GEN IV International Forum℠

SAFETY OF GEN-IV REACTORS

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Meet the presenter

Luca AMMIRABILE works at the European Commission (EC), Joint Research Centre in Petten, the Netherlands, where he is Group Leader of the NUclear Reactor Accident Modelling (NURAM) team of the Nuclear Reactor Safety and Emergency Preparedness Unit. His current research activities are among the others core thermal-hydraulic analyses, deterministic code application and development, and safety assessment of advanced reactors.

Since 2014, he has been co-chair of the working group on Risk and Safety of the Generation IV International Forum. He is also EC representative of the OECD/NEA Working Group on the Analysis and Management of Accidents (WGAMA) and Working Group on the Safety of Advanced Reactors (WGSAR).

Prior to joining the European Commission in 2007, Luca worked at Tractebel Engineering (now Tractebel Engie) in Belgium in the Thermalhydraulics and Severe Accident Section, where he was engaged among other in the development of innovative methodologies in support of the safety assessment of the Belgian Nuclear Power Plants.

Luca received his doctorate from the Imperial College London in 2003 and his master's degree in nuclear engineering from the University of Pisa, Italy in 1999.

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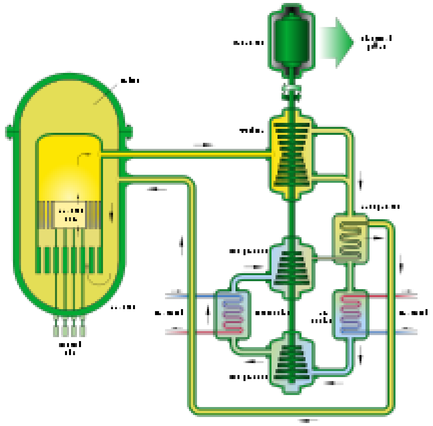
Outline

- GIF safety goals
- Risk and Safety Working Group
- Basis safety approach for Gen-IV reactors
- Integrated Safety Assessment Methodology (ISAM)
- ISAM application

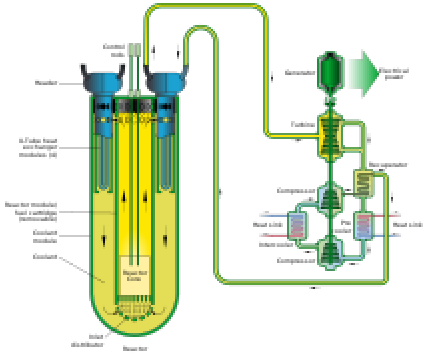
Gen IV Goals

- Three specific safety goals “to be used to stimulate the search for innovative nuclear energy systems and to motivate and guide the R&D on Generation IV systems”:
  - Generation IV nuclear energy systems operations will excel in safety and reliability.
  - Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
  - Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

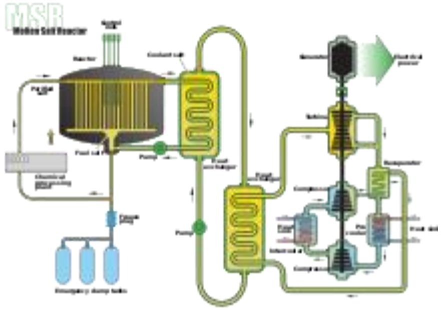
Gen IV Systems



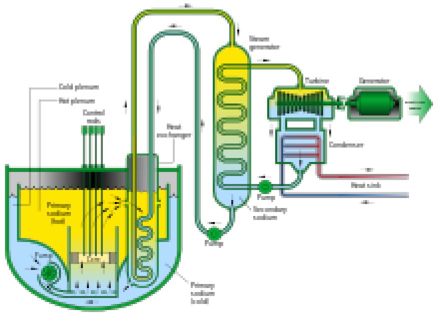
Gas-cooled Fast Reactor (GFR)



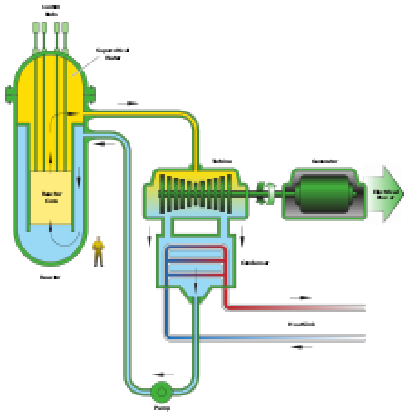
Lead-cooled Fast Reactor (LFR)



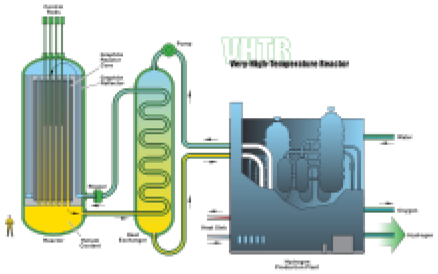
Molten Salt Reactor (MSR)



Sodium-cooled Fast Reactor (SFR)

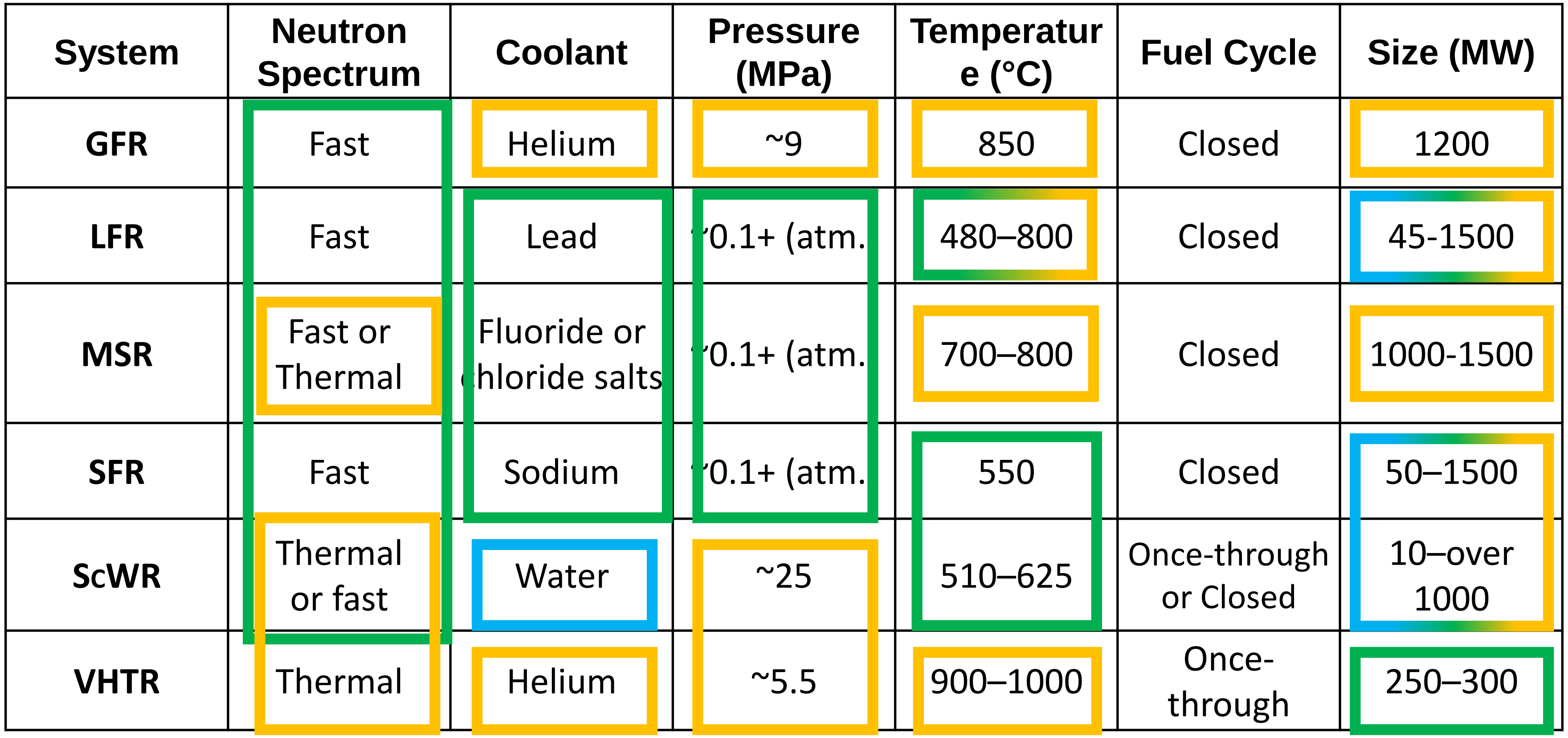


Supercritical-Water-cooled Reactor (ScWR)



Very-High-Temperature Reactor (VHTR)

Gen IV Systems



System	Neutron Spectrum	Coolant	Pressure (MPa)	Temperature (°C)	Fuel Cycle	Size (MW)
GFR	Fast	Helium	~9	850	Closed	1200
LFR	Fast	Lead	~0.1+ (atm.	480–800	Closed	45-1500
MSR	Fast or Thermal	Fluoride or chloride salts	~0.1+ (atm.	700–800	Closed	1000-1500
SFR	Fast	Sodium	~0.1+ (atm.	550	Closed	50–1500
ScWR	Thermal or fast	Water	~25	510–625	Once-through or Closed	10–over 1000
VHTR	Thermal	Helium	~5.5	900–1000	Once-through	250–300

Fast
Thermal

Water
Liquid-Metal
Molten-Salt
Inert-Gas

Atm.
Hi-Pressure

Mid. Temp.
Hi-Temp.

