Advanced LWRs

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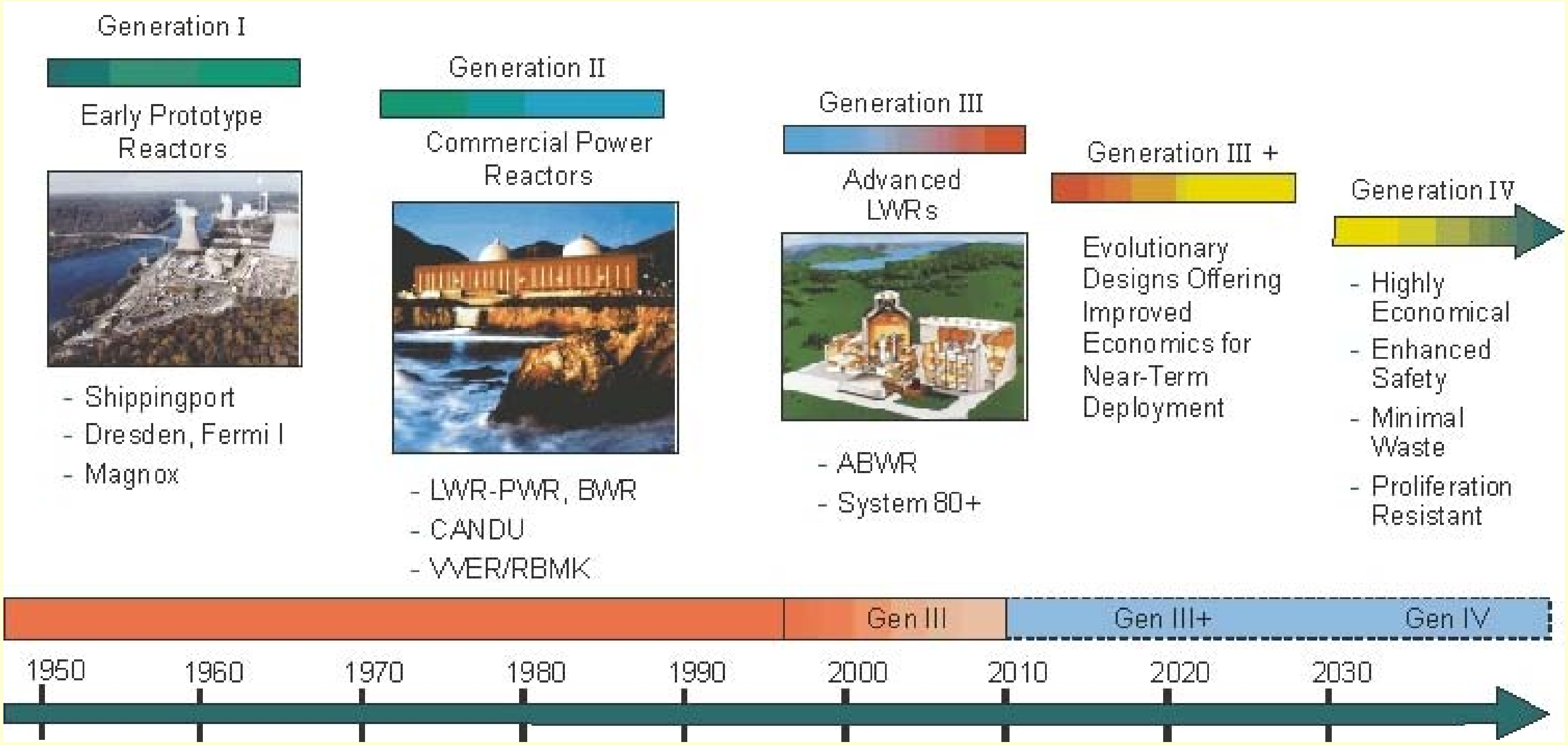
22.06: Engineering of Nuclear Systems

Center for Advanced Nuclear Energy Systems (CANES)

Outline

- Performance goals for near-term advanced LWRs
- Technical features of advanced LWRs:
  - US-EPR (Evolutionary Pressurized Reactor)
  - US-APWR (Advanced Pressurized Water Reactor)
  - AP1000 (Advanced Passive 1000)
  - ABWR (Advanced BWR)
  - ESBWR (Economic Simplified BWR)
- Summary of common characteristics
- Conclusions

Nuclear Reactor Timeline



Mission/Goals for Advanced LWRs

- Baseload generation of electricity (hydrogen is not emphasized)

- Improved economics. Targets:
  - Increased plant design life (60 years)
  - Shorter construction schedule (36 months*)
  - Low overnight capital cost (~$1000/kWe** for NOAK plant)
  - Low O&M cost of electricity (~ 1¢/kWh)

* First concrete to fuel loading (does not include site excavation and pre-service testing)

** Unrealistic target set in early 2000s. Current contracts in Europe, China and US have overnight capital costs >$3000/kWe

- Improved safety and reliability
  - Reduced need for operator action
  - Expected to beat NRC goal of CDF<10^{-4}/yr
  - Reduced large release probability
  - More redundancy <u>or</u> passive safety

U.S. NRC Certification of Advanced LWRs

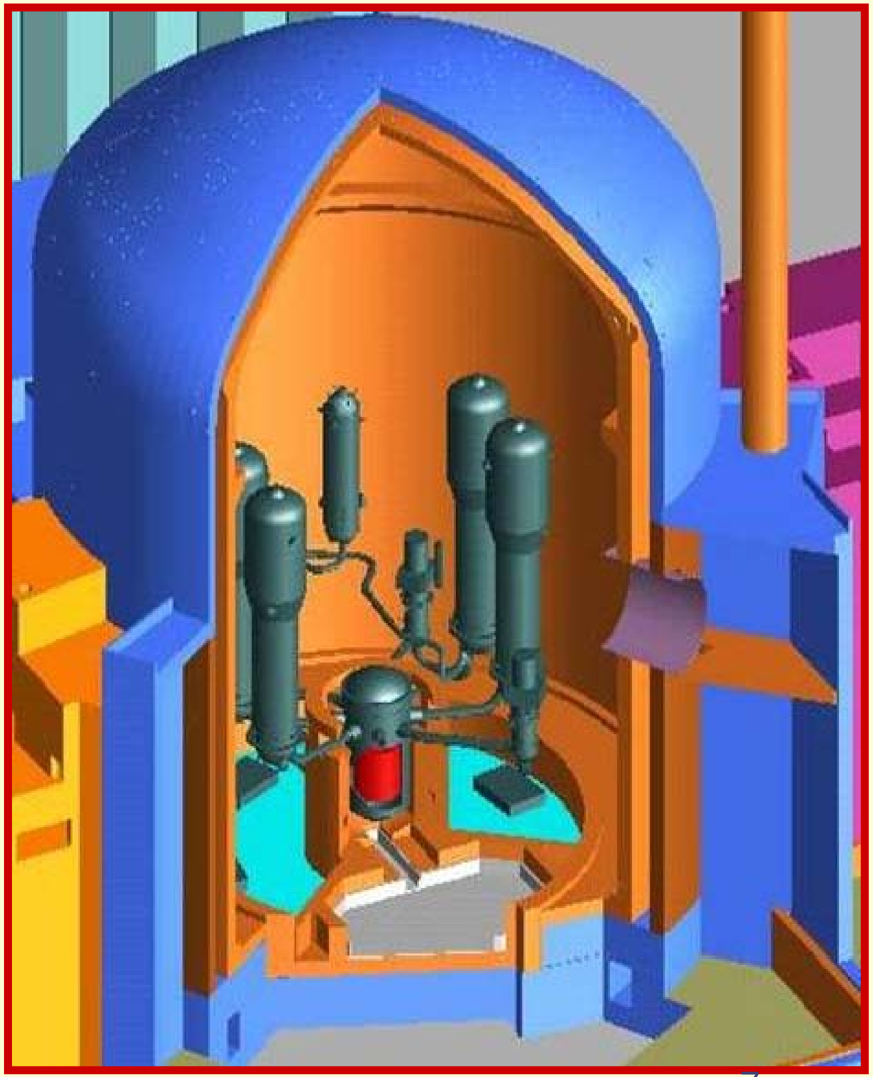
Design	Applicant	Type	Status
AP1000	Westinghouse-Toshiba	Advanced Passive PWR 1100 MWe	Certified, amendment under review
ABWR	GE-Hitachi	Advanced BWR 1350 MWe	Certified, Constructed in Japan/Taiwan
ESBWR	GE-Hitachi	Advanced Passive BWR 1550 MWe	Under review
US-EPR	AREVA	Advanced PWR 1600 MWe	Under review
US-APWR	Mitsubishi	Advanced PWR 1700 MWe	Under review

U.S. Economic Pressurized Reactor (US-EPR)

by Areva

US-EPR Overview

- 1600 MWe PWR
- Typical PWR operating conditions in primary system, pressure, temperatures, linear power, etc.
- 4 loops
- Higher pressure in SGs results in somewhat higher efficiency (35% net)
- Safety systems are active
- High redundancy



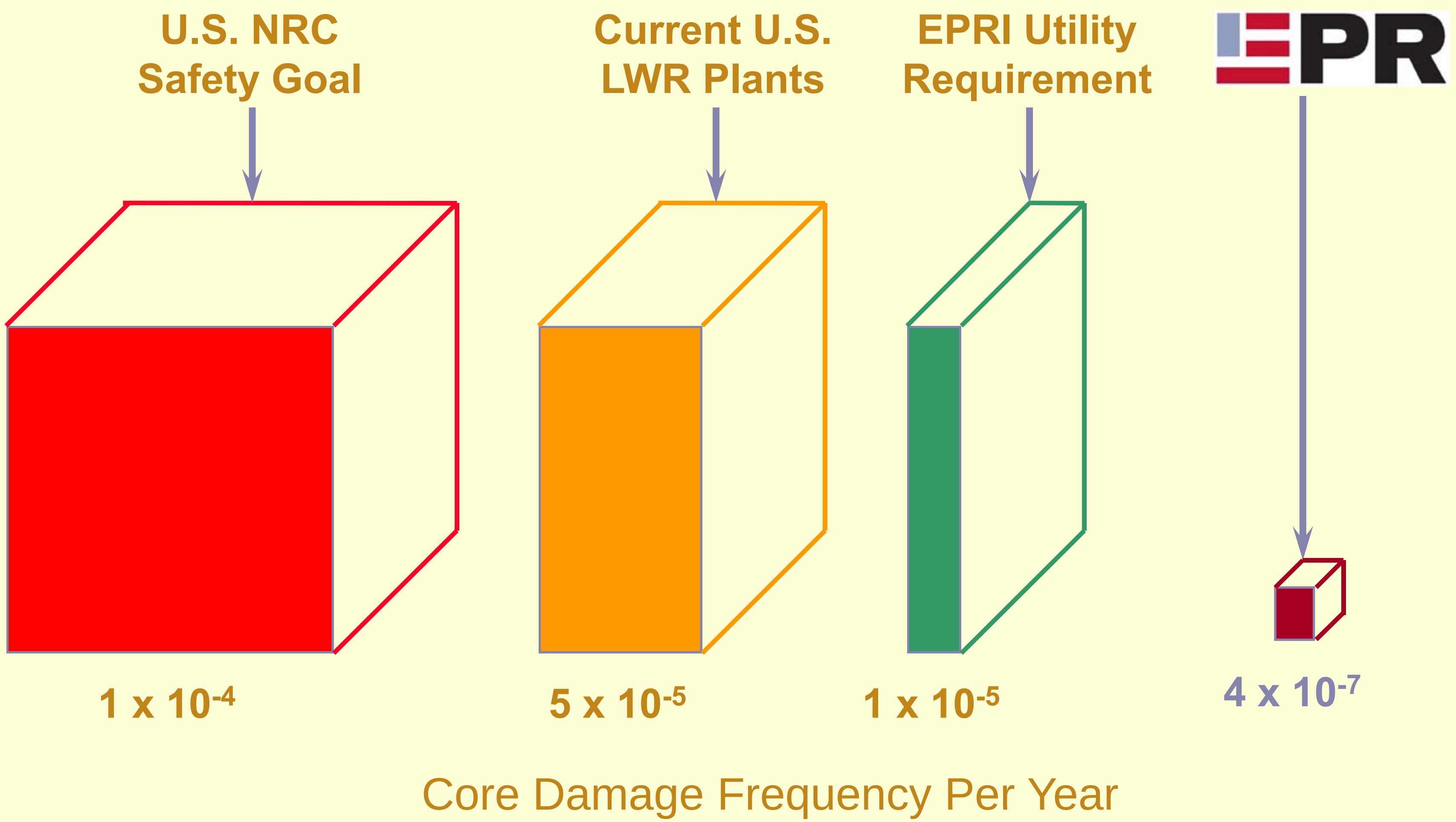
US-EPR Parameters

Parameter	Current 4-loop PWR	EPR
Design life, yrs	40	60
Net electric output, MWe	1100	1600
Reactor power, MWt	3411	4500
Plant efficiency, %	32.2	35.6
Cold/hot leg temperature, °C	292/325	296/329
Reactor pressure, MPa	15.5	15.5
Total RCS volume, m^3	350	460
Number of fuel assemblies	193	241
Type of fuel assemblies	17x17	17x17
Active length, m	3.66	4.20
Linear power, kW/m	18.3	16.4
Control rods	53	89
Steam pressure, MPa	6.7	7.7
Radial reflector	No	Yes
SG secondary inventory, ton	46	83

