Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Authors: Anna Maria Blixt Buhr
Jan Johansson
Peder Kock
Jonas Boson
Simon Karlsson
Jonas Lindgren
Elisabeth Tengborn

2018:22e

ESS research facility: Basis for emergency preparedness and response planning

Report number: 2018:22e **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Strål
säkerhets
myndigheten
Swedish Radiation Safety Authority

Authors: Anna Maria Blixt Buhr
Jan Johansson
Peder Kock
Jonas Boson
Simon Karlsson
Jonas Lindgren
Elisabeth Tengborn

2018:22e

ESS research facility: Basis for emergency preparedness and response planning

Date: May 2019
Report number: 2018:22e **ISSN:** 2000-0456
Available at www.stralsakerhetsmyndigheten.se

Summary

Northeast of Lund, Sweden, in the area of Brunnshög, is the site of European Spallation Source ERIC (ESS), a research facility that is under construction. When the facility (hereinafter frequently referred to as "ESS") is commissioned, a linear accelerator will supply protons to a rotating target of tungsten, whereupon neutrons are generated through spallation. Radioactive materials will be generated in the target and in surrounding components when they are irradiated by protons and neutrons.

The Swedish Radiation Safety Authority (SSM) decided on 25 April 2018 to have the ESS research facility classified in emergency preparedness category 2. Consequently, in the assessment of SSM, events may occur at ESS involving a release of radioactive materials warranting urgent protective actions for the population outside this facility; however, the risk of severe deterministic effects posed to people off-site can be ruled out. Thus, due to this decision, SSM is of the view that it is warranted to have emergency response planning in place for the population surrounding the ESS research facility.

For the purpose of enabling effective protective actions, it is suggested by SSM to have an urgent protective action planning zone (UPZ) established with a range of approximately 700 metres around ESS. The final design of this UPZ to surround the ESS facility should be adapted to prevailing conditions surrounding the site, as well as approved by Lund Municipality prior to ESS being taken into routine operation. The UPZ should have planning in place for effective implementation of the protective action of sheltering. In addition, it is recommended to carry out pre-planning of systems and procedures for warning the population.

Outside the site of ESS, SSM has assessed that no ground deposition can occur in connection with emergencies that justify the similar emergency planning distance proposed by SSM to surround Swedish nuclear power plants and the interim spent fuel storage facility at Oskarshamn.

Contents

1. Foreword

Northeast of Lund, Sweden, in the area of Brunnshög, is the site of European Spallation Source ERIC (ESS), a research facility that is under construction. When the facility is commissioned, a linear accelerator will supply protons to a rotating target of tungsten, whereupon neutrons are generated through spallation. The target is enclosed in a steel structure (the monolith vessel), which is also the location of other key functions for producing neutrons. These include coolant (helium and water), reflectors (beryllium) and moderators (water and liquid hydrogen). Reflectors are used to maximise the quantity of neutrons, and moderators are used to slow the neutrons to levels of energy that are useful for the planned experiments. Radioactive materials will be generated in the target and in surrounding components when they are irradiated by protons and neutrons.

The Swedish Radiation Safety Authority (SSM) has classified the ESS research facility in emergency preparedness category 2 [1] [2]. Consequently, in the assessment of SSM, events may occur at ESS warranting urgent protective actions for the population outside this facility; however, the risk of severe deterministic effects posed to people off-site can be ruled out. Thus, due to this decision, SSM strongly advises having emergency response planning in place for the population near this facility. Therefore, it is suggested by SSM to establish an urgent protective action planning zone (UPZ) to surround ESS. Within this zone, protective actions should be prepared. These preparations give capacity for implementation of effective protective actions for the general public in connection with an emergency originating from ESS.

SSM has determined a postulated event for ESS, which in the view of the Authority should serve as a basis for emergency response planning for this facility. For this event, the Authority has defined a representative source term describing releases assumed to follow such event. Thereafter, SSM carried out dispersion and dose calculations using historical weather data for the purpose of estimating the distances at which it is warranted to take different types of protective actions for the population. Perimeter protection surrounding ESS restricts public access to the area closest to the facility. The shortest range of the perimeter protection is a few hundred metres from the outlet point on the target building assumed by SSM for the postulated event. In its calculations, the assumption of SSM is that the general public is allowed to be present outside the area with restricted access surrounding ESS.

As far as possible, SSM has used as a platform the methods, analyses and positions adopted, as accounted for in SSM’s report no. *2017:27e, “Review of Swedish emergency planning zones and distances”* [3] (translated version). A presentation of the methods, procedures, analyses and standpoints specific to ESS is contained in Appendix 1.

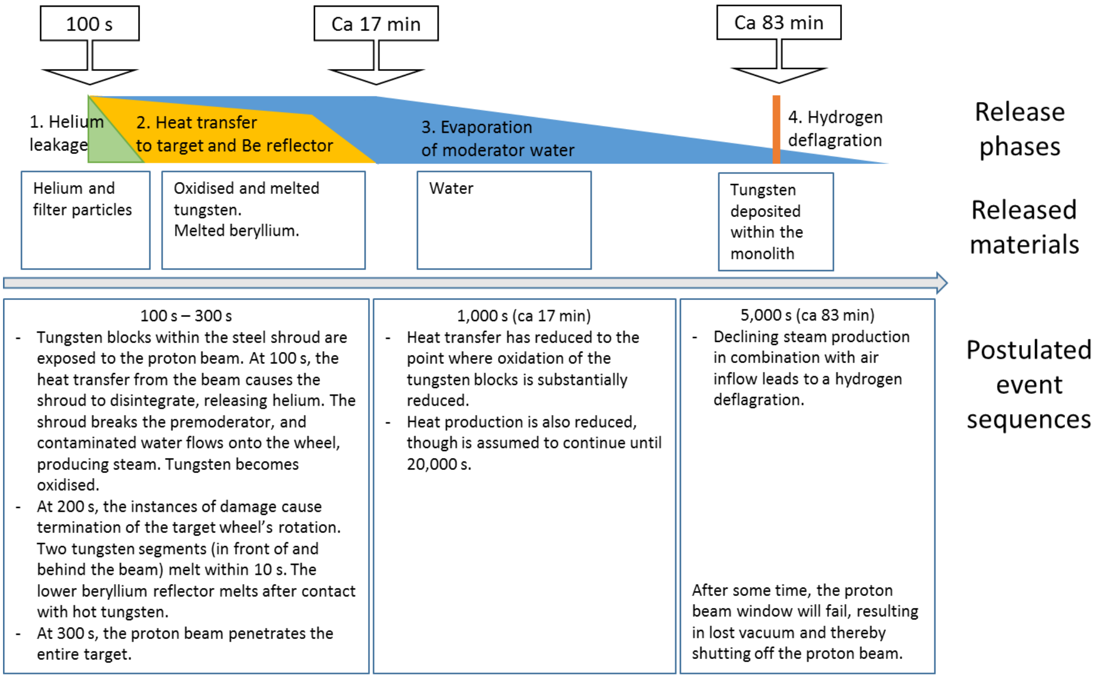
2. The postulated event

SSM has determined a postulated event for ESS, which in the view of the Authority should serve as a basis for emergency response planning for this facility [4]:

- **Loss of coolant during neutron production at full power.** This event involves a failure in helium cooling of the target, at the same time as the proton beam is still operating at full power. No safety systems or manual measures for shutting off the proton beam are allowed to be credited. This event results in overheating of the target and other parts of the target area, leading to their partial damage, whereupon radioactive materials are released [5].

SSM is of the assessment that the event involving loss of coolant in connection with neutron production at full power is the dimensioning event for the emergency preparedness and response planning in terms of both release magnitude and the period of forewarning. The period of forewarning is defined as the interval as of an event occurring and warning the population can commence, up until a release starting that warrants protective actions for the public.

The event sequence for the postulated event begins with lost helium cooling of the target, at the same time as the proton beam continues to irradiate the rotating target at full power (5 MW). As the energy continues to build up, the temperature increases in the target and surrounding shroud. The event sequence, release of radioactive materials, and induced radioactivity in and around the target can subsequently be broken down into several release phases, see Figure 1.



