Seismic Design of the EPR™ Building Structures

Olkiluoto OL-3 NPP - © AREVA

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Technical Meeting on Seismic safety of NPP

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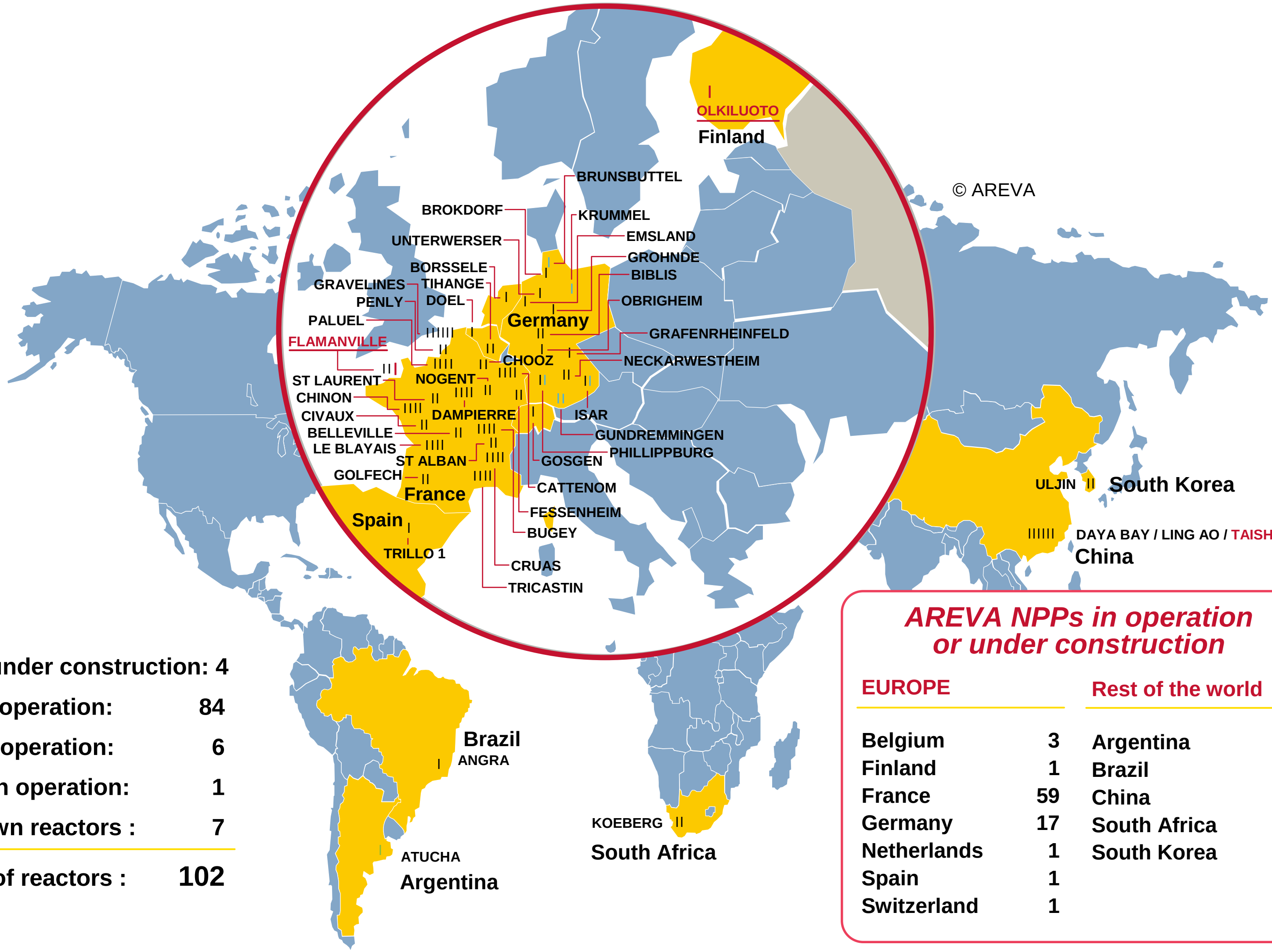
Contents