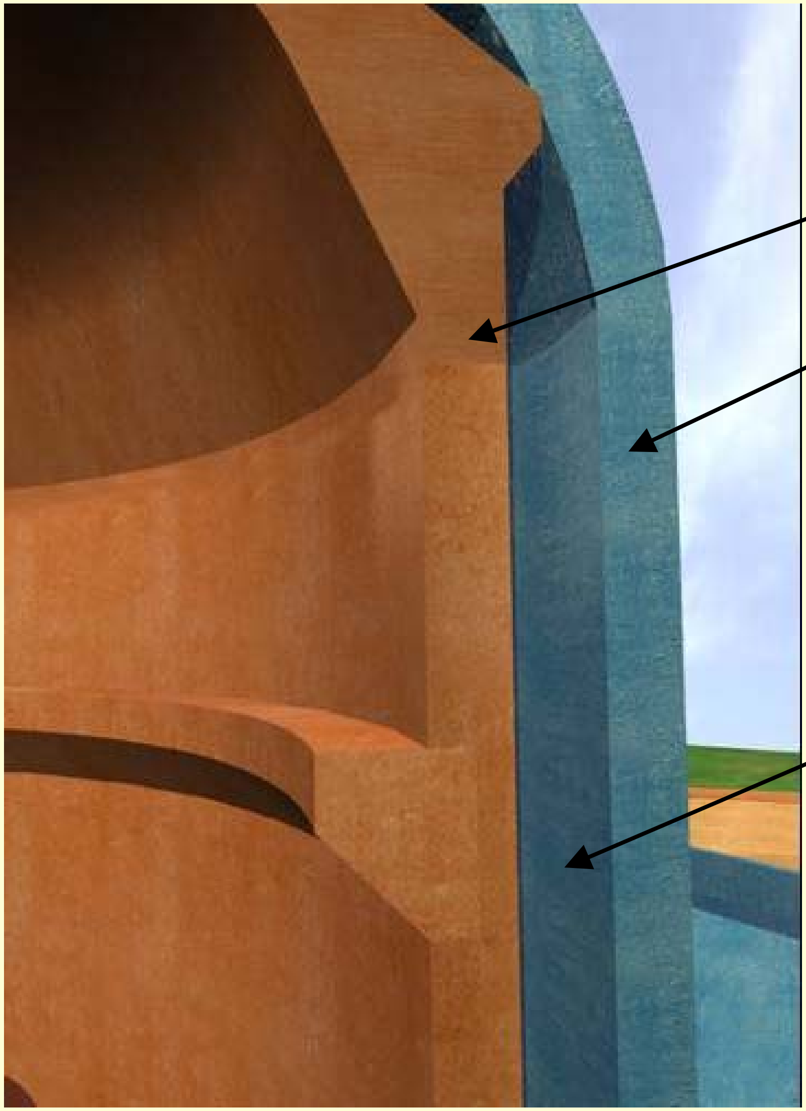
US-EPR Safety

- Four identical diesel-driven trains, each 100%, provide redundancy for maintenance or single-failure criterion (N+2)
- Physical separation against internal hazards (e.g. fire)
- Shield building extends airplane crash and external explosion protection to two safeguard buildings and fuel building (blue walls)

US-EPR Safety (2)

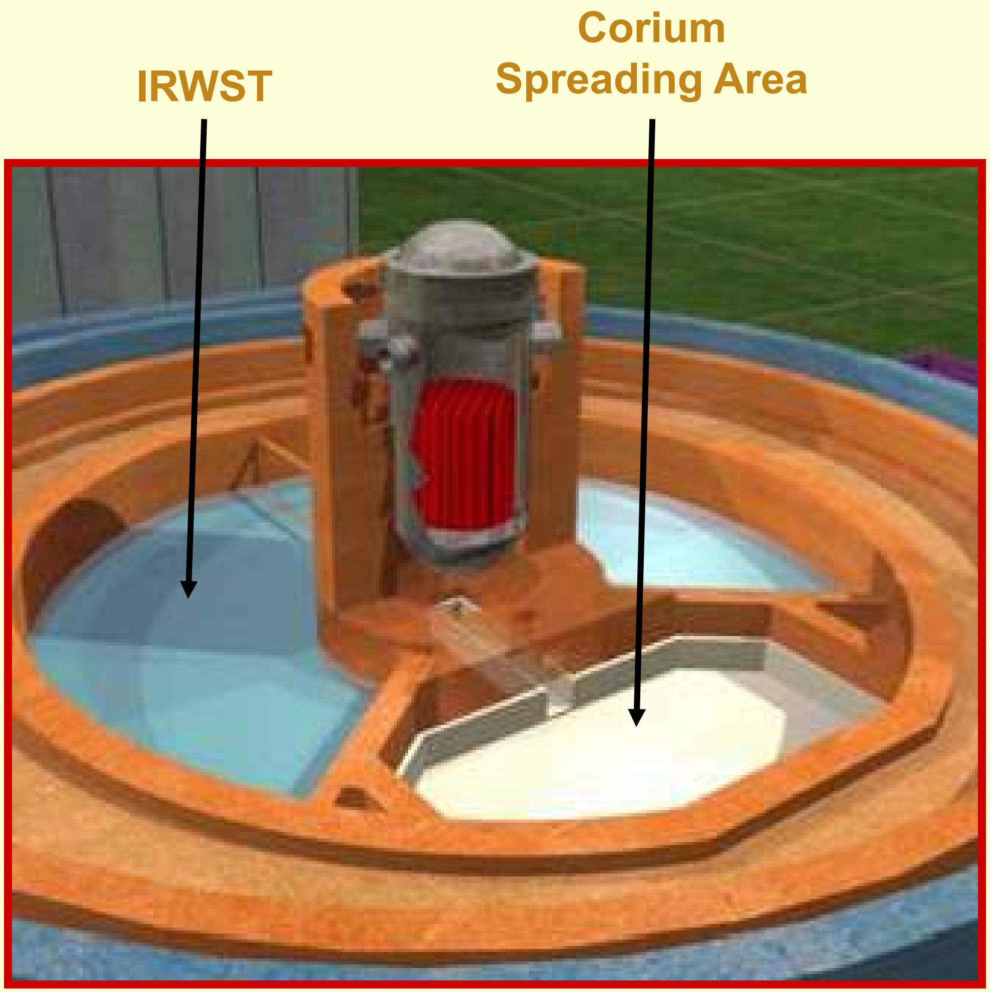


US-EPR Containment



- Inner wall pre-stressed concrete with steel liner
- Outer wall reinforced concrete
- Protection against airplane crash
- Protection against external explosions
- Annulus sub-atmospheric and filtered to reduce radioisotope release

US-EPR Severe Accidents Mitigation



Ex-vessel core catcher concept (passive)

- Molten core is assumed to breach vessel

- Molten core flows into spreading area and is cooled by IRWST water

- Hydrogen recombiners ensure no detonation within container

EPR is being built now

Olkiluoto – September 2009

Taishan – September 2009

Flamanville – October 2009

Olkiluoto 3 (Finland) - construction start 2004

Flamanville 3 (France) - construction start 2007

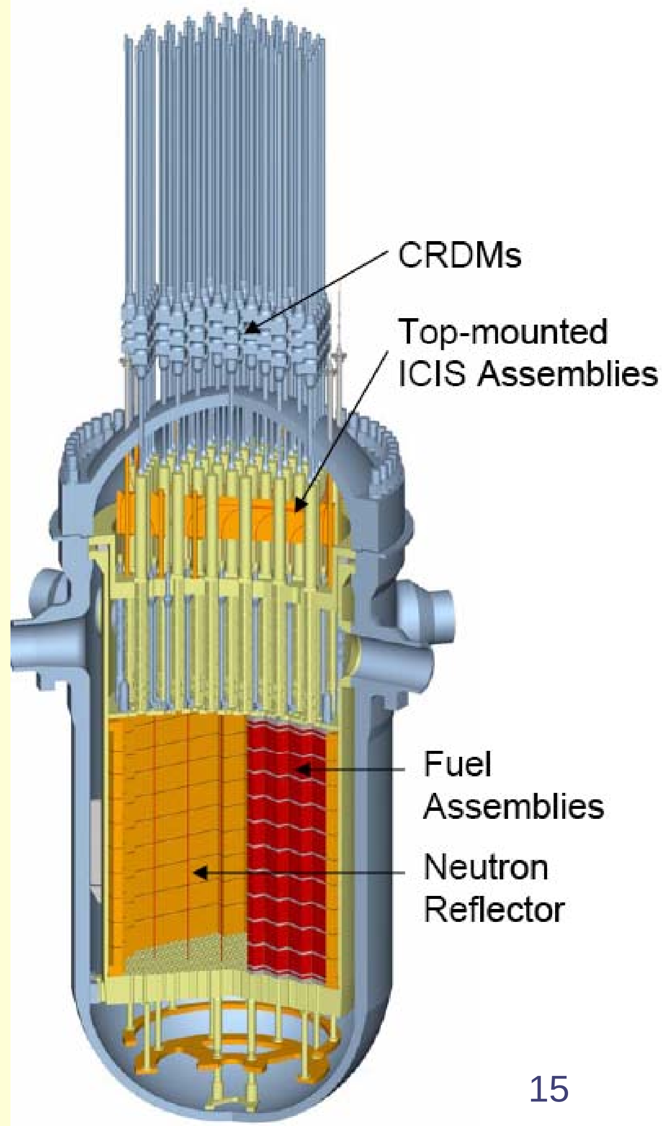
Taishan (China) – construction start 2008

U.S. Advanced PWR (US-APWR)

by Mitsubishi

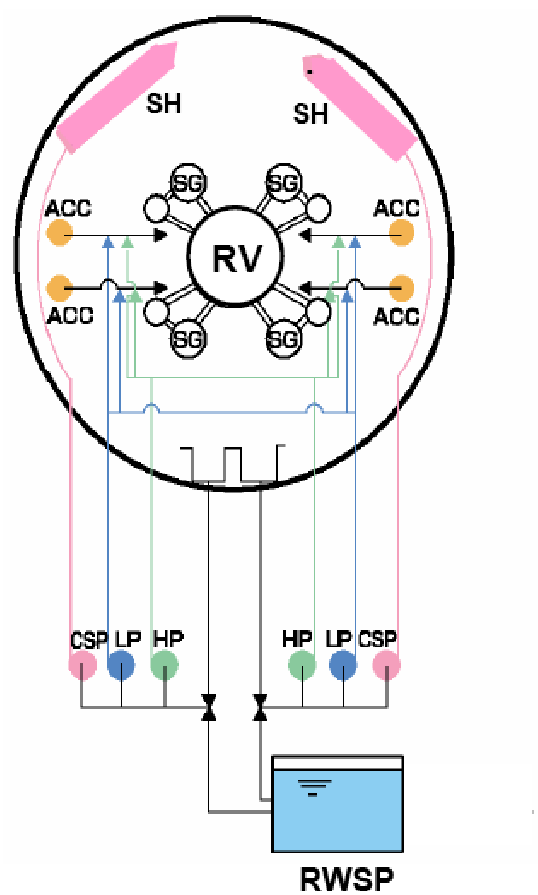
US-APWR Overview
(fundamentally similar to US-EPR)

- 1700 MWe PWR
- Typical PWR operating conditions in primary system, pressure, temperatures, etc.
- Long (14 ft.) fuel assemblies with reduced power density for 24 months operation
- 4 loops
- High efficiency turbine (70" blades) results in >35% thermal efficiency of plant
- RPV with no bottom penetrations
- Safety systems are active with high redundancy