Small
Mid.
Large

Risk and Safety Working Group

- “Promote a consistent approach on safety, risk, and regulatory issues between Generation IV systems”
- Propose safety principles, objectives, and attributes based on Gen-IV safety goals in order to guide safety related R&D plans
- Development and promotion of a technology-neutral Integrated Safety Assessment Methodology (ISAM)

Gen IV Safety Philosophy

- Further improvements are possible through advanced technologies and the early application of a improved safety philosophy for a robust design so that safety is “built-in” rather than “added on”.
- Design and safety assessment based on both deterministic and probabilistic approach, over wide-range of plant conditions including severe plant conditions.
- Handling of internal and external hazards.
- Modelling and simulation should play a large role in the design and the safety assessment.

Full implementation
of “defence in depth” in the design of
Gen IV systems

Explanation of Safety & Reliability Goals

- Excel in Operational Safety and Reliability

  Safety during normal operation, anticipated operational events

  → DiD Level 1-2 [N.O., AOO]

- Very low likelihood & degree of reactor core damage

  Minimizing frequency of initiating internal events, and introducing design features for controlling & mitigating accidents to avoid core damage

  → DiD Level 2-3 [Design for severe accident prevention]

- Eliminate the need for offsite emergency response

  Comprehensive safety architecture to manage & mitigate severe plant conditions and reducing the likelihood of early or large releases of radiation

  → DiD Level 4 [Design for severe accident mitigation]

Defence-in-Depth

Defence in depth (DiD) is a fundamental principle of nuclear safety for preventing accidents and mitigating their consequences.

The principle was introduced in the early 1970s, starting with three levels. Following the accidents at Three Mile Island and Chernobyl, two additional levels were added and the concept was formalised in 1996 in IAEA INSAG-10 with five levels.

Levels	Objective	Essential means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction and operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features and accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures and accident management
Level 5	Mitigation of radiological consequences of significant releases of radioactive materials	Off-site emergency response

Defence-in-Depth

- ***Exhaustive****: Identification of the risks, which leans on the fundamental safety functions, should be comprehensive.*
- ***Progressive****: Accident scenarios should entail the progressive failure of each DiD level without "short" sequences leading directly from level 1 to level 4.*
- ***Tolerant:*** *Small deviation of the physical parameters outside their expected range should not lead to severe consequences (i.e. no "cliff edges").*
- ***Forgiving****: Assure sufficient grace period for possibility of manual intervention and repair during accidental situations.*
- ***Balanced:*** *A specific accident sequence should not contribute to the global frequency of the damaged plant states in an excessive and unbalanced manner.*

Simple Design

Basis for design and assessment

- The design for Gen IV energy systems should cover the full range of plant states **including severe conditions**.
- Special attention to reinforced treatment of severe plant conditions through **provisions of measures** against such conditions.
- Internal-events and internal/external-hazards should be considered
- **Uncertainties** related to innovative technologies should be factored in.
- Specific efforts, both analytical and empirical, should be made for demonstrating the "**practical elimination**" of sequences associated with the potential for early or large releases.

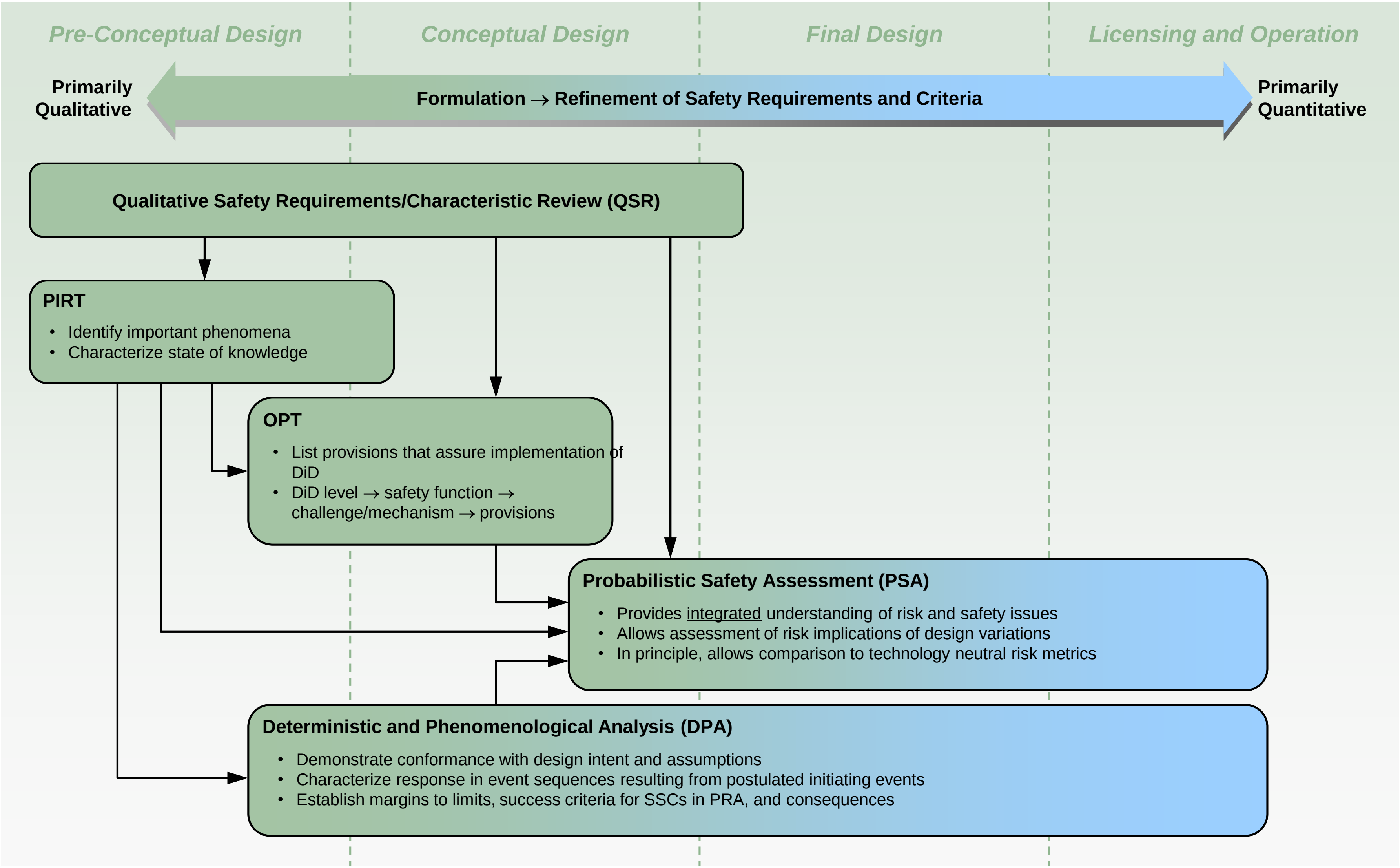
Plant States

Defense-in-Depth Levels				
Level 1	Level 2	Level 3	Level 4	Level 5
Operational states		Accident conditions		EP&R
Normal Operation	Anticipated Operational Occurrences	Design Basis Accidents	Design Extension Conditions	Residual risk and practically eliminated accidents
			Severe accidents	

Plant states considered in design
(safety analyses)

Out of the design
(addressed in level-5 of DiD)

Integrated Safety Assessment Methodology



Pre-Conceptual Design | *Conceptual Design* | *Final Design* | *Licensing and Operation*

Primarily Qualitative

Formulation → Refinement of Safety Requirements and Criteria

Primarily Quantitative

Qualitative Safety Requirements/Characteristic Review (QSR)

PIRT

- Identify important phenomena
- Characterize state of knowledge

OPT

- List provisions that assure implementation of DiD
- DiD level → safety function → challenge/mechanism → provisions

Probabilistic Safety Assessment (PSA)

- Provides integrated understanding of risk and safety issues
- Allows assessment of risk implications of design variations
- In principle, allows comparison to technology neutral risk metrics

Deterministic and Phenomenological Analysis (DPA)

- Demonstrate conformance with design intent and assumptions
- Characterize response in event sequences resulting from postulated initiating events
- Establish margins to limits, success criteria for SSCs in PRA, and consequences

ISAM Toolkit

- Qualitative Safety-characteristics Review (QSR)
  - A “check-list” as systematic and qualitative means of ensuring that the design incorporates desired safety attributes (preparatory step)
- Phenomena Identification and Ranking Table (PIRT)
  - Generates ranked tables for identifying system and component vulnerabilities, and relative contributions to safety and risk
  - Also helps to identify the gaps in knowledge base that require additional research and data for V&V
- Objective Provision Tree (OPT)
  - A tool for identifying the provisions for prevention, or control and mitigation, of accidents that could potentially damage the reactor
  - Complimentary to PIRT for selecting the ”lines of protection” against the identified phenomena