100 s – 300 s

- Tungsten blocks within the steel shroud are exposed to the proton beam. At 100 s, the heat transfer from the beam causes the shroud to disintegrate, releasing helium. The shroud breaks the premoderator, and contaminated water flows onto the wheel, producing steam. Tungsten becomes oxidised.
- At 200 s, the instances of damage cause termination of the target wheel's rotation. Two tungsten segments (in front of and behind the beam) melt within 10 s. The lower beryllium reflector melts after contact with hot tungsten.
- At 300 s, the proton beam penetrates the entire target.

1,000 s (ca 17 min)

- Heat transfer has reduced to the point where oxidation of the tungsten blocks is substantially reduced.
- Heat production is also reduced, though is assumed to continue until 20,000 s.

5,000 s (ca 83 min)

- Declining steam production in combination with air inflow leads to a hydrogen deflagration.

After some time, the proton beam window will fail, resulting in lost vacuum and thereby shutting off the proton beam.

Figure 1. Schematic illustration of the postulated event's sequences and release phases.

The postulated event is defined as occurring after the target has been used for five years, i.e. the maximum period of operation before replacement. Radioactive material is formed when tungsten and impurities in the target are irradiated by protons and neutrons. Consequently, after five years of use, ESS has the maximum allowable quantity of radioactive material present in the target at the research facility. This event is also postulated to occur when the proton beam is at full power of 2 GeV (5 MW). In the selected event, this implies that the heating of the target and other parts of the target area takes place at the potentially highest rate. Another assumption made is using a proton beam window between the target and the linear accelerator. Using this kind of window extends the period of time before the proton beam fails to function, if no safety systems or manual measures are credited for shutting off the proton beam. In the selected event, this means that the heating of the target and other parts of the target area takes place over the maximum possible duration of time. Lastly, the assumption is made that such release takes place directly into the surroundings by means of a pressure relief line from the target area. Other release pathways are possible; however, they all result in a smaller total release of radioactive materials from the facility.

3. Representative source term

For the postulated event, SSM developed a representative source term describing the release of radioactive materials to the surroundings. The representative source term provides information about the nuclides included in the release, the quantity of respective nuclide released, and the point in time of the release. The source term also provides information about the height of the release, distribution of iodine forms, and any heat content of the release.

SSM has also estimated the briefest feasible period of forewarning for the postulated event. The event sequence is rapid. For this reason, SSM is of the assessment that a release of radioactive materials warranting urgent protective actions for the public would begin after a couple of minutes as of the event unfolding.

3.1. Release sequence

The representative source term for the postulated event consists of four release phases. The initial phase is a release of helium and filter particles. It is assumed that this release begins after 100 seconds, and continuing over a duration of 10 seconds. All the helium in the cooling system and 1 per cent of the particles captured in the particle filters are assumed to disperse.

The second phase involves releases of melted and oxidised tungsten from the target, in addition to melted beryllium from the lower reflector. It is assumed that this release begins after 100 seconds, and continuing over a duration of approximately 1,000 seconds. This sequence is illustrated by Figure 2. The cause of the relatively constant release rate during the initial few minutes is that the gas in the area surrounding the target becomes saturated with aerosols. When the gas is saturated, the aerosol concentration has reached its maximum level. An assumed total of 41 per cent of accessible melted and oxidised tungsten is released from the target. The postulated release is also applied to noble gases, tritium, volatile materials and less volatile materials in the target, although the risk cannot be ruled out that higher levels of noble gases and tritium are released. Sensitivity analyses conducted by SSM nevertheless show that even if 100 per cent of the noble gases and tritium were released in the affected part of the target, the contribution to total effective dose from noble gases and tritium would be negligible. The release of melted and oxidised tungsten from the target predominates the entire total release of radioactive materials in the case of the postulated event. As far as the beryllium reflector is concerned, the assumed release is 100 per cent of noble gases and tritium, 10 per cent of volatile materials, and 1 per cent of less volatile materials.

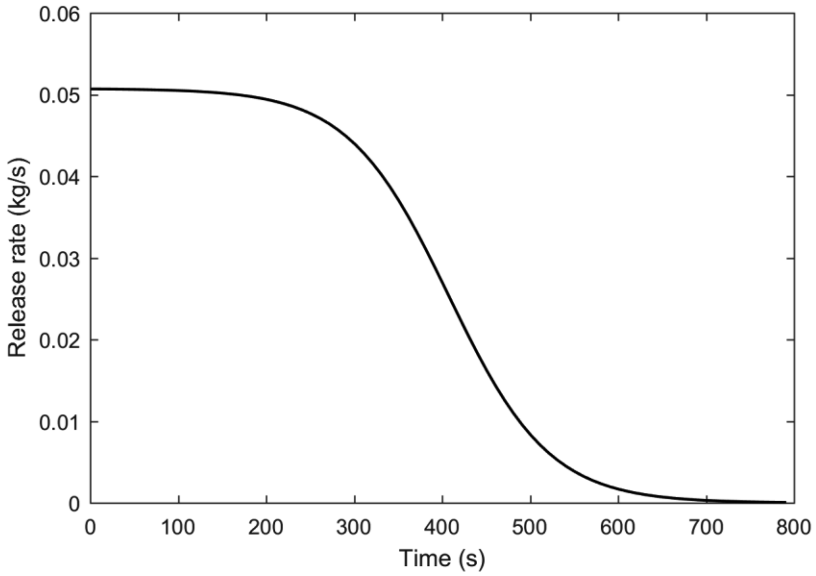


Figure 2. The release rate for the second source term phase for melted and oxidised tungsten from the target, and for melted beryllium from the lower beryllium reflector.

In the third phase, a release is generated by evaporated moderator water containing dissolved radioactive materials. It is assumed that this release begins after 100 seconds, and continuing over a duration of 10,000 seconds. The release rate occurs with a declining trend. In total, it is assumed that 44 per cent of the accessible water vaporizes. The total quantity of steam is based on an estimated 20,000 seconds, though the vaporization taking place during the last few hours is negligible.

In the fourth and final phase, the release occurs as a result of hydrogen detonation, which expels materials released previously from the target in connection with oxidation and melting of tungsten and subsequent deposition in the target area. This release is assumed to begin after 5,000 seconds, followed by instantaneous releases. In total, it is assumed that 0.5 per cent of the accessible material deposited in the target area will be released.

A summary account of the four release phases in the representative source term is provided by Table 1.

Table 1. Summary of quantities released during the postulated event’s four release phases.

Release phase	Materials	Quantity (kg)	Percentage released (%)	Initiation/release duration
1	Helium	30	100	100 s/10 s
	Filter particles	0.01	1	
2	Tungsten target (oxidised and melted)	50.3	41	100 s/17 min
	Beryllium reflector	15.7	100 (noble gases & H-3) 10 (volatile) 1 (less volatile)	
3	Moderator	400	44	100 s/166 min
4	Tungsten target	29.6	0.5	83 min/10 s

3.2. Selection of nuclides and released activity

The data provided by ESS for the representative source term for the postulated event includes 989 nuclides [6]. The estimates would take an excessive amount of time if all these nuclides were included in the dispersion and dose calculations. For this reason, SSM has reduced the number of nuclides in the source term by excluding nuclides that do not give a significant dose contribution or ground deposition. Nuclides were selected for the source term as per the following criteria:

- Nuclides of significance for estimating effective dose over a period of seven days
- Iodine isotopes of significance for estimating equivalent dose to the thyroid over a period of seven days
- Nuclides of significance for estimating effective dose from ground deposition during the first year.

Based on the first two criteria, SSM selected 49 nuclides. Altogether, these represent nearly 100 per cent of the effective dose over seven days. The selection also includes seven iodine isotopes, of which the majority were included to prevent underestimation of equivalent dose to the thyroid. Nuclides of significance for estimating effective dose from ground deposition during the first year coincide with the selected nuclides contributing to effective dose over the first seven days. With this rationale in mind, SSM excluded additional nuclides based on this criterion.

