Evaluation of Cs-137 Release Frequency Exceeding 100 TBq using MPAS Level 2 PSA Model and MELCOR

FNC Technology.
Gyeongyeol Kim, Hyun-bin Chang, MyeongKwan Seo
Suwon Lee, Jung Hyun Ryu

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FNC Technology Co., Ltd.

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1 Introduction

1 Introduction

Background

Background of Cs-137 Release Frequency Exceeding 100TBq

NSSC Notice No. 2026-1, Article 9

- The regulatory body shall verify whether the PSA results submitted by the licensee satisfy the following criteria
  - The risks of early fatality and latent cancer shall each be less than 0.1% of the total risk or meet equivalent performance goals (Target 1)
  - The total frequency of accidents resulting in Cs-137 release exceeding 100 TBq shall be less than 1.0×10^{-6} per year (Target 2)

Target 1

- NRC Safety Goal Policy Statement (QHO)
  - QHO(Quantitative Health Objectives): Early fatality risk ≤ 0.1 %, Latent cancer fatality risk ≤ 0.1%
- NUREG-1150
  - Level 1, 2, 3 PSA -> Dose assessment, Quantification of Early fatality risk and Latent Cancer fatality risk
- [NRC Regulatory Guide 1.174]
  - CDF ≤ 1.0E-4, LERF ≤ 1.0E-5

Target 2

- Derived from the LERF concept of Target 1
  - Conservatively increased by a factor of 10 to account for uncertainty (1.0E-5 -> 1.0E-6)
- Evaluated through Level 2 PSA Source Term Analysis

1 Introduction

Objective

Objective of Multi-Purpose Probabilistic Analysis of Safety(MPAS) PSA

- To verify the validity and adequacy of PSA results submitted by the licensee for both Target 1 and Target 2
  - Verification Method for Target 1
    - CDF: Derived from MPAS Level 1 PSA model
    - LERF: Derived from MPAS Level 2 PSA model
  - Verification Method for Target 2
    - Cs-137 Release Frequency Exceeding 100TBq: Derived from MPAS Level 2 PSA model & Source Term Analysis
    - Currently, no prior experience exists for regulatory Source Term Analysis

→ Independent Regulatory Verification of the Licensee's Cs-137 Release Frequency Exceeding 100 TBq

1 Introduction

Tools for Source Term Analysis

- APR1400 MPAS Level 2 PSA Model
  - Incorporation of New Strategies Included in the Accident Management Program (MACST, SAMG)
  - Applying state-of-arts Level 2 PSA Study results
    - RCSFAIL DET: RASP Handbook V5(NUREG-2195) & NUREG/CR-6109
  - DET updated based on severe accident progression analysis

- MELCOR Code
  - Severe Accident Thermal-Hydraulic and Source Term Analysis code
  - Source Term Behavior Simulation and Release Quantification for each Accident Sequence

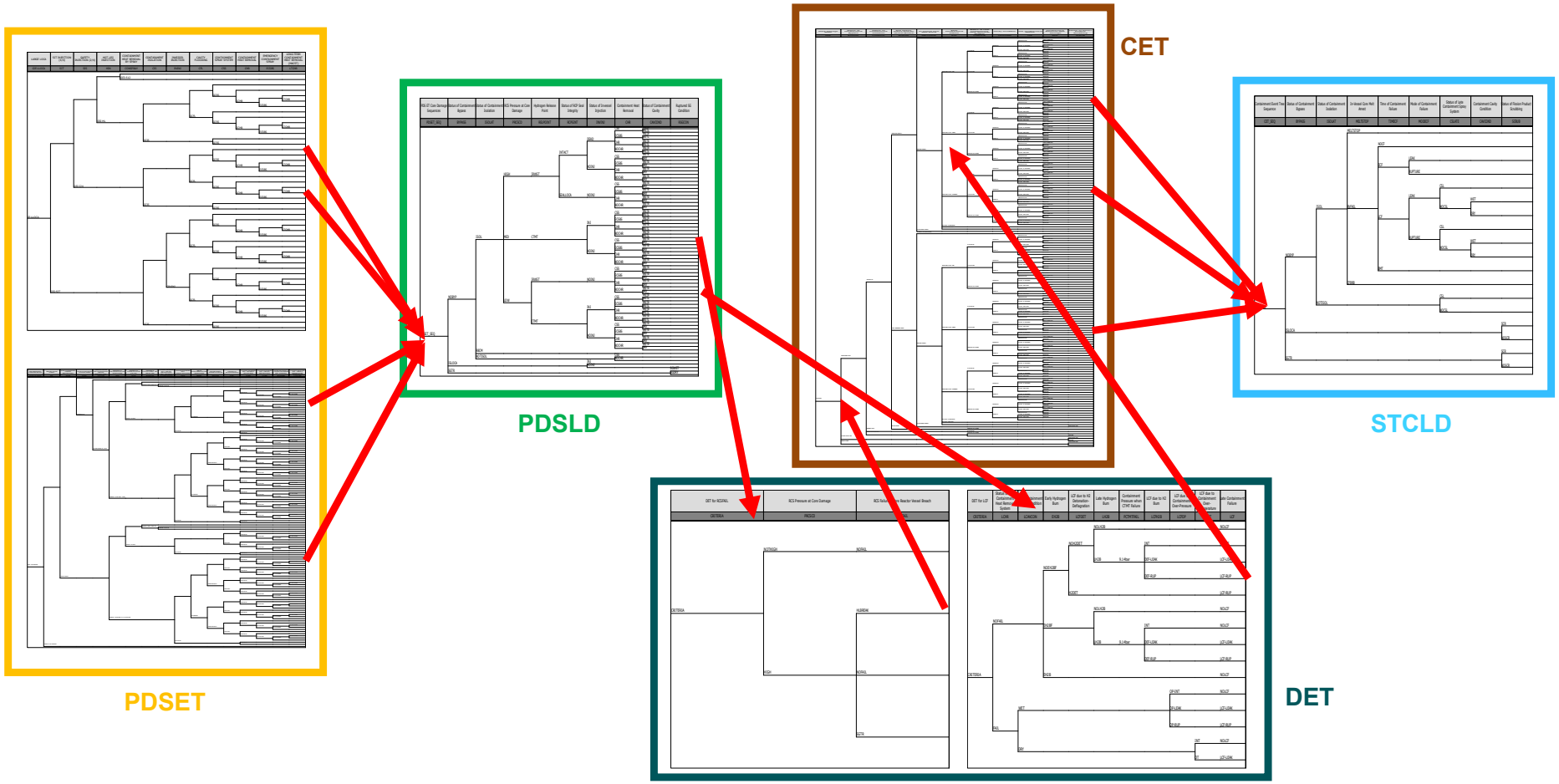
- Analysis Framework
  - Selection of accident sequences for analysis
  - Source Term Analysis using MELCOR
  - Quantification of the Cs-137 Release Frequency Exceeding 100 TBq
  - Comparison with the licensee's analysis results