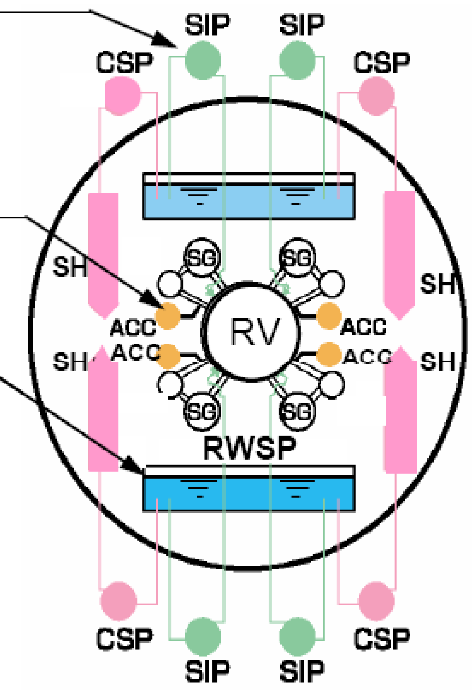


US-APWR Safety

Current 4 Loop PWR (2 train)	US-APWR (4 train)



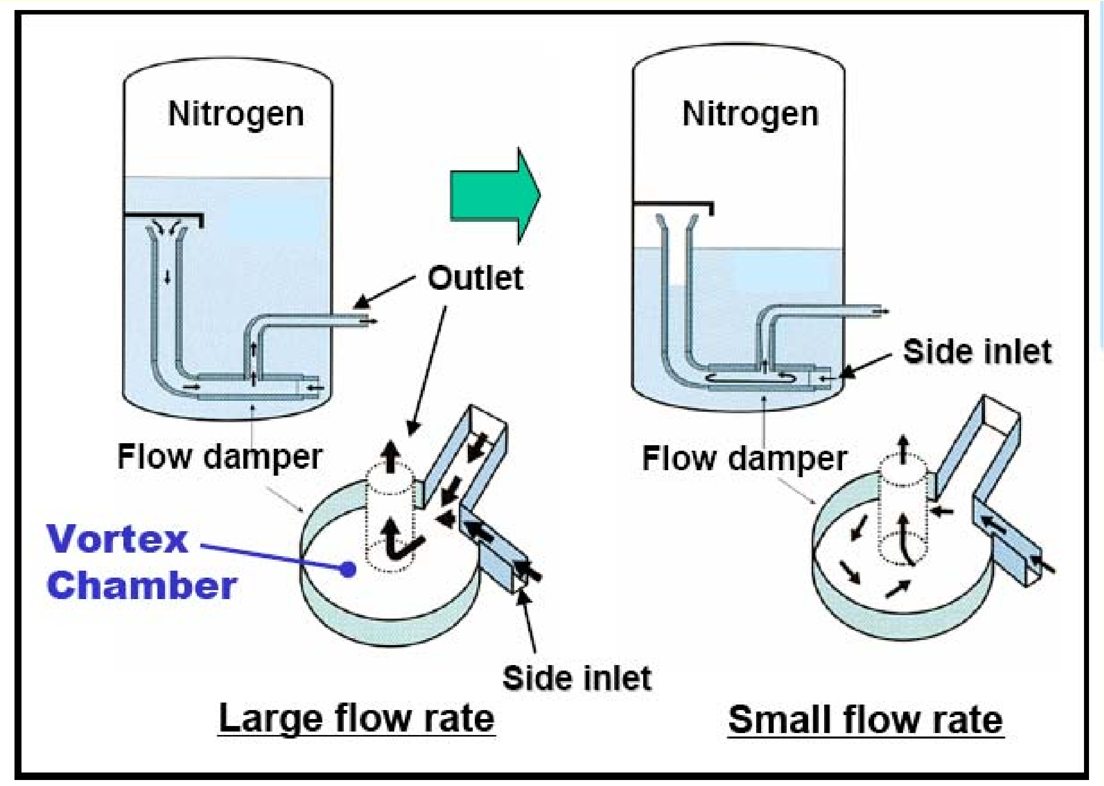
- **4 train (DVI)**
  → Higher Reliability
  Simplified Pipe Routing
- **Advanced Accumulator**
  → Elimination of HP
- **In-containment RWSP**
  → Higher Reliability



ACC	:Accumulator
HP	:High Head SIP
LP	:Low Head SIP
SIP	:Safety Injection Pump
CSP	:Containment Spray Pump
SH	:Spray Header
RV	:Reactor Vessel
RWSP	:Refueling Water Storage Pit

US-APWR Safety (2)

- *Accumulator design with flow damper eliminates need for active high-pressure injection system*



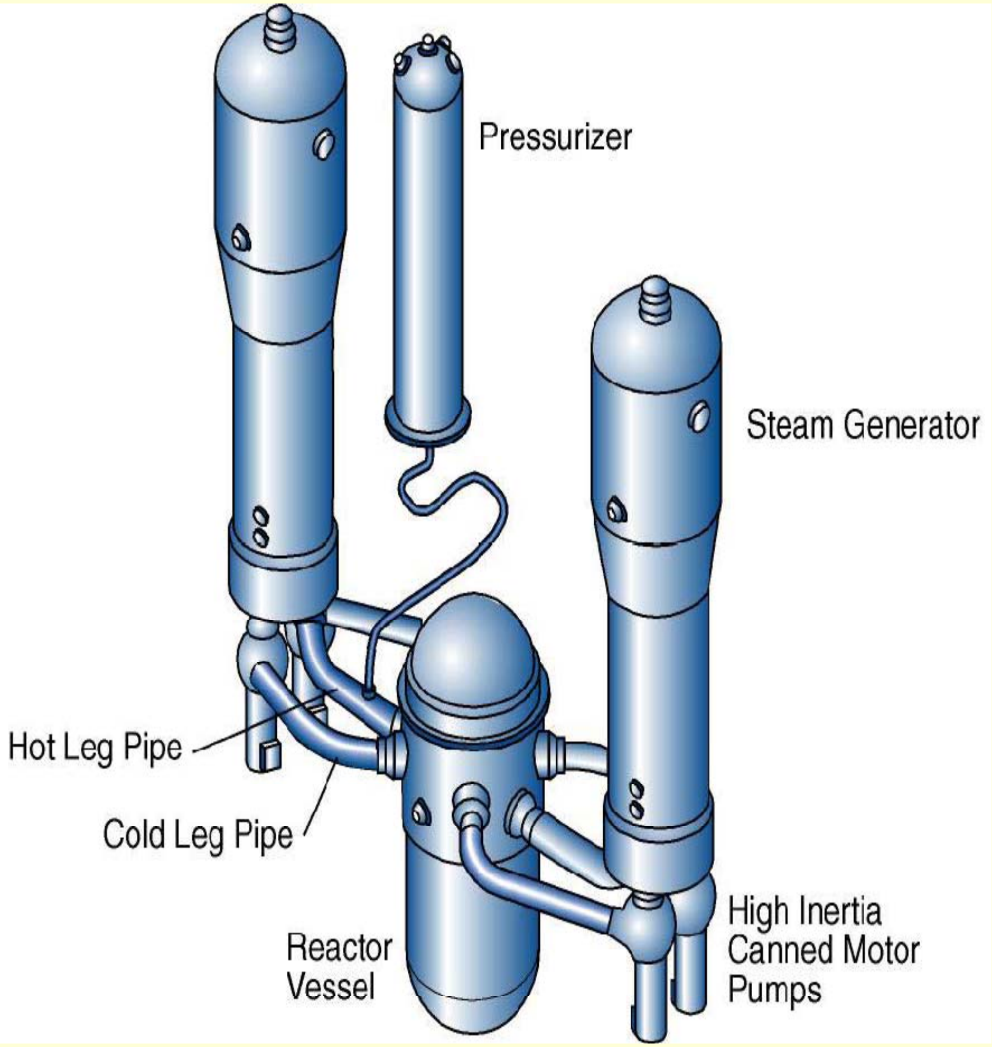
- *Severe accidents mitigation based on core-catcher concept similar to US-EPR*

Advanced Passive 1000
(AP1000)

by Westinghouse-Toshiba

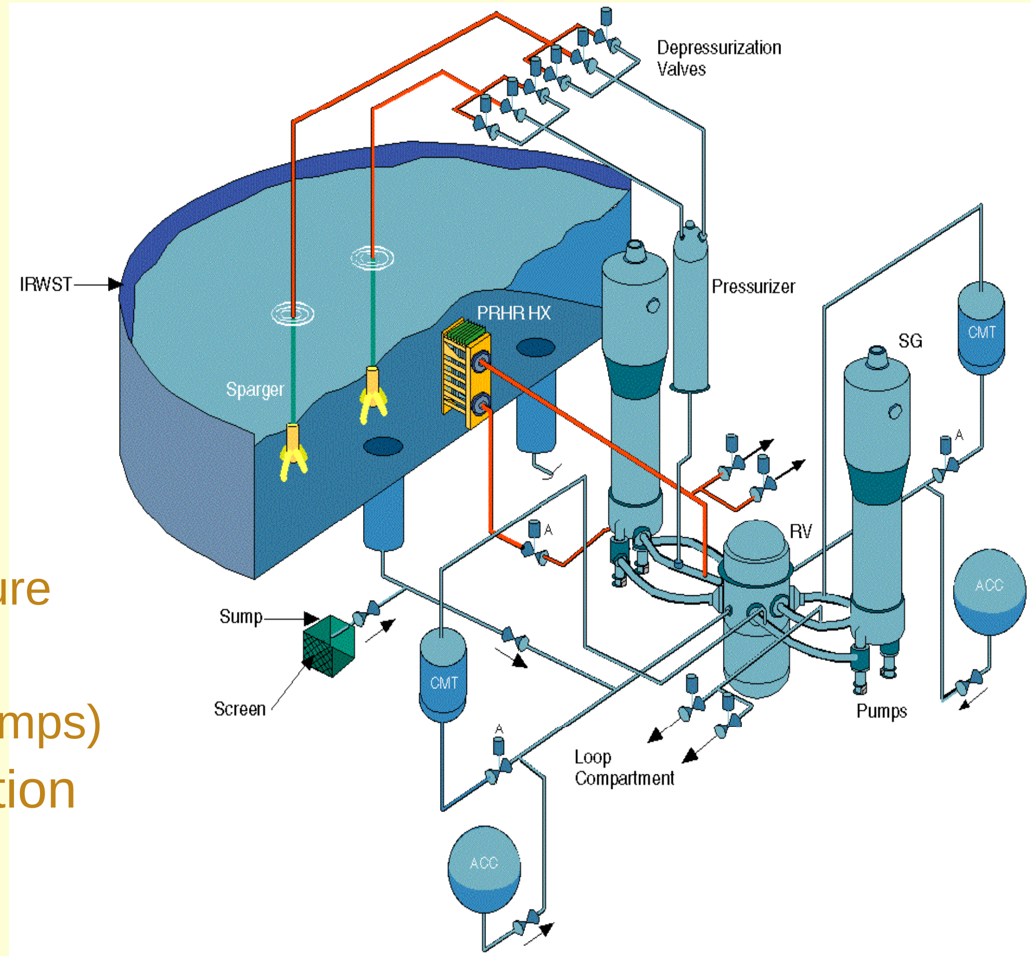
AP1000 Overview

- 1100 MWe PWR
- Typical PWR operating conditions, pressure, temperature, flow rates, linear power, etc.
- RPV with no bottom penetrations
- 2 loops, 2 SGs
- 4 recirculation pumps (canned motor pumps, no shaft seals)
- Large pressurizer
  - 50% larger than operating plants
- All safety-grade systems are passive



AP1000 Passive Core Cooling System

- PRHR HX
  - Natural circ. heat removal
- Passive Safety Injection
  - Core Makeup Tanks (CMT)
    - Full press, natural circ. inject
    - Replaces HPCI pumps
  - Accumulators
    - Kick in at intermediate pressure
  - IRWST Injection
    - Low press (replaces LPCI pumps)
  - Automatic RCS Depressurization