1. Presentation of the EPR™ Plant - AREVA NP's experience is based on the construction of 102 reactors worldwide

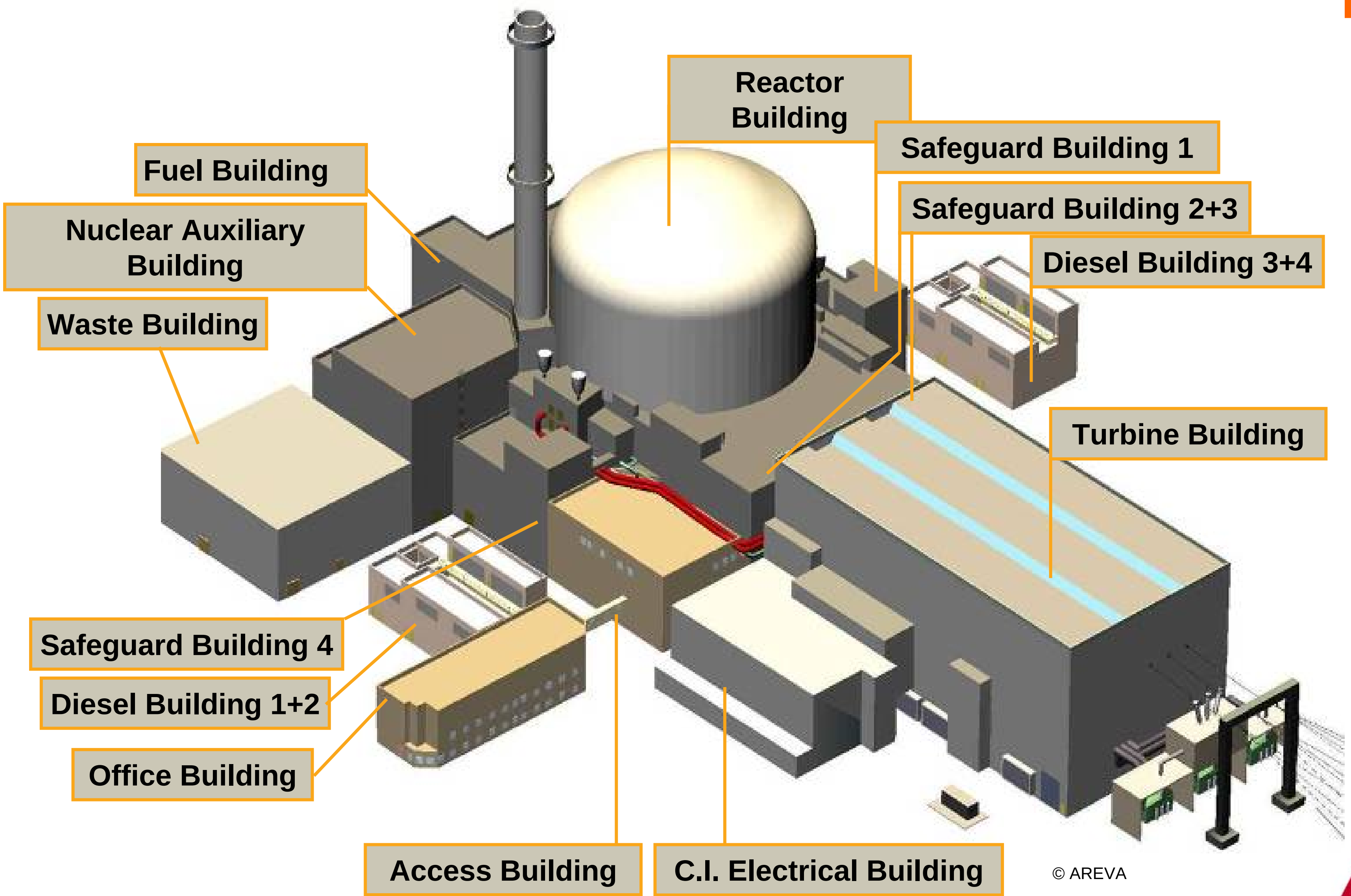


EPR™ under construction:	4
PWR in operation:	84
BWR in operation:	6
PHWR in operation:	1
Shutdown reactors :	7
Total # of reactors :	102

AREVA NPPs in operation or under construction

EUROPE		Rest of the world	
Belgium	3	Argentina	1
Finland	1	Brazil	1
France	59	China	6
Germany	17	South Africa	2
Netherlands	1	South Korea	2
Spain	1		
Switzerland	1		

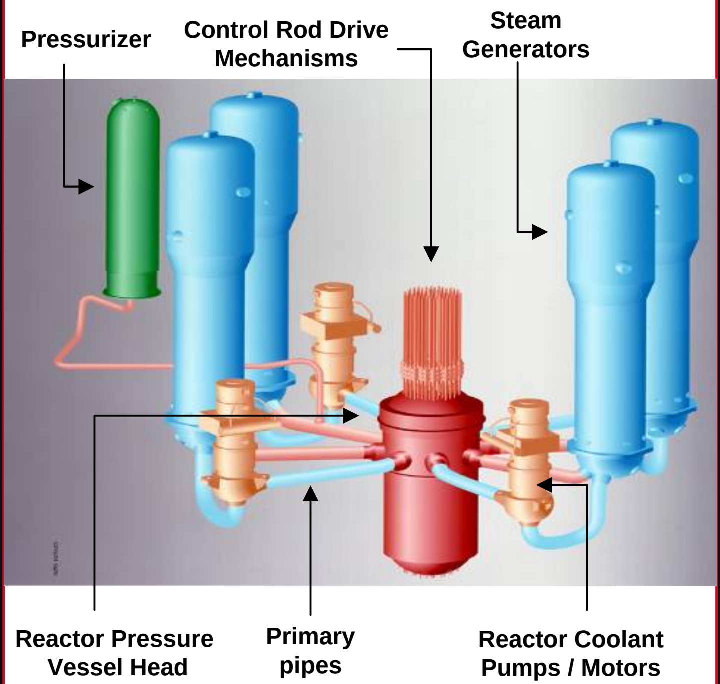
1. Presentation of the EPR™ Plant - Plot plan of the EPR™



1. Presentation of the EPR™ Plant - Reactor Building - Internal Structures and Main Systems and Components

Direct from AREVA's integrated plants

Integration of I&C for the Nuclear Island



Video – Duration = 3 min 45 sec

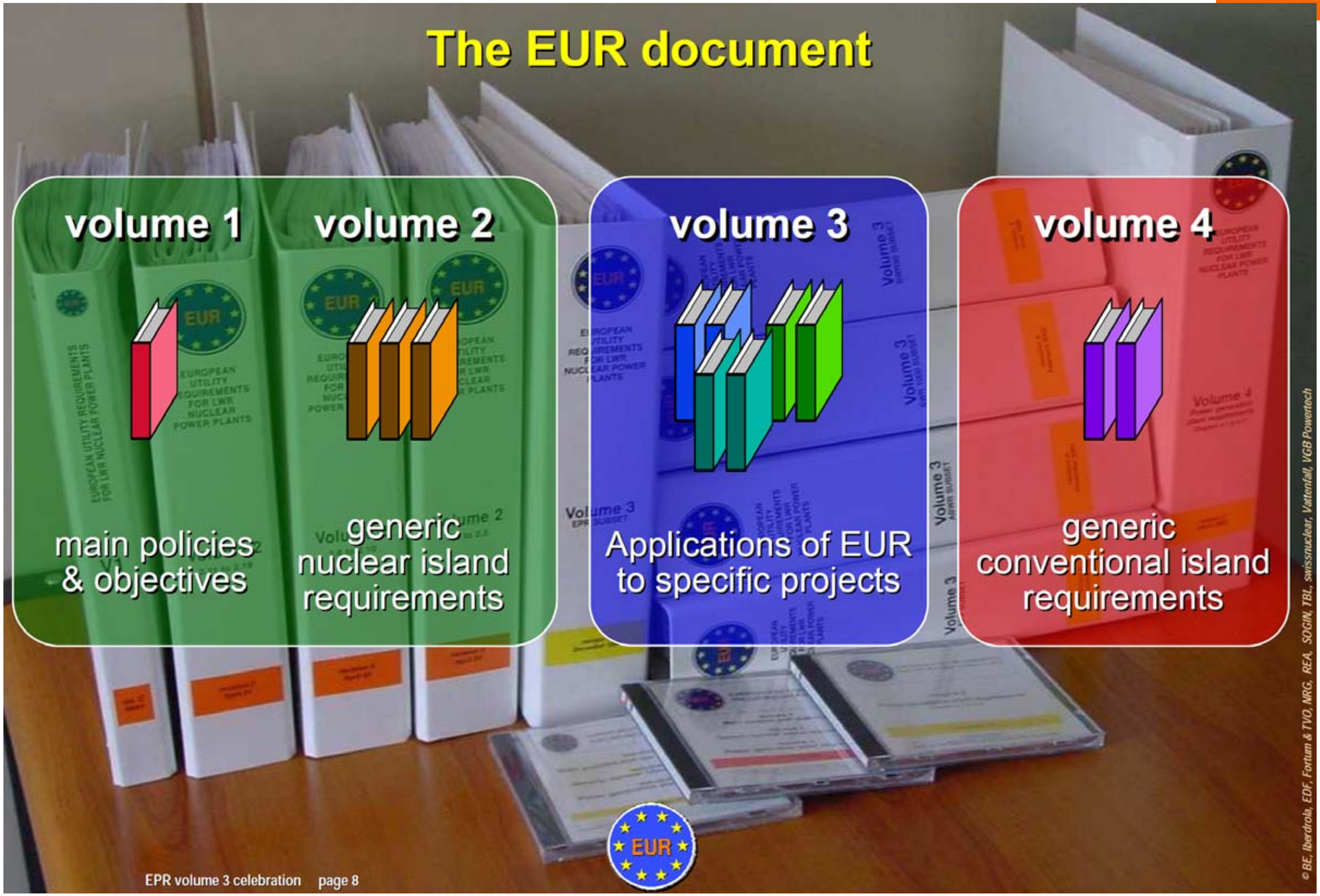
2. Design of the EPR™ in Compliance with EUR - Nuclear Safety Concept and Safety Principles