2 Methodology and Result

2 Methodology and Result

2.1 Selection of Accident Sequences for Analysis

APR1400 MPAS Level 2 PSA Model Structure



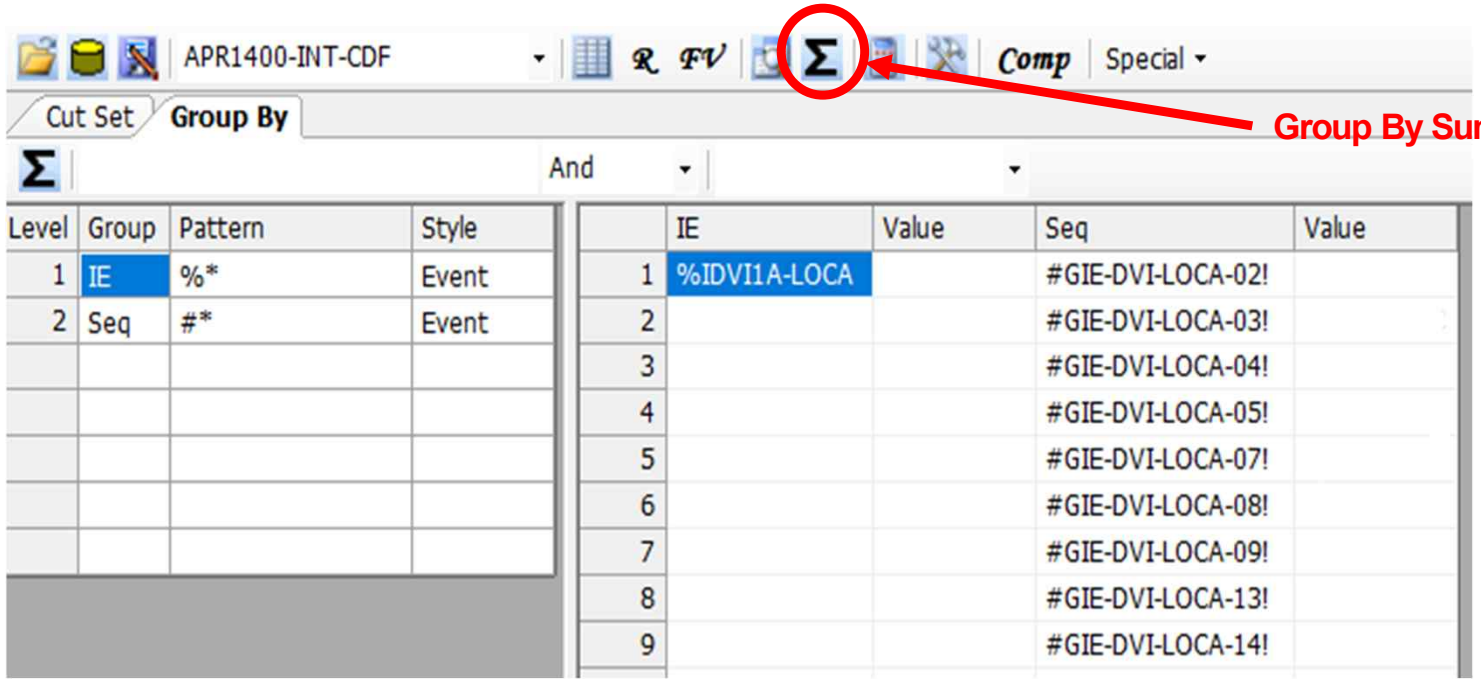
Identification of Accident Sequences and Release Pathways Based on the MPAS Level 2 PSA Model

2 Methodology and Result

2.1 Selection of Accident Sequences for Analysis

Analysis of the APR1400 MPAS Level 2 PSA Model Quantification Results (1/2)

- PDSET Quantification
  - Tools: AIMS, Ftrex
  - Output: Minimal CutSets (MCS) of Plant Damage State(PDS) Frequency
    - [Group By Summation]: Importance Analysis of Accident Sequences based on PDS frequency is possible



Level	Group	Pattern	Style
1	IE	%*	Event
2	Seq	#*	Event

	IE	Value	Seq	Value
1	%IDVI1A-LOCA		#GIE-DVI-LOCA-02!	
2			#GIE-DVI-LOCA-03!	
3			#GIE-DVI-LOCA-04!	
4			#GIE-DVI-LOCA-05!	
5			#GIE-DVI-LOCA-07!	
6			#GIE-DVI-LOCA-08!	
7			#GIE-DVI-LOCA-09!	
8			#GIE-DVI-LOCA-13!	
9			#GIE-DVI-LOCA-14!	

