to identify and categorize the waste streams from the ESS facility according to what the different treatment lines can handle and to suitable disposal facilities, iv) to identify, discuss and analyse the management of problematic waste; v) to define the main elements of the management of the radioactivity on ESS site, vi) to define the treatment/conditioning options appropriate for the waste streams and where they will be performed; vii) to define the waste disposal options and assess the disposal volumes needed.

1 Radioactive waste

1.1 Radioactive waste streams and amounts

All radioactive waste from ESS will be handled and disposed of within the Swedish system for management of radioactive waste. The waste classification system used within this work is in accordance with Swedish policy and practice that define the following waste classes: i) free release material; ii) very low level waste (VLLW); iii) SFR-waste: short-lived low- and intermediate level waste (SL-ILW); iv) SFL-waste: long-lived low-and intermediate level waste (LL-ILW); v) Heat generating waste. Swedish regulatory guidelines [2] were used to classify ESS waste based on clearance index approach. The derivation of the waste amounts was based on Monte Carlo calculations for high activated replaceable components during operation and decommissioning or on experience feedback from other similar facilities. As a first estimate, about **25,000 tons of waste** is expected to be sent for final disposal from operation and decommissioning. This figure does not consider VLLW that may be clearable during the lifetime of the facility or after its final shut-down.

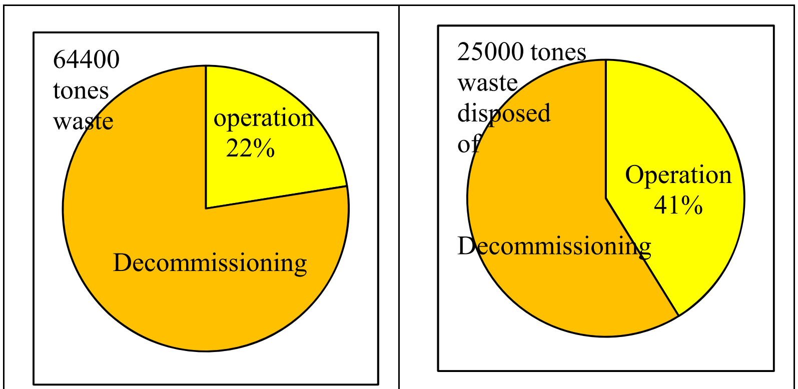

Figure 1. Mass repartition between operation and decommissioning waste: generated waste (left) and waste to be disposed of (right).

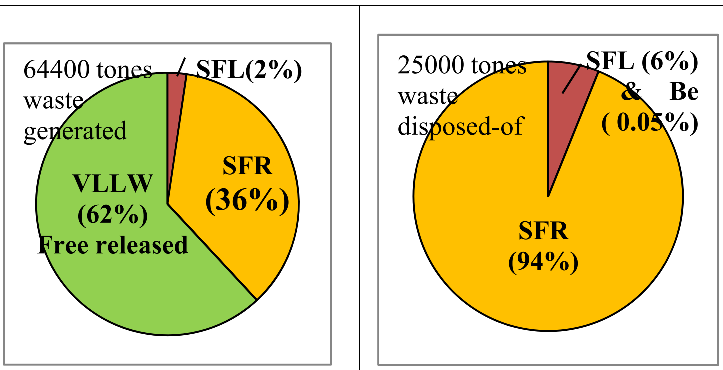

Figure 2. Mass repartition between categories considering both operation and decommissioning waste: generated waste (left) and waste to be disposed of (right).

The figure 1 shows that the major part of the waste will come from decommissioning (about 78%) from the waste generated and (about 59%) of the waste to be disposed of. The difference represents the amount of waste to be free released on site.

As shown in the figure 2 the main part of the radioactive waste (about 62%) may be classified as VLLW and further cleared and as SFR waste, without requiring deep final disposal. The reported values are estimations subjected to evolutions and regular updates. Special consideration was given to waste such: beryllium, tritiated water, spent-ion exchange resins, etc.

1.2 Waste treatment and conditioning options

A concept for optimized radwaste management of the ESS facility was further developed based on experience and lessons learned from nuclear facilities in operation and during decommissioning projects in Sweden. The principle flow chart for different ESS waste streams from the waste generated to disposal, underlying this concept, is shown in figure 3.

