VCU Virginia Commonwealth University

Department of Mechanical & Nuclear Engineering

Fundamentals of Nuclear Power

Osher Lifelong Learning Institute

Spring 2012

Proposed Program

SESSION	TOPIC	INSTRUCTOR
# 1 March 21	Basic concepts in nuclear physics, types of radiation, radiation decay, etc	James Miller
#2 March 28	Radiation health effects	Brian Hinderliter
#3 April 4	Nuclear power plant design, types of nuclear power plants, nuclear safety	Gokul Vasudevamurthy
#4 **April 11**	**Current status of nuclear power in the world, advanced reactors, SMRs, nuclear power construction projects**	**Sama Bilbao y León**
#5 April 18	The nuclear fuel cycle	James Miller
#6 April 25	Survey of large nuclear power accidents: Three Mile Island, Chernobyl and Fukushima Daiichi	Josh Bell Sama Bilbao y León
#7 May 2	Sociopolitics and nuclear power: used nuclear fuel management, Yucca Mountain, uranium mining	Invited Speakers
#8 May 8	Choice Topic: • Nuclear medicine and other applications of nuclear science and technology • The future of nuclear power: fast breeder reactors, fusion technology, nuclear power and other power sources. • History of the US Nuclear Navy	TBD

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Current status of nuclear power in the world

Prof. Sama Bilbao y León

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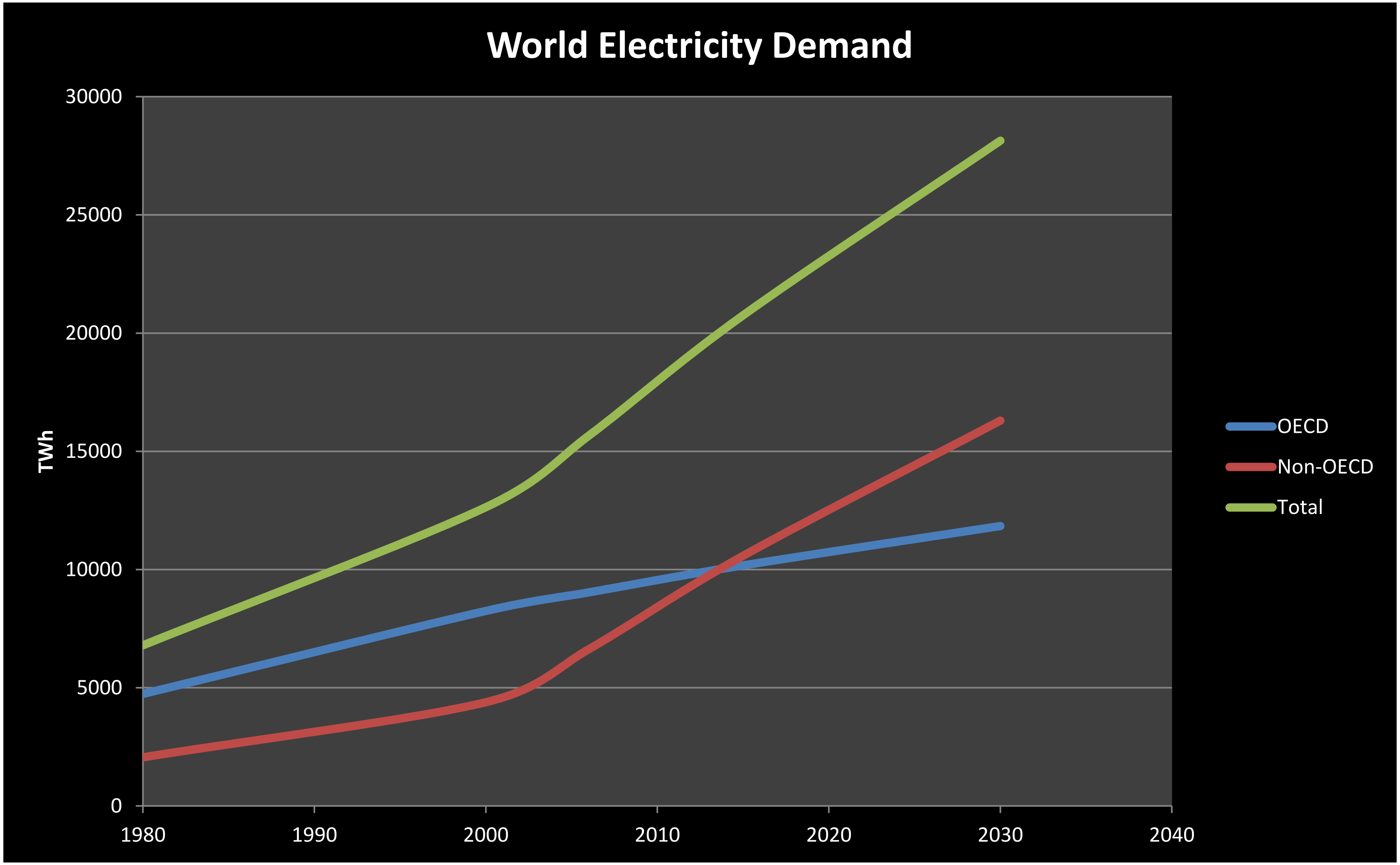
Predicted Global Electricity Demand



