Estimation of In-Containment Source Terms under Severe Accident for OPR1000 Plant with MAAP5 Code

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1. Introduction

Significant core damage due to lack of the heat removal in the nuclear power plant would lead to a release of large amount of fission product (FP) to the reactor coolant system and the containment atmosphere. The amount of airborne radioactive materials in the containment is strongly linked to the dose at the site boundary [1]. Therefore, the estimation of radioactive material inside the containment plays a key role in public health and the environment during severe accidents. This paper presents the estimation of the in-containment source term for the OPR1000 plant using selected sequences by the MAAP5.06 code in a realistic approach. The comparisons to the Alternative Source Terms (AST) described in NUREG-1465 [2] are also discussed.

2. MAAP5 Models for Fission Product Behavior

The structure of MAAP5 code consists of two pillars - thermal-hydraulic (TH) and fission product evaluation parts [3]. The TH module is calculated in advance and transfers the related thermophysical properties like temperature, pressure, and the mass flow rate between lumped nodes to the FP module. The MAAP5 FP module is divided into three parts based on physical location - in-core FP release, Reactor Coolant System (RCS) transportation, and in-containment. In this study, most of the MAAP5 modeling parameters in the input deck are based on the default values and the author's previous study for hydrogen distribution [4]. Regarding the FP release model, based on ORNL's VI-series benchmarking [5], the combination of the CORSOR-M model for noble gases and CsI/CsOH and the CORSOR-O model for the rest of the fission product groups has been selected. The analysis employs the limitation of the release of low-volatile FP groups by saturation vapor pressure.

MAAP5 has 18 FP groups in the chemical compounds structure. In comparison with the FP groups defined in NUREG-1465, which categorize groups according to elemental form, MAAP outputs are translated into elemental basis values, as shown in Table I.

Table I: FP Groups for MAAP5 and NUREG-1465

Number	MAAP5	Number	NUREG-1465
1	Xe, Kr	1	Xe, Kr
2	CsI, RbI	2	I
3	TeO_2	3	Cs, Rb
4	SrO	4	Te
5	MoO_2, TcO_2, RhO_2	5	Ba, Sr
6	CsOH, RbOH	6	Ru, Mo
7	BaO	7	La
8	La_2O_3, PrO_2, Nd_2O_3, etc.	8	Ce
9	CeO_2, NpO_2		
10	Sb		
11	Te_2		
12	UO_2		
13	Ag		
14	I_2		
15	CH_3I		
16	$CsMoO_4$		
17	RuO_2		
18	PuO_2		

3. MAAP5 Evaluation Results

3.1. Selection of Accident Sequences

The conventional baseline for selecting the accident sequences to be analyzed is to ensure they encompass the majority of scenarios that contribute to a risk of environmental radioactivity release. In this study, we will concentrate on the amount of airborne material inside the containment rather than the released fraction into the environment following containment failures. The sequences are selected in such a way that high contribution cases are based on the source term category (STC) of Level 2 Probabilistic Safety Analysis (PSA) while reserving containment integrity. Bypass sequences like Inter System LOCA (ISLOCA) and temperature-induced SGTR (TI-SGTR) are also neglected because they release the FP directly to the environment. As a result, three sequences show a high contribution to STC, while six sequences are selected from a deterministic viewpoint, as shown in Table II.

Table II: Selected Accident Sequences

Index	Sequence Name	Remarks
1	SBOR_S38	(SBO)(TDAFW for 8 hours)(Late Recovery of AC Power)(Recirculation Spray)
2	TLOCCW_S10	(TLOCCW) (TDAFW failed) (Bleed Operation failed)
3	MLOCA_S3	(MLOCA)(HPSI) (Recirculation failed)
4	LLOCA_BE_BASE	(LLOCA)(SIT)(SI failed)(CS failed)
5	LLOCA_BE_MACST	(LLOCA)(SIT)(SI failed)(CS failed)(IVI)(Late Recovery of CS) (Recirculation Spray)
6	SLOCA_BE_BASE	(SLOCA)(SIT)(SI failed)(Bleed Operation failed)(CS failed)
7	SLOCA_BE_MACST	(SLOCA)(SIT)(SI failed)(Bleed Operation failed)(CS failed) (IVI)(Late Recovery of CS) (Recirculation Spray)
8	SGTR_BE_BASE	(SGTR)(Broken SG Isolation)(SIT)(Bleed)(Feed failed)(CS failed)
9	SGTR_BE_MACST	(SGTR)(Broken SG Isolation)(SIT)(Bleed)(Feed failed)(CS failed) (IVI)(Late Recovery of CS) (Recirculation Spray)

