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Implementation of new safety requirements in post-Fukushima period (including LTO considerations)

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CONTENT OF THE PRESENTATION

Interpretation of selected issues associated with implementation of updated IAEA Safety Standards, in particular

1) consideration of all NPP states in the design envelope
2) reinforcement of the independence between levels of defence in depth
3) robustness of certain safety items against external hazards more severe than those included in the design basis
4) use of non-permanent (mobile) equipment in the design
5) practical elimination of early or large radioactive releases
6) trends in deterministic safety analysis

Conclusions

BACKGROUND

- After Fukushima Daiichi accident the international (IAEA) safety standards have been significantly enhanced
- Development in IAEA safety standards has been reflected in national regulations and best practices
- Formally the new requirements are directly applicable only for new NPPs, but through the PSR mechanism they apply also to existing NPPs as far as reasonably achievable
- More stringent requirements address all stages of NPP life and associated activities, including design and its safety demonstration
- While for new NPPs the application of new requirements is straight forward, for existing NPPs it may be connected with difficulties
- Continuous safety improvements in line with updated safety standards and national regulations is an essential component for acceptance of LTO for existing plants
- It is reasonable to address these issues in a coordinated and consistent manner

Deterministic safety analysis of all plant states

SIGNIFICANT CHANGES IN THE IAEA SAFETY GUIDE SSG-2 (REV.1) ON DETERMINISTIC SAFETY ANALYSIS FOR NPPS

- Coverage of **all plant states, from normal operation up to severe accidents, reflecting importance of independence between levels of defence**
- **More attention to evaluation of uncertainties** in deterministic safety analysis: sensitivity analysis or quantification of uncertainties
- Extending the scope of deterministic analysis by **including best estimate analysis of normal operation and anticipated operational occurrences**
- Extending the scope of **licensing type best estimate analysis for design extension conditions including severe accidents** (different from previous approach which was focused on support for accident management)
- Guidance for **demonstration of practical elimination of early and large releases**
- Guidance for performing **independent verification of safety analysis by operating organization**

PLANT STATES & DESIGN BASIS

Earlier Concept

Design basis | **Beyond Design basis (Accident Management)**

Operational States		Accident Conditions		
NO	(AOO) AO	DBAs (safety systems)	BDBA	Severe Accidents **(core melt)**

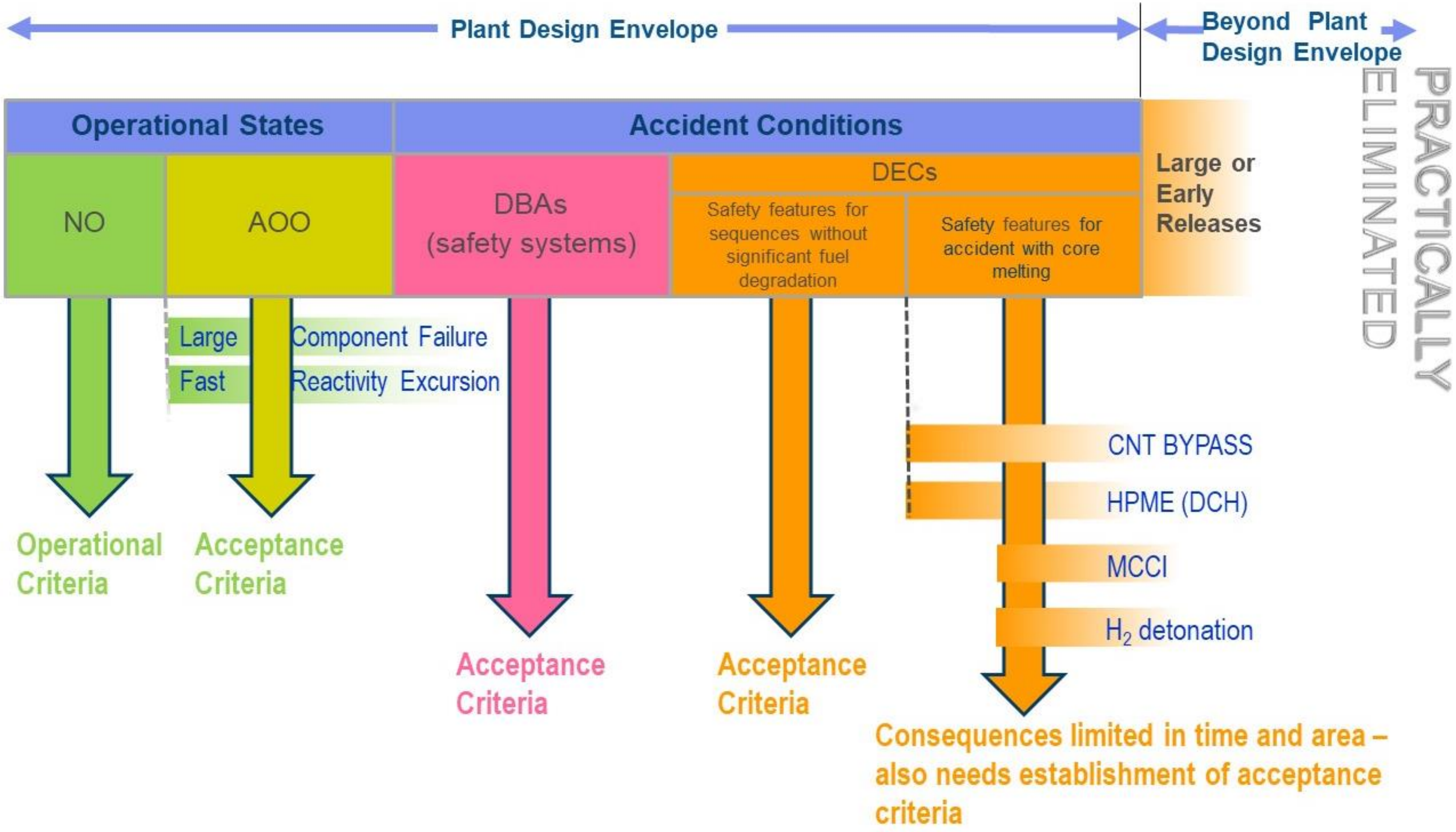
SSR-2/1 (Rev.1), 2016

General design basis
Plant design envelope)

