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Source terms and early protective measures at nuclear power plant accidents where the situation is unclear

Recommendation by the German Commission on Radiological Protection

Adopted at the 300th meeting of the German Commission on Radiological Protection on 27 and 28 June 2019

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Quellterme und frühe Schutzmaßnahmen bei Kernkraftwerksunfällen mit unklarer Lage

Empfehlung der Strahlenschutzkommission

Preface

The German Radiation Protection Act was enacted in 2017 and contains radiological emergency preparedness and response provisions requiring the Federal Radiological Situation Centre to draw up a radiological situation report in the event of a severe accident at a nuclear power plant. In general, forecasts of the source term anticipated as a result of the accident are required to draw up such a radiological situation report.

In 2018, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) issued an advisory mandate to the German Commission on Radiological Protection (SSK). As part of this mandate, the SSK was asked to estimate how to proceed at a very early stage of a core meltdown accident where the situation is unclear and no information is available about the anticipated source term of the releases.

The resulting recommendation was researched and prepared by members of a working group formed from the 'emergency preparedness and response' committee:

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1 Background

The enactment of the German Radiation Protection Act (StrlSchG) in 2017 saw the introduction of new radiological emergency preparedness and response provisions requiring the Federal Radiological Situation Centre to draw up a radiological situation report in the event of a national radiological emergency (in this case: a severe accident at a nuclear power plant). This situation report must be sent to the *Länder* (federal states), the Joint Information Centre of the German Federal State and the Regions (GMLZ) as part of the Federal Office of Civil Protection and Disaster Assistance (BBK), and the principal federal authorities stipulated in the general emergency response plan.

In general, a radiological situation report is based on forecasts of the source term anticipated as a result of the accident as well as on predictions provided by the RODOS (Real-time Online DecisiOn Support) system. These RODOS forecasts allow statements to be made about the area(s) likely to be contaminated, how contamination of the environment will develop over time, and the anticipated exposures for every applicable exposure path. This information then enables recommendations to be issued with a view to preparing and carrying out protective measures.

This advisory mandate constitutes a review of the unlikely event that source term forecasts are unavailable, no matter what the reason for that may be.

2 Advisory mandate

In its recommendation titled ‘forecast and estimation of source terms in the event of nuclear power plant accidents’ from 2014, the SSK recommends that operators report two source terms (the most likely source term and the source term with the highest release of activity and a probability exceeding 10 %) calculated using FaSTPro (formerly QPro) to the responsible emergency response authority if an incident occurs. In connection with this, on 23 January 2018 the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) asked the German Commission on Radiological Protection (SSK) to answer the following supplementary questions:

a. Should FaSTPro be unavailable, e. g. due to a power plant blackout, or should FaSTPro supply a trivial source term for other reasons, e. g. due to lack of input parameters, what would be a suitable default source term for the radiological situation report? Do the early phases of an incident at a plant with a typically long latency period justify the initiation of civil protection measures based on worst-case assumptions? The SSK recommended the further development and introduction of the NERDA approach (referred to as the HERCA/WENRA approach in this recommendation) in its recommendation for ‘further development of emergency management by implementing the lessons learned from Fukushima’ (published in the Federal Gazette Official Part, 4 January 2016, B3). Does the SSK consider this a sensible approach to such a scenario?

b. If FaSTPro delivers non-trivial source terms, the Federal Radiological Situation Centre (RLZ) needs to decide whether the radiological situation report should be based on the most likely source term or on the source term with the highest release of activity and a probability exceeding 10 %. In such instances, which of the two source terms is preferred? What criteria does the SSK recommend when selecting the source term to be used as a basis for a uniform radiological situation report?

3 Recommendations

The following recommendations refer to the approach used to draw up the radiological situation report and decide on early protective measures, i. e. evacuation, sheltering and iodine thyroid blocking, if a core meltdown accident is imminent or has occurred at a domestic or foreign nuclear power plant for which there is not enough information available about the state of the plant and the anticipated accident scenario.

Prior to implementation, a protective measure should always be scrutinised to determine whether it is necessary, achievable, reasonable and purposeful, and whether the attainable benefits outweigh any damage it may cause.

To this end, the SSK recommends the following:

Recommendation 1: If an emergency alert occurs and only incomplete information or only forecasts are available, the SSK recommends carrying out protective measures for the most likely accident scenario while also preparing measures for an accident with the highest anticipated release of radioactivity. If source term forecasts are available, the source term with the highest relative probability should be used for the most likely accident scenario. The source term with a relative probability exceeding 10 % should be assumed for an accident with the highest anticipated release of radioactivity.