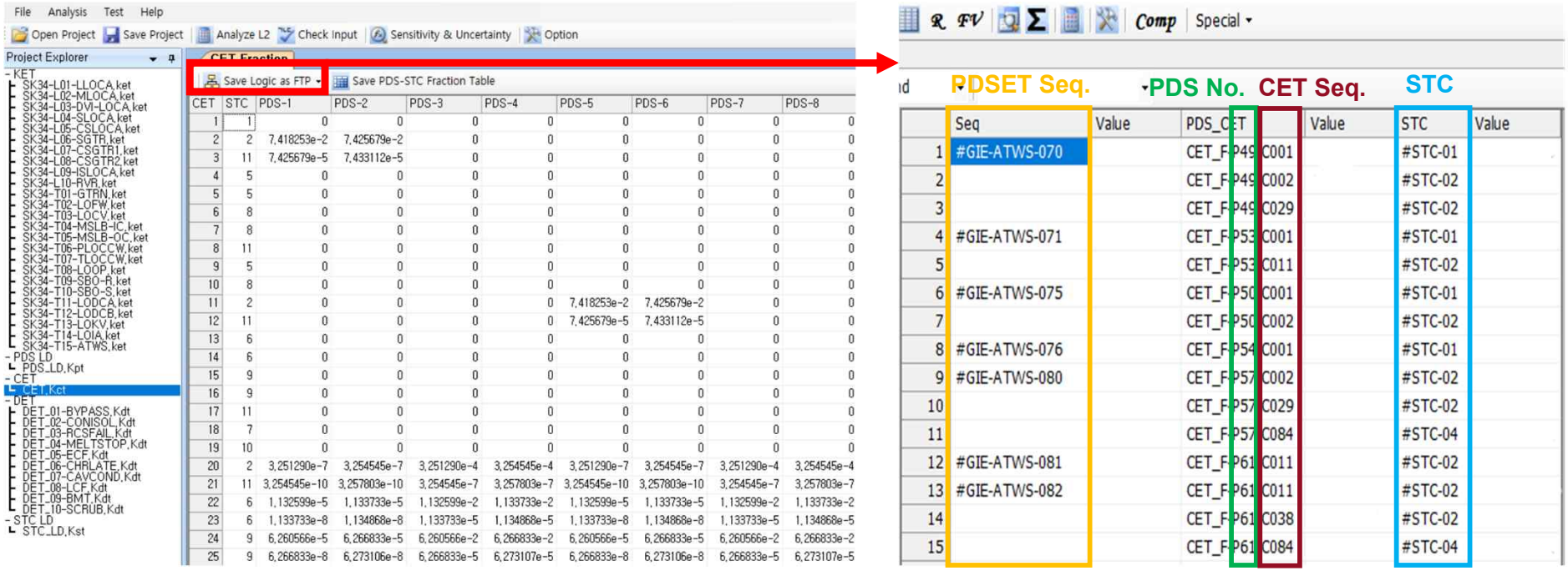
2 Methodology and Result

2.1 Selection of Accident Sequences for Analysis

Analysis of the APR1400 MPAS Level 2 PSA Model Quantification Results (2/2)

Level 2 (PDSLD - CET/DET – STCLD) Quantification

- Tool: AIMS-L2
- Outputs: PDS / CET / STC Frequency, PDS - CET Sequence(with STC) Mapping Table
- [Save Logic as FTP]
  - [PDSET Sequence] – [PDS No.] Mapping
  - [PDS No.] – [CET Sequence] – [STC] Mapping
  - AIMS [Group By Summation] : Importance Analysis across [PDSET Sequence] – [PDS No.] – [CET Sequence] – [STC]



2 Methodology and Result

2.1 Selection of Accident Sequences for Analysis

Classification of STCs by Containment Damage State

Containment Damage State	NOCF	ECF	LCF	BMT	CFBRB	NOTISO	BYPASS
STC No.	1 ~ 2	3 ~ 4	5 ~ 10	11	12	13~14	15 ~ 18

Procedure for Selecting Representative Accident Sequences

- 1) Selection of Accident Sequences by Containment Damage State
  - High-impact, high-frequency sequences selected
- 2) Review of Accident Progression
  - Inclusion of key severe accident phenomena confirmed
- 3) Definition of Containment Failure Conditions
  - Containment failure pressure, timing, and conditions defined

Result of Selecting Representative Accident Sequences

Containment Damage State	**Representative Accident Sequence**		
	PDSET Sequence	STC	Contribution (%)
NOCF	TLOCCW-28	2	40.6
ECF	TLOCCW-34	4	13.9
LCF	TLOCCW-30	9	30.3
BMT	TLOCCW-31	11	26.4
CFBRB	MLOCA-2	12	85.8
NOTISO	SBOS-300	14	6.3
BYPASS	ISLOCA-2	16	0.1

2 Methodology and Result

2.2 Source Term Analysis using MELCOR

Source Term Analysis using MELCOR

Development of MELCOR Input for Representative Sequences

- Initiating Event conditions
- Availability of safety-related systems
- Containment failure conditions by containment damage state
  - Failure pressure
  - Time of failure
  - Failure mode (Leakage or Rupture)
- Release pathways to the environment

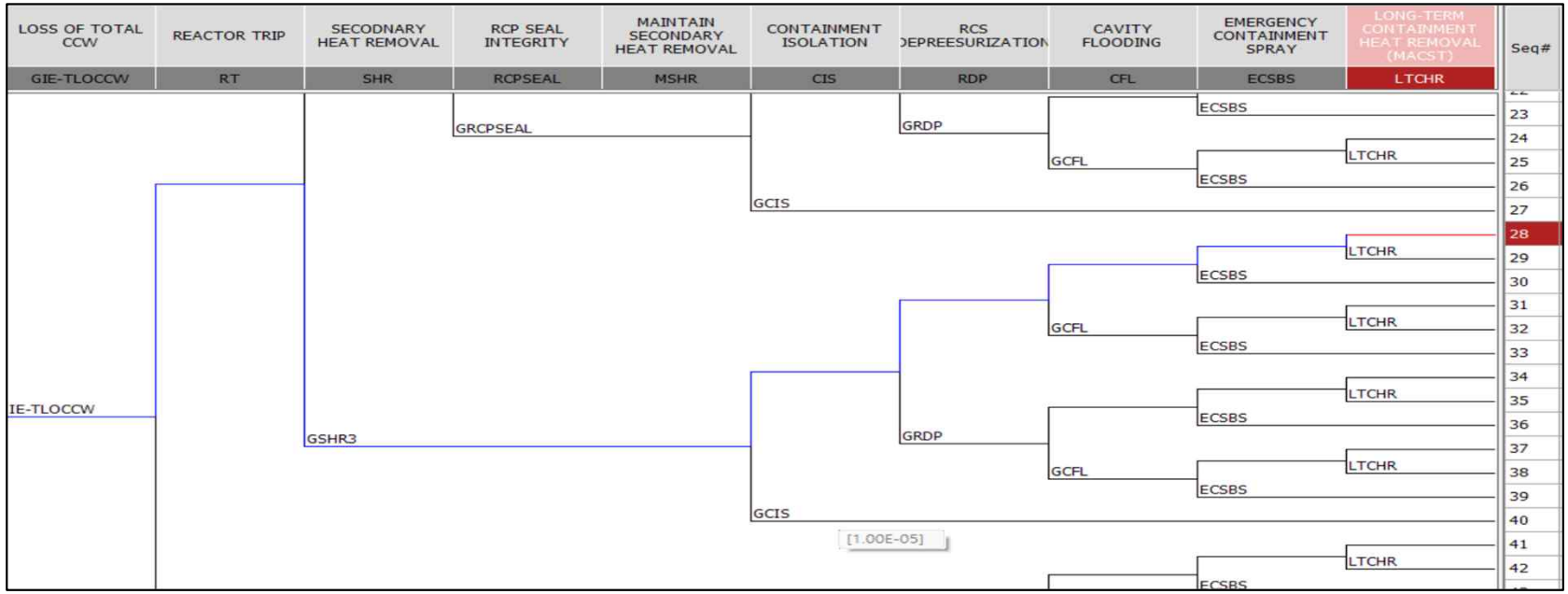
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