Beyond Design basis

Operational States		Accident Conditions			
NO	AO	DBAs (safety systems)	DECs: No core melt (Optional safety features)	DECs: Safety features for SAs	Conditions **practically eliminated**

SCOPE OF SAFETY ANALYSIS



SAFETY MARGINS AND CLIFF-EDGE EFFECTS

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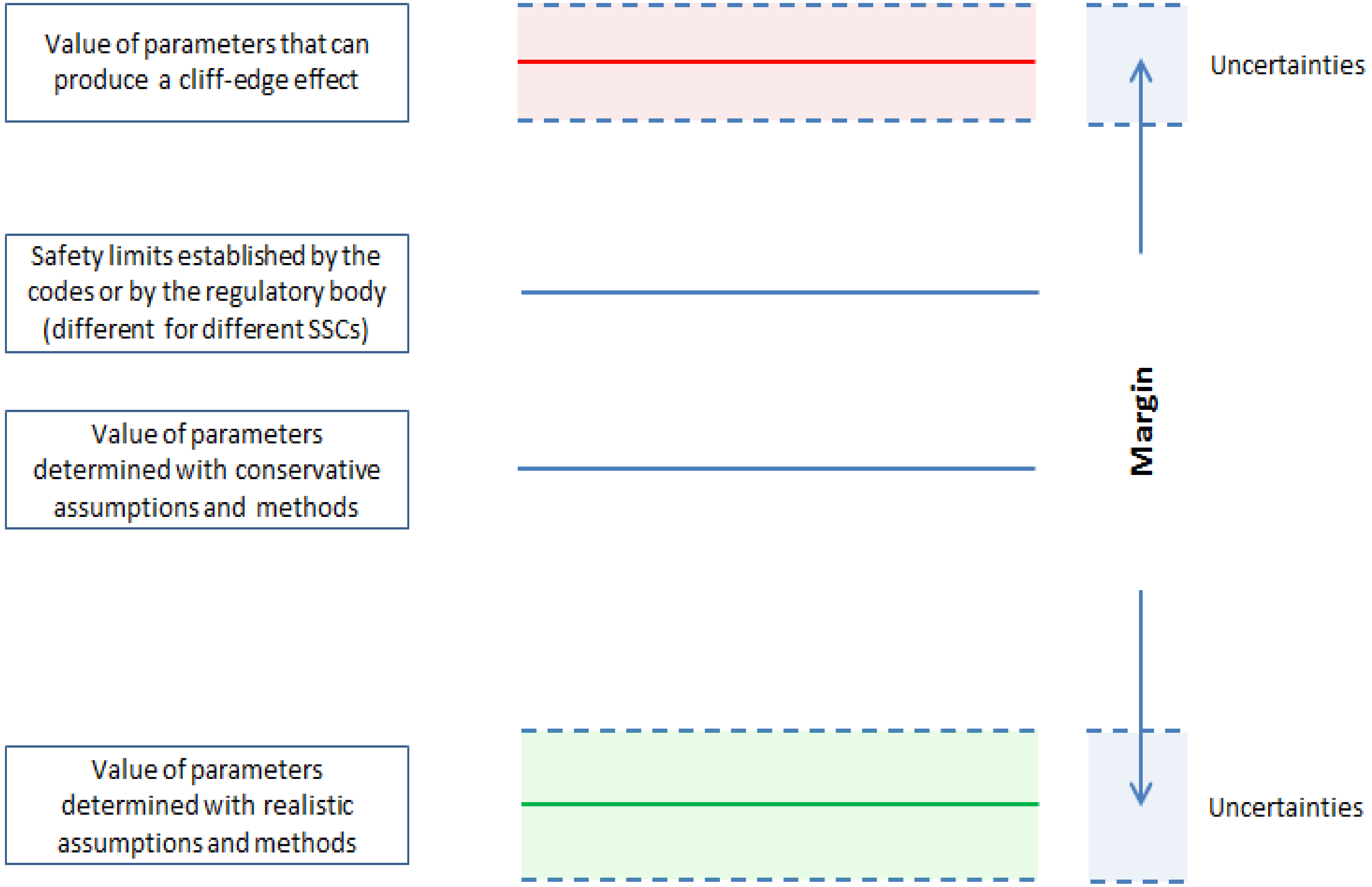
- Cliff edge effect implies high consequences following a small deviation in a “parameter”; typical cliff edge effect is a failure of a physical barrier or the occurrence of a large release
- Cliff-edge effects are prevented by sufficient margins
- Margins have to be maintained and cliff-edges prevented for all plant states



