The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

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Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

3 - 14 May 2010

Worldwide Technology Development of Advanced NPPs

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Worldwide Technology Development of Advanced NPPs

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IAEA/ICTP Workshop on Nuclear Reaction Data for Advanced Reactor Technologies
ICTP, Trieste, May 3 – 14, 2010

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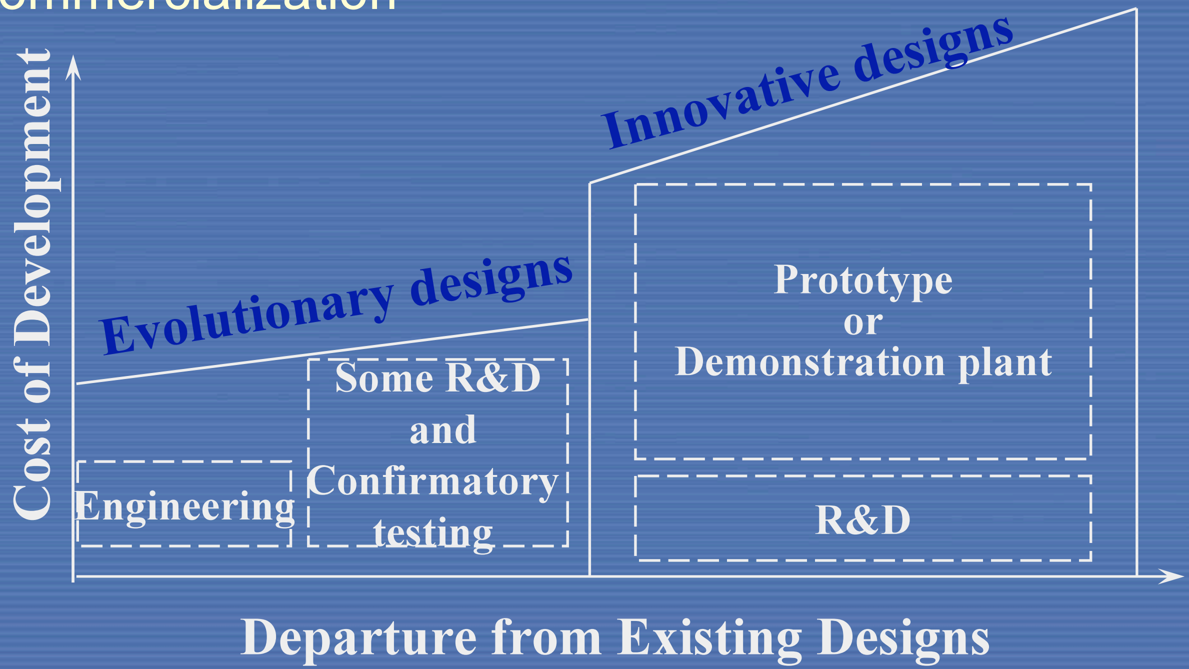
Advanced Designs

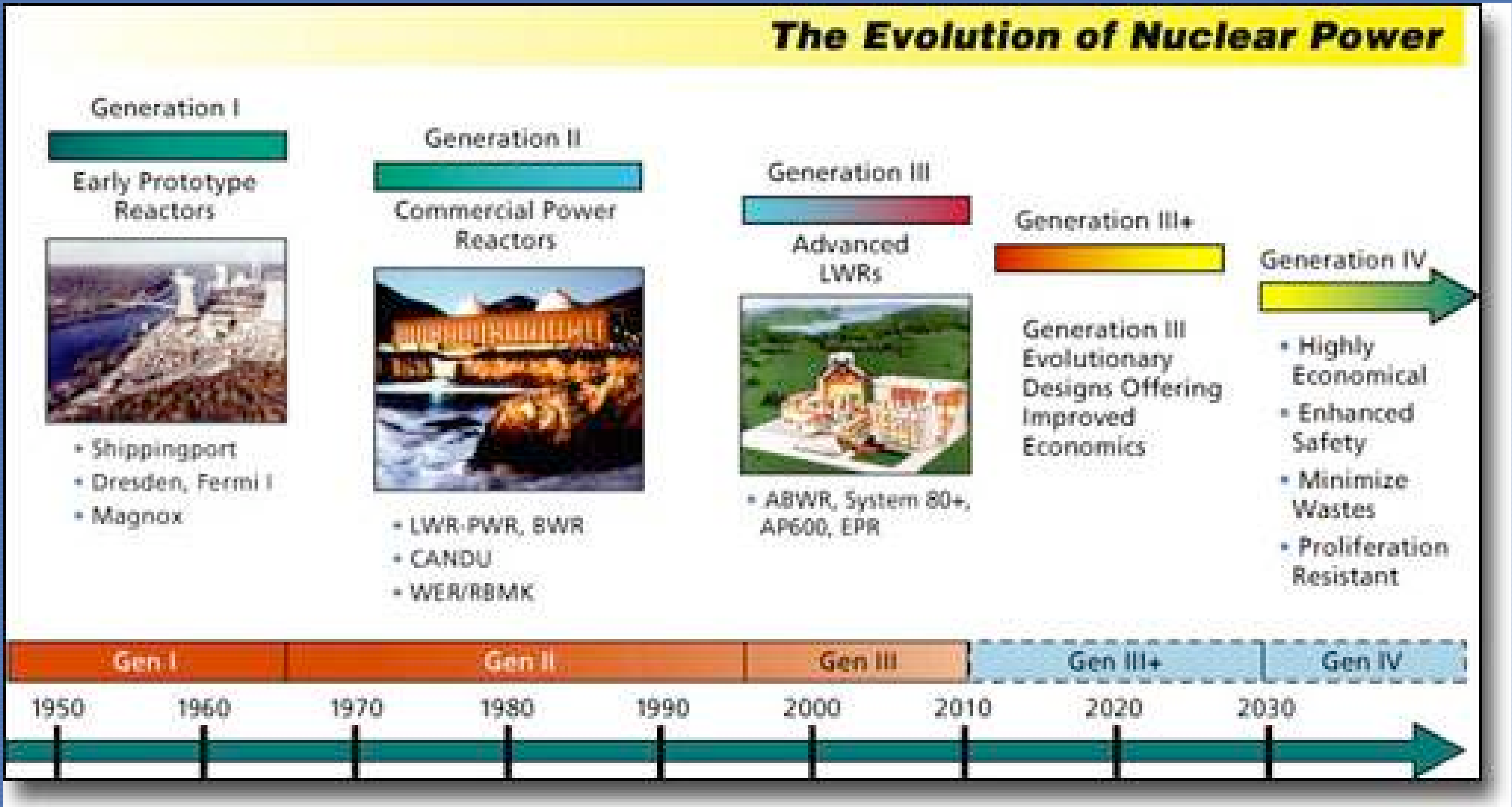
(defined in IAEA-TECDOC-936)

- **Evolutionary designs** - achieve improvements over existing designs through small to moderate modifications

- **Innovative designs** - incorporate radical conceptual changes and may require a prototype or demonstration plant before commercialization



Another classification…



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Evolutionary = Generation III & III+

- Current NPP → Generation II
- Advanced NPP
  - Evolutionary NPP → Generation III, Generation III+
  - Innovative NPP → Generation IV

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Motivation for new designs

- Economics
- Performance
- Safety

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DEVELOPMENT OF ADVANCED DESIGNS

Proven means:

- ***Standardization and series construction***

  Rep. of Korea's Standardized Plants ("OPRs"), Japan's ABWRs, India's HWRs
- ***Multiple unit construction at a site***

  France's 58 PWRs at 19 sites
- ***Improving construction methods to shorten schedule***

  Techniques used at Kashiwazaki-Kariwa 6 &7, Hamaoka 5 & Shika-2; Qinshan III 1&2; Lingau 1&2; Yonggwang 5&6; Tarapur 3&4
- ***In developing countries, furthering self-reliance by increasing portion of construction and component fabrication performed domestically***

  Experience at Qinshan III 1&2; Lingau 1&2; Yonggwang 5&6, Cernavoda 1&2
- ***Economy of scale***

  N4 and Konvoi to EPR; KSNP to APR-1400; ABWR to ABWR-II; AP-600 to AP-1000; 1550 MWe ESBWR; 220 MWe HWR to 540 & 700 MWe HWR; WWER-1000 to WWER-1500

DEVELOPMENT OF ADVANCED DESIGNS[2]

New Approaches:

- ***Streamlining regulatory requirements***
- ***Simplification***
- ***Modularization, factory fabrication, and series production*** (e.g. for SMRs)
- ***Development of highly reliable components and systems, including "smart" (instrumented and monitored) components*** with methods for detecting incipient failures to improve reliability and reduce dependence on costly redundancy and diversity practices
- ***Improving the technology base for reducing over-design*** decreasing the need for large margins simply to allow for limitations of calculational methodology and data uncertainties
- ***Development of passive safety systems[1]*** for cases where the safety function can be met more simply than with active systems
- ***Improved corrosion resistant materials***
- ***Design features for longer lifetime***

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[1] defined in IAEA-TECDOC-626

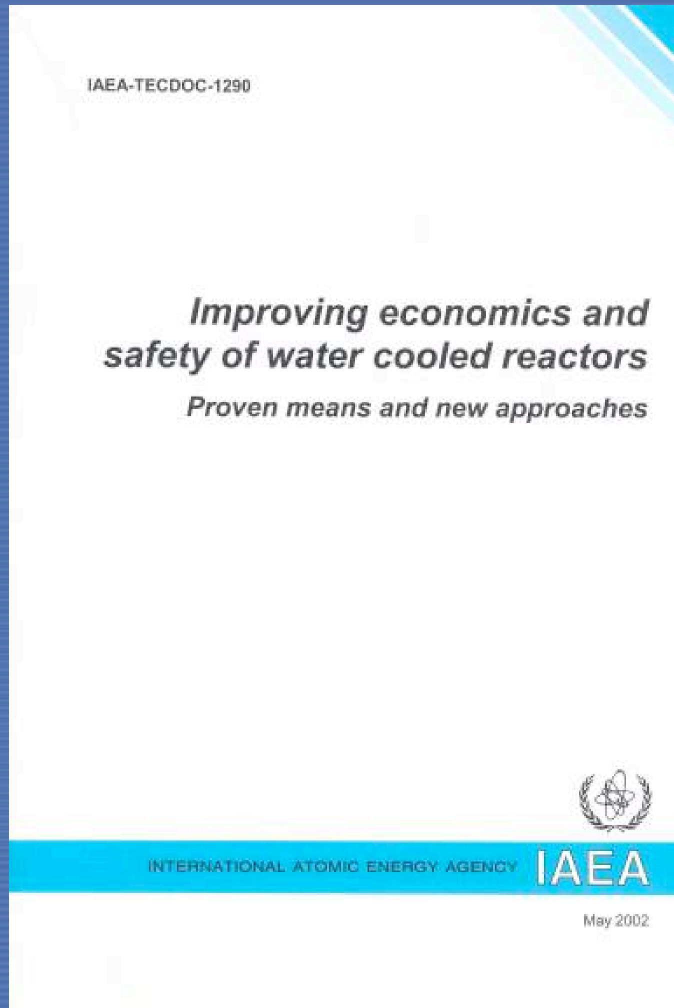
DEVELOPMENT OF ADVANCED DESIGNS[3]

New Approaches:

- ***Development of computer based techniques*** for co-ordinating design, procurement, manufacture, construction and maintenance
- ***Further development of PSA methods and databases to support***
  - plant simplification, and
  - establishment of risk-informed regulatory requirements
- ***Establishment of user design requirements*** including strong focus on economic competitiveness (EPRI-URD; European Utility Requirements, etc)
- ***Establishment of international consensus regarding commonly acceptable safety requirements*** so that standardized designs could be built in many countries without extensive re-design efforts
- ***Development of systems with higher thermal efficiency; and expanded applications***
- ***Advanced project management***

MEANS OF IMPROVING ECONOMICS WHILE MEETING STRINGENT SAFETY REQUIREMENTS

- Collaborative Assessment
  - 11 industrial organizations
  - 4 government agencies
  - EC and OECD-NEA


IAEA-TECDOC-1290

Improving economics and safety of water cooled reactors

Proven means and new approaches

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

May 2002

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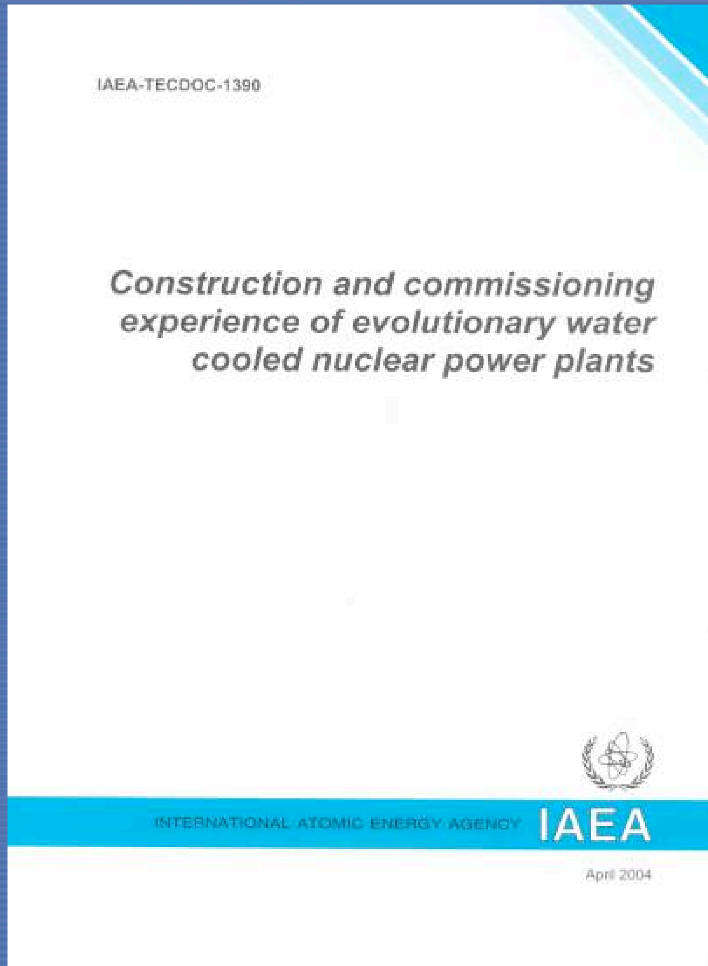
CONSTRUCTION AND COMMISSIONING

- Completing construction & commissioning on schedule and budget:
  - Qinshan III 1&2 (AECL CANDUs)
  - Kashiwazaki-Kariwa 6&7 (GE, Hitachi & Toshiba ABWRs)
  - Lingau 1&2 (Framatome PWRs)
  - Yonggwang 5&6 (KHNP KSNPs)
  - Tarapur 3&4 (NPCIL HWRs)

- New NE Series report on "CONSTRUCTION TECHNOLOGIES FOR NUCLEAR POWER PLANTS" to be published by 2010



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STATUS OF INNOVATIVE SMRs

- TECDOCs-1485 &-1536 address all reactor lines (LWRs, HWRs, GCRs, LMRs)
- Describe
  - Features pursued to improve economics
  - Provisions for efficient resource utilization
  - Safety features
  - Proliferation resistant and physical protection features
  - Enabling technologies requiring further R&D