NOCF Representative Accident Sequence (TLOCCW-28)

Characteristic of Accident Sequence

TLOCCW	RT	SHR	CIS	RDP	CFL	ECSBS	LTCHR
-	O	X	O	O	O	O	O



Design leakage release assumed

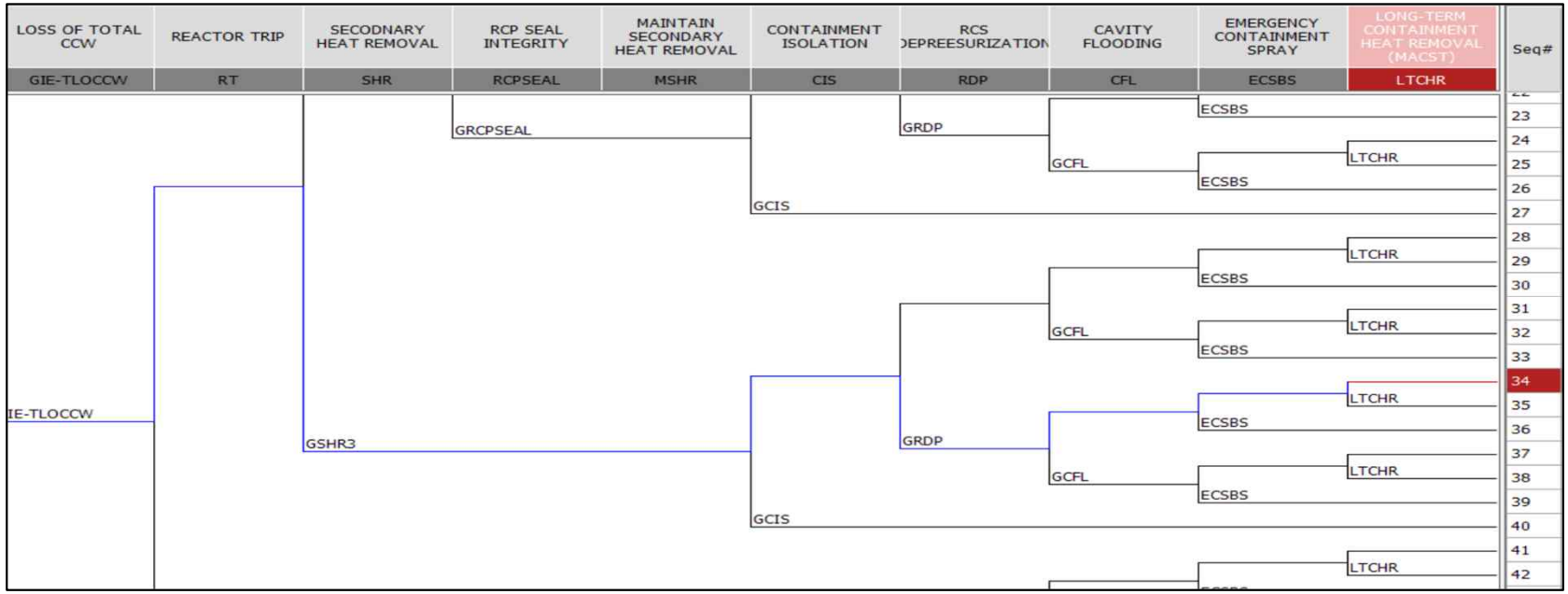
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

ECF Representative Accident Sequence (TLOCCW-34)

- Characteristic of Accident Sequence

TLOCCW	RT	SHR	CIS	RDP	CFL	ECSBS	LTCHR
-	O	X	O	X	O	O	O



- Design leakage release assumed
- Containment failure is assumed at the time of reactor vessel failure