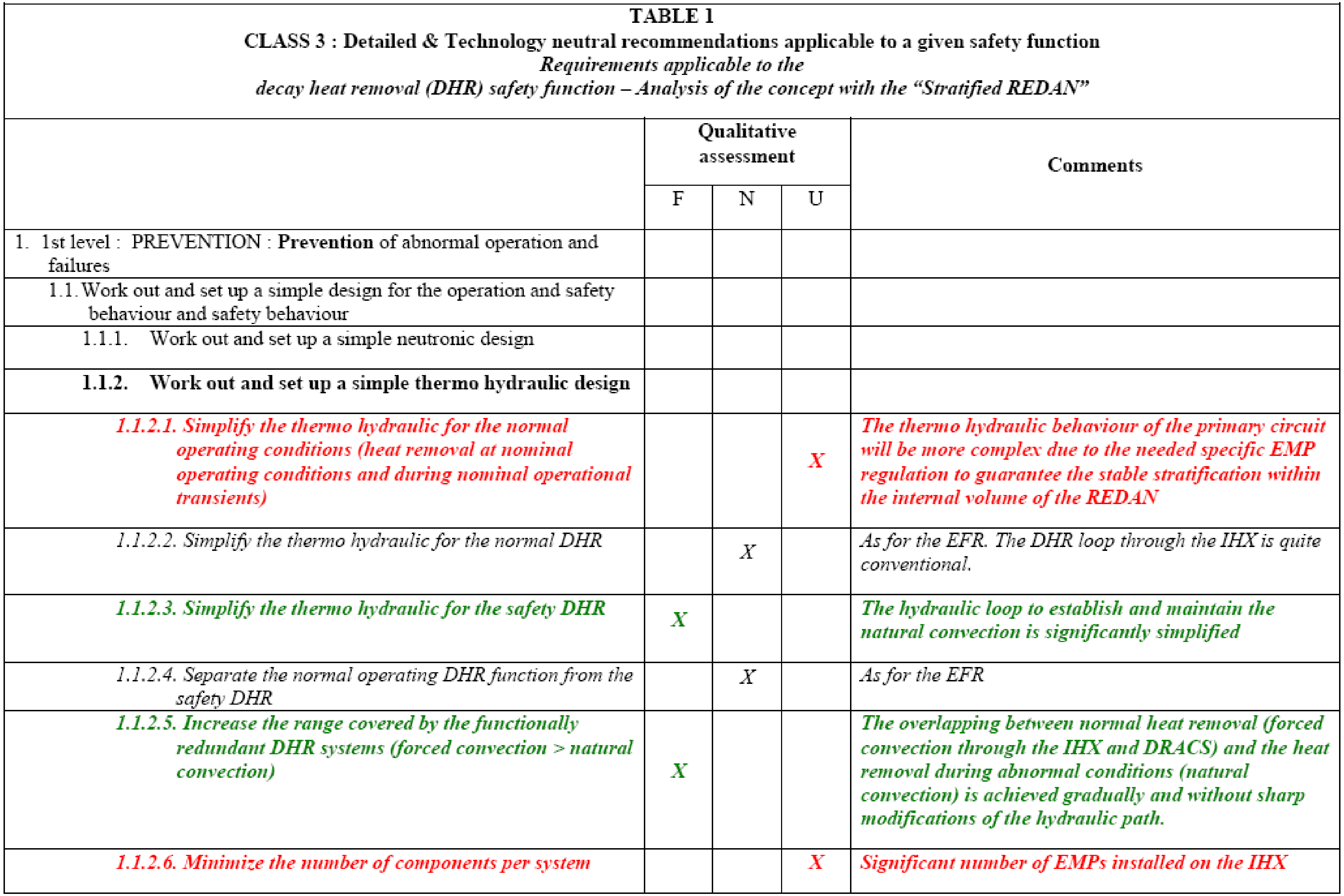


TABLE 1

CLASS 3 : Detailed & Technology neutral recommendations applicable to a given safety function

Requirements applicable to the

decay heat removal (DHR) safety function – Analysis of the concept with the "Stratified REDAN"

	Qualitative assessment			**Comments**
	F	N	U	
1. 1st level : PREVENTION : **Prevention** of abnormal operation and failures				
1.1. Work out and set up a simple design for the operation and safety behaviour and safety behaviour				
1.1.1. Work out and set up a simple neutronic design				
1.1.2. Work out and set up a simple thermo hydraulic design				
1.1.2.1. Simplify the thermo hydraulic for the normal operating conditions (heat removal at nominal operating conditions and during nominal operational transients)			*X*	***The thermo hydraulic behaviour of the primary circuit will be more complex due to the needed specific EMP regulation to guarantee the stable stratification within the internal volume of the REDAN***
1.1.2.2. Simplify the thermo hydraulic for the normal DHR		*X*		*As for the EFR. The DHR loop through the IHX is quite conventional.*
1.1.2.3. Simplify the thermo hydraulic for the safety DHR	*X*			***The hydraulic loop to establish and maintain the natural convection is significantly simplified***
1.1.2.4. Separate the normal operating DHR function from the safety DHR		*X*		*As for the EFR*
1.1.2.5. Increase the range covered by the functionally redundant DHR systems (forced convection > natural convection)	*X*			***The overlapping between normal heat removal (forced convection through the IHX and DRACS) and the heat removal during abnormal conditions (natural convection) is achieved gradually and without sharp modifications of the hydraulic path.***
1.1.2.6. Minimize the number of components per system			*X*	***Significant number of EMPs installed on the IHX***

QSR

ISAM Toolkit

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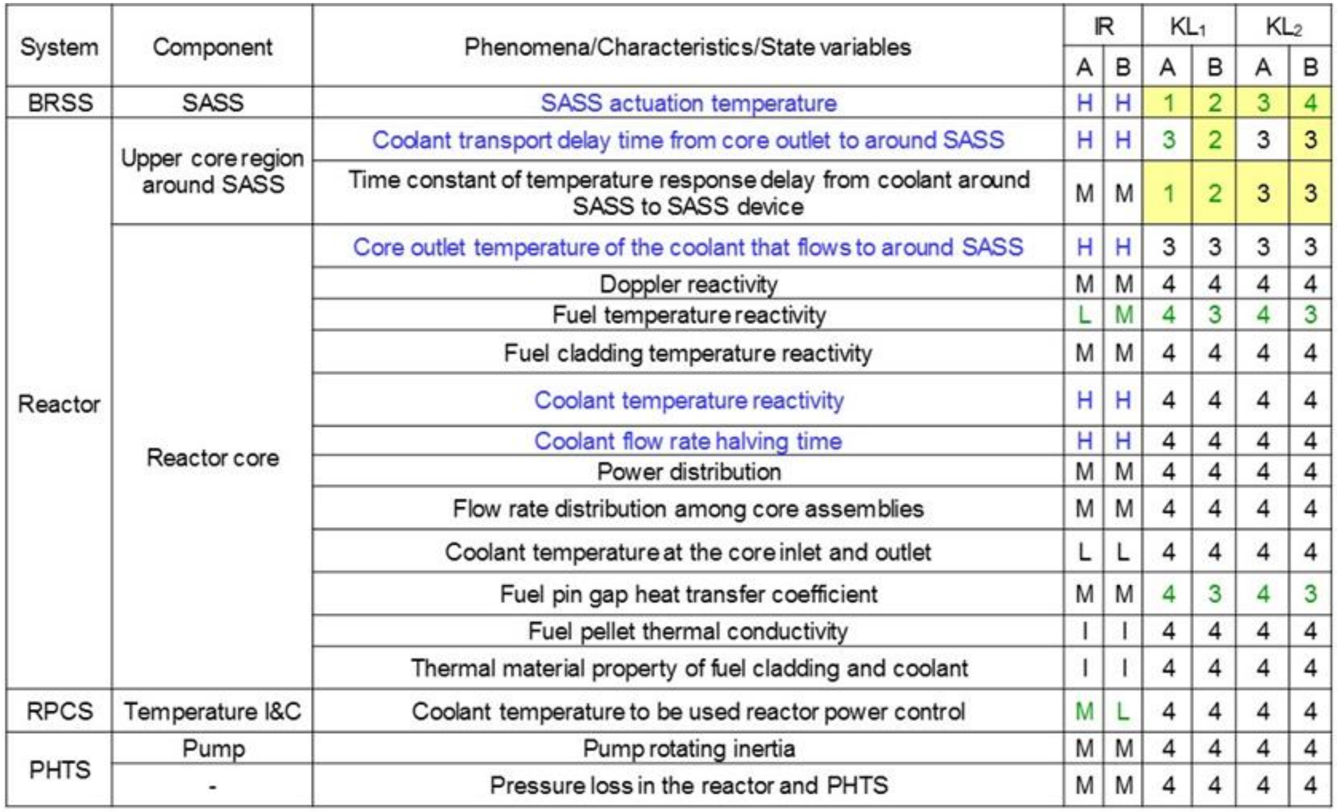
Knowledge Level [KL]

Importance Ranking [IR]