IAEA-TECDOC-1485

Status of innovative small and medium sized reactor designs 2005

Reactors with conventional refuelling schemes

IAEA-TECDOC-1536

Status of Small Reactor Designs Without On-Site Refuelling

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January 2007

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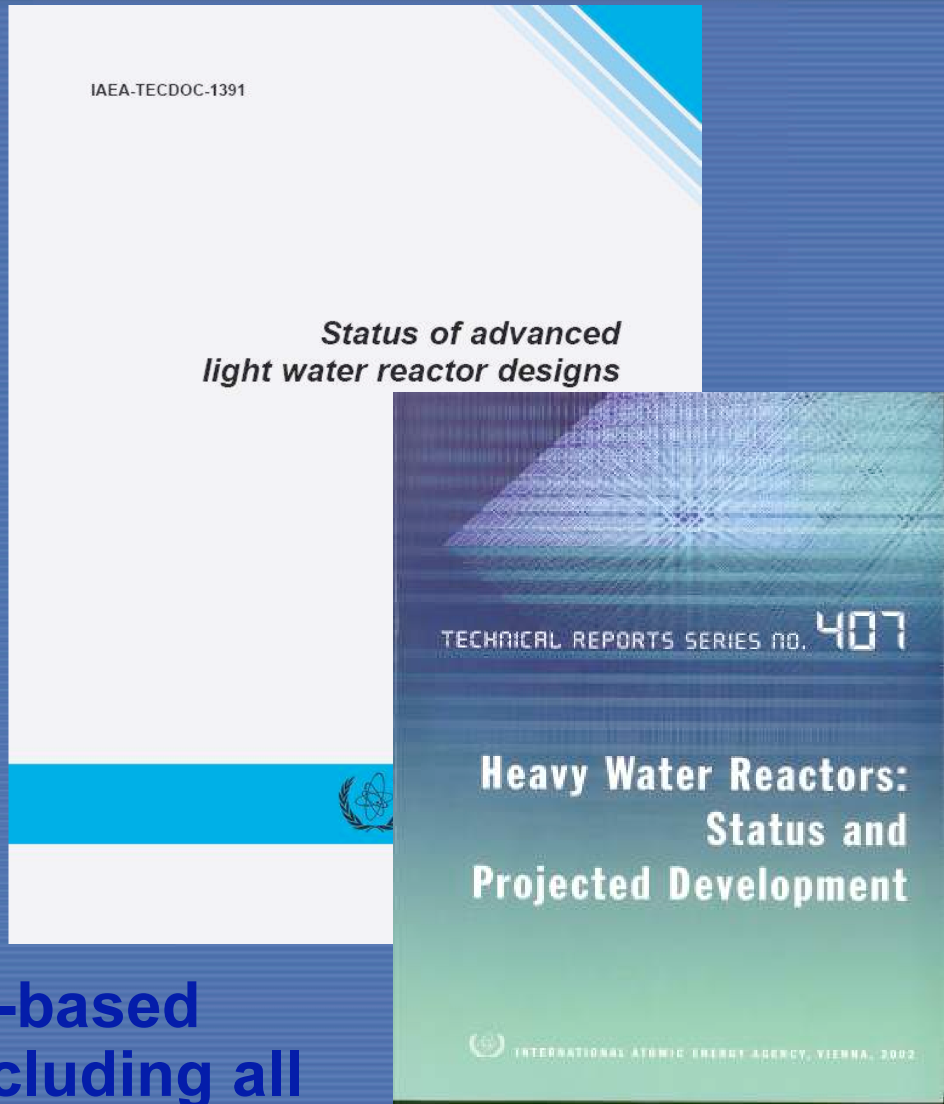
IAEA publishes technical descriptions of advanced plant designs

- Development goals & safety objectives
- Evolutionary and innovative
- Electricity or co-generation
  - Descriptions – each design:
    - Systems
      - Nuclear
      - Power conversion
      - I&C
      - Electrical
      - Safety
    - Summary level technical data
    - Design measures to enhance economy and reliability



Next: ARIS web-based status report including all reactor lines

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TECDOC - Status of Advanced LWR Designs

Large Size (above 700 MWe)

- ABWR and ABWR-II (GE,Hitachi and Toshiba)
- APWR and APWR+ (Mitsubishi and Westinghouse)
- BWR 90+ (Westinghouse Atom)
- EPR (Framatome ANP)
- SWR 1000 (Framatome ANP)
- ESBWR (GE)
- KSNP+ (KHNP)
- APR-1400 (KHNP)
- AP-1000 (Westinghouse)
- EP-1000 (Westinghouse/Genesi)
- WWER-1000 (Atomenergoproject /Gidropress, Russia); and WWER-1500
- CNP-1000 (CNNC)
- SCPR (Toshiba, et. al.)
- RMWR (JAERI)
- RBWR (Hitachi)

Medium size (300-700 MWe)

- AC-600 (CNNC)
- AP-600 (Westinghouse)
- HSBWR (Hitachi)
- HABWR (Hitachi)
- WWER-640 (Atomenergoproject /Gidropress)
- VK-300 (RDIPE)
- IRIS (Westinghouse)
- QS-600 co-generation plant (CNNC)
- PAES-600 with twin VBER-300 units (OKBM)
- NP-300 (Technicatome)

Small size (below 300 MWe)

- LSBWR (Toshiba)
- CAREM (CNEA/INVAP)
- SMART (KAERI)
- SSBWR (Hitachi)
- IMR (Mitsubishi)
- KLT-40 (OKBM)
- PSRD-100 (JAERI)

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NPPs Currently in Operation

TYPE	Number of Units	Total Capacity [MWe]
BWR	92	83,548
FBR	1	560
GCR	18	8,949
LWGR	15	10,219
PHWR	46	22,840
PWR	266	245,611
TOTAL	438	371,727

Source: PRIS, IAEA, 2010

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EVOLUTIONARY WATER COOLED REACTOR DESIGNS

Evolutionary LWRs

- 1380 MWe **ABWR** (Toshiba); 1360 or 1500 MWe **ABWR** (GE-Hitachi);
- 1700 MWe **ABWR-II** (Japanese utilities; GE-Hitachi or Toshiba);
- 1540 MWe **APWR** & 1700 MWe **APWR+** (Mitsubishi)
- 600 MWe **AP-600**; 1100 MWe **AP-1000**; and 335 MWe **IRIS** (Westinghouse)
- 1550 MWe **ESBWR** (GE-Hitachi)
- 1545 MWe **EPR** and 1250 MWe **SWR-1000** (Areva)
- 1100 MWe **ATMEA** (Areva & Mitsubishi)
- 1000 MWe **OPR** and 1400 MWe **APR** (KHNP and Korean Industry)
- 1000 MWe **CPR** (CGNPC); 650 MWe **CNP** (CNNC) and 600 MWe **AC-600** (NPIC)
- 1000 MWe **WWER-1000 /1200** (V-392); **WWER-1500**; and **WWER-640** (V-407) (AtomEnergoProm)

Evolutionary HWRs

- 700 MWe **Enhanced CANDU-6** (AECL)
- 1000 MWe **Advanced CANDU (ACR)** (AECL)
- 540 MWe & 700 MWe **HWR** (NPCIL)
- 700 MWe **AHWR** (BARC)

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Characteristics of Evolutionary Designs

- Improved Safety
- Improved Licensing
- Improved Economics
- Improved Construction
- Improved Operations
- Improved Standards
- Reduced Uncertainties
- First-Of-A-Kind Engineering (FOAKE)

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Characteristics of Evolutionary Designs

- **Improved Safety**
  - 4 Safety Trains
  - Aircraft Crash Protection (Double Containment)
  - Severe Accident Mitigation (Core Catcher)
  - Digital I&C Systems
  - Significantly Lower CDF and LRF Values
  - Passive Safety System Features
- **Improved Licensing**
  - Standardized Designs (DCD approval)
  - Streamlined Licensing Process (e.g., COL,GDA)

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Characteristics of Evolutionary Designs

- **Improved Economics**
  - Standardized, Simplified, Robust Design
  - Higher Plant Efficiency
  - 60 year Plant Life
  - 90+% Capacity Factor
- **Improved Construction**
  - Modular Design
  - Prefab of Systems and Components off-site
  - Open Top Construction

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Characteristics of Evolutionary Designs

- **Improved Operations**
  - Less Radioactive Waste
  - Less Doses to Plant Staff
  - Less Maintenance (fewer active systems)
  - Shorter Outages (typically 15 days)
- **International Standards**
  - Compliant with IAEA QA and Safety Guides
  - Compliant with EPRI URD
  - Compliant with EUR
  - Further Benefits from Code Harmonization

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Characteristics of Evolutionary Designs

- **Reduced Uncertainties for Owner/Investor**
  - Anticipated as a result from all improvements
  - Not yet demonstrated for 3G NPPs
- **First-Of-A-Kind Engineering (FOAKE)**
  - So far FOAKE efforts underestimated
  - Benefits from Standardization not yet reached
  - Significant re-learning of NPP Construction Lessons

BOILING WATER REACTORS (BWR)

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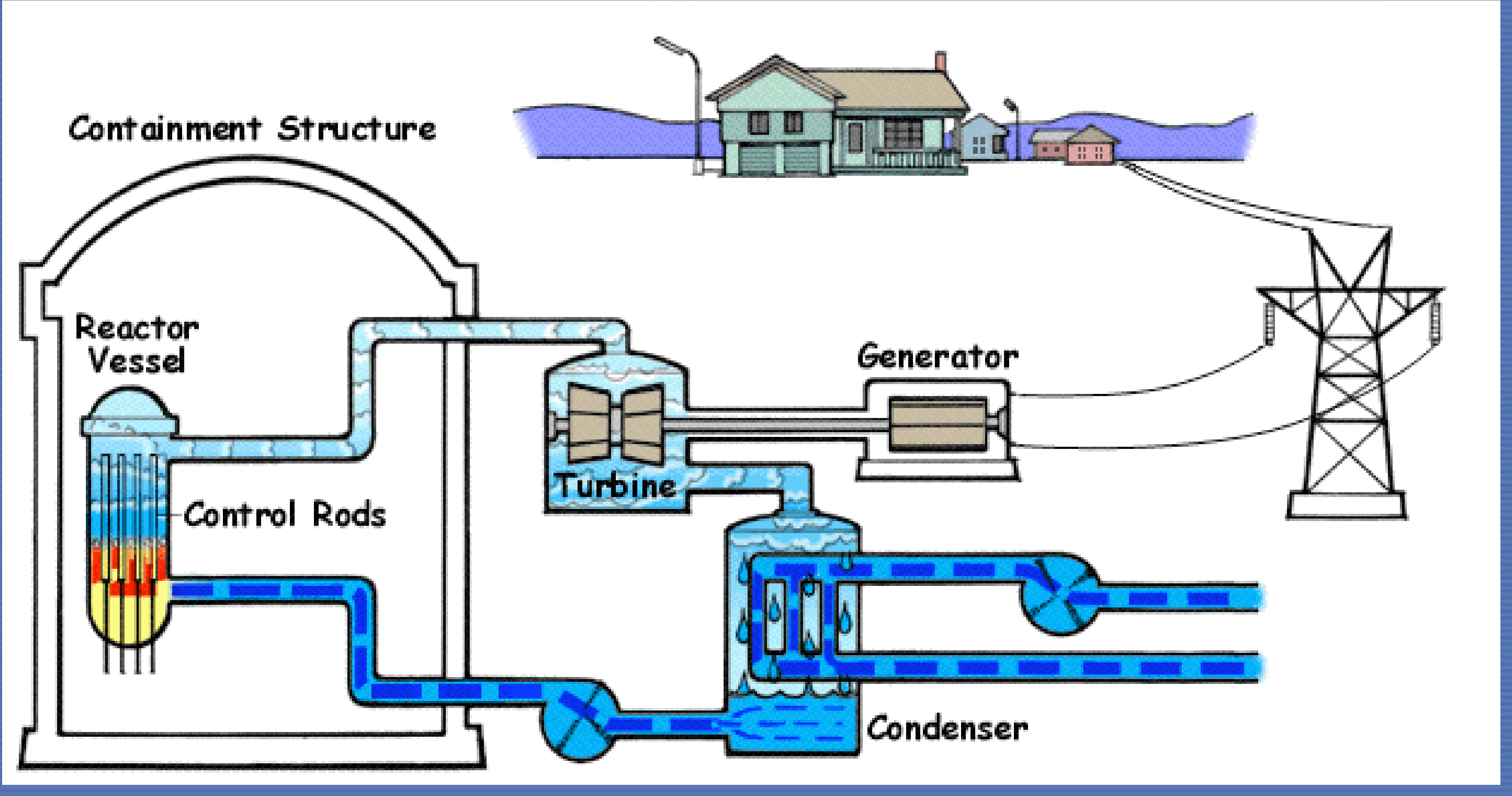
Boiling Water Reactor



Evolution of Commercial NPP Designs - BWR

- **GE is the 'mother' of all BWRs:**
  - in the1950's GE and AECL developed the CANDU prototype design
  - early 1960's GE made a strategic switch to light water BWR concept
  - next GE deployed the BWR concept in U.S., Europe and Japan via license agreements with AEG (merged into KWU), Hitachi, Toshiba
  - refused to give a license to ASEA/Sweden (who later became ABB)
- **ABB developed their own BWR independently of GE:**
  - in mid-1970's deployed the 'original' ABWR design (4-Division, Reactor Internal Pumps, Fine-Motion-Control-Rod-Drives, etc)
  - Built (6) plants of ABWR-type in Sweden / Finland - first ABB ABWR startup was 1978 TVO OL1 in Finland (built in 48 months)
  - In 1978 the Swedish ABWR Technology was transferred to GE / Hitachi / Toshiba under Agreement ➔ ABWR redesigned for TEPCO by GE/Hitachi/Toshiba Team with participation of ABB

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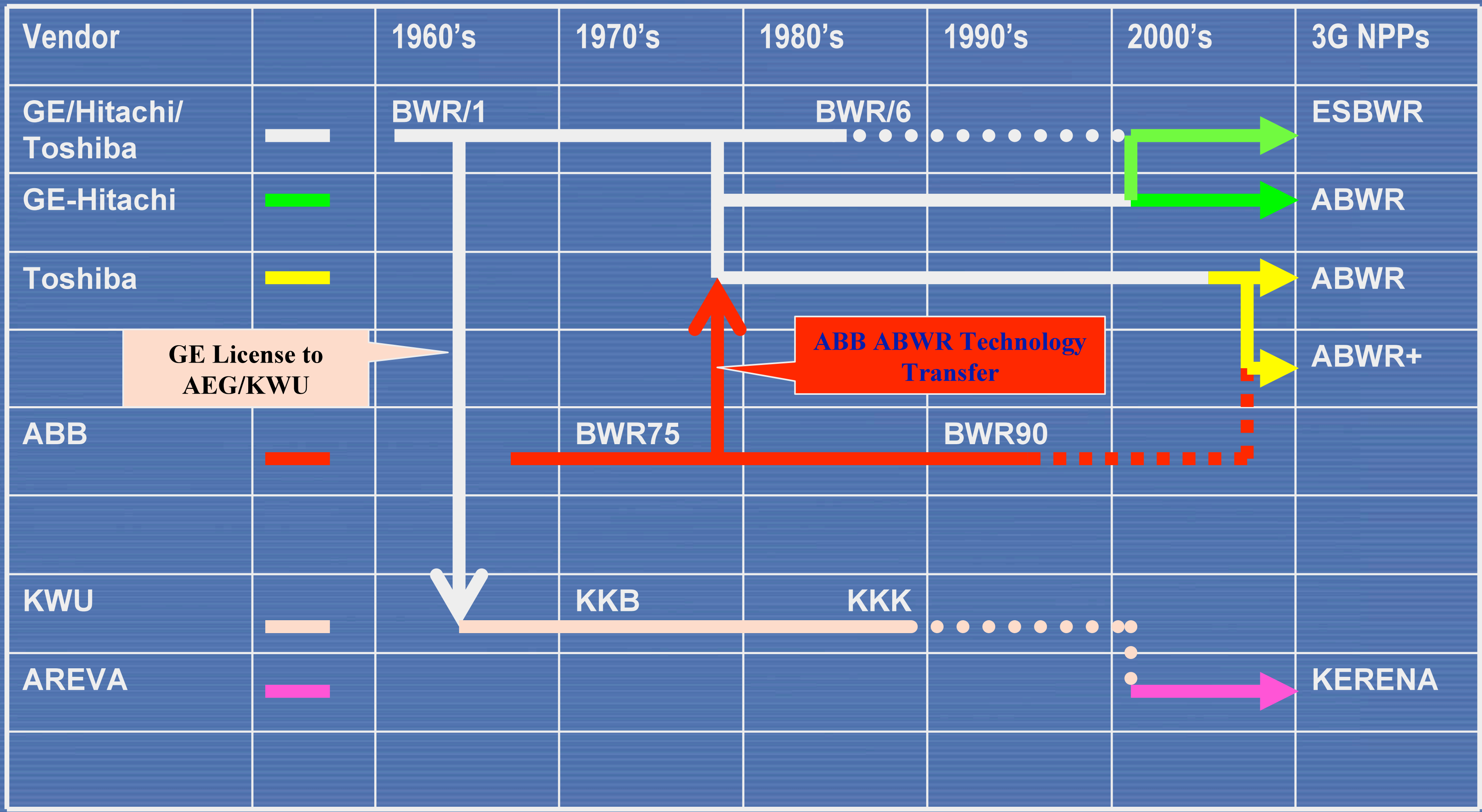
Evolution of Commercial NPP Designs – BWR (2)