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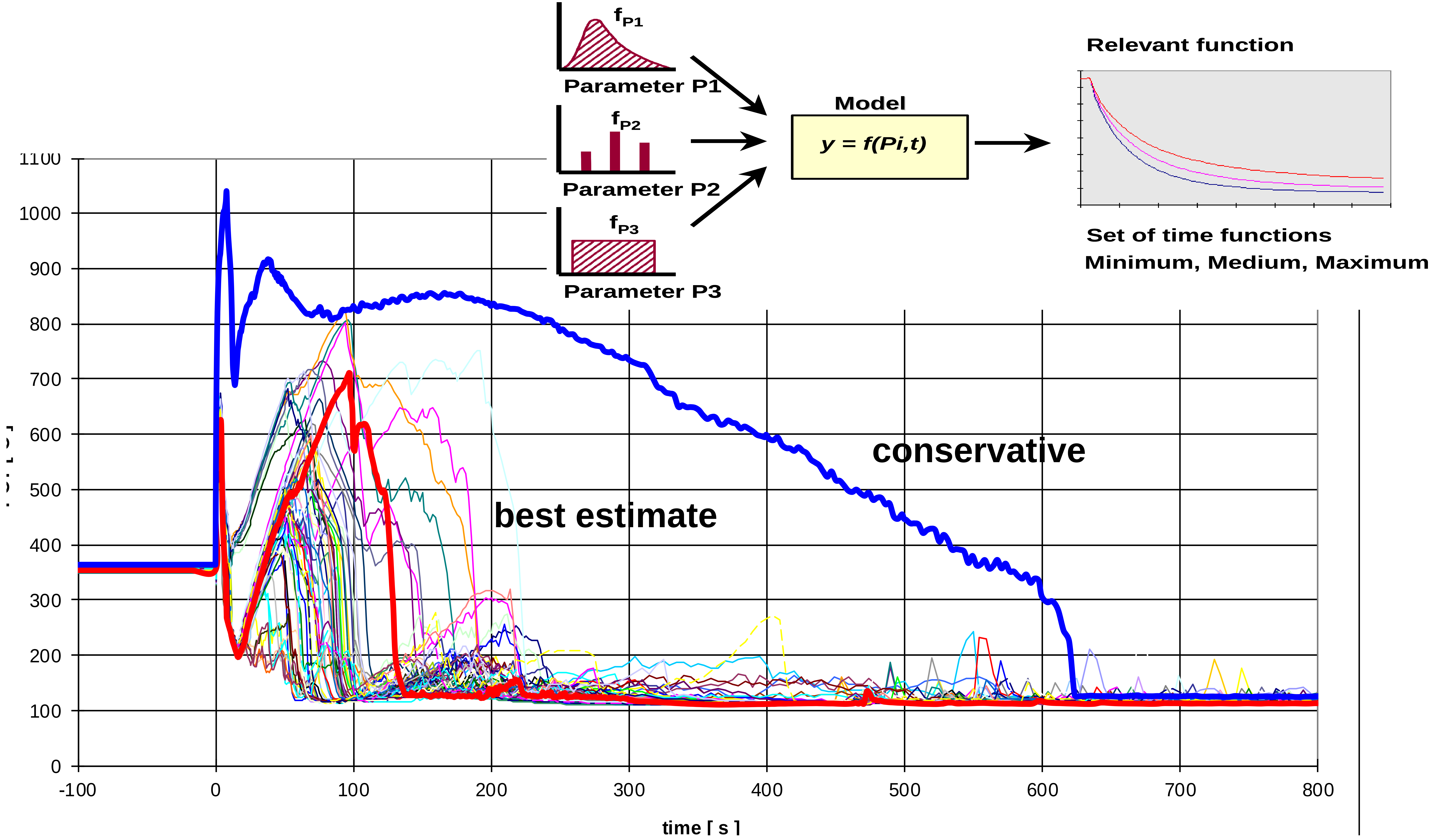
OPTIONS FOR COMBINATIONS OF COMPUTER CODES AND INPUT DATA

Approachesc onsidered as conservative analysis

Option	Computer code type	Assumptions on systems availability	Type of initial and boundary conditions
Conservative	Conservative	Conservative	Conservative
Combined	Best estimate	Conservative	Conservative
Best estimate plus uncertainties (BEPU)	Best estimate	Conservative	Best estimate; partly most unfavourable conditions
Realistic	Best estimate	Best estimate	Best estimate

TYPICAL COMPARISON OF CONSERVATIVE AND BEST-ESTIMATE LB LOCA ANALYSIS (VVER 1000)



OVERVIEW OF LEVEL OF CONSERVATISMS FOR DIFFERENT PLANT STATES

Plant state	Conservatism		Operator actions
	Code	Plant parameters & System performances	
Normal operation	BE	Conservative	BE
AOO (realistic)	BE	BE	BE
DBA + AOO (conservative)	BE*	Conservative	30 minutes
	BE + uncertainties	BE + uncertainties	30 minutes
DEC w/o significant fuel degradation	BE*	Conservative	30 minutes
	BE + uncertainties	BE + uncertainties	30 minutes
	BE*	BE**	BE
DEC w/ core melt	BE*	Conservative	>30 minutes
	BE*	BE**	BE

- BE*: sensitivities have to prove conservatism
- BE**: sensitivities needed to show no cliff-edge effect

OVERVIEW OF ANALYSIS RULES: SYSTEMS CREDITED FOR DIFFERENT PLANT STATES

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Plant state	Systems credited in the analysis			SFC	Mainte-nance (if allowed)
	Control & Limitation	Safety	DEC		
Normal operation	Operating	Not activated	Not activated	No	Yes
AOO (realistic)	Operating	Not activated	Not activated	No	No
DBA + AOO (conservative)	Fail	Yes	Not activated	Yes	Yes
DEC w/o significant fuel degradation	Fail	Yes if not affected by sequence	Yes	No	Possibly no
DEC with core melt	Fail	No except if fully independent from sequence	Yes except if not fully independent from sequence	No	Possibly no

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Independence between different levels of defense

INDEPENDENCE BETWEEN DIFFERENT LEVELS OF DEFENSE

- Objective of independence is to ensure that the **failure of one level should not cause the failure of the subsequent levels**
- This is achieved by **incorporating design features such as redundancy, separation and diversity (prevention of common cause failures)**
- **Defense in depth levels cannot be fully independent**: e.g. sharing of some structures, systems and components (control room, containment, control rods), the operators and the impact of hazards, among other factors
- Independence of the levels of defence in depth needs be understood as the **degree of independence to be the highest possible**.
- There is the need of **effective independence, in particular between levels 3 and 4**
- **Safety systems and safety features for design extension conditions at multiunit sites required separately for each unit**
- **Robustness of levels of defence should be demonstrated by safety analysis**

EXAMPLES OF WEAKENED INDEPENDENCE OF LEVELS OF DEFENCE

- Normal operation systems used for spent fuel pool cooling performing function of emergency injection in case of accidents
- Use of the pressurizer relief or safety valves both for design basis accidents as well as in severe accidents
- Absence of dedicated containment heat removal system for severe accidents
- Use of the same pathway for residual heat removal to the ultimate heat sink (e.g. essential service water cooling system) from both safety systems as well as from safety features for design extension conditions
- Use of the same sensors for initiation of actions of both safety systems as well as safety features for design extension conditions

ROBUSTNESS AGAINST EXTERNAL HAZARDS

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IAEA REQUIREMENTS ON ADEQUATE MARGINS FOR EXTERNAL HAZARDS

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SSR-2/1, Rev. 1 (IAEA,2016), Para. 5.21a : “The design of the plant shall provide for an adequate margin to protect items ultimately necessary to prevent large or early radioactive releases in the event of levels of natural hazards exceeding those to be considered for design taking into account the site hazard evaluation”.