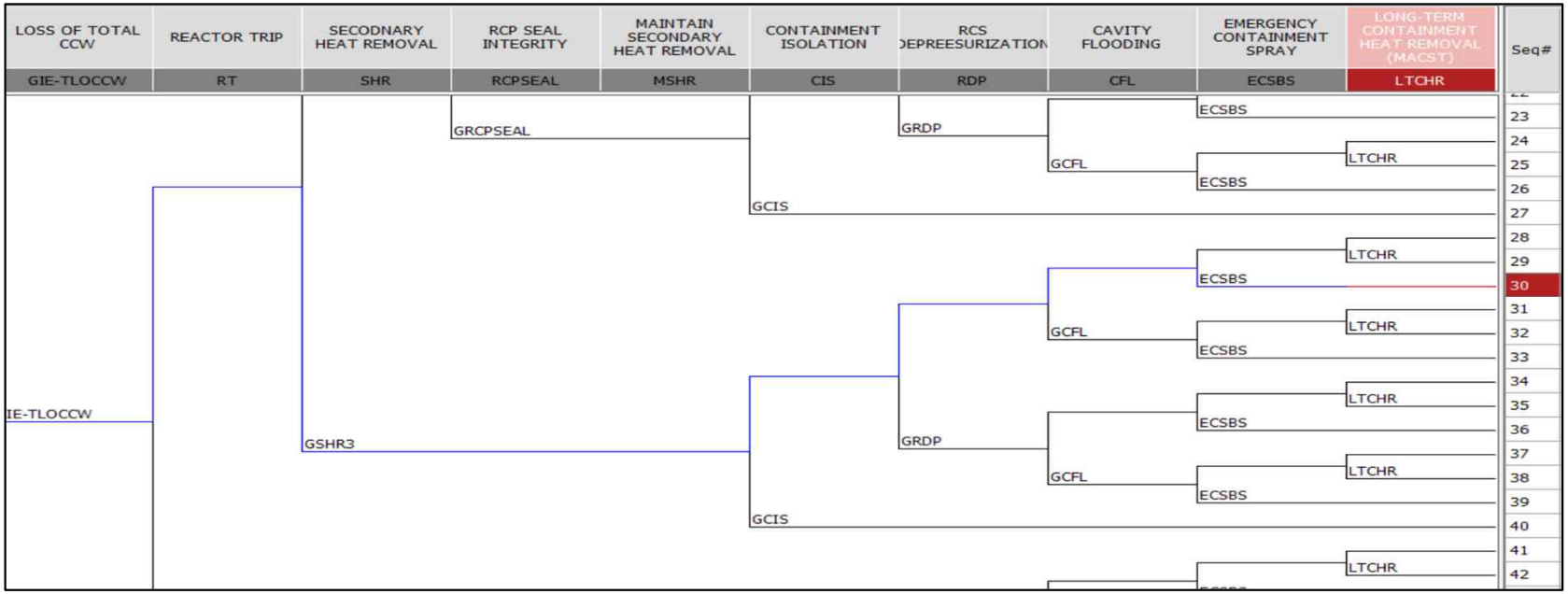
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

LCF Representative Accident Sequence (TLOCCW-30)

- Characteristic of Accident Sequence

TLOCCW	RT	SHR	CIS	RDP	CFL	ECSBS	LTCHR
-	O	X	O	O	O	X	X



- Design leakage release assumed
- Containment failure is assumed upon reaching the pressure corresponding to a 5% failure probability on the containment fragility curve

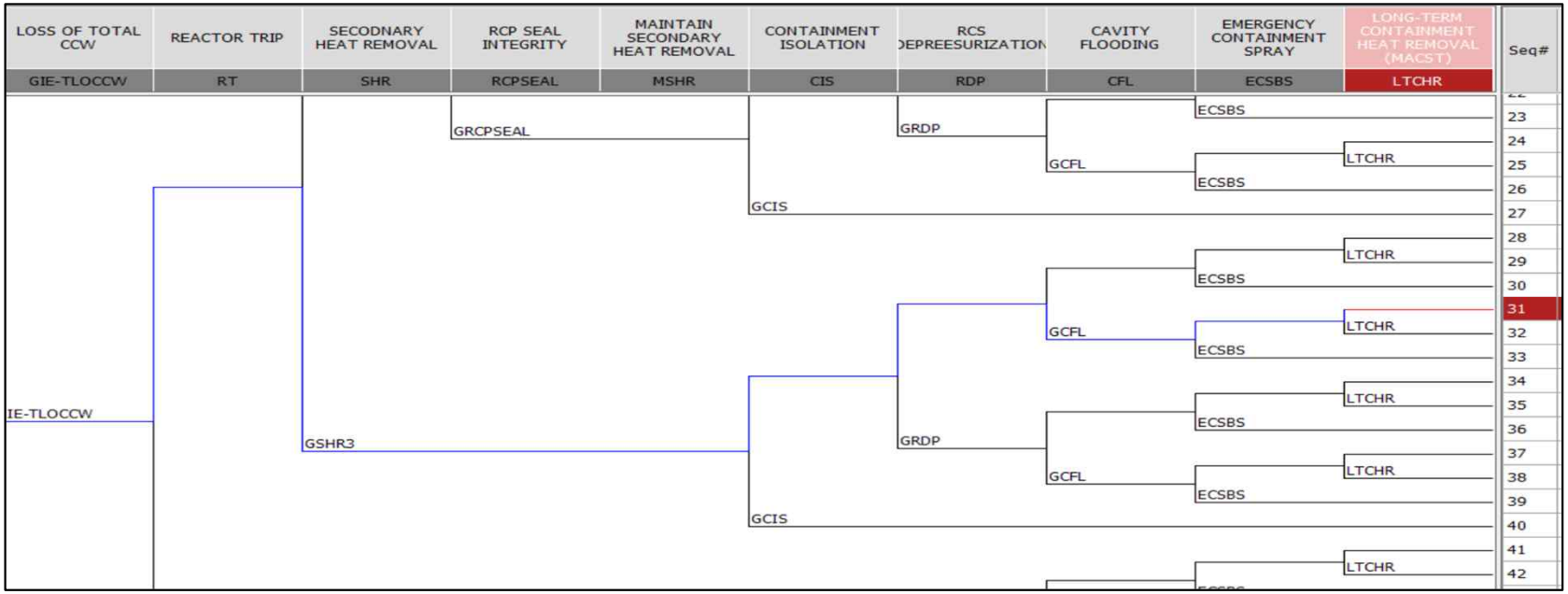
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

BMT Representative Accident Sequence (TLOCCW-31)

- Characteristic of Accident Sequence

TLOCCW	RT	SHR	CIS	RDP	CFL	ECSBS	LTCHR
-	O	X	O	O	X	O	O



- Design leakage release assumed
- Basemat melt-through (BMT) is assumed when the cavity floor erosion reaches a specified depth

