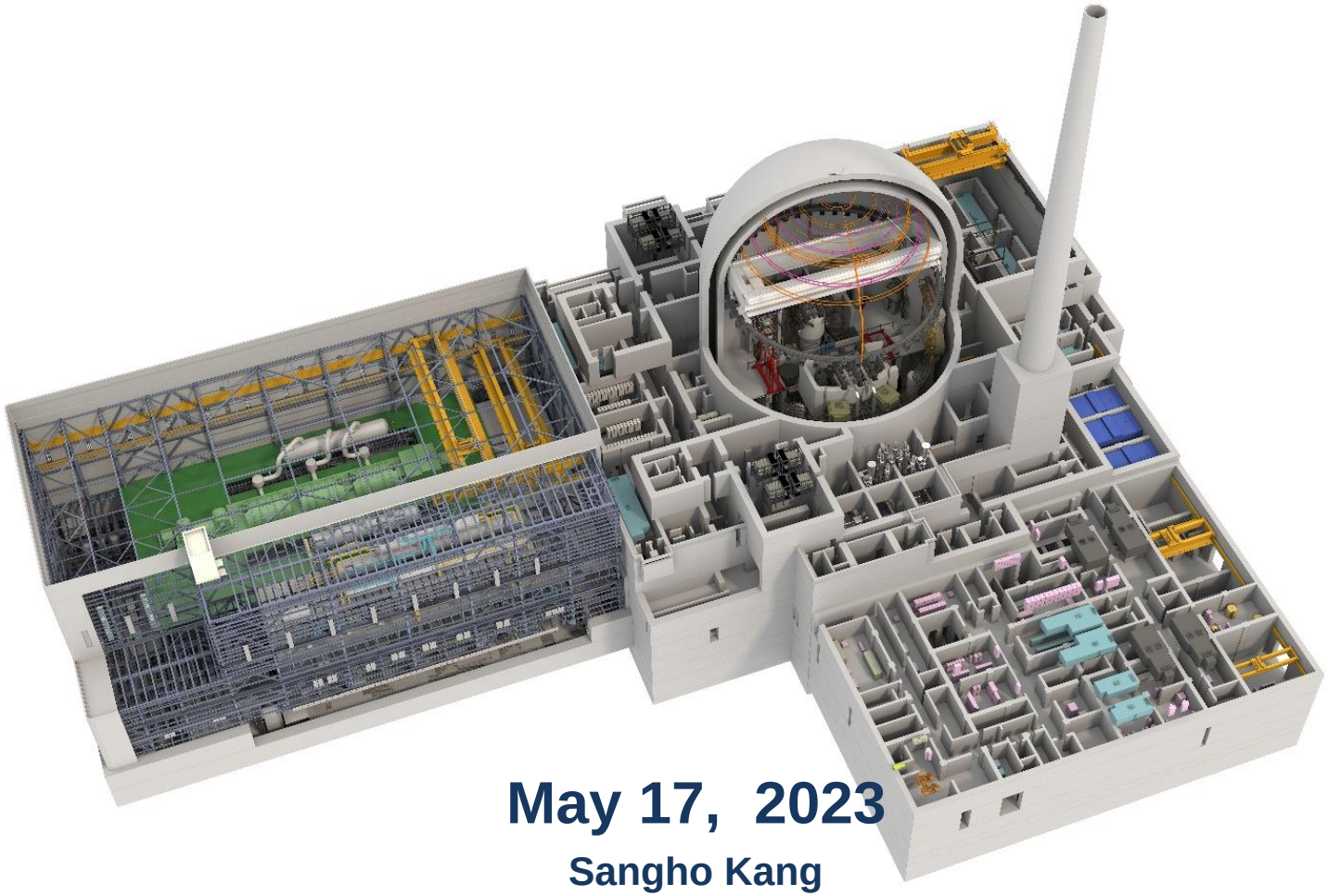
Safety Design of APR1000 & Lessons Learned from EUR Assessment



May 17, 2023

Sangho Kang

KEPCO E&C

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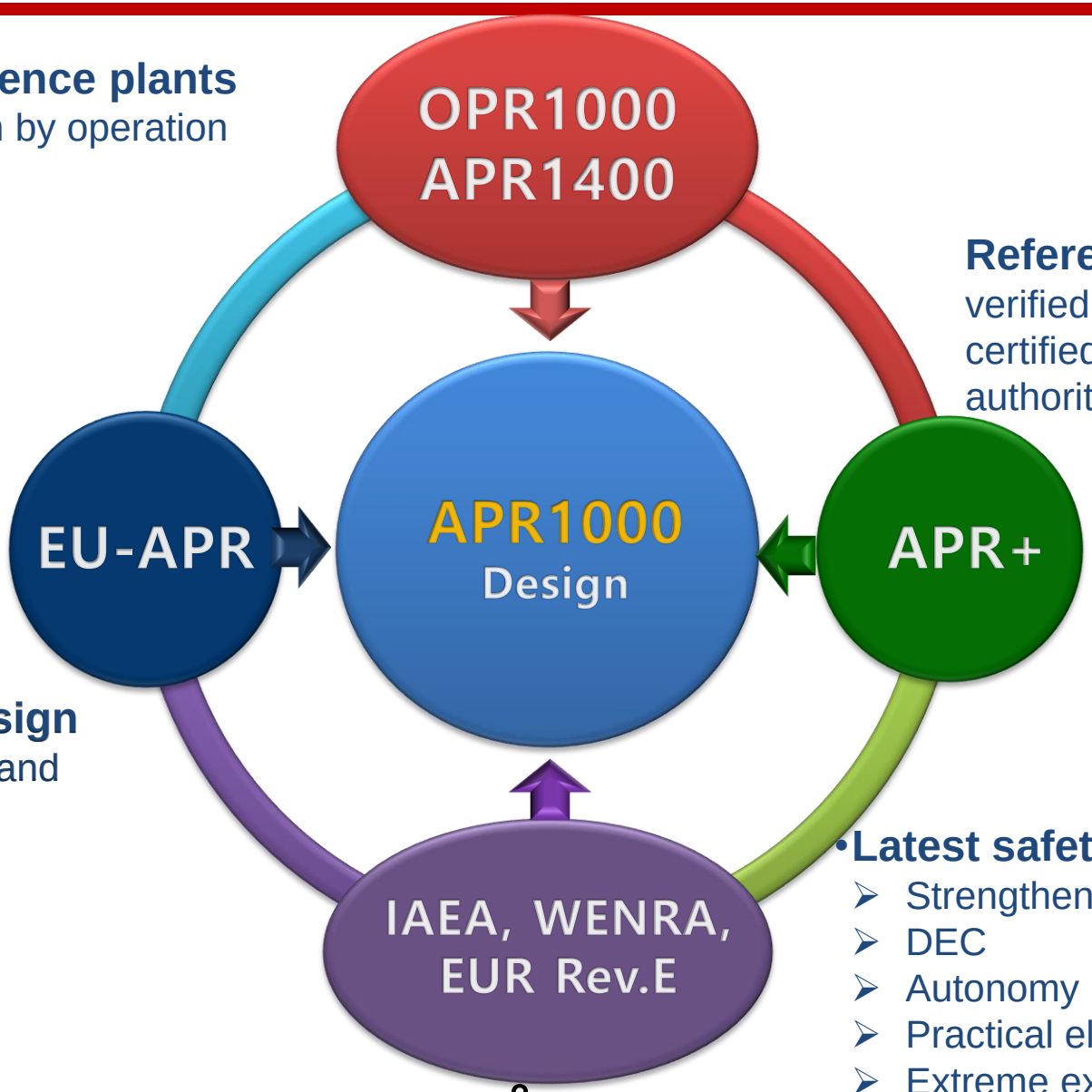
I.1 APR1000 Technologies (1/10)