PIRT



System	Component	Phenomena/Characteristics/State variables	IR		KL_1		KL_2	
			A	B	A	B	A	B
BRSS	SASS	SASS actuation temperature	H	H	1	2	3	4
Reactor	Upper core region around SASS	Coolant transport delay time from core outlet to around SASS	H	H	3	2	3	3
		Time constant of temperature response delay from coolant around SASS to SASS device	M	M	1	2	3	3
	Reactor core	Core outlet temperature of the coolant that flows to around SASS	H	H	3	3	3	3
		Doppler reactivity	M	M	4	4	4	4
		Fuel temperature reactivity	L	M	4	3	4	3
		Fuel cladding temperature reactivity	M	M	4	4	4	4
		Coolant temperature reactivity	H	H	4	4	4	4
		Coolant flow rate halving time	H	H	4	4	4	4
		Power distribution	M	M	4	4	4	4
		Flow rate distribution among core assemblies	M	M	4	4	4	4
		Coolant temperature at the core inlet and outlet	L	L	4	4	4	4
		Fuel pin gap heat transfer coefficient	M	M	4	3	4	3
		Fuel pellet thermal conductivity	I	I	4	4	4	4
		Thermal material property of fuel cladding and coolant	I	I	4	4	4	4
RPCS	Temperature I&C	Coolant temperature to be used reactor power control	M	L	4	4	4	4
PHTS	Pump	Pump rotating inertia	M	M	4	4	4	4
	-	Pressure loss in the reactor and PHTS	M	M	4	4	4	4

Knowledge Base Gap Determination				
Adequacy of knowledge	Rank of Phenomenon			
	H	M	L	I
(4) Fully known; small uncertainty				
(3) Known; moderate uncertainty				
(2) Partially known; large uncertainty	GAP	GAP		
(1) Very limited knowledge; uncertainty cannot be characterized	GAP	GAP	GAP	

ISAM Toolkit

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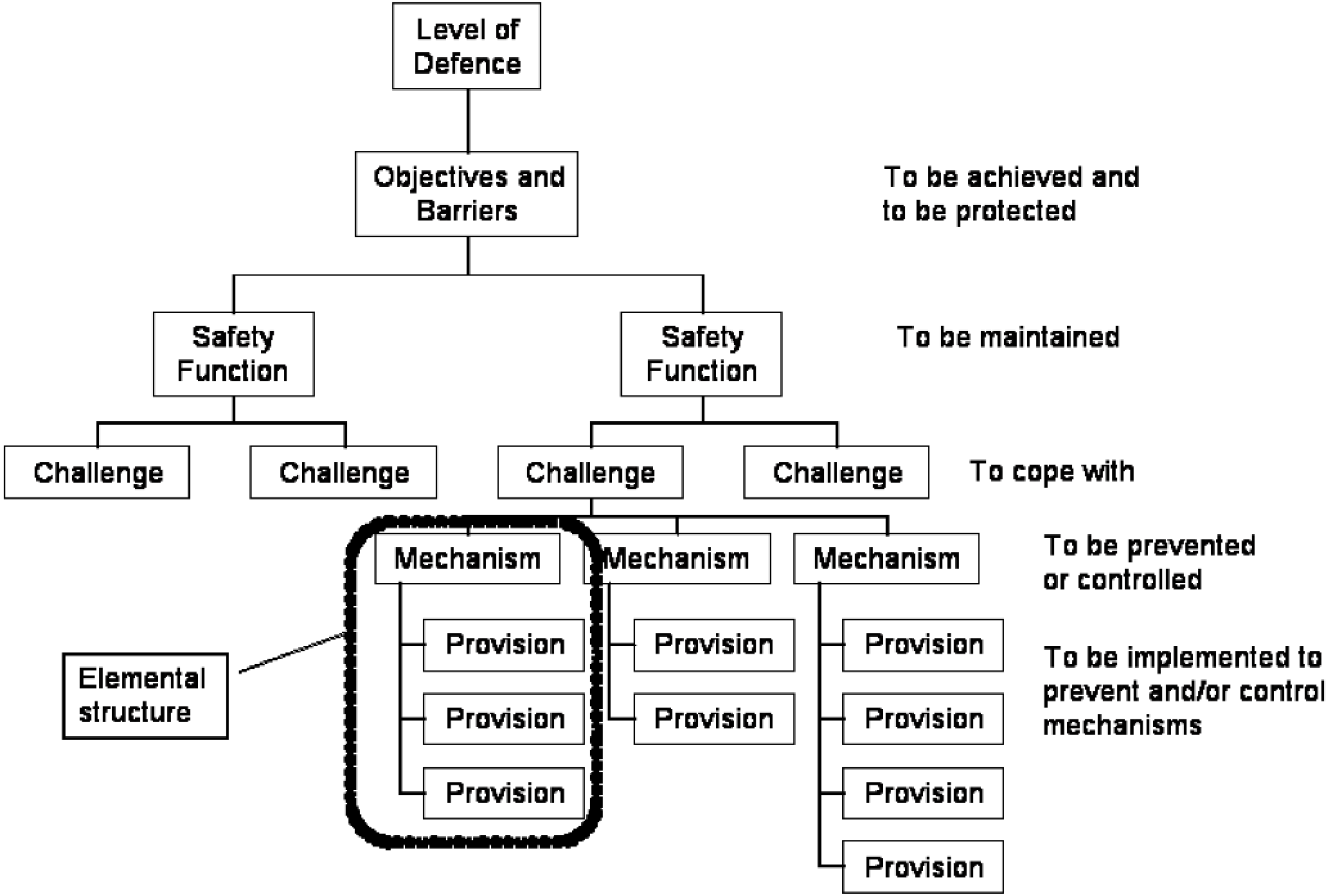
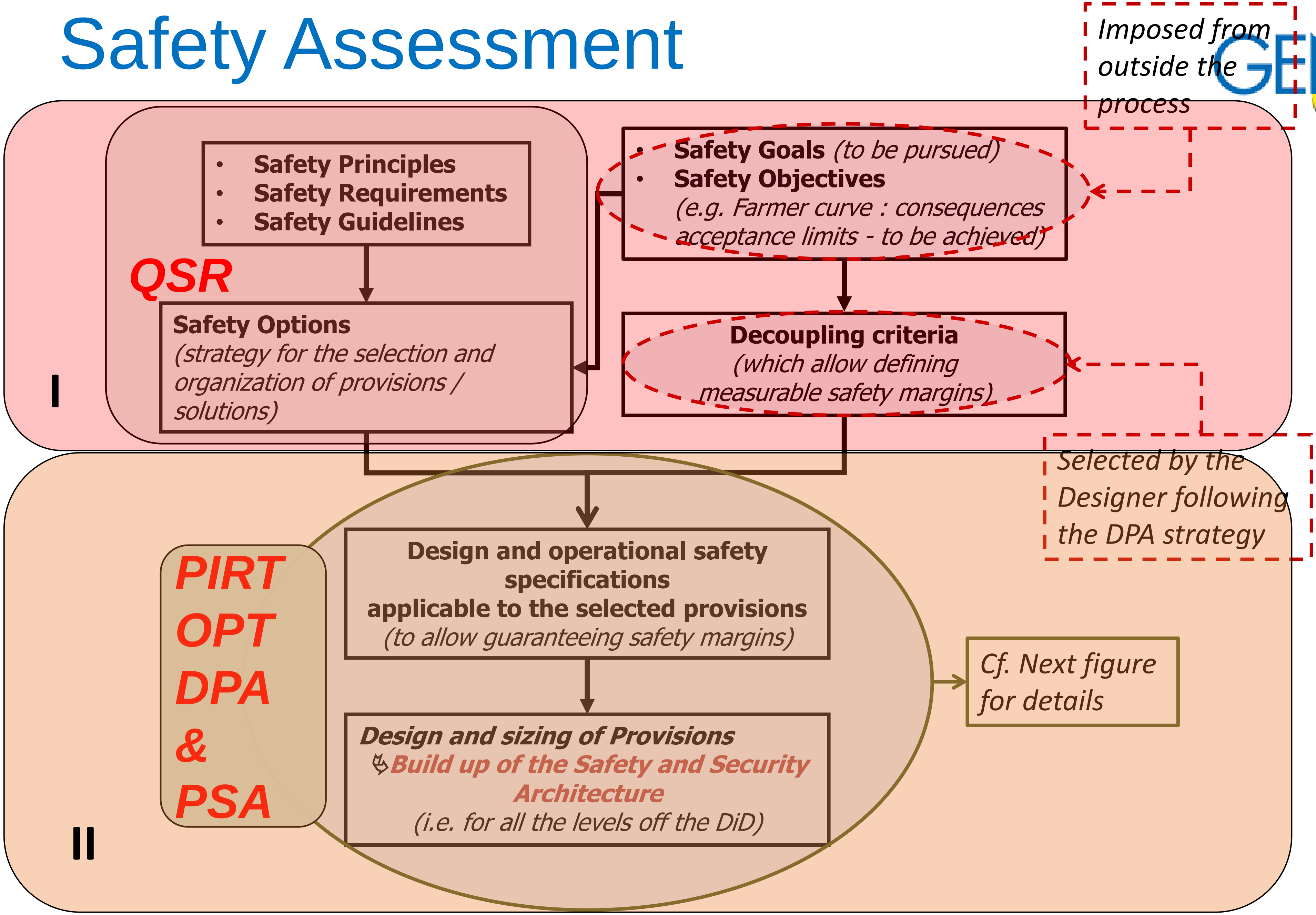

Level of Defence
Objectives and Barriers
To be achieved and to be protected
Safety Function
Safety Function
To be maintained
Challenge
Challenge
Challenge
Challenge
To cope with
Mechanism
Mechanism
Mechanism
To be prevented or controlled
Elemental structure
Provision
Provision
Provision
Provision
Provision
Provision
Provision
Provision
Provision
To be implemented to prevent and/or control mechanisms

OPT

ISAM Toolkit

- Deterministic and Phenomenological Analyses (DPA)
  - Traditional safety analyses to assess the system’s response to known safety challenges and guide concept/design development
  - Involves the use of conventional safety analysis codes and provides input to PSA
- Probabilistic Safety Analysis (PSA)
  - Assures a broader coverage of the accident space
  - Performed and iterated, beginning in the late pre-conceptual design phase, and continuing through the final design stages
  - A structured means of providing answers to three basic questions:
    - What can go wrong?
    - How likely is it?
    - What are the consequences?