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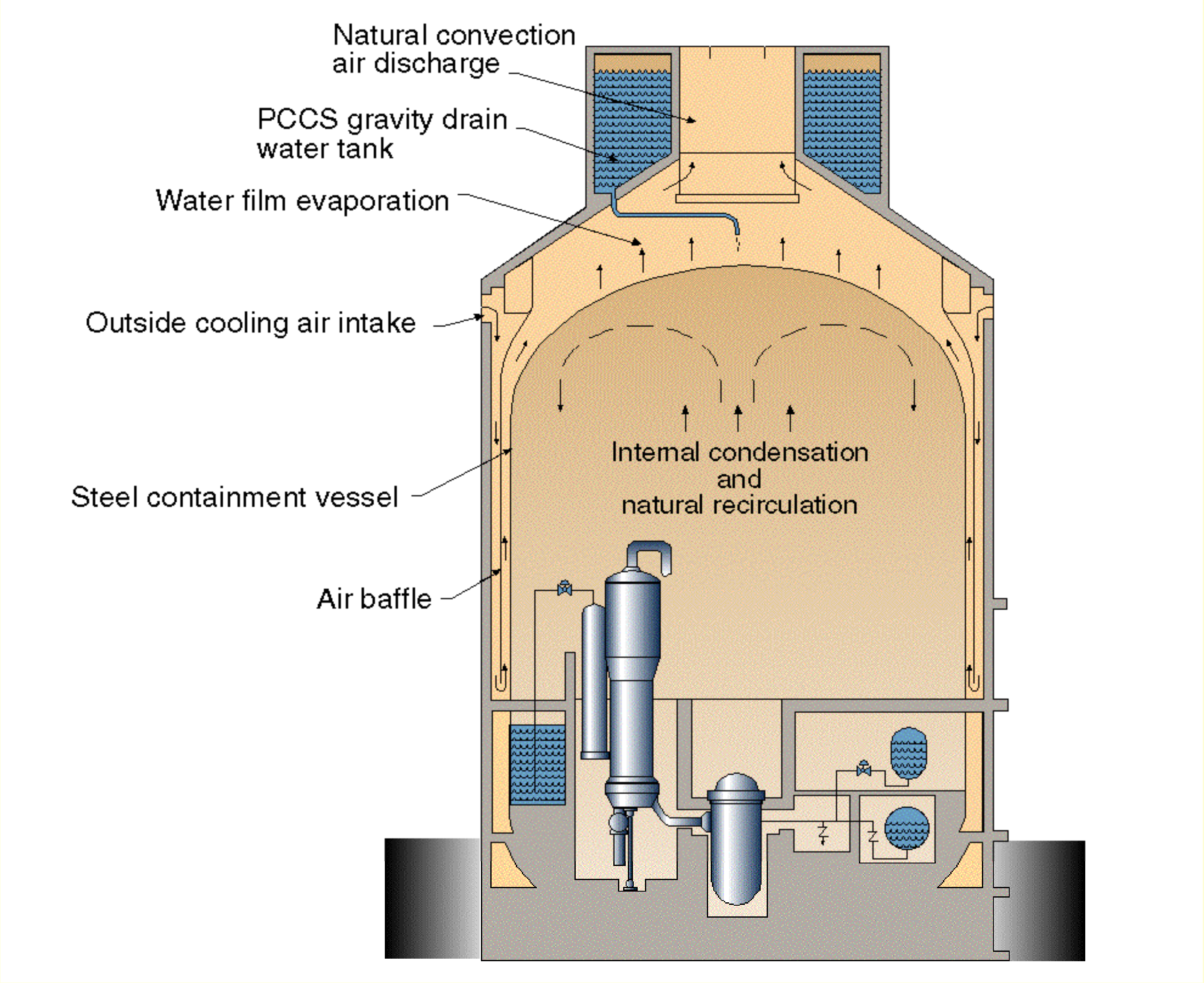
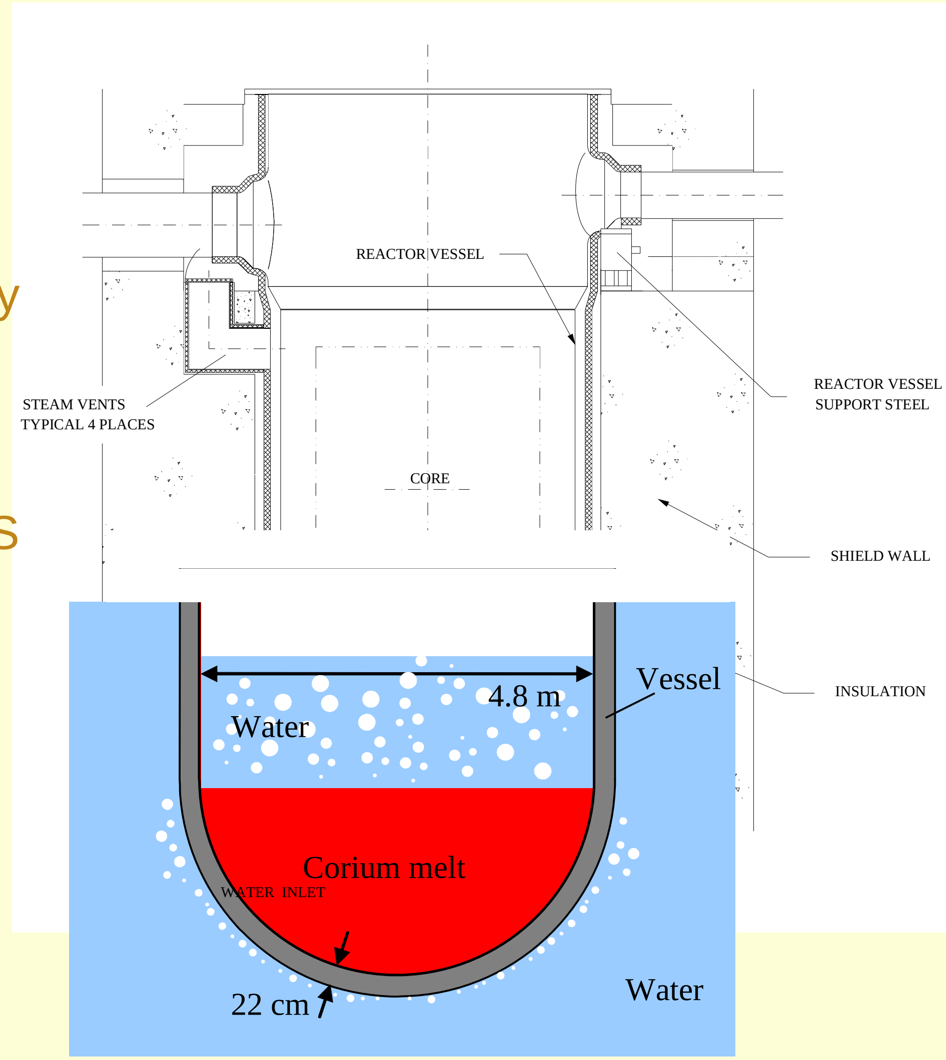
AP1000 Passive Containment Cooling System



AP1000 Severe Accidents Mitigation

- Core-Concrete Interaction
  - In-Vessel Retention (IVR) / ex-vessel cooling
  - Means of cooling damaged core
  - Tests and analysis of IVR reviewed by U.S. NRC
- High Pressure Core Melt
  - Eliminated by redundant, diverse ADS
- Hydrogen Burn, Detonation
  - Hydrogen vent paths from RCS kept away from containment shell
  - Redundant, diverse igniters
- Steam Explosions
  - Ex-vessel prevented by IVR



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AP1000 videos

ECCS
http://www.ap1000.westinghousenuclear.com/ap1000_psrs_pccs.html

PCCS
http://www.ap1000.westinghousenuclear.com/ap1000_psrs_pcs.html

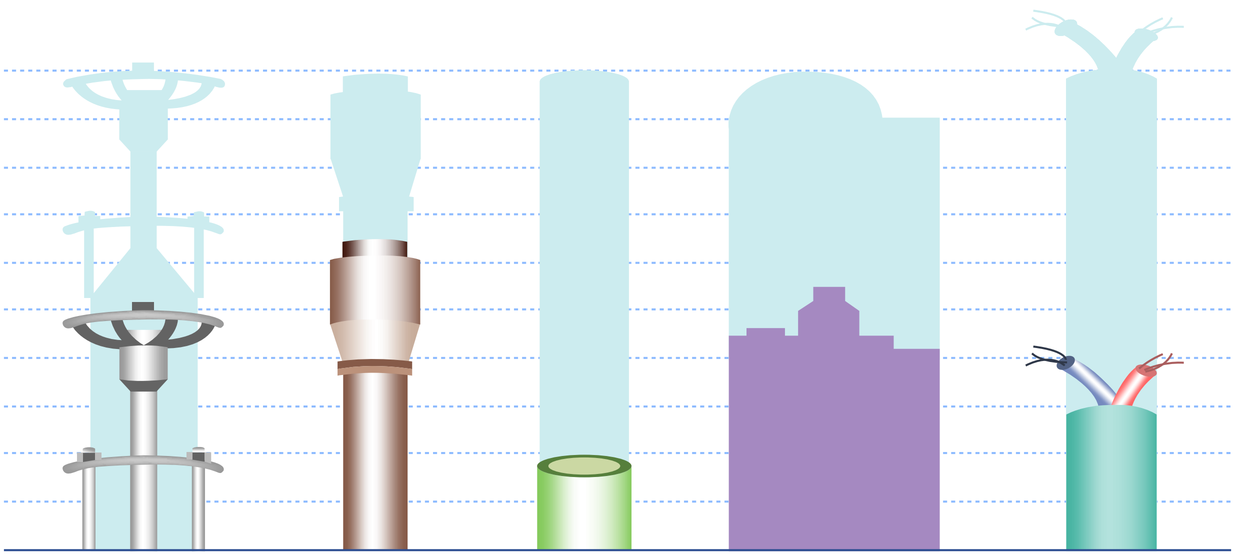
IVR
http://www.ap1000.westinghousenuclear.com/ap1000_safety_ircd.html

AP1000 Safety Margins and Risk

	Typical Plant	AP1000
• Loss Flow Margin to DNBR Limit	~ 1 - 5%	~16%
• Feedline Break (^oF) Subcooling Margin	>0^oF	~140^oF
• SG Tube Rupture	Operator actions required in 10 min	Operator actions **NOT** required
• Small LOCA	3" LOCA core uncovers PCT ~1500^oF	< 8" LOCA **NO** core uncovery
• Large LOCA PCT (^oF) with uncertainty	2000 - 2200^oF	<1600^oF (1)

	Core Damage Frequency		Large Release Frequency	
	At-Power	**Shutdown**	**At-Power**	**Shutdown**
Internal Events	2.41E-07 /yr	1.23E-07 /yr	1.95E-08 /yr	2.05E-08 /yr
Internal Floods	8.80E-10 /yr	3.22E-09 /yr	7.10E-11 /yr	5.40E-10 /yr
Internal Fires	5.61E-08 /yr	8.52E-08 /yr	4.54E-09 /yr	1.40E-08 /yr
Sub-Totals	2.98E-07 /yr	2.11E-07 /yr	2.41E-08 /yr	3.50E-08 /yr
Grand-Totals	5.09E-07		5.92E-08	
NRC Safety Goals	1 E-4		1 E-6	

Use of passive safety systems simplifies the plant

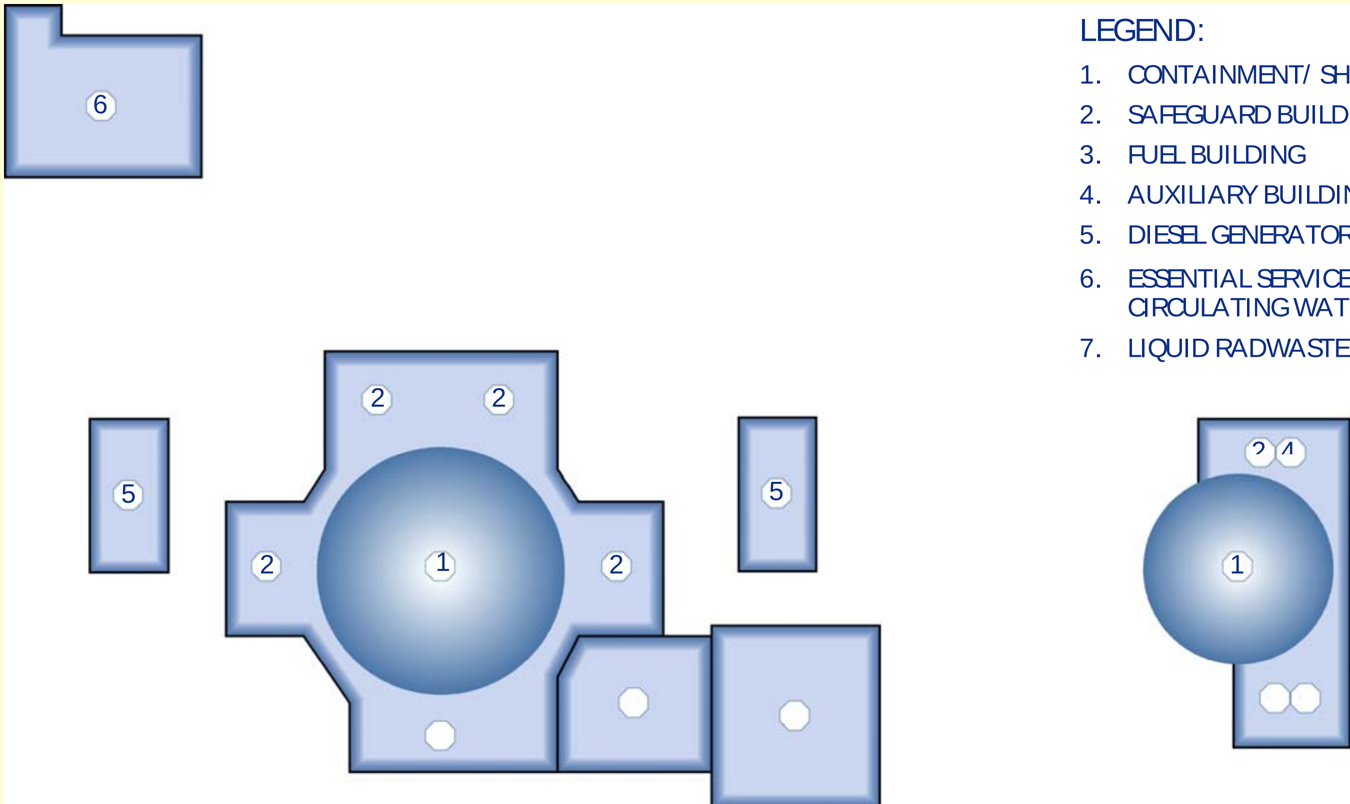


Reduced Number of Components:

	1000 MW Reference	AP 1000	Reduction
Safety Valves	2844	1400	51%
Pumps	280	184	34%
Safety Piping	11.0 x 10^4 feet	1.9 x 10^4 feet	83%
Cable	9.1 mil. feet	1.2 mil. feet	87%
Seismic Building Volume	12.7 mil. ft^3	5.6 mil. ft^3	56%

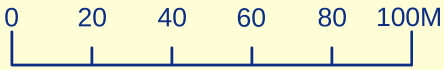
Image by MIT OpenCourseWare.

