9 SOURCE TERMS

Contents

List of Tables

9 SOURCE TERMS

As discussed in Sections 8 and 21, the containment response to a severe accident is depicted by the end states of containment event trees. These end states become the “release categories” that are used to characterize potential source terms. The source terms will be used in the offsite consequence analysis presented in Section 10.

Table 9-1 summarizes the ESBWR release categories and associated frequencies. As indicated in the table, the release category “TSL”, which depicts an intact containment with only leakage providing a source term, is the most likely release category. Other release categories have much lower calculated frequencies. For conservatism, a truncation frequency was used to represent some of these release categories. Specifically, if the calculated probability of the category was less than 10^{-15}, the truncation value of 10^{-15} was carried forward for the consequence evaluation.

The source term evaluation was performed with the MAAP computer code, which produces the distribution of radionuclides released to the environment as a function of time. Each release category is represented by one or two severe accident sequence that was selected and modeled to represent the group of potential severe accidents that could be associated with that release category. In some cases, both low pressure and high pressure classes were selected for the same release category to represent broader and more thorough contribution of accident sequences. If multi sequences were selected for a given release category, each sequence is weighted by its sequence frequency contribution to the sequence class.

The selection is based on several factors, including the frequency of the various sequences that lead to the end state and ensuring that the associated source term calculations are reasonably bounding.

The selected sequence provides a conservative basis for the source term quantification. The following sections describe the representative sequences and the bases for choosing them. As indicated in the following sections, conservative assumptions were typically made to account for analytical and phenomenological uncertainties. Table 9-1 includes the representative MAAP sequences as well as the time of initial release, and cumulative release fractions of noble gas and CsI at 24 and 72 hours after onset of core damage. Tables 9-2 and 9-3 provide the radionuclide release spectrum for 24 and 72 hours after onset of core damage, respectively.

Appendix 9A presents additional documentation on MAAP cases used for source term calculations

9.1 BREAK OUTSIDE OF CONTAINMENT (BOC)

The release category “Break Outside-of-Containment” represents sequences in which the RPV communicates directly with the environment due to an unisolated piping break that connects the RPV directly to an area outside of containment. From the Level 1 PRA, three outside-containment break locations contributed to the core damage frequency: breaks in a feedwater line, breaks in a Main Steam Line (MSL) and breaks in a RWCU/SDC line. The RWCU/SDC break event tree includes both a mid-level connection to the RPV and a lower head drain line connection. Although the largest contribution to outside-containment break is associated with the feedwater line, selecting the RWCU/SDC pipe break is conservative because its lower elevation in the RPV results in a more rapid loss of coolant inventory. Both the mid-level location and the lower drain line location were selected to represent the BOC release category.

Therefore, the representative sequences for this category is “BOCsd_nIN” and “BOCdr_nIN. This are unisolated break outside of containment in the shutdown cooling piping followed by no injection into the RPV. In these scenarios, the release begin at the onset of fuel damage and proceeds directly to the environment.

The third BOC class, Main steam line breaks, are a full order of magnitude less likely than the FDW breaks (Table 7.2-1). Also, MSL breaks are connected to the RPV at high elevation, and as such do not result in as bounding a scenario as the RWCU/SDS lines.

9.2 CONTAINMENT BYPASS (BYP)

The release category “Bypass” represents those sequences in which containment isolation has not occurred due to failure of the Containment Isolation System (CIS) function. Thus, there is a direct path from the containment atmosphere to the environment when the severe accident is initiated.

To determine the source term, a large diameter pipe opening was assumed from the time of accident initiation. Sequences in which the RPV is depressurized generally result in an earlier time to core uncovery than those involving failure to depressurize. As a result, the source term is generated earlier and the containment radionuclide concentration is developed earlier because of the path through the DPVs into containment. Both a low pressure sequence and high pressure sequence are selected to represent a thorough cross-section of the sequences. Because of the reliability of the deluge system (i.e., the probability of BYP with failed deluge is below the truncation level), the representative sequences are modeled with deluge success and are termed as “T_nIN_BYP” and “T_nDP_nIN_BYP”. In these scenarios, the releases begin at the onset of fuel damage and proceeds directly to the environment.