In Table 2, SSM presents the five nuclides contributing the most to effective dose over a period of seven days, the five nuclides contributing the most to effective dose from ground deposition during the first year (weeks 1-52), and the five nuclides contributing the most to effective dose from ground deposition during the first year, disregarding the very first week (i.e. weeks 2-52). The effective dose from ground deposition during the first year, with and without contributions during the first week, as presented in Table 2, illustrates the fact that certain nuclides with a shorter half-life are a significant factor behind ground dose during the first week. However, the significance declines thereafter.

Table 2. Nuclides contributing the most to effective dose over a period of seven days; to effective dose from ground deposition during the first year; and to effective dose from ground deposition during the first year, disregarding the very first week.

Sequence	Contribution to effective dose over a period of seven days	Contribution to effective dose during weeks 1 to 52 due to ground deposition	Contribution to effective dose during weeks 2 to 52 due to ground deposition
1	Gd-148	Hf-172	Hf-172
2	W-187	Ta-182	Ta-182
3	Hf-172	W-187	Hf-175
4	Ta-182	Hf-175	W-181
5	Hf-178n[1]	W-181	Lu-173

[1] In this report, SSM has used the notations for nuclides following the JEFF 3.1 Nuclear Data Library [7].

Table 3 provides a summary account of selected nuclides and released activity to the atmosphere on the part of the postulated event at ESS.

Table 3. Compilation of selected nuclides and released activity to the atmosphere on the part of the postulated event at ESS. The table shows total released activity and activity released during release phase 2 (0-20 min.) and release phase 4 (80-85 min.). The contribution from release phases 1 and 3 to total released activity is negligible. For this reason, the contributions from phases 1 and 3 are set at 0 Bq in the representative source term.

Release group	**Nuclide**	**Half-life**	**Activity (Bq)**		
			Total	0-20 min	80-85 min
Volatile	Cd-109	1.27 y	3.8E+11	3.8E+11	2.7E+09
	I-120	1.36 h	5.8E+11	5.8E+11	2.3E+09
	I-121	2.12 h	6.9E+11	6.8E+11	3.5E+09
	I-122	3.63 min	6.5E+11	6.4E+11	3.3E+09
	I-123	13.2 h	8.4E+11	8.4E+11	5.9E+09
	I-124	4.18 d	1.1E+11	1.1E+11	7.7E+08
	I-125	59.4 d	7.5E+11	7.5E+11	5.4E+09
	I-126	13.0 d	2.9E+10	2.9E+10	2.1E+08
	Te-118	6.00 d	8.8E+11	8.7E+11	6.3E+09
Less volatile	Ce-139	138 d	8.8E+11	8.8E+11	6.3E+09
	Eu-147	24.0 d	1.2E+12	1.2E+12	8.7E+09
	Gd-146	48.3 d	9.7E+11	9.7E+11	7.0E+09
	Gd-148	74.6 y	3.5E+10	3.5E+10	2.5E+08
	Gd-153	240 d	8.2E+11	8.1E+11	5.9E+09
	Hf-170	16.0 h	5.8E+12	5.8E+12	3.9E+10
	Hf-172	1.87 y	4.1E+12	4.1E+12	3.0E+10
	Hf-173	23.9 h	1.1E+13	1.1E+13	8.0E+10
	Hf-175	70.0 d	1.1E+13	1.1E+13	8.2E+10
	Hf-178n	31.0 y	2.5E+11	2.4E+11	1.7E+09
	Hf-181	42.4 d	9.5E+11	9.4E+11	6.8E+09
	Lu-169	1.42 d	5.9E+12	5.8E+12	4.1E+10
	Lu-170	2.01 d	7.8E+12	7.8E+12	5.6E+10
	Lu-171	8.25 d	9.3E+12	9.3E+12	6.7E+10
	Lu-172	6.70 d	5.2E+12	5.1E+12	3.7E+10
	Lu-173	1.34 y	6.7E+12	6.7E+12	4.8E+10
	Re-182	2.67 d	9.3E+11	9.2E+11	6.5E+09
	Re-184	38.0 d	6.8E+11	6.7E+11	4.9E+09
	Re-186	3.78 d	1.1E+13	1.1E+13	7.9E+10
	Re-188	17.0 h	8.3E+12	8.3E+12	5.6E+10
	Ta-173	3.14 h	8.4E+12	8.4E+12	4.6E+10
	Ta-174	1.14 h	8.9E+12	8.9E+12	3.5E+10
	Ta-175	10.5 h	1.3E+13	1.3E+13	8.5E+10
	Ta-176	8.09 h	1.6E+13	1.6E+13	1.1E+11
	Ta-177	2.35 d	2.2E+13	2.2E+13	1.6E+11
	Ta-179	1.61 y	2.2E+13	2.2E+13	1.5E+11
	Ta-180	8.08 h	7.2E+12	7.2E+12	4.6E+10
	Ta-182	115 d	7.4E+12	7.4E+12	5.3E+10
	Ta-183	5.09 d	1.1E+13	1.1E+13	8.0E+10
	Ta-184	8.70 h	4.0E+12	3.9E+12	2.6E+10
	Tb-149	4.12 h	8.1E+11	8.1E+11	4.7E+09
	Tm-166	7.70 h	3.6E+12	3.6E+12	2.6E+10
	Tm-167	9.25 d	4.3E+12	4.2E+12	3.0E+10
	W-177	2.20 h	1.3E+13	1.3E+13	6.3E+10
	W-178	21.6 d	2.2E+13	2.2E+13	1.6E+11
	W-181	121 d	8.6E+13	8.5E+13	6.1E+11
	W-185	75.1 d	2.6E+14	2.6E+14	1.9E+12
	W-187	23.9 h	6.7E+14	6.6E+14	4.6E+12
	Yb-166	2.36 d	3.4E+12	3.4E+12	2.4E+10
	Yb-169	32.0 d	7.0E+12	6.9E+12	5.0E+10

3.3. Other parameters in the source term

In the case of the postulated event, SSM assumes that the release occurs via the pressure relief line from the target area, which has an exhaust point on the roof of the target building at a height of 30 metres above the ground. The coordinates of the outlet point are N 6177910 and E 390002 (SWEREF99) [8].

SSM has assumed that all the iodine in the release is in elemental form. This is a conservative assumption, since the dose coefficients for elemental iodine are higher than the dose coefficients for particulate and organic iodine.

There is no assumption by SSM that the release has any heat content. This means that SSM does not expect any plume rise to occur due to thermal energy. Nor does SSM expect any plume rise owing to vertical movement of the release. Calculations of plume rise are subject to great uncertainty. In order to exclude possible underestimation of the calculated doses in the vicinity, SSM has applied a conservative assumption that no plume rise will occur.

4. Dispersion and dose calculations

SSM performed dispersion and dose calculations based on historical weather data for the purpose of identifying the distances at which dose criteria and intervention levels are exceeded in the case of the postulated event at ESS. Calculations were performed using weather data comprising the period 2006-2015, with a total of around 2,750 dispersion and dose calculations, thus giving a sufficient statistical basis for taking into account variations in weather conditions around ESS.

This chapter presents distances at which dose criteria and intervention levels for different protective actions are exceeded if the respective 70, 80 or 90 per cent of all occurring weather scenarios are taken into account. For more information about the selection of reference levels, dose criteria, intervention levels and calculation methods, please see this translated publication from SSM: report 2017:27e, “Review of Swedish emergency planning zones and distances” [3], and Appendix 1.

4.1. Contributions from different exposure pathways

SSM has identified significant exposure pathways to enable an assessment of urgent protective actions that are warranted in the case of the postulated event at ESS. SSM carried this out by studying contributions occurring via different exposure pathways to an unprotected person over a period of seven days. The effective dose over seven days includes contributions from the exposure pathways of inhalation (inhalation dose), passing radioactive cloud (cloud dose), and ground deposition (ground dose). The level of contributions from the different exposure pathways to effective dose over seven days is affected by weather conditions during the release in question. At low wind speeds, the relative contribution from inhalation dose is larger than from the other dose contributions. If rain occurs, the relative contribution from ground dose increases compared to other dose contributions.