- Items ultimately necessary to prevent early or large release include at least:
  - Containment (and spent fuel pool) structure
  - Systems necessary to contain the molten core and to remove heat from the containment and transfer heat to the ultimate heat sink in severe accident conditions
  - Systems to prevent hydrogen detonations
  - Alternative power supply (alternative to the emergency power supply)
  - Supporting systems to allow the functionality of the systems above
  - Control room (habitability)
- The design of these items is expected to be particularly robust and to include margins to withstand loads and conditions generated by natural external hazards exceeding those derived from the site evaluation; this implies that cliff edge effects should not occur not only for small variations but also for significant variations of the loads and conditions.

DESIGN FOR EXTERNAL HAZARDS

Design options for natural external hazards exceeding the design bases (the approach to be followed will depend on the nature of the hazard and the function of the systems, structures and components and has to be decided by the designer and the safety authority).

1.To adopt a higher value of the design basis event for the systems, structures and components

2.To demonstrate, following a best estimate approach, with high level of confidence **that values of parameters for which cliff edge effects would occur are not reached because of adequate design margin.**

Example: The capacity to withstand a 50% exceedance of design basis earthquake is considered for larger margins that are required for the equipment ultimately necessary to prevent large or early releases.

Use of non-permanent equipment

USE OF NON-PERMANENT EQUIPMENT

- IAEA Safety Requirements for design require implementing design **provisions to enable the connection of some types of non-permanent equipmen**t in a smooth and safe manner (for situations exceeding the design basis).
- Sufficiently robust, fixed connecting points located on easy accessible places should be installed, but the equipment considered in the design for coping design extension conditions should be permanently installed.
- **What is not permanent is not part of the design, it is part of operational provisions – accident management (?)**
- Not permanent sources remain as essential parts of operating provisions for safety, it means parts of the accident management

USE OF NON-PERMANENT EQUIPMENT

Quick connecting points

+

Mobile DG (0.32 MW);

Mobile DG (2,0 MW)

?

Stable SBO DG (3,2 MW)

Implementation of the concept of practical elimination of early or large radioactive releases

REQUIREMENTS ON PRACTICAL ELIMINATION

- **IAEA Safety Requirements for design SSR-2/1 Rev. 1**
  - para. 2.11 :“plant event sequences that could result in high radiation doses or in a large radioactive release have to be ‘practically eliminated”.
  - Practical elimination of early or large releases by design provisions is strictly required by Req. 5, para 4.3, Req. 20, para 5.27 and 5.31
- **EU Council Directive 2014/87/EURATOM of 8 July 2014 on nuclear safety and WENRA Safety Objectives for New Nuclear Power Plants include similar requirements**
- **IAEA TECDOC-1791 and draft of one of safety guides**
  - provides certain guidance how to demonstrate practical elimination of early and large releases; this guidance was used as a basis for the approach described in this presentation

STEPS FOR DEMONSTRATION OF PRACTICAL ELIMINATION

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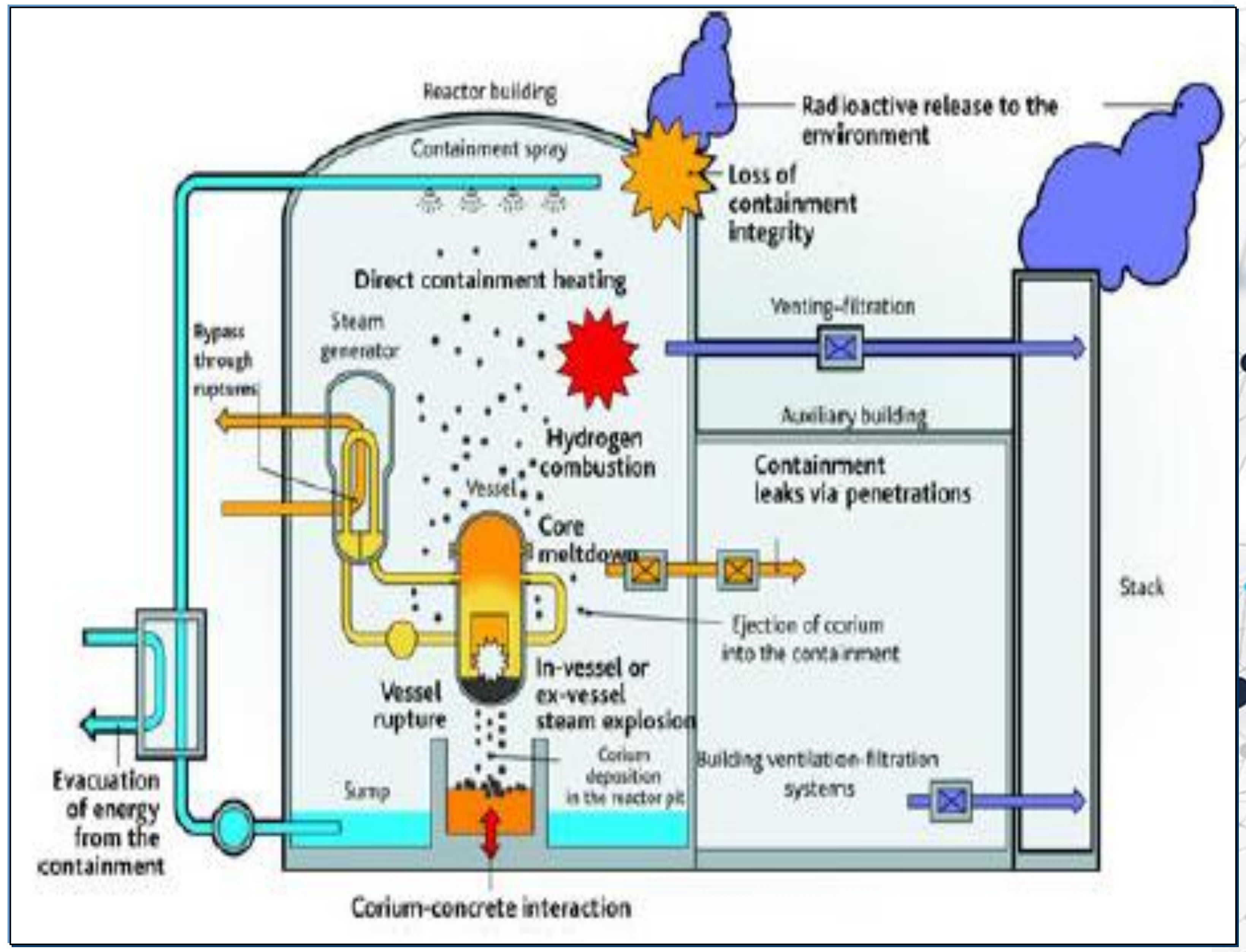
- **Steps towards practical elimination:**
  - **1st step: identification of the conditions (challenges) to be practically eliminated**
  - **2nd step: whenever possible, demonstration of practical elimination based on physical impossibility** (e.g. insufficient hydrogen/oxygen concentration, intrinsic safety coefficients, etc.)
  - **3rd step: identification and implementation of design provisions for prevention of the challenges**
  - **4th step: identification and implementation of operational provisions (procedures) for prevention of the challenges**
  - **5th step: deterministic safety analysis and engineering judgment of effectiveness of the provisions**
  - **6th step: whenever appropriate, probabilistic safety analysis showing very low probability of failure of provisions**
- **A frequency value of about 1x 10^{-7} per reactor year for each of the conditions identified is acceptably low for the concept**