9.3 CORE-CONCRETE INTERACTION DRY (CCID)

The release category “Core-Concrete Interaction-Dry” applies to sequences in which the containment fails due to core concrete interaction and the lower drywell debris bed is uncovered i.e., the deluge function is unsuccessful.

In these sequences, the core-concrete interaction is not limited by water cooling the debris bed, nor is the radionuclide release limited by the potential scrubbing action of an overlying water pool. Sequences in which the RPV is not depressurized may result in earlier RPV failure, thus initiating earlier CCI. To represent more accurate risk contribution, both a low pressure sequence and a high pressure sequence were selected to represent the CCID source term category. The sequences are termed as “T_nIN_nD_CCID” and “T_nDP_nIN_nD_CCID” to indicate transients failure of injection and the deluge functions.

9.4 CORE-CONCRETE INTERACTION-WET (CCIW)

The release category "Core-Concrete Interaction-Wet" applies to sequences in which the containment fails due to core concrete interaction even though the lower drywell debris bed is covered with water. In such sequences, the deluge system has functioned to cover the debris bed with water, but the BiMAC is not successful in assuring debris bed cooling. The extent of water penetration into the debris bed, independent of the BiMAC, and thus, the potential for debris bed cooling, is subject to assumption. In the worst-case hypothetical condition, the debris bed is impermeable by the overlying water pool and the extent of CCI could approach that of a dry debris bed. To address this uncertainty associated with the debris bed coolability, the debris bed was modeled as being impermeable, thus maximizing the core-concrete interaction that could occur with an overlying water pool. Unlike the CCID release category, the overlying water pool is present, which provides the potential for scrubbing of the radionuclides evolved from the debris bed.

The representative sequences are termed as "T_nIN_CCIW" and "T_nDP_nIN_CCIW" and differ from the representative CCID sequences only in that the deluge system functions.

9.5 DIRECT CONTAINMENT HEATING (DCH)

The release category "Direct Containment Heating" applies to sequences in which the RPV fails at high pressure and a significant DCH event occurs. From Section 21.3, catastrophic containment failure due to DCH is physically unreasonable. Local damage to the liner in the lower drywell will be studied as a sensitivity case in Section 11. As such no DCH sequence is selected for the baseline case.

9.6 EX-VESSEL STEAM EXPLOSION (EVE)

The release category "Ex-vessel Steam Explosion" applies to sequences in which the RPV fails at low pressure and a significant steam explosion occurs. As indicated in Section 21.4, containment leak tightness and failure of the BiMAC function is physically unreasonable for all but 1% of the sequences contributing to the core damage frequency. A conservative approach was used to develop the source term associated with an EVE, specifically:

- Liner damage was assumed to be significant enough to result in containment depressurization, which occurs at the time of RPV failure,
- No credit was taken for mitigation of the release; i.e., liner damage was assumed to result in direct communication with the environment, and
- Due to uncertainties about potential equipment damage and the distribution of water through containment after the EVE, no credit is taken for a lower drywell water pool that would minimize the source term.

The dominant Class I sequence, a transient with no injection and successful RPV depressurization, provided the basis for this category. To address the preceding points, the sequence was modeled with deluge failure and containment failure occurring at the time of RPV failure. The representative sequence is termed "T_nIN_nD_EVE".

9.6.1 EVE (CCIW*) (Deleted)

9.7 FILTERED RELEASE (FR)

The ESBWR design includes the potential to manually vent the containment from the suppression chamber air space. This action may be implemented to limit the containment pressure increase if containment heat removal fails or core-concrete interaction generates enough non-condensables to overpressurize the containment. Venting the suppression chamber forces the radionuclides through the suppression pool, which reduces the magnitude of the source term.