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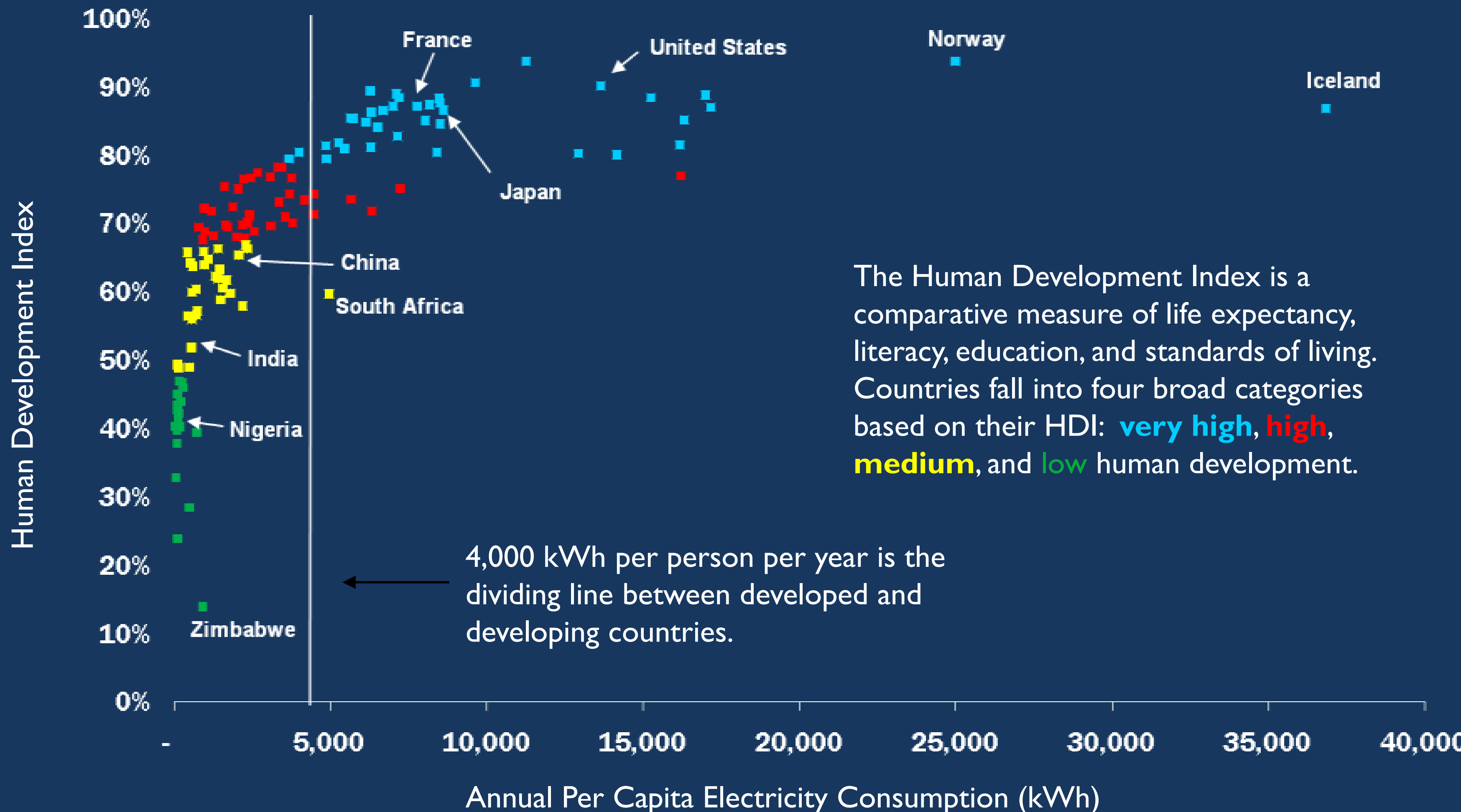
Correlation Between Human Development and Per Capita Electricity Consumption