- **Nuclear Reactor Safety requires the Fulfillment of three functions at all times**
  - Control of the chain reaction, i.e. control of the power generated
  - Cooling of the fuel to remove residual heat, including cooling after the chain reaction has stopped
  - Containment of radioactive products
- **Nuclear Reactor Safety relies upon two main Principles**
  - The three protective barriers
  - Defense in Depth
- **The aforementioned Nuclear Reactor Safety Concept is implemented in the European Utility Requirements (EUR)**
- **The EPR™ is designed in compliance with EUR**

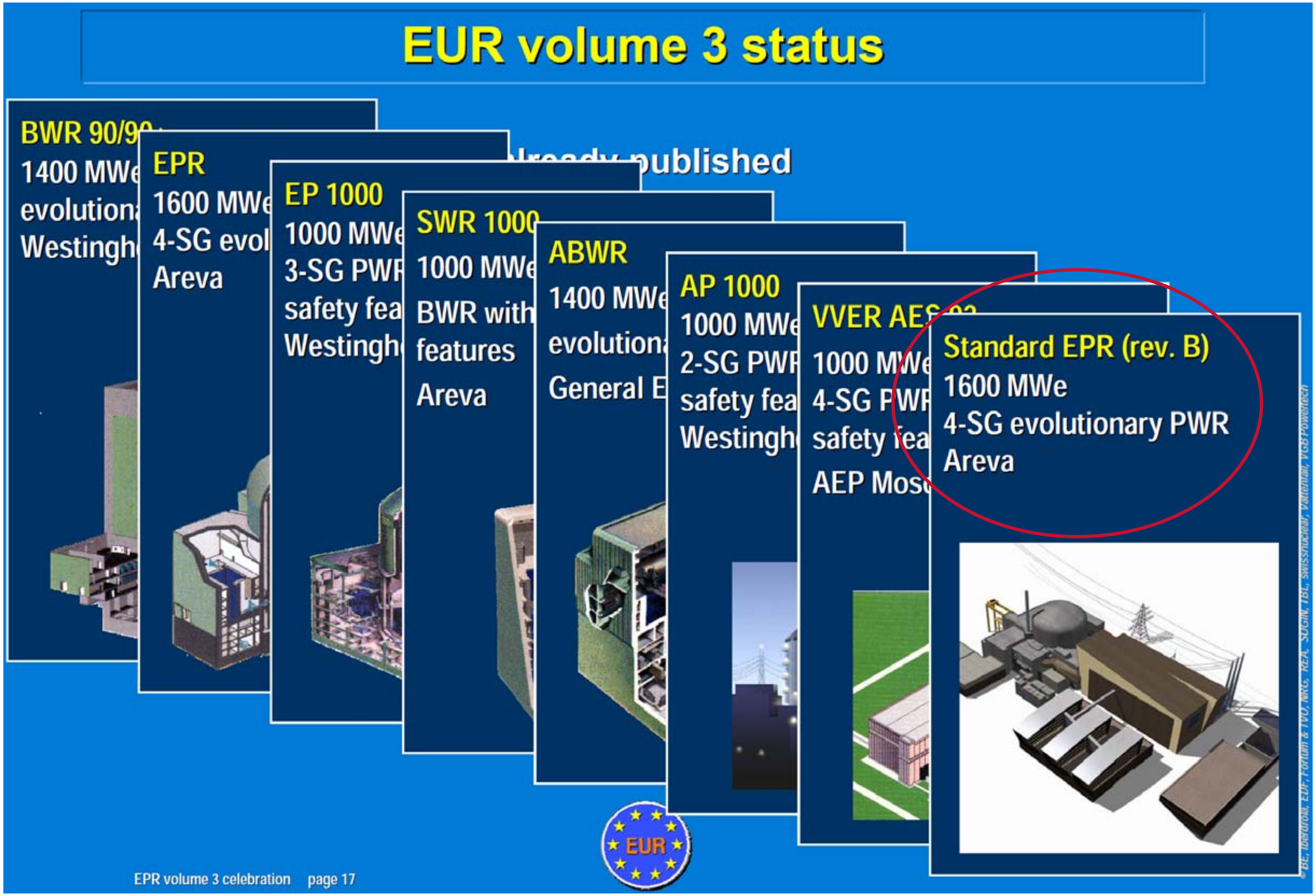
2. Design of the EPR™ in compliance with EUR - European Utility Requirements Document

- The EUR document represents a set of technical requirements compiled by the investors/operators (utilities) and NPP vendors
  - Created on a wide experience basis – 16 operators from Europe and 6 international NPP vendors
  - Used by the NPP vendors as a design guidelines for designing their new standardized LWR plants
- Does not favor any specific design
- Prohibits only design features with bad operational experience or an unacceptable industrial risk
- Helps to homogenize the safety requirements of new plants
- Helps to align new plants to a high level of performance
- Is fully operational – already used as bidding specification in Finland, Bulgaria, South Africa, Turkey and in other countries worldwide

2. Design of the EPR™ in Compliance with EUR - Contents of the EUR Document



2. Design of the EPR™ in Compliance with EUR -
Contents of Volume 3 of the EUR Document –
Compliance Assessment of the Certified Standard Plants



© F. Hédin, European Utility Requirements

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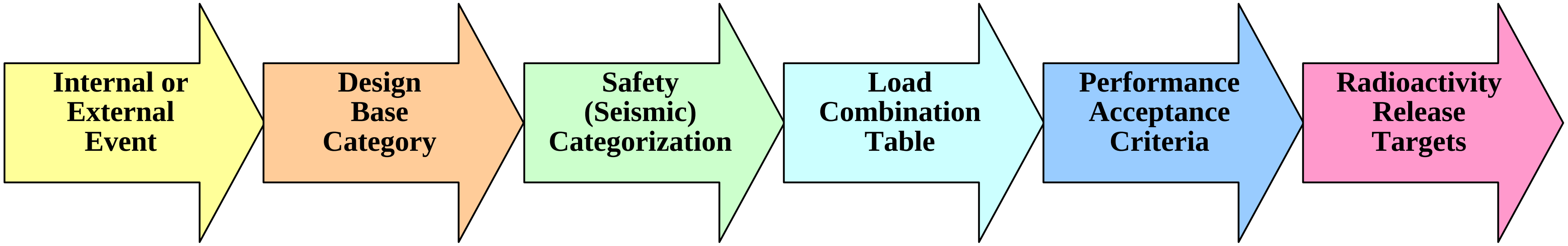
2. Design of the EPR™ in Compliance with EUR – EUR Safety Approach (1/2)

