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Review and investigation of the operational arrangements and procedures – *Emergency preparedness for long lasting releases*

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ARTICLE

Emergency preparedness for long lasting releases – source terms

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Abstract – The Fukushima-Daiichi nuclear power plant (NPP) accident has demonstrated the possibility of long-lasting releases of radionuclides from a damaged NPP over several weeks. The objective of this paper is to provide long lasting potential environmental source terms (ST) for the typical reactor units that are being in operation in various European countries. The main aim is to provide environmental ST for testing of the current off-site nuclear emergency planning in European countries with accident scenarios based on lessons learned from the Fukushima accident and to derive recommendations how to improve the current planning. There are described the environmental ST's for three, the most frequent, reactor types – Pressurizer Water Reactor (PWR), Boiling Water Reactor (BWR) a and VVER-440 (VVER = Russian acronym for PWR) that are under operation in Germany, Slovakia, Finland and Spain, but they can be considered as typical for NPP's under operation in another European countries, too.

Keywords: reactor severe accident scenario / long lasting release / source terms

1 Introduction

In all countries with nuclear installations detailed emergency management strategies have been developed in the past. In nearly all cases such strategies are based on accident scenarios where the duration of the release of radionuclides to the environment is limited to some hours or at maximum a few days. The Fukushima-Daiichi accident has demonstrated the possibility of long-lasting releases of radionuclides from a nuclear power plant (NPP) over several weeks. The overall objective of the work package described in this paper is to prepare long-lasting environmental ST's for typical reactor units that are in operation in European countries with the aim to test the current off-site nuclear emergency planning in European countries with accident scenarios based on lessons learned from the Fukushima accident and to derive recommendations how to improve the current planning. The tests should demonstrate whether protective measures foreseen in the current emergency planning could adequately reduce the radiological consequences of NPP accidents with long lasting severe releases similar to the release from the Fukushima-Daiichi NPP.

2 Source terms

The key aspect of this work is the investigation of hypothetical source terms leading to long-lasting releases of radionuclides and which are applicable to nuclear installations in various European countries. Source terms are either be developed using computer codes for modelling the progression of severe accidents (SA) or be derived from existing studies of potential releases from nuclear installations (including probabilistic safety assessment results). The source terms have been derived for NPPs with Pressurized Water Reactors (PWR or VVER) and Boiling Water Reactors (BWR) that are in operation in Germany, Slovakia, Finland and Spain. These source terms correspond to the International Nuclear and Radiological Event Scale (INES) – categories: 5 (accident with wider consequences), 6 (serious accident) and 7 (major accident). All data regarding the described environmental ST's are taken from the report (Gering *et al.*, 2014).

It should be mentioned that in case of Fukushima-Daiichi NPP accident the Nuclear Industrial and Safety Agency (NISA) in Japan declared the accident at level 7 (UNSCEAR, 2013). The accident was a consequence of earthquake of magnitude 9 along the Japan trench and the following tsunami. Significant release of the radioactive materials to the atmosphere began on 12th of March and the release rate varied considerably in magnitude within the following one week, with marked increases associated with particular events at each unit (*e.g.* venting of primary containments and hydrogen explosions). After the first week, the rates of release gradually declined. By the beginning of April, the release rates had fallen to a thousandth or less of the release rates that occurred during the first week of the accident. The estimates of the "total" release to atmosphere of ^{131}I fell within the range of

Table 1. Description of environmental source terms for German NPP's.

Source term name	FKI	FKF	FKA
Reactor type	PWR	PWR	PWR
Initiating event	Break on main circulation line (10 cm^2)	Break on main circulation line (10 cm^2)	Break of the steam generator (SG) boiler tube (6 cm^2)
Description of scenario	Core damaged; CONT not damaged; Depressurization of CONT by **filtered** venting.	Core damaged; CONT not damaged; Depressurization of CONT by **unfiltered** venting.	Core damaged; CONT damaged.
Begin of release (after end of chain reaction)	12.4 h (venting after 57 h; height: ~150 m)	12.4 h (venting after 57 h height: ~150 m)	21 h (height: ~30 m)
Duration of release	86 h (40 h through venting)	86 h (40 h through venting)	50 h (through damaged CONT)[b]
Total release			
^{131}I	3 PBq	20 PBq	300 PBq
^{137}Cs	0.0003 PBq	0.3 PBq	30 PBq
^{133}Xe	5 000 PBq	5 000 PBq	2 000 PBq
Radiological equivalent of ^{131}I activity[a]	2.8 PBq	34 PBq	1 600 PBq
INES category	5	6	7

[a] Radiological equivalent of the ^{131}I has been calculated according to INES (2009) methodology.
[b] Activity release before CONT damage is negligible.