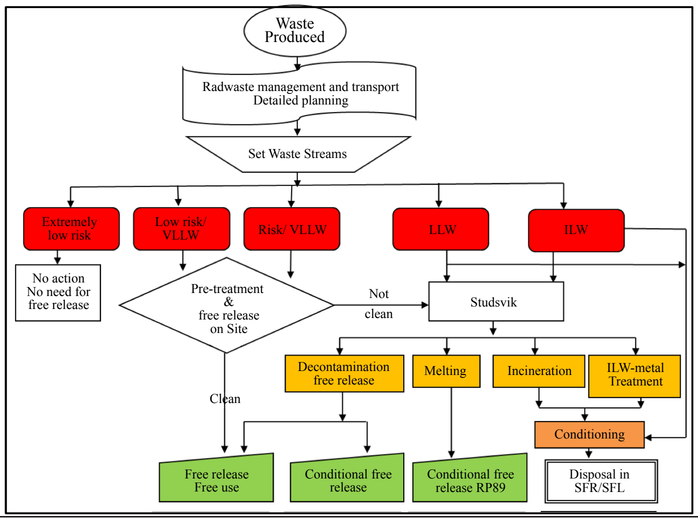

Figure 3. Flow chart for radwaste logistics at the ESS facility during operation.

As is shown in the figure the waste streams were divided into risk-based categories. Treatment/conditioning solutions compatible with the existing experience (where available) in the waste Swedish system were proposed for the identified waste streams. Majority of waste that will not be free released on site will be sent for treatment/conditioning in Studsvik company. In the reference scenario it is considered that spent ion exchange resins and tritiated water arising during the operation of the purification system of the target will be conditioned on-site before shipment. The details of what conditioning processes will be used are still subject to studies.

Careful attention should be given to the ESS waste packages assigned as ILW/SFL type waste because the waste acceptance criteria for SFL disposal facility are not yet assessed. The treatment and conditioning of this type of waste may be performed in Studsvik according to two potential options: i) segmentation and conditioning or ii) melting ILW/encasing ILW in molten LLW. Both potential options mentioned above require an initial investment (cost and time) either for upgrading of an existing facility (the hot cell or the pond) or for commissioning of a new facility (optimized pond or a ILW melting device) in Studsvik. Other potential variant is to use ductile cast iron containers designed to meet requirements for on-site storage, transport and disposal. ESS will work closely with Studsvik and Swedish disposal operator, SKB, to agree on suitable packages.

The final state of ESS VLLW waste could be free release. In Sweden the clearance concept was recently adopted [2] and a code of practice for clearance procedures was developed [3].

This guideline will be used by ESS to create the routines/instructions for the waste free release, in agreement with Swedish regulations.

As requested by Swedish law in the frame of the ESS waste management plan the Best Available Technique (BAT) is being used to determine the optimum logistics for the waste [4]. In this respect emphasis was driven towards evaluation of the pros and contras of the options and finding the optimum solution for handling of the high activated components of the facility.

According with Swedish waste management system practice [5] each waste that is transported to final disposal shall be described in a waste type description (WTD) document**.** In this respect the data about the optimized waste streams and their treatment/conditioning will later be used to prepare the WTD reports for further submittal to the authority for approval.

1.3 Waste disposal. Assessment of disposal volumes needed.

Based on the assessment undertaken here a rough estimation of the waste volumes to be disposed of in Swedish disposal system has been made. Comparing the estimated values with the capacity of existing and planned repositories in Sweden it was found that the ESS waste will take up to 15 % of the disposal volume for the Swedish radioactive waste management system. Additionally collaboration work with SKB is underway to identify indicator nuclides in order to provide input necessary to include ESS waste in the design and safety assessment and make complementary licensing for planned disposal facilities.

1.4 Onsite management of radioactive waste.

An overview of the waste management on the ESS site is also given with emphasis upon the characterization of generated waste and traceability of the waste during the whole process—from the dismantling of the components to the final disposal is an important step in waste management.

ESS intends to use three complementary radiological characterization methods: i) radiation detection, ii) direct Monte Carlo calculations and iii) matrix method [6].

Waste storage options: hot cell and interim storage facility for radioactive materials are analyzed in terms of their capacity requirements and the preliminary data relevant for the waste streams planning. In addition, the design principles and good practices that will be followed to minimize the activity and the volume of radioactive waste generated from ESS facility operation and maintenance

2 Emissions and radiological impacts

The evaluation of the environmental impact of ESS during the design phase, as well as during the operation of the facility is a mandatory request of Swedish Nuclear Authority. Therefore the radiological consequences from potential radioactive waste discharges arising from ESS were also assess. These discharges are in form of gaseous discharges to the atmosphere from a stack, aqueous discharges to public sewer and migration of contaminant with the groundwater. Only airborne releases are presented in this section.

2.1 Source term estimates.

The source term for atmospheric releases can be separated into two distinct release operations:

- On-line emissions, and
- Emissions resulting from processing.

2.1.1 Online emissions

The continuously venting of the air from the tunnel during operation may be assumed also mainly for releasing of the moisture and heat. The ventilation system within the linac tunnel was defined in [7]. The table 1 shows the source term derived based on calculations performed in [8] where 1 Watt/m beam loss was assumed. The effectiveness of the HEPA filters to be used within the tunnel was taken from [9].