To represent the FR category, a sequence with failure to insert negative reactivity was conservatively selected because such a sequence would pressurize containment more quickly than the much more probable non-ATWS sequences. The sequence assumes RPV failure at low pressure, consistent with the discussion in Section 8.2.1.1. Operator guidance regarding venting has not been developed, but it is assumed that venting would be delayed until containment integrity is threatened. The analysis assumes that venting does not occur until the containment pressure reaches 90% of the containment ultimate strength. No credit was given in the analysis for closing the vent after reducing the containment pressure. The representative sequence is termed “T-AT_nIN _nCHR_FR”.

9.8 OVERPRESSURE-VACUUM BREAKER (OPVB)

The release category “OPVB” applies to sequences in which vacuum breaker failure has occurred. Failure of vacuum breakers to close, or to be open in a pre-existing condition, results in failure of the containment pressure suppression function, which in turn also fails containment heat removal. Thus, such sequences would be expected to result in an earlier release than overpressure sequences with failure of containment heat removal alone.

To represent more broad contribution of both high and low pressure sequences, two representative sequences are selected for this category. The event trees illustrate that the OPVB category is logically reached only if deluge/BiMAC function successfully. Thus, the sequences termed as “T_nDP_nIN_VB” and “T_nIN_VB” are used to represent the OPVB release category.

9.9 OVERPRESSURE- EARLY CONTAINMENT HEAT REMOVAL LOSS (OPW1)

The release category “OPW1” applies to sequences in which containment heat removal fails within 24 hours after event initiation. A sequence with RPV failure at high pressure was selected to represent this release category because RPV failure generally occurs earlier than if the vessel were depressurized and the loss of containment heat removal failure probability is higher than for low pressure sequences. Thus, the representative sequence becomes “T_nDP_nIN_nCHR_W1”. Containment heat removal is conservatively assumed to be unavailable for the duration of the sequence.

9.10 OVERPRESSURE- LATE CONTAINMENT HEAT REMOVAL LOSS (OPW2)

The release category “OPW2” applies to sequences in which containment heat removal fails after the period covered by OPW1 (post-24 hours) and up to 72 hours after onset of core damage. In such sequences, the passive PCCS system becomes unavailable after 24 hours due to failure to connect to a supplemental water pool; FAPCS availability is also evaluated at this time. The representative sequence is the same as that used for OPW1 except that containment heat removal is terminated at 24 hours after event initiation, consistent with the PCCS design basis. The representative sequence is termed "T_nDP_nIN_nCHR_W2".

9.11 TECHNICAL SPECIFICATION LEAKAGE (TSL)

The category "Technical Specification Leakage" applies to sequences in which the containment is intact and the only release is due to the maximum leak rate allowed by Technical Specifications. Sequence T_AT_nIN_TSL was selected as representative of this category because the core damage time is relatively early for ATWS sequences. For additional conservatism, the area of containment leakage corresponding to the maximum allowable Technical Specification leak rate was doubled to produce the representative source term used for this release category. The representative source term is termed "T-AT_nIN_TSL2x".

9.12 SUMMARY

Potential release categories were defined in Sections 8 and 21. The source terms associated with each release category were developed using MAAP simulations of a representative sequence. Conservative assumptions were used in the selection and simulation of the representative sequence. Table 9-1 summarizes the release category, representative sequence and the cumulative release fractions for noble gases and CsI. Table 9-2 provides source terms for the period 24 hours after onset of core damage. Table 9-3 provides source terms for the period 72 hours after onset of core damage. The source terms and associated release category frequencies are used in the offsite consequence analysis described in Section 10.