CONDITIONS TO BE PRACTICALLY ELIMINATED

1. **Events that could lead to prompt reactor core damage and consequent early containment failure**
   a. Failure of a large component in the reactor coolant system
   b. Uncontrolled reactivity accidents

2. **Severe accident phenomena which could lead to early containment failure:**
   a. Direct containment heating
   b. Large steam explosion
   c. Explosion of combustible gases, including H2 or CO

3. **Severe accident phenomena which could lead to late containment failure:.**
   a. Basemat penetration or containment by-pass due to molten core concrete interaction (MCCI)
   b. Long term loss of containment heat removal
   c. Explosion of combustible gases, including H2 or CO



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CONDITIONS TO BE PRACTICALLY ELIMINATED

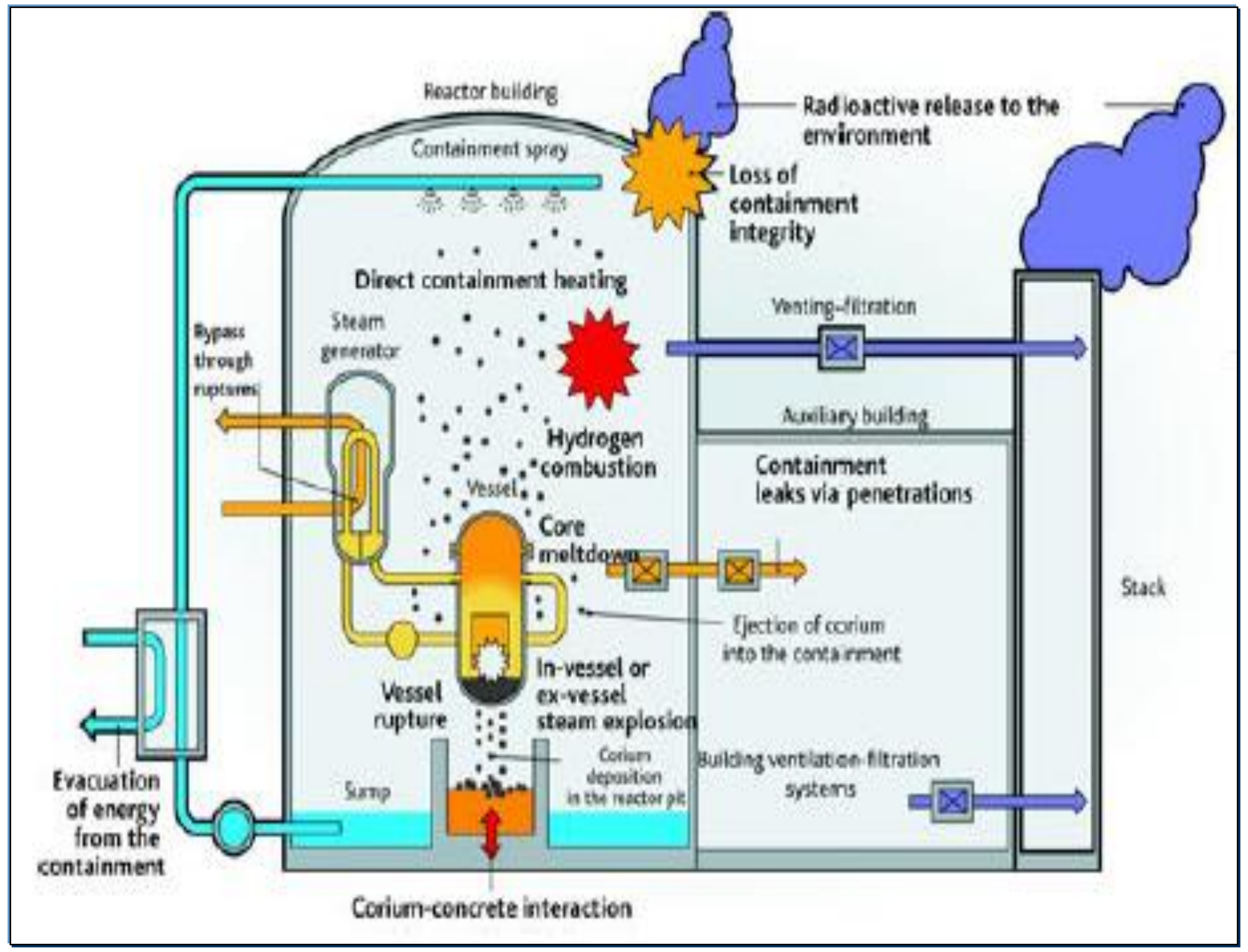
4. Severe accident with containment by-pass

a) Loss of coolant accident with the potential to drive the leakage outside of the containment via supporting systems (interface system-LOCAs).

b) Containment bypass consequential to severe accident progression (e.g. induced steam generator tube rupture);

c) Severe accident in which the containment is open (e.g. shutdown state).