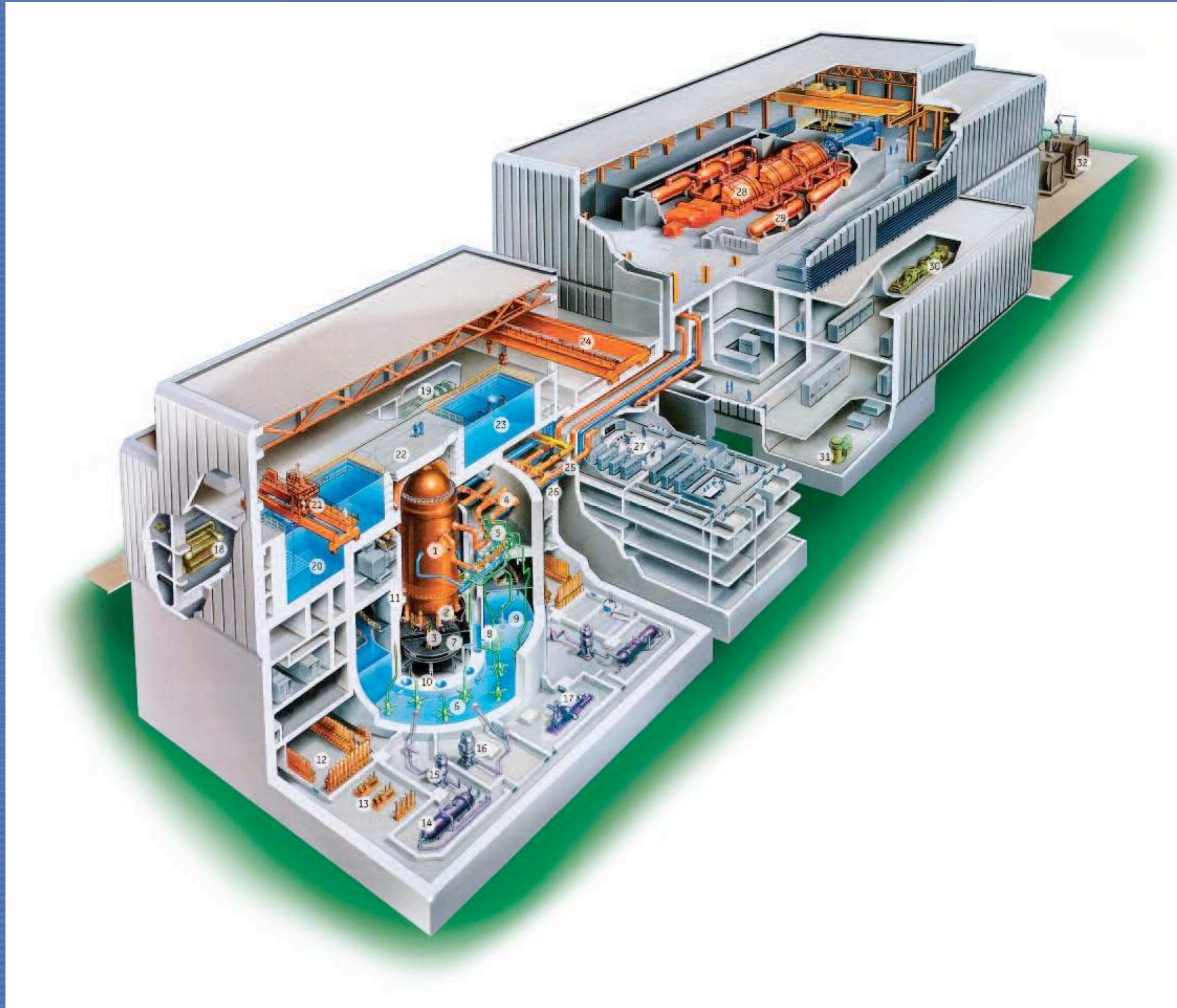
- **KWU (later merged into AREVA):**
  - KWU also designed their own ‘ABWR-type’ BWR (Reactor Internal Pumps, Fine-Motion-Drives, etc) and built (6) such BWRs in Germany
  - late 1990’s AREVA decided to ‘revive’ the KWU BWR line and started out developing the SWR-1000 ➔ now renamed KERENA
- **GE-Hitachi:**
  - in 2000’s GE-Hitachi merged their nuclear business
  - started to develop the ESBWR concept – based on ABWR but relying on natural circulation and passive systems
  - ESBWR name has changed several times reflecting its original pedigree (European Simplified BWR, later Economic Simplified BWR)
- **Toshiba:**
  - in 2006 split from GE/H/T family when taking over Westinghouse
  - developing ‘European’ ABWR+ / 1650MWe with aircraft protection incorporating features from ABB BWR90+ design

Evolution of Commercial NPP Designs – BWR (3)



Advanced Boiling Water Reactor (ABWR)

- Originally by GE, then Hitachi & Toshiba
- Developed in response to URD
- First Gen III reactor to operate commercially
- Licensed in USA, Japan & Taiwan, China
- 1380 MWe - 1500 MWe
- Shorter construction time
- Standardized series
  - 4 in operation (Kashiwazaki-Kariwa -6 & 7, Hamaoka-5 and Shika-2)
  - 7 planned in Japan
  - 2 under construction in Taiwan, China
  - Proposed for South Texas Project (USA)



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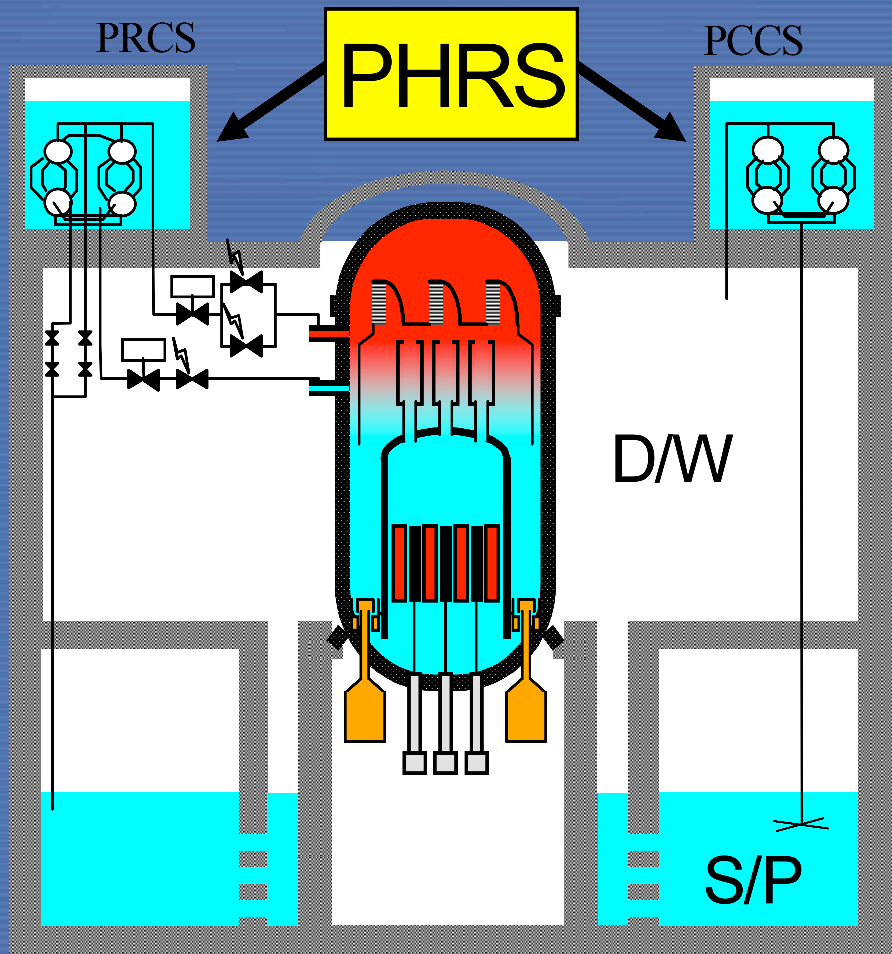
ABWR-II

- Early 1990s – TEPCO & 5 other utilities, GE, Hitachi and Toshiba began development
- 1700 MWe
- Goals
  - 30% capital cost reduction
  - reduced construction time
  - 20% power generation cost reduction
  - increased safety
  - increased flexibility for future fuel cycles
- Goal to Commercialize – latter 2010s



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ABWR

- Combines best BWR design features from Europe, Japan and USA
- Available from two competing Vendors (GE-Hitachi and Toshiba)
- Reactor Core has margins to uprate from 1370 MWe to 1800 MWe
- Proven Construction and Operation Costs

DCD Certified
Original NRC approval in 1997

Updates via Departures on R-COLA

1 COLA in review in USA

Reference Plant – STP 3&4 – COL in 2011,
COD planned for 2016

OE from Toshiba Japan
4 ABWRs in operation

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ABWR (2)

- 3/4-Train Safety Systems
- Reactor Internal Pumps eliminate external loops
- Fully digital I&C
- Modularized design & Prefab construction experience
- Integrated containment and reactor building
- Lowest Core Damage Frequency amongst Evolutionary Designs
  (except for ESBWR)
- Proven Capital and O&M cost structure (in Japan)
- No Steam Generators – reduced life time costs
- No external coolant loops and no core uncovery

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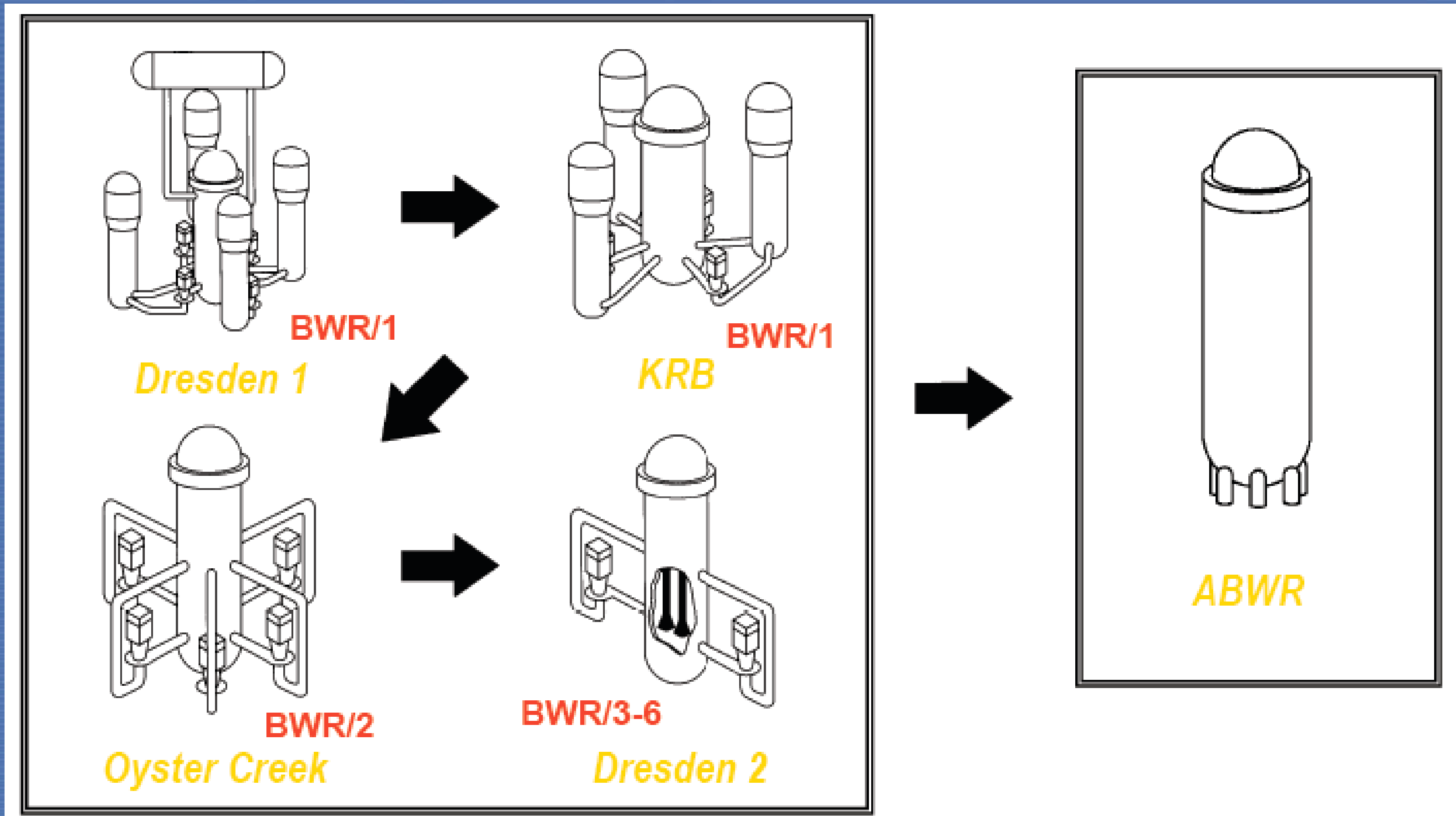
Design Evolution - ABWR (3)



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ABWR (4)

Pro’s	Con’s
• 4 ABWRs in operation in Japan • 4 ABWRs under construction in Asia • EPC contract in US for STP-3/4 • Proven costs and schedules in Asia & US • Very good overall economics • No Steam Generators • Standard BWR fuel design • Strong competition in fuel supply • US NRC one-step license (1997) • Pre-fabricated modules for proven short construction time	• No large aircraft protection design - this will be mitigated in Toshiba’s coming Europeanized ABWR 1650MWe Design • No separate corium catcher • Non-Europeanized design causing higher life time O&M costs, spare parts issues, etc • Schedule & cost impact to get EU licensing approval (aircraft protection) • Re-licensing by US NRC to get COLA • 3/4-Train Safety System