Recommendation 2: If a core meltdown accident is imminent or has occurred, either in Germany or in another country less than 200 km from the German border, the following approach should be used during the pre-release phase:

If source term forecasts are available, early protective measures for the most likely accident scenario should be carried out in line with Recommendation 1 and RODOS predictions. Irrespective of source term forecasts, a dispersion calculation for radioactive noble gases can be used to forecast potentially affected areas and arrival times of a radioactive cloud.

If there are no source term forecasts available, or if only implausible information is available, the HERCA/WENRA approach (HERCA-WENRA 2014), the SSK recommendations on planning areas (SSK 2014a) and the SSK recommendation for ‘further development of emergency response due to the implementation of experiences from Fukushima’ (SSK 2015) should be followed in line with Recommendation 1. Here, an unfiltered release of pressure is assumed as the most likely accident scenario, and an uncovered steam generator tube leak is assumed as the worst-case accident scenario. For the purpose of the radiological situation report, this means that the source term for incident category II[1] is assumed as the most likely source term, with the source term for incident category III assumed as the worst-case source term as per Table 1).

1 In this recommendation, possible accident scenarios are divided into four incident categories based on the judgement evaluation factors (JEFs) provided in the HERCA-WENRA approach (HERCA-WENRA 2014) (cf. Section 4.3.)

Table 1: Source terms to be assumed for incident categories II and III.

Incident category	Noble gases in Bq	I-131 in Bq	Cs-137/134 in Bq
II	3E18	3E16	3E14
III	3E18	3E17	3E16

The SSK recommends a differentiated approach as per Tables 2 and 3 for early protective measures such as evacuation, sheltering and iodine thyroid blocking. Here, a distinction is made as to whether a release is still hours away (Table 2) or whether a release is imminent or has already begun (Table 3). The scope of early protective measures to be carried out depends on the prevailing weather conditions and whether dispersion calculations are available.

Remark 1: The areas in which the measures in Tables 2 and 3 are either prepared or carried out should be adapted to the given local conditions such as terrain, population density and administrative boundaries.

Remark 2: The situation must be monitored closely and the situation report updated accordingly. If RODOS is available, incident category II should be assumed as the most probable source term. Should the prevailing weather conditions lead to dispersion calculations requiring early protective measures for larger areas than those set out in Tables 2 and 3, the SSK recommends extending said protective measures to incorporate the larger areas.

Table 2: Recommendations for early protective measures if a release is still hours away.

	Most likely accident scenario **Incident category II**	**Worst-case accident scenario** **Incident category III**
Always	Evacuation should be carried out within a 5 km radius if there is enough time to do so before the release is forecast to start. Otherwise, iodine thyroid blocking, sheltering and subsequent evacuation should be prepared.	
Wind direction variable	Iodine thyroid blocking and sheltering should be prepared up to 20 km around nuclear power plants.	- Iodine thyroid blocking, sheltering and subsequent evacuation[1)] should be prepared up to 20 km - Iodine thyroid blocking and sheltering should be prepared up to 100 km - Iodine thyroid blocking should be prepared for children and pregnant women up to 200 km
Wind direction steady	Iodine thyroid blocking and sheltering should be prepared in a semicircle up to 20 km in the direction of dispersion.	- Iodine thyroid blocking, sheltering and subsequent evacuation[1)] should be prepared in a semicircle up to 20 km in the direction of dispersion - Iodine thyroid blocking and sheltering should be prepared in a semicircle up to 100 km in the direction of dispersion - Iodine thyroid blocking should be prepared for children and pregnant women in a semicircle up to 200 km in the direction of dispersion
Wind direction steady and dispersion calculations are available	Iodine thyroid blocking and sheltering should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors.	- Iodine thyroid blocking, sheltering and subsequent evacuation[1)] should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors - Iodine thyroid blocking and sheltering should be prepared up to 100 km in the sector in the direction of dispersion and the two adjacent sectors - Iodine thyroid blocking for children and pregnant women should be prepared up to 200 km in the sector in the direction of dispersion and the two adjacent sectors

[1)] The need for subsequent evacuation depends, among other things, on the local dose rate measured once the cloud has passed by.

Table 3: Recommendations for early protective measures if a release is imminent or has already begun.