5. Significant fuel degradation in a storage pool and uncontrolled releases



DEMONSTRATION OF PRACTICAL ELIMINATION – EXAMPLES OF DESIGN AND OPERATIONAL MEASURES

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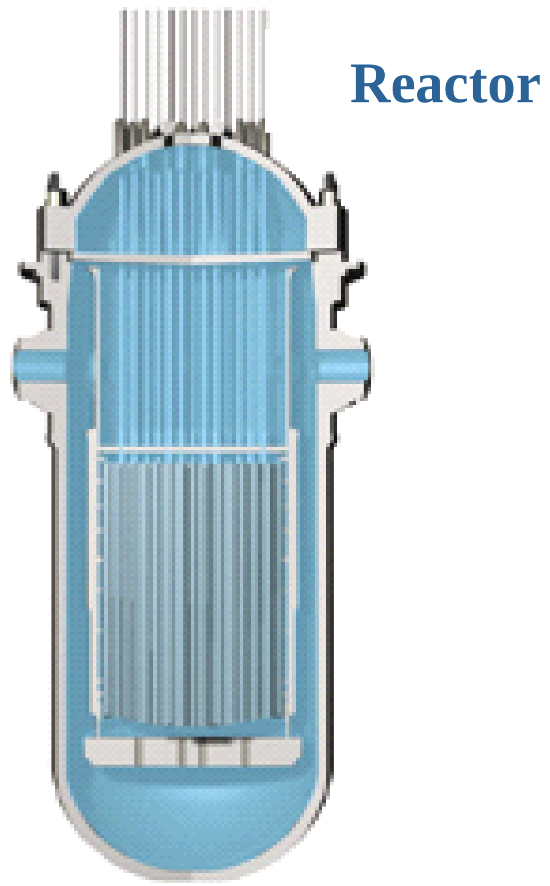
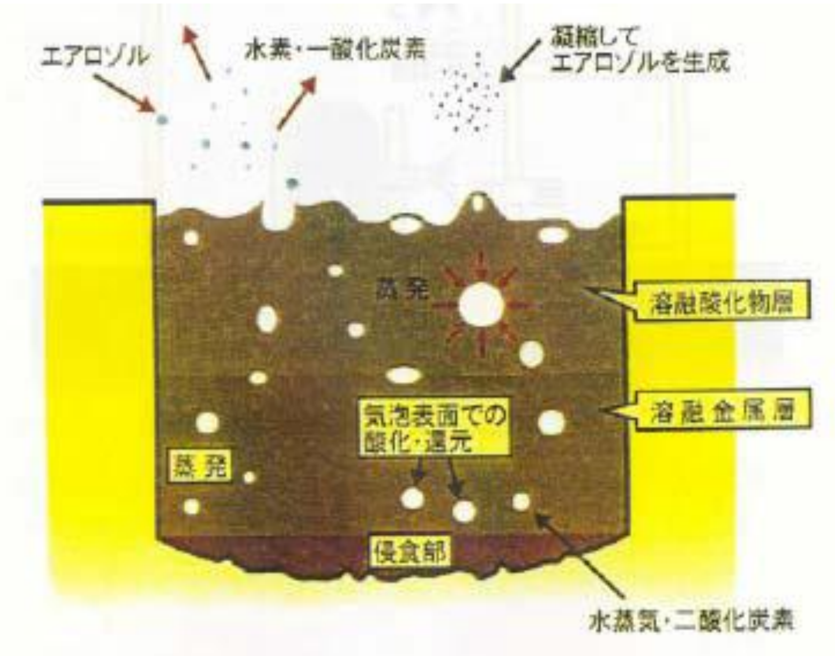
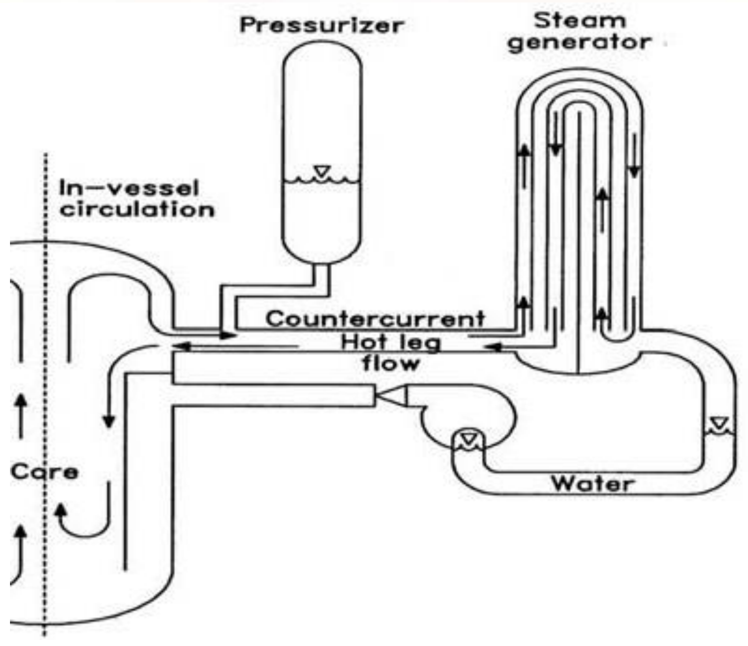
- **Example: Reactor pressure vessel rupture**
  - the most suitable composition of materials selected;
  - the metal component or structure as defect-free as possible;
  - the metal component or structure tolerant of defects.;
  - the mechanisms of growth of defects known
  - design provisions and suitable operation practices in place to minimize thermal fatigue, stress corrosion, embrittlement, pressurized thermal shock, overpressurization, etc.
  - an effective in service inspection and surveillance programme in place during the manufacturing and the operation
- **Example: Containment boundary melt-through**
  - Stabilization of the core inside the vessel (In-Vessel Retention) or outside the vessel (core catcher) to prevent the corium reaching the containment wall
- **Example: Containment by-pass through the steam generator in combination with a severe accident**
  - Reliable isolation of the steam generator secondary side
  - Rapid depressurization of the primary circuit
  - Ensuring steam generator tubes flooded by secondary coolant







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DEMONSTRATION OF PRACTICAL ELIMINATION – EXAMPLES OF DESIGN AND OPERATIONAL MEASURES