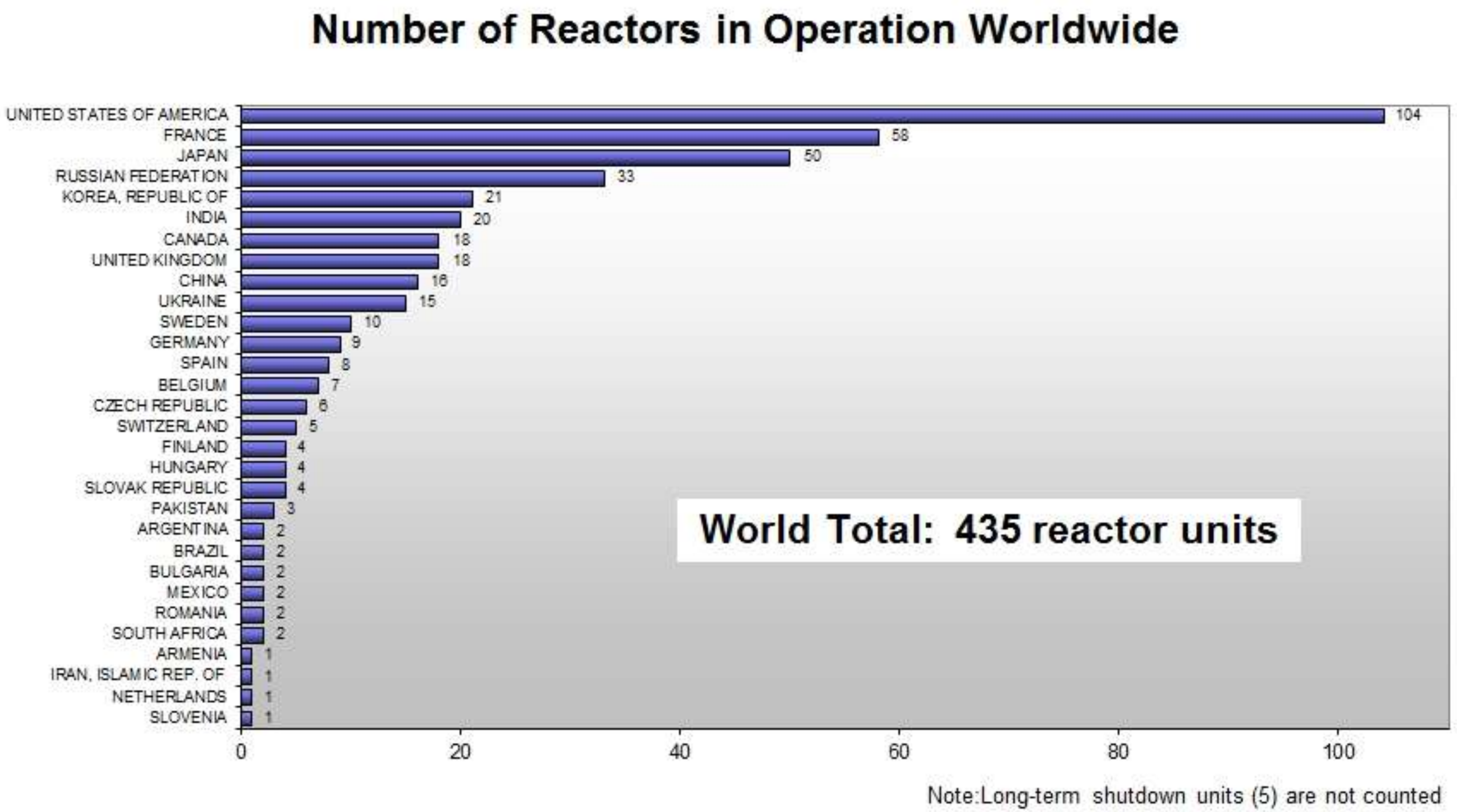
The Human Development Index is a comparative measure of life expectancy, literacy, education, and standards of living. Countries fall into four broad categories based on their HDI: **very high**, **high**, **medium**, and low human development.