- The EUR safety approach is based upon:
  - Well-established deterministic methods, augmented by
  - Probabilistic methods using appropriate analyses and Numerical Targets:
    - Core Damage cumulative frequency shall be lower than 10^{-5}/reactor year
    - Cumulative frequency of exceeding the Criteria for Limited Impact shall be lower than 10^{-6}/reactor year
    - Sequences potentially involving either the early failure of the Primary Containment or very large releases shall have a cumulative frequency well below the previous target of 10^{-6}/reactor year
  - The safety targets stem from the extensive experience of the EUR promoters in terms of the design, assessment and operation of existing reactors.
  - The results of the Probabilistic Risk Analysis (PRA) also indicate the balance of the design features from the safety point of view, and help to identify the weakest points that possibly need to be strengthened

2. Design of the EPR™ in Compliance with EUR – *EUR Safety Approach (2/2)*

- To compensate for potential human and mechanical failures, a Defense-in-Depth concept is implemented, centered on several levels of protection to prevent the release of radioactive materials to the environment:
  - Level I: Prevention of deviations from Normal Operation
  - Level II: Detection of deviations from Normal Operation and provision of means to prevent such deviations leading to Accident conditions
  - Level III: Provision of engineered safeguards to control and mitigate the Design Basis Accident conditions (redundancy, diversity)
  - Level IV: Prevention and mitigation of Severe Accidents (severe accident design features)

- The implementation of the Defense-in-Depth safety approach is ensured by consideration of the following conceptual steps for every internal/external event:



2. Design of the EPR™ in Compliance with EUR – Design Base Categories and Frequency of Occurrence

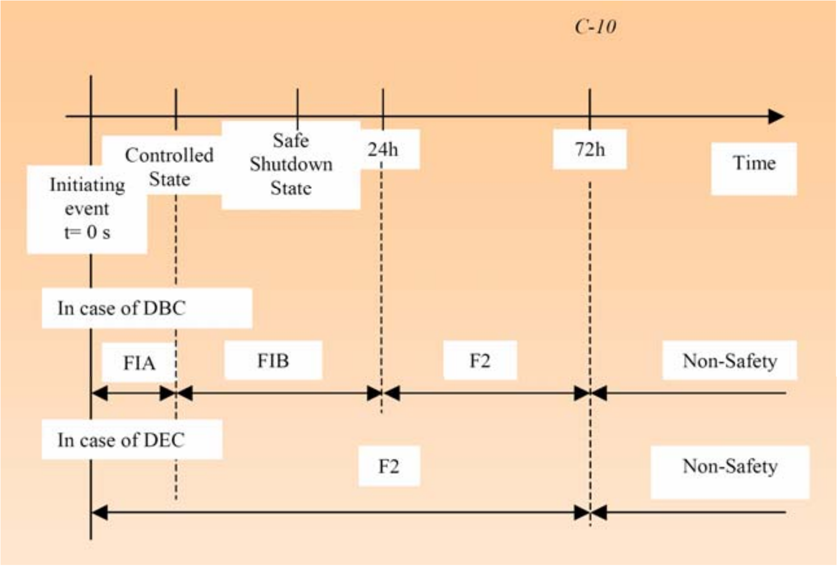
Categories acc. to EUR	System condition	Estimated frequency *f* of occurrence per year
DBC 1	Normal operation	--
DBC 2	Abnormal (incident) operation	$f > 10^{-2}$
DBC 3	Accident condition (Category 1)	$10^{-4} \leq f \leq 10^{-2}$
DBC 4	Accident condition (Category 2)	$10^{-6} \leq f \leq 10^{-4}$
DEC	Design extension conditions (multiple failure scenarios)	$f < 10^{-6}$
SA	Severe Accident (core melt)	$f < 10^{-7}$

2. Design of the EPR™ in Compliance with EUR – Safety Functions & Categories

DEFINITION OF THE SAFETY FUNCTIONS

Safety category	Definition
F1A	All safety functions including supporting functions to reach the “controlled state” after DBC 2 to DBC 4
F1B	All safety functions including supporting functions to reach the safe shutdown state after DBC 2 to DBC 4
F2	Safety functions needed for DEC and SA, for internal hazards (fire), control of radioactivity in normal operation
NS	All the rest, not classified

SAFETY CATEGORIZATION AND SAFETY FUNCTIONS ACCORDING EUR AS TIME-DEPENDENT FUNCTIONS



SAFETY FUNCTIONS AND SAFETY CATEGORIES ACCORDING TO EUR SECTION 2.1.6.8

Highest Safety Function Level performed	Safety Category	Seismic Category
F1A, F1B	**I**	**I**
F2	**II**	**I, S or N (case by case)**
Non-Safety	**Non-Safety (NS)**	**S, N (case by case)**

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2. Design of the EPR™ in Compliance with EUR –
Building Structures of NI – Safety & Seismic Categorization (Excerpt)

Structure	Safety Cat. EUR	Seismic Cat. EUR
Reactor Building (UJA/B)	I	I
Inner Containment		
- Containment structural members, including pre-stressing tendons and ancillaries, containment liner	I	I
- Penetration sleeves, equipment hatch, personnel air locks and all related welded parts		
Internal concrete structures	I + II	I
- Structural members of the reactor pit, including IRWST- and reactor cavity pool liner, embedded steel parts and all structures supporting SC1 equipment		
- Outer Containment, APC Shell	I	I
Common Base Slab (beneath the Reactor Building)	I	I
Fuel building (UFA) - Structural members, liner for spent fuel pool, transfer compartment, EBS - water tank, embedded steel parts	I	I
Safeguard Buildings 1+4UJH/UJK with steam and feed water valve compartments 1+4UJE - Structural members, also including EFWS tanks, steel liner, embedded steel parts	I	I
Safeguard Buildings 2+3UJH/UJK - Structural members, also including EFWS tanks, steel liner, embedded steel parts	I	I
Nuclear Auxiliary Building (UKA) - Structural members	II	I
Radioactive Waste Building (UKS) Structural members	II	I
Emergency Power Generating Buildings (1-4UBP) - Structural members	I	I

3. Seismic Design of the EPR™ – Overview of EUR Seismic Design Levels

Internal or External Event → **Design Base Category** → **Safety (Seismic) Categorization** → **Load Combination Table** → **Performance Acceptance Criteria** → **Radioactivity Release Targets**

Example: SSE

Safe Shutdown Earthquake (SSE)	DBC – Accident condition	Seismic Categories I & S SSC	Load Combination Table	Structural Integrity (Leak-Tightness)	Release Targets for DBC Category 4

Example: OBE (not required by EUR)

Operational Basis Earthquake (OBE)	DBC 2 – Abnormal (Incident) Operation	Seismic Categories I & S & N SSC	Load Combination Table	Structural Integrity (Leak-Tightness)	Release Targets for DBC Category 2

3. Seismic Design of the EPR™ –
EUR Design Basis Earthquake (DBE)

- The EPR™ was originally designed to withstand the EUR Design Basis Earthquake (DBE). This design basis earthquake is defined by standard design acceleration and a set of seismic spectra reflecting the European conditions.

- A set of three European DBE spectra is given for “hard”, “medium” and “soft” soil. A standard design acceleration level of PGA = 0.25 g is required for these three spectra.

- The Plant Designer shall demonstrate that the standard Plant remains in a safe condition for the whole range of parameters (soil conditions) for the DBE.