Reference plants
proven by operation

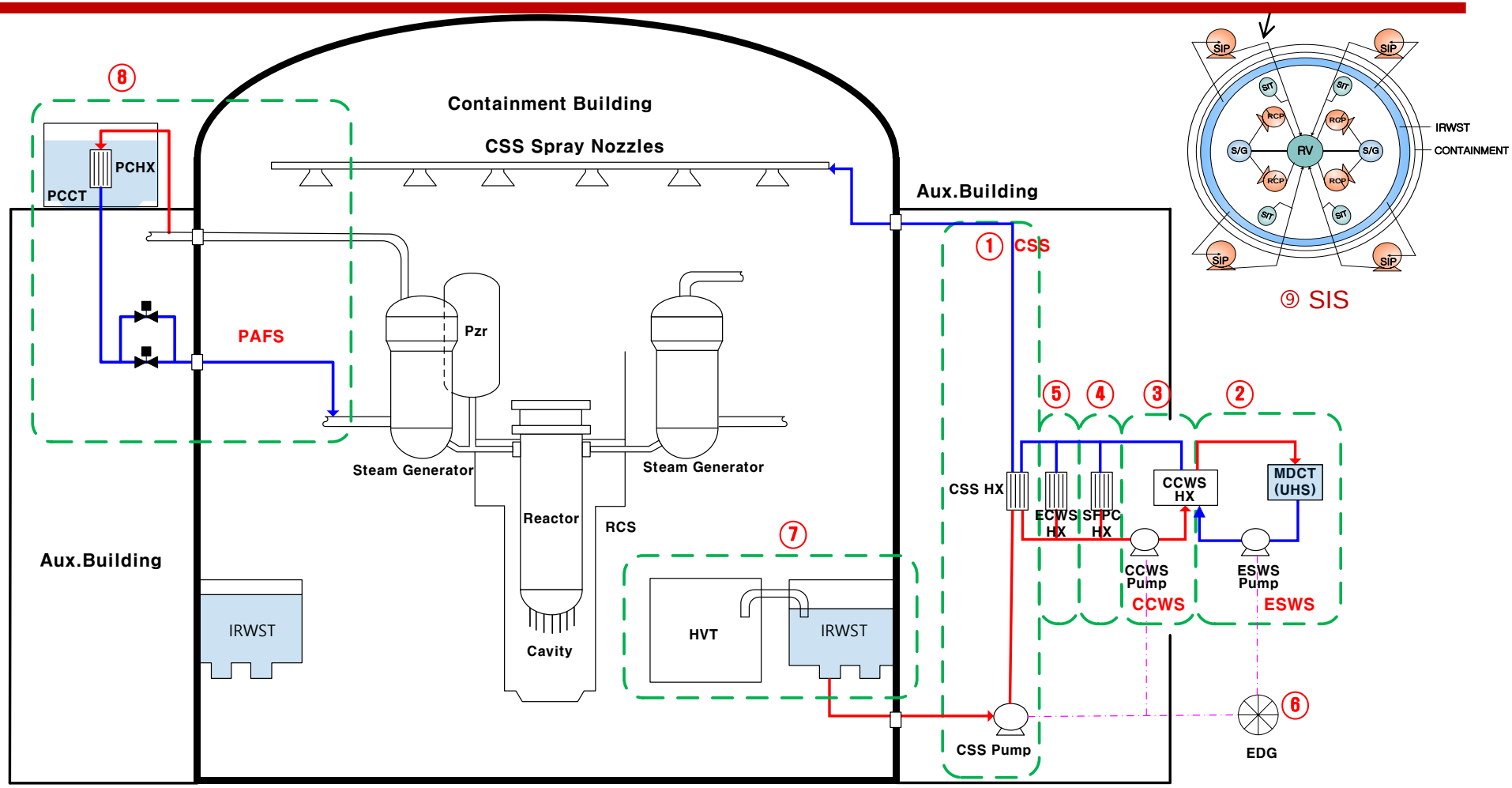


Reference design
verified by tests and certified by Korean authority

Reference design
verified by tests and certified by EUR

- **Latest safety requirements**
  - Strengthened DiD
  - DEC
  - Autonomy
  - Practical elimination
  - Extreme external hazards

I.1 APR1000 Technologies: DBA Safety Systems (2/10)



① CSS : Containment Spray System
② ESWS : Essential Service Water System
③ CCWS : Component Cooling Water System
④ SFPCS : Spent Fuel Pool Cooling System
⑤ ECWS : Essential Chilled Water System
⑥ EDG : Emergency Diesel Generator for DBA
⑦ IWSS: Incontainment Water Storage System
⑧ PAFS : Passive Auxiliary Feedwater System
⑨ SIS: Safety Injection System

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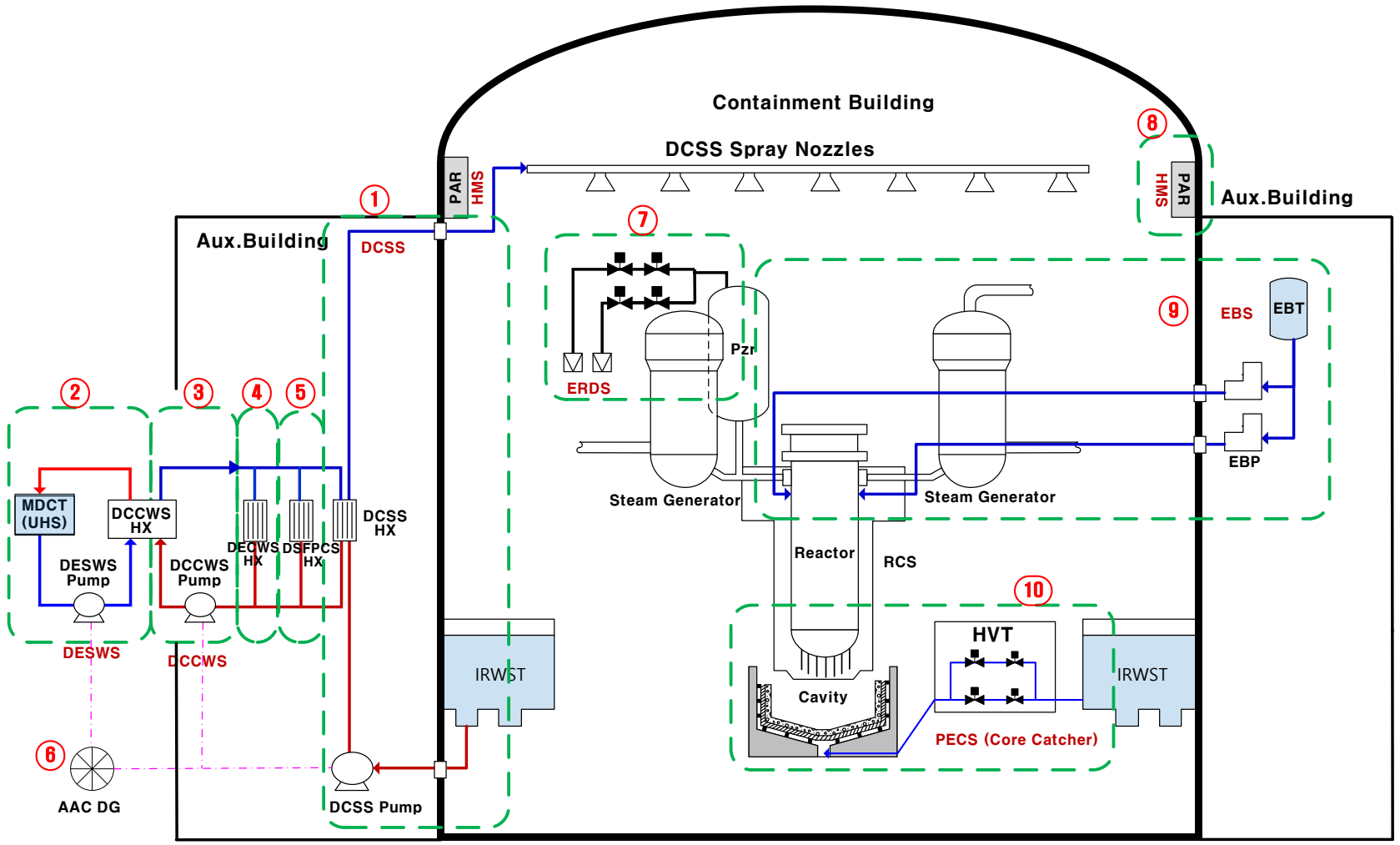
I.1 APR1000 Technologies: DEC Safety Features (3/10)



① DCSS : Diverse Containment Spray System
② DESWS : Diverse Essential Service Water System
③ DCCWS : Diverse Component Cooling Water System
④ DECWS : Diverse Essential Chilled Water System
⑤ DSFPCS : Diverse Spent Fuel Pool Cooling System
⑥ AAC DG: Safety Grade DG for DEC
⑦ ERDS : Emergency Reactor Depressurization System
⑧ HMS : Hydrogen Mitigation System (including PAR)
⑨ EBS : Emergency Boration System
⑩ PECS : Passive Ex-vessel Corium Retaining and Cooling System