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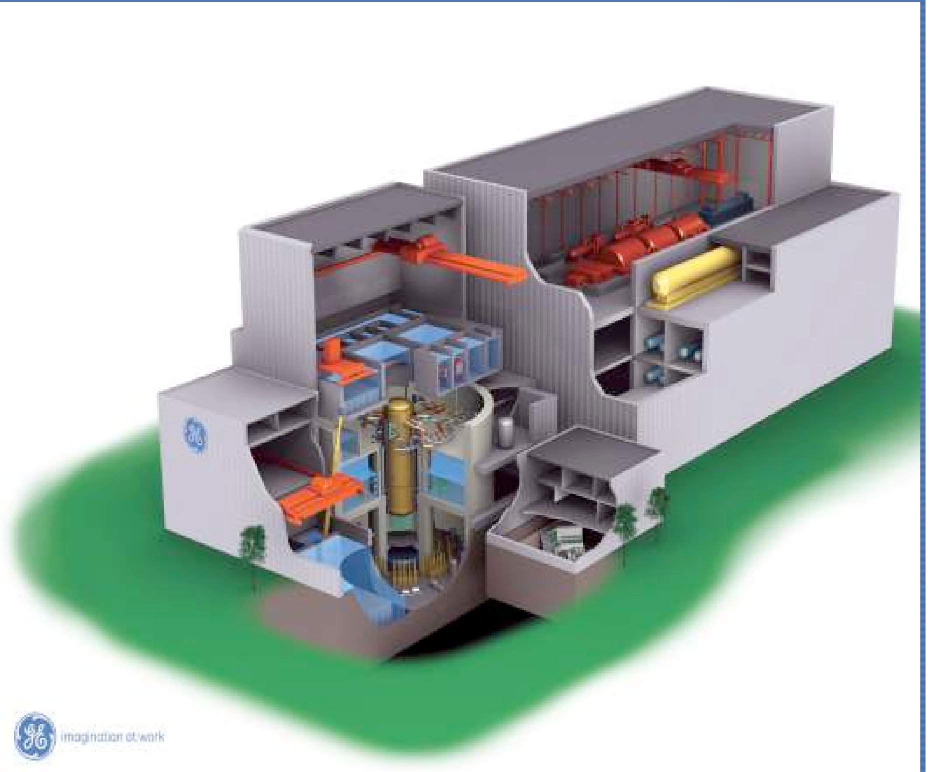
ESBWR

- Developed by GE
- Development began in 1993 to improve economics of SBWR
- 4500 MWt (~ 1550 MWe)
- In Design Certification review by the U.S.NRC
- Meets safety goals 100 times more stringent than current
- 72 hours passive capability
- Key Developments
  - NC for normal operation
  - Passive safety systems
    - Isolation condenser for decay heat removal
    - Gravity driven cooling with automatic depressurization for emergency core cooling
    - Passive containment cooling to limit containment pressure in LOCA
  - New systems verified by tests



ESBWR

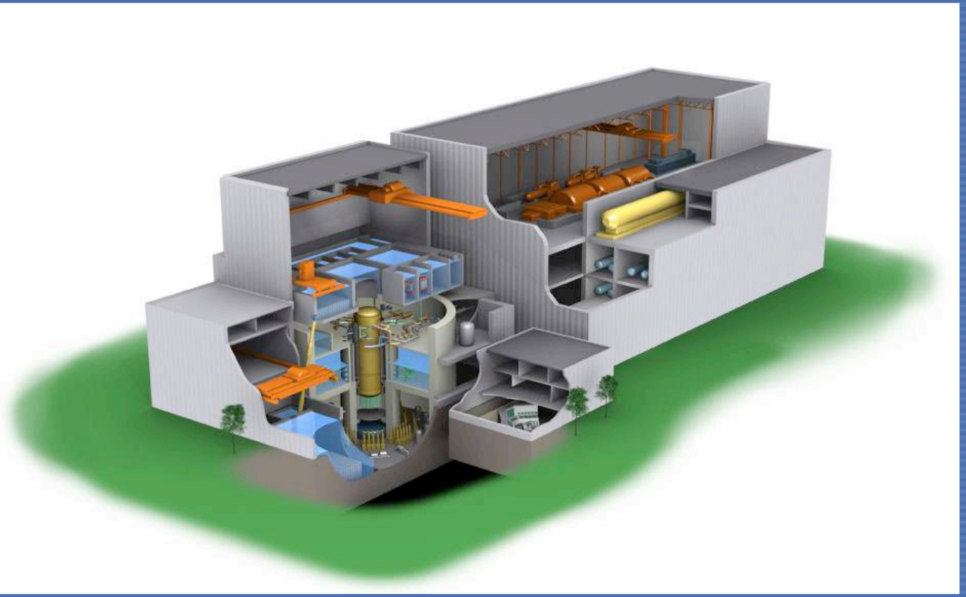
- Originally European Simplified BWR (many EU Institutions have contributed with both design and testing of components)
- Next it became Economic Simplified BWR
- Natural Circulation Boiler with largest core in the world
- 1535 MWe output at 50% of coolant flow in standard BWR
- Many passive safety features
- Greatly reduced number of systems

DC Application (Rev 6) under review – Certification expected 2011

Passive Design

2 COLAs in review

Reference Plant – North Anna – COL in 2011



ESBWR (2)

- Simpler safer BWR using passive concepts to the max
- No Operator action required for up to 72 hours
- 11 ABWR systems eliminated from ESBWR
- 25% of pumps, valves and motors eliminated
- Passive Residual heat transfer to atmosphere
- Using best features of existing BWRs / ABWR
- Core Damage Frequency 1.7E-8, is lowest in world
- Reduced construction costs and schedule
- Reduced O&M costs
- Prefab and modular design reduce construction costs

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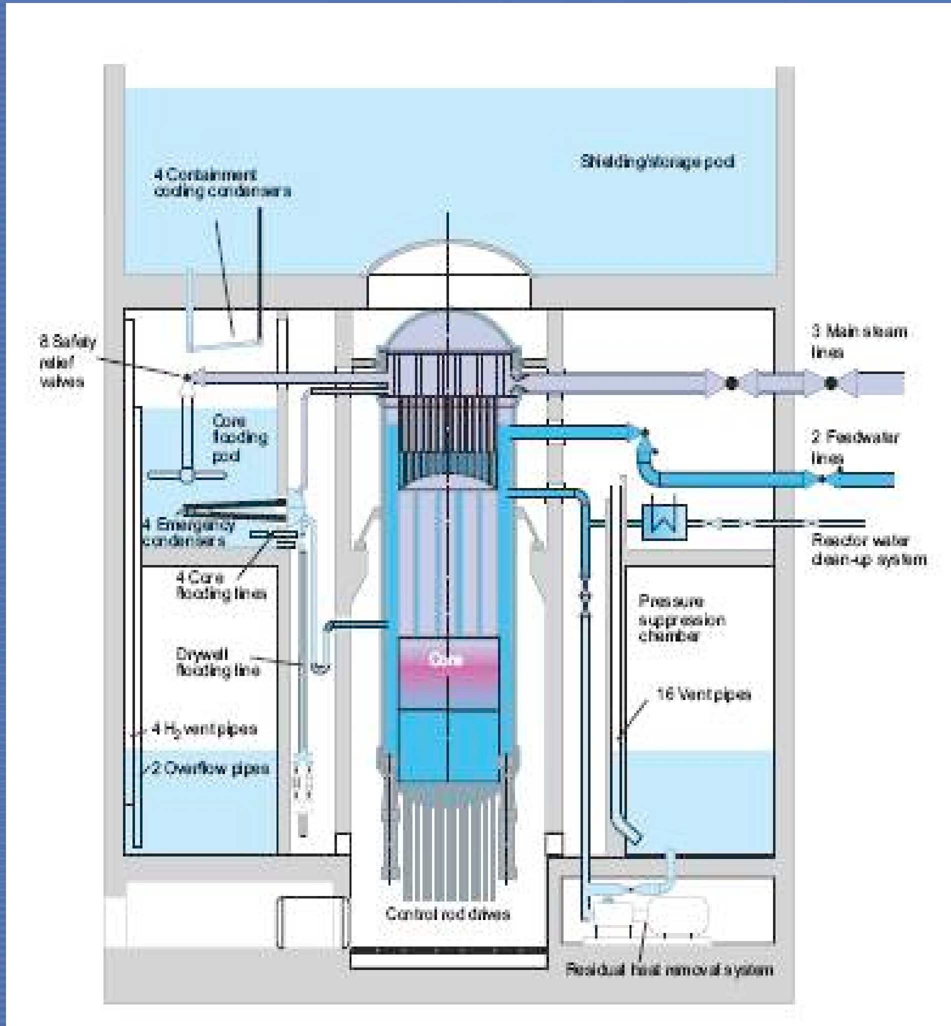
ESBWR (3)

Pro's	Con's
• great economy of scale - combined with reduced number of systems and components (simplified design) • promises lowest overnight costs possible • no SG's, much lower plant refurbishment costs than PWRs (over lifetime) • Pre-fabricated modules for shortest construction time	• Design Certification not approved (NRC review) • None in operation • Largest pressure vessel that can be manufactured • Needs 1132 fuel assemblies of 10 ft length, means 30% more fuel bundle manufacturing, transportation, dry storage, final disposal costs • ESBWR gives away advantage of forced flow: internal pumps like in ABWR would allow 40-50% more output from same RPV without changing CDF values • Natural circulation causes significant new uncertainties in itself (core stability of large core) • Load-follow with feedwater temperature control (instead of pumps) • 30% higher spent fuel costs (shorter fuel length)

KERENA = SWR-1000

- AREVA
- Reviewed by EUR
- Uses internal re-circulation pumps
- Up-rated 1250 MWe version was offered for Finland-5
- New systems verified by test (e.g. FZ Jülich test of isolation condenser)



PRESSURIZED WATER REACTORS (PWR)

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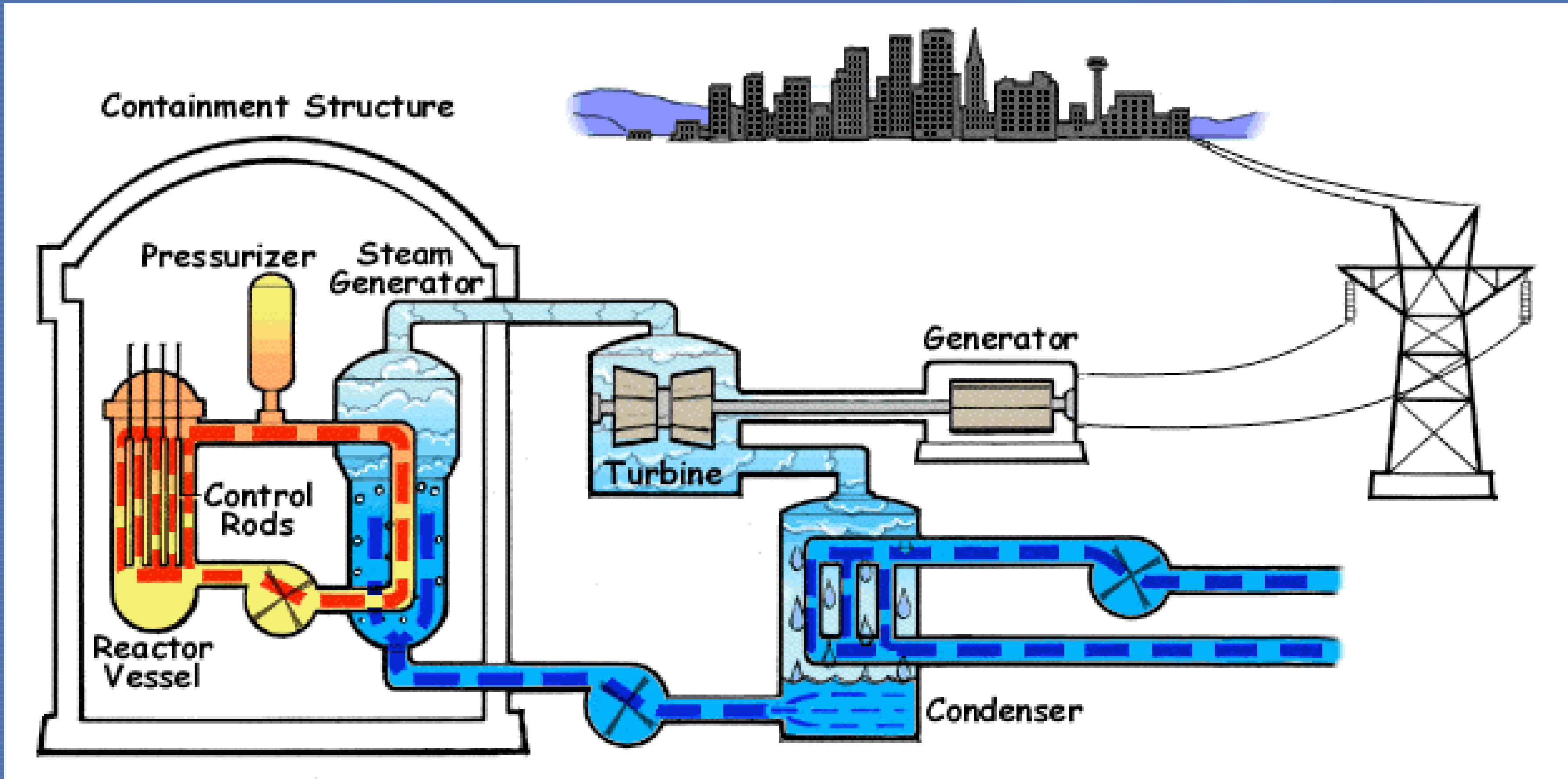
Pressurized Water Reactor



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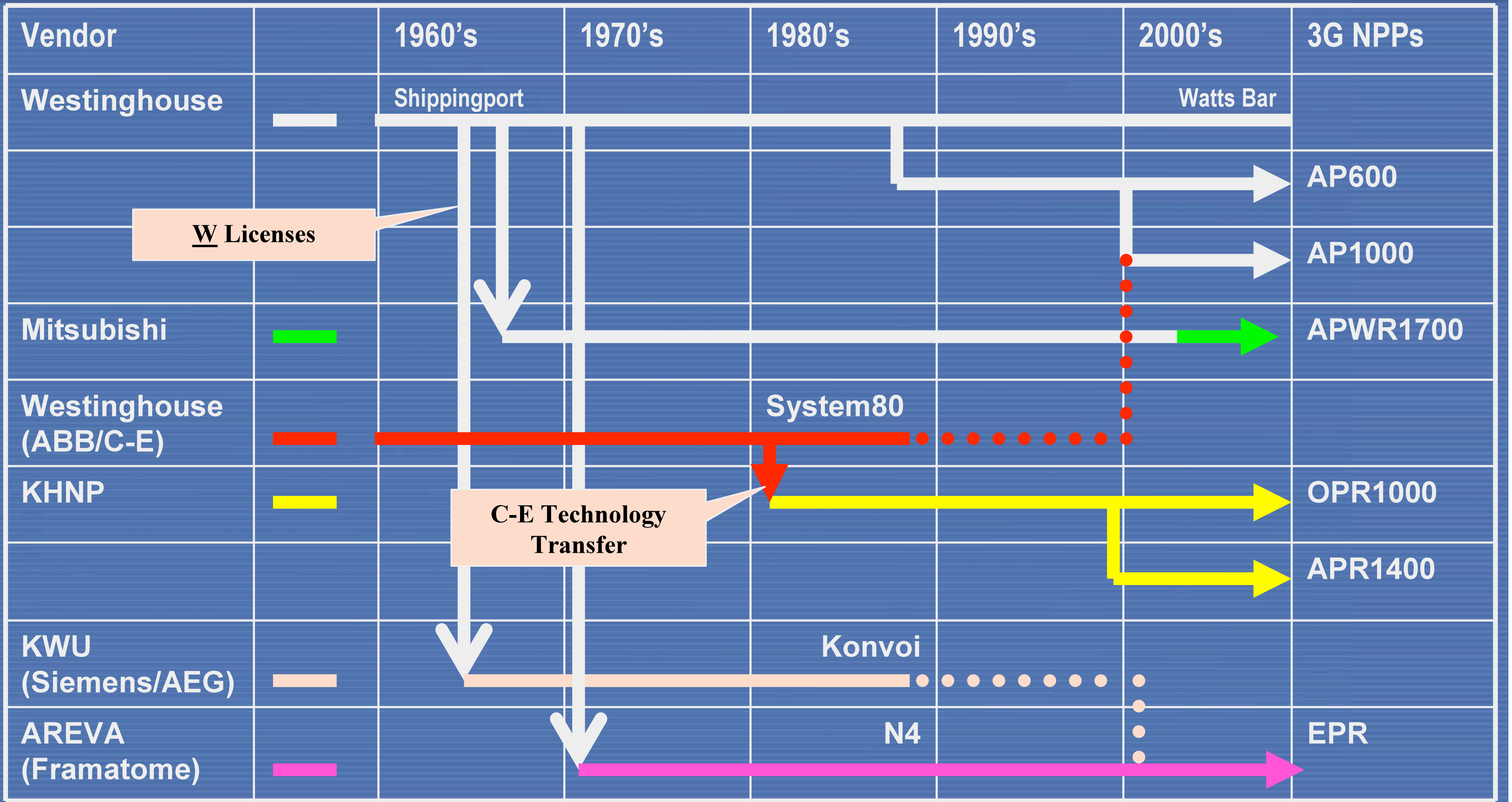
Evolution of Commercial NPP Designs - PWR