…and Reduces Safety/Seismic Building Volume



EPR
Safety / Seismic Structures

AP1000
Safety / Seismic Structures



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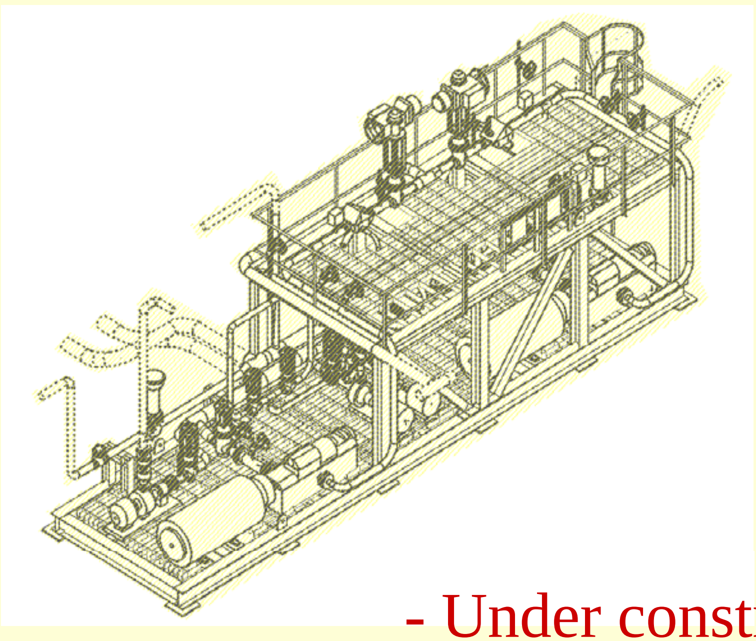
AP1000 Construction

- Simplification of Systems
  - Reduction in bulk materials and field labor
- Maximum Use of Modularization
  - 300 rail-shippable equipment and piping modules
  - 50 large structural modules (assembled on-site)



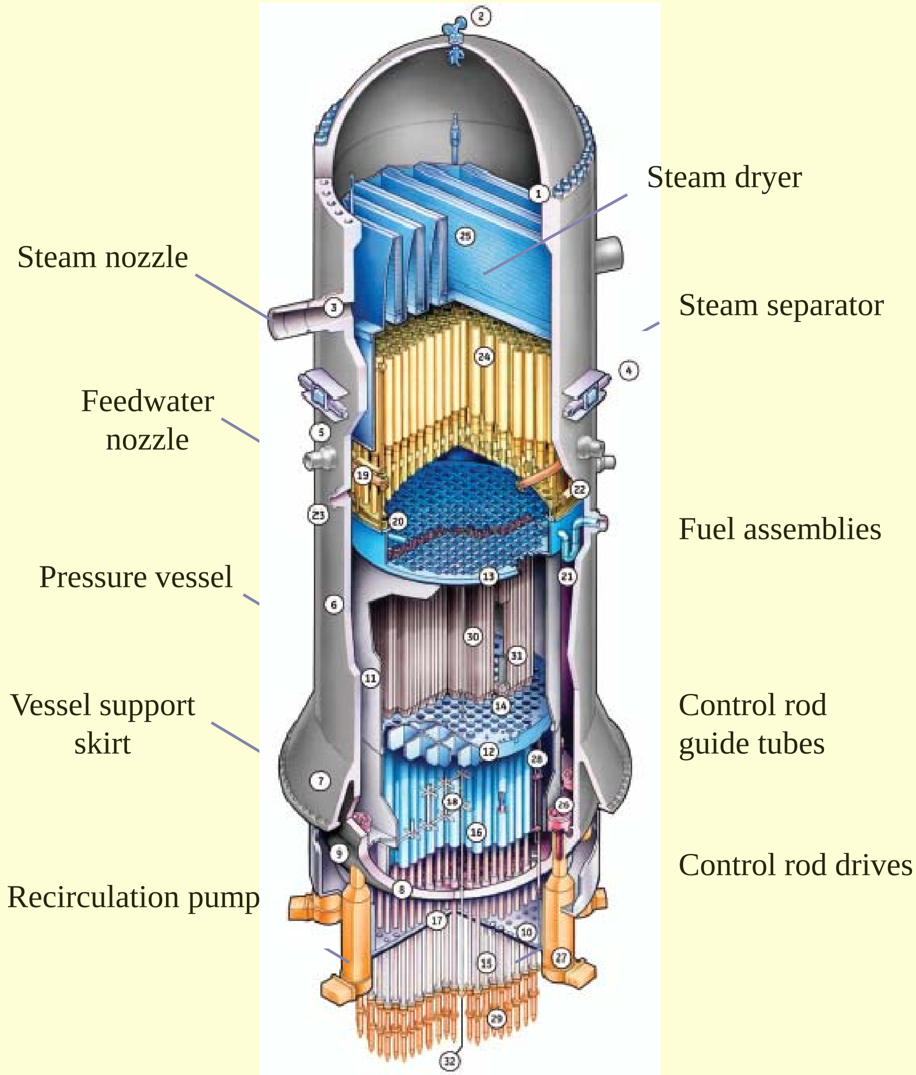
- Under construction at Taishen (China) since 2008

- 4 P&E orders in US

Advanced BWR (ABWR) and Economic Simplified BWR (ESBWR)

by General Electric-Hitachi

ABWR Overview



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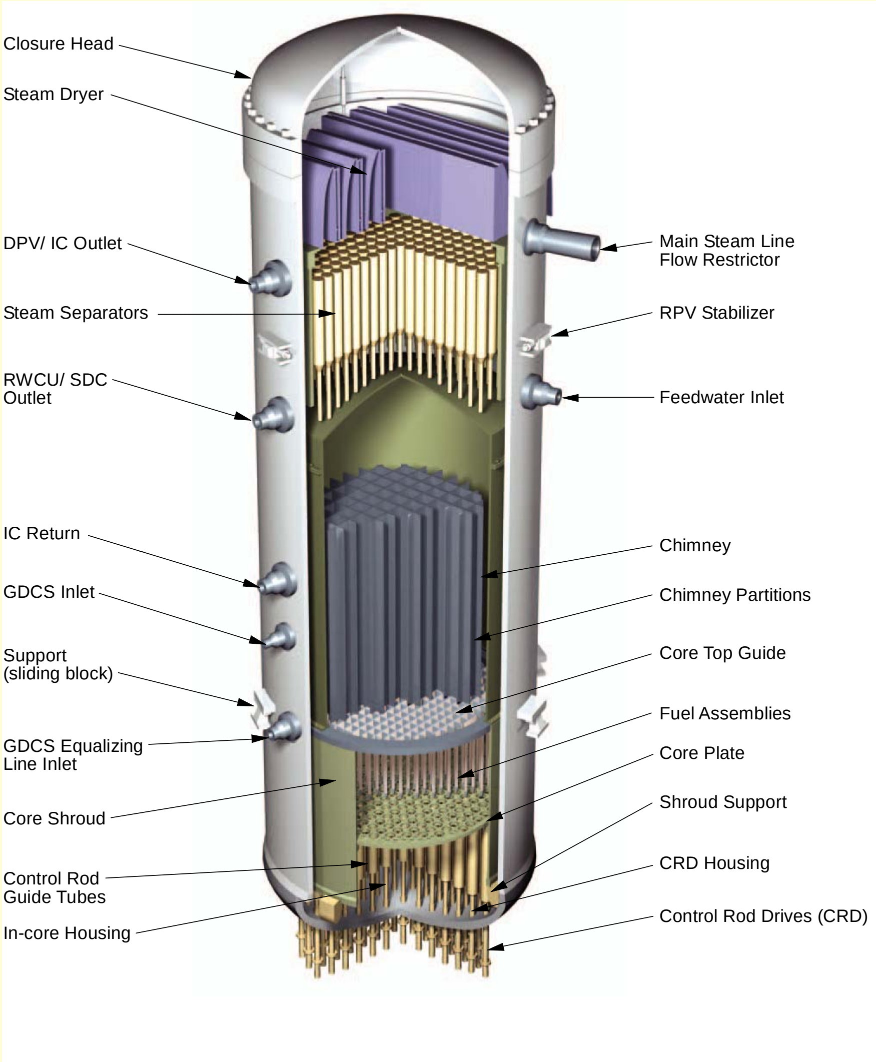
- 1350 MWe BWR
- Typical BWR operating conditions, pressure, temperature, linear power, etc.
- Internal recirculation pumps (no jet pumps) = no external loop
- Large vessel with large water inventory + no large piping = no core uncovery
- Redundant active safety systems
- Proven technology (built and operated for over ten years in Japan and Taiwan)

