

Importance Analysis of SAMG related basic events using Level 2 PSA



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연구 배경

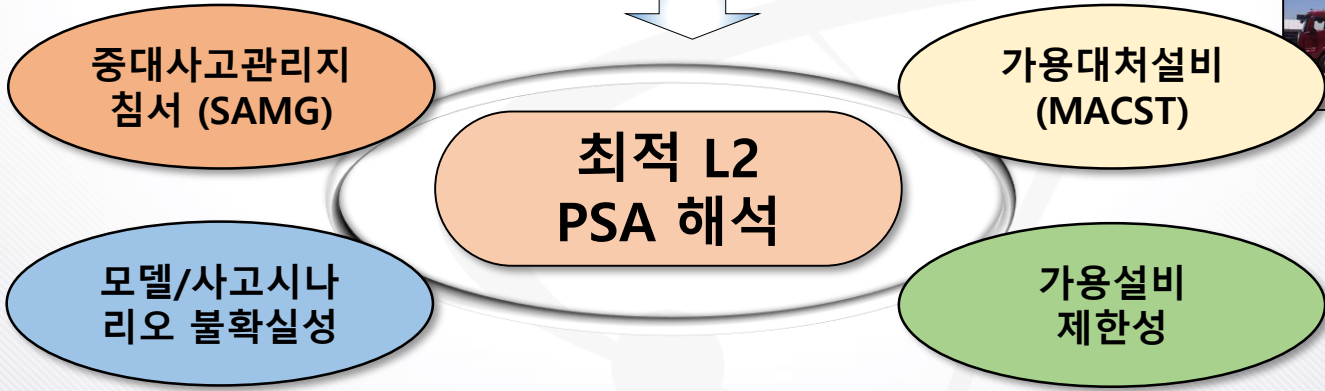
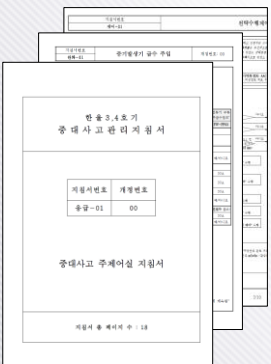
- 원자력안전법 개정 ('16) → PSA의 역할 증대

- 중대사고 법제화 및 안전목표 명시 대응 필요

- (Cs-137 > 100 TBq) < 10^{-6} /yr

- 리스크 최적 평가: Level 2 평가 결과의 과보수성 극복

- 중대사고 영역의 최적 평가 필요: SAMG 반영



중대사고관리지침서 (SAMG)

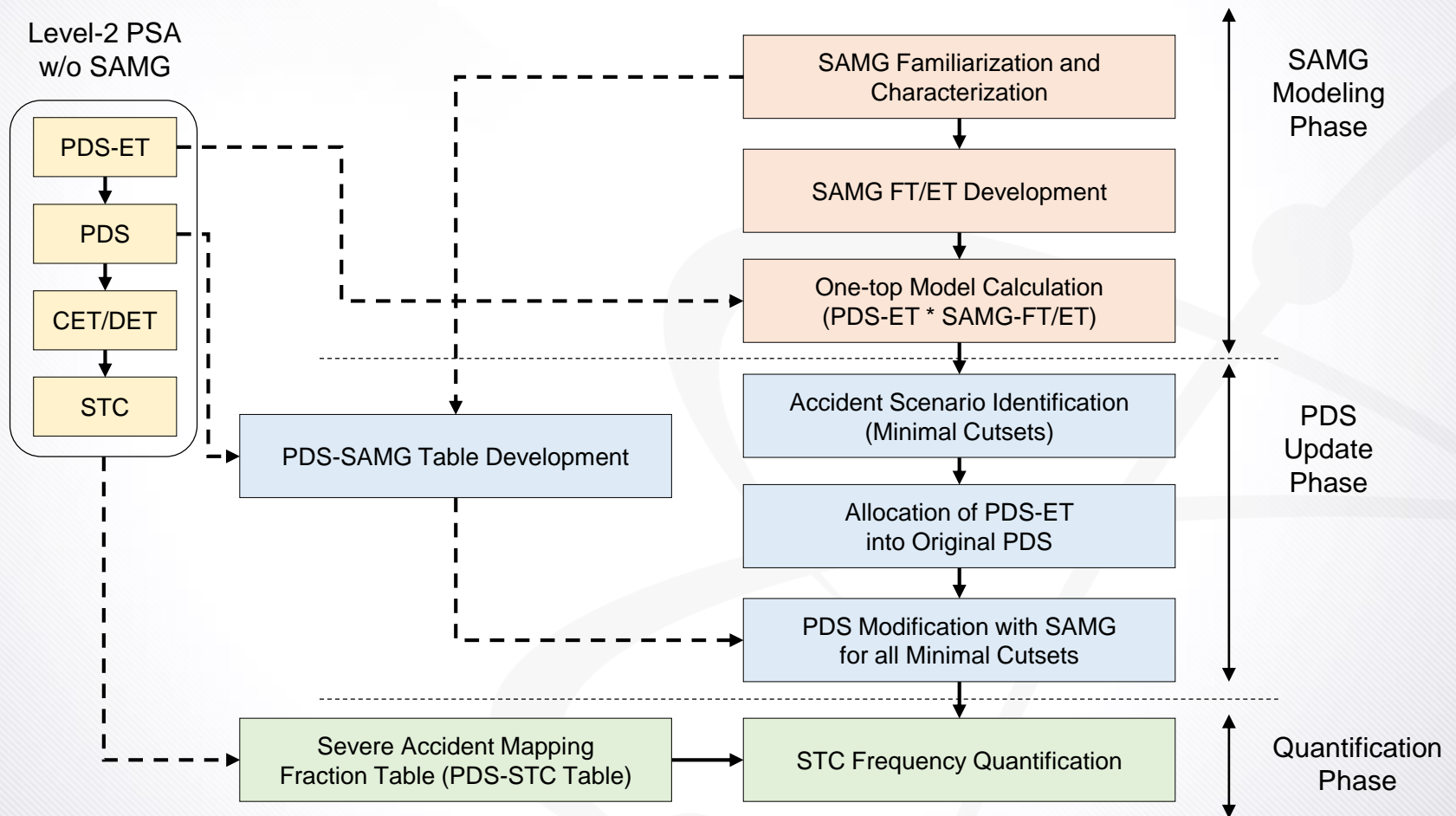
- 중대사고 진입 후 사고경위/발전소 상태에 따라 가용할 수 있는 중대사고 완화 수단, 전략 등 사고완화를 위한 지침 제공

중대사고관리 완화전략 주요 조치 내용 (예시: OPR-1000)

지침서 번호	조치	목적	사용기기/계통
완화-01	SG 급수 주입	- RCS 열제거원 확보 - SG 건전성 유지	- 보조급수계통 - 증기방출밸브
완화-02	RCS 감압	- 저압주입 노심냉각 - DCH/SG크립파손 방지	- 안전감압밸브 - 가압기 보조살수
완화-03	RCS 냉각수 주입	- 노심 붕괴열 제거 - RPV 파손 방지/지연	- 고압/저압 안전주입계통 - 살수/충전 펌프
완화-04	CTMT 냉각수 주입	- RPV 외벽냉각 - MCCI 방지/완화	- 격납건물 살수계통
완화-05	FP 방출 제어	- 격납건물 및 보조건물로 의 방출 감소	- 격납건물 살수계통 - 보조건물 배기계통
완화-06	CTMT 상태제어	- 격납건물 건전성 유지 - 방사능물질 방출 감소	- 격납건물 살수계통
완화-07	CTMT내 수소 제어	- 격납건물 내 수소 위험 및 연소 방지	- 수소 점화기 - 수소 재결합기