Table 1. Source term for airborne release from online operations: contribution from the linac tunnel.

Nuclide	$T_{1/2}$(s)	Chemical form		Production** in the tunnel (Bq/year)	Source Term (Bq/year) r=5/h
C-11	1.22E+03	CO, CO_2	gas	8.92E+10	8.93E+10
N-13	5.98E+02	*NO_2*	*gas*	8.80E+10	8.81E+10
O-15	1.22E+02	O_2	gas	4.92E+10	4.93E+10
Be-7*	4.60E+06	BeO_2	aerosol	2.51E+10	7.56E+06
H-3	3.89E+08	H_2O	vapor	1.87E+09	1.87E+09
Ar41	6.58E+03	Ar	*gas*	1.51E+09	1.51E+09
P-32*	1.23E+06	PO_2	aerosol	4.25E+08	1.28E+05
P-33*	2.19E+06	PO_2	aerosol	9.51E+08	2.86E+05
S-35*	7.54E+06	SO_2	aerosol	2.67E+08	8.01E+04

* Effectiveness of the HEPA filter of 99.97%

** Total volume of the tunnel is 11550 m^3

On-line emissions through the stack into the atmosphere from the target station are supposed to be negligible. This assumption is based on the fact that helium cooling loop of the target is a closed circuit. The amount of volatiles removed from the loop depends on their fractional release from the tungsten target, which in turn depends sensitively on the target operating temperature and accumulated damages. As a conservative assumption for the purpose of assessing environmental impact, in [10] it was assumed that all of the volatiles produced in the target are readily released into the helium coolant. Using further a conservative assumption of 2% per day leakage rate from the pipes of the loop, the release to the environment is given in the table 2.

Table 2. Source term arising from leakage to the environment by the primary helium coolant loop.

Nuclide	Activity in He loop (Bq)	Source Term (Bq/year)
H-3	2.00E+11	8.32E+11
I-125	9.00E+10	3.74E+8*

•A filter effect with (99.9%) was considered for ^{125}I leaked from the He loo

2.1.2 Processing emissions

The main contributions to atmospheric releases arising from processing operations are provided in the table 3. The first two rows show data from on-site cementation of tritiated contaminated water.

This water is a result of the purification loop in the primary target helium and may be generated directly from activated cooling water systems.

The remaining items in the table are resulting from target dismantling. The ^{125}I and ^{148}Gd releases are included for reference, despite low release rates.

Finally, hot cell operations that will cut the target shaft will necessarily generate small releases of activated steel as aerosols, along with small amounts of aggregated and activated tungsten dust. The amounts of airborne particulates are estimated by the following conservative assumptions: 0.1% of the stainless steel in the shaft is cut, and 0.1% of the cut material has a size distribution allowing transport as suspended particles.

These particles will pass through 99.9% efficient HEPA filtration; therefore a release factor of 1E-09 on the shroud is possible, though unlikely. As resulted from table 2 tritium is a big contributor to release and radionuclide inventory at the facility.

Table 3. Source term for airborne release from processing operations.

Nuclide	Chemical form	Activity (Bq)	Release Fraction	Source Term
^{3}H	H20, gas	6.00E+14	1%	6.00E+12 Bq/y
^{125}I	HI, HIO3	1.00E+08	1%	1.00E+06 Bq/y
^{3}H	gas	Wheel:6E14	4.E-5 to 0.1%	2E+9 to 6E+11 Bq/5y
^{181}W	Dust/aerosol	Wheel:10E15	4.00E-08	5.00E+07 Bq/5y
^{179}Ta	Dust/aerosol	Wheel:8E15	4.00E-08	3.00E+07 Bq/5y
^{148}Gd	Dust/aerosol	Wheel:8E11	4.00E-08	3.00E+04 Bq/5y

2.2 Effective dose assessment

2.2.1 Dispersion and deposition

The dispersion was derived applying the standard Gaussian dispersion formula [11]. The main parameters and assumptions used are given in [10]. In this study an overall deposition velocity of about 5 mm s^{-1} to outdoor horizontal surfaces was used. The long-term deposition factor on the ground is then simply estimated multiplying the dispersion value with that velocity. The calculated dispersion and deposition parameter for the ESS reference release point and ESS critical groups are listed in table 4. In the table HL stands for a hypothetical presence reference population group identified just at the border of the land owned by ESS located in the most frequent wind direction.

Table 4. Topological relations and calculated dispersion and deposition factors for the ESS reference release point.