Safety Assessment



Imposed from outside the process

- **Safety Goals** *(to be pursued)*
- **Safety Objectives** *(e.g. Farmer curve : consequences acceptance limits - to be achieved)*

Decoupling criteria *(which allow defining measurable safety margins)*

Selected by the Designer following the DPA strategy

- **Safety Principles**
- **Safety Requirements**
- **Safety Guidelines**

QSR

Safety Options *(strategy for the selection and organization of provisions / solutions)*

I

Design and operational safety specifications applicable to the selected provisions *(to allow guaranteeing safety margins)*

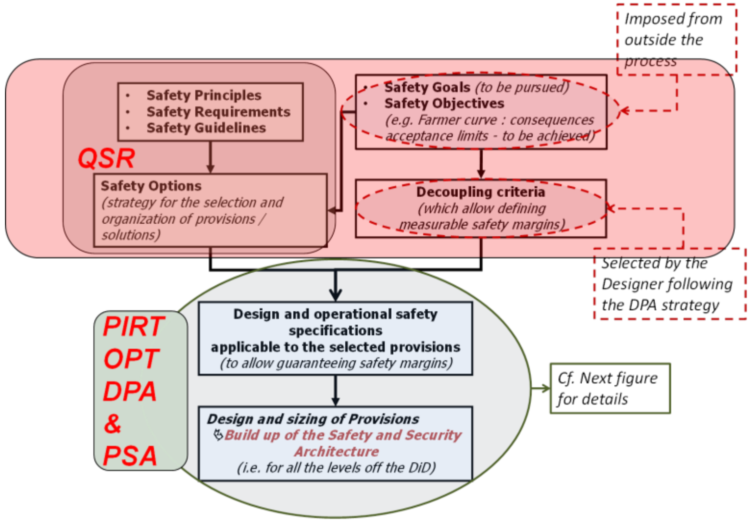
Design and sizing of Provisions
↳ ***Build up of the Safety and Security Architecture***
(i.e. for all the levels off the DiD)

PIRT
OPT
DPA
&
PSA

II

Cf. Next figure for details

	QSR	PIRT	OPT	DPA	PSA
Regulatory Framework (Goals, objectives, principles, requirements, guidelines)	✓				
Selection of Safety Options and provisional Provisions		✓	✓	✓	✓
1. Compliance / consistency of the design options with the principles, requirements and guidelines	✓				
2. Identification, prioritization and correction (if feasible) of discrepancies,	✓	✓			
3. Identification of challenges to the safety functions,		✓	✓		
4. Identification of mechanisms (initiating events) and selection of significant (envelope) plants conditions to be considered for the design basis,		✓	✓	✓	
5. Identification and selection of needed provisions,	✓	✓	✓		
6. Design and sizing of the provisions,			✓	✓	
7. Response to transients (safety analysis),				✓	✓
8. Final assessment for a safety architecture that should be:					
○ *Exhaustive,*		✓	✓		
○ *Progressive,*			✓	✓	✓
○ *Tolerant,*				✓	✓
○ *Forgiving,*				✓	✓
○ *Balanced.*					✓



Imposed from outside the process

QSR

- **Safety Principles**
- **Safety Requirements**
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Safety Options
(strategy for the selection and organization of provisions / solutions)

- **Safety Goals** *(to be pursued)*
- **Safety Objectives**
(e.g. Farmer curve : consequences acceptance limits - to be achieved)

Decoupling criteria
(which allow defining measurable safety margins)

Selected by the Designer following the DPA strategy

PIRT
OPT
DPA
&
PSA

Design and operational safety specifications applicable to the selected provisions
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Design and sizing of Provisions
Build up of the Safety and Security Architecture
(i.e. for all the levels off the DiD)

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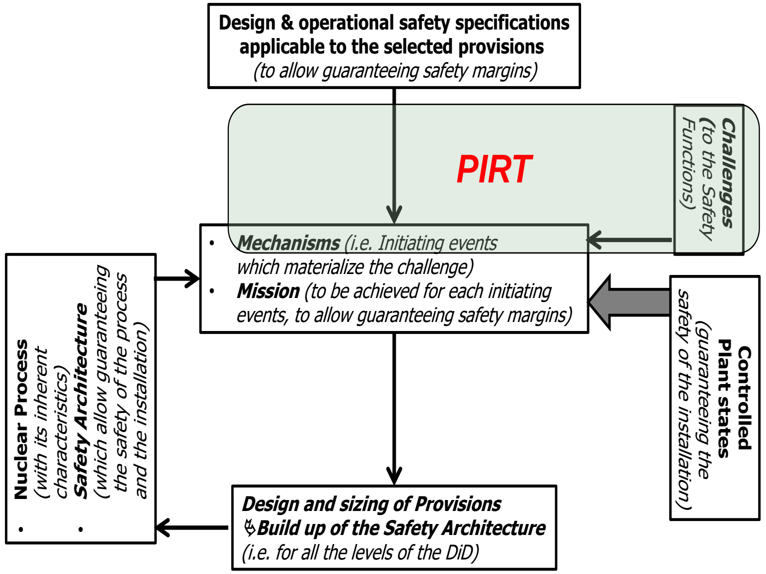

Design & operational safety specifications applicable to the selected provisions
(to allow guaranteeing safety margins)

PIRT

Challenges *(to the Safety Functions)*

- ***Mechanisms*** *(i.e. Initiating events which materialize the challenge)*
- ***Mission*** *(to be achieved for each initiating events, to allow guaranteeing safety margins)*

- **Nuclear Process** *(with its inherent characteristics)*
- ***Safety Architecture*** *(which allow guaranteeing the safety of the process and the installation)*

Controlled Plant states *(guaranteeing the safety of the installation)*

Design and sizing of Provisions
⇨Build up of the Safety Architecture
(i.e. for all the levels of the DiD)

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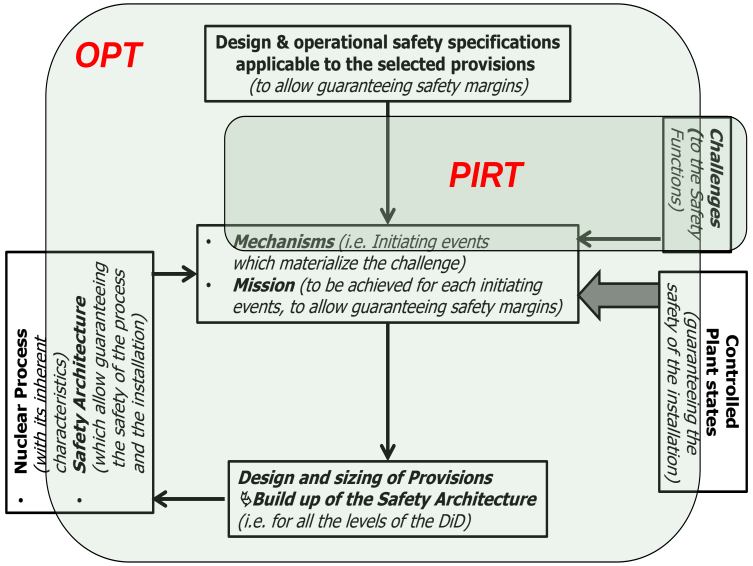

OPT

Design & operational safety specifications applicable to the selected provisions
(to allow guaranteeing safety margins)

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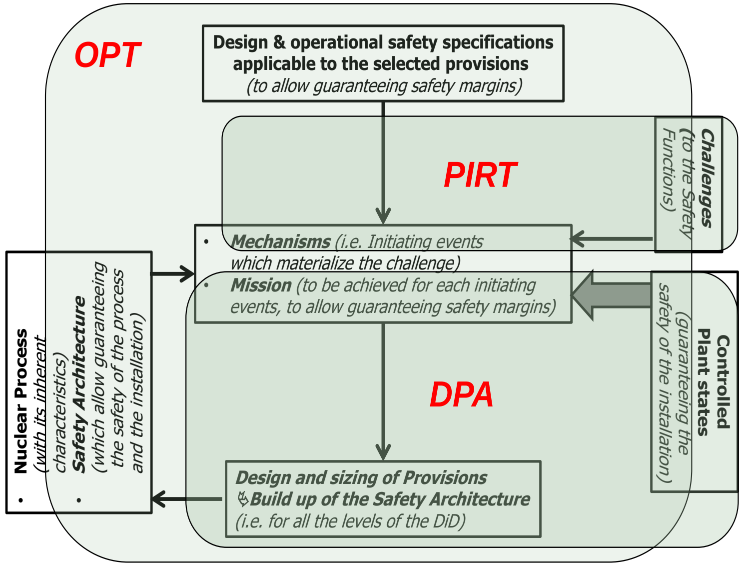