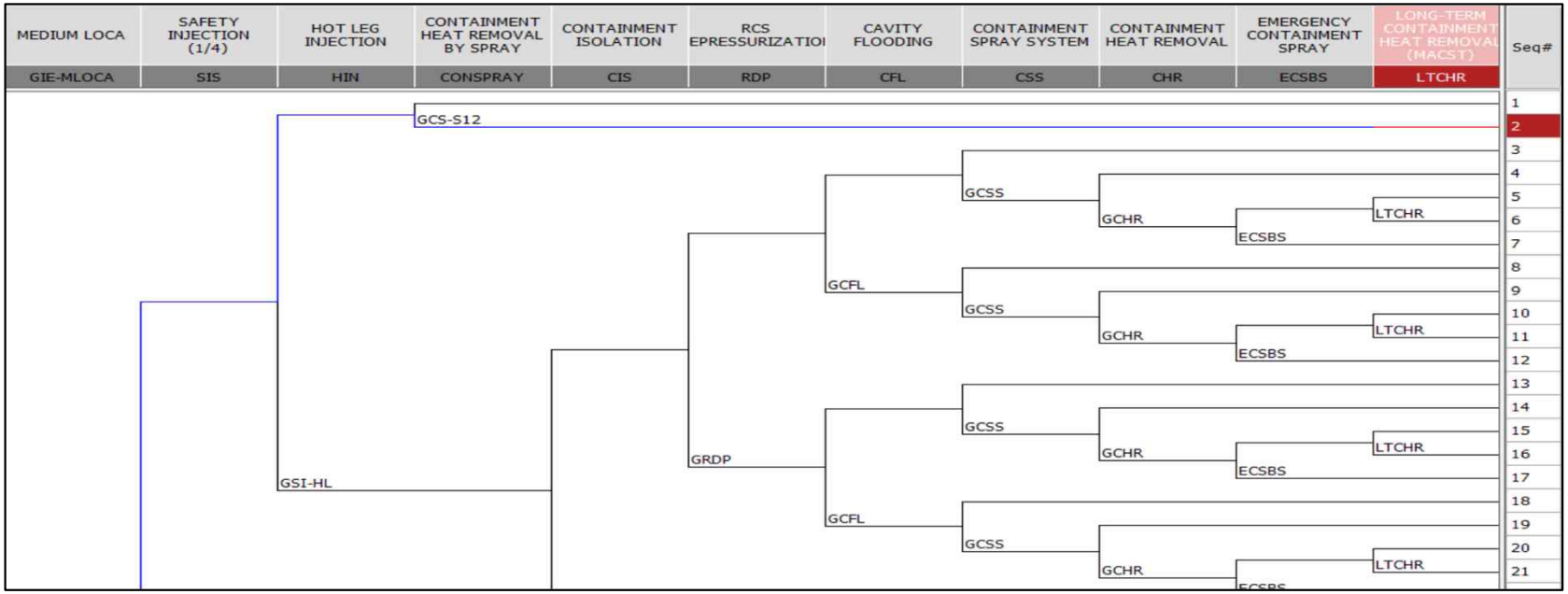
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

CFBRB Representative Accident Sequence (MLOCA-2)

- Characteristic of Accident Sequence

MLOCA	SIS	HIN	CONSPRAY
-	O	O	X



- Design leakage release assumed
- Containment failure is assumed upon reaching the pressure corresponding to a 5% failure probability on the containment fragility curve

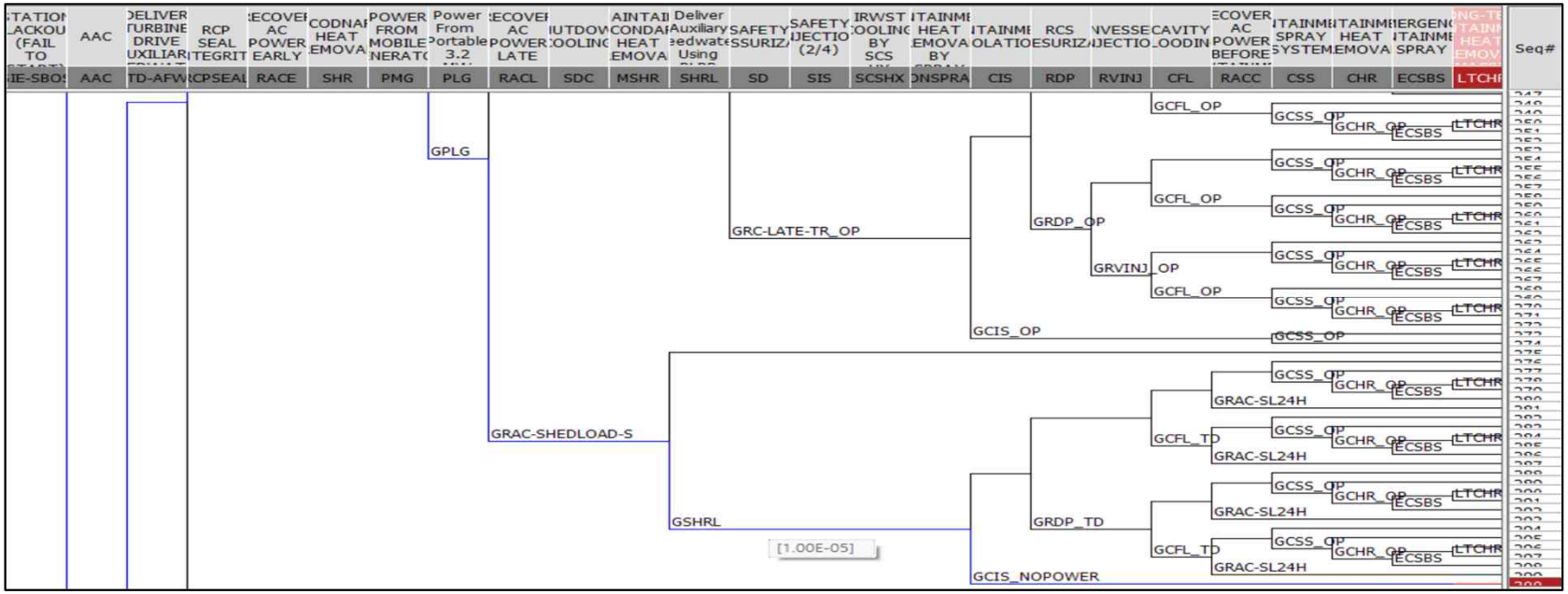
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