- A standard design resultant from the DBE is expected to be able to withstand a higher site specific Safe Shutdown Earthquake (SSE) magnitude than the DBE, as the SSE will be related to a single spectra and a single set of soil conditions.

3. Seismic Design of the EPR™ – EUR Lower level earthquake (OBE)

- An Operating Basis Earthquake (OBE) has not been specified in the EUR Document.

- The definition of the OBE is not seen as a primary safety requirement, but more as an investment protection issue (or for satisfaction of local licensing requirements).

- The Owner will be responsible for specifying these ground motions together with the methodology and criteria for dealing with them. Such requirements would deal with an earthquake under which no specific inspection would be required to continue operation.

- Experience has shown that if structures and systems have to be stiffened to meet the requirements of a demanding OBE level, this may be detrimental to their behavior in Normal Operation (e.g. thermal restraint effects).

3. Seismic Design of the EPR™ – EUR Site-Specific Safe Shutdown Earthquake (SSE)

- For licensing purposes, the Owner will determine, on the basis of the seismicity and geology of the site and its surrounding area, the parameters of the site specific Safe Shutdown Earthquake (SSE)

- The Designer shall demonstrate that the standard design is satisfactory when checked against the site-specific SSE in conjunction with the specific properties of the chosen site and local design requirements

- The standard Design is not intended to envelop all possible combinations of national regulations and site conditions. If necessary the Designer may have to make modifications or additional studies to ensure the Standard Design is satisfactory for particular sites

- The SSE is usually defined in the international practice for an annual probability of exceedance of 10^{-4} (i.e. return period of 10 000 years)

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3. Seismic Design of the EPR™ –
EUR Site-Specific Seismic Margin Assessment Review Level Earthquake (SMA-RLE)

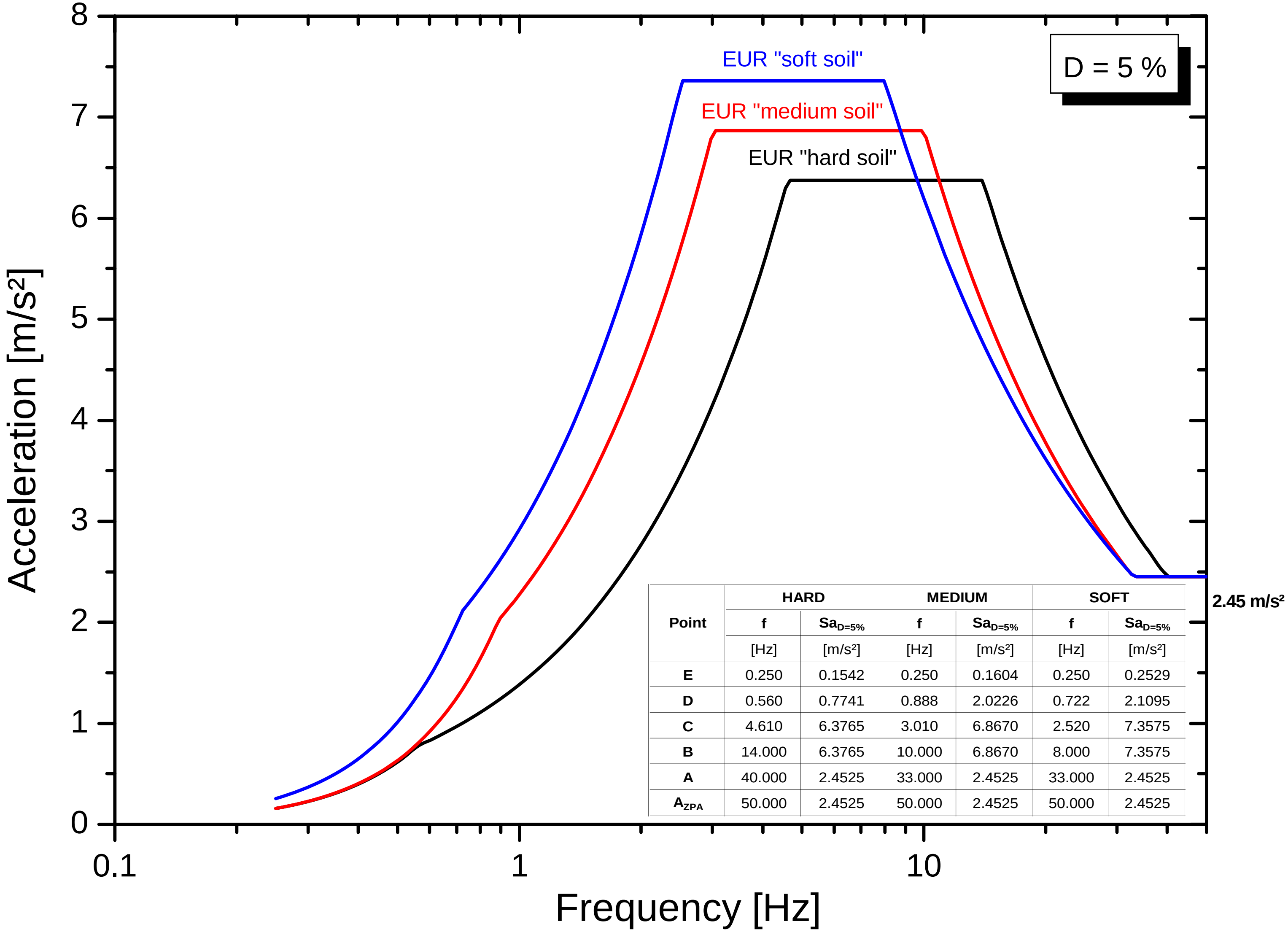
- A site-specific seismic margin analysis of the structures and equipment shall be carried out, to ensure that adequate safety margins exist in the seismic design of the main structures and components beyond the design basis conditions.
- Review Level Earthquake: According to the EUR the design shall withstand earthquakes with a margin of 40 % on the horizontal PGA above the design SSE level. At present a 60 % margin is targeted for the EPR™.
- The objective shall be to establish the seismic capability of a minimum set of plant structures and systems needed to avoid core damage, then bring the plant to and maintain it in a Safe Shutdown State.
- This demonstration shall be made following a best-estimate methodology.
- The assessment shall identify the items without sufficient margins in the capacity of the design.
- For items without sufficient margins, a comprehensive Seismic Margin Assessment Programme shall be established using analyses and tests.
- The SMA-RLE is defined for a smaller annual probability of exceedance than the SSE, e.g. 10^{-5} (i.e. return period of 100 000 years).
  In this way it is ensured that there are no cliff-edge effects from earthquakes slightly exceeding the design basis.

3. Seismic Design of the EPR™ – *Foundation Soil Properties according to EUR*

Nine typical soils are identified in the EUR, three in each site category. The three ground motion spectra given in the EUR shall therefore be used for the three identified sites – “soft”, “medium” and “hard”.