Level 2 PSA SAMG 모델링 방법론*

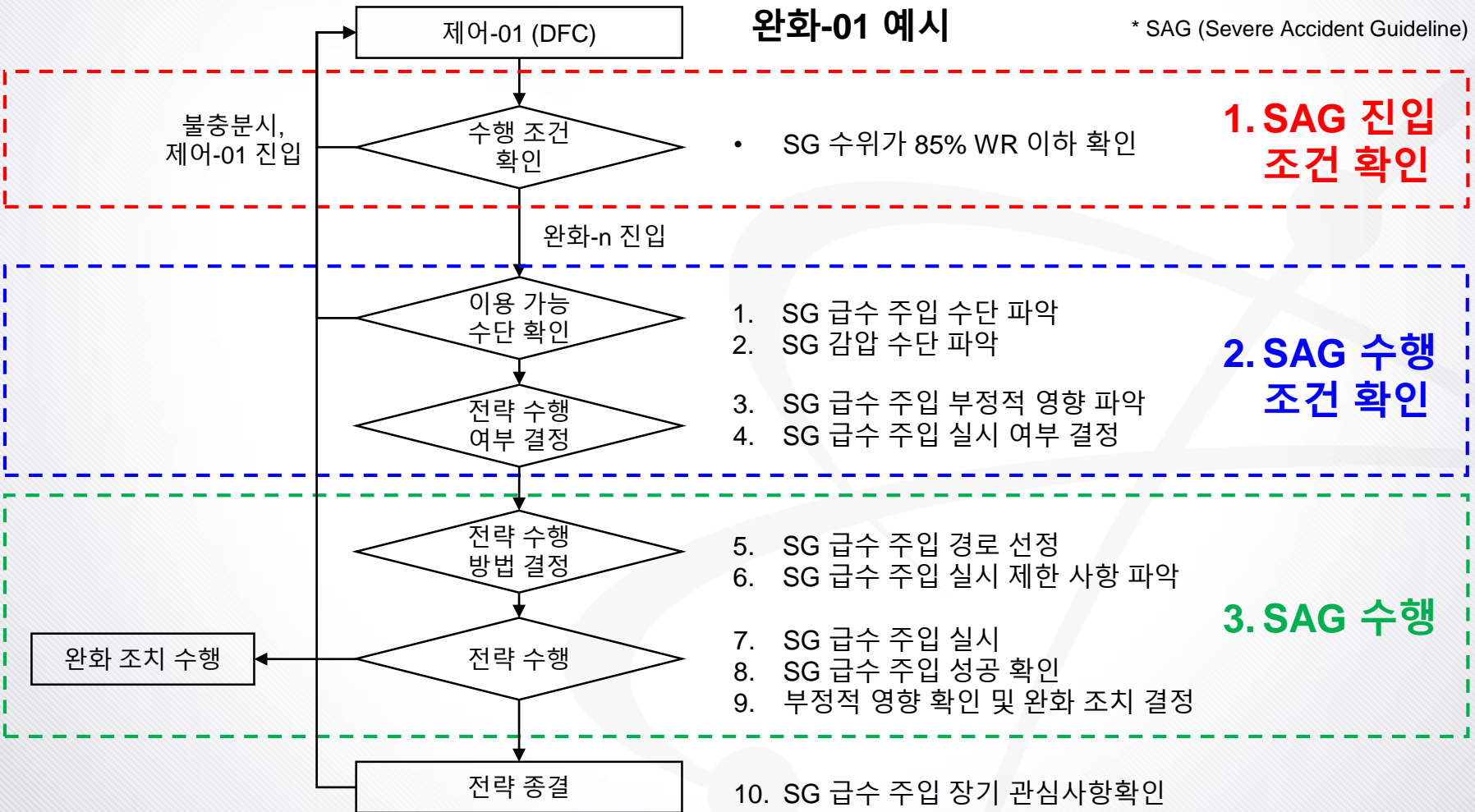
■ SAMG Modeling → PDS Update → Quantification



* J. Cho, S. H. Lee, J. Kim, Framework to Model Severe Accident Management Guidelines into Level 2 Probabilistic Safety Assessment of a Nuclear Power Plant, *Reliability Engineering & System Safety*, 2021 (submitted)