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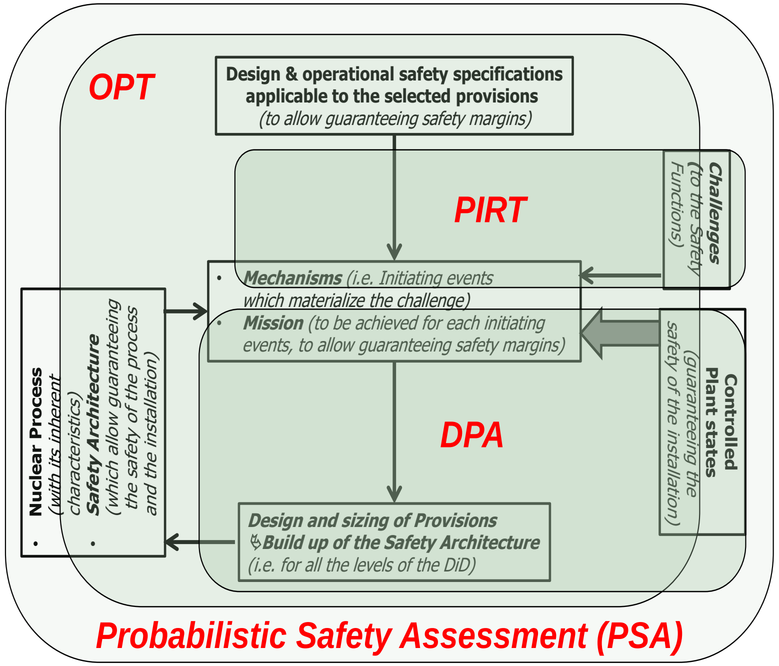


OPT

Design & operational safety specifications applicable to the selected provisions
(to allow guaranteeing safety margins)

PIRT

Challenges *(to the Safety Functions)*

- ***Mechanisms*** *(i.e. Initiating events which materialize the challenge)*
- ***Mission*** *(to be achieved for each initiating events, to allow guaranteeing safety margins)*

- **Nuclear Process** *(with its inherent characteristics)*
- ***Safety Architecture*** *(which allow guaranteeing the safety of the process and the installation)*

Controlled Plant states *(guaranteeing the safety of the installation)*

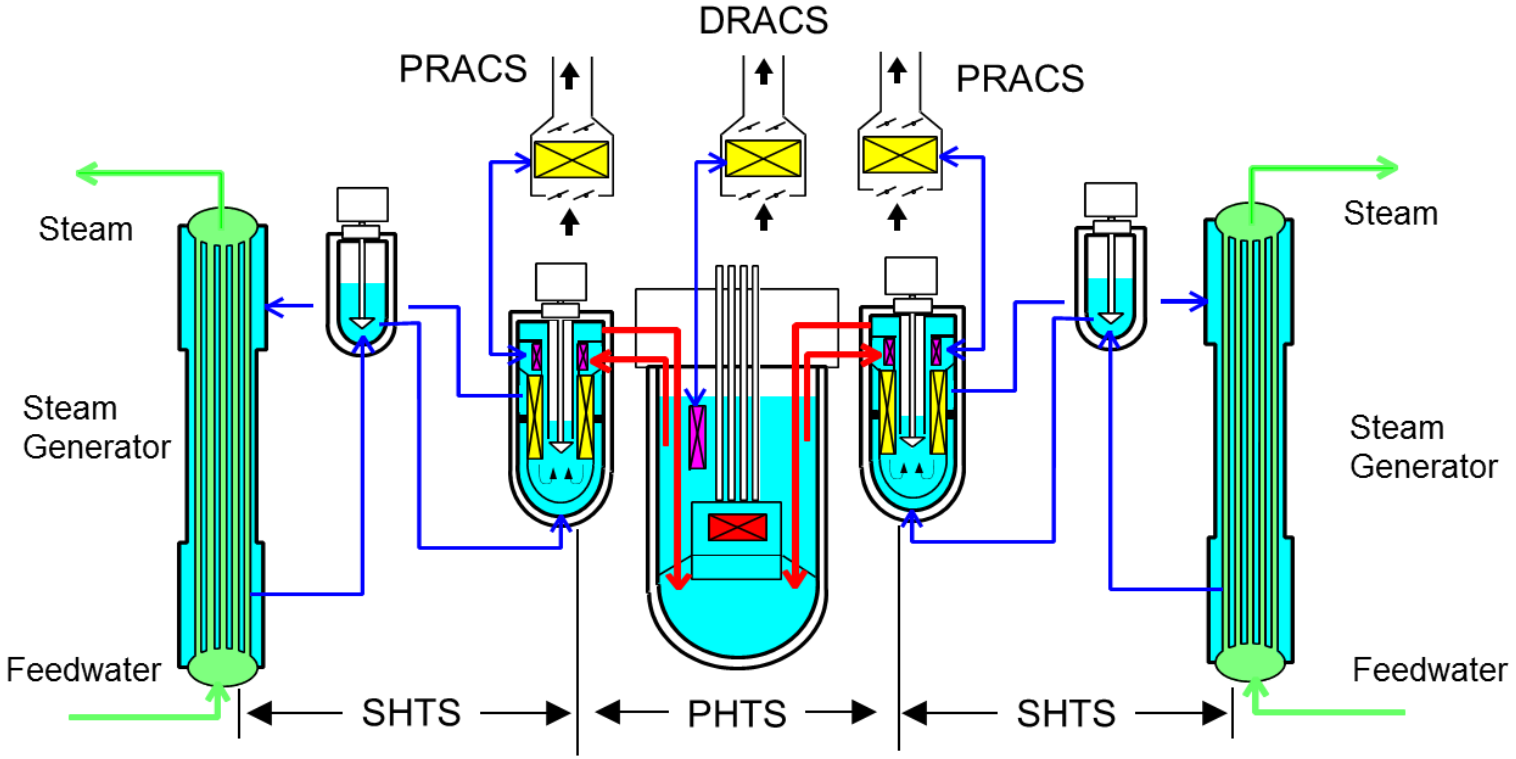
DPA

Design and sizing of Provisions
↳Build up of the Safety Architecture
(i.e. for all the levels of the DiD)

Probabilistic Safety Assessment (PSA)