	Most likely accident scenario **Incident category II**	**Worst-case accident scenario** **Incident category III**
Always	Iodine thyroid blocking and sheltering should be carried out up to 5 km, and subsequent evacuation[1] should be prepared.	
Wind direction variable	Iodine thyroid blocking and sheltering should be carried out up to 20 km around nuclear power plants.	- Iodine thyroid blocking and sheltering should be carried out up to 20 km; subsequent evacuation[1] should be prepared - Iodine thyroid blocking and sheltering should at least be prepared up to 100 km - Iodine thyroid blocking should be prepared for children and pregnant women up to 200 km
Wind direction steady	Iodine thyroid blocking and sheltering should be carried out in a semicircle up to 20 km in the direction of dispersion.	- Iodine thyroid blocking and sheltering should be carried out in a semicircle up to 20 km in the direction of dispersion; subsequent evacuation[1] should be prepared - Iodine thyroid blocking and sheltering should at least be prepared in a semicircle up to 100 km in the direction of dispersion - Iodine thyroid blocking should be prepared for children and pregnant women in a semicircle up to 200 km in the direction of dispersion
Wind direction steady and dispersion calculations are available	Iodine thyroid blocking and sheltering should be carried out up to 20 km in the sector in the direction of dispersion and the two adjacent sectors.	- Iodine thyroid blocking and sheltering should be carried out and subsequent evacuation[1] should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors - Iodine thyroid blocking and sheltering should at least be prepared up to 100 km in the sector in the direction of dispersion and the two adjacent sectors - Iodine thyroid blocking for children and pregnant women should be prepared up to 200 km in the sector in the direction of dispersion and the two adjacent sectors

[1] The need for subsequent evacuation depends, among other things, on the local dose rate measured once the cloud has passed by.

Recommendation 3: If an emergency alert announces that an accident is occurring within a short time, or if a release has already begun at the time of alert, evacuation of the 5 km central zone is not justifiable from a radiological perspective. The only option here is sheltering and, if iodine tablets have already been distributed, iodine thyroid blocking. Evacuation can only take place once the release ends or the radioactive cloud has passed as determined by local dose rate measurements.

Recommendation 4: If a core meltdown accident is imminent or has occurred in a European country within 200 km of the German border, the approach provided in Recommendation 2 should be followed during the pre-release phase: In the event that no source term forecasts were provided from abroad, an unfiltered release of pressure, i. e. incident category II, should be assumed as the most likely accident scenario, and incident category III assumed as the worst-case accident scenario.

Recommendation 5: If a core meltdown accident is imminent or has occurred in a European country more than 200 km away from the German border, the following approach should be used during the pre-release phase: Early protective measures are not expected to be required in Germany due to a core meltdown accident in a country more than 200 km away from the German border, meaning there is no urgency as is typical of the pre-release phase. The SSK or SSK emergency advisory board should review the need for and appropriateness of protective measures based on environmental radioactivity forecasts or measurements.

4 Scientific background

4.1 Introduction

The present recommendation to select source terms for drawing up a radiological situation report and for early protective measures should enable a swift response to an accident at a nuclear power plant for which there is not enough information available. The time between reaching the criteria for triggering a disaster alert (RSK and SSK 2013) and commencement of releases may range from a few hours to several days.

Once releases occur and initial data are available about the environmental radioactivity caused by the accident, there is then also (indirect) information available about the source term which should be used as a basis for deciding on additional measures to be taken.

In its recommendation from 2014 (SSK 2014b), the SSK specified the following with a view to requiring the operator to forecast the source term:

'The operator's duty to assist in ascertaining the situation, and the information to be passed on are anchored in the Basic Recommendations for Emergency Preparedness (BMU 2008).

As per the requirements of the Basic Recommendations for Emergency Preparedness, the operator is obliged to forecast source terms and to update initial forecasts using data from available measurements.

- *An initial forecast of the source term must take place within the scope of the situation assessment required after an alert has been issued.*

- *'The forecast can be updated once the operator or remote nuclear reactor monitor provides reliable measurements and emission data.' (Section 4.3.1 of BMU 2008)*
- *'The operator's measuring services and systems are required to take measurements during the release phase in order to determine the source term.' (Section 4.3.2 of BMU 2008)*

The type and scope of source term information to be supplied are defined in more detail in the Basic Recommendations for Emergency Preparedness (Annex 7.4 in BMU 2008). Here, a distinction is made between the pre-release phase and the phase after which releases begin. Among other things, the following information about the source term must be provided during the pre-release phase:

- *'Estimated time of commencement of release (lead time)*
- *Forecast of release over time*
- *Anticipated extent of release and possible composition of emission (noble gases/iodine/suspended particles)*
- *Statements about the potential release path (release via the chimney or other expected paths, including information about the release height)'.'*

The SSK also recommended the operator's emergency centre have access to calculation software so it can predict the anticipated source terms as soon as possible (SSK 2014b).