In the case of the postulated event at ESS, the largest contribution to effective dose over seven days will be from inhalation dose, followed by ground dose and thereafter cloud dose. Inhalation dose represents more than half of the effective dose, whereas the cloud dose is insignificant. In its turn, the contribution from Gd-148 represents more than half of the contribution to effective dose over seven days, regardless of whether or not the release occurs in connection with precipitation. Since Gd-148 emits only alpha radiation, its contribution to effective dose is entirely from the inhalation dose.

In the case of the postulated event at ESS, the distances will become longer on the part of adults where the dose criteria for effective dose over seven days are exceeded, than compared to children. Usually, children receive a higher radiation dose than adults in cases of equivalent exposure due to children’s greater sensitivity to ionising radiation. This factor is reflected by the dose coefficients, which are usually higher for children than compared to adults. In the case of the postulated event at ESS, the dose contribution from inhalation predominates. Since adults inhale more air per unit of time compared to children, adults receive a larger intake of radioactive substances. The difference in inhaled air volume per unit of time is greater than the difference in dose coefficients between children and adults in the case of these nuclides.

4.2. Evacuation

The outcomes of the dispersion and dose calculations in the case of the postulated event at ESS demonstrate that the dose criterion for evacuation, at 20 mSv effective dose over seven days, is not exceeded outside the area with restricted access, even if 90 per cent of all occurring weather scenarios are taken into account. Thus, precautionary evacuation, and evacuation during an ongoing release, are unwarranted. The outcomes of the dispersion and dose calculations also demonstrate that the intervention level for relocation due to ground deposition, at 800 kBq/m^2 of Ta-182, is not exceeded outside the area with restricted access, even if 90 per cent of all occurring weather scenarios are taken into account. Thus, it is unwarranted to plan for relocation due to ground deposition. For a more detailed description of the intervention level for relocation due to ground deposition, see Appendix 1.

4.3. Sheltering

Figure 3 shows the distribution of distances at which the dose criterion for sheltering, at 10 mSv effective dose over seven days, is exceeded on the part of adults in the case of the postulated event at ESS. The greatest distance at which the dose criterion is exceeded is shorter than 400, 700, and 1,400 metres, respectively, if 70, 80 and 90 per cent of the occurring weather scenarios are taken into account. The corresponding distances are somewhat shorter for children, see Figure 4.

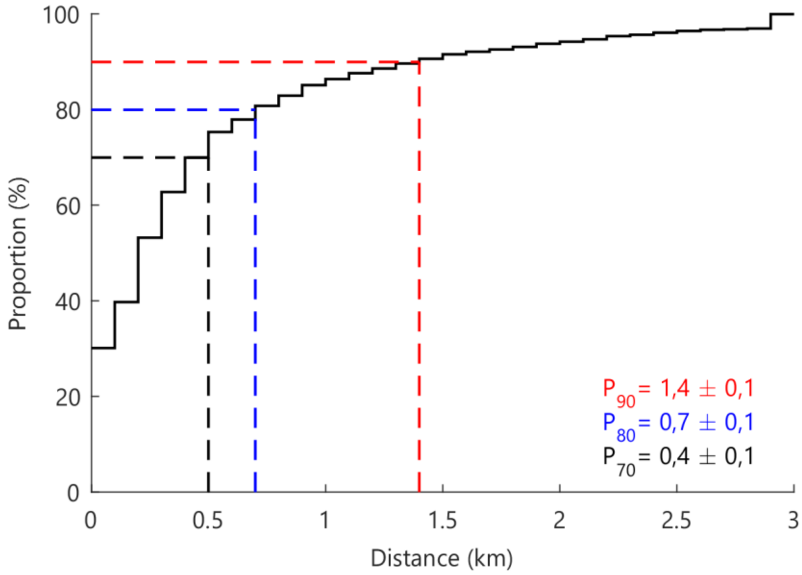


Figure 3. Distribution of the greatest distances at which the dose criterion for sheltering, at 10 mSv effective dose, is exceeded for adults in the case of the postulated event at ESS. In the figure, the 70th, 80th and 90th percentiles are marked.

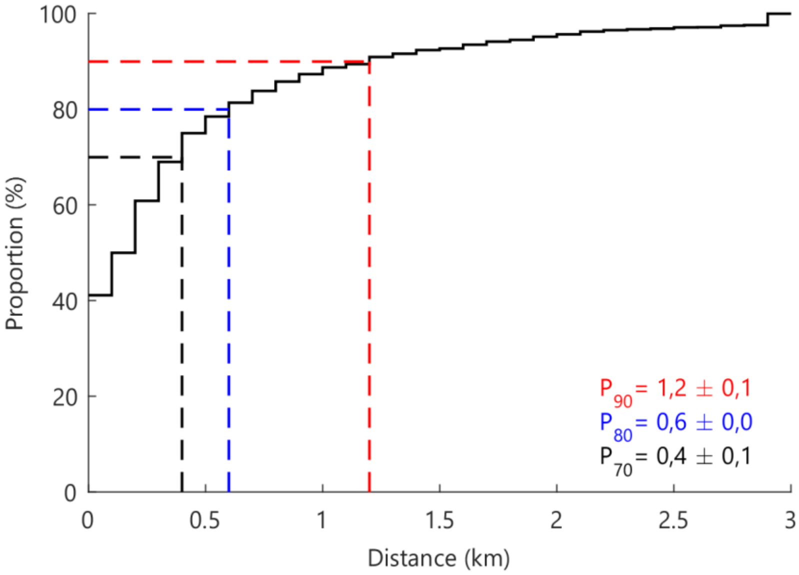


Figure 4. Distribution of the greatest distances at which the dose criterion for sheltering, at 10 mSv effective dose, is exceeded for children aged 12 months in the case of the postulated event at ESS. In the figure, the 70th, 80th and 90th percentiles are marked.

4.4. Iodine thyroid blocking

The outcomes of the dispersion and dose calculations demonstrate that the dose criterion for predistribution of iodine thyroid blocking (ITB), at 50 mSv equivalent dose to the thyroid in the case of both adults and children, is not exceeded outside the area with restricted access, even if 90 per cent of all occurring weather scenarios are taken into account. SSM has also looked into the distances within which the dose criterion for intake of predistributed ITB, at 10 mSv equivalent dose to the thyroid in the case of children, is exceeded. Within this distance, it may be warranted to recommend sheltering to reduce thyroid doses to children, although this would be unwarranted on the basis of effective dose. The outcomes of the dispersion and dose calculations do demonstrate, however, that the dose criterion for intake of predistributed ITB is not exceeded outside the area with restricted access, even if 90 per cent of all occurring weather scenarios are taken into account. Therefore, it is unwarranted to conduct planning for sheltering in a radius around ESS solely for the purpose of reducing thyroid doses to children.

.

5. Basis for the urgent protective action planning zone

Another outcome from the dispersion and dose calculations shows that sheltering may be warranted for adults at respective distances extending to 400, 700 and 1,400 metres from the outlet point at ESS if 70, 80 and 90 per cent, respectively, of all occurring weather scenarios are taken into account. The corresponding distances are somewhat shorter for children. The outcomes also show that neither evacuation of the population, nor intake of ITB by the population, would be warranted during an emergency at ESS. The overall conclusion of SSM is to recommend the establishment of a UPZ to surround ESS. Within this zone, the protective action of sheltering should be pre-planned.

As far as concerns temporary visitors, planning for sheltering should imply enabling of either indoor stay within the UPZ, or leaving the area by foot in the event of an alarm issued by ESS. In the assessment of SSM, it is feasible to have the planning encompass more than 70 per cent of all occurring weather scenarios relating to ESS. For those working in the zone, it should be possible to implement sheltering within a distance greater than 400 metres, while at the same time having temporary visitors leave the UPZ in time prior to a release. However, SSM views it as infeasible to have the planning encompass 90 per cent of all occurring weather scenarios. This is because of the unlikelihood of temporary visitors leaving a 1,400 metre UPZ in time prior to a release. Consequently, the overall conclusion of SSM is that a UPZ to surround ESS should encompass 80 per cent of all occurring weather scenarios. Thus, its range should be approximately 700 metres. This level of ambition is on a par with the suggestion of SSM concerning emergency planning zones and distances surrounding other facilities whose activities involve ionising radiation, where emergency preparedness planning is required to protect the population.