- **Westinghouse (W) is the 'mother' of all PWRs:**
  - in late 1950's naval reactor (Nautilus) was put on Land (Shippingport)
  - in 1960's W deployed the PWR in U.S., Europe and Asia via license agreements with Mitsubishi and Siemens (later merged into KWU)
  - early 1970 W licensed Framatome to build the 58 PWR French fleet and many more PWRs worldwide (eventually more PWRs than W)
  - W / Mitsubishi developed the evolutionary APWR until Toshiba takeover of W
  - in 1990's and 2000's W developed the passive safety AP600/1000
- **KWU (Siemens/AEG merger):**
  - in 1970's and 1980's KWU developed their own PWR design resulting in the 1300 MWe class Konvoi design
- **AREVA (Framatome/KWU merger):**
  - developed their own 1400 MWe N4 design, which was combined with Konvoi design to develop & deploy the European PWR (EPR)

Evolution of Commercial NPP Designs – PWR (2)

- **Combustion-Engineering (C-E, later ABB/C-E, then W):**
  - C-E independently developed their own PWR designs for U.S. market, which in key technical areas was ahead of W (even today the key components in AP1000 are based on C-E technology)
  - crowning achievement was the System-80 design (Palo Verde-1/2/3)
  - C-E made a total Technology Transfer Agreement with South Korea, which is the basis for their fleet of (12) OPR1000 (8 in operation), and (4) APR1400 (under construction)
- **KHNP (Korean Hydro & Nuclear Power Company):**
  - the OPR1000 was directly based on C-E System-80/80+ design
  - the APR1400 is using Korean technology, and represents a further development of the System-80+ design
  - Korean's claim that APR1400 is not under U.S. Part 810 Export Rule (compare to AREVA/EPR considered no longer U.S. design)

Evolution of Commercial NPP Designs – PWR (3)



NOTE: B&W is not shown here since they had limited impact (7 PWRs) apart from TMI.

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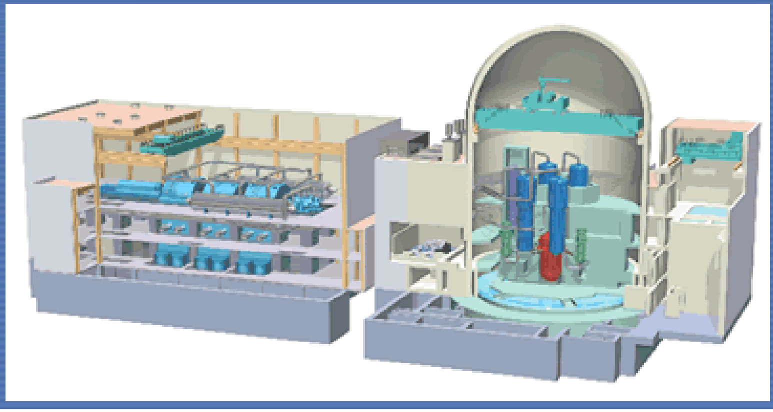
Credit: EXCEL SERVICES CORPORATION

Advanced Pressurized Water Reactor APWR & APWR+

- Mitsubishi & Japanese utilities
- 2x1540 MWe APWRs planned by JAPC at Tsuruga-3 & -4
  - Advanced neutron reflector (SS rings) improves fuel utilization and reduces vessel fluence
- 1700 MWe “US APWR” in Design Certification by the U.S.NRC
  - Evolutionary, 4-loop, design relying on a combination of active and passive safety systems
  - Full MOX cores
  - 39% thermal efficiency
  - Selected by TXU for Comanche Peak
- 1700 MWe “EU-APWR” to be evaluated by EUR



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APWR

- Advanced PWR developed by Westinghouse/MHI
- 1538 MWe Output in Tsuruga-3/4 in Japan startup in 2016/17
- 1700 MWe in US by increased SG / TG performance (same Thermal Power)
- Comanche Peak planned for 2017/18

Reference Plant – Comanche Peak – COL in 2012/13

DC Amendment under review – Certification expected 2012

Active Design

1 COLA in review

OE from Tsuruga-3/4 startup in Japan2015/16

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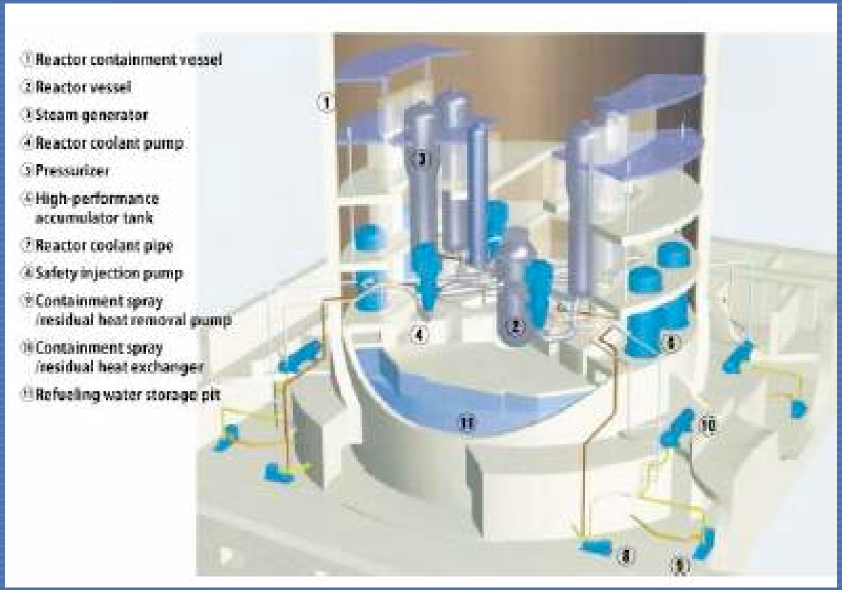
APWR (2)

- 4-Train Safety System (4 x 50%)
- Core has extra Neutron reflector to improve fuel economy
- In-Containment Refueling Water Storage
- Thermal Effciency 39% in USA Version – 160 MWe extra from TG plant
  - means 30% larger heat transfer surface in SGs
  - last stage Turbine Blades increased from 54” to 70” length



- Can handle full MOX fuel core
- Reduced Staff exposure
- Fully Digital I&C
- Reduced Operational Waste
- PreFab and modularized design

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APWR (3)

Pro's	Con's
• Based on Japanese 1538 MWe APWR under construction by 2010/11 • Robust PWR design with very small technology leap • Extensive global nuclear experience • Excellent safety features • Use of high reliability Gas Turbine instead of Diesel Generator	• None in operation • Design certification schedule is still uncertain • New/unproven steam generator design – squeezing 160 MWe extra from same TG • New and unproven low pressure turbine (70" last stage blades unproven/MHI) • Not one of the lead COL programs in USA • No protection against commercial aircraft • No Core Catcher

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APR-1400

- Developed in Rep. of Korea (KHNP and Korean Industry)
- 1992 - development started
- Based on CE's System 80+ design (NRC certified)
- 1400 MWe - for economies of scale
- Incorporates experience from the 1000 MWe Korean Standard Plants
- Relies primarily on well proven active safety systems
- First units will be Shin-kori 3,4
  - completion 2013-14
- Design Certified by Korean Regulatory Agency in 2002

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APR1400

– Evolutionary-type PWR reactor with a capacity of 1400 MWe

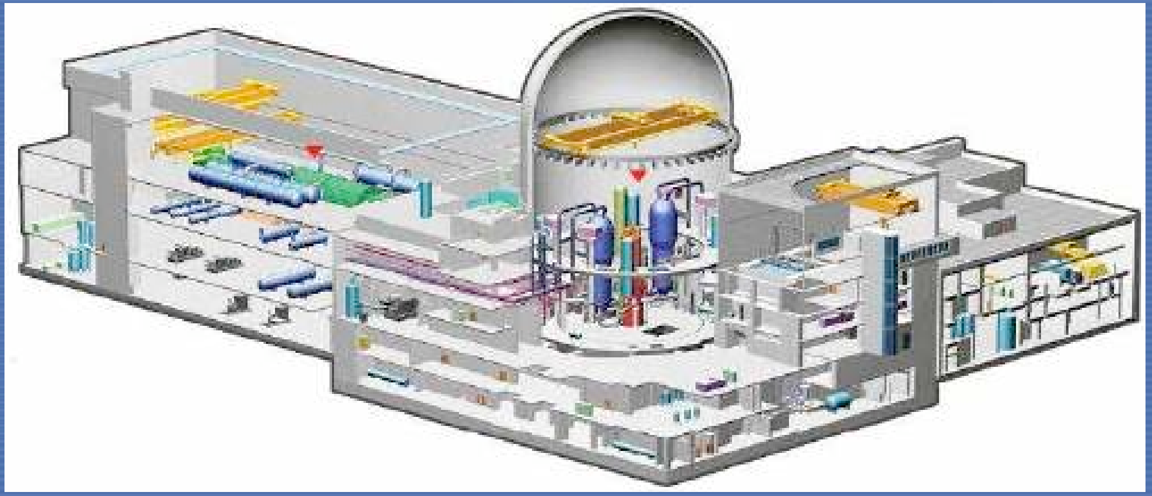
– Designed with the concept of a standardized plant

– Incorporation of construction & operation experiences of OPR1000

– New design features based on world-wide ALWR R&D

– Based on System80+ design features

– Shin-Kori-3/4 startup 2014/15



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APR1400 (3)

Pro's	Con's
• Design based on EPRI ALWR (URD) • Shin-Kori-3/4 under construction • Robust plant design with relatively small technology leap • Excellent safety features: - 4-Trains of safety systems - Passively operating safety injection - In-containment refueling water storage tank (IRWST) - Each train has a high-pressure safety injection pump and a SIT with a fluidic device (FD).	• None in operation • No US design certification (but NRC System-80 one-step licensing) • The largest Steam Generators ever to be manufactured (new/unproven) • No international NPP construction experience outside South Korea • Not designed against commercial aircraft crash • No Core Catcher • Uncertainty about Toshiba / Westinghouse / US Congress (Part 810) permissions.

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EPR

- AREVA
- 1600 MWe PWR
- Incorporates experience from France's N4 series and Germany's Konvoi series
- Meets European Utility Requirements
- Incorporates well proven active safety systems
  - 4 independent 100% capacity safety injection trains
- Ex-vessel provision for cooling molten core
- Design approved by French safety authority (10.2004)
- Under construction
  - Olkiluoto-3 (operation by 2011?)
  - Flamanville-3 (operation by 2012)
- Planned in China (2 units at Taishan) and India
- U.S.NRC is reviewing the US EPR Design Certification Application

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EPR

- **Large evolutionary PWR**
- **Capacity ranges from 1600 – 1700 MWe**
- **Combination of French N4 and German Konvoi design**
- **50% Cost & schedule overrun at 1st EPR in Finland is not due to EPR design**

DC Application under review – Certification expected 2012

Active Design - Standardization

4 COLAs in review

Reference Plant – Calvert Cliffs – COL in 2012

OE from Flamanville & Olkiluoto projects

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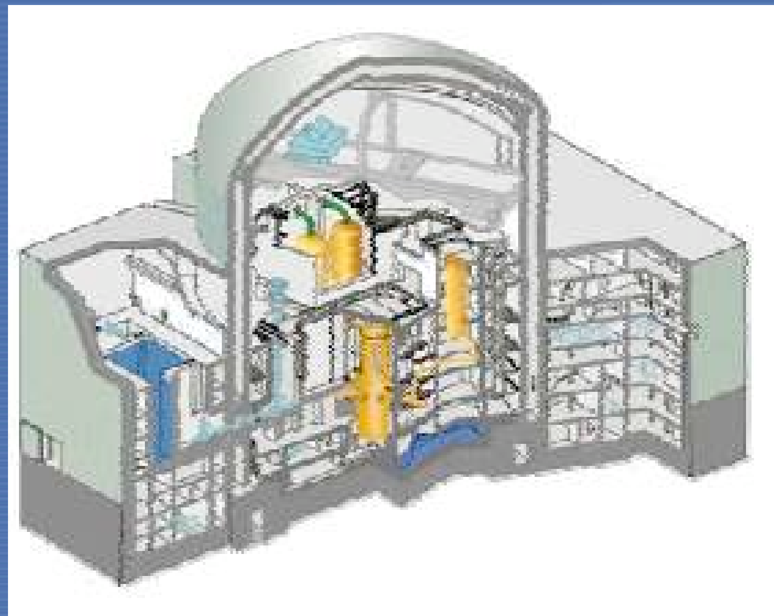
EPR (2)

- 4-Train Safety Systems
- Double Containment to protect against commercial aircraft crash
- Core Catcher for severe accident mitigation
- Can run on full MOX Core
- Higher Plant Efficiency (37%)
- Digital I&C (Siemens TELEPERM-XS)
- 10-15% less uranium consumption
- 15 days outages
- Above 90% life time capacity factor
- Robust design with small technology leap



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EPR (3)

Pro's	Con's
• great economy of scale • higher thermal efficiency saves U • 100% MOX core possible • Metric design/"Europeanized" – saves O&M costs (spare part costs savings) • Double wall containment (aircraft protection) • Lessons learned from TVO OL-3 and EdF/FL-3 construction will provide valuable lead over competitor designs • standard fuel design – strong competition	• unchanged number of systems and components (complex design) • higher O&M costs • highest temp/duty PWR fuel • unproven SG lifetime • Large foot print needs larger site • Grid connection can be an issue • No Pre-fabricated modules for short construction schedule • Needs largest rates of sustained concrete pouring/month during construction

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Chinese advanced PWRs CPR (CGNPC) and CNP (CNNC)

- CPR-1000
  - Evolutionary design based on French 900 MWe PWR technology
  - Reference plant: Lingau-1&2 (NSSS Supplier: Framatome; commercial operation in 2002)
  - Lingau-3&4 are under construction (with > 70% localization of technology; NSSS Supplier: Dongang Electric Corporation);
  - Now a Standardized design
  - Hongyanhe 1 and Ningde 1 under construction; more units planned: Hongyanhe 2,3,4; Ningde 2,3,4; Fuquing 1,2; Fanjiashan 1&2; and Yangjiang 1,2,3,4,5,6

- CNP-650
  - Upgrade of indigenous 600 MWe PWRs at Qinshan (2 operating & 2 under construction)

AP-600 and AP-1000

- Westinghouse
- AP-600:
  - Late 80’s–developed to meet URD
  - 1999 - Certified by U.S.NRC
  - Key developments:
    - passive systems for coolant injection, RHR, containment cooling
    - in-vessel retention
    - new systems verified by test
- AP-1000:
  - pursues economy-of-scale
  - applies AP-600 passive system technology
  - Certified by U.S.NRC (2006) [1]
  - Contract for 4 units in China
    - Sanmen & Haiyang: 2013 – 2015
  - Contract for 2 units in US
    - Plant Vogtle
    - Proposed in several other sites in US