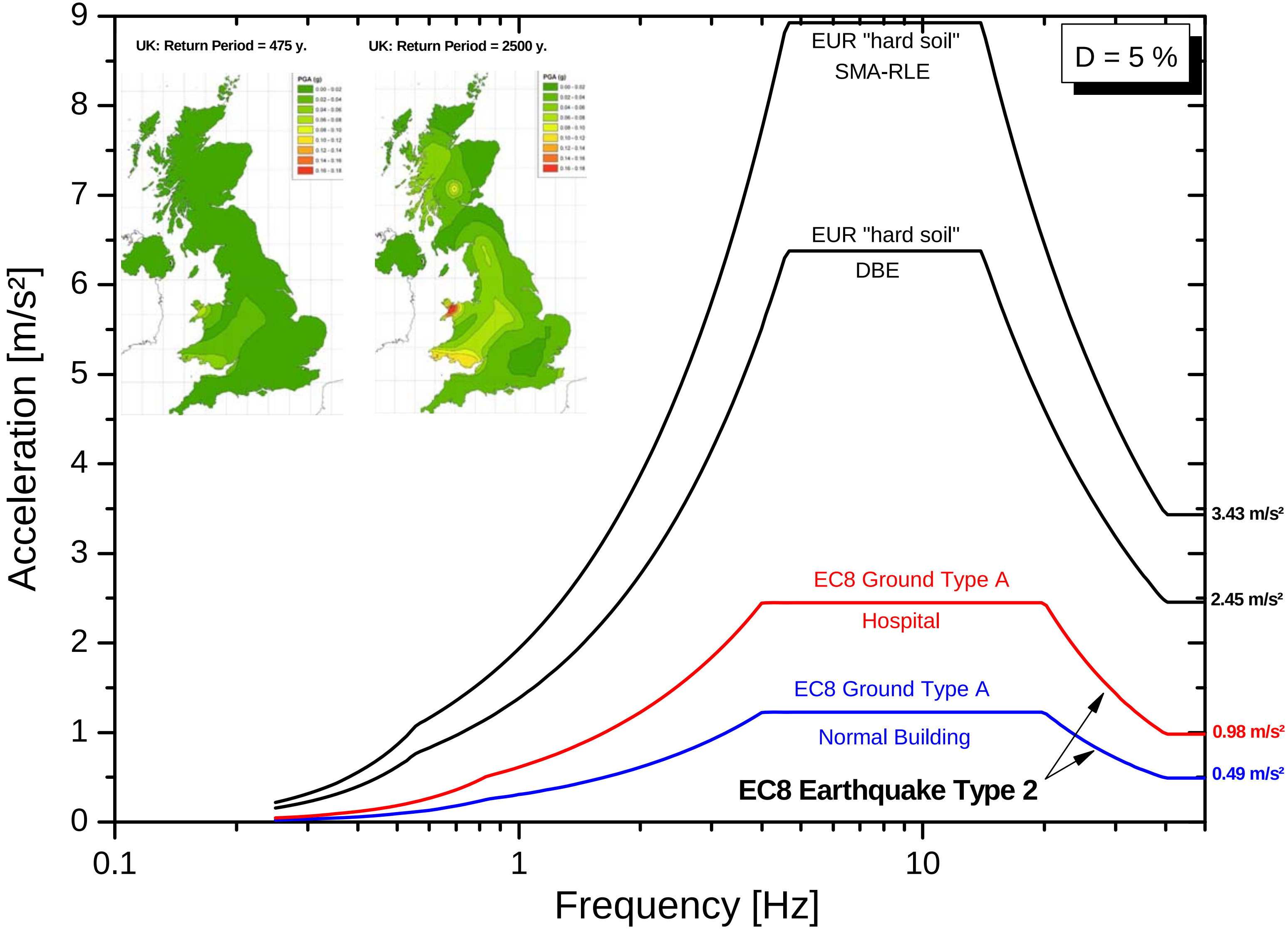
Type of Spectrum	Soft (S)			Medium (M)			Hard (H)		
	S250	**S350**	**S500**	**M600**	**M800**	**M1100**	**H1200**	**H1700**	**H2500**
Shear wave velocity (m/s)	250	350	500	600	800	1100	1200	1700	2500
Mass density (kg/m3)	2000			2200			2500		
Poisson’s ratio (-)	0.47			0.40			0.35		
Internal damping (%)	5			4			3		
Free field shear modulus G_{max} (MPa)	125	245	500	792	1408	2662	3600	7225	15625
G_{max} beneath structures (MPa)	125	270	600	950	1690	2930	3960	7225	15625
Effective G beneath structures (MPa)	113	243	540	903	1606	2782	3960	7225	15625
Effective Young’s modulus (MPa)	331	714	1588	2527	4495	7789	10692	19508	42188

3. Seismic Design of the EPR™ – EUR Ground Response Spectra



Point	HARD		MEDIUM		SOFT	
	f	$Sa_{D=5\%}$	f	$Sa_{D=5\%}$	f	$Sa_{D=5\%}$
	[Hz]	[m/s²]	[Hz]	[m/s²]	[Hz]	[m/s²]
E	0.250	0.1542	0.250	0.1604	0.250	0.2529
D	0.560	0.7741	0.888	2.0226	0.722	2.1095
C	4.610	6.3765	3.010	6.8670	2.520	7.3575
B	14.000	6.3765	10.000	6.8670	8.000	7.3575
A	40.000	2.4525	33.000	2.4525	33.000	2.4525
A_{ZPA}	50.000	2.4525	50.000	2.4525	50.000	2.4525