It is shown from the analysis that the postulated event has a rapid sequence with a short period of forewarning. For this type of event, the assessment of SSM is that the criteria are met for a radiological emergency. For this reason, SSM is of the opinion that a system should be in place for issuing warnings urging the general public to stay indoors, seek shelter, or leave the UPZ should an emergency take place at the facility with a likely impact on the surroundings. SSM also considers that an Important Public Announcement (IPA) is an appropriate tool for this purpose. Issuing timely alerts and warnings presupposes ESS initiating the procedure for broadcasting an IPA.

SSM also considers that the UPZ should be defined by natural geographical boundaries that make the zone easy to identify by the public and emergency workers alike. The UPZ should also have a design enabling effective implementation of planned protective actions. This is also recommended in the event of future expansion around the ESS site.

To the southwest, the UPZ should be delineated by a suitable road through Science Village, at an approximate distance of 700 m. To the northeast, the property of ESS gives adequate distance. To the northwest, the E22 motorway is located within a distance shorter than 700 metres from the target building of ESS. Nevertheless, SSM is of the opinion that the E22 can be used as a boundary for the UPZ, also that motorists using the E22 should be permitted to pass by during an ongoing release. When passing by in a vehicle on the E22, the potential radiation dose received is lower than the dose that could be received by temporary visitors leaving the UPZ by foot. On the other hand, stopped traffic would risk delaying passing vehicles over an extended period of time, thus resulting in possibly higher radiation doses. To the southeast, the UPZ should be suitably delineated at an approximate distance of 700 m.

Outside the area with restricted access around ESS, SSM has assessed that no ground deposition can occur in connection with emergencies that justify an extended planning distance, which is proposed by SSM to surround the nuclear power plants and the interim spent fuel storage facility at Oskarshamn.

6. Sensitivity analyses

SSM conducted sensitivity analyses for the purpose of looking into how the distances at which exceeded dose criteria and intervention levels are impacted by the kinds of uncertainty defined by the basis of the representative source term for the postulated event. SSM identified two kinds of uncertainty in the underlying material that are of key significance: the concentration of radioactive material in the tungsten block hit by the proton beam, in addition to the particle size of the release in question.

6.1. Distribution of radioactive material in the target

In the case of the postulated event, ESS accounted for the existence of uncertainty in terms of the concentration of radioactive material contained in the tungsten block hit by the proton beam [5]. Analyses from ESS demonstrate that the surfaces hit by the proton beam may have a concentration of radioactive material exceeding the average level of the target by 50 per cent. Against this background, SSM conducted a sensitivity analysis assuming a 50 per cent larger release of radioactive material from the target than compared to the representative source term.

The outcomes of this sensitivity analysis, with a higher concentration of radioactive material in the target, show an increase in the distances at which dose criteria and intervention levels for protective actions are exceeded, with the exception of distances linked to ITBs. These distances are not affected. The distances increase at which the dose criterion for evacuation, at 20 mSv effective dose over seven days, is exceeded, which means that evacuation outside the area with restricted access may be warranted if 70 per cent or more of all occurring weather scenarios are taken into account. The distances also increase at which the intervention level is exceeded for relocation due to ground deposition of 800 kBq/m^2 of Ta-182. Thus, relocation outside the area with restricted access owing to ground deposition cannot be ruled out if 90 per cent of all occurring weather scenarios are taken into account. The distances increase by just over 60 per cent at which the dose criterion for sheltering, at 10 mSv effective dose over seven days, is exceeded.

6.2. Particle size

ESS presented findings from experiments looking into the aerodynamic diameter of particles in the target area [9]. However, the experiments accounted for by ESS are insufficiently broad in scope to enable drawing of definite conclusions concerning the distribution of particle sizes occurring in a release in the case of the postulated event.

SSM has assumed a particle size in the release having a diameter of 1 micrometre of Activity Median Aerodynamic Diameter (AMAD) in the dispersion and dose calculations. Particle size affects the dose coefficients for inhalation doses, as do the processes carried out as part of the dispersion calculations defining the concentration of airborne particles and deposition on the ground. For this reason, assumed particle size has an impact on the distances at which dose criteria and intervention levels are exceeded. SSM has conducted a sensitivity analysis on the part of larger particles having a diameter of 5 micrometres (AMAD).

The outcomes of this sensitivity analysis, based on larger particle size, show an increase in the distances at which dose criteria and intervention levels for protective actions are exceeded, with the exception of distances linked to ITB. These distances are not affected.

The distances increase at which the dose criterion for evacuation, at 20 mSv effective dose over seven days, is exceeded, which means that evacuation outside the area with restricted access may be warranted if 80 per cent or more of all occurring weather scenarios are taken into account. The distances also increase at which the intervention level is exceeded for relocation due to ground deposition of 800 kBq/m^2 of Ta-182. Thus, relocation outside the area with restricted access owing to ground deposition cannot be ruled out if 90 per cent of all occurring weather scenarios are taken into account. The distances increase by just over 30 per cent at which the dose criterion for sheltering, at 10 mSv effective dose over seven days, is exceeded.

It is not possible for SSM to conduct a sensitivity analysis for particles of smaller size. The model used by SSM for performing dispersion calculations is unsuitable for particles having diameters smaller than 1 micrometre (AMAD). For this reason, it is not possible for SSM to assess how particle sizes under 1 micrometre (AMAD) have an impact on distances at which dose criteria and intervention levels are exceeded.

6.3. Conclusion drawn from sensitivity analyses

In both cases, the outcomes of the sensitivity analyses, based on a higher concentration of radioactive material in the target and assuming larger particle size, demonstrate that the risk of requiring off-site evacuation can no longer be ruled out. Another factor is the increasing distances at which sheltering may be warranted. However, for the corresponding percentage of weather scenarios, the distances at which evacuation may be warranted are encompassed by the distances at which sheltering may be warranted in the case of the postulated event. Sheltering in the affected buildings in question, within an approximate radius of 700 metres, offers adequate protection. Consequently, SSM does not consider that the outcomes of the sensitivity analyses warrant any planning for evacuation around ESS. On the other hand, the outcomes of the sensitivity analyses reinforce SSM’s standpoint on recommending a range of the UPZ extending approximately 700 m, with planning in place advised for sheltering within this zone.

7. Residual dose

SSM used the reference level 20 mSv effective dose as a basis for dimensioning the proposed UPZ to surround ESS. The reference level applying to ESS is stipulated by the Radiation Protection Ordinance [10]. Here, it refers to residual dose, in other words, a dose received after protective actions have been taken. The actual protective actions that can be taken in connection with a nuclear or radiological emergency depend on the circumstances of the event. However, planning for emergency preparedness has the aim of keeping doses below the selected reference level.

A reference level is not directly applicable to dispersion and dose calculations. With this rationale in mind, SSM selected dose criteria for different protective actions applying to an unprotected person over a period of seven days, and used these criteria in the dispersion and dose calculations. For example, in the case of the protective action of sheltering, the dose criterion is 10 mSv effective dose to an unprotected person over a period of seven days. Estimated distances produced using this dose criterion serve as a basis of SSM's proposal regarding recommended distances within which sheltering should be pre-planned.