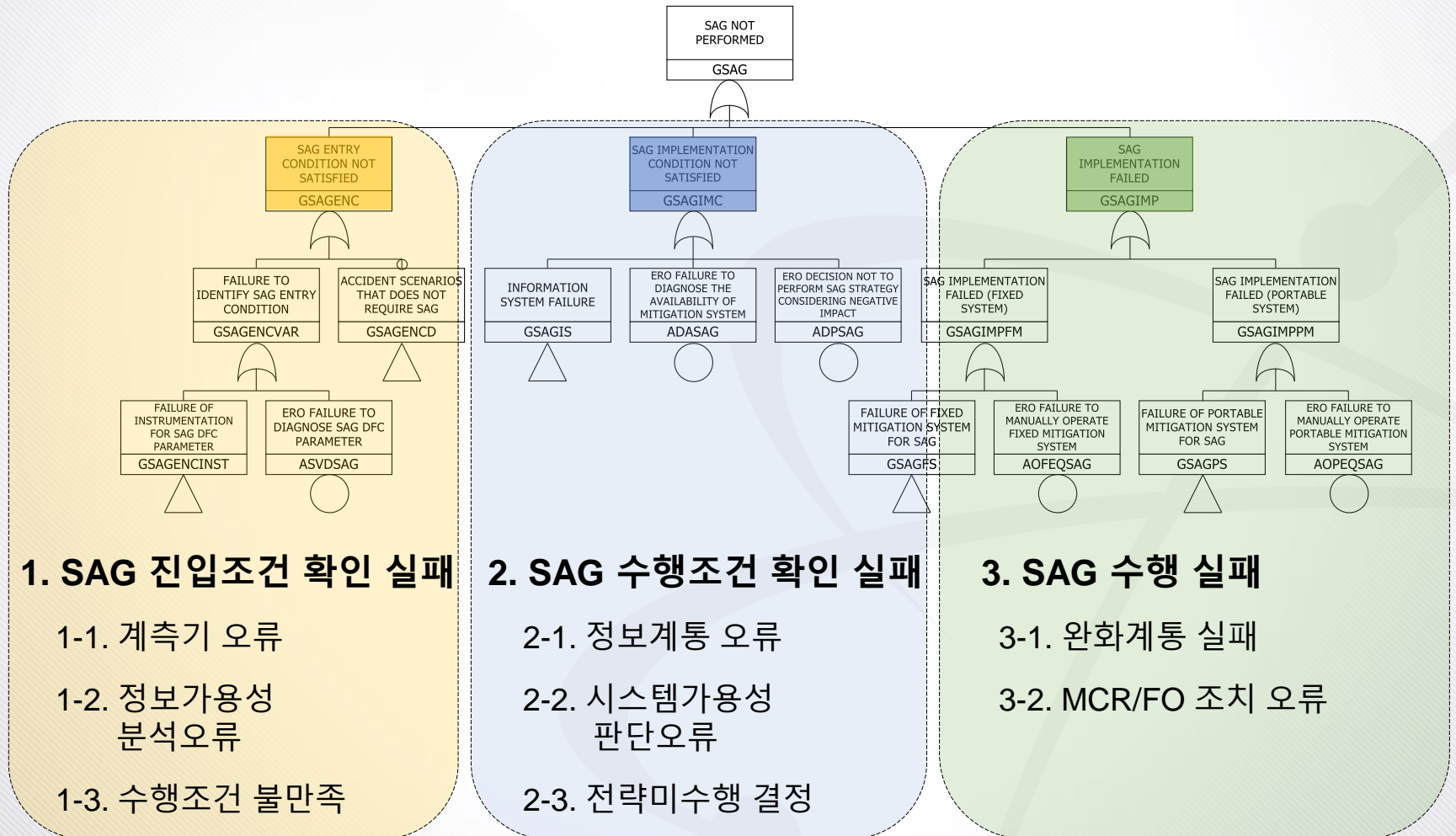
SAMG-FT/ET Model Development

■ SAMG 기반 FT 요소 도출



SAMG-FT/ET Model Development

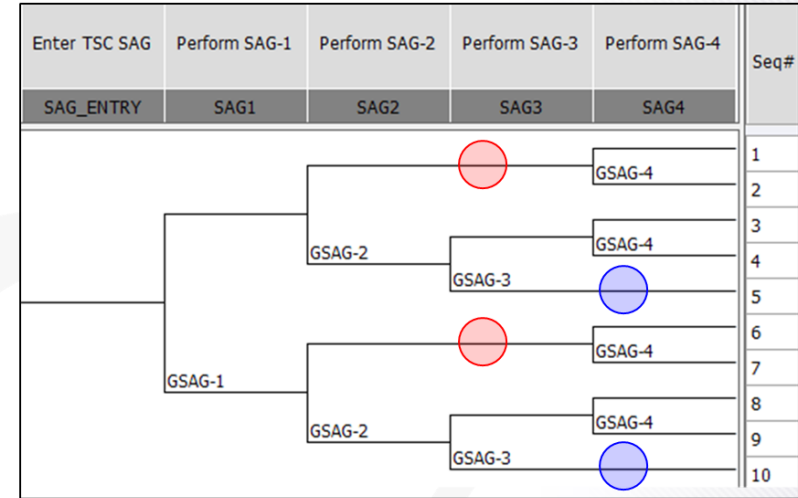
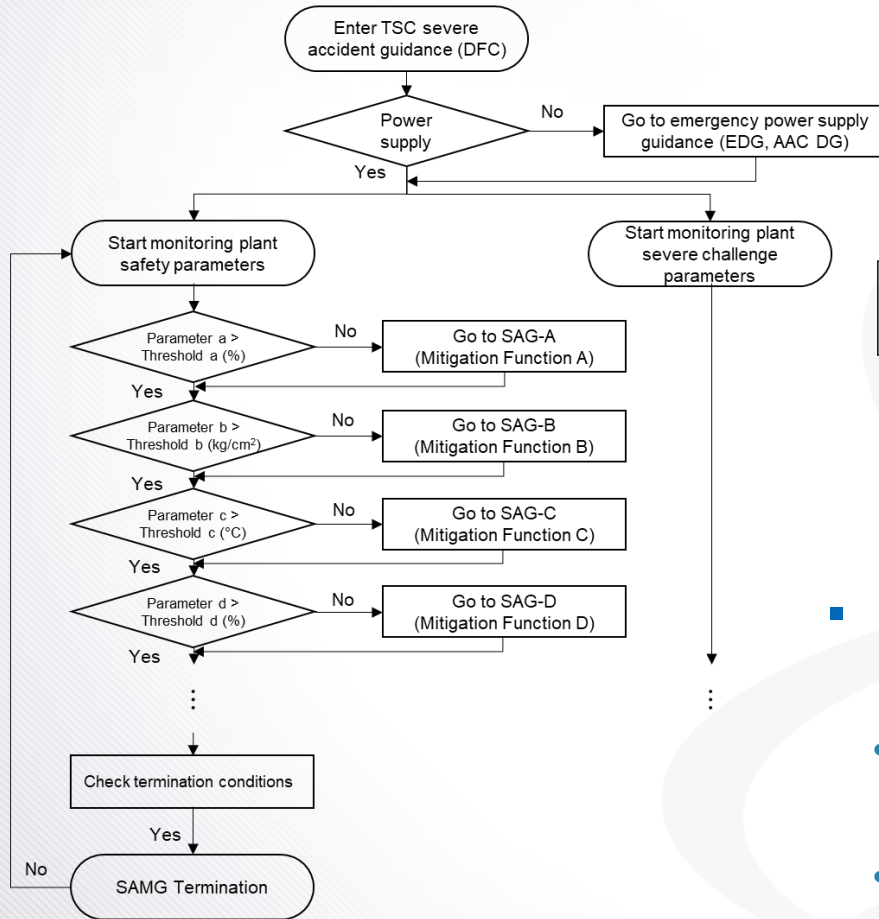
■ SAMG 지침서 기반 FT 모델 개발



* FO (Field Operator)

SAMG-FT/ET Model Development

■ SAMG 지침서 기반 ET 모델 개발

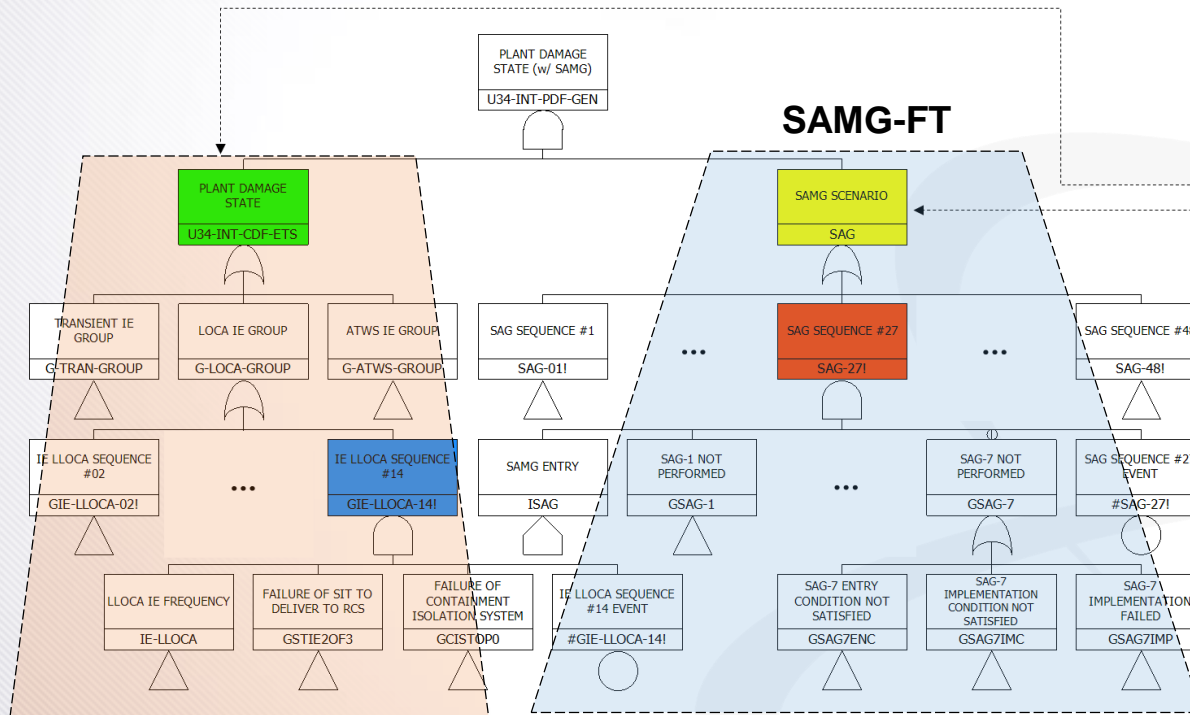


■ Diagnostic flow chart (DFC) 기반 heading 및 branching 정의

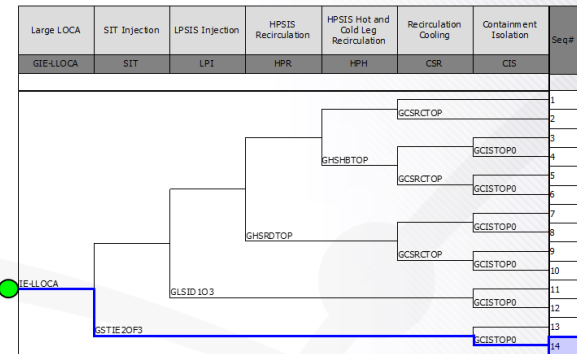
- DFC 기반 SAG 수행 순서에 따라 ET heading 정의
- SAG 별 기능적 dependency에 따라 nonsense branching 제외