100–500 PBq (1×10^{15}) and those of ^{137}Cs in the range of 6–20 PBq (UNSCEAR, 2013). These ranges comprised about 2–8% of the total inventory of ^{131}I and about 1–3% of the total inventory of ^{137}Cs in the three operating reactors (Units 1–3) at the time of the accident. The total releases of ^{133}Xe to the atmosphere assumed by the Committee are 7 300 PBq (UNSCEAR, 2013). Estimated direct releases to the ocean of ^{131}I fell within the range of 10–20 PBq and those of ^{137}Cs in the range 3–6 PBq (UNSCEAR, 2013; note that these values does not comprise radionuclides initially released to the atmosphere and subsequently deposited onto the ocean surface).

2.1 Potential source terms for German NPP's

The source terms considered in this study for German NPP's have been derived by GRS (Gesellschaft für Anlagen- und Reaktorsicherheit). All three environmental ST's (marked as FKA, FKI, and FKF) are based on accident scenarios leading to complete core damage followed by failure of the RPV leading to Molten Corium Concrete Interaction (MCCI) in the reactor cavity.

These environmental ST's have been derived in the frame of a research project by GRS (GRS-A-3580) to provide up to date source terms for Real-time On-line DecisiOn Support system (RODOS) in 2010. The GRS performed Probabilistic Safety Assessment studies – Level 2 (PSA L2) for German BWR's and the environmental ST's for RODOS were selected "according to criteria like frequency, extent of the source term and speed of the accident sequence" (GRS-A-3580). The main characteristics of selected SA scenarios and associated ST's are presented in Table 1.

2.2 Potential source terms for Slovakian NPP's

Three environmental ST's which are considered in this study for Slovak NPP's have been derived by VUJE (VUJE, Inc.) and all are based on accident scenarios leading to core damage. The ST's have been selected from the PSA L2 study for Unit 3 of the Mochovce NPP (VVER-440/213 unit with vacuum bubble-condenser system) and have been calculated by means of the validated integral SA code MELCOR1.8.5. The considered three SA scenarios with associated environmental ST's have been calculated for ~2 days of release duration (in accordance with PSA L2 methodology) and comprise scenarios with different initiating events and mainly of different timing for begin of major release of radionuclides to environment due to containment failure.

To simulate long lasting release like in Fukushima-Daiichi accident the original ST's have been extended to duration of ~8 days in this study, *i.e.* all time periods of the original ST's as

Table 2. Description of environmental source terms for Slovakian NPP's (VVER-440/213 unit).

Source term name	STC6-8d	STC10-8d	STC30-8d
Reactor type	VVER	VVER	VVER
Initiating event	STATION BLACKOUT– total loss of Alternate Current (AC) power	Break on main circulation line (28 cm^2)	Break on the SG primary collector head (14 cm^2)
Description of scenario	Primary circuit depressurization– SAM; Core damaged; Corium in-vessel retention by application of SAM; CONT damaged;	Core damaged; RPV failure (SAM– reactor cavity flooding not successful) CONT **early** damaged;	Primary circuit depressurization– SAM; Core damaged; Corium in-vessel retention by application of SAM; CONT **late** damaged;
Begin of release (after end of chain reaction)	11 h (after 56 h through CONT break; height: 25 m)	4 h (after 18 h through CONT break; height: 25 m)	14 h (after 92 h through CONT break; height: 25 m)
Duration of release	181 h (136 h through damaged CONT)	188 h (174 h through damaged CONT)	178 h (100 h through damaged CONT)
Total release			
^{131}I	67 PBq	105 PBq	3.7 PBq
^{137}Cs	12 PBq	18 PBq	0.7 PBq
^{133}Xe	930 PBq	2 000 PBq	6 400 PBq
Radiological equivalent of ^{131}I activity[a]	630 PBq	920 PBq	38 PBq
INES category	7	7	6

[a] Radiological equivalent of the ^{131}I has been calculated according to INES (2009) methodology.

well as timing of important events (*e.g.* time of CONT failure since the accident initiation) have been stretched in time by a factor of 4 resulting in the new ST's marked as STC6-8d, STC10-8d and STC30-8d.

It should be mentioned that all VVER-440/213 units (4 + 2 under finalisation) are already equipped with Severe Accident Management (SAM) systems devoted to mitigate ST and radiological consequences in case of SA occurring. SAM involves, *e.g.* system dedicated for primary circuit depressurization, diesel generator for SAM (DG SAM), dedicated JNR system for injection of water to primary circuit and containment spray system from external source of borated water (3 × 500 m^3 of water; as minimum 1 000 m^3 is available, but later additional water can be added). In the original analyses the usage of JNR system for water delivery into RPV was not supposed. Therefore, the justification of the timing prolongation can be made through assumption that JNR system was used for water delivery into RPV but not on sufficient level, *i.e.* preventing or ending of core melt was not successful but process of core degradation was significantly prolonged (it is supposed that after 8 days from accident initiation the degraded core – corium is successfully flooded, cooled down and stabilized).