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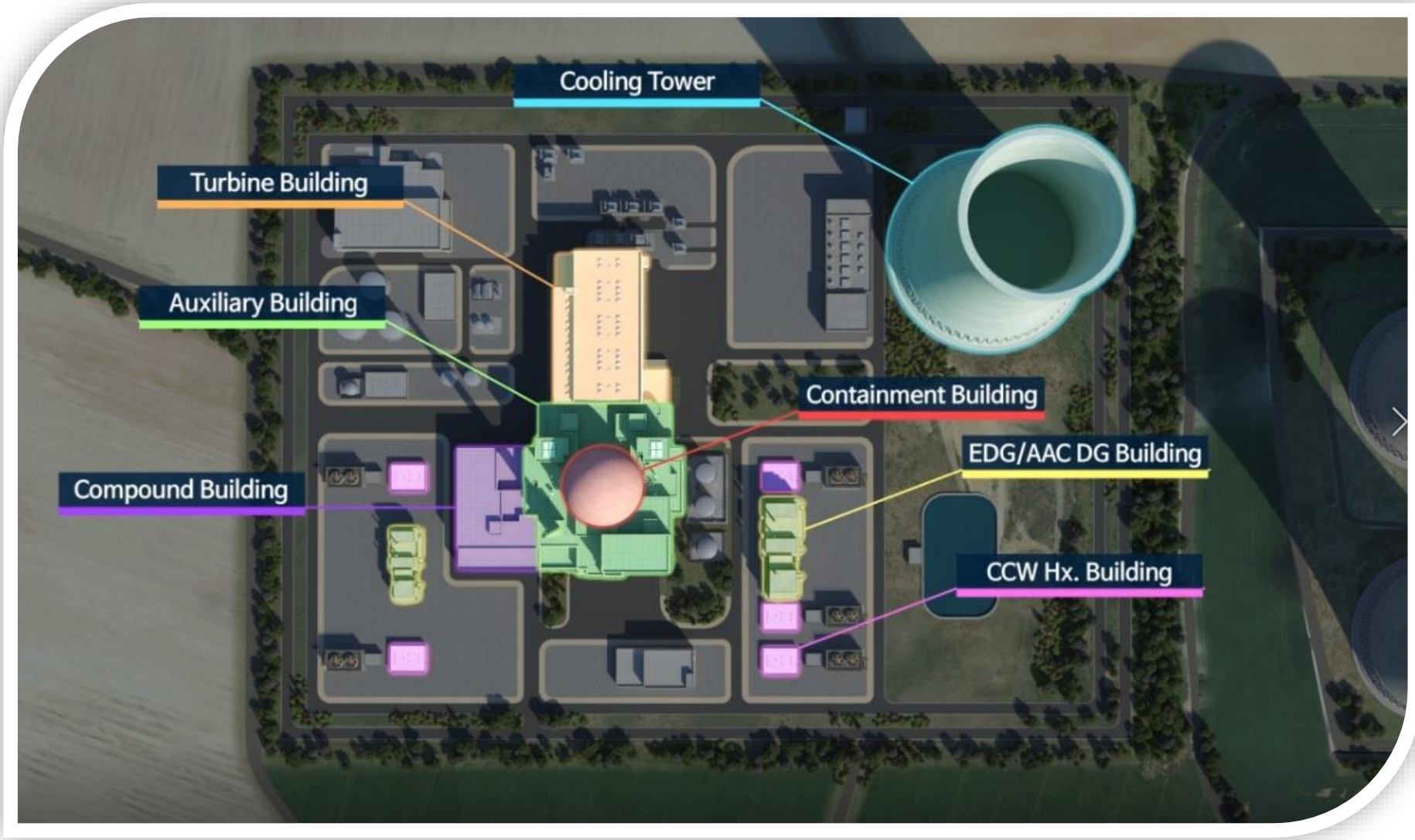
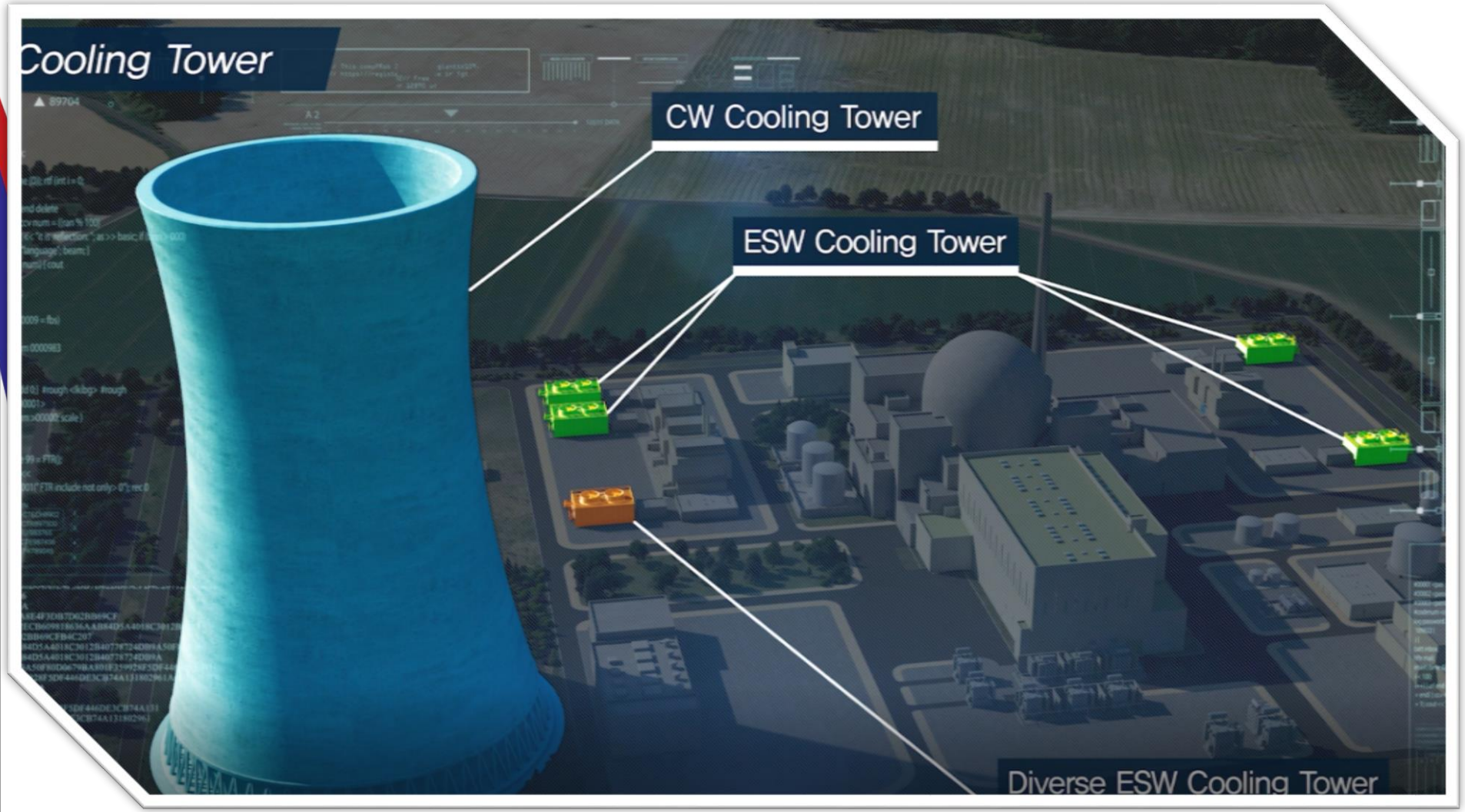
I.1 APR1000 Technologies: Site Layout (4/10)

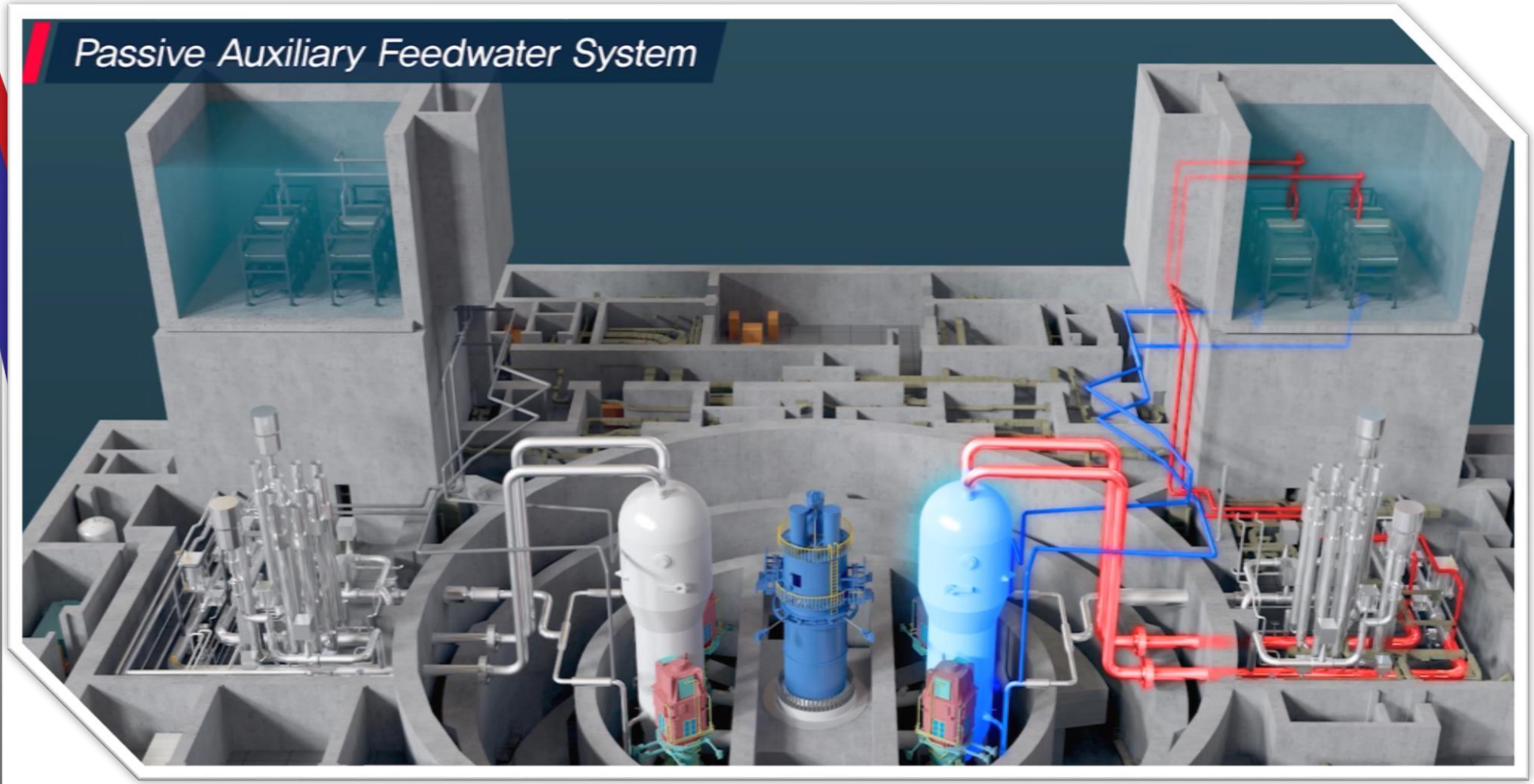


I.1 APR1000 Technologies: Aircraft Crash Protection (5/10)