OneTop Model Generation

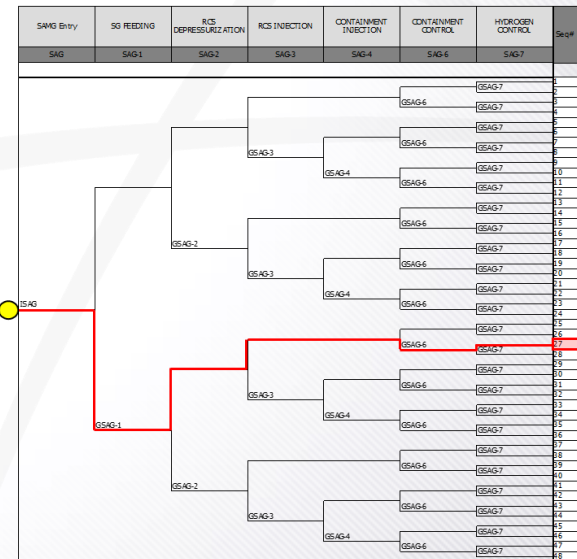
■ PDS + SAMG-FT/ET → OneTop Model



PDS-ET

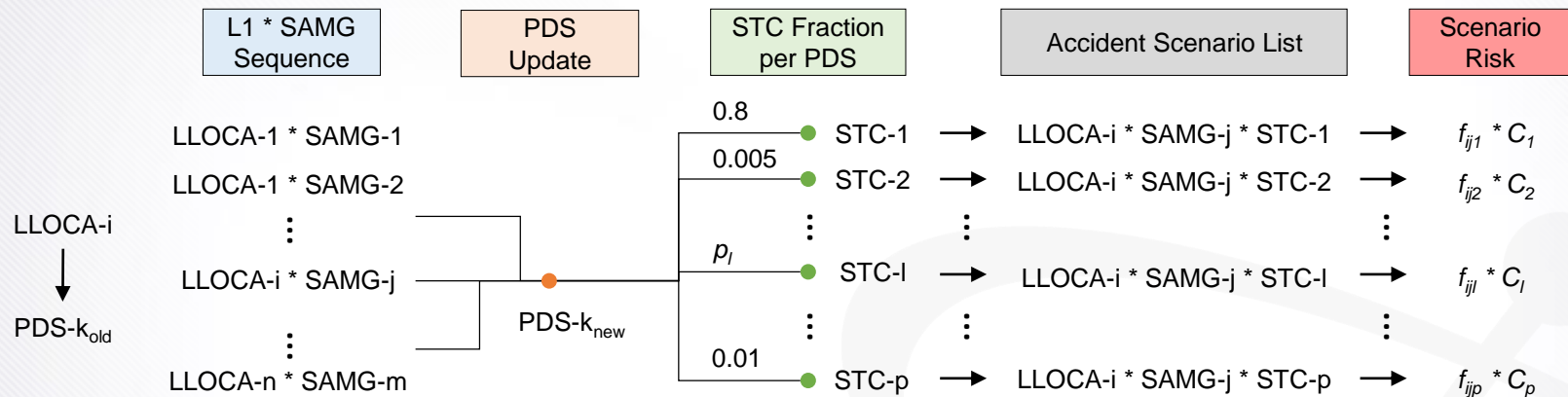


SAMG-ET



Quantification and Analysis

Update PDS → New STC → Risk Calculation



PDS-SAMG	23	24	25	26	27	28	29	30	31	32
PDS-32	32	32	4	5	6	6	7	8	9	9
PDS-33	31	31	4	5	6	6	7	8	9	9
PDS-34	32	32	4	5	6	6	7	8	9	9
PDS-35	35	35	4	4	35	35	7	7	35	35
PDS-36	35	36	4	5	36	36	7	8	36	36

Updated PDS and STC based on PDS-SAMG table

#	Freq.	Initiator	BE#1	BE#2	BE#3	BE#4	BE#5	BE#6	BE#7	Original PDS	SAMG	Revised PDS	STC
1	8.05E-08	%ILOOP	EGDGK3T-1A1B1E	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	-	32	#SAG-25!	4	1
2	6.26E-08	%ILOOP	EGDGW3T-1A1B1E	/NR-AC60HR	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-10!	-	32	#SAG-25!	4	1
3	5.95E-08	%IML-1A	HSOPHHLCLR	#GIE-MLOCA-3!	-	-	-	-	-	14	#SAG-41!	11	1
4	2.21E-08	%ITLOCCW	RCPSEAL_2S	#GIE-TLOCCW-2!	-	-	-	-	-	19	#SAG-37!	11	1
5	1.29E-08	%IRVR	#GIE-RVR-1!	-	-	-	-	-	-	10	#SAG-13!	4	1
6	1.22E-08	%ILOOP	EGDGK3T-1A1B1E	GSAG7ENCVARC	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	32	#SAG-26!	5	1
7	1.22E-08	%ILOOP	AOMNEGSAG7	EGDGK3T-1A1B1E	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	32	#SAG-26!	5	1

Importance Analysis for SAMG-related BEs

■ Importance Measure

■ Birnbaum

- $B_i = R_i^+ - R_i^-$

■ Fussel-Vesely

- $FV_i = B_i P_i = (R_0 - R_i^-) / R_0$

- R_0 : base 리스크

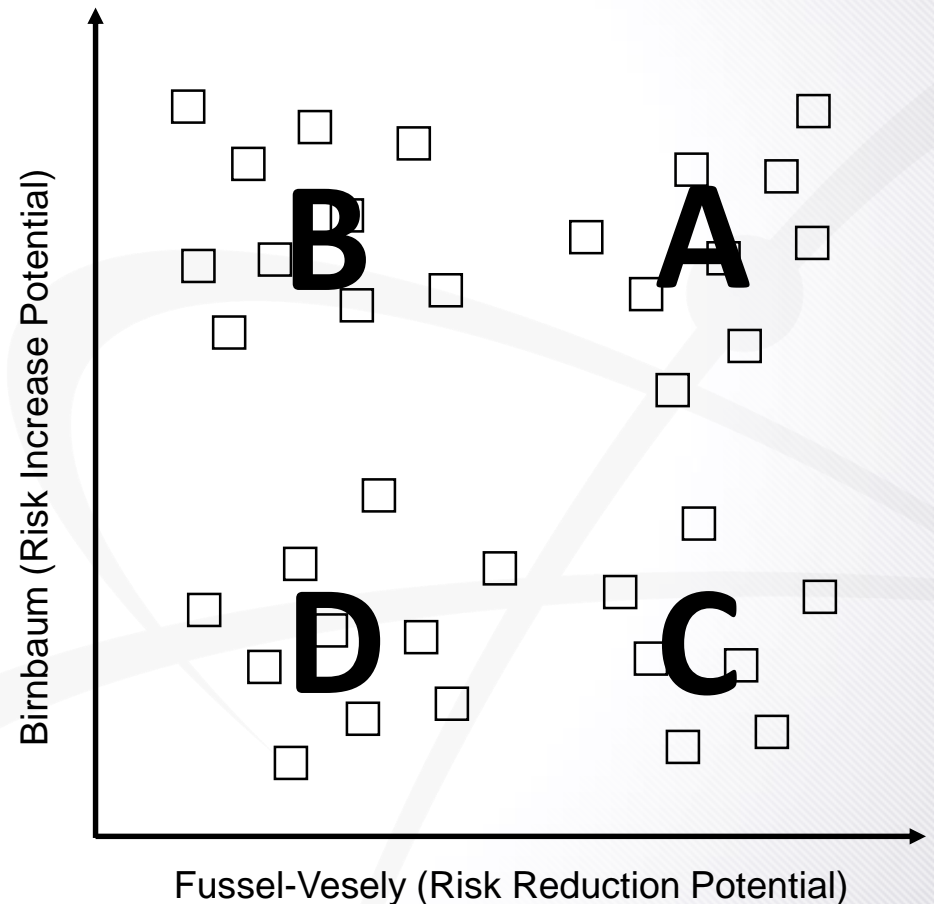
- R_i^+ : 기기 i의 이용불능에 의해 증가된 리스크

- R_i^- : 기기 i의 완벽작동에 의한 감소된 리스크

■ Component Importance

- Effective control methods are needed for $A > B = C > D$.