3.2. In-Containment Source Terms Estimation and Comparison with NUREG-1465

For the selected sequences, the amount of in-containment source term is evaluated with MAAP5 code, and the results are illustrated in Fig. 1 through Fig. 3 for FP group 1 (Xe, Kr), group 2 (Iodine), and group 3 (Cs, Rb), respectively. Table III summarizes the fraction of release for gap release, early in-vessel release, ex-vessel release, and late in-vessel release for three FP groups. As shown in Fig. 1, noble gases (Xe, Kr) would easily be released into the containment once the core has been damaged. Therefore, the fraction of in-containment release increases very quickly in the early phase of core damage. The sequences that have mitigation actions show the suppression of release in some contexts; however, discontinuing mitigation allows for rapid release again (i.e., SBOR_S38, TLOCCW_S10, SLOCA_BE_BASE, SLOCA_BE_ MACST, and SGTR_BE_MACST sequences). The final fraction of release is larger than 0.95 for every sequence that is close to that of NUREG-1465. Fig. 2 and Fig. 3 represent a similar trend for Iodine and Cs/Rb, respectively. However, the final release fractions are found to be 0.35-0.75 for Iodine and 0.30-0.70 for Cs/Rb, which are considerably lower than those of NUREG-1465 (i.e., 0.75).

Table III: Comparison of Release Fraction of Release Phase by MAAP5 and NUREG-1465

Release Phase / Sequences	Gap release	Early in-vessel	Ex-vessel	Late in-vessel
FP Group 1 (Xe, Kr)				
NUREG-1465	0.05	0.95	0	0
SBOR_S38	0.05	0.949	0	0
TLOCCW_S10	0.048	0.950	0	0
MLOCA_S3	0.048	0.949	0	0
LLOCA_BE_BASE	0.05	0.944	0	0
LLOCA_BE_MACST	0.05	0.947	0	0
SLOCA_BE_BASE	0.042	0.938	0	0
SLOCA_BE_MACST	0.043	0.948	0	0
SGTR_BE_BASE	0.027	0.943	0	0
SGTR_BE_MACST	0.027	0.949	0	0
FP Group 2 (Iodine)				
NUREG-1465	0.05	0.35	0.25	0.1
SBOR_S38	0.05	0.672	0.000	0.006
TLOCCW_S10	0.022	0.404	0.002	0.009
MLOCA_S3	0.033	0.282	0.000	0.107
LLOCA_BE_BASE	0.05	0.442	0.002	0.028
LLOCA_BE_MACST	0.05	0.442	0.002	0.031
SLOCA_BE_BASE	0.014	0.692	0.004	0.005
SLOCA_BE_MACST	0.014	0.292	0.002	0.089
SGTR_BE_BASE	0.011	0.616	0.002	0.000
SGTR_BE_MACST	0.011	0.616	0.002	0.016
FP Group 3 (Cs, Rb)				
NUREG-1465	0.05	0.25	0.35	0.1
SBOR_S38	0.051	0.632	0.000	0.007
TLOCCW_S10	0.019	0.368	0.002	0.005
MLOCA_S3	0.032	0.236	0.000	0.037
LLOCA_BE_BASE	0.051	0.361	0.003	0.012
LLOCA_BE_MACST	0.051	0.361	0.003	0.015
SLOCA_BE_BASE	0.013	0.274	0.007	0.005
SLOCA_BE_MACST	0.013	0.291	0.002	0.027
SGTR_BE_BASE	0.010	0.578	0.002	0.000
SGTR_BE_MACST	0.010	0.578	0.002	0.005
Sequences / Release Phase	Gap release	Early in-vessel	Ex-vessel	Late in-vessel

All sequences analyzed in this study are characterized by the so-called 'wet cavity' when vessel fails, therefore the likelihood of extensive ex-vessel release is limited. Accordingly, the behavior of the release fraction is strongly correlated with the degree of in-vessel core degradation, regardless of the FP groups, as shown in Fig 4. The damaged core node in the MAAP5 code is defined as nodes whose fuel geometry is non-intact.