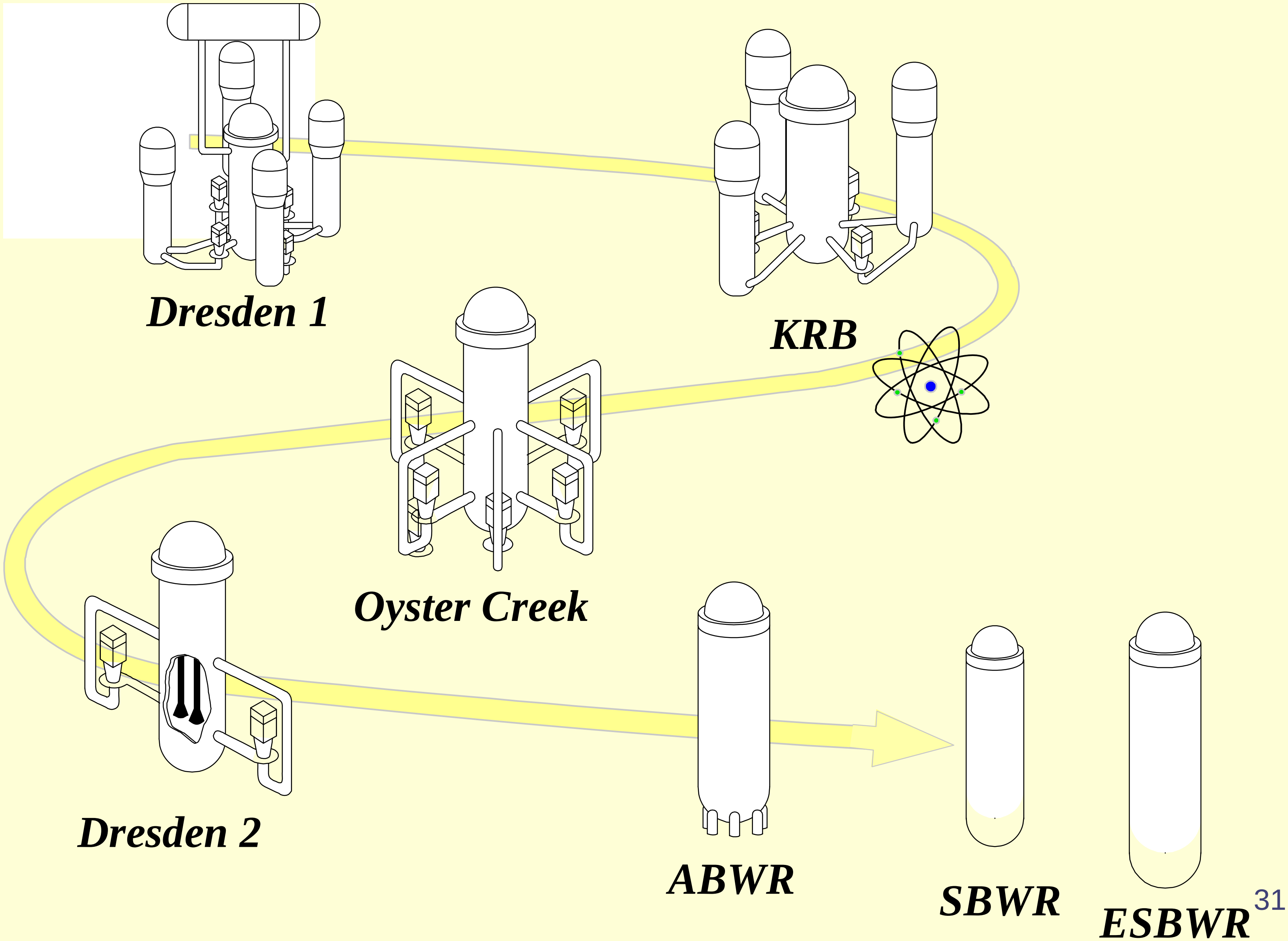
ESBWR Overview



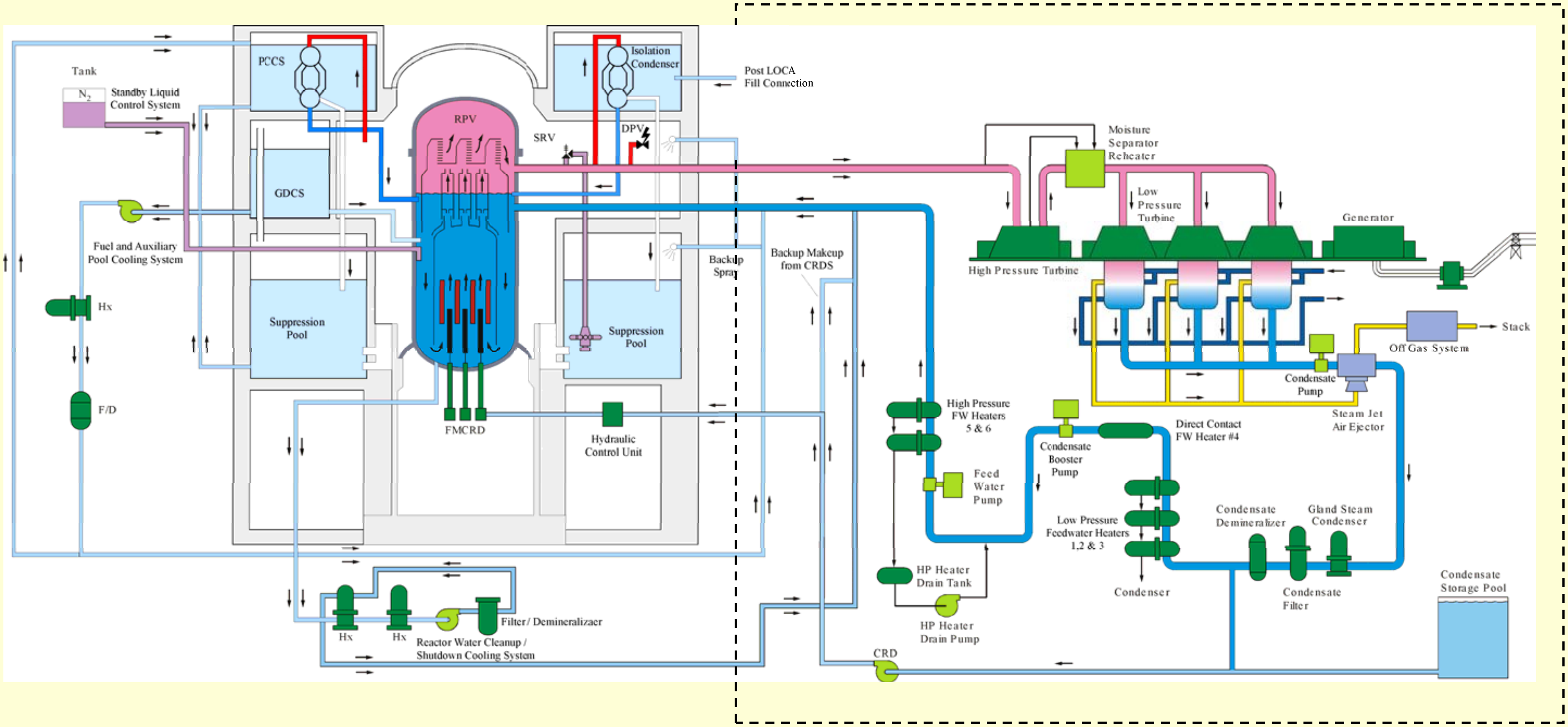
ESBWR Reactor

- 1550 MWe BWR
- Typical BWR operating conditions, pressure, temperature, linear power, etc.
- Natural circulation reactor = No reactor pumps
- Large vessel with large water inventory
- Core at lower elevation within vessel
- All safety-grade systems are passive

BWR Primary System Evolution



ABWR & ESBWR Balance of Plant is Traditional



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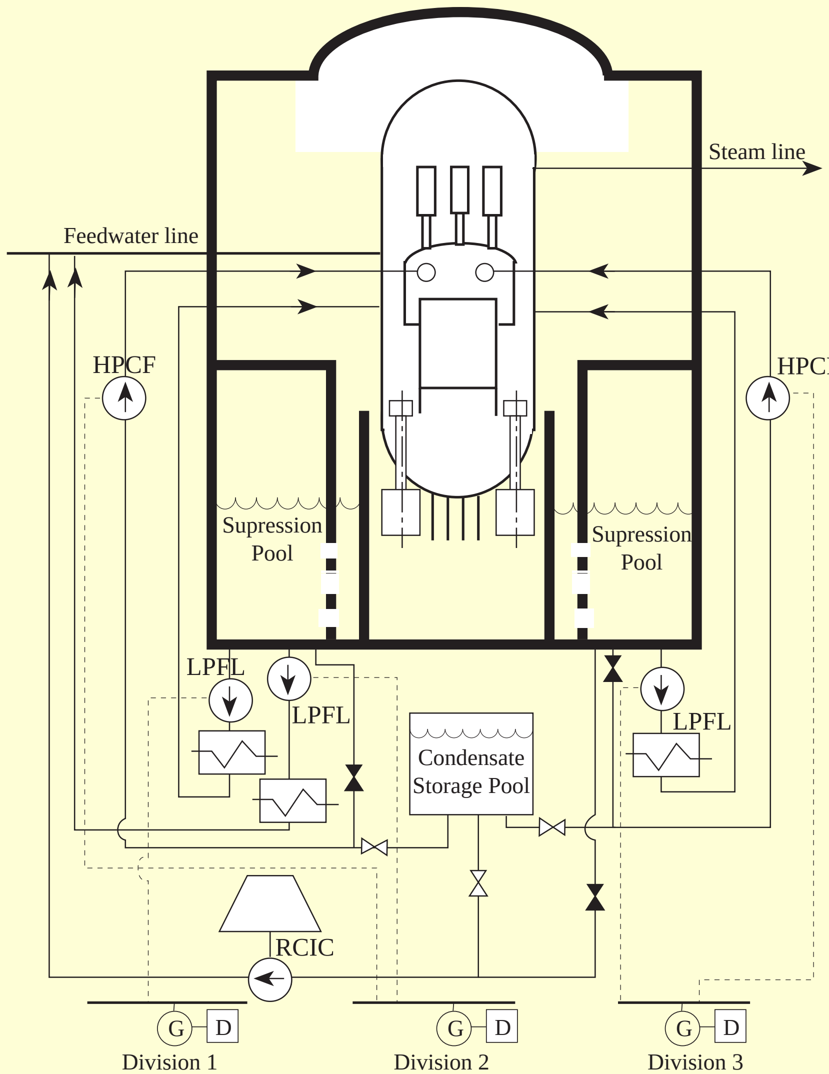
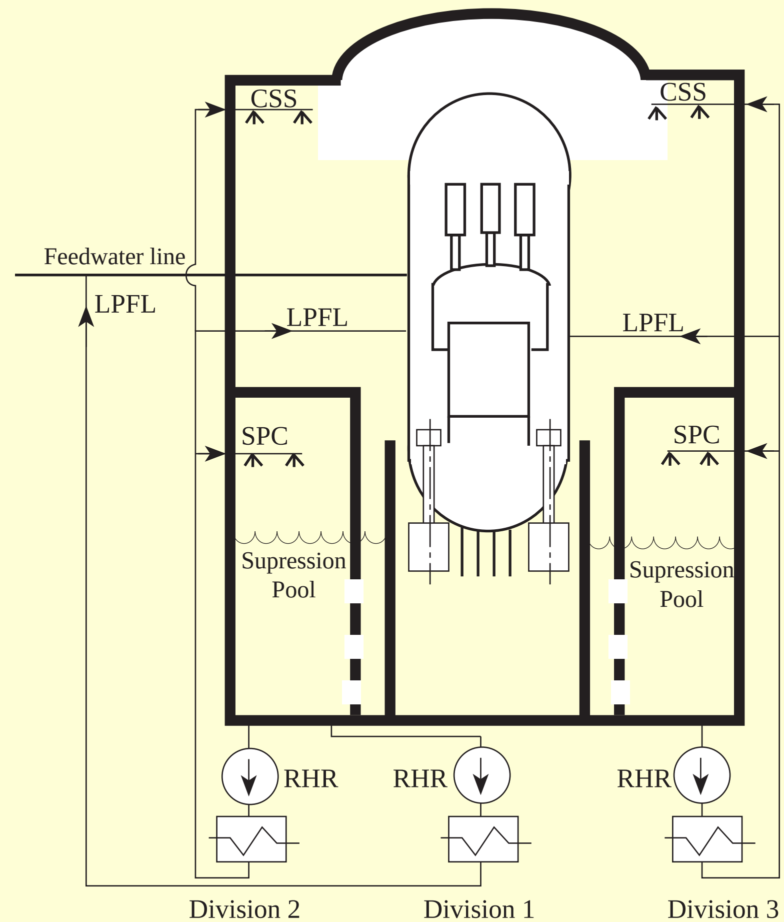
ABWR & ESBWR Parameters

Parameter	BWR/4-Mk I(Browns Ferry 3)	BWR/6-Mk III (Grand Gulf)	ABWR	ESBWR
Power (MWt/MWe)	3293/1098	3900/1360	3926/1350	4500/1550
Vessel height/dia. (m)	21.9/6.4	21.8/6.4	21.1/7.1	27.7/7.1
Fuel Bundles (number)	764	800	872	1132
Active Fuel Height (m)	3.7	3.7	3.7	3.0
Power density (kW/L)	50	54.2	51	54
Recirculation pumps	2(large)	2(large)	10	zero
Number of CRDs/type	185/LP	193/LP	205/FM	269/FM
Safety system pumps	9	9	18	zero
Safety diesel generator	2	3	3	zero
Core damage freq./yr	1E-5	1E-6	1E-7	1E-7
Safety Bldg Vol (m^3/MWe)	115	150	160	<100