The main characteristics of prolonged three SA scenarios and associated ST's are presented in Table 2.

2.3 Potential source terms for Finnish NPP's

Two environmental ST's which are considered in this study for Finnish NPP's have been provided by STUK's Nuclear Reactor Regulation department's Risk Analysis office and are based on accident scenarios leading to core damage. The ST's have been selected from the PSA L2 study, one for PWR Unit and one for BWR Unit. The main characteristics of these two SA scenarios and associated ST's are presented in Table 3.

2.4 Potential source terms for Spanish NPP's

The environmental ST for Spanish NPP's has been estimated by the Spanish Regulatory Authority (CSN) and has been provided for this study by CIEMAT (Centro de Investigaciones Energéticas, Médioambientales y Tecnológicas). Source term MA-SBO-173 is based on an accident scenario leading to complete core damage and is at present, the only potential long lasting ST considered for Spanish NPP's. Although all the Spanish NPP's keep updated their PSA, including those related to internal events at power (PSA L2), the framework in which the MA-SBO-173 source term was derived is the National Action Plan resulting from the Stress Tests after Fukushima. The main characteristics of the SA scenario and associated ST (MA-SBO-173) are presented in Table 4.

Table 3. Description of environmental source terms for Finnish NPP's.

Source term name	LO-NCR-APC04	OL-RHR-12
Reactor type	PWR (VVER440 with ice condenser)	BWR
Initiating event	TRANSIENT (loss of feed-water, offsite power and service water)	Loss of heat removal during planned shut-down
Description of scenario	Failure of primary circuit depressurization; Core damaged; Corium in-vessel retention – SAM; CONT damaged due to overpressure;	Core damaged; Failure of RPV 8 h after accident initiation – MCCI; Failure of filtered venting; CONT damaged due to overpressure;
Begin of release (after end of chain reaction)	10 h (after 34 h through CONT break; height: near ground level)	6 h (after 13 h through CONT break; height: near ground level)
Duration of release	62 h (38 h through damaged CONT)	32 h (27 h through damaged CONT)
Total release		
^{131}I	60 PBq	10 PBq
^{137}Cs	0.2 PBq	1 PBq
^{133}Xe	2 000 PBq	1 000 PBq
Radiological equivalent of ^{131}I activity[a]	61 PBq	55 PBq
INES category	7	7

[a] Radiological equivalent of the ^{131}I has been calculated according to INES (2009) methodology.

3 Conclusions

In the work package described in this paper the SA environmental ST's have been investigated that mostly leading to long-lasting releases of radionuclides and which are applicable to nuclear installations in various European countries. The main characteristics of these environmental ST's are the following:

- Three reactor types have been considered, these are PWRs, BWRs and VVER-440/213.
- The accident scenarios leading to the accidental releases of radioactivity include core melt followed by total core damage scenarios in all cases, combined with CONT damage in 7 cases, while in the remaining 3 cases releases occur through venting.

Table 4. Description of environmental source terms for Spanish NPP with PWR.

Source term name	MA-SBO-173
Reactor type	PWR
Initiating event	STATION BLACKOUT – total loss of AC power
Description of scenario	Running out of batteries 24 h after accident initiation – dry out of SG's; Core damaged; RPV failure – start of MCCI; CONT not damaged – depressurization of CONT by filtered venting;
Begin of release (after end of chain reaction)	32 h
Duration of release	48 h (first) + 14 h (filtered venting) + 12 h (last) = 74 h
Total release	
^{131}I	8.6 PBq
^{137}Cs	1.7 PBq
^{133}Xe	2 610.0 PBq
Radiological equivalent of ^{131}I activity[a]	88.7 PBq
INES category	7

[a] Radiological equivalent of the ^{131}I has been calculated according to INES (2009) methodology.

- The amount of ^{131}I released in the 9 scenarios varies between 3 PBq and 300 PBq.
- The duration of the releases varies between 22 h and 188 h (~8 days).
- Most of the releases would be rated as INES 7, with only 2 cases rated as INES 6 and one case as INES 5.

Results of this work (i.e. selected long lasting environmental ST's) have been used as an input for the knowledge data bases of the review of emergency preparedness for long lasting releases, i.e. for development of the accident scenario used for radiological consequence assessment and evaluation assessment.

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