NOTISO Representative Accident Sequence (SBOS-300)

- Characteristic of Accident Sequence

SBOS	AAC	TD-AFW	RCPSEAL	PMG	PLG	RACL	SHRL	CIS
-	X	O	O	X	X	X	X	X



- Design leakage release assumed
- Failure of containment penetration isolation

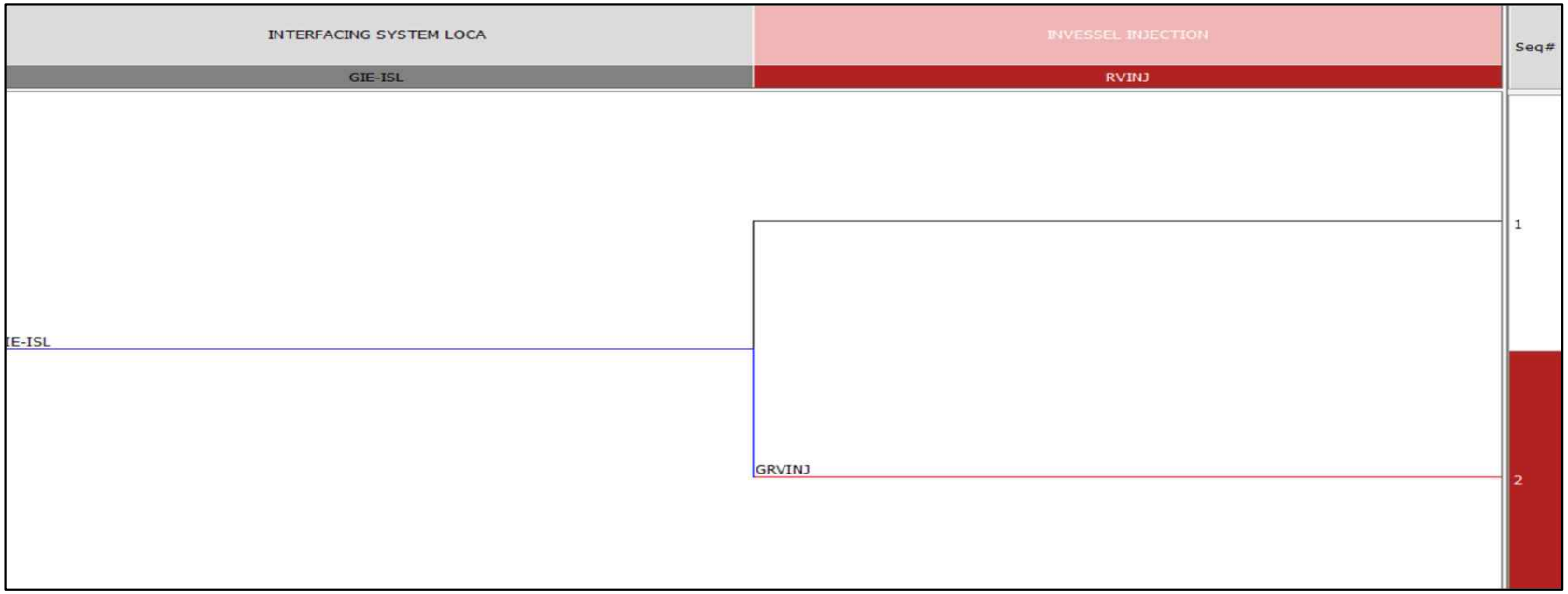
2 Methodology and Result

2.2 Source Term Analysis using MELCOR

BYPASS Representative Accident Sequence (ISLOCA-2)

- Characteristic of Accident Sequence

ISLOCA	HPI
-	X



- Design leakage release assumed
- ISLOCA assumed due to rupture of the shutdown cooling system suction line

2 Methodology and Result

2.3 Quantification of the Cs-137 Release Frequency Exceeding 100 TBq

- Calculation of Cs-137 Release by Containment Damage State
  - Identification of the initial Source Term inventory in the core
  - Calculation of the total release quantity of fission products containing Cs
    - Class 2(CS)
    - Class 16(CSI)
    - Class 17(CSM)
  - Derivation of the Cs mass fraction within Cs-containing fission product compounds using molar fractions
    - Class 2(CS)
      - Cs 100%
    - Class 16(CSI)
      - CsI: M_{Cs} = 132.905 g/mol, M_{I} = 126.904 g/mol
      - Cs mass fraction: M_{Cs} / (M_{Cs} + M_{I}) = 0.5116
    - Class 17(CSM)
      - Cs_2MoO_4 : M_{Cs} = 132.905 g/mol, M_{Mo} = 95.950 g/mol, M_{O} = 15.999 g/mol
      - Cs mass fraction: 2 M_{Cs} / (2 M_{Cs} + M_{Mo} + 4 M_{O}) = 0.6243
  - Application of the Cs-137 inventory fraction relative to the initial Cs inventory
  - Calculation of Cs-137 activity
    - Using the Cs-137 mass (m), molar mass (M), Avogadro's number (N_A), and decay constant (λ)
    - $A = \lambda \frac{m}{M} N_A$

2 Methodology and Result

2.3 Quantification of the Cs-137 Release Frequency Exceeding 100 TBq

Cs-137 Release Calculation Card in MELCOR

```
!                cfname        icfnum        cftype
CF_ID        'Cs_Frac_Envir'          1300          ADD
!             cfscal        cfadcn
CF_SAI         0.00449           0.0
!             icflim
CF_ULB         DEFAULT           0.0           0.0
!      size
CF_ARG    3 !n                  cfarg          arscal        aradcn
          1 RN1-TYCLT(CS,CTYP-6,RAD)                1.0
          2 RN1-TYCLT(CSI,CTYP-6,RAD)        0.51155600
          3 RN1-TYCLT(CSM,CTYP-6,RAD)         0.6243        !0.73478922 = Cs2Mo, 0.6243 = Cs2MoO4
!
!                cfname        icfnum        cftype
CF_ID        'Cs_mass_Env'          1350          ADD
!             cfscal        cfadcn
CF_SAI         1.0           0.0
!             icflim
CF_ULB         DEFAULT           0.0           0.0
!      size
CF_ARG    3 !n                  cfarg          arscal        aradcn
          1 RN1-TYCLT(CS,CTYP-6,RAD)                1.0
          2 RN1-TYCLT(CSI,CTYP-6,RAD)        0.51155600
          3 RN1-TYCLT(CSM,CTYP-6,RAD)         0.6243        !0.73478922 = Cs2Mo, 0.6243 = Cs2MoO4
```