ABWR Safety

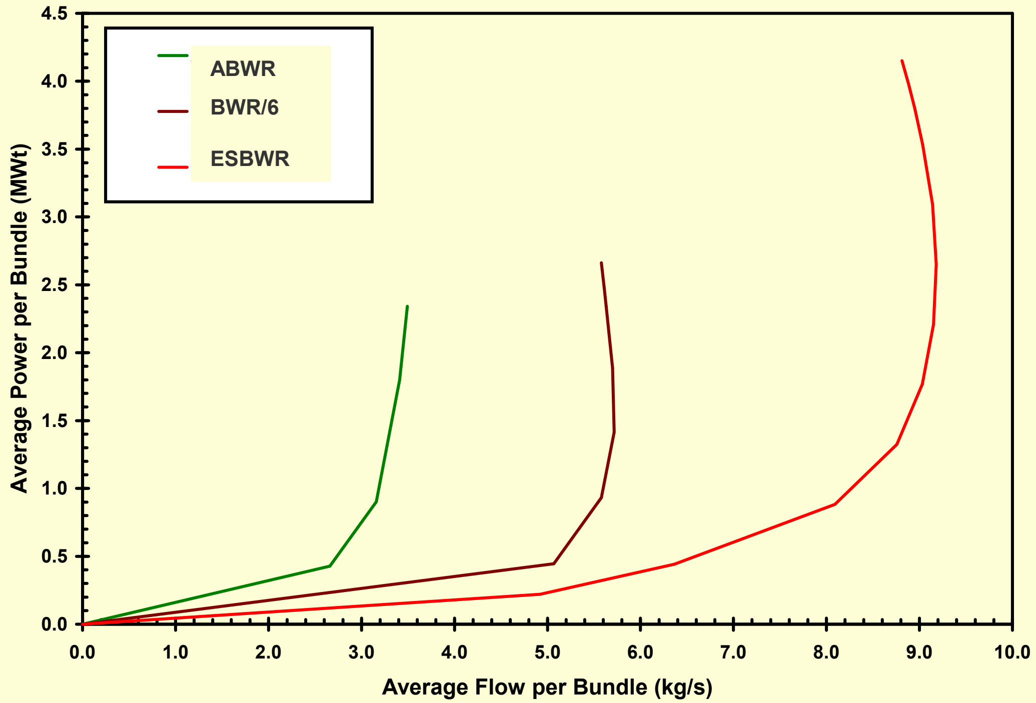


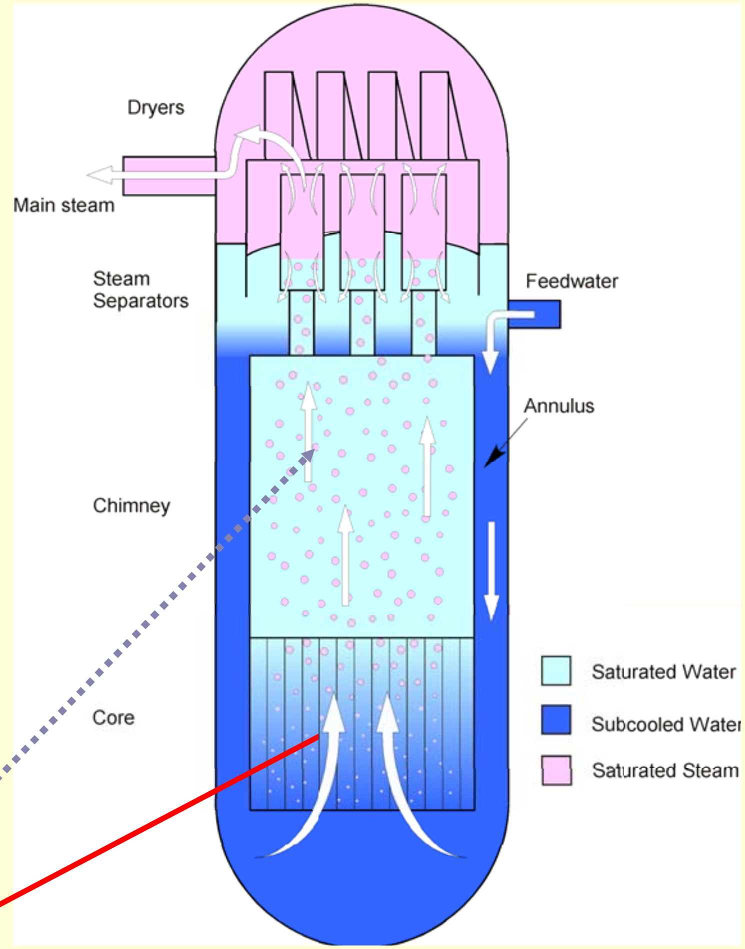
ECCS



RHR

ESBWR Enhanced Natural Circulation





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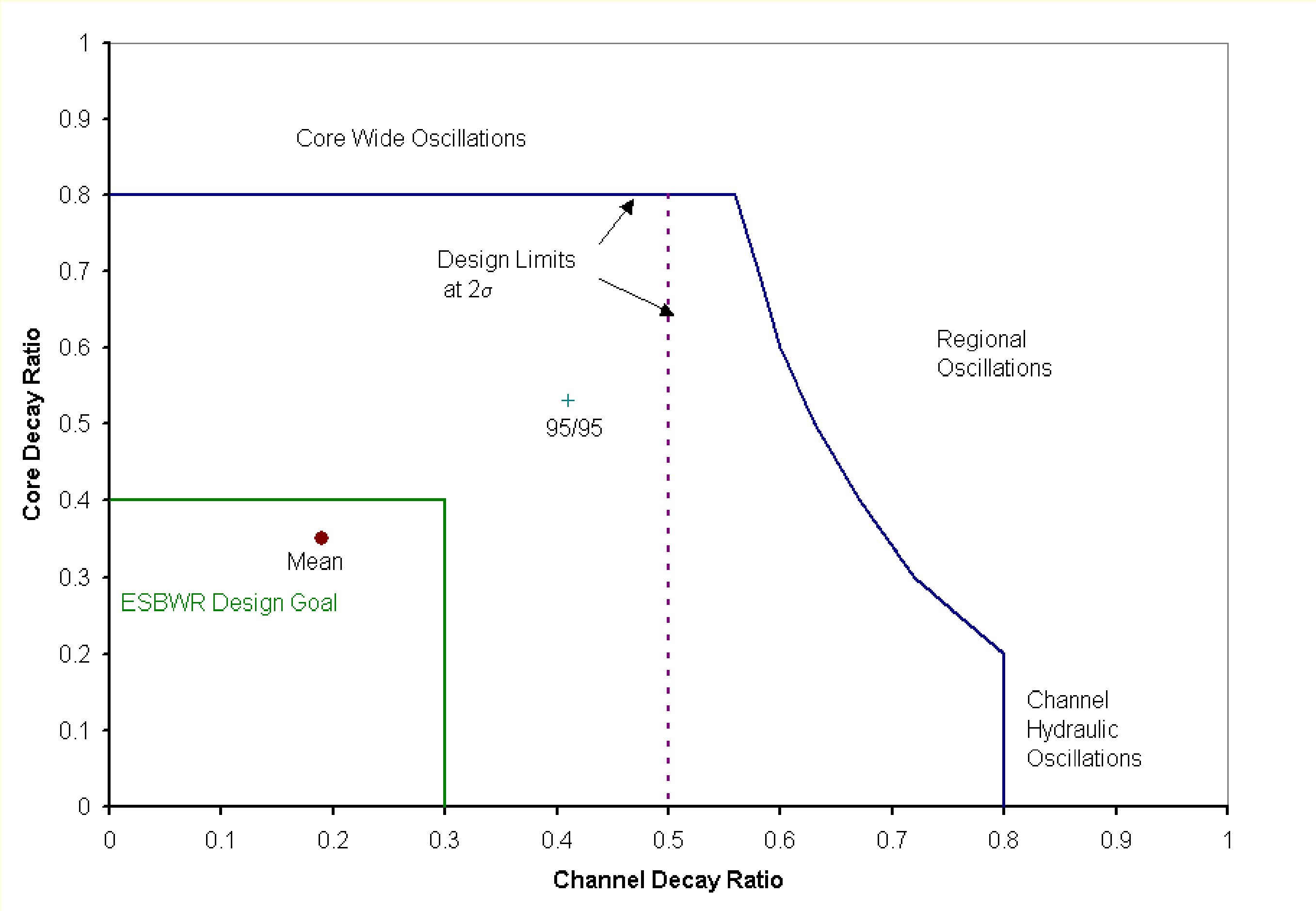
- Higher driving head
  - Chimney/taller vessel
- Reduced flow restrictions
  - Shorter core
  - Increase downcomer area

ESBWR Stability



ESBWR is designed to operate with significant margin to any instability regions

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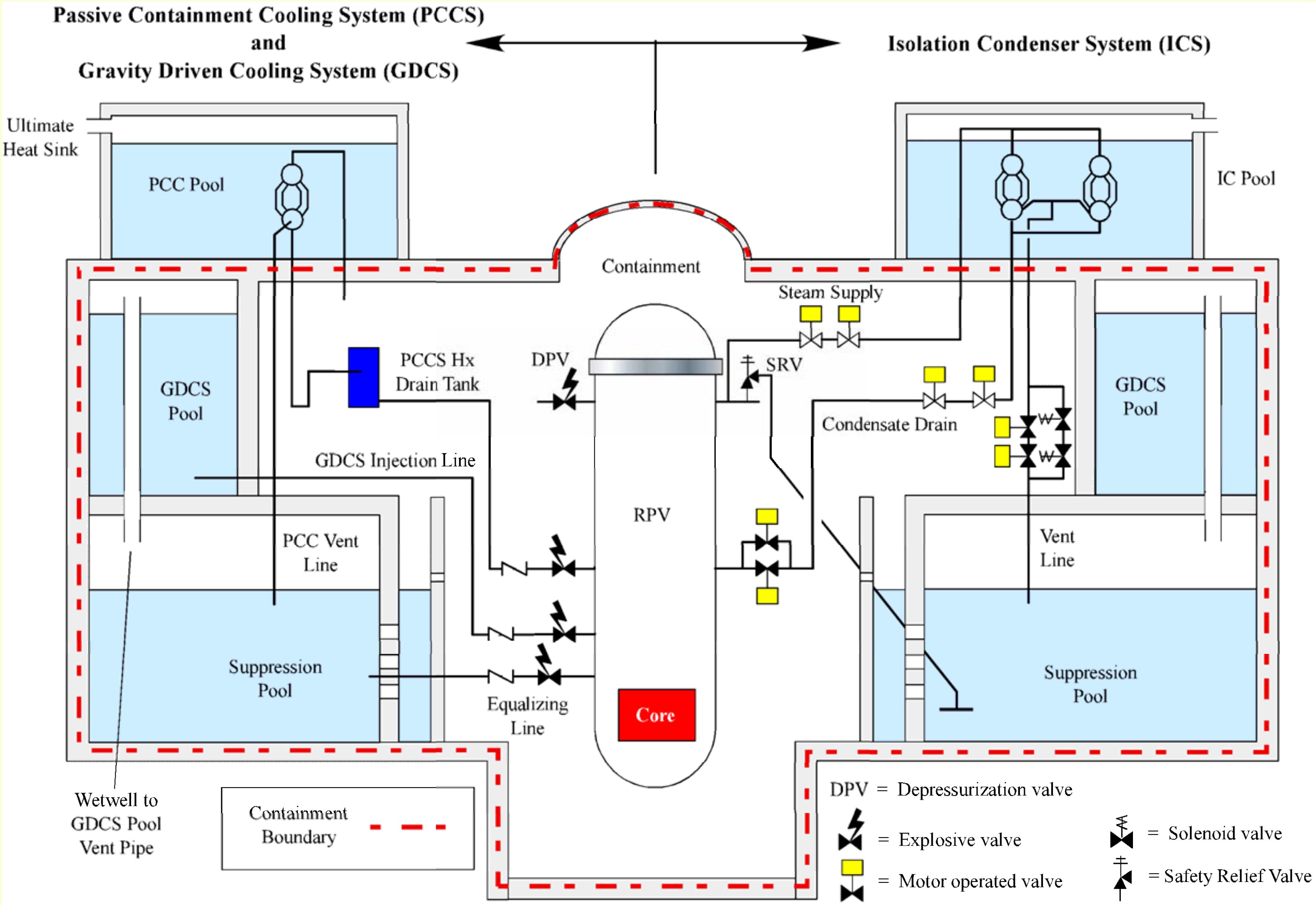
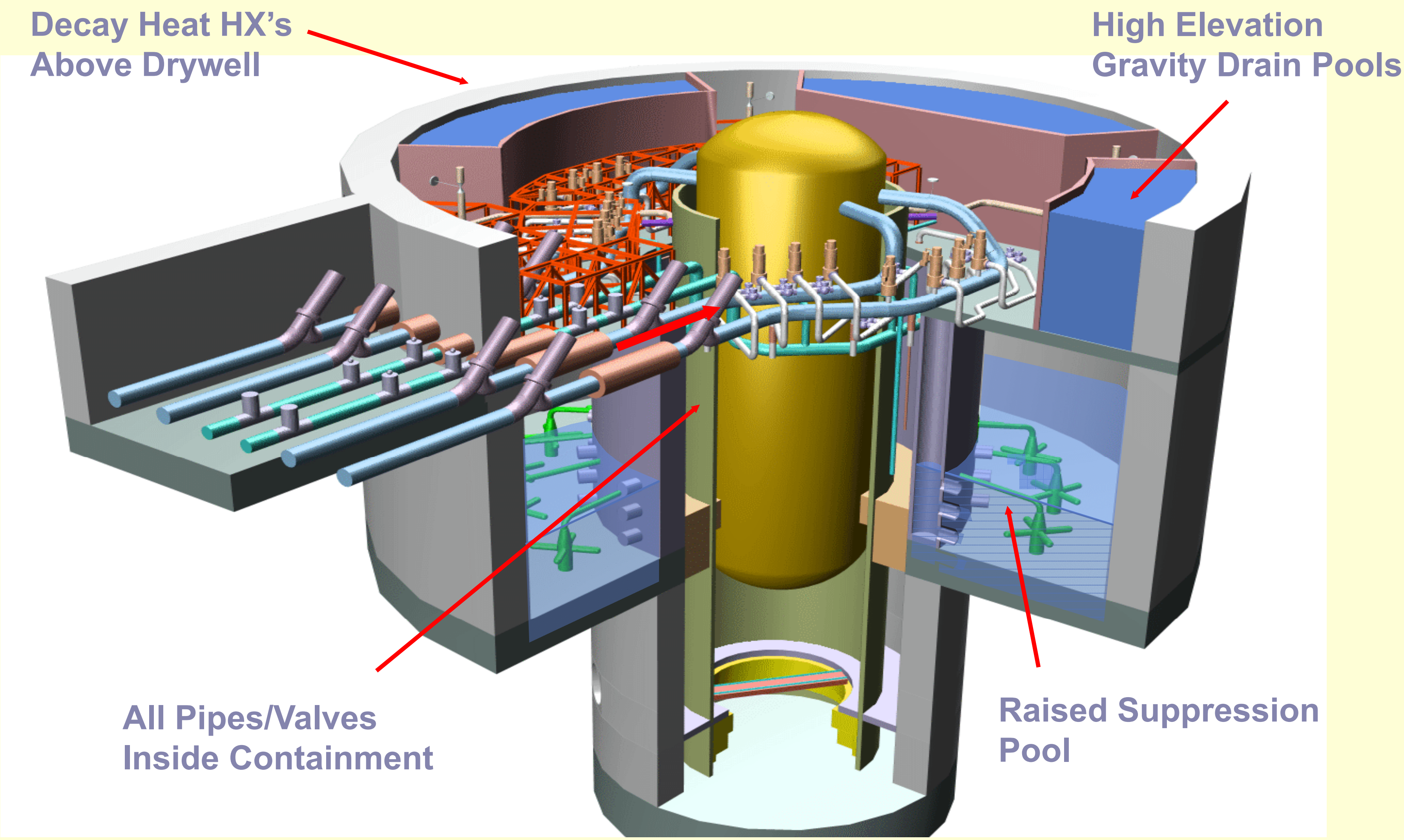
ESBWR Passive Safety