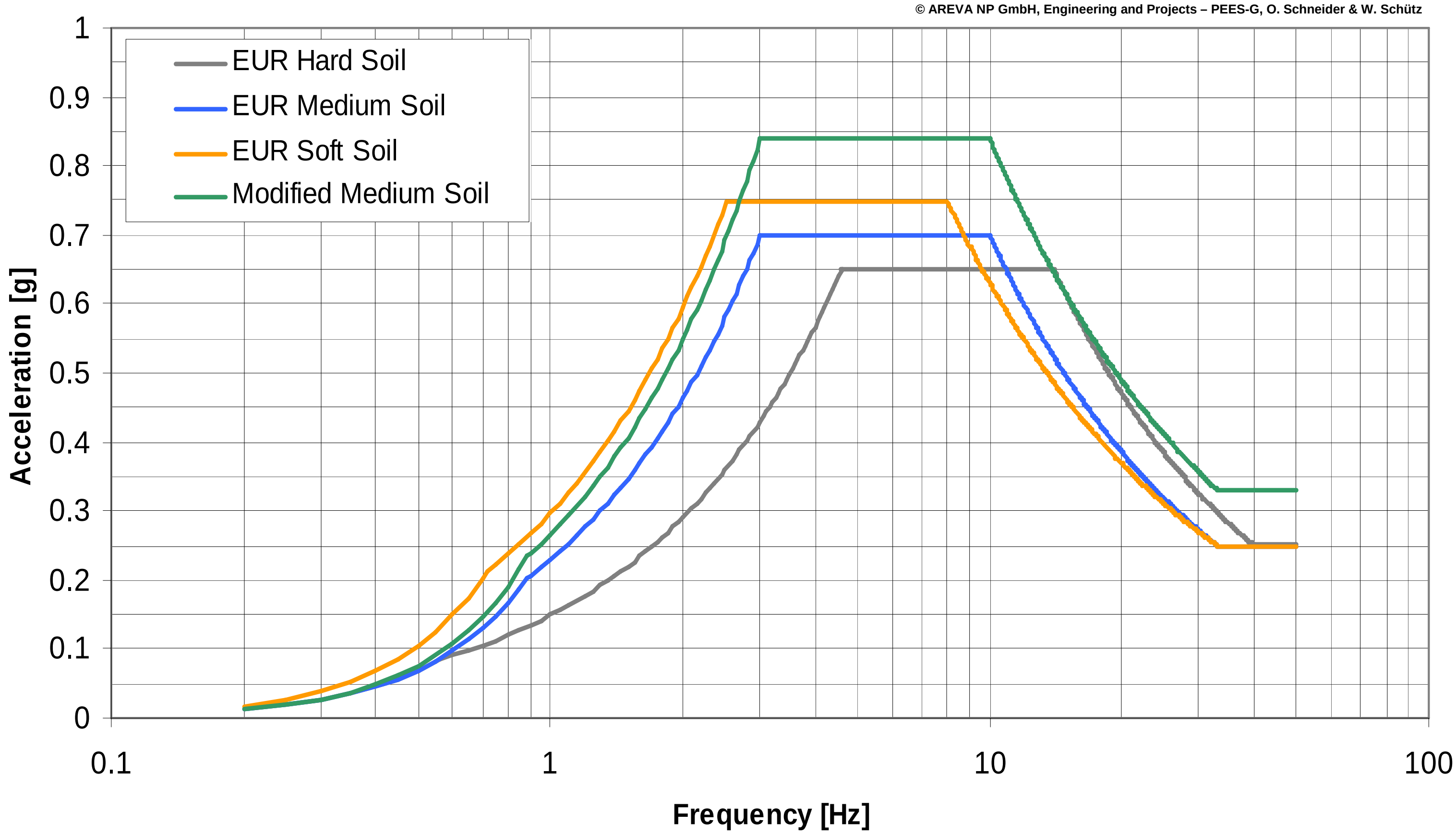
3. Seismic Design of the EPR™ –
Comparison: EUR Spectra vs. EC8-Spectra for a UK Site



3. Seismic Design of the EPR™ –
Seismic Analysis Method – compliant with EUR Appendix 2.4A

- **Input Motion** **(1/2)**
- **Soil-structure interaction Analysis**
  - finite element methods
  - impedance methods
  - displacements values
- **Modeling of structures and substructures**
  - general requirements
  - modeling of stiffness
  - modeling of mass
  - modeling of hydrodynamic effects
  - dynamic de-coupling criteria
- **Direct integration method**
  - time steps
- **Modal analysis** **(2/2)**
  - convergence
  - number of modes
  - modal damping
- **Combination of modes and directions**
  - mode combination
  - combination of directions
- **Response spectra generation**
  - time history method
  - transfer function methods
  - floor response spectra

4. Examples – Example 1 –
EPR™ Margin at SSE-Level: EUR-Spectra scaled with PGA = 0.25g vs. PGA = 0.33g



EPR™ Seismic Margin at SSE-Level: EUR-Spectra scaled with PGA = 0.25g vs. PGA = 0.33g

Comparison: Floor Response Spectra for medium MA (EUR-M600) soil conditions and EPR™ envelop design spectra scaled for PGA = 0.25g

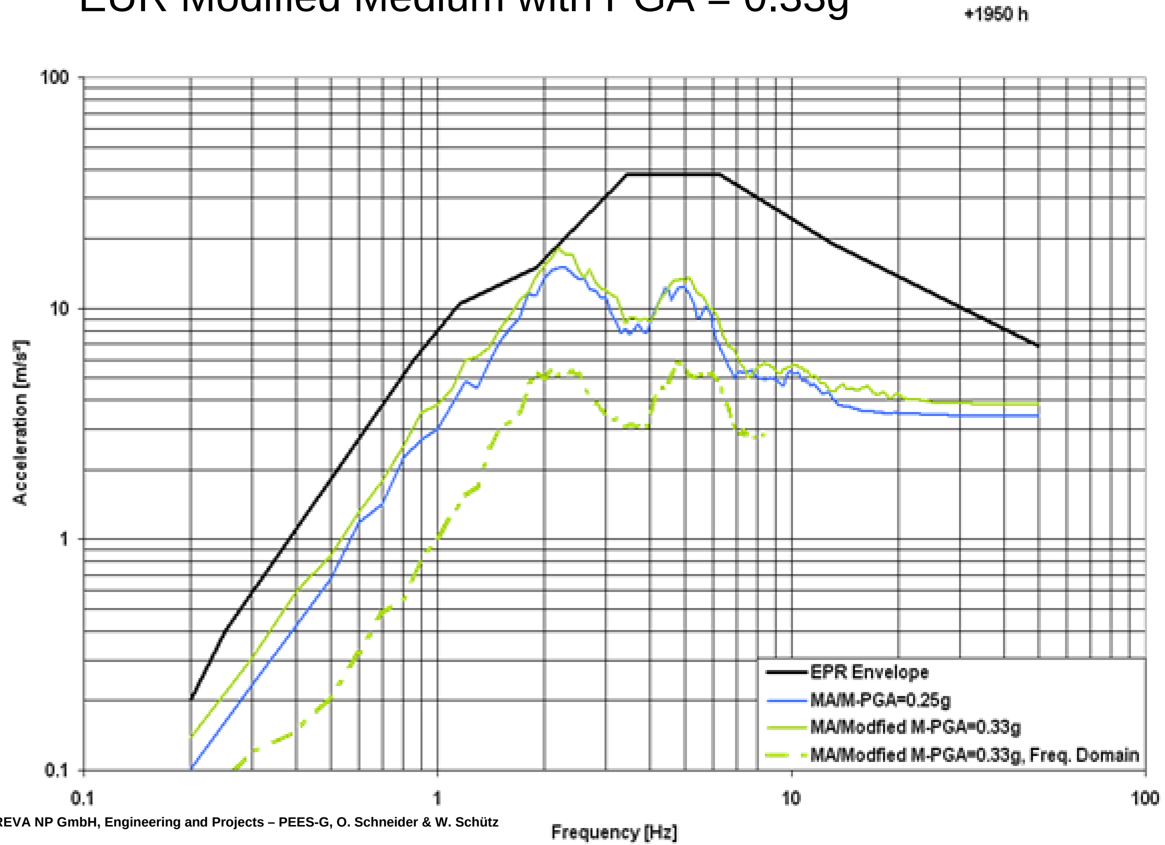
Analysis Procedure: Modal Time History Superposition vs. Frequency Domain