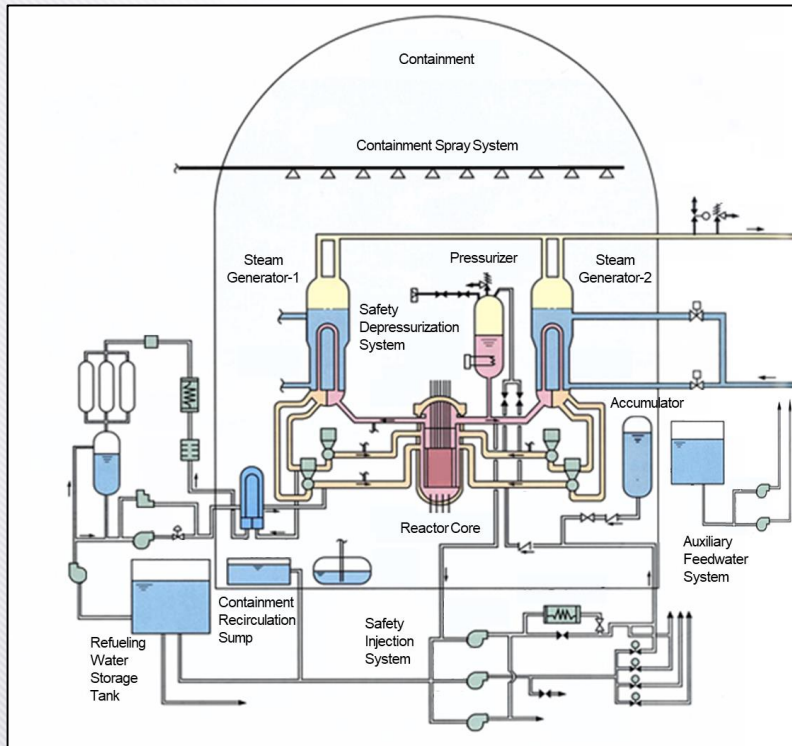
Scatter Plot of Basic Events Importance Measure



Application

■ OPR-1000 SAMG

- Portable pump is assumed for MACST equipment



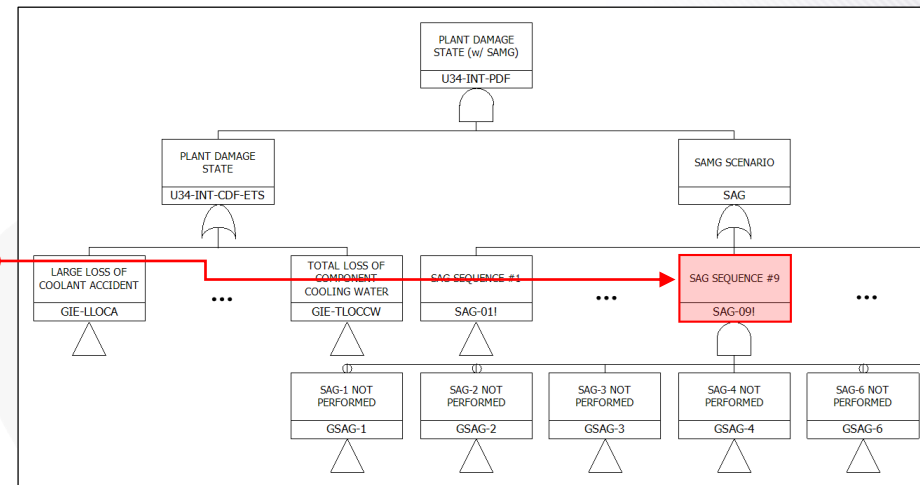
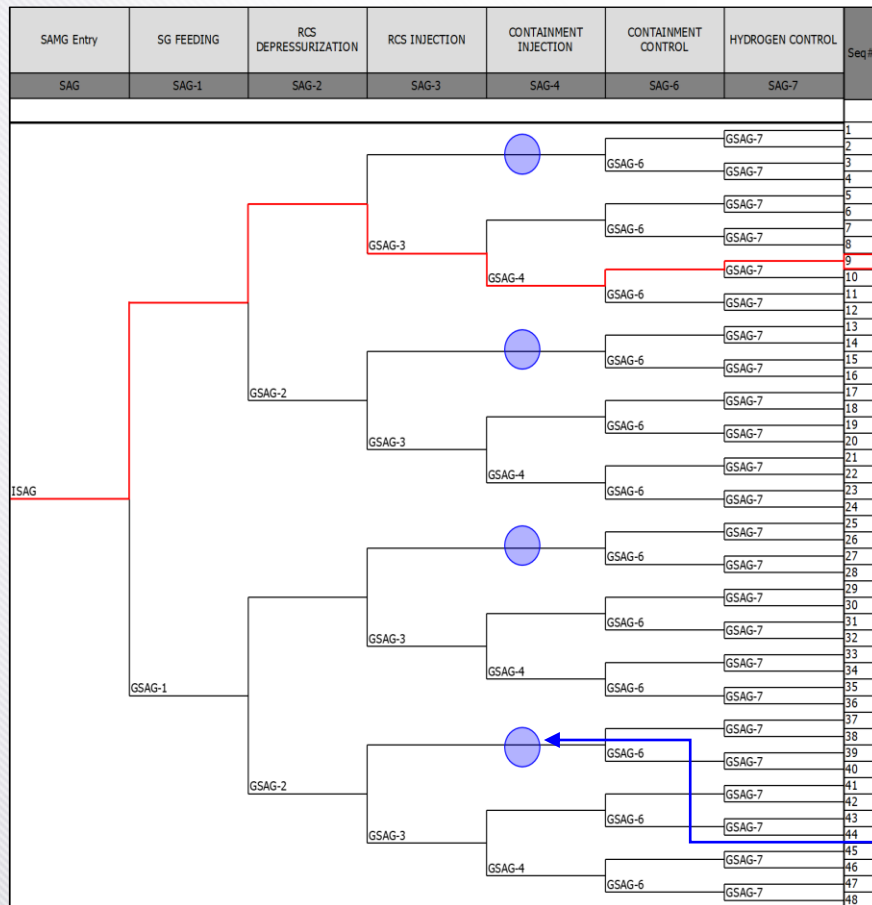
Safety systems of OPR-1000

Mitigation Systems for OPR-1000 SAMG strategies

Mitigation Function	Strategy	Fixed System	Portable System
Prevention of core melt-through (in-vessel)	SG Injection (SAG-1)	Feedwater pump (MDP, TDP) SG depressurization (ADV, MSSV, TBV)	Portable pump (Diesel) SG depressurization (ADV, MSSV, TBV)
	RCS Depressurization (SAG-2)	Safety depressurization valve	N/A
	RCS Injection (SAG-3)	High-pressure safety injection (HPSI) pump	Portable pump (Diesel)
Prevention of radioactive material release (ex-vessel)	Containment Injection (SAG-4)	Containment spray (CS) pump	Portable pump (Diesel)
	Containment Condition Control (SAG-6)	Containment spray (CS) pump	Portable pump (Diesel)
	Containment Hydrogen Control (SAG-7)	H ₂ igniter	N/A