In order to verify that the emergency preparedness planning proposed by SSM makes it possible to keep doses below the reference level, SSM performed calculations of residual effective dose, with the assumption that sheltering is feasible out to an approximate radius of 700 metres from ESS. In these calculations, SSM presupposes the possible existence of buildings just outside the perimeter protection surrounding ESS, at an approximate distance of 200 m from the outlet point. For this reason, SSM performed calculations of possible radiation doses that might be received at this distance during sheltering. In addition, SSM assumes that sheltering is a possibility, not only in buildings providing satisfactory protection against exposure to ionising radiation in the event of a release, e.g. relatively large office buildings presupposed by SSM to reduce radiation doses to one-tenth (shielding factor of 0.1), but also in smaller buildings similar in scale to ordinary detached houses, where SSM assumes that radiation doses are reduced by half (shielding factor of 0.5). SSM also performed calculations on the likely radiation dose to an individual who is located outdoors during the release, just outside the UPZ.

It is shown from the dispersion and dose calculations that an adult located indoors at a distance of 200 m from the outlet point at the ESS facility may receive an effective dose of approximately 10 mSv in a building offering relatively inferior protection, and an effective dose of approximately 2 mSv in a building offering better protection, if 90 per cent of all weather scenarios are taken into account. It is also shown from the dispersion and dose calculations that an adult located outdoors at a distance of 700 m from the outlet point at the ESS facility may receive an effective dose of approximately 13 mSv if 90 per cent of the weather scenarios are taken into account. On the whole, the calculations show that the proposed range of the UPZ is adequate for keeping doses below the reference level of 20 mSv in the case of the postulated event at ESS, with the assumption that the protective action of sheltering is carried out in this zone.

8. Remediation and radiation monitoring

8.1. Remediation

SSM has calculated the greatest distances for the postulated event at ESS warranting possible consideration of different remedial actions. The outcomes are shown in Figures 5 to 7, and summarised in Table 4. The distances presented here correspond to expected additional doses from ground deposition during the first year following this event, in the interval 1-50 mSv effective dose. An analysis of the extent to which remedial actions are warranted following an emergency occurring at ESS must be based on the actual ground deposition that has occurred owing to the emergency, while also taking into account ingrowth and half-lives on the part of the nuclides contributing most significantly to ground dose in the long term. For this reason, the outcomes presented should only be viewed as indicative in terms of possibly warranted remedial actions in the case of an emergency situation at ESS. For a detailed description of the different intervention levels for remediation, see Appendix 1.

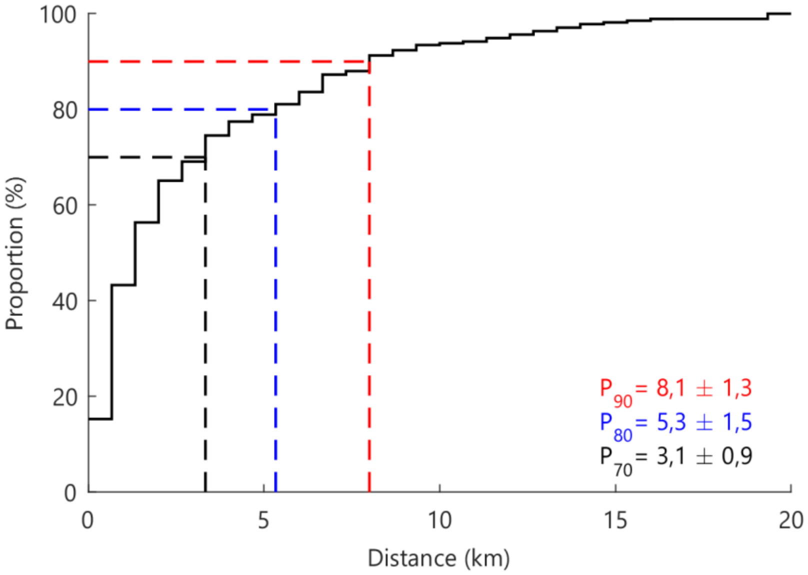


Figure 5. Distribution of the greatest distances at which 40 kBq/m^2 of ground deposition of Ta-182 is exceeded due to the postulated event at ESS. The ground deposition is estimated to result in a radiation dose of 1 mSv during the first year.

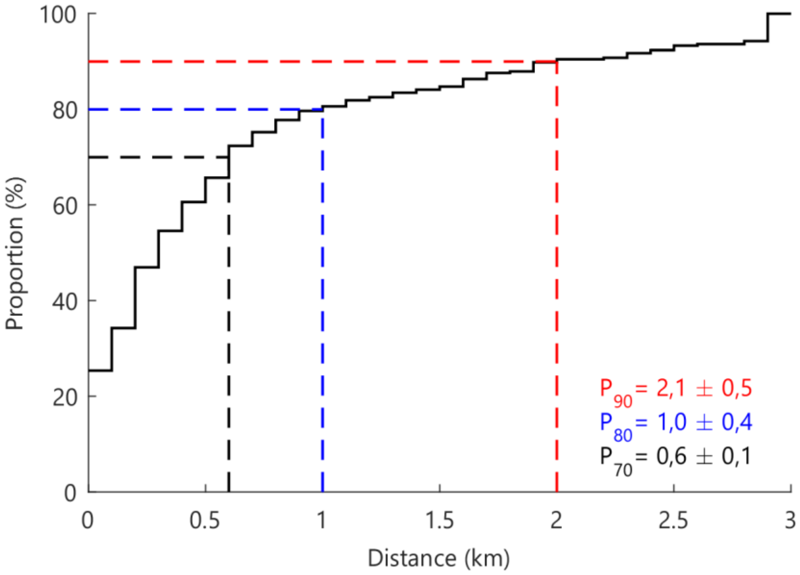


Figure 6. Distribution of the greatest distances at which 200 kBq/m^2 of ground deposition of Ta-182 is exceeded due to the postulated event at ESS. The ground deposition is estimated to result in a radiation dose of 5 mSv during the first year.

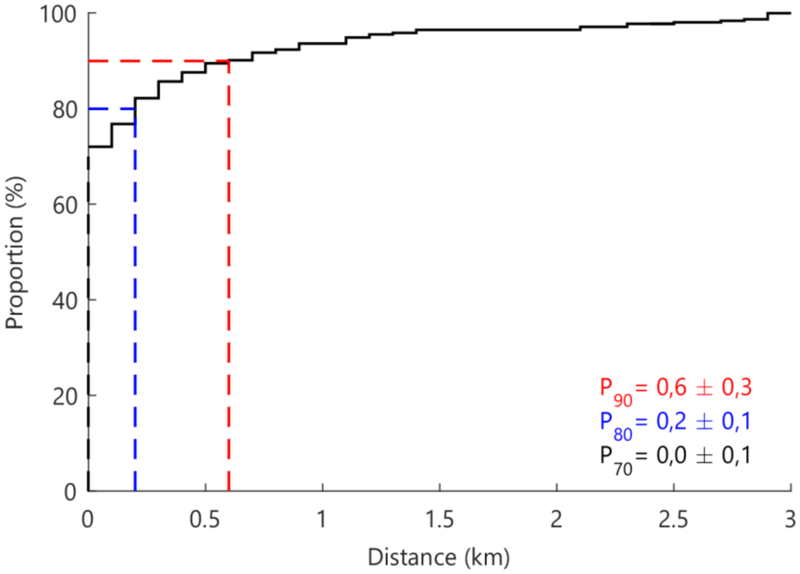


Figure 7. Distribution of the greatest distances at which 400 kBq/m^2 of ground deposition of Ta-182 is exceeded due to the postulated event at ESS. The ground deposition is estimated to result in a radiation dose of 10 mSv during the first year.

Table 4. Summary of the greatest distances at which intervention levels for remediation are exceeded in the case of the postulated event at ESS if 70, 80 and 90 per cent, respectively, of all occurring weather scenarios are taken into account ("-" signifies that the intervention level is not exceeded outside the site of the facility). The doses shown in the table refer to additional effective dose due to ground deposition during the first year.