'The calculation software must meet the following requirements:

- *In the event of an incident, the software should perform calculations based on the assessments and results of a level 2 PSA (probabilistic safety analysis) for a nuclear power plant as well as on the current state of the plant. Efficient use of this method depends on whether and which plant parameters are collected automatically and can be used by the system.*
- *It should still be possible to use this method even if certain information about the state of the plant is not available.*
- *Requirements in terms of user-friendliness and ease of use should ensure that the software can also be used without error in the event of an accident.*
- *Uncertainty about the progression of an accident when an incident occurs should be taken into account by providing relevant information about probability and accompanying source terms.*
- *Information about the relevant nuclide composition should be provided so as to be able to calculate exposure. In addition, the height of the release above the ground and, where possible, the release's thermal energy content should be provided.*

The operator should notify the responsible emergency response authorities of the most likely source term and the source term with the highest release of activity and a probability exceeding 10 %.

As the level 2 PSA currently conducted within the scope of a periodic safety review only covers accidents which occur in the reactor core during power operation as well as pre-planned emergency or repair measures, the following requirement is also recommended:

- *If emergency measures or repairs are being carried out during an accident which were not planned in advance, the source term forecasts provided by the operator must be updated accordingly.'*

4.2 Estimating source terms with and without FaSTPro

The following methods can be used for source term forecasts:

- Expert estimates based on advance calculations of accident scenarios, summarised in tables or manuals
- High-speed simulation methods (only to be performed by trained users)
- Probabilistic methods based on a plant-specific PSA (FaSTPro). At present, two such methods are used to forecast source terms for domestic plants: FaSTPro and a method based on estimates by experts.

Source term forecast software: FaSTPro (formerly QPro)

FaSTPro is only used in the event of a severe accident where core damage is anticipated or has already occurred. The basic principle of FaSTPro is to use a level 2 PSA (hereafter referred to as PSA 2) to improve source term forecasts without the need for any major additional effort. Observations and measurements are also assessed to update the PSA results in line with the current state of the plant. The core functionality of the software involves merging observations with PSA 2 results in order to calculate a final result consisting of various possible source terms and their given probabilities.

Every nuclear plant in Germany now has a PSA 2, meaning that there is information available about the various accident scenarios and their probability of occurrence. A PSA 2 delivers different source terms depending on the accident scenario. The results of the PSA 2 are updated with current information by way of a Bayesian belief network.

A particular problem arising in connection with source term forecasts is the calculation of I-131 components in aerosol or elementary form. To date, predictions are calculated using the MELCOR code (releases in substance classes, CsI (aerosol from the core)). MELCOR accounts for chemisorption of CsI on surfaces, leading to the release of elementary I_2. However, it does not account for the iodine chemistry in the sump. If there are no MELCOR calculations available, FaSTPro assumes a distribution of 99 % aerosol iodine and 1 % elementary iodine. At present, there are few findings available about the dynamics involved in the production of organoiodine compounds in the reactor.

FaSTPro runs on standard Windows PCs with a corresponding power supply, meaning there are no special requirements in this regard. Brief outages may occur due to hardware defects (e. g. monitor, keyboard, hard drive) or software errors (e. g. BIOS, updates, DLL libraries, viruses). A backup laptop or USB stick containing a FaSTPro installation could be held in reserve to reduce the likelihood of an outage. All nuclear power plants in Germany use FaSTPro, except for unit 2 at Philippsburg nuclear power plant (KKP 2) and block 2 at Neckarwestheim nuclear power plant (GKN II).

Source term forecasts based on estimates by experts

A team of analysts on behalf of EnBW (Energie Baden-Württemberg AG), operator of both KKP 2 and GKN II, uses a comprehensive source term library and the effects of potential mitigating measures to estimate the most likely and radiological worst-case source term from the PSA 2 results.

The operator has developed a special concept to estimate the source terms. The response unit for severe design basis accidents is responsible for source term forecasts and has prepared plant-specific source term libraries. The nuclear supervisory authority has also adopted these detailed source terms, which were calculated using PSA 2 codes whose parameters were validated, e. g. with MELCOR. The calculation code has been extended to include a new organoiodine model. Here, calculations for both plants were performed using a real core inventory (61 nuclides) summarised into nuclide groups with decay chains accounted for in simplified form. These results were then used to select 13 basic scenarios and an additional 16 sub-scenarios. All of the data are then entered into extensive Excel tables together with macros, in turn enabling the data to be used as an input for dispersion software. The source terms modelled in these scenarios start with the assumed onset of core damage following an emergency shutdown (scram). For reasons of conservatism, this point in time was selected as early as possible for every scenario and does not correspond with the time at which core damage is most likely to start. In the event of an incident, the actual time at which core damage starts should be updated using the integrated macro to correct for the decay of the resulting source term.

The response unit was provided with documentation containing a simple flowchart, information on selecting the anticipated source term, information about selecting the source term with the most severe consequences, and information about preparing a radiological situation report. All of these documents are provided in folders which are readily available to the response unit. Non-availability of the system is therefore inconceivable because all of the requisite documentation is available in paper form at the plant, the emergency control room, and the nuclear supervisory authority.