OPR-1000 SAMG FT/ET Model

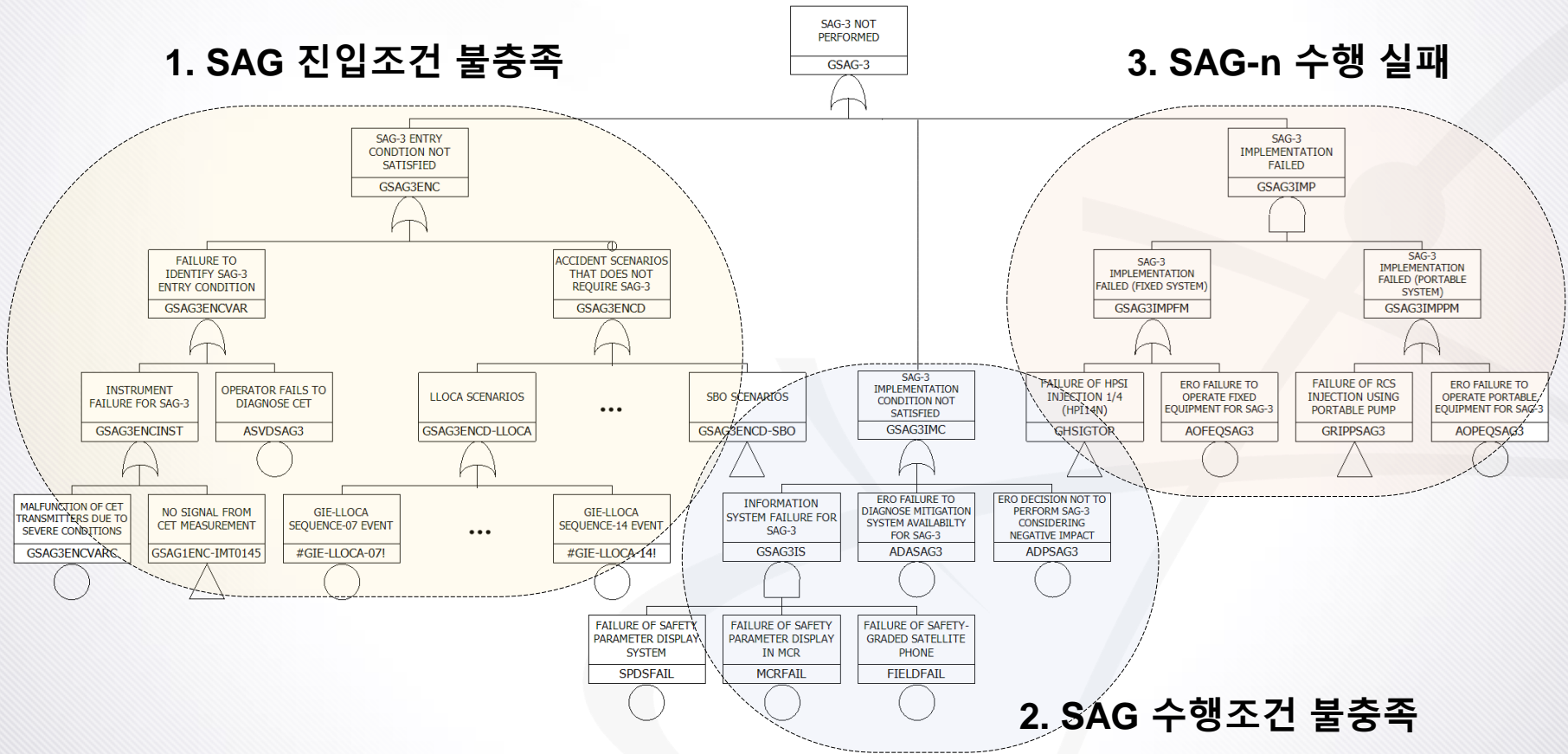
- SAMG-ET is developed based on OPR-1000 SAMG DFC



- SAG-3 and SAG-4 strategies perform the same safety function (cool down the RCS).
- TSC is assumed not to implement SAG-4 if SAG-3 is successfully performed.
 → no branching btw SAG-3 and 4

OPR-1000 SAMG FT/ET Model

- Top Event : GSAG-3 (SAG-3 NOT PERFORMED)



SAMG-FT model for SAG-3 strategy of OPR-1000

OPR-1000 SAMG FT/ET Model

■ Basic Event Probability (Expert Judgement)

(Mechanical) SAMG-related basic events probability in SAMG-FT model

SAG	Basic Event Name	Type	Description	Value
SAG-1	GSAGIENCVARC	Mechanical (instrumentation)	Malfunction of SG level transmitter due to severe conditions	1.00E-01
	SPDSFAIL*	Mechanical (information)	Failure of the safety parameter display system (SPDS)	1.00E-03
	MCRFAIL*	Mechanical (information)	Failure of the MCR SPD	1.00E-03
	FIELDFAIL*	Mechanical (information)	Failure of the safety-graded satellite phone	1.00E-03
	DDPPSSAG1	Mechanical (MACST)	Diesel-driven portable pump (DDP) (standby) fails to start	4.36E-03**
	DDPPR1SAG1	Mechanical (MACST)	DDP (standby) fails to run (< 1 hr)	9.81E-04**
	DDPPR2SAG1	Mechanical (MACST)	DDP (standby) fails to run (> 1 hr)	4.55E-02**

(Human) SAMG-related basic events probability in SAMG-FT model ***

SAG	Basic Event Name	Type	Description	Value
SAG-1	ASVDSAG1	Human (diagnosis)	Operator fails to diagnose SG level	1.00E-03
	ADASAG1	Human (diagnosis)	Operator fails to identify mitigation system availability for SAG-1	1.00E-02
	ADPSAG1	Human (decision)	TSC decides to not perform SAG-1 considering negative impact	5.00E-02
	AOFEQSAG1	Human (operation)	Operator fails to operate a fixed system for SAG-1	1.00E-02
	AOPEQSAG1	Human (operation)	Operator fails to operate a portable system for SAG-1	1.00E-01

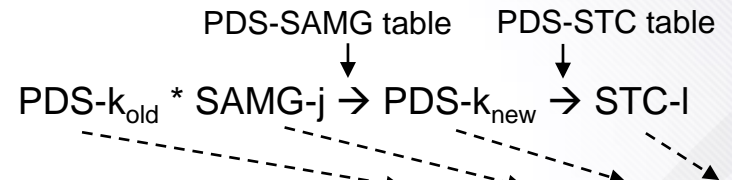
* Event also applicable to SAG-2, 3, 4, 6, 7

** Values referred from NUREG/CR-6928

*** J. Kim et al., Level 2 HRA: A SAMG-based Detailed HRA Method, KAERI/TR-8118/2020, 2020.

Quantification

- Top 20 high-frequency accident scenarios (PDS * SAMG * STC)



#	Freq.	Initiator	BE#1	BE#2	BE#3	BE#4	BE#5	BE#6	BE#7	Original PDS	SAMG	Revised PDS	STC
1	8.05E-08	%ILOOP	EGDGK3T-1A1B1E	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	-	32	#SAG-25!	4	1
2	6.26E-08	%ILOOP	EGDGW3T-1A1B1E	/NR-AC60HR	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-10!	-	32	#SAG-25!	4	1
3	5.95E-08	%IML-1A	HSOPHHLCLR	#GIE-MLOCA-3!	-	-	-	-	-	14	#SAG-41!	11	1
4	2.21E-08	%ITLOCCW	RCPSEAL_2S	#GIE-TLOCCW-2!	-	-	-	-	-	19	#SAG-37!	11	1
5	1.29E-08	%IRVR	#GIE-RVR-1!	-	-	-	-	-	-	10	#SAG-13!	4	1
6	1.22E-08	%ILOOP	EGDGK3T-1A1B1E	GSAG7ENCVARC	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	32	#SAG-26!	5	1
7	1.22E-08	%ILOOP	AOMNEGSAG7	EGDGW3T-1A1B1E	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	32	#SAG-26!	5	1
8	1.17E-08	%ILOOP	EGDGK3T-1A1B1E	NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-12!	-	-	32	#SAG-48!	32	2
9	1.06E-08	%IGTRN	MTC	RPRDFCEA12OF28	/TB-TRIP	#GIE-	-	-	-	-	-	-	1
10	9.52E-09	%ILOOP	EGDGW3T-1A1B1E	GSAG7ENCVARC	/NR-AC60HR	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-10!	32	#SAG-26!	5	1
11	9.52E-09	%ILOOP	AOMNEGSAG7	EGDGW3T-1A1B1E	/NR-AC60HR	NR-AC7HR	/PSV	/RCPSEAL_2S	#GIE-SBOS-10!	32	#SAG-26!	5	1
12	9.07E-09	%ILOOP	EGDGK3T-1A1B1E	GSAG6ENCVARC	NR-AC15HR	/NR-AC60HR	/PSV	/RCPSEAL_2S	#GIE-SBOR-10!	32	#SAG-27!	6	17
13	9.04E-09	%IML-1A	AOMNEGSAG7	HSOPHHLCLR	#GIE-MLOCA-3!	-	-	-	-	14	#SAG-42!	12	1
14	9.04E-09	%IML-1A	GSAG7ENCVARC	HSOPHHLCLR	#GIE-MLOCA-3!	-	-	-	-	14	#SAG-42!	12	1
15	8.90E-09	%ILOOP	EGDGK3T-1A1B1E	/NR-AC15HR	/PSV	/RCPSEAL_2S	SDOPHLATE	#GIE-SBOR-08!	-	32	#SAG-25!	4	1

SAMG-related basic events are included in MCS

Importance Analysis

■ Importance Measure

- R : Scenario 리스크 ($f_{ijl} * C_j$)