[1] Amended Application currently under review

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AP1000

- Advanced Passive 1100 MWe PWR Design, scaled up from AP600
- Simplified systems and reduced number of systems & components
- Modular construction & Prefab reduce construction schedule uncertainties

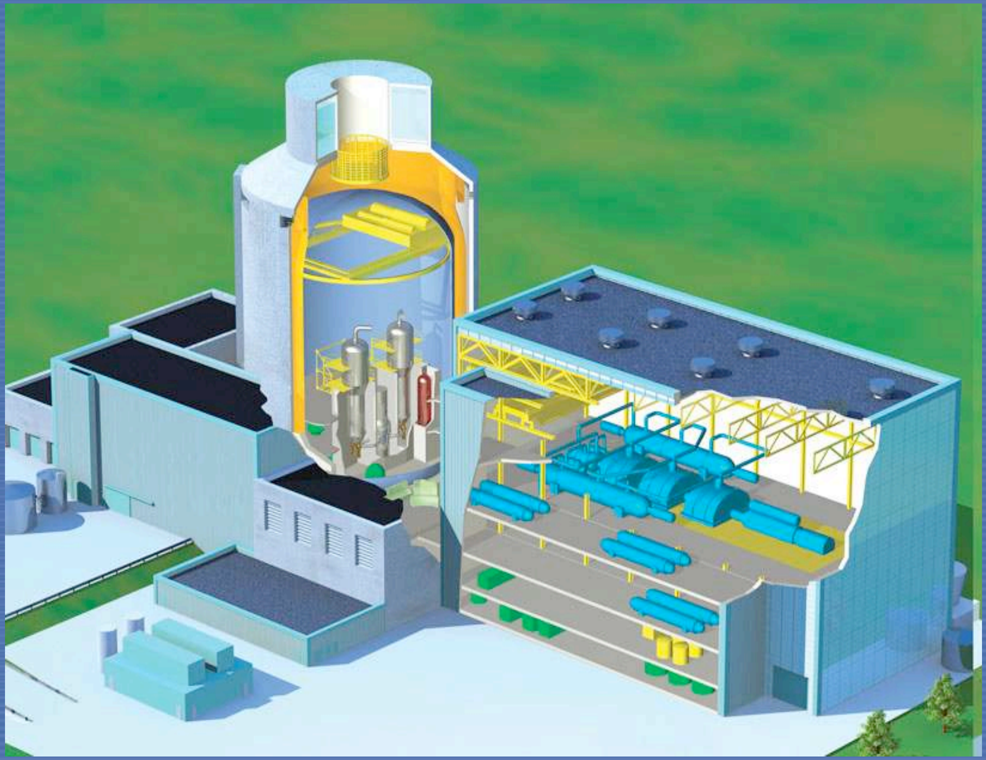
DC Amendment (Rev 17) under review – Certification expected 2011

Passive Design – Standardization

7 COLAs in review

Reference Plant – Vogtle 3&4 – COL expected in 2011

OE from China Haiyang & Sanmen projects expected by 2015



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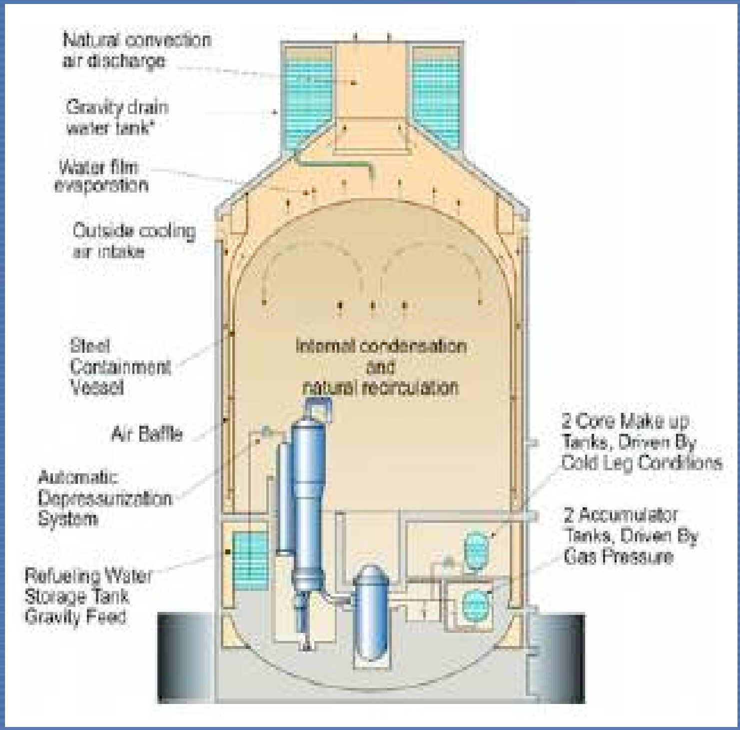
AP1000 (2)

- Passive Safety Systems – use forces of nature (gravity, convection, natural circulation to improve safety and simplify systems)
- Passive systems are used for core cooling, containment isolation, residual heat removal and containment cooling
- No outside electricity needed for 72 hours
- Number of pumps and safety class valves reduced by about 50%
- In-vessel retention of core melt
- Passive Containment Cooling system
- Proven PWR components



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AP1000 (3)

Pro's	Con's

• Reduced number of systems and components (simplified design)
• Lower core outlet temperature (20F lower) eliminates fuel crud/corrosion problems
• 17x17XL fuel – strong competition
• Footprint advantage for small sites
• Less restrictions with grid connection due to smaller output
• Pre-fabricated modules for short construction time
• Fewer components / equipment should reduce O&M costs – offsetting the size disadvantage in life time O&M costs.
	• None in operation
	• It takes 3 x AP1000 to produce same TWh's as 2 x EPR1600, which means multiplying cost factors by x1.5 to produce same life time TWh:
	  ○ Staffing numbers, extra overhead
	  ○ Number of outages over lifetime
	  ○ Spare parts, equipments, components
	  ○ Doses over lifetime
	  ○ Waste volumes over lifetime
	  ○ Decommissioning costs
	• Lower thermal efficiency (34%) needs more U
	• 15 days outages / 18 months ➔ 600 days over lifetime x 1.5 ➔ 900 days vs 600 days for EPR
	• SG lifetime unproven
	• In-Vessel Reactor Coolant Pumps unproven
	• NRC looking into seismic for AP1000 ➔ revised Design Certification by mid-2011
	• Aircraft protection not sufficient (EUR criteria) this will be fixed in DCD Amendment 17

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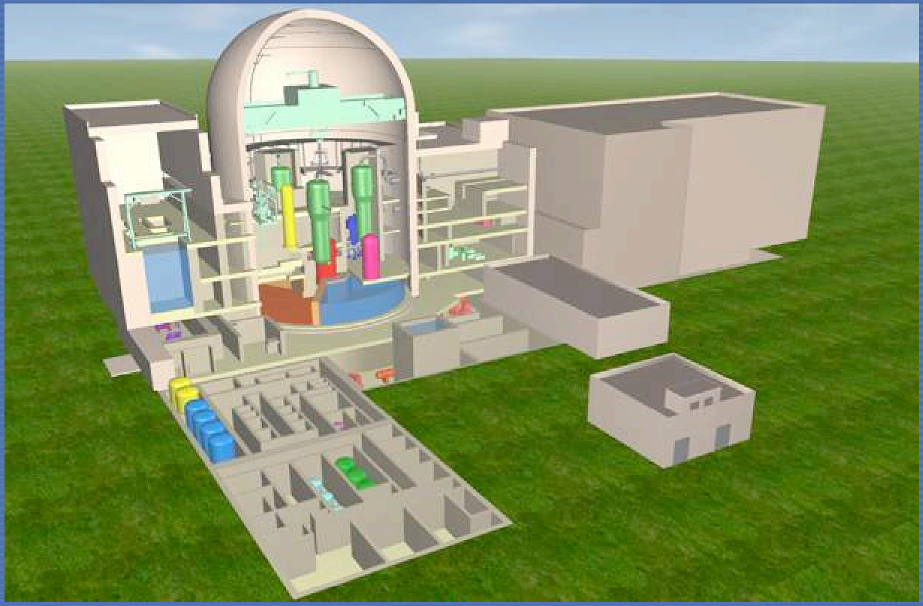
ATMEA

- 1100 MWe, 3 loop plant
- Combines AREVA & Mitsubishi PWR technology
- Relies on active safety systems & includes core catcher
- Design targets:
  - 60 yr life
  - 92% availability
  - 12 to 24 month cycle; 0-100% MOX



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Evolution of Commercial NPP Designs - VVER

- **Rosatom / AtomStroyExport (ASE):**
  - today Rosatom is vertically integrated like a Russian AREVA
  - VVER program started out in 1960's with 200 MWe plant design, and in 1970's it became the successful VVER-440 fleet
  - characteristic for all VVERs are following:
    - Hexagonal fuel lattice (allows smaller RPV transportable by rail)
    - Horizontal SGs (long life, no issues like Western SGs)
  - in 1980's the VVER1000 came along, named AES91, and it has been exported to Tianwan/China (in operation), Kudankulam/India (strtup next year), and Busher/Iran (startup next year)
  - latest VVER1000 is AES92 type satisfies EUR – to be built at Belene
  - the AES92 has been stretched to 1200 MW class, named AES2006
  - all VVER1000 and VVER1200 have Siemens TELEPERM XS I&C

Evolution of Commercial NPP Designs – VVER (2)

Vendor		1960's	1970's	1980's	1990's	2000's	3G NPPs
Rosatom / AtomStroyExport		Novovoronesh	VVER210				
			Loviisa	VVER440		Mochovce	
				Zaporozhie		Tianwan	VVER1000/ AES91
							VVER1200/ AES2006

WWER-1000 / 1200 (AEP)

- The state-owned AtomEnergoProm (AEP), and its affiliates (including AtomStroyExport (ASE) et.al) is responsible for nuclear industry activities, including NPP construction
- Advanced designs based on experience of 23 operating WWER-440s & 27 operating WWER-1000 units
- Present WWER-1000 construction projects
  - Kudankulam, India (2 units)
  - Belene, Bulgaria (2 units)
  - Bushehr, Iran (1 unit)
- WWER-1200 design for future bids of large size reactors

- Tianwan
  - first NPP with corium catcher
  - Commercial operation: Unit-1: 5.2007; Unit-2: 8.2007
- Kudankulam-1 & 2
  - Commercial operation expected in 2009
  - Core catcher and passive SG secondary side heat removal to atmosphere

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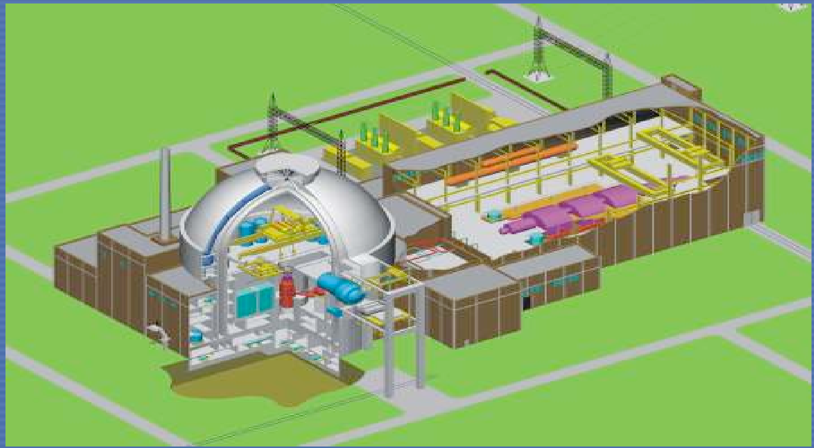
WWER-1200

Commissioning of 17 new WWER-1200s in Russia expected by 2020

- Novovoronezh – 2 units
- Leningrad – 4 units
- Volgodon – 2 units
- Kursk – 4 units
- Smolensk – 4 units
- Kola – 1 unit



- Uses combination of active and passive safety systems
- One design option includes core catcher; passive containment heat removal & passive SG secondary side heat removal
- 24 month core refuelling cycle
- 60 yr lifetime
- 92% load factor

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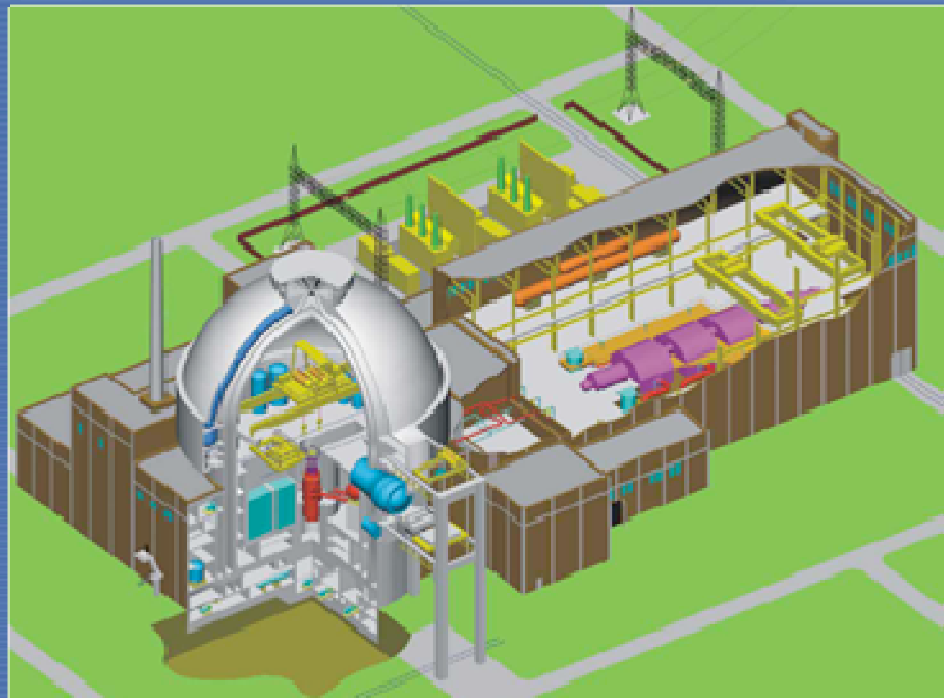
VVER1200/AES2006

- Designed by Rosatom / Atomstroyexport (ASE)
- Advanced VVER1000 version, scaled up to 1160 MWe (small step)
- 4-loop design with horizontal SGs
- Development from VVER1000
- Most recent VVER1000 NPPs:
  - in China (Tianwan-1/2)
  - in India (Kudankulam-1/2)
  - in Iran (Busher)



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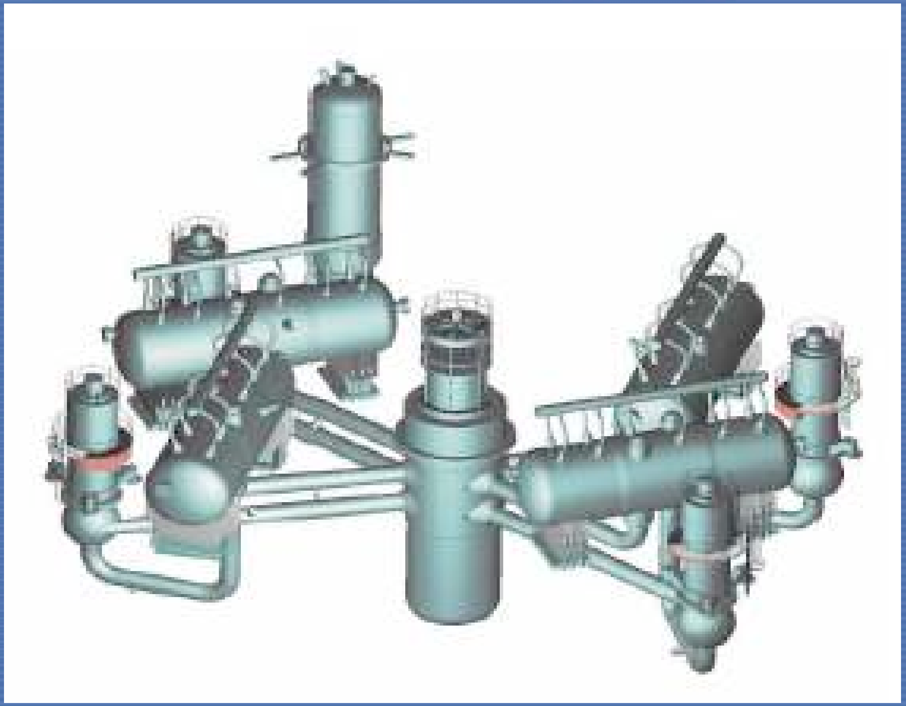
VVER1200/AES2006 (2)