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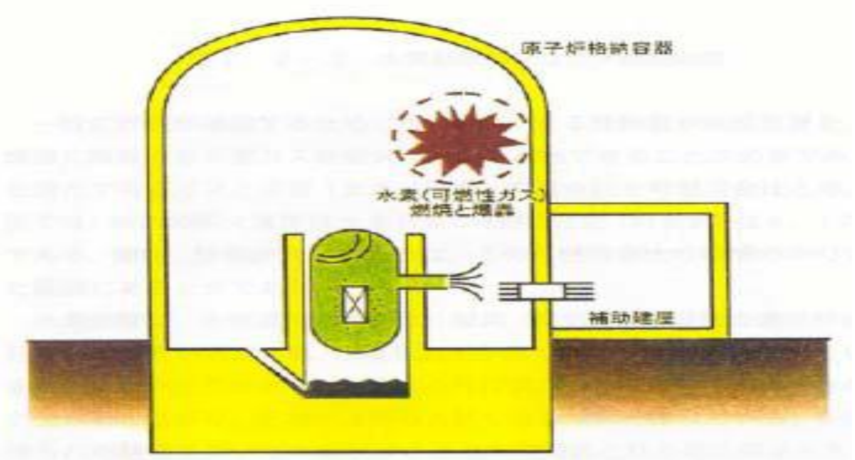
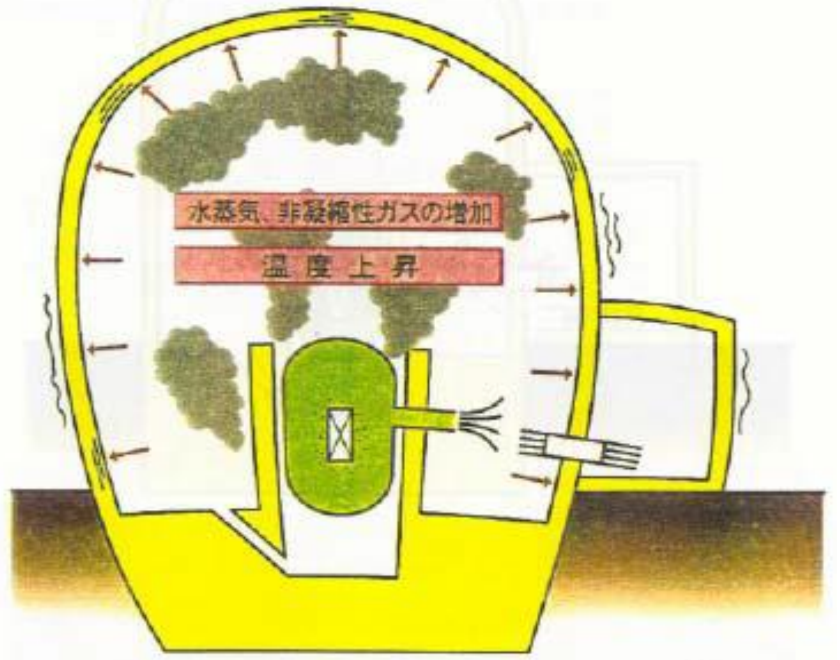
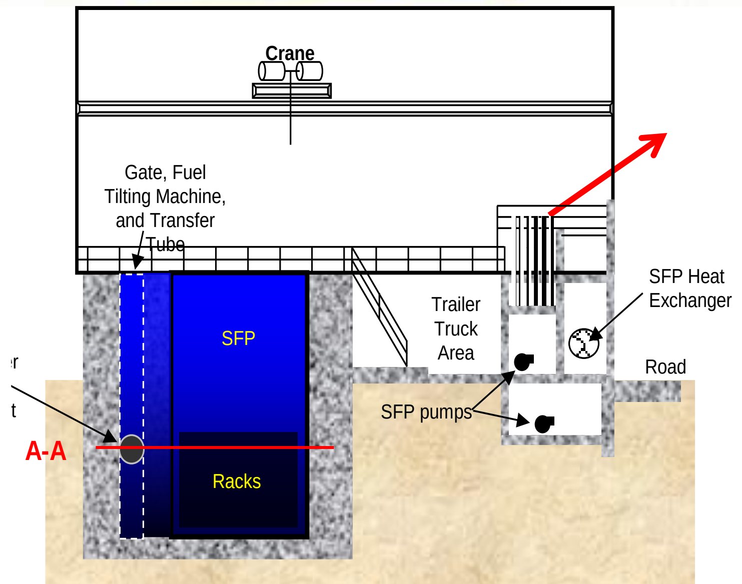
- **Example: Hydrogen detonation**
  - Measures: large containment volume, inert atmosphere, provisions for good mixing, adequate number and design of recombiners or igniters, etc.
- **Example: High pressure core melt conditions**
  - Reliable means to ensure opening of depressurization valves of the reactor coolant system, a diverse system to depressurize the system
- **Example: Slow overpressurization of containment**
  - Large thermal capacity of the containment
  - Enhancement of containment heat removal systems
  - Dedicated containment spray/ heat removal systems
  - Containment filtered venting
- **Example: Significant fuel degradation in storage pool**
  - Robust pool structure designed against all hazards
  - Avoiding siphoning of water out of the pool
  - Redundant lines for pool cooling
  - Reliable instrumentation for pool level monitoring.
  - Additional means to compensate any loses of coolant







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What could be the main directions for further enhancements of deterministic safety analyses?

HARMONIZATION OF APPROACHES FOR DEMONSTRATION OF PRACTICAL ELIMINATION OF EARLY OR LARGE RADIOACTIVE RELEASES

- IAEA Safety Requirements strictly require ensuring and demonstrating these capabilities in the NPP design (as a new requirement)
- Demonstration is required to be included in the plant SAR
- New NPP design already have many design provisions necessary for practical elimination
- However, no existing SARs (including new ones) explicitly cover these capabilities
- SSG-2 provides some insights how to support practical elimination by DSA as an important component for demonstration
- However, ensuring practical elimination is more complex task than just DSA, it requires implementation of design provisions, operational provisions, using engineering judgment, DSA and PSA
- There are certain ideas how to cover comprehensively the whole issue
- These is a need for establishing broader international consensus on the acceptable ways
- The solution can become even more important for SMRs, since without that it will be difficult to facilitate licensing of these plants