■ Birnbaum

- $B_i = R_i^+ - R_i^-$

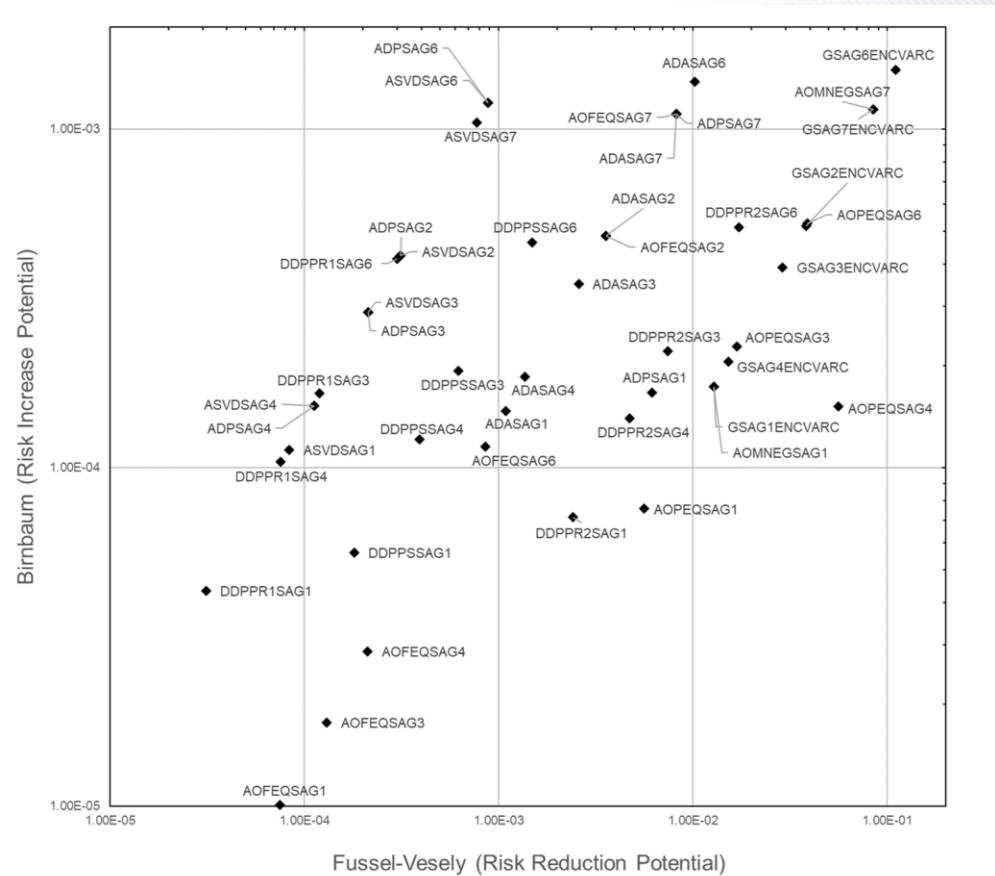
■ Fussel-Vesely

- $FV_i = B_i P_i = (R_0 - R_i^-) / R_0$

- R_0 : base 리스크

- R_i^+ : 기기 i의 이용불능에 의해 증가된 리스크

- R_i^- : 기기 i의 완벽작동에 의한 감소된 리스크



Importance Analysis

■ Region A (High RIP, High RRP)

- Risk is most sensitive to changes in reliability or effects of failure
 - Most effective control methods must be provided by improving its reliability

■ Related Basic Events

- **GSAG_nENCVARC** (n=1~7)
(Malfunction of DFC parameter transmitters due to severe condition)

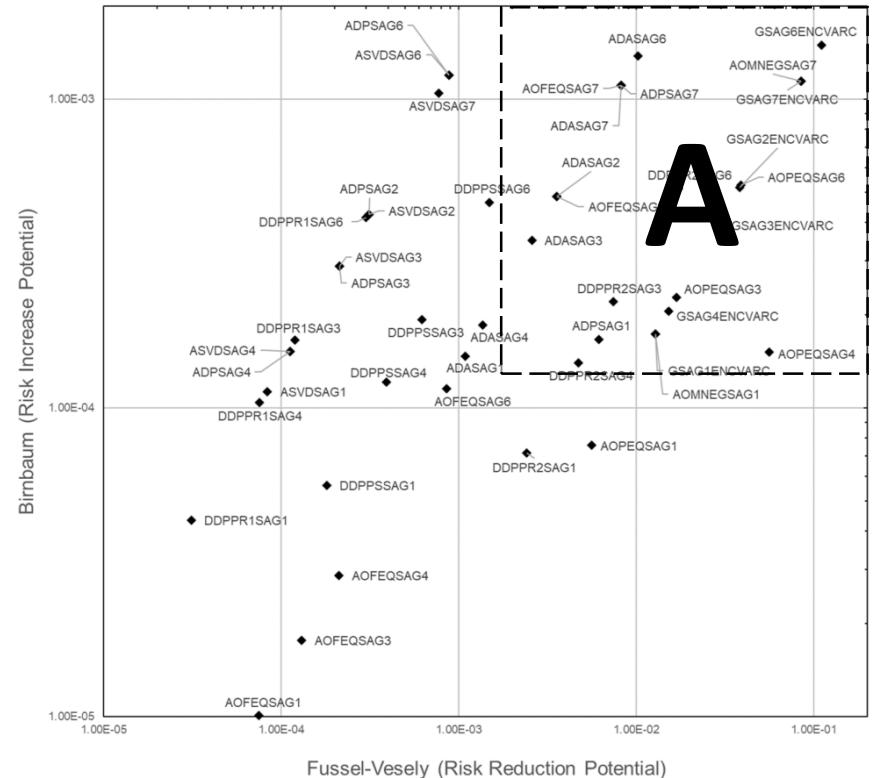


Installation of redundant DFC instrumentation that is highly reliable in extreme condition

- **ADASAG_n** (n=1~7)
(Failure of operator to identify mitigation system availability during SAG)



Operating practice review and appropriate education for MCR operators and TSC members



Importance Analysis

■ Region B (High RIP, Low RRP)

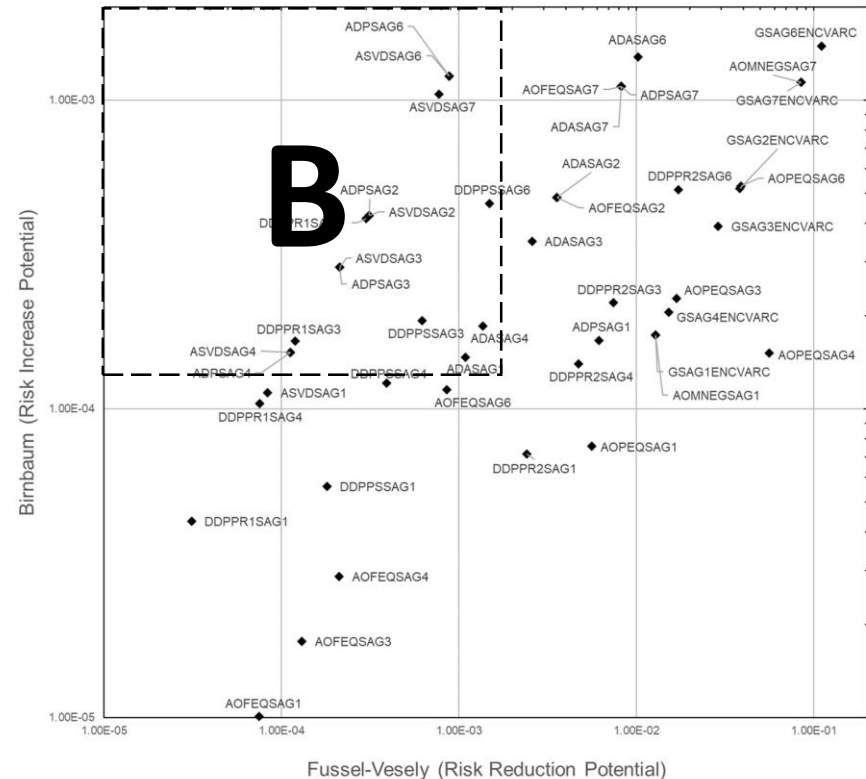
- They are low in RRP due to their high reliability or existing practices
→ but, overall risk could increase if these events are to degrade in reliability

■ Related Basic Events

- ASVSAG_n (n=1~7)
(Failure of operator to diagnose DFC parameter)
- ADPSAG_n (n=1~7)
(Failure of operator to identify mitigation system availability during SAG)