- 4-Trains with capacity 4 x 100% (ECCS) and 4 x50% (Boron Injection)
- No Operator's intervention needed for 24 hours
- Horizontal steam generators guarantee longest life time
- Use of passive systems (containment, residual heat removal)
- Double Containment
- Core Catcher
- Proven Construction schedules
  for VVER1000:
  - 2 plants in operation in China
  - 2 more plants start up in India 2010
- Siemens Digital I&C (TELEPERM-XS)
- Belene / Bulgaria will be first in EU
  and required to follow EU standards



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VVER1200/AES2006 (3)

Pro’s	Con’s
• 4-Train safety systems • Double Containment • Core Catcher • Passive heat removal systems • Siemens TELEPERM-XS I&C • VVER1000 plants in operation • Proven construction schedule • Safety features equal to EPR • Cheaper and easier to construct	• Size: It takes 3 x VVER1200 to produce same lifetime TWh’s as 2 x EPR-1600. This means multiplying cost factors by x1.5: - Staffing numbers, extra overhead - Maintenance outages over lifetime - Spare parts, equipments, components - Doses over lifetime - Waste volumes over lifetime - Decommissioning costs • Does not fulfill NQA-1 requirements • No Western-style QA (Inspections and tracing components from start of manufacturing) • No NRC regulatory compliance • Questions on availability of spare parts 60 years • Lack of competition on fuel supply

HEAVY WATER REACTORS (HWR)

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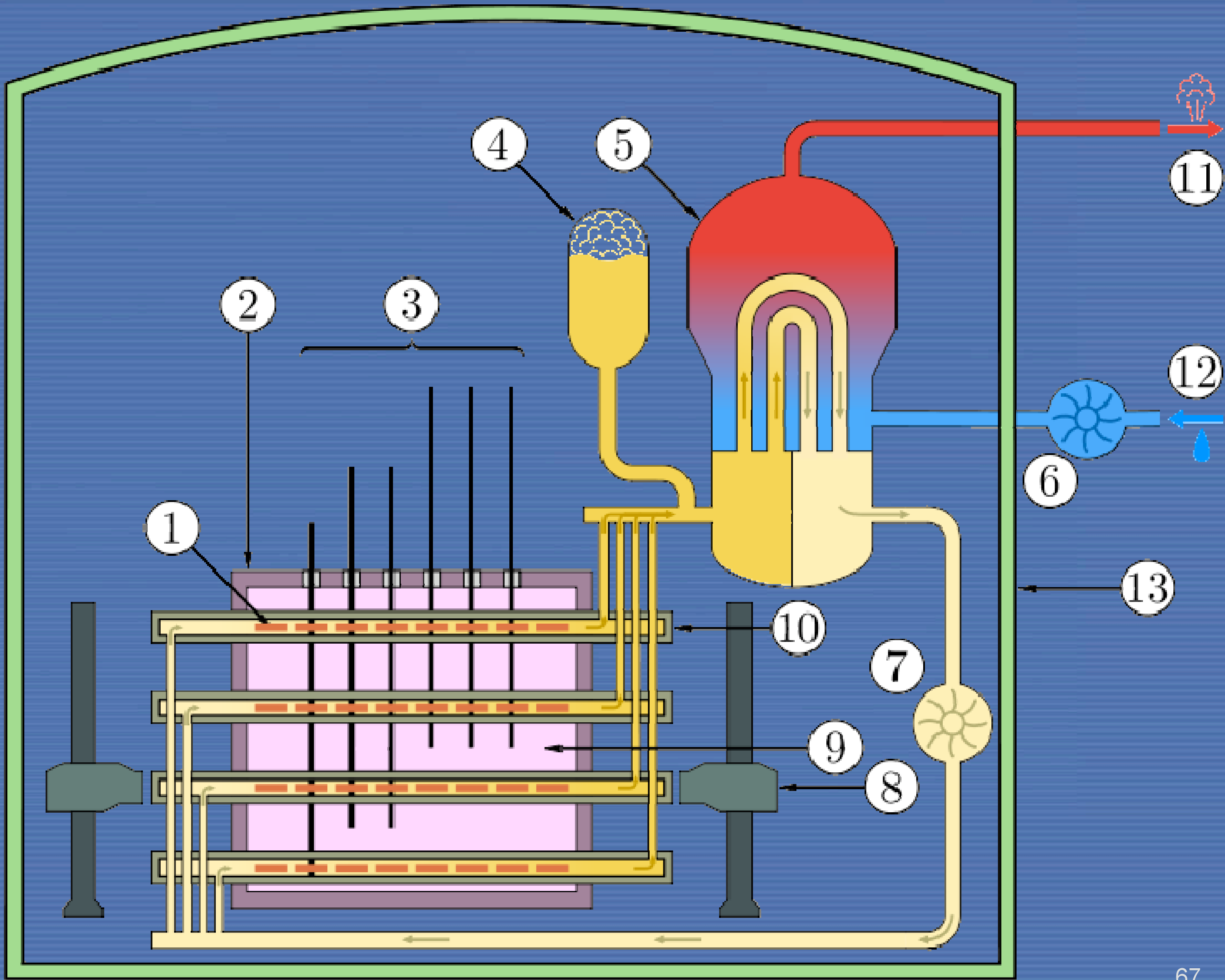
Heavy Water Reactor (HWR)

1. Nuclear Fuel
2. Calandria
3. Control Rods
4. Pressurizer
5. Steam Generator
6. Light Water Pump
7. Heavy Water Pump
8. Nuclear Fuel Reload Machine
9. Heavy water moderator
10. Pressure Tubes
11. Steam
12. Condensate Water
13. Containment



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Evolution of Commercial NPP Designs - HWR

- **GE / AECL:**
  - in the 1950's GE and AECL cooperated on the development of the CANDU prototype design (NRU, NPD plants)
- **AECL:**
  - in 1960's AECL developed CANDU design with typical characteristics:
    - Heavy water moderated and cooled
    - Pressure tubes / on-line refueling
    - Runs on natural uranium
  - in 1970' & 1980's two standard CANDU designs (C-6/C-9) were deployed in Canada and worldwide (C-6 only)
  - in 1990's the ACR700 was developed, but failed to get acceptance in U.S. Consequently, a scaled up ACR1000 was developed.
  - with ACR1000, AECL moves the CANDU design towards PWR, utilizing light water cooling and enriched uranium (2.4% initially, but ultimately 4%) to reach higher burnup

Evolution of Commercial NPP Designs – CANDU (2)

Vendor	1950's	1960's	1970's	1980's	1990's	2000's	3G NPPs
GE / AECL		NRU & NPD					
AECL CANDU-6			Pickering	Point Lepreau		Cernavoda	Enhanced Candu-6 (EC6)
AECL CANDU-9			Bruce		Darlington		
AECL ACR700							
AECL ACR1000							ACR1000

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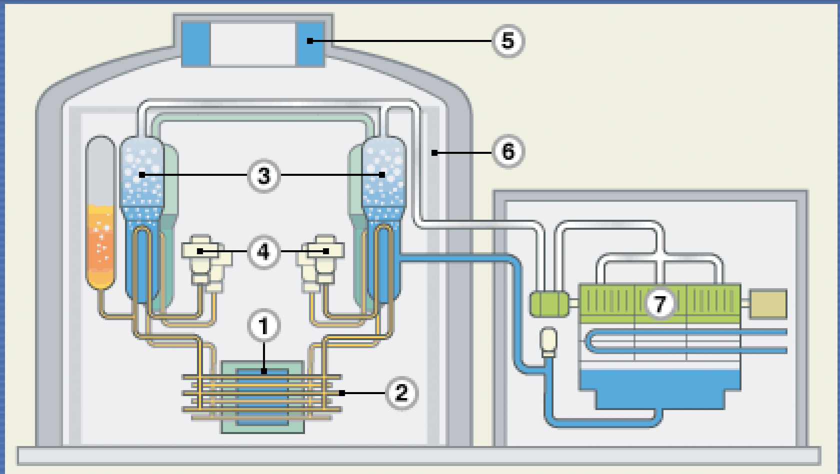
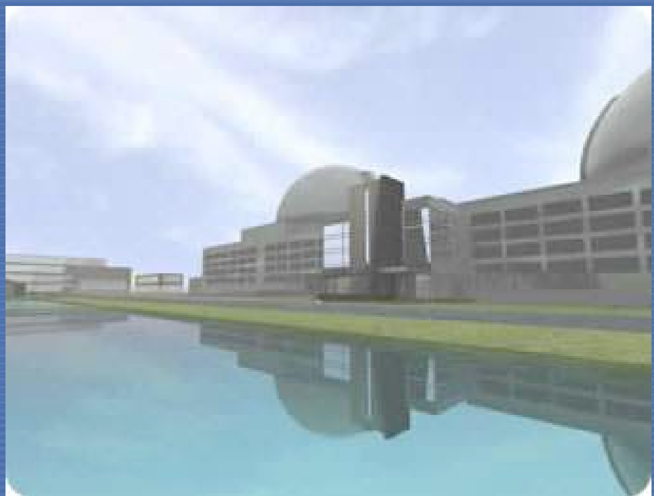
Credit: EXCEL SERVICES CORPORATION

ACR-700 & ACR-1000





- AECL
- 700 MWe Enhanced CANDU-6
- 1000 MWe Advanced CANDU reactor
- 284 / 520 horizontal channels
- Low enriched uranium– 2.1%,
- 60 yr design life
- Continuous refueling
- Combination of active and passive safety systems
- CNSC has started “pre-project” design review
- Energy Alberta has filed *an Application for a License to Prepare Site* with the CNSC -- for siting up to two twin-unit ACR-1000s --- commissioning by ~2017
- 30 CANDU operating in the world
  - 18 Canada (+2 refurbishing, +5 decommissioned)
  - 4 South Korea
  - 2 China
  - 2 India (+13 Indian-HWR in use, +3 Indian-HWR under construction)
  - 1 Argentina
  - 2 Romania (+3 under construction)
  - 1 Pakistan

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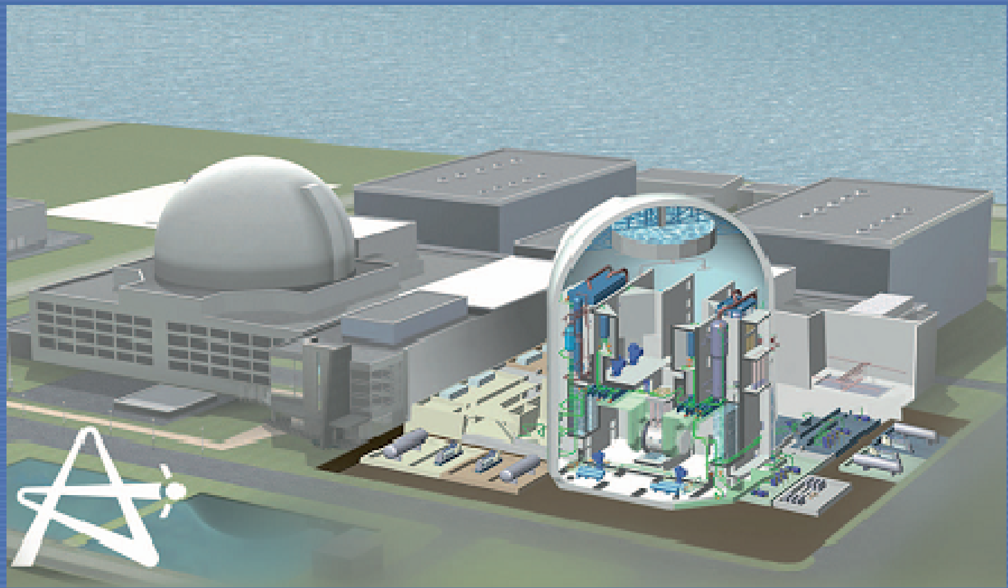
ACR1000

- 1165 MWe advanced CANDU (evolutionary development)
- Light-water-cooled, heavy-water-moderated
- 2.4% enriched uranium in fuel achieves 20 MWd/kgU burnup (4.0% enriched fuel to achieve 40 MWd/kgU burnup / future target)
- 4-Loop design
- Strengthened containment building (single wall)
- Reactor Vault is waterfilled (Core catcher function)
- CDF = 3.4E-7



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ACR1000 (2)

- Retains all basic CANDU features:
  - modular design and construction
  - horizontal pressure tube core
  - heavy water moderator
  - on-line refueling
  - on-line maintenance
- 60% reduced heavy water inventory
- Can burn MOX, Thorium fuels
- 2.4% enriched uranium fuel ensuring negative reactivity coefficients

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ACR1000 (3)

Pro's	Con's

• Reduced number of systems and components (simplified design)
• Some Passive safety
• Pressure tube replacement is lifetime limit
• Best Uranium utilization plant
• Fuel flexibility (U, RU, Pu, Th)
• Full MOX core possible
• On-line refuelling
• Most modularized design, proven construction schedule
	• None in operation
	• It takes 3 x ACR1000 to produce same lifetime TWh's as 2 x EPR1600, which means multiplying cost factors by x1.5:
	  • Staffing numbers, extra overhead
	  • Maintenance outages over lifetime
	  • Spare parts, equipments, components
	  • Doses and Waste volumes over lifetime
	  • Decommissioning costs
	• Pressure Tubes need replacement after ~30yr
	• Moving towards PWR characteristics (20 MWd/kgU Burnup vs 60 MWd/kgU for PWRs)
	• Lost some important CANDU features, namely near Breeder fuel utilization ➔ using DUPIC fuel to burn LWR spent fuel

India's HWR

- 540 MWe PHWR [evolution from current 220 MWe HWRs]
  - » Nuclear Power Corporation of India, Ltd.
  - » First units: Tarapur-3 & -4 connected to grid (2005 & 6)
- 700 MWe PHWR [further evolution – economy of scale]
  - » NPCIL
  - » Regulatory review in progress
  - » Use of Passive Decay Heat Removal System; reduced CDF from PSA insights
  - » Better hydrogen management during postulated core damage scenario
  - » First units planned at Kakrapar & Rawatbhata

- Advanced HWR
  - » BARC
  - » for conversion of Th232 or U238 (addressing sustainability goals)
  - » vertical pressure tube design with natural circulation

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SMALL AND MEDIUM SIZE REACTORS (SMR)