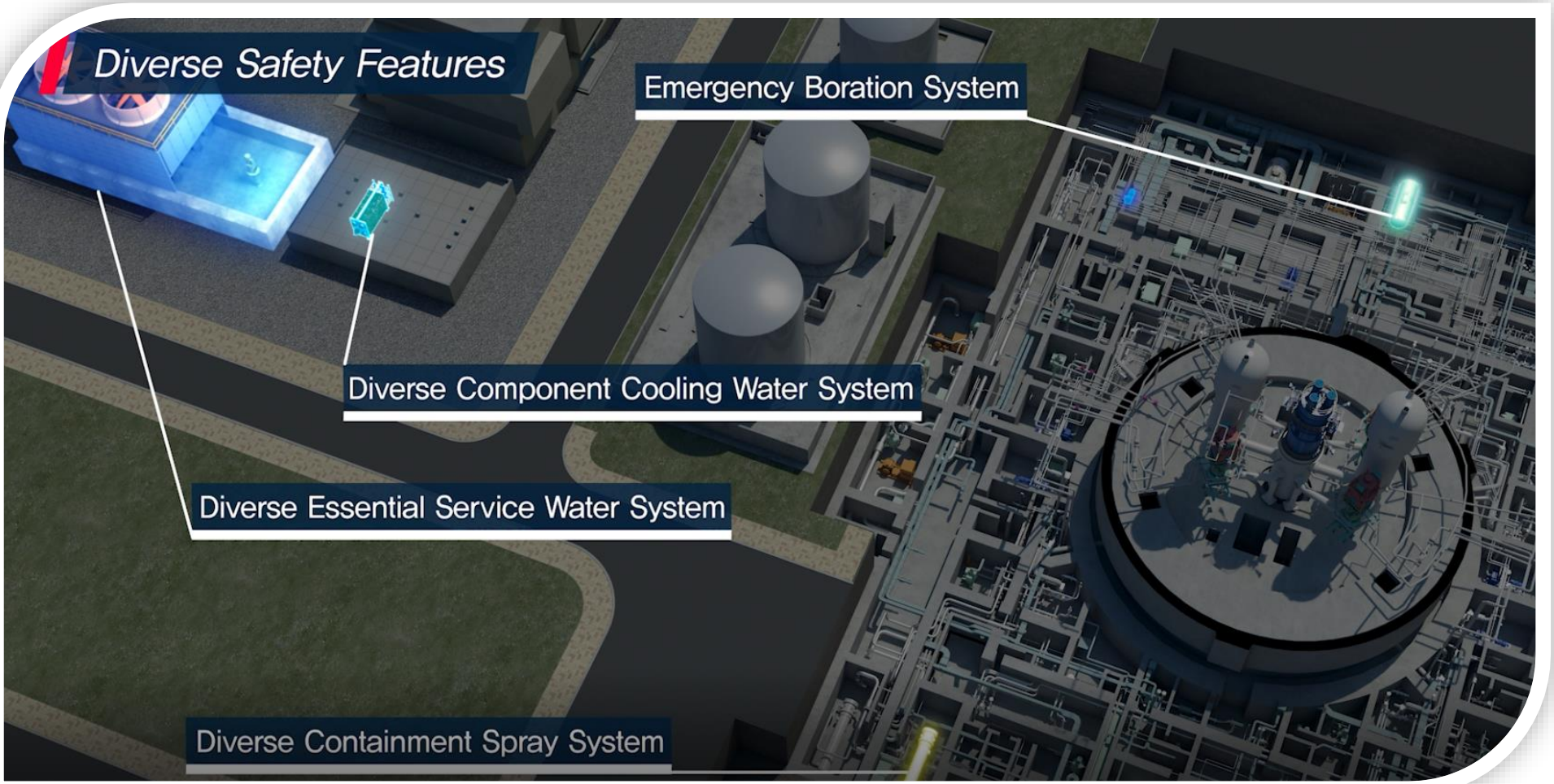
I.1 APR1000 Technologies: Cooling Towers (6/10)



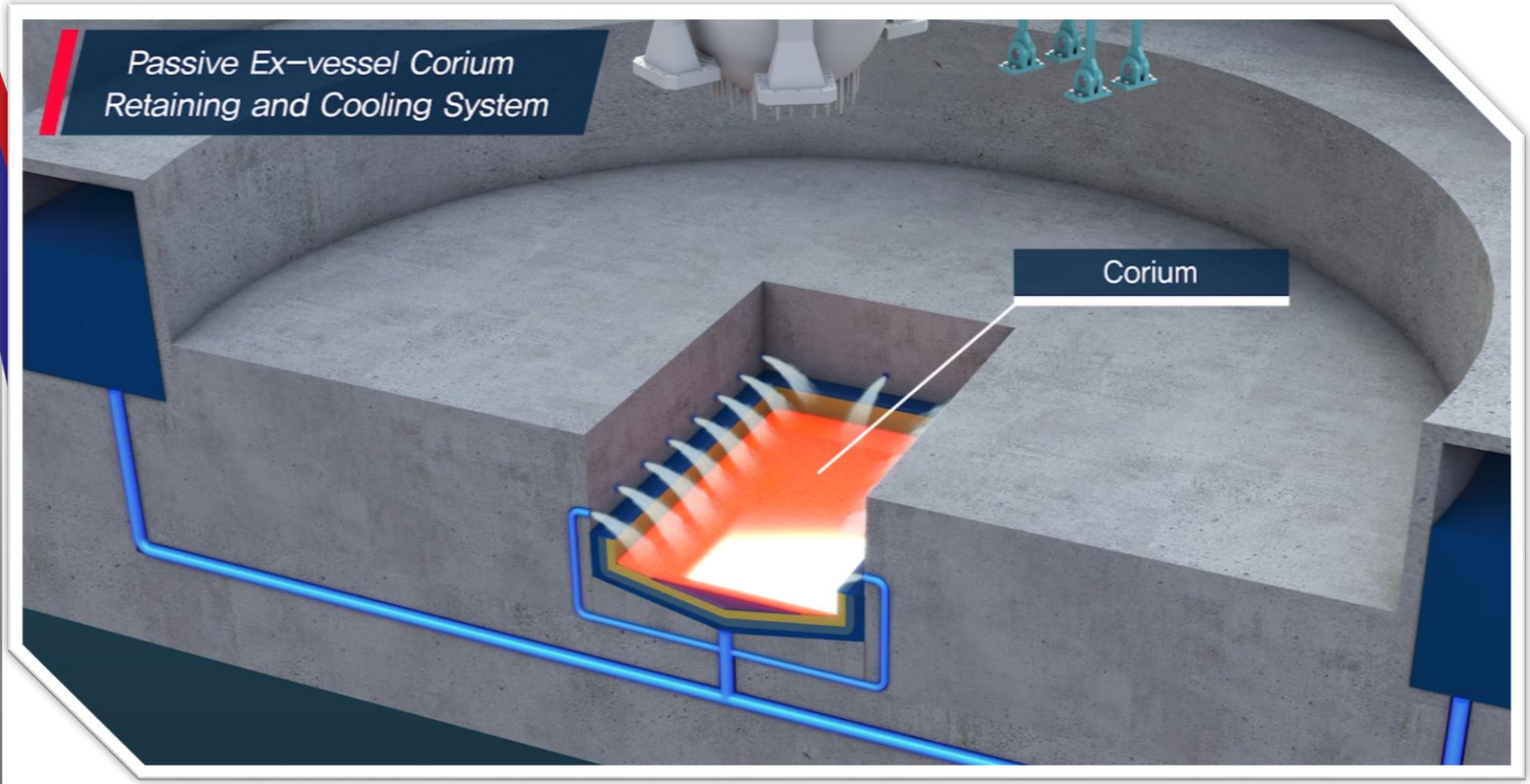
I.1 APR1000 Technologies: PAFS (7/10)



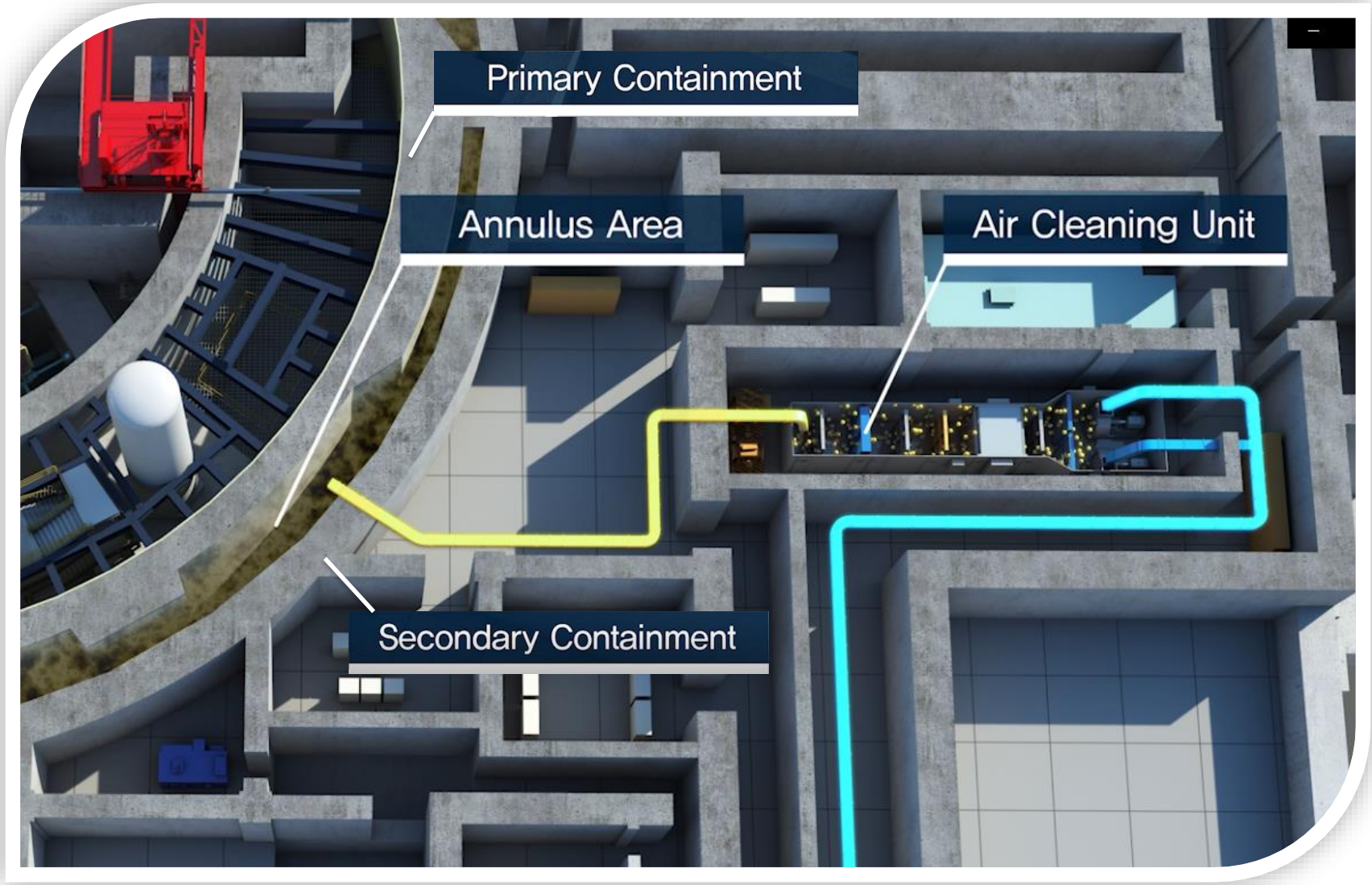
I.1 APR1000 Technologies: Diverse Safety Features (8/10)