2 Methodology and Result

2.3 Quantification of the Cs-137 Release Frequency Exceeding 100 TBq

Cs-137 Release Quantity and Frequency of Releases Exceeding 100 TBq

Containment Damage State	Cs-137 Release Quantities (TBq)	Frequency (/yr)	Contribution (%)
NOCF	~10.0	~2.0E-06	44.7
ECF	~100,000.0	~1.0E-08	0.2
LCF	~10,000.0	~2.0E-06	47.0
BMT	~10.0	~1.5E-07	3.5
CFBRB	~10,000.0	~1.5E-07	3.1
NOTISO	~100,000.0	~1.5E-08	0.3
BYPASS	~100,000.0	~5.5E-08	1.2

Release Category	Frequency (/yr)	Contribution (%)
Cs-137 (> 100 TBq)	~2.5E-06	51.8

2 Methodology and Result

2.4 Comparison with the Licensee's Analysis Results

Comparison of Cs-137 Release Quantity (Licensee vs MPAS)

- Comparison of corresponding STCs by Containment Damage State (Licensee vs MPAS)

Containment Damage State	Licensee		MPAS	
	STC	Cs-137 Release Quantities (TBq)	STC	Cs-137 Release Quantities (TBq)
NOCF	10	~1.0	2	~10.0
ECF	15	~10,000.0	4	~100,000.0
LCF	20	~100.0	9	~10,000.0
BMT	11	~0.01	11	~10.0
CFBRB	7	~10,000.0	12	~10,000.0
NOTISO	6	~10,000.0	14	~100,000.0
BYPASS	3	~100,000.0	16	~100,000.0

- NOCF and BMT < 100 TBq in both analyses
- MPAS results generally higher than licensee results

3 Conclusion and Further Studies

3 Conclusion and Further Studies

Wrap up

- Selection of Representative Accident Sequences by Containment Damage State (MPAS Level 2 PSA)
  - Selection of sequences with significant radiological impact and high frequency
  - Review to ensure inclusion of key severe accident phenomena
  - Definition of containment failure conditions for each representative sequence

- Source Term Analysis Using MELCOR
  - Simulation of accident progression for representative sequences by containment damage state
    - Consideration of initiating event conditions, availability of safety-related systems, containment failure conditions, and release pathways to the environment

- Calculation of Cs-137 Release Quantity and Frequency of Releases Exceeding 100 TBq
  - Calculation of Cs-137 release quantity using formulation
  - Cs-137 release quantities exceed 100 TBq for all damage states except NOCF and BMT

3 Conclusion and Further Studies

Comparison Results with the Licensee's PSA

- Consistency between independent analyses supports the reliability of Source Term Analysis
  - Different analysis codes were used:
    - Licensee: MAAP
    - MPAS model: MELCOR
  - Containment damage states exceeding 100 TBq of Cs-137 release are identical in both analyses

- Differences in Cs-137 release quantity are observed for the same Containment Damage States
  - MPAS-based results are generally higher than the licensee's results
    - **LCF**: MPAS (MELCOR) ≈ 100× higher than licensee (MAAP)
    - **BMT**: MPAS (MELCOR) ≈ 1,000× higher than licensee (MAAP)
  - Differences are attributed to the modeling approach for source term release through containment design leakage

3 Conclusion and Further Studies

Further Studies

- Cs-137 release frequency exceeding 100 TBq (~2.5E-06/yr) exceeds the regulatory limit
  - Conservative TLOCCW initiating event frequency in Level 1 PSA
    - Fault Tree-based calculation
      - Plant configuration during power operation not considered
        - Fail to run modes applied to standby equipment, with a 1-year mission time
        - 4/4 Common Cause Failure (CCF) assumed for ESW pumps
      - Approximately 5 times higher than the licensee's initiating event frequency
    - Majority of TLOCCW sequences classified as late containment failure (LCF)
      - Driven by failure of containment spray and heat removal
  - Conservative Source Term Analysis by Containment Damage State
    - Most conservative sequence selected for each containment damage state
      - Some STCs within the same damage state may result in Cs-137 release below 100 TBq
    - STC-level Source Term Analysis
      - Potential reduction of the estimated Cs-137 release frequency exceeding 100 TBq
      - Input Development for MPAS Level 3 PSA

- Further Studies
  - Re-evaluation of TLOCCW initiating event frequency
  - Source Term Analysis for representative accident sequences at the STC level

Q&A

FNC TECHNOLOGY CO., LTD.

ABOUT

(주)미래와도전
FNC Technology Co., Ltd.

본사

16954 경기도 용인시 기흥구 흥덕1로 13, 32층
(영덕동, 흥덕아이티밸리 타워동)
+82-31-8065-5114

대전지사

대전광역시 유성구 대덕대로 593, 10층 1004-1호
(도룡동, 대덕테크비즈센터)
+82-42-867-5114

미래에너지기술연구소

경기도 용인시 기흥구 탑실로 46,
미래에너지기술연구소
+82-31-8005-5618

설비개발연구센터

경기도 용인시 기흥구 탑실로 46,
미래에너지기술연구소
+82-31-8065-5114

UAE 아부다비지사

Office 904, Capital Tower, Al Rawhah,
PO Box 95133, Abu Dhabi, UAE
+971-2-643-5144

미국 메릴랜드지사

11140 Rockville Pike, Suite 380A,
Rockville, MD 20852 USA
+1-202-577-5537

THANK YOU

FNC TECHNOLOGY CO., LTD.