Percentile	Distance (km)
A remediation plan should be produced and basic remediation measures may be warranted (higher than 1 mSv)	
70	~ 3
80	~ 5.5
90	~ 8
Basic remediation measures are likely to be warranted (higher than 5 mSv)	
70	~ 0.5
80	~ 1
90	~ 2
Advanced remediation measures may be warranted (higher than 10 mSv)	
70	-
80	-
90	~ 0.5
Advanced remediation measures are likely to be warranted (higher than 20 mSv)	
70	-
80	-
90	-
Advanced remediation measures are likely to be insufficient for allowing resettlement of the area for several years (higher than 50 mSv)	
70	-
80	-
90	-

8.2. Radiation monitoring

In the case of the postulated event at ESS, the period of forewarning is brief, with a rapid release sequence. Consequently, a prerequisite for reconstructing the event sequence, and retrospectively estimating the radiation doses to individuals located off-site at the time of a release from ESS, presupposes automatic monitoring stations that perform continuous measurements. Instruments of this kind can also be an important tool for enabling rescue services to determine whether a release is occurring, as well as when a release has ceased. SSM is of the view that instruments that measure dose rate are sufficient for these purposes.

The outcomes of dispersion and dose calculations show that remediation may be warranted as a consequence of the postulated event at ESS. For this reason, it may be necessary to perform radiation monitoring with the objective of mapping the extent of the deposition and activity levels of different nuclides. SSM's analysis shows that gamma-emitting nuclides would predominate the radiation dose from ground deposition. One approach to mapping ground deposition of gamma-emitting nuclides can be to combine instruments that measure dose rate with instruments that measure activity levels of individual nuclides.

SSM’s analysis also shows that the risk of a ground deposition of Gd-148, an emitter of alpha radiation, cannot be ruled out in the case of the postulated event at ESS. Gd-148 only emits alpha radiation, which makes it difficult to detect in the field. On the other hand, the outcomes of the dispersion and dose calculations show that the gamma-emitting nuclide Gd-146 can be used as a marker for estimating ground deposition of Gd-148 even at low deposition levels, see also Appendix 1. The marker nuclide Gd-146 can be detected using the same instruments that are used to map ground deposition of other gamma-emitting nuclides.

References

[1] *Beslut om beredskapskategori för ESS* (Decision on emergency preparedness category for ESS), SSM2018-1037-5, Swedish Radiation Safety Authority, 2018.

[2] *Underlag till placering i beredskapskategori för ESS och beredskapsplaneringen för ESS* (Underlying documentation for placement of ESS in an emergency preparedness category, and emergency preparedness planning for ESS), SSM2018-1037-4, Swedish Radiation Safety Authority, 2018.

[3] SSM report 2017:27e: “Review of Swedish emergency planning zones and distances”, Swedish Radiation Safety Authority, 2017.

[4] ESS report. *Komplettering – reviderat källtermsunderlag* (Supplementary information. Revised source term documentation), SSM2018-1037-2, Swedish Radiation Safety Authority, 2018.

[5] ESS report. “Description of the bounding target loss of cooling accident,” ESS-0092293, ESS, 3 April 2018.

[6] ESS report. “AA03a_LP-104B Source term to SSM”, ESS-0095522, ESS, 3 April 2018.

[7] “The JEFF-3.1 Nuclear Data Library,” No. 6190, OECD/NEA, 2005.

[8] ESS report. “Source term for emergency planning zone,” ESS-0274564, ESS, 3 April 2018.

[9] ESS report. “Tungsten Oxidation and AeroSol Transport (TOAST)”, ESS-0151001, ESS, 3 April 2018.

[10] Swedish Code of Statutes, Radiation Protection Ordinance (2018:506), 2018.

[11] ICRP, “Compendium of Dose Coefficients based on ICRP Publication 60,” ICRP Publication 119. Ann. ICRP 41 (Suppl.), 2012.

Appendix 1

Foreword

This appendix accounts for the methods, analyses and standpoints that are specific to ESS. Other methods, analyses and standpoints covered and accounted for in this report are discussed in SSM report 2017:27e, “Review of Swedish emergency planning zones and distances” [3].

Intervention levels

A release from ESS could give rise to a ground deposition in which several nuclides contribute to ground dose. During the first seven days, the contribution from W-187 predominates the effective dose from ground deposition. However, W-187 has a half-life of approximately 24 hours, for which reason other nuclides with a longer half-life will predominate the ground dose in the longer term. Hf-172, followed by Ta-182, are the two nuclides contributing the most to ground dose during the first year. Nonetheless, a large proportion of the ground dose from Hf-172 is from its secondary decay product Lu-172, whose ingrowth occurs during the first weeks before equilibrium is achieved. This factor facilitates more straightforward estimation of the yearly dose from ground deposition on the basis of measurements of Ta-182, than compared to Hf-172/Lu-172. For this reason, intervention levels are given for Ta-182. During the first year, SSM’s estimation is that one–fifth of the ground dose would originate from Ta-182. This is a conservative assumption, as short-lived nuclides are also taken into account.

SSM has set the intervention level for relocation due to ground deposition at 800 kBq/m^2 of Ta-182, corresponding to a ground dose of 20 mSv effective dose during the first year. Development of this intervention level involved taking into account a penetration depth of 1 cm, assuming that sheltering reduces the dose from ground deposition by half, also that an average individual spends 80 per cent of their time indoors over the course of one year.

SSM has set the intervention levels for remediation in accordance with the same principle as above. The intervention levels are set at 40 kBq/m^2 of Ta-182 for an annual additional dose of 1 mSv effective dose, 200 kBq/m^2 of Ta-182 for an annual additional dose of 5 mSv effective dose, and 400 kBq/m^2 of Ta-182 for a yearly additional dose of 10 mSv effective dose. The intervention level at which advanced remediation measures are likely to be warranted matches the intervention level for relocation due to ground deposition, i.e. 800 kBq/m^2 of Ta-182. The intervention level at which advanced remediation measures are likely to be insufficient for allowing resettlement of the area (for several years) is set at 2,000 kBqm^2 of Ta-182.

The nuclide Gd-148 would dominate the inhalation dose should a release occur from ESS. The nuclide Gd-148 emits only alpha radiation, which makes it difficult to detect in the field. The nuclide Gd-146 emits gamma radiation, so it can be used as a marker for mapping ground deposition of Gd-148. Measurement of Gd-146 can be performed using a nuclide-specific technique, either applied directly to Gd-146, or indirectly by detecting the decay product, Eu-146. In SSM’s estimation, a ground deposition of 10 kBq/m^2 of Gd-146 corresponds to a ground deposition of approximately 0.4 kBq/m^2 of Gd-148. This estimation is based on the relationship between Gd-146 and Gd-148 in the target, in addition to the presumption that both the isotopes are released and dispersed at the same magnitude.

Meteorological wind data

A wind rose illustrates wind directions and wind speeds at a specific location for a defined height above the ground. The wind direction indicates from which direction the wind blows. Wind roses for ESS have been generated for the data point in the meteorological data (HIRLAM E05) that lies closest to the outlet point of this facility. The wind rose illustrates the wind direction and wind speed conditions at a height of 25 metres above the ground surface, distributed between 24 wind directions and 8 wind speed intervals, see the left-hand wind rose shown in Figure 8. Calm conditions and weak wind (below 0.5 m/s) are excluded in the wind rose as it is difficult to assess wind direction in these cases. However, these conditions only represent approximately 0.4 per cent of all occurring weather scenarios. Since ground deposition of radioactive materials is significantly affected by precipitation, a wind rose is also shown illustrating wind directions during precipitation conditions (the lower limit for precipitation is set at 0.2 mm/h of precipitation), see the right-hand wind rose shown in Figure 8. Figure 9 illustrates wind speed at a height of 25 metres, in the form of a histogram. Average wind speed at this height is 4.5 m/s.