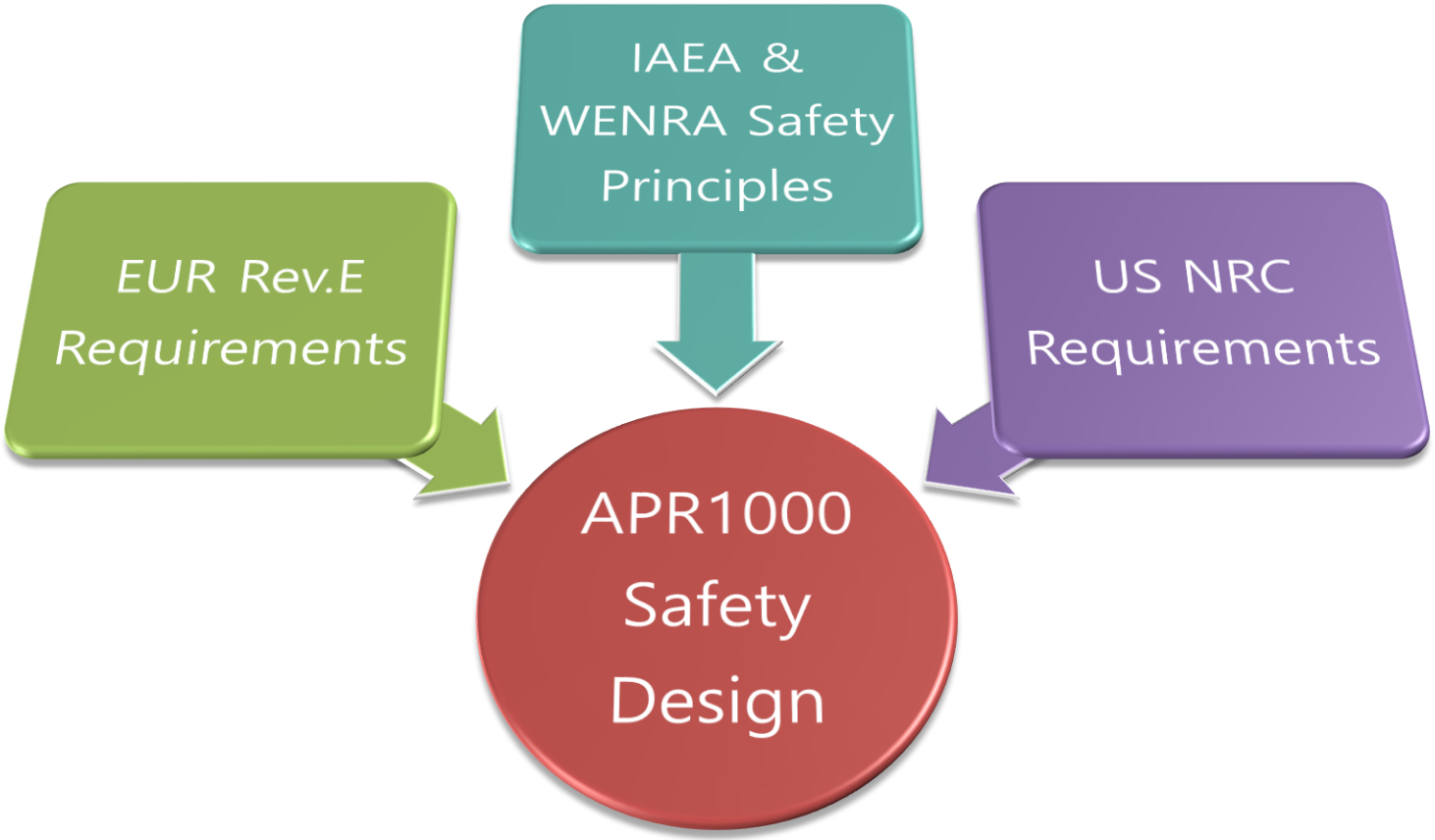
I.1 APR1000 Technologies: Core Catcher (9/10)



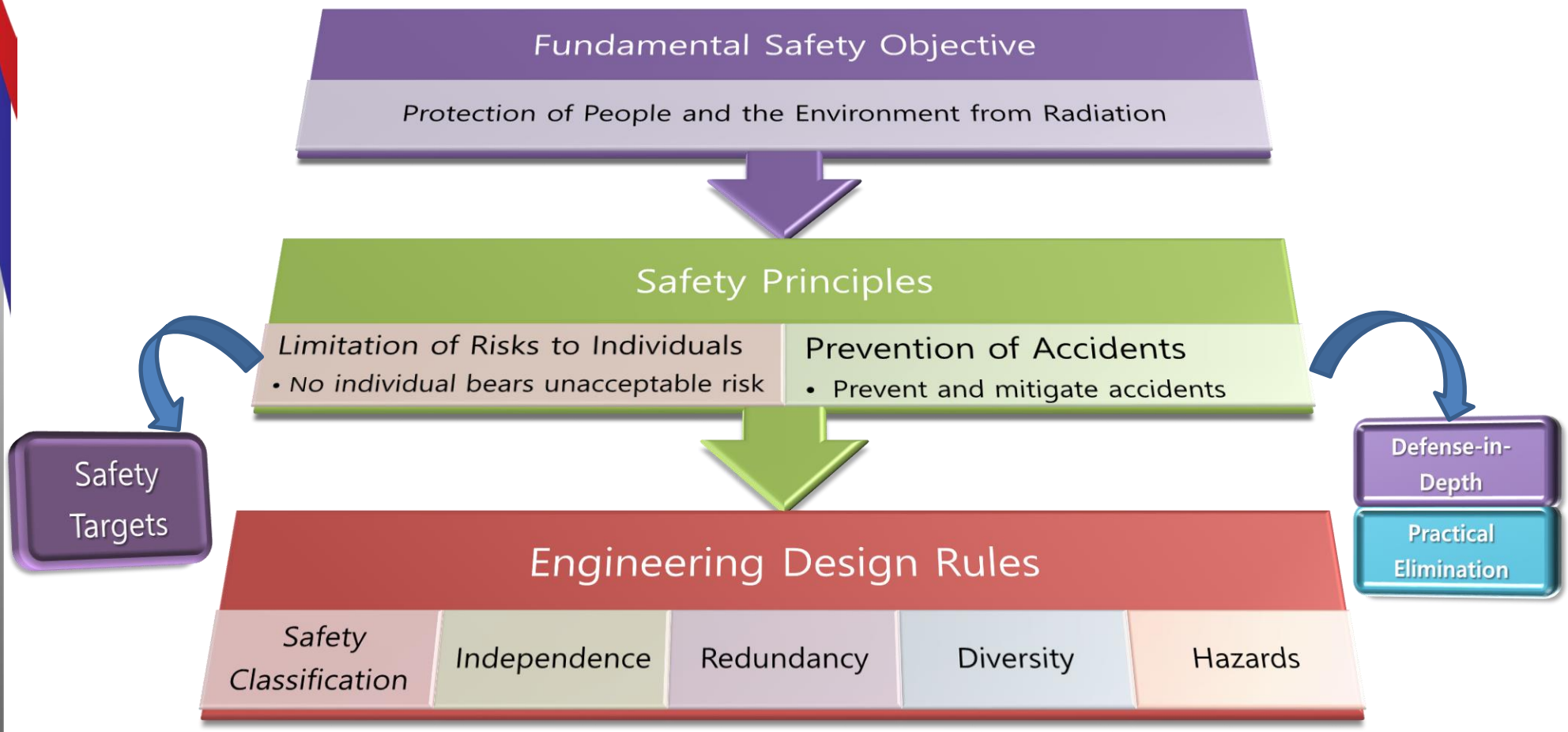
I.1 APR1000 Technologies: Double Containment (10/10)



I.2 Safety Requirements



I.3 Hierarchy of Safety Design Approaches



I.4 Safety Targets

Deterministic Targets

NO & AOO
- Negligible radiological impact

DBA
- No or minor radiological impact
- Very limited restriction on foodstuff consumption

DEC-A (Multiple Failures)
- No or minor radiological impact

DEC-B (Severe Accident)
- Limited protective measures

Probabilistic Targets

- **CDF < 1×10^{-5}/RY**
- **LRF < 1×10^{-6}/RY**

I.5 Defense-in-Depth & Acceptance Criteria

Levels of DiD		Categorization		Event Frequency (/RY)	Physical Barrier Acceptance Criteria [1]			Radiological Acceptance Criteria
					Fuel	RCS	CTMT	
Level 1		NO		-	Maintain fuel integrity	< P_{Design_RCS}	< P_{design_CTMT}	0.1 mSv/yr
Level 2		AOO		$10^{-2} < F \leq 10^{0}$	Maintain fuel integrity	< 1.1 P_{Design_RCS}	< P_{design_CTMT}	0.1 mSv
Level 3	3a	DBA	DBA 1	$10^{-4} < F \leq 10^{-2}$	Fuel failures accepted. Core coolable geometry retained	< 1.1 P_{Design_RCS}	< P_{design_CTMT}	1 mSv
			DBA 2	$10^{-6} < F \leq 10^{-4}$				5 mSv
	3b	DEC-A	Multiple failure	$10^{-6} < F \leq 10^{-4}$	Fuel failures accepted. Core coolable geometry retained	< 1.25 P_{Design_RCS}	< P_{FLC_CTMT}	10 mSv
Level 4		DEC-B	Severe Accident [2]	$F \leq 10^{-6}$	N/A[3]	N/A[3]	< P_{FLC_CTMT}	50 mSv (3km, 7d) 10 mSv (5km, 2d) 10 mSv (5km, 7d, I) 100 mSv (800m, 50y after end of release)

1) Applies to reactor accidents. (Only fuel and radiological criteria are applied for spent fuel accident. Only radiological criteria are applied for other accidents.)
2) Events that are practically eliminated shall demonstrate that their occurrence is either physically impossible or extremely unlikely.
3) No criteria is necessary since the core is in melting condition.