Computerized supporting system regarding severe accident progression for operators' decision making during SAMG operation



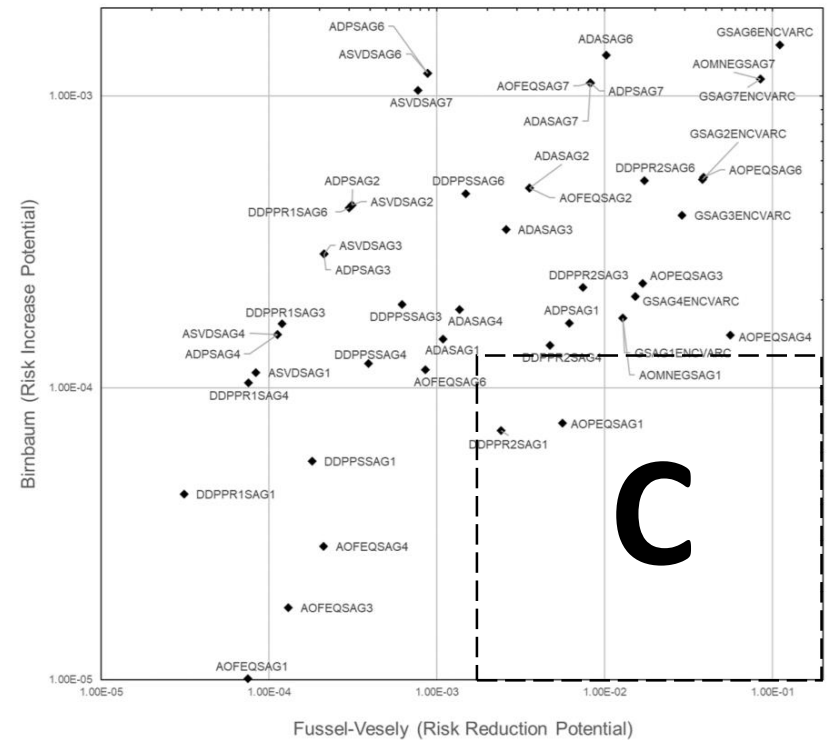
Importance Analysis

■ Region C (Low RIP, High RRP)

- The events contribute significantly to overall risk but not have an impact on risk even if they degrade in reliability
- Related Basic Events
 - DDPPR2SAG_n (n=1~7)
(Mechanical failure of MACST equipment, portable diesel pump)
 - AOPEQSAG1
(Failure of field operators to operate MACST equipment for SAG-1)



Introduce more reliable or improved operation methods for flexible and portable equipment



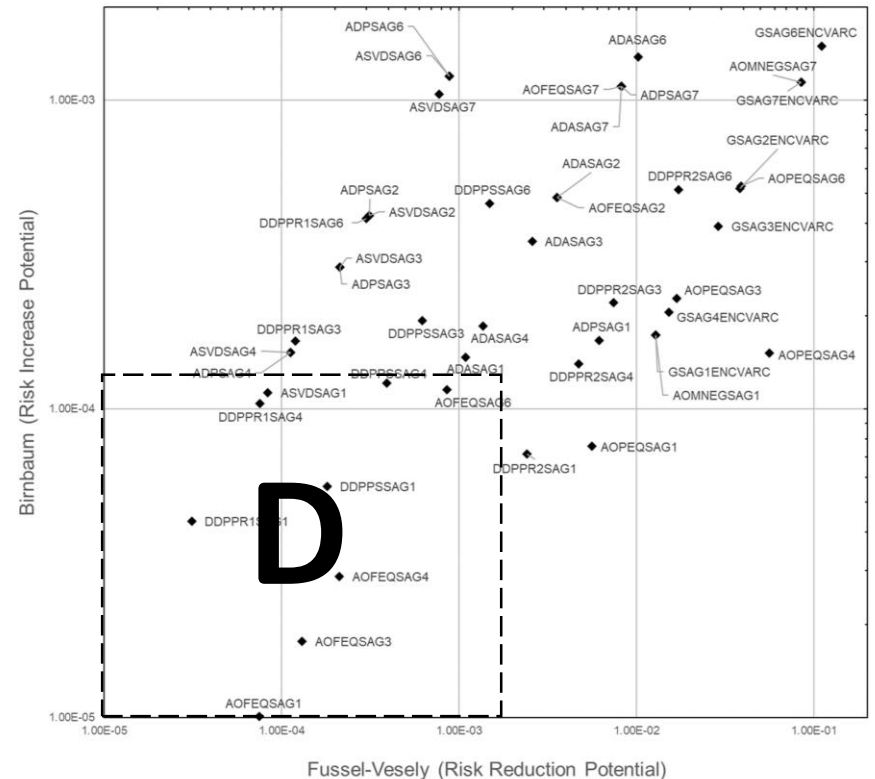
Importance Analysis

■ Region D (Low RIP, Low RRP)

- Since they have little contribution to overall risk, simple control methods that would be provided to prevent failure
- Related Basic Events
 - DDPPSSAG1
(Mechanical failure of MACST equipment, portable diesel pump (fail to start))
 - DDPPR1SAG1
(Mechanical failure of MACST equipment, portable diesel pump (fail to run (< 1hr)))



Replacement or repair of components after their failure may be sufficient considering its cost-effectiveness



Conclusion



체르노빌원전사고, 1986



비엔나선언('15)
방사능물질 실질적 배제

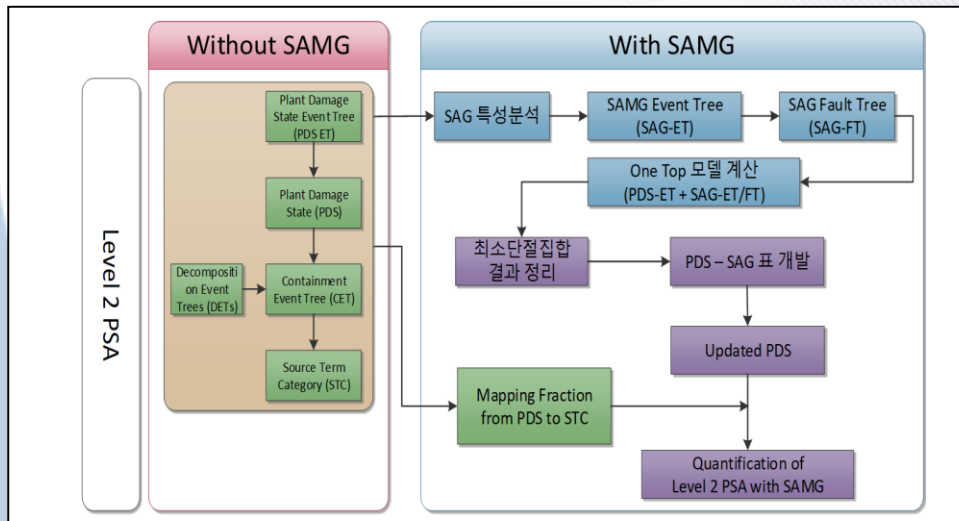


후쿠시마원전사고, 2011



원자력안전법 개정('16)
가동원전 사고관리계획서 제출('19)

원전 중대사고 리스크 평가를 위한 L2 PSA 모델링 방법론



원전안전 현안: 중대사고 관리

과기부 미래원자력 안전역량 강화방안('18.12): 중대사고 및 대규모 방사선누출사고 방지 원천기술 개발

원안위 원자력안전기준 강화 종합대책('19.3): 후쿠시마 사고 이후 국제적으로 강화된 안전기준 적용

산업부 Nu-Tech 2030('19.09): 중대사고 대비 안전기술 확보 및 최신기술반영 안전성고도화 추진

'원전안전 기술개발 필요성 및 개발 방향' 설문('19.12): 인적오류 (SAMG 수행) 중요 위험요인(24.9%)으로 인식

중대사고 L2 PSA 분석 (/w SAMG)

SAMG 등 다양한 사고관리계획을 고려한 현실적인 L2 리스크의 정량적 평가

L2 리스크 최소화를 위한 사고관리계획의 개선사항 도출 및 최적화

SAMG 관련 MACST기기 및 MCR/TSC 운전원 관련 위험요소 도출 및 개선방안 제안



THANK YOU