Table 9-1

Release Categories

Source Term	Release Category	MAAP CASE	Total Release Frequency (per year)	Time of Plume Release (hr)	NG Release Fraction 24 hrs after onset of core damage	CsI Release Fraction 24 hrs after onse of core damage	NG Release Fraction 72 hrs after onset of core damage	CsI Release Fraction 72 hrs after onse of core damage
1	BOC	BOCsd_nIN_R1	1.47E-10	0.7	9.7E-01	7.0E-01	9.8E-01	7.0E-01
2		BOCdr_nIN_R1		0.6	2.4E-01	1.1E-01	2.6E-01	1.3E-01
3	BYP	T_nIN_BYP_R1	5.6E-11	0.7	9.5E-01	2.1E-01	9.7E-01	3.0E-01
4		T_nDP_nIN_BYP_R1		1.3	5.3E-01	3.3E-02	6.8E-01	3.5E-02
5	CCID	T_nIN_nD_CCID_R1	ε	25.8	0.0	0.0	9.1E-01	6.2E-02
6		T_nDP_nIN_nD_CCID_R1		16.0	9.1E-01	6.7E-02	9.6E-01	3.5E-01
7	CCIW	T_nIN_CCIW_R1	9.9E-11	25.6	0.0	0.0	8.9E-01	1.6E-05
8		T_nDP_nIN_CCIW_R1		18.4	6.4E-01	1.2E-04	8.3E-01	1.1E-02
9	EVE	T_nIN_nD_EVE_R1	6.10E-10	7.4	8.3E-01	2.8E-02	8.3E-01	1.5E-01
10	FR	T-AT_nIN_nCHR_FR_R1	ε	28.9	0.0E+0	0.0E+0	1.0E+00	6.1E-03
11	OPVB	T_nDP_nIN_VB_R1	6E-12	13.8	4.3E-01	1.33E-04	9.6E-01	4.1E-03
12		T_nIN_VB_R1		8.7	8.6E-01	5.0E-03	1.0E+00	1.5E-02
13	OPW1	T_nDP_nIN_nCHR_W1_R1	ε	34.2	0.0	0.0	1.0E+00	1.5E-02
14	OPW2	T_nDP_nIN_nCHR_W2_R1	ε	53.1	0.0E+0	0.0E+0	1.0E+00	1.5E-02
15	TSL	T_AT_nIN_TSL2x_R1	1.12E-08	0.5	2.7E-03	1.6E-04	2.7E-03	1.6E-04

ε Less than 1E-12

Table 9-2

Radionuclide Source Terms

(Release Fraction 24 hours after onset of core damage)

Source Term	Xe/Kr	CsI	TeO_2	SrO	MoO_2	CsOH	BaO	La_2O_3	CeO_2	Sb	Te_2	UO_2
1	9.7E-01	7.0E-01	4.6E-01	1.3E-02	1.7E-01	3.6E-01	3.1E-02	2.5E-04	1.2E-03	4.6E-01	6.4E-04	3.0E-06
2	2.4E-01	1.1E-01	1.2E-01	4.5E-04	1.6E-02	3.3E-02	2.0E-03	3.1E-05	1.4E-04	5.7E-02	1.1E-06	1.0E-06
3	9.5E-01	2.1E-01	1.3E-01	4.6E-03	6.2E-02	1.0E-01	1.3E-02	1.8E-04	8.5E-04	1.9E-01	5.1E-04	5.5E-06
4	5.3E-01	3.3E-02	2.0E-03	4.1E-02	2.3E-02	1.2E-02	4.0E-02	4.1E-02	4.1E-02	7.2E-02	3.6E-04	3.4E-06
5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
6	9.1E-01	6.7E-02	5.0E-02	7.8E-07	3.4E-07	2.4E-02	7.2E-06	3.6E-07	4.7E-07	7.1E-02	1.0E-07	1.8E-07
7	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
8	6.4E-01	1.2E-04	1.9E-05	2.6E-06	2.1E-06	5.0E-05	2.7E-06	2.5E-06	2.5E-06	1.6E-04	2.4E-07	8.4E-10
9	8.3E-01	2.8E-02	7.0E-02	1.7E-03	6.5E-05	1.3E-01	7.2E-04	4.9E-05	6.6E-04	1.9E-01	4.9E-04	3.3E-06
10	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
11	4.3E-01	1.3E-04	2.0E-05	1.9E-06	1.6E-06	9.0E-05	2.0E-06	1.8E-06	1.8E-06	1.3E-04	3.6E-06	1.7E-10
12	8.6E-01	5.0E-03	8.6E-05	1.2E-05	2.3E-06	1.2E-03	6.1E-06	1.2E-06	8.7E-06	2.2E-02	3.8E-05	8.1E-08
13	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
14	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
15	2.7E-03	1.6E-04	9.9E-05	2.6E-06	6.2E-05	5.9E-05	1.3E-05	1.1E-07	3.7E-07	1.6E-04	7.5E-10	3.3E-10