I.6 Compliance With WENRA Safety Objectives

WENRA Objectives	APR1000 Implementation
O1 • **NO, AOO and Prevention of Accidents** • Reduce frequency of abnormal events • Reduce escalation to accident	▶ Apply international code & standards ▶ Provide control systems and Tech. Specs.
O2 • **Accidents Without Core Melt** • No or minor radiological impact • Reduce CDF & Radioactive Releases • Reduce impact of external hazards & malevolent acts	▶ Comply with DBA & DEC-A radiological targets ▶ Comply with CDF and LRF targets ▶ Design against DBEH and verify against RSEH
O3 • **Accidents With Core Melt** • PE of early or large releases • Limited protective measures	▶ Demonstrate of PE of large or early releases ▶ Comply with radiological targets for DEC-B
O4 • **Independence Between DiD Levels** • Enhance independence, in particular, through diversity	▶ Provide safety systems for DBA ▶ Provide diverse safety features for DEC-A & B

I. Safety Requirements and DiD Concepts

II. Safety Design Approaches

II.1 Redundancy & Independence
II.2 Autonomy
II.3 External Hazards
II.4 NPE & ELAP
II.5 Practical Elimination
II.6 Safety Classification
II.7 Engineering Design Rules

III. Lessons Learned from EUR Assessment

II.1 Redundancy & Independence

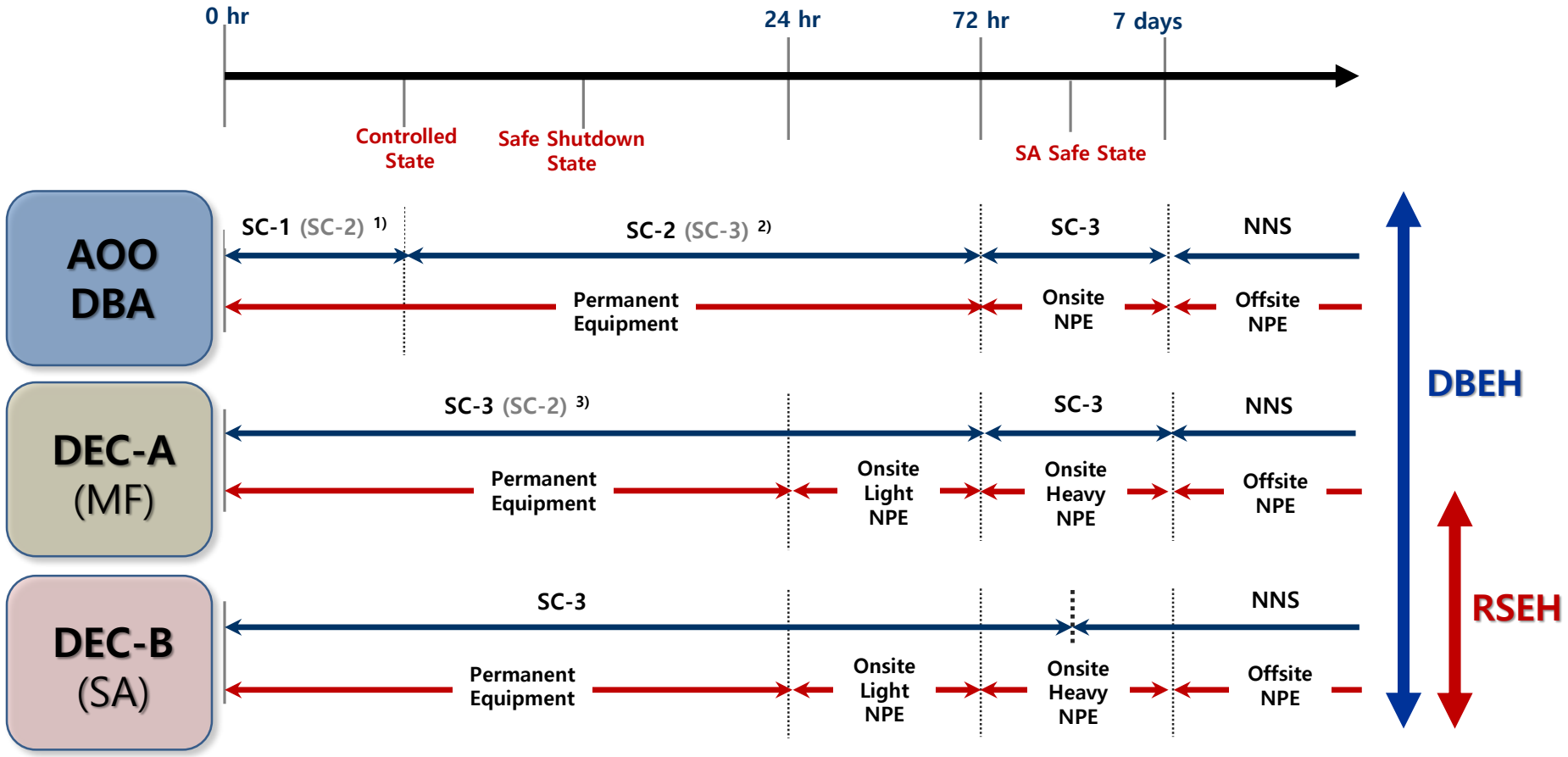
Redundancy

- Provide 4 trains for AOO and DBA safety systems
- Provide 1 train for DEC safety features

Independence & Diversity

- Use independent diverse systems for DiD 3b from DiD 3a
  - Systems : EBS, EBDS, DCSS, DSFPCS, DPS, D-CCS, DIS, DMA, ...
  - Events : ATWS, SBO, TLOFW, LOUHS, LORHR, LOCCW, LOECW, LOSFPC, MSGTR, ...
- Use independent dedicated safety features for DiD 4
  - Systems: ERDS, PECS, PAR, DCSS (DCSS, DCCWS, DESWS, DECWS), AMCS, ...
  - Events : Severe accidents
- Provide separate power and cooling water for the systems used for two or more DiD levels

II.2 Plant Autonomy



❖ APR1000 is designed to reach and maintain Safe Shutdown State or SA Safe State using only permanent equipment for 7 days

1) SC-2 if the consequence of its failure is of 'medium' severity
2) SC-3 if the consequence of its failure is of 'medium' severity
3) SC-2 if it provides a backup of SC-1 function

II.3 External Hazards (1/3)

- **Application of Environmental Condition Resistance Level (ECRL)**

SSC Class	Applicable SSCs	Design Requirements
ECRL 1	• Required to remain functionally operable and/or structurally intact in **AOO or DBA** • Required to meet safety objective for accident without core melt (O2), in case of **DBEH** conditions • Required in case of **DEC-A NOT initiated by RSEH**	• **Designed, constructed and qualified** to withstand; - Effects of the **environmental conditions** they are required, and - Effects of **DBEH** to be considered
ECRL 2	• Required to meet safety objective for accident with core melt (O3), in case of **DEC-B and RSEH** • Required in case of **DEC-A initiated by RSEH**	• **Designed, constructed and qualified** to withstand; - Effects of the **environmental conditions** they are required, and - Effects of **DBEH** to be considered • **Verified to have sufficient margin** to withstand **RSEH**
ECRL S	• SSCs which themselves are not required to remain functionally and structurally, but whose failure could prevent ECRL 1&2 SSCs from functioning	• **Designed, constructed and verified** to prevent their failure from impairing the SSCs for ECRL 1 or 2
ECRL N	• All SSCs not assigned to ECRL 1, 2 & S	• **Designed and constructed** to operational environment al conditions and level of hazards

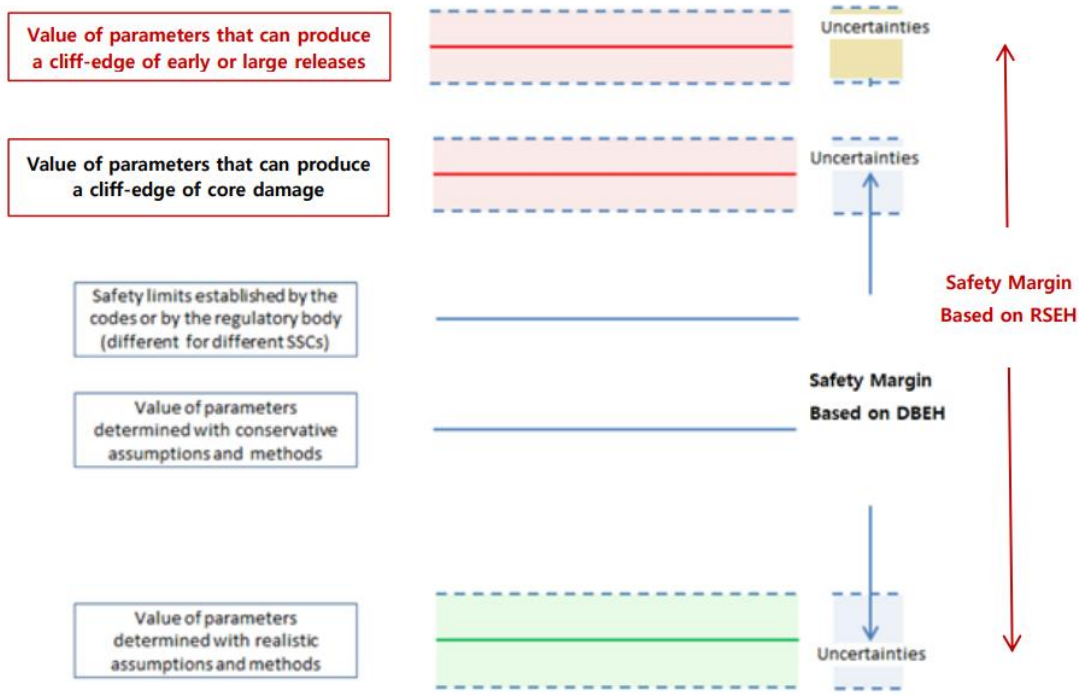
II.3 External Hazards (2/3)