Air	Västra Odarslöv farm / HL				Östra Torn farm			
release point	Distance (m)	Azimuth (°)*	χ (s m^{-3})	ζ (m^{-2})	Distance (m)	Azimuth (°)^{1}	χ (s m^{-3})	ζ (m^{-2})
TS edge H = 45 m	660	180/ 90 (HL)	2E-5 (= 50 m, σ_z = 30 m)	1E-7	330	180	5E-6 (σ_y = 30 m, σ_z = 20 m)	2.5E-8

* Degrees from North

2.2.2 Dose calculation

The radio-ecological models, describing the transport, dispersion and accumulation of radioactivity in various environmental matrices, were further combined with radiological models transforming an external exposure or an intake of radioactivity into the effective dose. The methodology that was applied to estimate ingestion dose is based on the ECOSYS model that is implemented in ARGOS system. Essentially, the outcome of the NKS PARDNOR project [12] implemented recently in ECOSYS system was heavily used for the present estimates. The following exposure pathways were assessed for the three age groups of the ESS critical groups:

- External dose from the contaminated plume during its passage
- External dose from deposition of airborne contaminants on surfaces
- External dose from deposition of airborne contaminants on humans
- Internal exposure due to inhalation of radioactive air (direct from the plume and resuspension);
- Internal exposure due to ingestion of radionuclides in: green vegetable, root vegetable, fruits, meat, leaver and milk from caw, sheep, pork and chicken, milk products.

The parameters and assumptions used in calculations are provided in [10].

The table 5 and table 6 give the estimated annual doses break downed by radionuclide and pathway for the local population group living in Vastra Oderslov (the ESS agriculture critical group) and for HL.

Table 5. Annual dose contributions (Sv/y) from release of radionuclides to air during normal operation at a hypothetical reference person placed within the prevalent wind direction (wind blows towards RP during 20% of the year)

	Activity*$_{outlet}$	Tritium	Inhalation			External			Total Reference
Nuclide	(Bq y^{-1})	(adult)	(1y)	(15 y)	(adult)	plume	deposition	skin	person
H-3	**7.43E+12**	**4.09E-07**							**4.09E-07**
Be-7	1.00E+07		**2.30E-13**	6.79E-14	5.48E-14	5.80E-14	1.02E-11	3.40E-13	1.08E-11
C-11	2.60E+12					2.80E-07			***2.80E-07***
N-13	2.70E+12					2.60E-07			***2.60E-07***
O-15	1.50E+12					5.40E-08			***5.40E-08***
Ar-41	4.10E+10					6.20E-09			6.20E-09
I-125	**3.74E+08**		**8.28E-10**	2.58E-10	1.84E-10	5.28E-13	5.92E-11	2.72E-12	8.90E-10
Total		**3.64E-06**	**4.16E-11**	1.30E-11	9.23E-12	**6.00E-07**	1.32E-11	4.76E-13	**1.01E-06**

Table 6. Annual dose contributions (Sv/y) from routine release of radionuclides to air during normal operation at Vastra Oderslov farm (agriculture group).

	Activity*$_{outlet}$	Tritium	Ingestion			Inhalation			External			Total Reference
Nuclide	(Bq y^{-1})	(adult)	(1 y)	(15 y)	(adult)	(1y)	(15 y)	(adult)	plume	deposition	skin	person
H-3	**7.43E+12**	**4.09E-07**										**4.09E-07**
Be-7	1.00E+07		**2.50E-11**	6.73E-12	5.38E-12	**2.30E-13**	6.79E-14	5.48E-14	2.90E-14	5.10E-12	1.70E-13	3.10E-11
C-11	2.60E+12								1.40E-07			1.40E-07
N-13	2.70E+12								1.30E-07			1.30E-07
O-15	1.50E+12								2.70E-08			2.70E-08
Ar-41	4.10E+10								3.10E-09			3.10E-09
I-125	**3.74E+08**		**9.06E-08**	3.50E-08	2.38E-08	**8.28E-10**	2.58E-10	1.84E-10	2.64E-13	5.92E-11	2.72E-12	9.14E-08
P-32	6.90E+05		**6.56E-06**	8.97E-07	5.59E-07							6.56E-06
P-33	1.10E+06		**1.54E-06**	2.20E-07	1.21E-07							1.54E-06
S-35	2.00E+05		**2.20E-06**	4.00E-07	1.52E-07							2.20E-06
Total		3.64E-06	**1.03E-05**	**1.52E-06**	**8.33E-07**	**4.16E-11**	**1.30E-11**	**9.23E-12**	**3.00E-07**	**8.06E-12**	**3.06E-13**	1.11E-05

3. Conclusion

One of the main outcomes of this report is the descriptions provided on all waste types and the waste management considered. The waste amounts reported here are based upon the baseline design of the facility [1] whose design now enters a more refined stage. The operation/maintenance plans of the facility shall be developed and optimized as well. Therefore the current data are estimations subjected to evolutions and regular updates.

Additionally, this work concludes that all the annual doses to exposed groups as a result of airborne discharges into the environment are a small fraction from 50 μSV y^{-1} ESS limit for members of the public

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