Table 9-3

Radionuclide Source Terms

(Release Fraction 72 hours after onset of core damage)

Source Term	Xe/Kr	CsI	TeO_2	SrO	MoO_2	CsOH	BaO	La_2O_3	CeO_2	Sb	Te_2	UO_2
1	9.8E-01	7.0E-01	4.6E-01	1.3E-02	1.7E-01	3.7E-01	3.1E-02	2.5E-04	1.2E-03	5.0E-01	6.5E-04	3.0E-06
2	2.6E-01	1.3E-01	1.2E-01	4.5E-04	1.6E-02	3.6E-02	2.0E-03	3.1E-05	1.4E-04	6.0E-02	1.3E-06	1.0E-06
3	9.7E-01	3.0E-01	1.3E-01	4.6E-03	6.2E-02	1.2E-01	1.3E-02	1.8E-04	8.5E-04	3.1E-01	5.1E-04	5.5E-06
4	6.8E-01	3.5E-02	6.1E-03	4.1E-02	2.3E-02	2.5E-02	4.0E-02	4.1E-02	4.1E-02	7.5E-02	3.8E-04	3.4E-06
5	9.1E-01	6.2E-02	7.6E-02	1.1E-07	3.2E-07	1.4E-01	4.0E-06	6.9E-09	1.3E-08	3.7E-02	2.7E-07	3.6E-08
6	9.6E-01	3.5E-01	7.7E-02	8.1E-07	4.0E-07	6.2E-02	1.1E-05	3.6E-07	4.7E-07	1.4E-01	1.3E-07	2.0E-07
7	8.9E-01	1.6E-05	7.8E-07	3.3E-08	2.1E-07	2.8E-05	1.3E-07	2.2E-09	1.2E-08	3.5E-02	7.6E-07	5.0E-10
8	8.3E-01	1.1E-02	1.1E-02	2.7E-06	2.2E-06	2.8E-02	2.8E-06	2.6E-06	2.6E-06	8.1E-03	4.7E-07	1.2E-09
9	8.3E-01	1.5E-01	1.5E-01	1.7E-03	6.5E-05	2.3E-01	7.5E-04	4.9E-05	6.6E-04	2.8E-01	4.9E-04	3.4E-06
10	1.0E+00	6.1E-03	2.6E-04	7.1E-09	3.3E-08	4.0E-03	3.5E-08	5.1E-10	2.2E-09	1.6E-01	2.3E-05	1.5E-11
11	9.6E-01	4.1E-03	7.0E-03	7.5E-06	1.6E-06	1.1E-02	4.9E-06	1.8E-06	1.9E-06	6.1E-02	1.8E-05	2.5E-10
12	1.0E+00	1.5E-02	1.9E-03	1.2E-05	2.3E-06	6.8E-03	6.1E-06	1.2E-06	8.7E-06	3.3E-01	4.6E-05	8.1E-08
13	9.9E-01	3.7E-04	9.9E-04	5.6E-08	9.3E-08	8.9E-03	7.1E-08	5.4E-08	5.4E-08	3.0E-03	1.6E-07	5.7E-13
14	9.7E-01	8.5E-05	3.7E-05	1.1E-08	7.2E-09	7.6E-04	1.1E-08	1.0E-08	1.0E-08	5.1E-03	7.4E-08	3.2E-13
15	2.7E-03	1.6E-04	9.9E-05	2.6E-06	6.2E-05	5.9E-05	1.3E-05	1.1E-07	3.7E-07	1.7E-04	7.6E-10	3.3E-10