4,000 kWh per person per year is the dividing line between developed and developing countries.

Source: Human Development Index – 2010 data United Nations; Annual Per Capita Electricity Consumption (kWh) - 2007 data World Bank

Updated: 4/11

Reactors Currently in Operation



Source: PRIS, IAEA, 01/2012

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Reactors Currently in Operation

TYPE	Number of Units	Total Capacity [MWe]
BWR	84	77,621
FBR	2	580
GCR	17	8,732
LWGR	15	10,219
PHWR	47	23,160
PWR	270	247,967
TOTAL	435	368,279

Source: PRIS, IAEA, 01/2012

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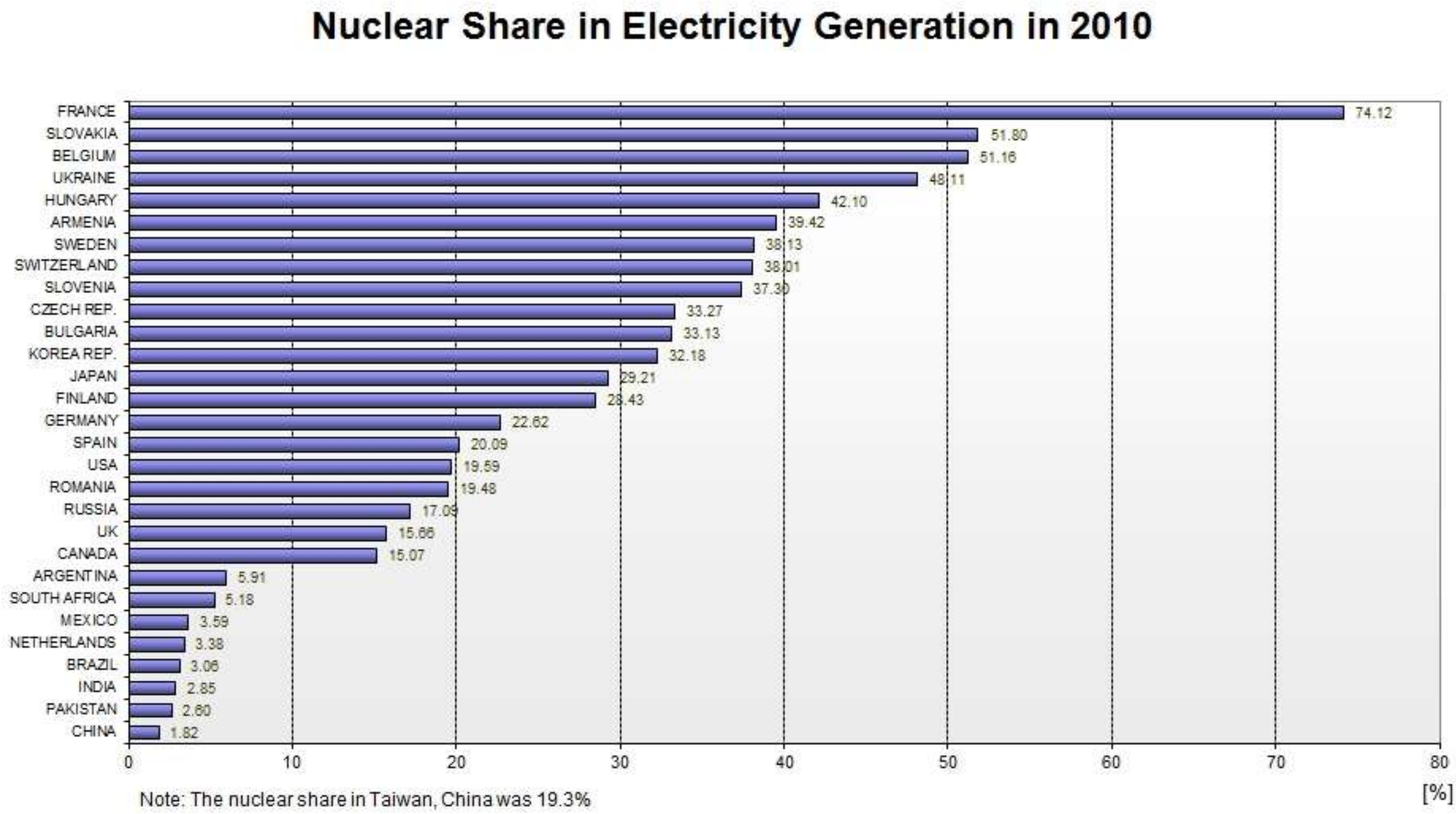
Nuclear Electricity Generation