Excitation: EUR Medium with PGA = 0.25g, EUR Modified Medium with PGA = 0.33g

Elevation: +19.50 m

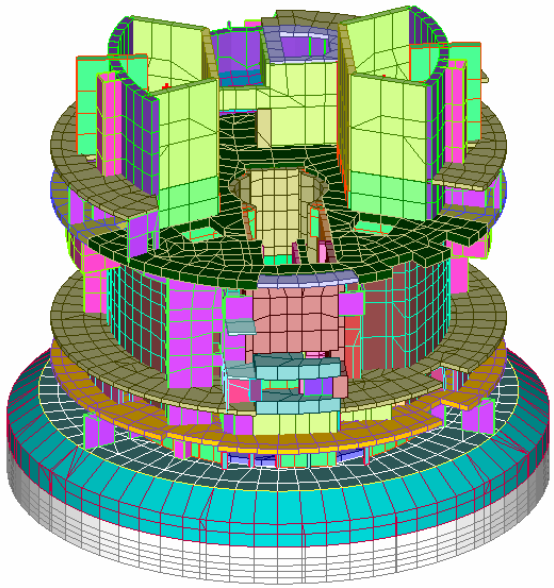
horizontal

D=4%

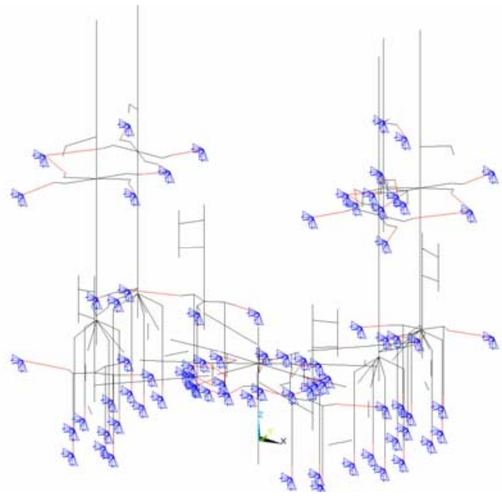


4. Examples – Example 2 –
EPR™ Seismic Margin at SSE-Level: Lumped Mass vs. Coupled Analysis of NSSS

- **Two dynamic analysis have been performed**
  - Reactor Building + NSSS considered as lumped mass
  - Reactor Building + NSSS represented by a super element



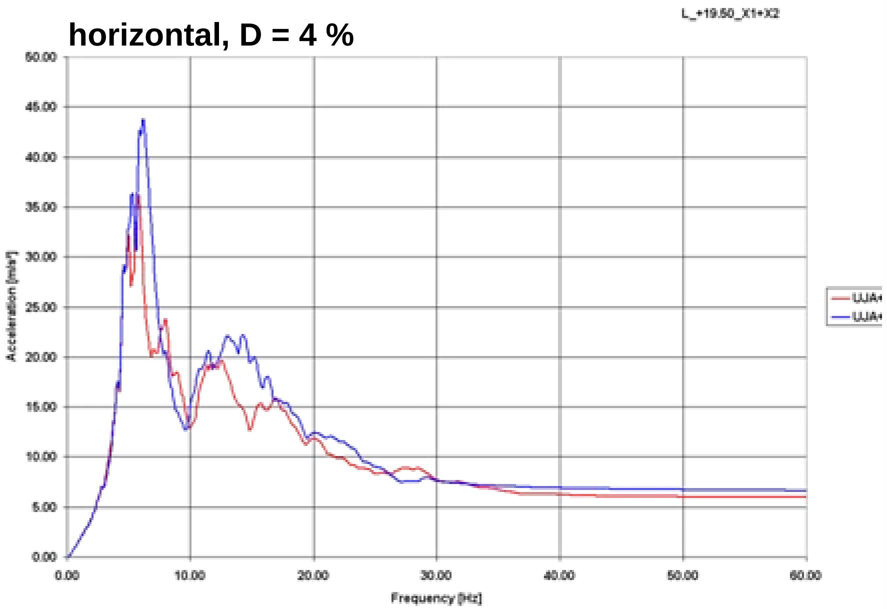
Reactor Building Finite Element Model

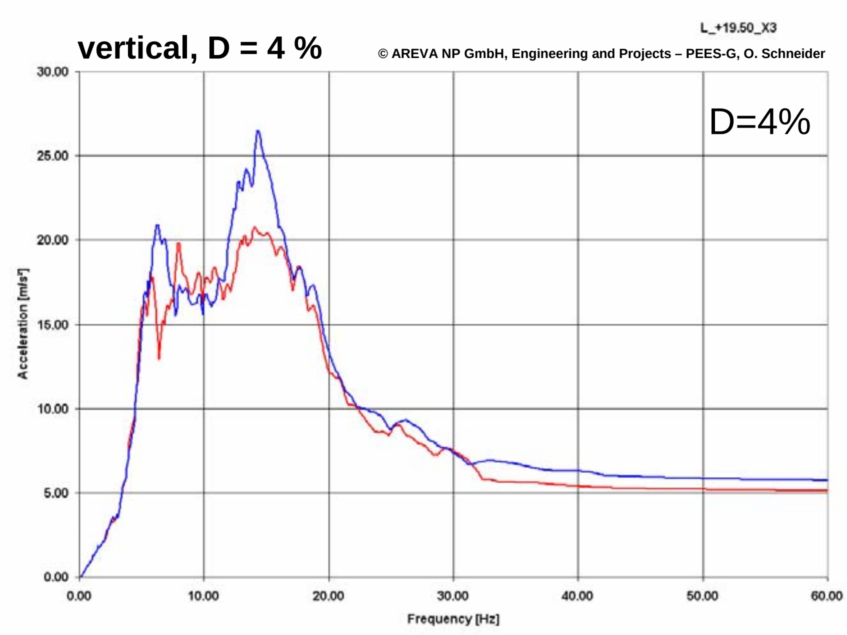


Nuclear Steam Supply System (NSSS) Super Element

4. Examples – Example 2 –
EPR™ Seismic Margin at SSE-Level: Lumped Mass vs. Coupled Analysis of NSSS

Comparison:	Floor Response Spectra: Lumped Mass vs. Coupled Analysis
Soil Conditions:	HA (~ EUR-H1700)
Analysis Procedure:	Modal Time History Superposition
Excitation:	EUR Hard with PGA = 0.25g
Elevation:	+ 19.50 m





5. Summary and Conclusions

- The EPR™ was originally designed to withstand the EUR Design Basis Earthquake (DBE). This earthquake is defined by a PGA = 0.25 g and a set of three spectra given for “hard”, “medium” and “soft” soil reflecting the European conditions.
- Ongoing studies investigate a seismic design of the EPR™ for EUR-Spectra scaled to a PGA of 0.30g and higher values.
- The EPR™ resultant from the DBE is expected to be able to withstand a higher site specific Safe Shutdown Earthquake (SSE) magnitude than the DBE, as the SSE is related to a single spectra and a single set of soil conditions.
- Two examples for reduction of over-conservative assumptions in the seismic design demonstrate the high seismic margin of the EPR™ plant at SSE-level, which is well above 0.30g in terms of PGA.
- Present SMA studies show that the site-specific seismic margin of a minimum set of plant structures and systems needed to avoid core damage and bring the plant to and maintain it in a Safe Shutdown State – following a best-estimate analysis methodology – will be well above 0.40g in terms of PGA.

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