Group	SSCs Ultimately Necessary to Prevent Early or Large Release	Functions
Structures	• Containment Building • Auxiliary Building • AAC DG Building • DESW Cooling Tower • DCCWS HX Building	• Maintain structural integrity of buildings th at houses the equipment below
Systems and Components	• PECS • ERDS • HMS • DCSS • Containment Isolation Valves	• Maintain containment integrity after core melt
	• DSFPCS (incl. SFP water level monitoring)	• Maintain SFP cooling
	• DCCWS • DESWS	• Transfer heat to UHS
	• ECWS • MCR HVAC System • Diverse Electrical and I&C Equipment Room HVAC System • AAC DG Building HVAC System	• Provide room cooling for essential items • Maintain habitability of MCR
	• AAC DG	• Supply power to essential equipment
	• AMCS • CIM (for HVAC Control)	• Provide monitoring and control

II.3 External Hazards (3/3)

❖ To Avoid Cliff Edge Effect = To Ensure Sufficient Margin

- DBEH: Conservative Design
- RSEH: Two Approaches



<Concept of Safety Margin against DBEH & RSEH>

Approach 1

- **Conservative design based on the RSEH parameters**
  - Ambient Air temperature
  - External flooding
  - High wind
  - Tornado, Missile, etc

Approach 2

- **Design based on DBEH parameters and verify using best estimate analysis**
  - Earthquake

<Two Approaches for Design against RSEH>

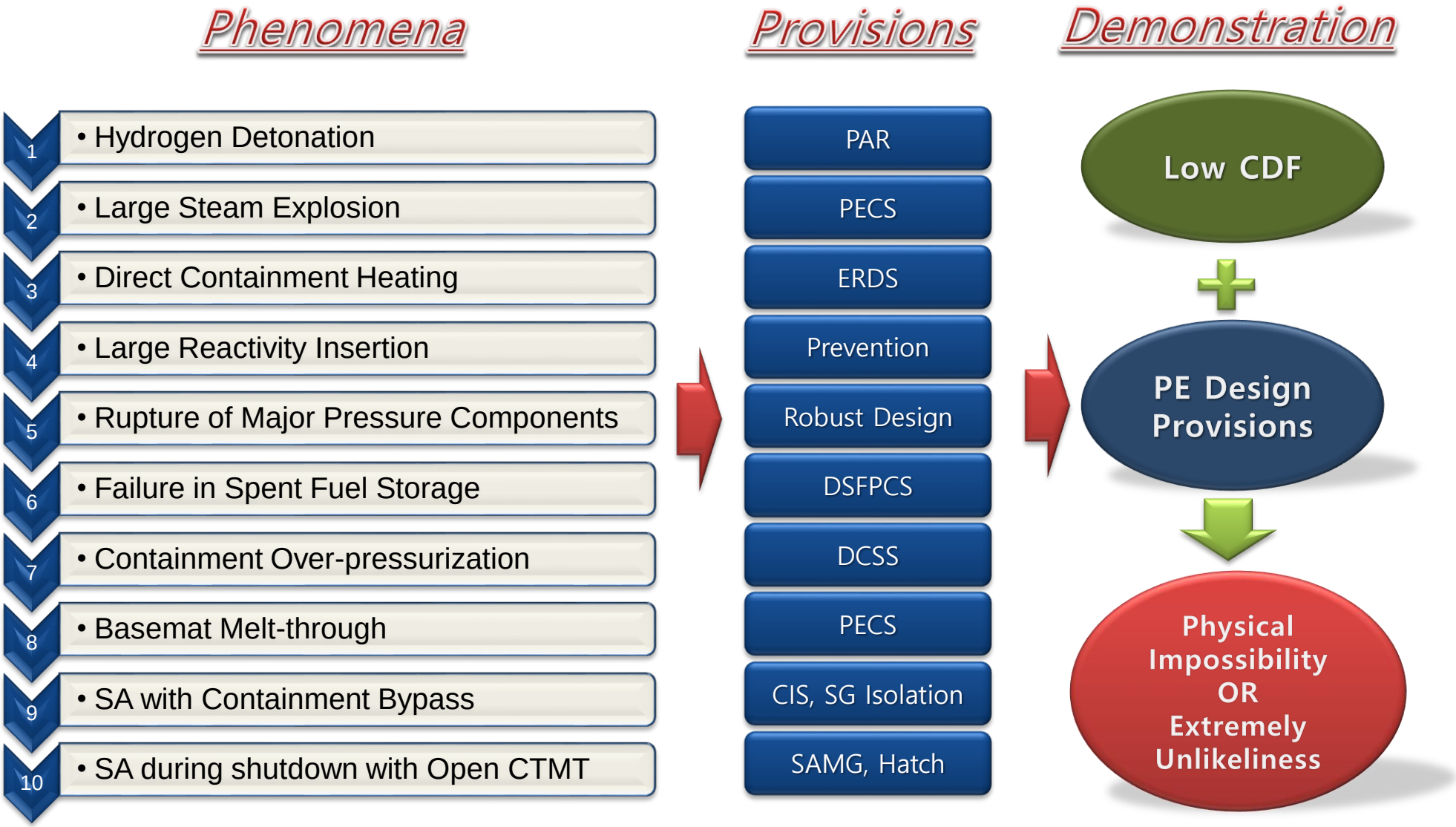
II.4 NPE & ELAP

- List of NPE (Non-permanent Equipment) Required

Conditions		Required NPE	Functions
AOO, DBA or DEC		• Offsite Fuel Oil Supply • 1 Offsite Mobile Pump	• Provides EDG or AAC DG with fuel oil after 7 days from offsite • Provides makeup water to MDCT basin of ESWS or DESWS from UHS pond after 7 days
Beyond DEC	ELAP	• 1 Onsite Mobile DG	• Provides power to DCSS, DSFPCS, DCCWS, DECWS and DESWS on 24 hours after the occurrence of ELAP
	Others (e.g., ELAP + LOUHS)	• 3 Onsite Mobile Pumps	• Provides external water supply to Emergency Containment Spray Backup System (ECSBS), SFP and MDCT after 24 hours of the BDEC

- ELAP (Extended Loss of AC Power) Strategy
  - Definition : Loss of all AC Power (= Offsite Power + EDG + AAC DG)
  - Design target: O3
  - Strategy
    - ~ 24 h : Reach and maintain safe state using PAFS
    - 24 h - 7 d : Reach and maintain SASS using DCSS and DSFPCS powered by Onsite Mobile DG
    - 7 d ~ : Restore power and maintain SASS

II.5 Practical Elimination (1/2)



II.5 Practical Elimination (2/2)

❖ Demonstration = Provisions + DSA and/or PSA

Sequences to be Practically Eliminated	Provisions	DSA	PSA (<1.0E-7/ry)
1. Hydrogen Detonation	PAR	No DDT	8.54E-09
2. Large Steam Explosion	PECS	No failure of cavity st ructure	2.03E-10
3. Direct Containment Heating	ERDS	P_{RCS} < 20 bar	3.18E-10
4. Large Reactivity Insertion	Prevention	Sub-criticality	N/A
5. Rupture of Major Pressure Components	Robust Design	No rupture	< 1.0E-07
6. Failure of Spent Fuel Storage	DSFPCS, Makeup	No heatup of fuel	1.12E-08
7. Containment Over-pressurization	DCSS	P < FLC Pressure	5.79E-08
8. Basemat Melt-Through	PECS	MCCI termination	1.16E-08
9. Containment Bypass	CIS, SG Isolation	N/A	9.10E-08
10. During Shutdown with Open Containment	SAMG, EQH	N/A	1.02E-09

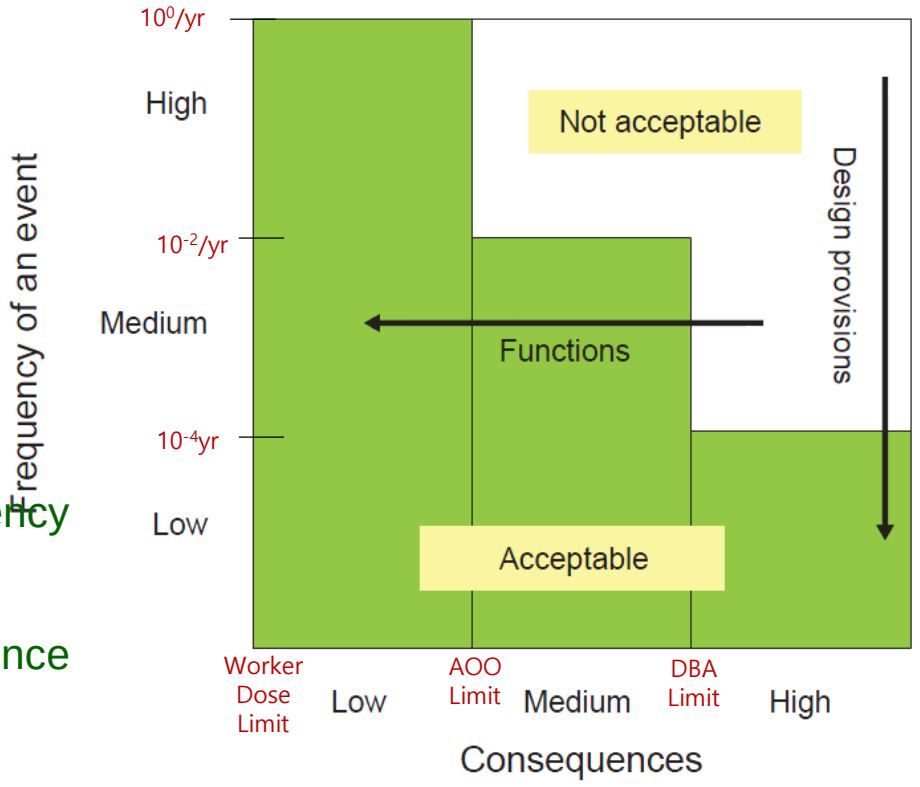
II.6 Safety Classification (1/2)

❖ Methods for Safety Classification

- Identify SSCs important to safety and classify based on their functions and Safety Significance
- Safety significance shall be primarily based on deterministic approach and supplemented probabilistically
  - Safety Function to be performed
  - Consequences of failure
  - Frequency to be called upon
  - Time or Period