A comparison of the EnBW source terms with the reference source terms FKA, FKI and FKF shows a broad spectrum of anticipated releases for the same scenario. Among other things, this is due to differing assumptions in the modelled accident scenario (particularly for FKA), inventory assumptions (refuelling schedules, geometry, burnup times, reactor power during cycle), release time assumptions and duration assumptions (decay corrections), and containment leakage assumptions. A comparison of the EnBW source term database with the RODOS source term database shows the following:

For filtered pressure release:

- In general, RODOS provides somewhat higher emissions than the EnBW reference source terms
- RODOS provides a higher iodine release as a result of including organoiodine compounds
- There are differences between KKP 2 and GKN II, particularly in terms of inventory. An end-of-cycle inventory was used from the last cycle for both plants. The level of short-lived radionuclides was much lower at KKP 2 due to a longer stretchout operation at a reduced power output prior to the end of the cycle.

For unfiltered pressure release:

- Calculations using the EnBW reference source terms provided somewhat higher iodine releases and lower Cs emissions.
- Calculations using the EnBW reference source terms for accidents involving an uncovered steam generator heat pipe leak provided releases similar to the values predicted by PSA 2, making them much higher than those calculated with the FKA variant used in the RODOS database.

Compared to previous predictions, e. g. FaSTPro, the treatment of iodine chemistry used in the source terms leads to a ratio of I_2/RI[2] = 2:1 in the containment where only 2 % was gas and 98 % was CsI. The highly differing decontamination factors of the venturi scrubbers for the three forms of iodine even indicate a dominant release of organoiodine for scenarios involving a filtered pressure release.

In summary, all source term forecasts are based on assumed prevailing hazardous states and their subsequent accident scenarios. This is based on the PSA 2 results which are updated either by way of mathematical operations or by applying expert knowledge. A different source term, e. g. replenishing a defective steam generator, is generally arrived at when taking mitigating measures or repair forecasts into account. In the case of the EnBW plants, this is based on expert estimates. Corresponding enhancements in FaSTPro are currently being investigated.

However, the predicted source terms themselves are worst-case analyses based on PSA 2 and an assumed fixed accident scenario where additional mitigating measures within the scope of emergency response at the plant are not taken into account. To compound this, there are still major deficits in terms of release modelling and atmospheric transport of the various iodine species present during a core meltdown accident. There are no FaSTPro calculations available for foreign plants, so information gaps are filled using the HERCA/WENRA approach instead.

4.3 Procedure based on the HERCA/WENRA approach

The HERCA/WENRA approach was developed to enable a swift response to an accident at a nuclear power plant for which there is not enough information available. The Federal Radiological Situation Centre should be in a position to swiftly prepare a useful radiological situation report along with radiological foundations for decision-making with regard to protective measures.

In keeping with the HERCA/WENRA approach, a few parameters are used to create incident categories 0, I, II and III (in red below in Figure 1) which determine the source terms provided in the radiological situation report. The incident category then incorporates the level of urgency and prevailing weather conditions to determine the rules for selecting early protective measures. Three estimates are required to stipulate HERCA/WENRA rules: the incident category, the anticipated start of release, and the wind direction (steady or variable). Instructions on defining incident categories based on available information are provided below in Figure 1.

The source terms to be assumed for the various incident categories in the HERCA/WENRA approach are provided in Table 4. No information is provided with regard to release durations.

a) Core damage		
□	Not anticipated	⇒ □ **0**
□	Anticipated in __ hrs	⇒ b)
□	Has occurred or is imminent	⇒ b)

[2] RI: organic iodine compounds

b) Containment failure	
☐ Not anticipated	⇒ c)
☐ Anticipated in __ hrs	⇒ ☐ **III**
☐ Has occurred or is imminent	⇒ ☐ **III**

c) Containment pressure release	
☐ Not required	⇒ ☐ **0**
☐ Filtered in approx. __ hrs	⇒ ☐ **I**
☐ Unfiltered in approx. __ hrs	⇒ ☐ **II**
☐ Not available or ineffective	⇒ ☐ **III**

Figure 1: Three estimates (a to c) used to derive the incident category

Table 4: Source terms for incident categories I to III.

Incident category[1]	**Noble gases in Bq**	**I-131 in Bq**	**Cs-137/134 in Bq**
I	3E18	3E15	3E11
II	3E18	3E16	3E14
III	3E18	3E17	3E16

[1] Retrospectively, incident categories I, II and III correspond with levels 5, 6 and 7 of the INES classification system.

RODOS calculations for radioactive noble gases can be used to determine potentially affected areas because noble gases are transported in the same way as air masses in the atmosphere. Here, radioactive noble gases are only of radiological relevance up to a distance of 5 km when irradiated directly by the cloud. Another mitigating factor in terms of the radiological relevance of radioactive noble gases is the fact that they mostly have relatively short half-lives.