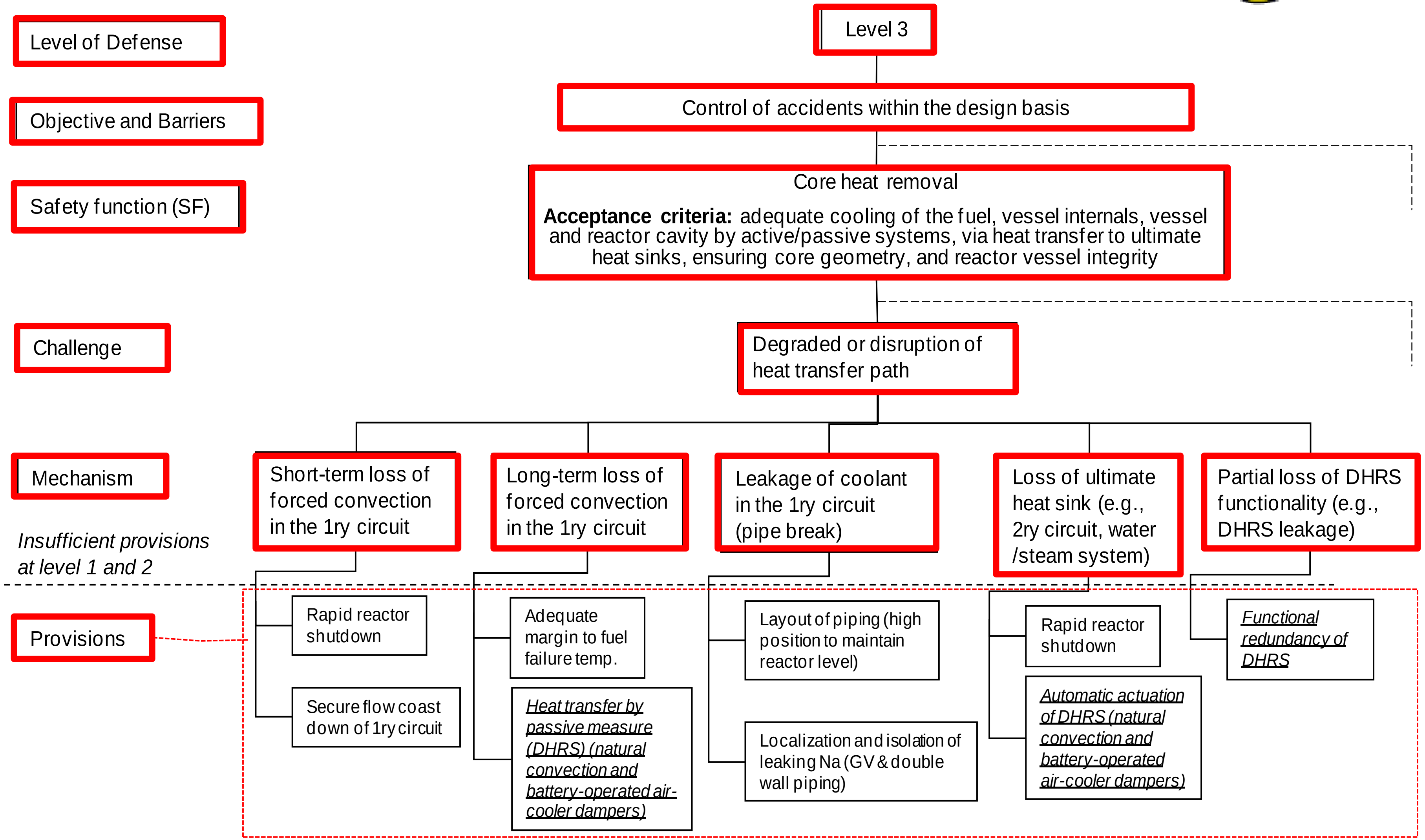
Practical example of ISAM use

Decay Heat Removal System of JSFR : 2 PRACS and 1DRACS each 100% heat removal capacity, with Final heat sink of Air



PRACS: Primary Reactor Auxiliary Cooling System
PHTS: Primary Heat Transport System
DRACS: Direct Reactor Auxiliary Cooling System
SHTS: Secondary Heat Transport System

OPT Lvl 3 for Core Heat Removal



Level of Defense

Objective and Barriers

Safety function (SF)

Challenge

Mechanism

Insufficient provisions at level 1 and 2

Provisions

Level 3

Control of accidents within the design basis

Core heat removal

Acceptance criteria: adequate cooling of the fuel, vessel internals, vessel and reactor cavity by active/passive systems, via heat transfer to ultimate heat sinks, ensuring core geometry, and reactor vessel integrity

Degraded or disruption of heat transfer path

Short-term loss of forced convection in the 1ry circuit
- Rapid reactor shutdown
- Secure flow coast down of 1ry circuit

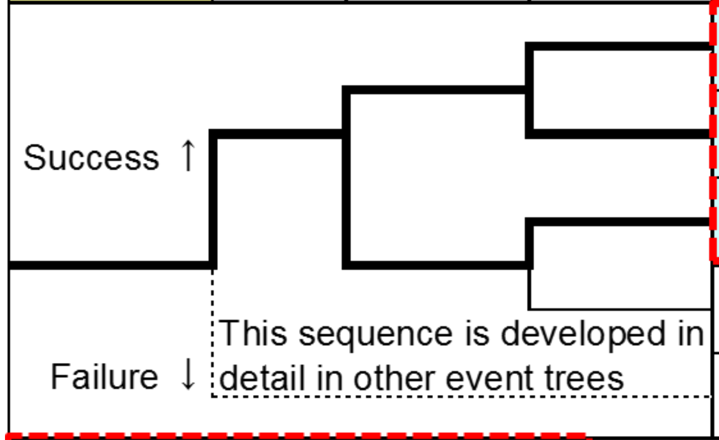
Long-term loss of forced convection in the 1ry circuit
- Adequate margin to fuel failure temp.
- *Heat transfer by passive measure (DHRS) (natural convection and battery-operated air-cooler dampers)*

Leakage of coolant in the 1ry circuit (pipe break)
- Layout of piping (high position to maintain reactor level)
- Localization and isolation of leaking Na (GV & double wall piping)

Loss of ultimate heat sink (e.g., 2ry circuit, water /steam system)
- Rapid reactor shutdown
- *Automatic actuation of DHRS (natural convection and battery-operated air-cooler dampers)*

Partial loss of DHRS functionality (e.g., DHRS leakage)
- *Functional redundancy of DHRS*

- ✓ Scenarios analyzed by DPA was "identified by PSA", in advance of DPA
- ✓ PSA, based on event tree model, gives "Success" or "failure within 24hours"

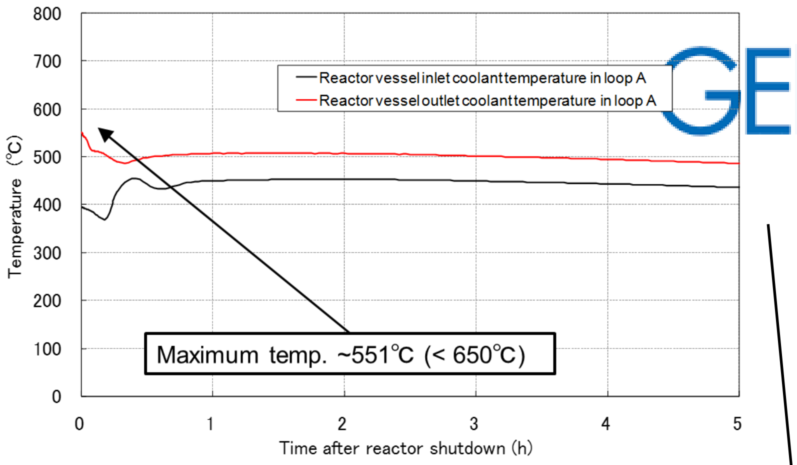


Loss of circulation capability in PRACS-B	Reactor SCRAM	Passive cooling by using PRACS-A *	Passive cooling by using DRACS *	Seq. No.	Accident sequence	Core integrity
IC07-B	RS	ANC	DNC			
				1	/RS*/ANC*/DNC (Successful DBA scenario)	**Should be OK** (1)
				2	/RS*/ANC*DNC (Passive cooling by using PRACS-A alone)	**Unknown** (1)
				3	/RS*ANC*/DNC (Passive cooling by using DRACS alone)	**Unknown** (1)
				4	/RS*ANC*DNC (Loss of all heat sink)	Damage
				5	-	-

(1) Need to be confirmed by DPA

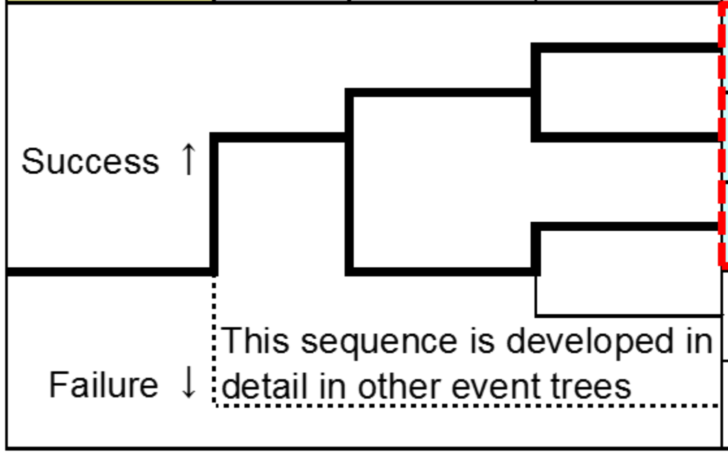
**PLOHS: Protected Loss Of Heat Sink. Insufficient heat removal capacity event included.*

DPA of Sequence No.1
(identified by PSA)

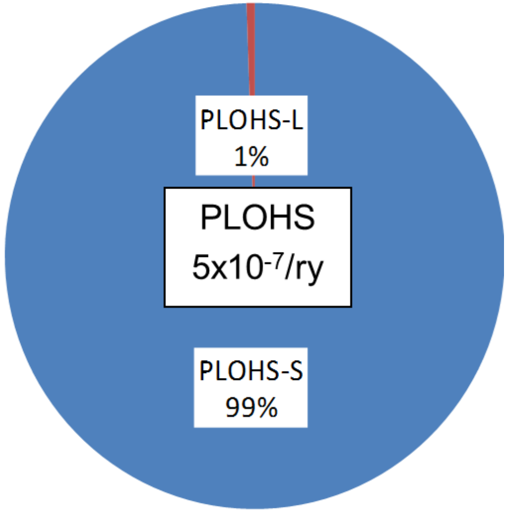


Maximum temp. ~551℃ (< 650℃)

- The DPA results are “input (returned) to “PSA”;