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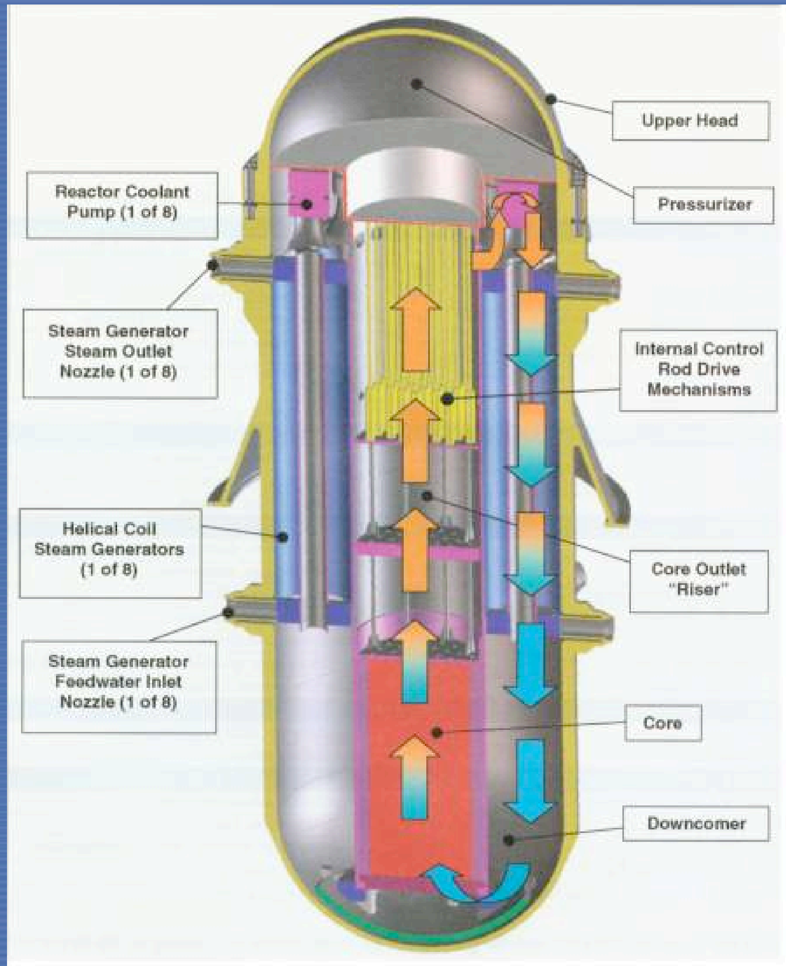
IRIS (International Reactor Innovative and Secure)

- Westinghouse
- 100-335 MWe
- Integral design
- Design and testing Involves 19 organizations (10 countries)
- Pre-application review submitted to the USNRC in 2002
- To support Design Certification, large scale (~6 MW) integral tests are planned at SPES-3 (Piacenza, IT)
  - Construction start – late 2009
- Westinghouse anticipates Final Design Approval (~2013)



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CAREM (Central Argentina de Elementos Modulares)

- Developed by INVAP and Argentine CNEA
- Prototype: 25 MWe
- Expandable to 300 MWe
- Integral reactor
- Passive safety
- Used for electric and non-electric applications
- Nuclear Safety Assessment to be submitted end of 2009
- Prototype planned for 2012

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NuScale

- Oregon State University (USA)
- 45 MWe
- 90% Capacity Factor
- Integral reactor
- Modular, scalable
- Passive safety
- Online refueling
- To file for Design Certification with US NRC in 2010.

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SMART

- Korea Atomic Energy Research Institute
- 330 MWe
- Integral reactor
- Passive Safety
- Used for electric and non-electric applications

Floating Reactors

- Provide electricity, process heat and desalination in remote locations
- KLT-40S (150 MWt → 35 MWe)
- VBER-150 (350 MWt → 110 MWe)
- VBER-300 (325 MWe)

Construction of pilot plant (2 units) started April 2007

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INNOVATIVE WATER COOLED REACTORS

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Generation IV Reactor Designs

- Several design concepts are under development to meet goals of
  - Economics
  - Sustainability
  - Safety and reliability
  - Proliferation resistance and physical protection
- All concepts (except VHTR) are based on closed fuel cycle
- Concepts include small, modular approaches
- Most concepts include electrical and non-electrical applications
- Significant R&D efforts are still required
- International cooperation needed for pooling of resources

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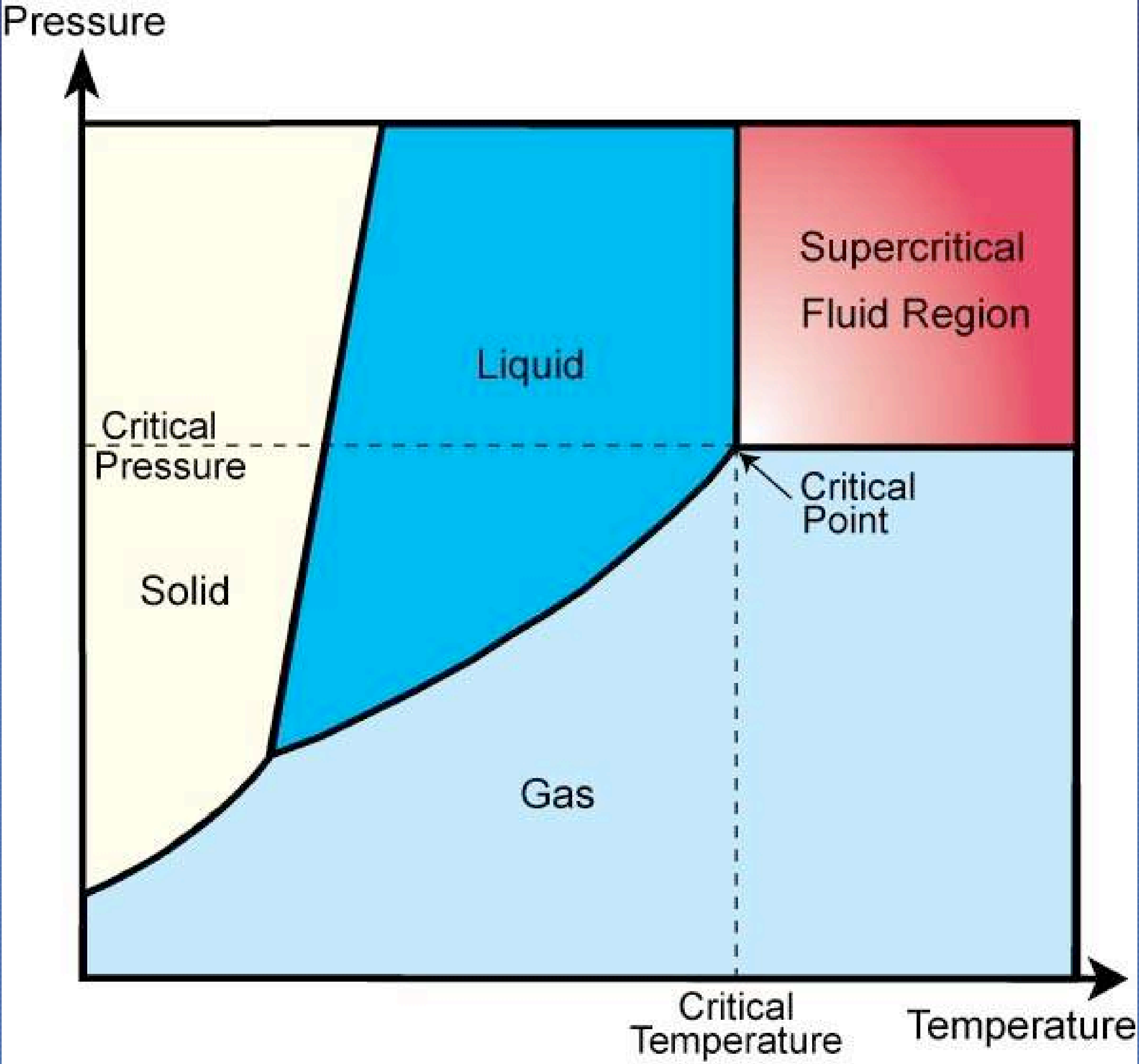
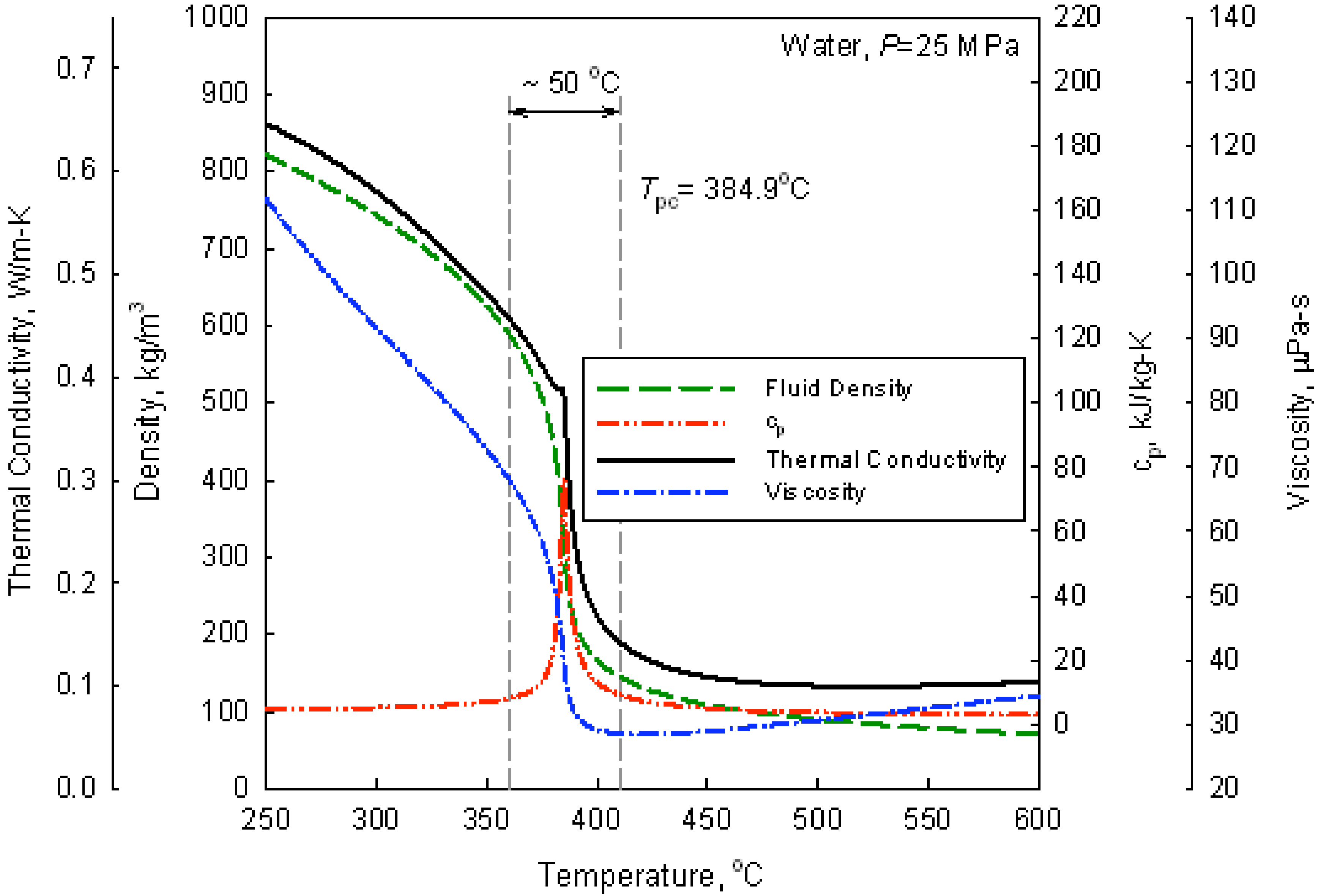
Generation IV Reactor Designs

- Gas Cooled Fast Reactors (GFR)
- Very High Temperature Reactor (VHTR)
- Super-Critical Water Cooled Reactor (SCWR)
- Sodium Cooled Fast Reactor (SFR)
- Lead-Cooled Fast Reactor (LFR)
- Molten Salt Reactor (MSR)



Pressure
Supercritical
Fluid Region
Liquid
Critical
Pressure
Critical
Point
Solid
Gas
Critical
Temperature
Temperature



Water, P=25 MPa
~ 50 °C
T_pc= 384.9°C
Fluid Density
c_p
Thermal Conductivity
Viscosity
Thermal Conductivity, W/m-K
Density, kg/m^3
c_p, kJ/kg-K
Viscosity, μPa-s
Temperature, °C
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
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300
400
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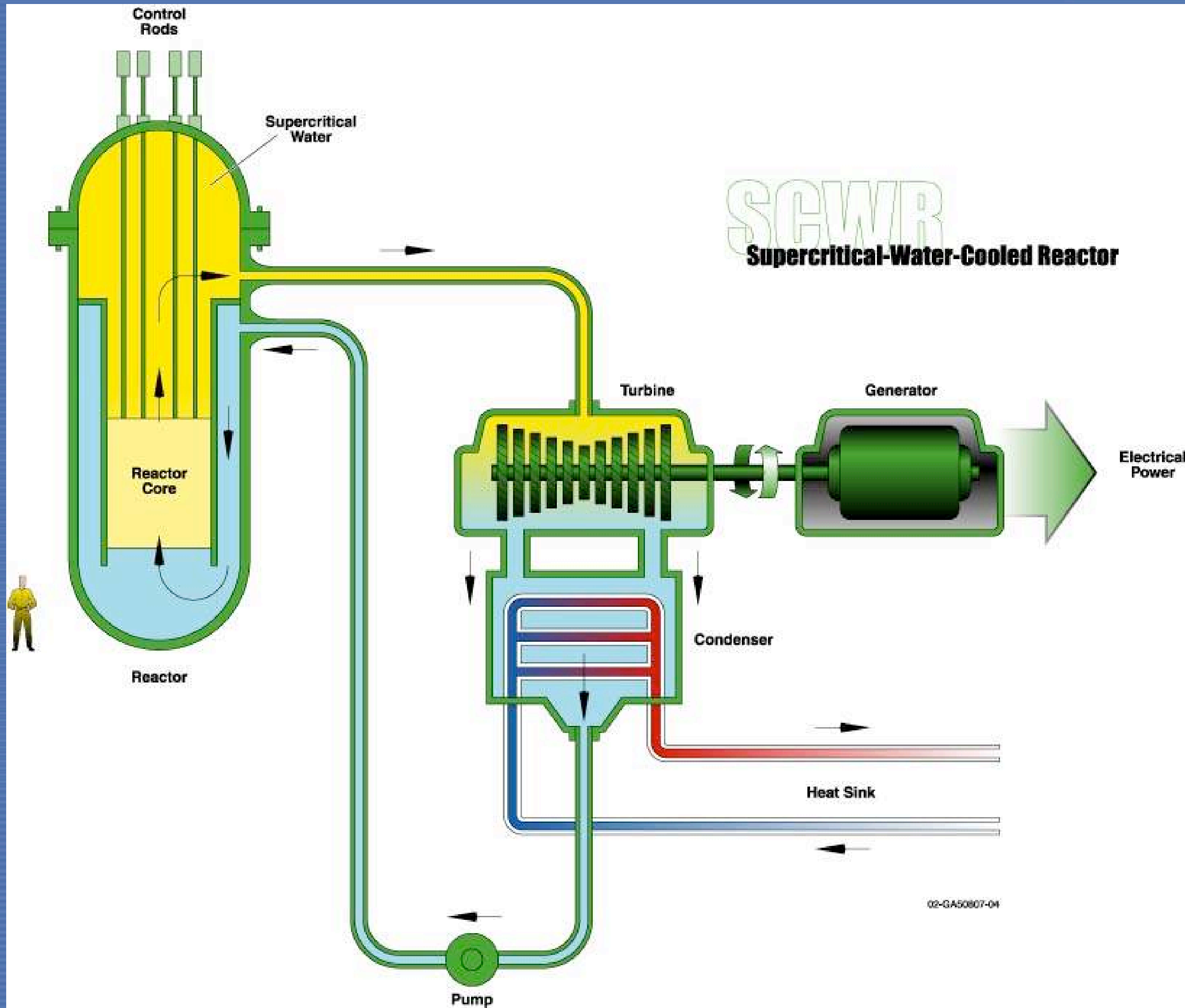
Super-Critical Water Cooled Reactor



Thank you!