If RODOS calculations are available, the source terms for iodine and Cs radionuclides provided in Table 4 should be used to create the radiological situation report if any other information is missing.

If RODOS calculations are also unavailable, the source terms in Table 4 should be assumed and action then taken in line with the HERCA/WENRA approach, as described in detail in Recommendation 2.

The following information is important when putting this into practice. No early protective measures are required for incident category 0 as this covers a design basis accident. The most likely accident scenario at a German nuclear power plant involves a filtered pressure release, i. e. incident category I, for which the HERCA/WENRA approach requires the same early protective measures as for incident category II. In addition, it is not possible to predict with any certainty whether filtering is available. As a result, an unfiltered pressure release (incident category II) is assumed as a precaution. The most unfavourable (worst-case) accident scenario is assigned to incident category III. With the exception of an uncovered steam generator heat pipe leak, the results of PSA 2 determine relative probabilities well below 1 % for incident category III scenarios.

To this end, the SSK recommends the following principle: 'Do what's likely to happen and prepare for what's unlikely to happen!' Putting this relatively simple approach into practice means acting as though incident category II is likely to occur, yet all the while preparing for incident category III.

Prior to implementation, a protective measure should always be scrutinised to determine whether it is necessary, achievable, reasonable and purposeful, and whether the attainable benefits outweigh any damage it may cause. The lessons learned from the Fukushima Daiichi accident showed that protective measures carried out without any such prior scrutiny can even lead to the loss of life (NAIIC 2012, Yasumura 2014).

Recommendation 1: If a disaster alert occurs and only incomplete information or only forecasts are available, the SSK recommends carrying out protective measures for the most likely accident scenario while also preparing measures for an accident with the highest anticipated release of radioactivity. If source term forecasts are available, the source term with the highest relative probability should be used for the most likely accident scenario. The source term with a relative probability exceeding 10 % should be assumed for an accident with the highest anticipated release of radioactivity.

The following questions should also be taken into account: What can emergency response authorities do? What measures are achievable, reasonable and purposeful? What collateral damage can be expected?

The same approach should be used for accidents involving nuclear power plants in other European countries near the German border.

4.4 Response to the questions in the advisory mandate

In the event of such circumstances, what would be a suitable default source term for the radiological situation report?

According to PSA 2, the most common accident scenario by far involves a filtered pressure release. However, as the HERCA/WERA approach recommends the same early protective measures for both incident categories I and II, an unfiltered pressure release, i. e. incidence category II, should be assumed as a precaution as the most likely source term for domestic accidents for the purpose of the radiological situation report. Unless other information is available, an unfiltered pressure release should also be assumed as a precaution for nuclear power plants in neighbouring countries, thus assuming the release of 3E16 Bq I-131 and 3E14 Bq Cs-134/137.

Do the early phases of an incident at a plant with a typically long latency period justify the initiation of civil protection measures based on worst-case assumptions?

No! Action should be taken to counter the most likely scenario (a filtered or unfiltered pressure release, i. e. incident category I or II), with preparations made for the worst-case scenario (an uncovered steam generator heat pipe leak, i. e. incident category III). The SSK notes that unjustified measures may also cause additional damage.

The SSK recommended the further development and introduction of the HERCA/WENRA approach in its recommendation for ‘further development of emergency response due to the implementation of experiences from Fukushima’ (published in the Federal Gazette Official Part, 4 January 2016, B3). Does the SSK consider this a sensible approach to such a scenario?

> Yes! HERCA/WENRA shows that there are not that many options available which can be carried out well in line with the SSK recommendation for ‘further development of emergency management by implementing the lessons learned from Fukushima’.

If FaSTPro delivers non-trivial source terms, the Federal Radiological Situation Centre needs to decide whether the radiological situation report should be based on the most likely source term or on the source term with the highest release of activity and a probability exceeding 10 %. In such instances, which of the two source terms is preferred?

> When preparing the radiological situation report, a choice should be made based on Table 1, using incident category II as the most likely source term and making preparations for incident category III as the worst-case scenario.

What criteria does the SSK recommend when selecting the source term to be used as a basis for a uniform radiological situation report?

> Incident category II (an unfiltered pressure release) should be assumed as the most likely source term for domestic nuclear power plants and power plants in other European countries near the German border. An unfiltered pressure release should also be assumed for accidents abroad.