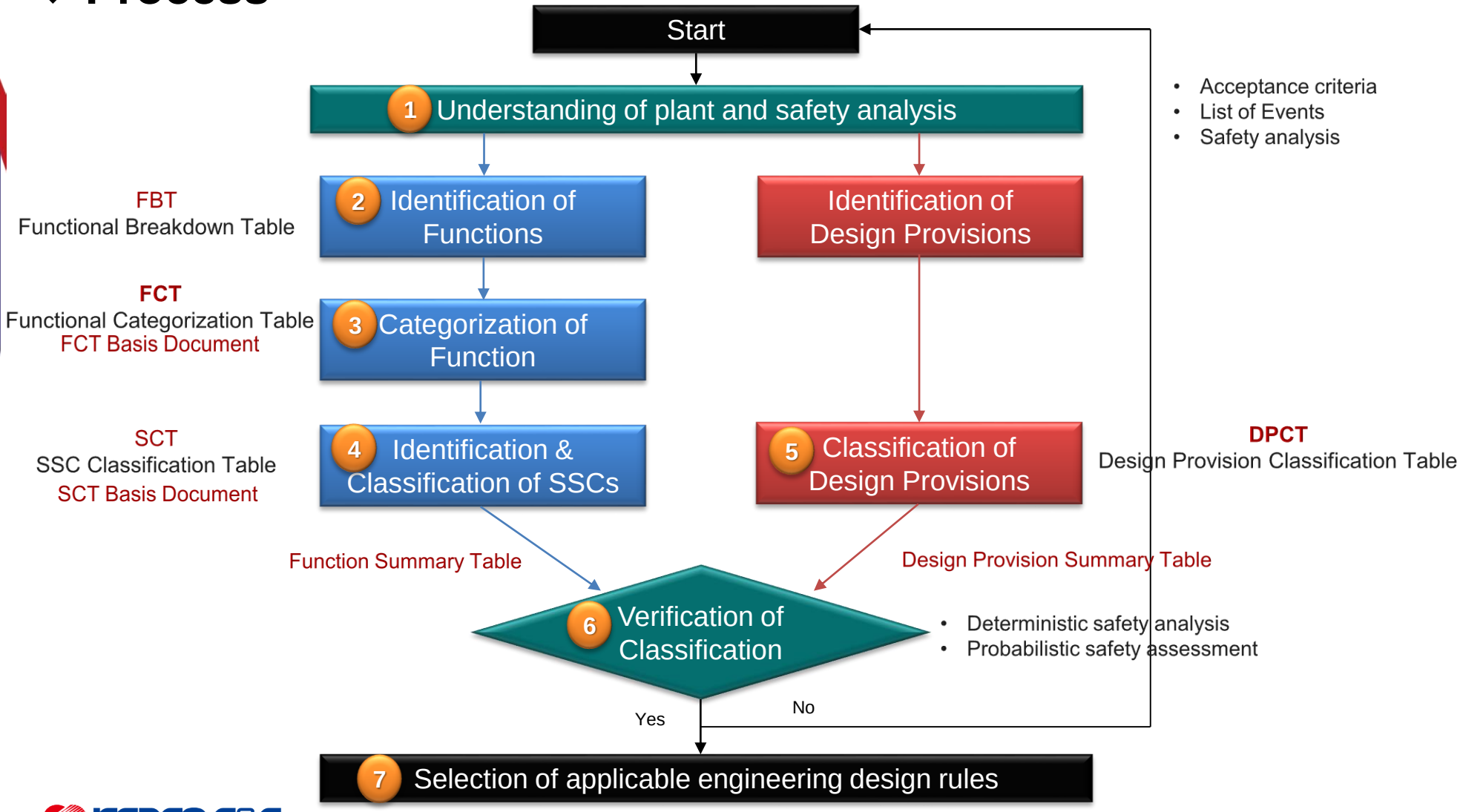
❖ Principle of Risk Reduction

- Function
  - Reduce consequence at the same frequency
- Design Provisions
  - Reduce frequency at the same consequence



II.6 Safety Classification (2/2)

❖ Process

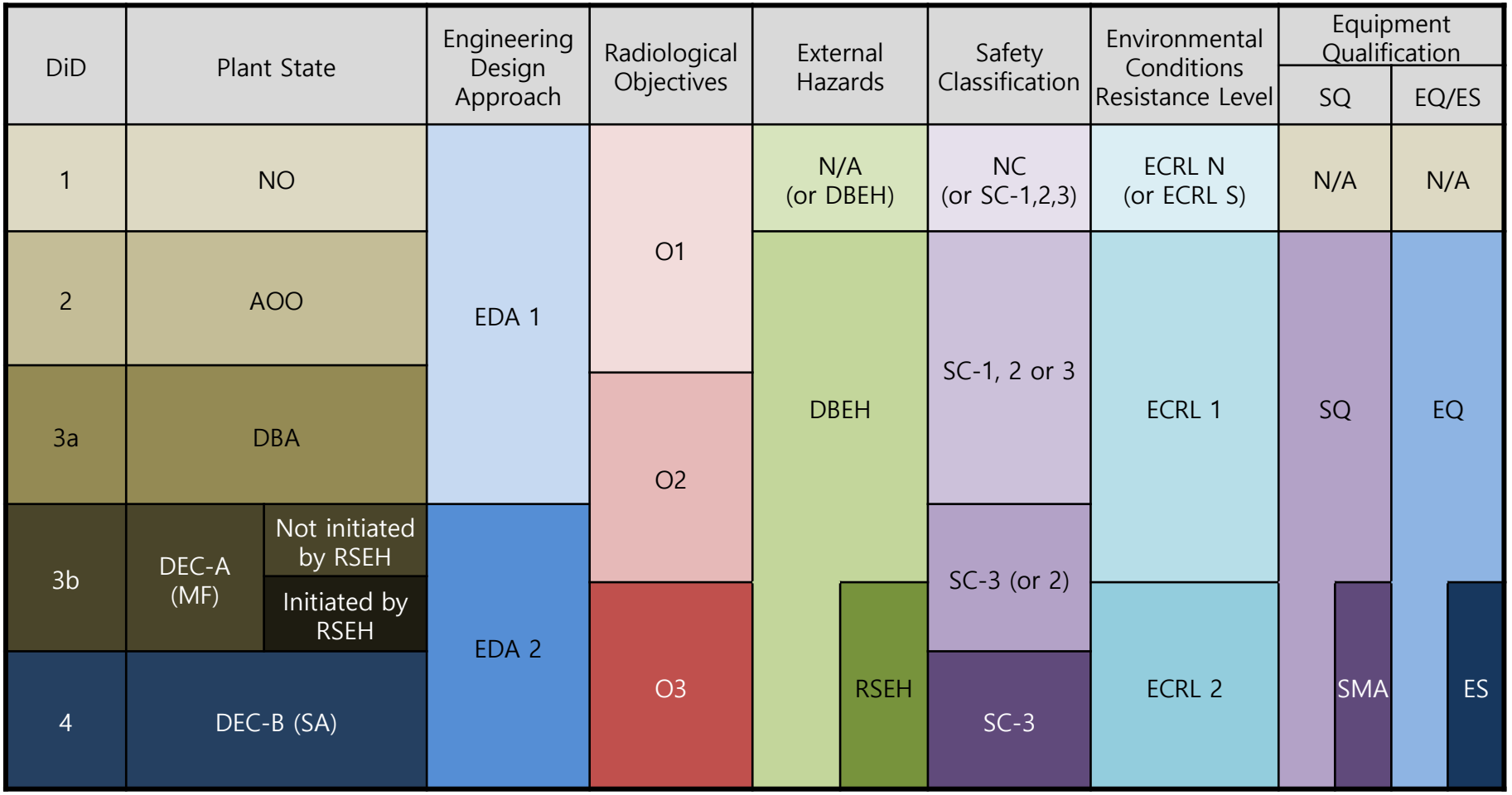


II.7 Engineering Design Rules (1/2)

Safety Classes		Single Failure Criterion	Physical Separation/ Electrical Isolation	Emergency Power	Periodic Test	Hazards Loads	Environmental Qualification
SC-1		○	○	○	○	○	○
SC-2	System for Safe State (1)	○	○	○	○	○	○
	Back-up of SC-1 system for DEC (2)	X	○ (for redundant components)	○	○	○	○
SC-3	DEC Mitigation System (5)	X	○ (for redundant components)	○	○	○	○
	Important to Safety Systems not used for DBA/DEC (7)	X	X	Functional Analysis required	○	Functional Analysis required	Functional Analysis required

(1) Systems necessary to reach and maintain a safe state.
(2) Systems designed for design extension conditions as a backup of a system assigned to safety class 1.
(5) Systems designed to mitigate the consequences of design extension conditions but not assigned to safety class 2.
(7) Systems not required meeting the acceptance criteria established for design basis accidents or design extension conditions but that are in the group of systems important to safety.

II.7 Engineering Design Rules (2/2)



- **EDA** : Engineering Design Approach
- **O3** : Objective 3 (Limited protective measures)
- **ECRL** : Environmental Condition Resistance Level
- **ES** : Equipment Survivability
- **O1** : WENRA Objective 1 (Negligible impact),
- **DBEH** : Design Basis External Hazards,
- **SQ** : Seismic Qualification,
- **SMA** : Seismic Margin Assessment
- **O2** : Objective 2 (No or minor impact),
- **RSEH** : Rare and Severe External Hazards
- **EQ** : Environmental Qualification,

III. Lessons Learned from EUR Assessment

- EUR Rev.E was developed to fully adopt the latest IAEA and WENRA safety requirements identified after Fukushima accident

- High compliance ratings of APR1000 against EUR Rev.E attribute to:
  - Strengthened DiD principle,
  - Consideration of Design Extension Conditions,
  - Enhanced Plant Autonomy,
  - Demonstration of Practical Elimination,
  - Robust design against Rare and Severe External Hazards,
  - Application of new Safety Classification.

- Successful EUR assessment of APR1000:
  - Proved a highest level safety and performance of APR1000 standard design
  - Demonstrated licensibility of APR1000 for new NPP build projects in Europe
  - Contributed to improve EUR for Revision F

Thank you

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