ESBWR Passive Safety



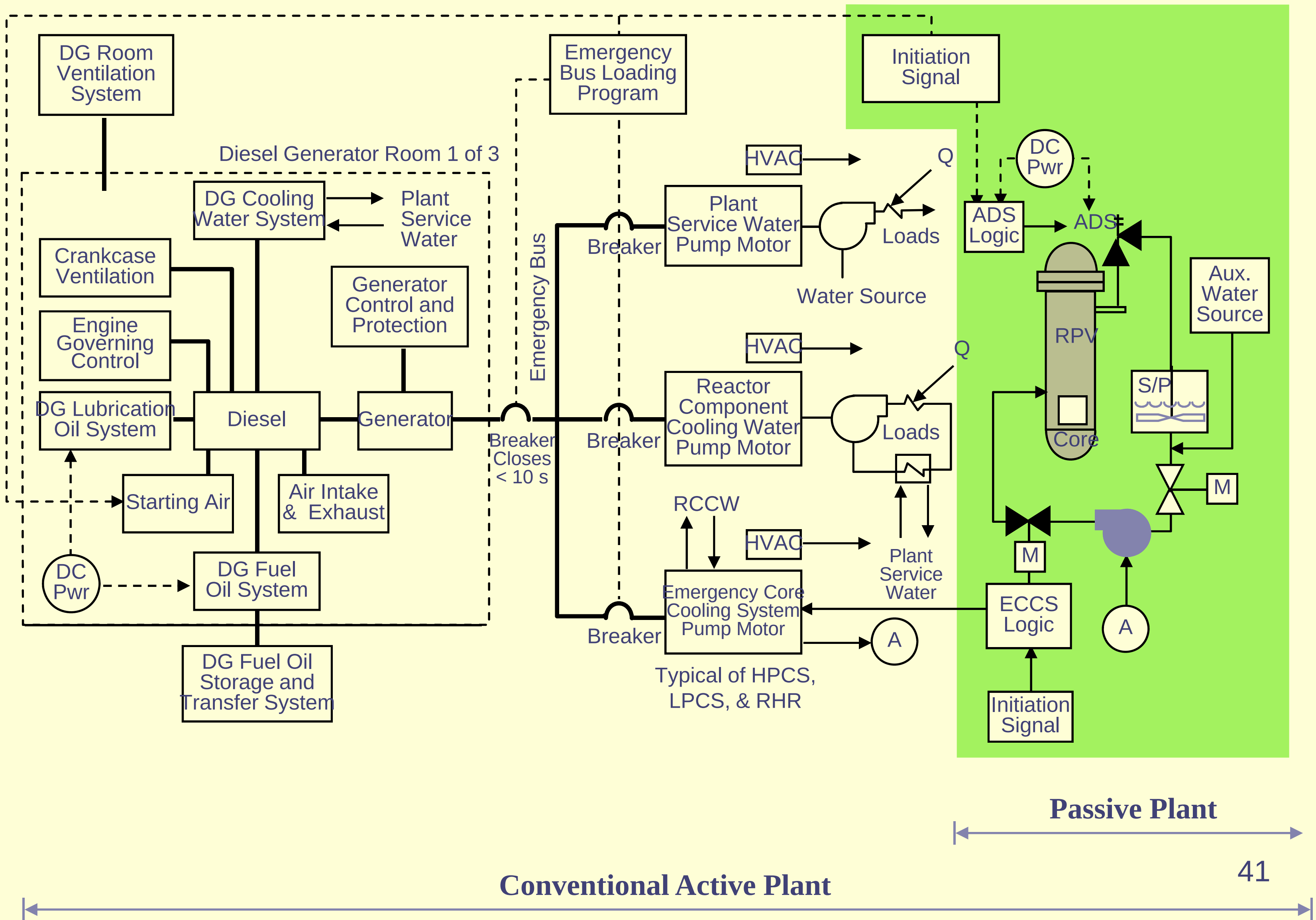
ESBWR Passive Systems

- Isolation Condensers System (ICS)
  - High pressure residual heat removal
- Safety Relief Valves (SRV)
  - Prevent reactor overpressurization discharging steam into suppression pool
- Suppression Pool
  - Absorbs blowdown energy during LB-LOCA.
- Gravity Driven Cooling System (GDCS)
  - Low pressure residual heat removal following LB-LOCA. Keeps the core covered.
- Passive Containment Cooling System (PCCS)
  - Long-term heat removal from containment
  - No operator action needed for 72 hours

ESBWR Severe Accident Mitigation

- Containment filled with inert gas
- In-vessel retention is complicated by CRDM penetrations, so it is not done.
- Quench molten core by deluge from the GDCS tanks
- If molten material drips through vessel, there is a sacrificial concrete shield (core catcher) on the containment floor
- Easy to refill PCCS pool and continue to remove the heat from the vessel indefinitely
- Fission Product Control
  - Hold up and filtering

Comparison of Safety System - Passive vs. Active



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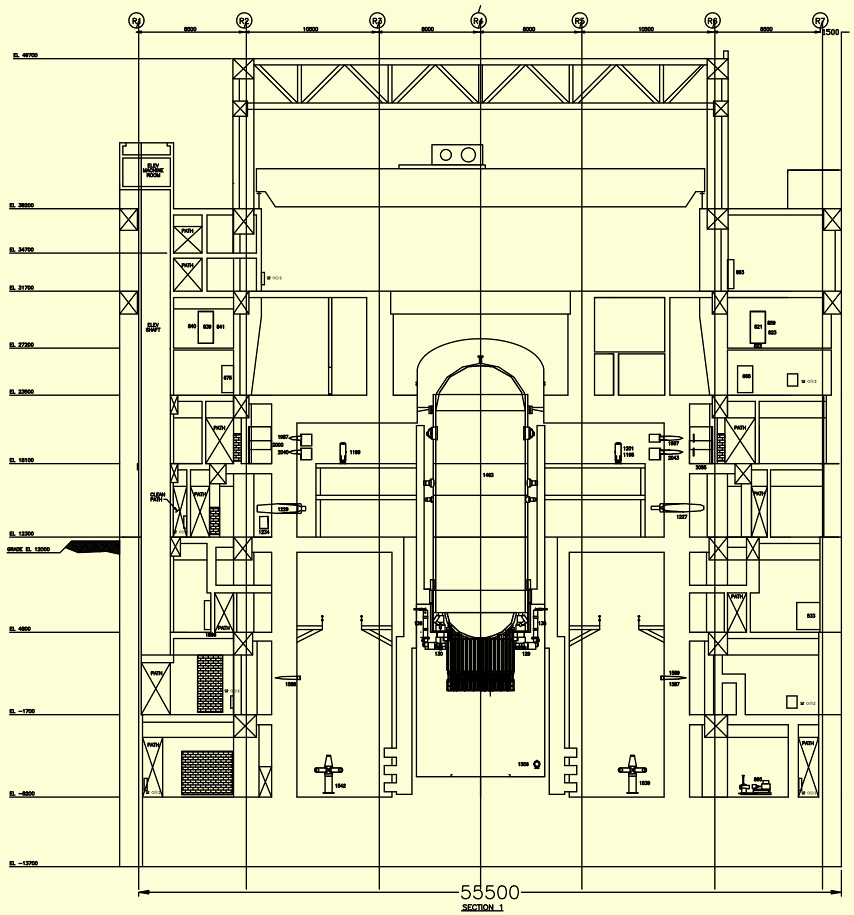
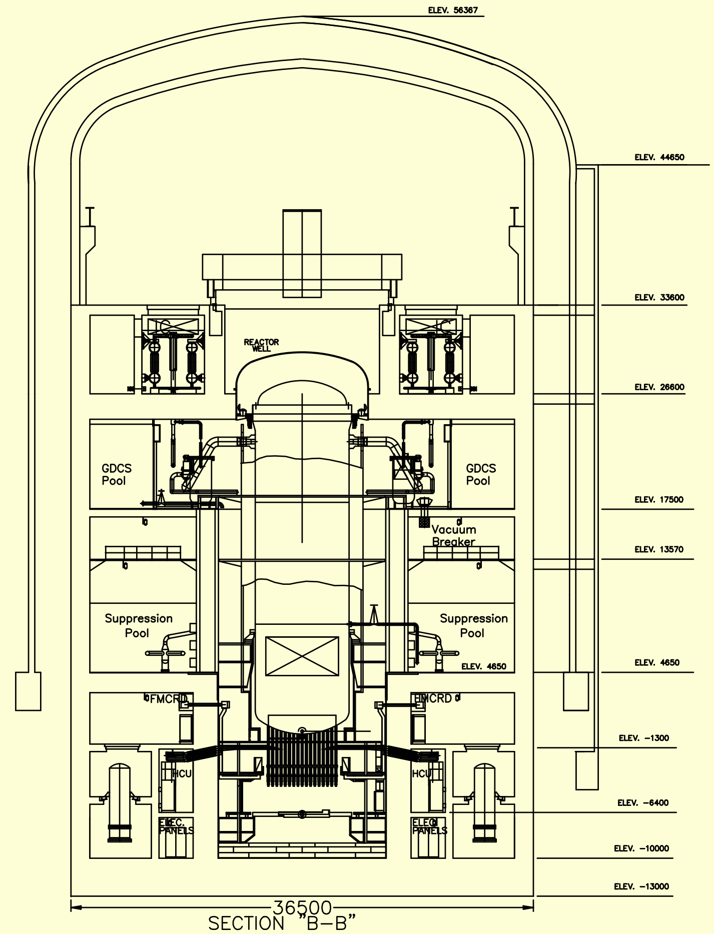
Reduction in Systems & Buildings with Passive Systems



ABWR



ESBWR

(higher power, smaller building)

Summary Features of Advanced LWRs

Reactor	**US-EPR**	**US-APWR**	**AP1000**	**ABWR**	**ESBWR**
Neutron spectrum	Thermal	Thermal	Thermal	Thermal	Thermal
Coolant/moderator	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O	H_2O/H_2O
Fuel	LEU pins	LEU pins	LEU pins	LEU pins	LEU pins
Use of proven technology	++	++	+	++	+
Plant simplification			++		++
Modular construction			+		+
Economy of scale	++	++		+	++
High thermal efficiency	+	+			
Passive safety			+		+
Mitigation of severe accidents	Core catcher	Core catcher	In-vessel retention	-	Core catcher

Potential Issues for Deployment of Advanced LWRs in the U.S.

- No capabilities for manufacturing heavy components left. Need to buy from overseas.
- Shortage of specialized workforce experienced in nuclear construction (e.g., welders).
- Slow licensing process
- Financial risk in deregulated markets

22.06 Engineering of Nuclear Systems
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