The SSK therefore recommends the following approach:

1. Incident category II should be assumed as the most likely scenario for accidents in Germany, with action taken accordingly. Emergency response preparations should be made for incident category III, i. e. the radiological worst-case scenario; see Recommendation 3.
2. The radiological situation report should be prepared in line with incident category II, but the situation should continue to be monitored closely so as to be able to update the radiological situation report if necessary.
3. Each considered measure should be scrutinised to determine whether it is necessary, achievable, reasonable and purposeful, and what collateral damage can be expected as a result.
4. Accidents in other European countries near the German border should be treated in the same way as domestic accidents because the radiological risk is similar and may require the same measures.

Recommendation 2: If a core meltdown accident is imminent or has occurred, either in Germany or in another country less than 200 km from the German border, the following approach should be used during the pre-release phase:

If source term forecasts are available, early protective measures for the most likely accident scenario should be carried out in line with Recommendation 1 and RODOS predictions. Irrespective of source term forecasts, a dispersion calculation for radioactive noble gases can be used to forecast potentially affected areas and arrival times of a radioactive cloud.

If there are no source term forecasts available, or if only implausible information is available, the HERCA/WENRA approach (HERCA-WENRA 2014), the SSK recommendations on planning areas (SSK 2014a) and the SSK recommendation for ‘further development of emergency management by implementing the lessons learned from Fukushima’ (SSK 2015) should be followed in line with Recommendation 1. Here, an unfiltered release of pressure is assumed as the most likely accident scenario, and an uncovered steam generator tube leak is assumed as the worst-case accident scenario. For the purpose of the radiological situation report, this means that the source term for incident category II is assumed as the most likely source term, with the source term for incident category III assumed as the worst-case source term as per Table 1 in Chapter 3.

The SSK recommends a differentiated approach as per Tables 2 and 3 for early protective measures such as evacuation, sheltering and iodine thyroid blocking. Here, a distinction is made as to whether a release is still hours away (Table 2) or whether a release is imminent or has already begun (Table 3). The scope of early protective measures to be carried out depends on the prevailing weather conditions and whether dispersion calculations are available.

The SSK recommends the following points:

If a release is only hours away, this is the approach to take to counter the most likely accident scenario:

- Evacuation should be carried out within a 5 km radius if there is enough time to do so before the release is forecast to start. Otherwise, iodine thyroid blocking, sheltering and subsequent evacuation should be prepared.
- If the wind direction is variable, iodine thyroid blocking and sheltering should be prepared up to 20 km.
- If the wind direction is steady, iodine thyroid blocking and sheltering should only be prepared in a semicircle up to 20 km in the direction of dispersion.
- If the wind direction is steady and dispersion calculations are available, iodine thyroid blocking and sheltering should only be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors.

If a release is only hours away, this is the approach to take to counter the worst-case accident scenario:

- Evacuation should be carried out within a 5 km radius if there is enough time to do so before the release is forecast to start. Otherwise, iodine thyroid blocking, sheltering and subsequent evacuation should be prepared.
- If the wind direction is variable:

    - Iodine thyroid blocking, sheltering and subsequent evacuation should be prepared up to 20 km
    - Iodine thyroid blocking and sheltering should be prepared up to 100 km
    - Iodine thyroid blocking should be prepared for children and pregnant women up to 200 km
- If the wind direction is steady:
    - Iodine thyroid blocking, sheltering and subsequent evacuation should be prepared in a semicircle up to 20 km in the direction of dispersion
    - Iodine thyroid blocking and sheltering should be prepared in a semicircle up to 100 km in the direction of dispersion
    - Iodine thyroid blocking should be prepared for children and pregnant women in a semicircle up to 200 km in the direction of dispersion
- If the wind direction is steady and dispersion calculations are available:
    - Iodine thyroid blocking, sheltering and subsequent evacuation should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors
    - Iodine thyroid blocking and sheltering should be prepared up to 100 km in the sector in the direction of dispersion and the two adjacent sectors
    - Iodine thyroid blocking for children and pregnant women should be prepared up to 200 km in the sector in the direction of dispersion and the two adjacent sectors

If a release is imminent or has already begun, this is the approach to take to counter the most likely accident scenario:

- Iodine thyroid blocking and sheltering should be carried out up to 5 km; subsequent evacuation should be prepared
- If the wind direction is variable, iodine thyroid blocking and sheltering should be carried out up to 20 km
- If the wind direction is steady, iodine thyroid blocking and sheltering should be carried out up to 20 km in a semicircle up to 20 km in the direction of dispersion
- If the wind direction is steady and dispersion calculations are available, iodine thyroid blocking and sheltering should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors

If a release is imminent or has already begun, this is the approach to take to counter the worst-case accident scenario:

- Iodine thyroid blocking and sheltering should be carried out up to 5 km; subsequent evacuation should be prepared
- If the wind direction is variable:
  - Iodine thyroid blocking and sheltering should be carried out up to 20 km; subsequent evacuation should be prepared
  - Iodine thyroid blocking and sheltering should at least be prepared up to 100 km
  - Iodine thyroid blocking should be prepared for children and pregnant women up to 200 km
- If the wind direction is steady:
  - Iodine thyroid blocking and sheltering should be carried out in a semicircle up to 20 km in the direction of dispersion; subsequent evacuation should be prepared
  - Iodine thyroid blocking and sheltering should at least be prepared in a semicircle up to 100 km in the direction of dispersion
  - Iodine thyroid blocking should be prepared for children and pregnant women in a semicircle up to 200 km in the direction of dispersion
- If the wind direction is steady and dispersion calculations are available:
  - Iodine thyroid blocking and sheltering should be carried out and subsequent evacuation should be prepared up to 20 km in the sector in the direction of dispersion and the two adjacent sectors
  - Iodine thyroid blocking and sheltering should at least be prepared up to 100 km in the sector in the direction of dispersion and the two adjacent sectors
  - Iodine thyroid blocking for children and pregnant women should be prepared up to 200 km in the sector in the direction of dispersion and the two adjacent sectors

Remark 1: The areas in which measures as per Tables 2 and 3 are either prepared or carried out should be adapted to the given local conditions, e. g. terrain, population density and administrative boundaries.

Remark 2: The situation should be monitored closely and the situation report adapted accordingly. If RODOS is available, incident category II should be assumed as the most probable source term. Should the prevailing weather conditions lead to dispersion calculations with the assumed source term indicating larger areas for early protective measures than those set out in Tables 2 and 3, the SSK recommends extending said protective measures to incorporate these larger areas.

Remark 3: Chapter 3 provides the measures set out in Recommendation 2 in Tables 2 and 3.

Remark 4: The need for subsequent evacuation depends on the local dose rate measured once the cloud has passed by.

Recommendation 3: If an alert announces that an accident is occurring at pace, or if a release has already begun at the time of alert, evacuation of the 5 km central zone is not justifiable from a radiological perspective. The only option here is sheltering and, if iodine tablets have already been distributed, iodine thyroid blocking. Evacuation can only take place once the release ends or the radioactive cloud has passed as determined by local dose rate measurements.

Recommendation 4: If a core meltdown accident is imminent or has occurred in a European country within 200 km of the German border, the approach provided in Recommendation 2 should be followed during the pre-release phase: In the event that no source term forecasts were provided from abroad, an unfiltered release of pressure, i. e. incident category II, should be assumed as the most likely accident scenario, and incident category III assumed as the worst-case accident scenario.

Recommendation 5: If a core meltdown accident is imminent or has occurred in a European country more than 200 km away from the German border, the following approach should be used during the pre-release phase: Early protective measures are not expected to be required in Germany due to a core meltdown accident in a country more than 200 km away from the German border, meaning there is no urgency as is typical of the pre-release phase. The SSK or SSK emergency advisory board should review the need for and appropriateness of protective measures based on environmental radioactivity forecasts or measurements.

5 References

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6 Glossary

FaSTPro	Fast Source Term Prognosis: FaSTPro is a piece of software used to forecast source terms. It should only be used in the event of a severe accident where core damage is expected or has already occurred, and requires the convocation of the emergency advisory board. (Hage and Löffler 2017)
FKA, FKI, FKF	Reference source terms of the source term library for the Real-time Online DecisiOn Support (RODOS) system (Löffler et al. 2010)
HERCA	Heads of the European Radiological Protection Competent Authorities is a voluntary association which brings together 56 radiation protection authorities from 32 European countries to identify common issues and propose practical solutions for these issues, generally covered by provisions of the EURATOM Treaty.
MELCOR	MELCOR is a fully integrated, engineering-level computer code developed by Sandia National Laboratories for the U.S. Nuclear Regulatory Commission to model the progression of severe accidents in nuclear power plants. (Sandia National Laboratories 2005)
PSA	A Probabilistic Safety Assessment calculates probabilities and analyses systems to determine risks at an industrial plant or facility. It also serves to show potential scenarios along with their probability and possible consequences.
RODOS	Real-time Online DecisiOn Support system to prepare a decision-making and forecast model which can be used in a radiological emergency to calculate future contamination of the environment and anticipated doses of affected persons.
Containment	Reinforced structure enclosing a nuclear reactor to contain the escape of radioactive steam or gas and prevent it from entering the atmosphere and surrounding area in an uncontrolled manner.
Venturi scrubber	Venturi scrubbers use the differential between high velocity gases and free-flowing water to create droplets which entrap contaminants, hold them in suspension and deliver them as a highly concentrated slurry.
WENRA	Western European Nuclear Regulators Association: Cooperation between European nuclear regulatory bodies to discuss the safety aspects involved in operating nuclear plants and facilities.