Source: PRIS, IAEA, 01/2012

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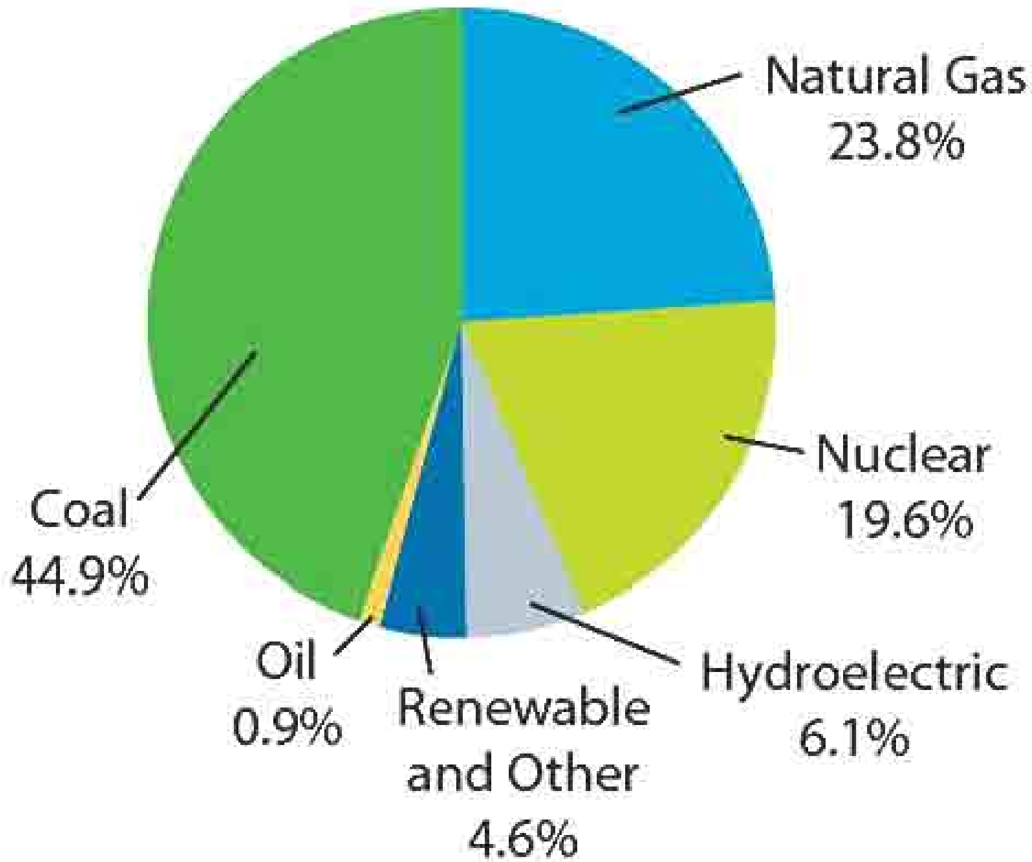