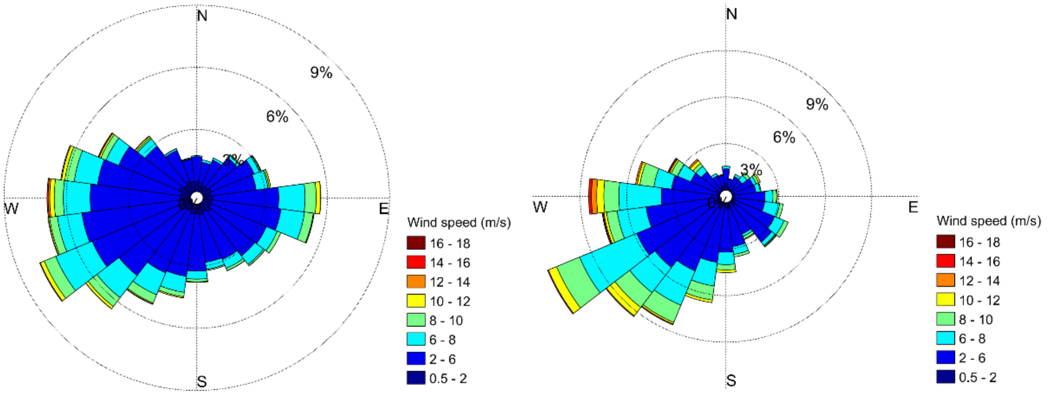


Figure 8. Wind roses for ESS: in total (to the left) and only during precipitation (to the right). Weak winds are not illustrated in the figures.

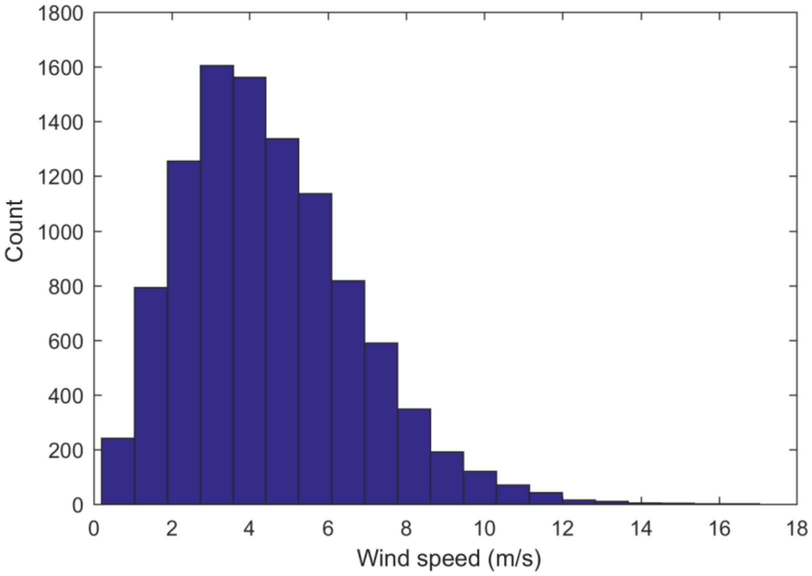


Figure 9. Wind speed at a height of 25 metres in the vicinity of ESS. Count is the number of occurrence in the data set.

Dispersion and dose calculations

Dispersion calculations

SSM's analysis of possible impacts on the population due to a release from ESS has a focus on the vicinity of this facility. Consequently, with the aim of improving this analysis, SSM modified certain parameters of the dispersion calculations in relation to previous sensitivity analyses conducted on the part of other facilities [3]. SSM conducted more realistic modelling of vertical wind shear (trifurcation). Due to the brief release sequence, SSM also used a higher frequency of model puffs (quantities of released activity). SSM also used an adaptation of the advection time step (the course of time step when the activity quantity's horizontal air movement is monitored in the calculations) in relation to the selected resolution in the computational grid and the prevailing average wind speed at release height. This adaptation constitutes an improved capacity for modelling of effects at short distances from the outlet point. An additional aspect is SSM's use of the dispersion and dose calculations for ESS to calculate the contribution from ground dose over the course of seven days by applying RIMPUFF, a model for calculating dispersion and dose. This was done by having the modelling of activity concentration in the air and on the ground cover a period of seven days after the initial release.

Absorption type

The nuclide-specific and age-specific dose coefficients used by SSM in the dose calculations are sourced from ICRP 119 [11], Table G1 (aerosols), and Table H1 (reactive gases). For all the nuclides, the dose coefficients were selected conservatively on the basis of the absorption type[1] (F/M/S/V) giving the largest dose contribution to adults. This is because adults, in the case of the ESS facility, would receive larger inhalation doses than children. The absorption types used in the dose calculations are shown in Table 5. In some cases, two absorption types are used to illustrate the same substance. This is because in

---

[1] The abbreviations F, M and S signify different rates (Fast, Medium and Slow) in connection with uptake by the body after inhalation. Iodine is treated as a reactive gas, and instead having absorption type V (Vapour).

these cases, different isotopes of the same element have different absorption types giving the largest dose to an adult per inhaled unit of Becquerel.

Table 5. Assumed absorption type when calculating inhalation dose.

Element	Absorption type
Cd	F
Ce	S
Eu	M
Gd	F/M
Hf	F/M
I	V
Lu	S
Re	M
Ta	M/S
Tb	M
Te	S
Tm	M
W	F
Yb	S

Decay and ingrowth

In the calculations of source terms, SSM calculated decay and ingrowth individually for all 989 nuclides. In the case of some nuclides, however, the model for calculating dispersion and dose, RIMPUFF, cannot take ingrowth into account. For these nuclides, SSM instead modelled ingrowth by using a simplified procedure. For each nuclide, the dose calculations include the components of inhalation dose, cloud dose, and ground dose. As far as concerns inhalation dose, the dose coefficients already take into account ingrowth of any prospective decay products occurring following a case of intake. As regards cloud dose and ground dose, SSM has, in the cases where equilibrium occurs during the release, totalled the dose coefficients for the corresponding contributions on the part of parent nuclides and decay products, as shown in Table 6. In these cases, the decay product is excluded from the source term to avoid taking decay products into account twice.

In other cases, where equilibrium does not occur during the release, SSM modelled the nuclides individually, excluding ingrowth from the parent nuclide to the decay product. This simplified procedure results in slight underestimation of the decay product's level of activity. The effect is likely to be most significant for ground dose, although the predominant exposure pathway through inhalation is impacted less significantly since the inhalation dose only occurs while the release is passing. In SSM's calculations, excluding ingrowth results in underestimation of ground dose by approximately 7 per cent during the first week. The total effect on effective dose over a period of seven days is thus in the range of 1 per cent, which is negligible in this context in relation to other uncertainties in the source term and the calculations of dispersion and dose. This conclusion is based on calculations performed by SSM showing that the ground dose contributes 10-25 per cent of the total effective dose during seven days.

An additional special case considered by SSM, by applying a simplified procedure, is ingrowth of I-122 from the parent nuclide, Xe-122. In this case, I-122 is modelled in the dispersion and dose calculations by setting the half-life equal to the parent nuclide's half-life. SSM is of the opinion that this approximation is reasonable, since both the nuclides are in equilibrium already once the release is in progress.

Table 6. Nuclides for which a simplified procedure is applied to decay and ingrowth in the dispersion and dose calculations.

Nuclide	Decay product	Summed coefficients
Gd-146	Eu-146	Cloud and ground dose
Hf-172	Lu-178m	Cloud and ground dose
Hf-178n	Hf-178m	Cloud dose
Ta-183	W-183m	Cloud dose
Te-118	Sb-118	Cloud and ground dose

2018:22e

The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

The Swedish Radiation Safety Authority works proactively and preventively to protect people and the environment from the harmful effects of radiation, now and in the future. The Authority issues regulations and supervises compliance, while also supporting research, providing training and information, and issuing advice. Often, activities involving radiation require licences issued by the Authority. The Swedish Radiation Safety Authority maintains emergency preparedness around the clock with the aim of limiting the aftermath of radiation accidents and the unintentional spreading of radioactive substances. The Authority participates in international co-operation in order to promote radiation safety and finances projects aiming to raise the level of radiation safety in certain Eastern European countries.

The Authority reports to the Ministry of the Environment and has around 300 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

Strålsäkerhetsmyndigheten
Swedish Radiation Safety Authority

SE-171 16 Stockholm
Solna strandväg 96

Tel: +46 8 799 40 00
Fax: +46 8 799 40 10

E-mail: registrator@ssm.se
Web: stralsakerhetsmyndigheten.se

Ale Tryckteam AB, Bohus, 2019