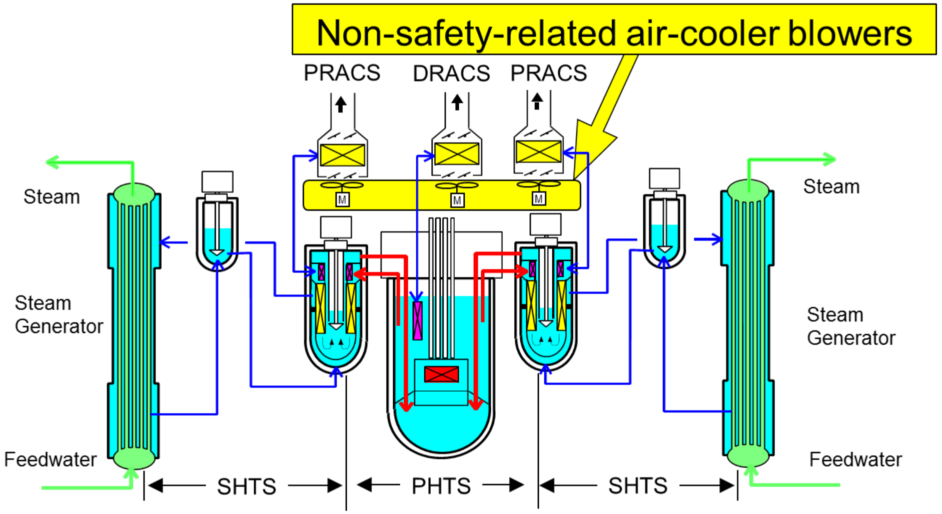
Loss of circulation capability in PRACS-B	Reactor SCRAM	Passive cooling by using PRACS-A *	Passive cooling by using DRACS *	Seq. No.	Accident sequence	Core integrity
IC07-B	RS	ANC	DNC			
				1	/RS*/ANC*/DNC (Successful DBA scenario)	OK$^{(1)}$
				2	/RS*/ANC*DNC (Passive cooling by using PRACS-A alone)	Damaged$^{(2)}$
				3	/RS*ANC*/DNC (Passive cooling by using DRACS alone)	Damaged$^{(2)}$
				4	/RS*ANC*DNC (Loss of all heat sink)	Damage
				5	-	-

PSA result
Initial design

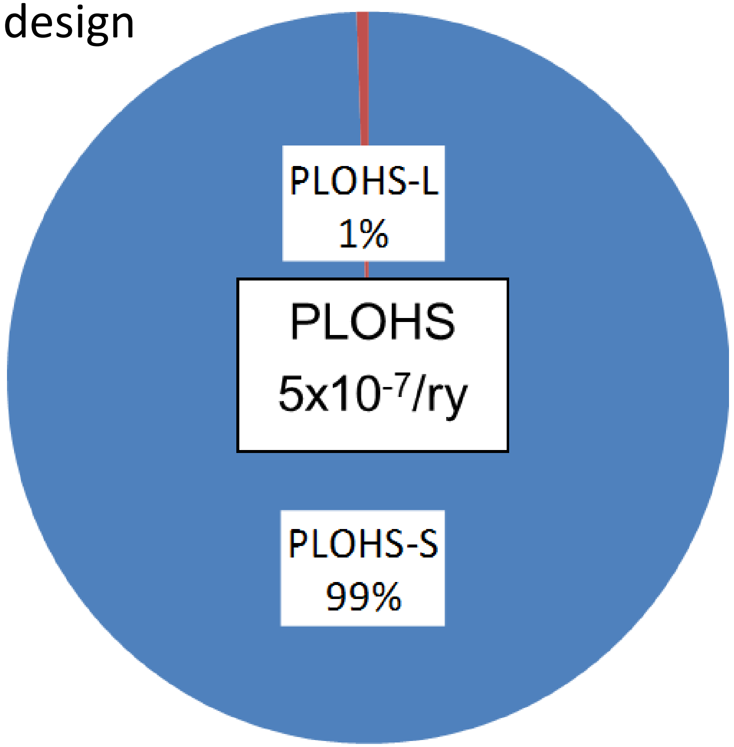


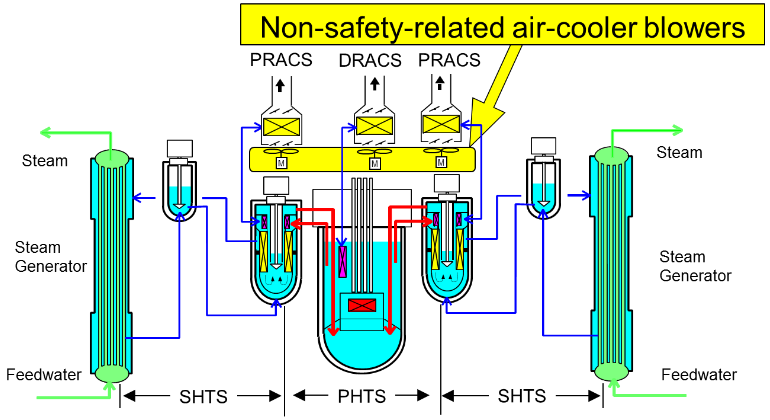
PLOHS-S:
PLOHS sequences that occurs <u>within 24hours after reactor shutdown</u>
PLOHS-L:
PLOHS sequences that occurs <u>after successful decay heat removal during 24hours and within the mission time of 1month</u>

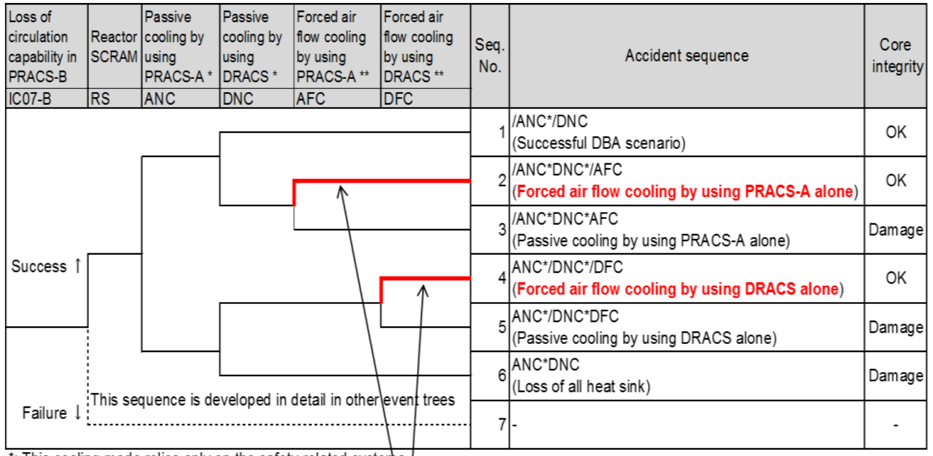
- Option for risk reduction
  Enhance heat removal capacity of a single train of DHRS within 24 hours



Initial design







Loss of circulation capability in PRACS-B IC07-B	Reactor SCRAM RS	Passive cooling by using PRACS-A * ANC	Passive cooling by using DRACS * DNC	Forced air flow cooling by using PRACS-A ** AFC	Forced air flow cooling by using DRACS ** DFC	Seq. No.	Accident sequence	Core integrity
						1	/ANC*/DNC (Successful DBA scenario)	OK
						2	/ANC*DNC*/AFC (**Forced air flow cooling by using PRACS-A alone**)	OK
						3	/ANC*DNC*AFC (Passive cooling by using PRACS-A alone)	Damage
						4	ANC*/DNC*/DFC (**Forced air flow cooling by using DRACS alone**)	OK
						5	ANC*/DNC*DFC (Passive cooling by using DRACS alone)	Damage
						6	ANC*DNC (Loss of all heat sink)	Damage
						7	-	-

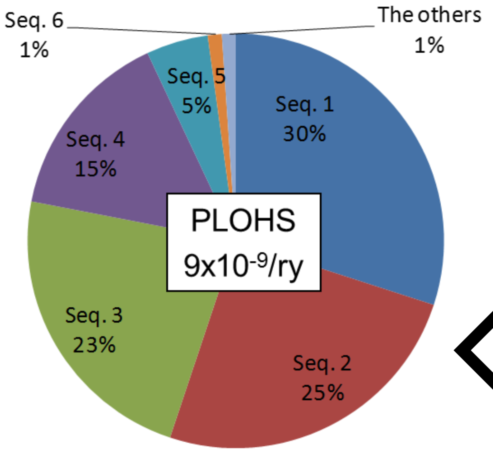
*; This cooling mode relies only on the safety-related systems.

**; This cooling mode relies not only on the safety-related systems but also on automatic actuation of the non-safety-related systems (i.e., air blower, electric power systems).

Additional success path

Improved design

1/50!!



9×10^{-9} /ry

Summary

- RSWG aims to enhance safety through advanced technologies and the early application of a improved safety philosophy
- Full, systematic implementation of defence-in-depth (safety should be built-in, not added-on)
- No new tools but a systematic methodology for a robust demonstration
- ISAM to support safety assessments

Ongoing RSWG activities

- Update Basis of Safety Approach for Gen-IV systems
- RSWG reports (with contributions from SSCs) to date:
  - White Papers on pilot application of ISAM
    - Demonstrate applicability of ISAM as a self-assessment for each of the six Gen-IV systems
    - Provide guidance on improving safety features based on the ISAM approach
  - Safety Assessment Reports for six Gen-IV systems
    - Snapshot of high-level safety design attributes, challenges and remaining R&D needs
  - Contributions to SFR, LFR, GFR, SCWR and VHTR safety design criteria

***RSWG web page** https://www.gen-4.org/gif/jcms/c_9366/risk-safety*

Upcoming webinars

20 March 2019	The Allegro Experimental Gas Cooled Fast Reactor Project	Dr. Ladislav Belovsky, UJV Rez, A.s., Czech Republic
15 April 2019	European Sodium Fast Reactor: An Introduction	Dr. Konstantin Mikityuk, PSI, Switzerland
22 May 2019	Formulation of alternative cement matrix for solidification/stabilization of nuclear waste	Mr. Matthieu de Campos, CEA, France