NUREG-1465 assumes the hypothetical accidents that complete core melt, failure of the RPV and MCCI under low pressure sequences. However, the sequences considered in this study differs in terms of the presence of the partially non-melt core, the operation of containment spray and very limited contribution of MCCI. Those aspects make the lower release fraction of iodine and Cs elements.

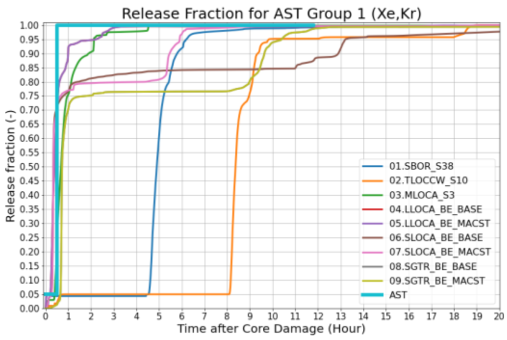

Fig. 1. Release fraction of AST Group 1 (Xe, Kr) to in-containment relative to initial in-core inventory.

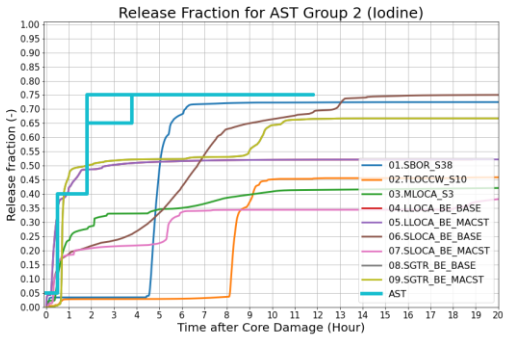

Fig. 2. Release fraction of AST Group 2 (Iodine) to in-containment relative to initial in-core inventory.

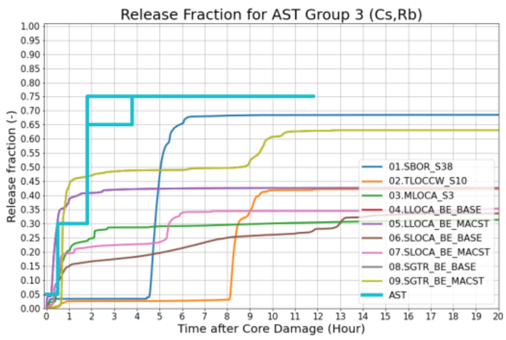

Fig. 3. Release fraction of AST Group 3 (Cs, Rb) to in-containment relative to initial in-core inventory.

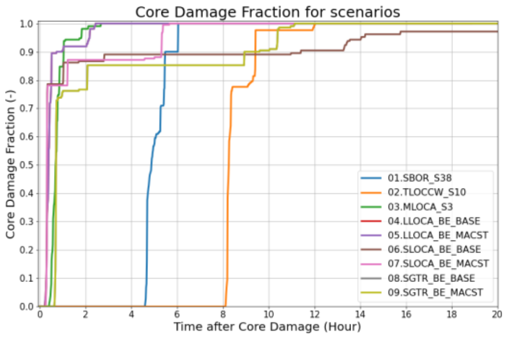

Fig. 4. Fraction of damaged core nodes from MAAP5 calculation.

4. Summary

The aim of this study is to estimate the in-containment source term for the selected sequences with the MAAP5 code using a realistic approach. The conditions studied would contain as much of the radioactive airborne material as possible without compromising containment integrity. The analysis results are also compared with NUREG-1465 source terms for noble gases, iodine, and Cs/Rb group. MAAP5 predicts a similar fraction of noble gases as NUREG-1465. However, a lower release fraction is predicted for iodine and Cs/Rb species compared to that of NUREG-1465. This study, as part of a project to develop new measurement and indicating systems for in-containment activity and dose during severe accidents at operating plants, is able to contribute to establishing the initial and boundary conditions for new measurement sensors.

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