HARMONIZATION OF APPROACHES FOR SAFETY ANALYSES OF RADIOLOGICAL CONSEQUENCES OF REACTOR ACCIDENTS

- Radiological consequences represent the direct measure of the level of safety, are publicly sensitive and thus influencing public trust, have trans-boundary effects and implications, are cross-cutting elements contained in several documents of the safety case
- Basic rules used for the analysis of consequences should be consistent with general rules for other kinds of safety analysis (e.g. conservative versus best estimate)
- Existing guidance documents are much less elaborated and less consistent compared to traditional thermal-hydraulic analyses
- Thermal-hydraulic and radioactivity transport are closely coupled, but analyses frequently performed by different group of experts, resulting in calculational decoupling between the processes
- The current approaches used in different countries differ, including acceptance criteria
- International harmonization of approaches to determination of radiological consequences is needed

INTEGRATION OF NEUTRONIC, THERMAL-HYDRAULIC AND STRUCTURAL ANALYSES

- Historically, due to limited capabilities of the computer, these aspects were analysed by separate computer codes
- The same problem exists for radiological consequence analysis, addressed separately
- It is still the frequent case, that analysis by one code provides an input for other codes
- In this approach, the feedback between the different phenomena is lost (neutronic, t-h and structural aspects are interlinked)
- There are already capabilities to address all relevant aspects using coupling the computer codes
- Further developments/improvements are envisaged in this area

ROUTINE USE OF QUANTIFICATION OF UNCERTAINTIES AT LEAST FOR ANTICIPATED OPERATIONAL OCCURRENCES AND DESIGN BASIS ACCIDENTS

- At present, many organisations prefer using BE codes with conservative parameter values, initial and boundary conditions
- Best estimate analysis with quantification of uncertainties offers much broader utilization of the results, not exclusively for licensing but at the same time for development of operating procedures etc.
- Uncertainty quantification provides reassurance that intentional conservatism was actually ensured
- Uncertainty evaluation provides also essential information for specification of parameters for conservative analysis
- Uncertainty evaluations considered in many cases as time consuming; there is a need to improve practicability of methods
- General trend in licensing calculations should be from fully conservative analysis to best estimate analysis with evaluation of uncertainties

ESTABLISHING CLEAR LINKS BETWEEN ANALYSIS OF INTERNAL AND EXTERNAL HAZARDS AND SAFETY ANALYSIS OF PLANT STATES

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- Safety analysis to be included in SAR should cover analysis of internal and external hazards
- Internal and external hazards represent a wide variety of events potentially affecting the safety of a NPP through many different mechanisms; the hazard analysis is therefore very complex
- Analysis of hazards consists of several components: functional analysis, propagation analysis, DSA, qualification analysis
- Propagation analysis is the most specific part of the hazard analysis
- There is a link between propagation analysis of hazards and deterministic safety analysis of plant states
- Results of analysis of hazards as well as of DSA provide inputs for the design of SSCs
- More specific guidance for systematic and consistent approach to safety analysis of all kinds of hazards would be helpful

BROADER USE OF CFD CODES FOR SAFETY ANALYSIS, COUPLING OF CFD AND SYSTEM CODES, ACCEPTANCE AND USE OF CFD CODES IN LICENSING

- For many applications, computational fluid dynamics codes (CFD) represent powerful tools
- Examples of their applications include prediction of CHF, mixing processes for reactivity accidents, PTS analyses, stratification of molten corium in severe accidents
- CFD codes are not accepted for licensing due to limited possibilities of their validation
- At present, lack of results from CFD codes is compensated by using experimentally based coefficients
- It may be expected that in the future, more confidence in CFD predictions will be achieved and CFD codes will become accepted tolls for safety analysis

COLLECTING AND SHARING EXPERIENCE IN SAFETY ANALYSIS OF SMALL MODULAR REACTORS

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- SMRs have many advantages but at the same time many disadvantages compared to large NPPs
- SMRs still represent very large radiological source of risk
- However, design of protective barriers can be significantly simpler compared to large NPPs
- There are large possibilities for practical elimination of accident sequences resulting in early or large radioactive releases
- Advantages of SMRs should be reflected in simplified licensing process; if licensing process for SMRs remains the same as for large NPPs, it would be very complicated to built any
- Still most probably, the economic advantages, if implemented for example by factory made NPPs could be determining the successful deployment of SMRs

FURTHER INTEGRATION OF DETERMINISTIC AND PROBABILISTIC SAFETY ANALYSIS

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- Specification of all possible scenarios (more complex than standard PSA, since in addition to failure of whole systems the failures of individual trains are considered)
- Performing BEPU analysis for each of the specified scenarios
- Determination of frequency of exceedance for each of the acceptance criteria (PCT, oxidation, number of failed elements, effective doses, etc)
- Calculation of overall frequency of exceedance for each individual criterion, taking into account probability of individual scenarios
- Overall frequency of exceedance represent a a newly defined safety margin for a given criterion

CONCLUSIONS

- Plants states to be explicitly considered in the design basis (design envelope) should include design extension conditions, covering both accidents without significant fuel damage as well as severe accident. In addition to safety systems, there shall be **special safety features for design extension conditions (preferably diverse) to cope with such accident conditions, implemented separately for each unit**

- In deterministic safety analysis, more attention should be paid to **demonstration of independence between levels of defence and independence between the units, demonstration of adequacy of design for design extension conditions , quantification of uncertainties, demonstration of practical elimination of early and large releases**

- **Independence between systems, structures and components** aimed to perform at different level of defence should be strengthened by limited sharing the systems between the levels and preventing common cause failures. In particular **independence between safety systems and safety features for design extension conditions are of special importance**, including I&C, auxiliary and support systems (such as electrical power supply, cooling systems) and other potential cross cutting systems.

CONCLUSIONS

- Items ultimately necessary to prevent large or early radioactive releases should be designed with **increased (adequate) margins against external natural hazards** to function even in the event of levels of hazards exceeding those to be considered in the design basis.
- The design should include sufficiently **robust, fixed points for connecting non-permanent (mobile sources)** should be installed on easy accessible places. Non-permanent sources preferably should not be considered as a part of the design, but they should remain an essential component of operational measures, belonging to accident management.
- Plant conditions that could result in **early or large radioactive releases have to be practically eliminated with demonstration included in the safety documentation.**
- **There are broad possibilities for further enhancements of deterministic safety analysis as an important component of safety demonstration, including existing plants for their long term operation**

Thank you for your attention

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