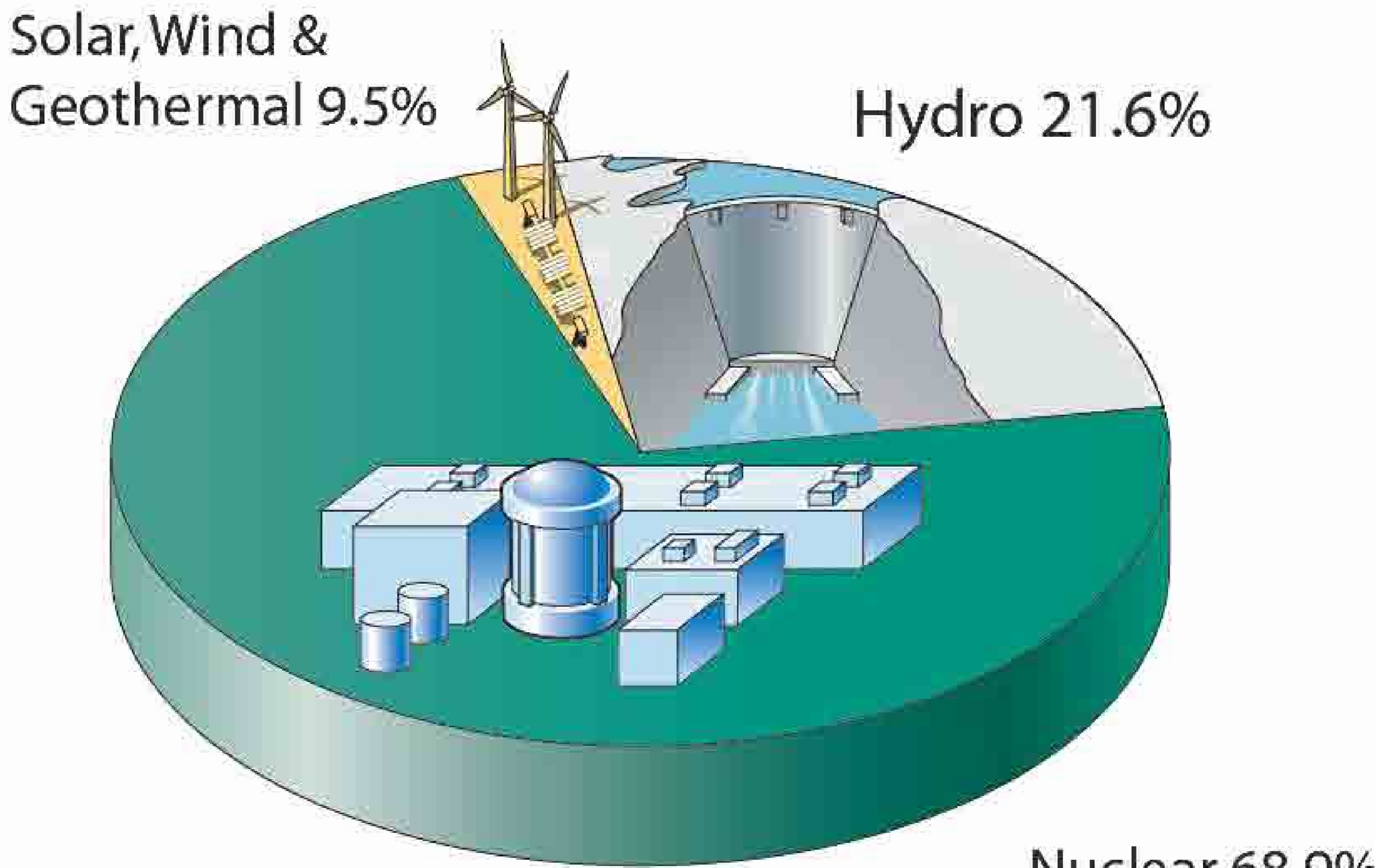
U.S. Electricity Generation Fuel Shares 2010

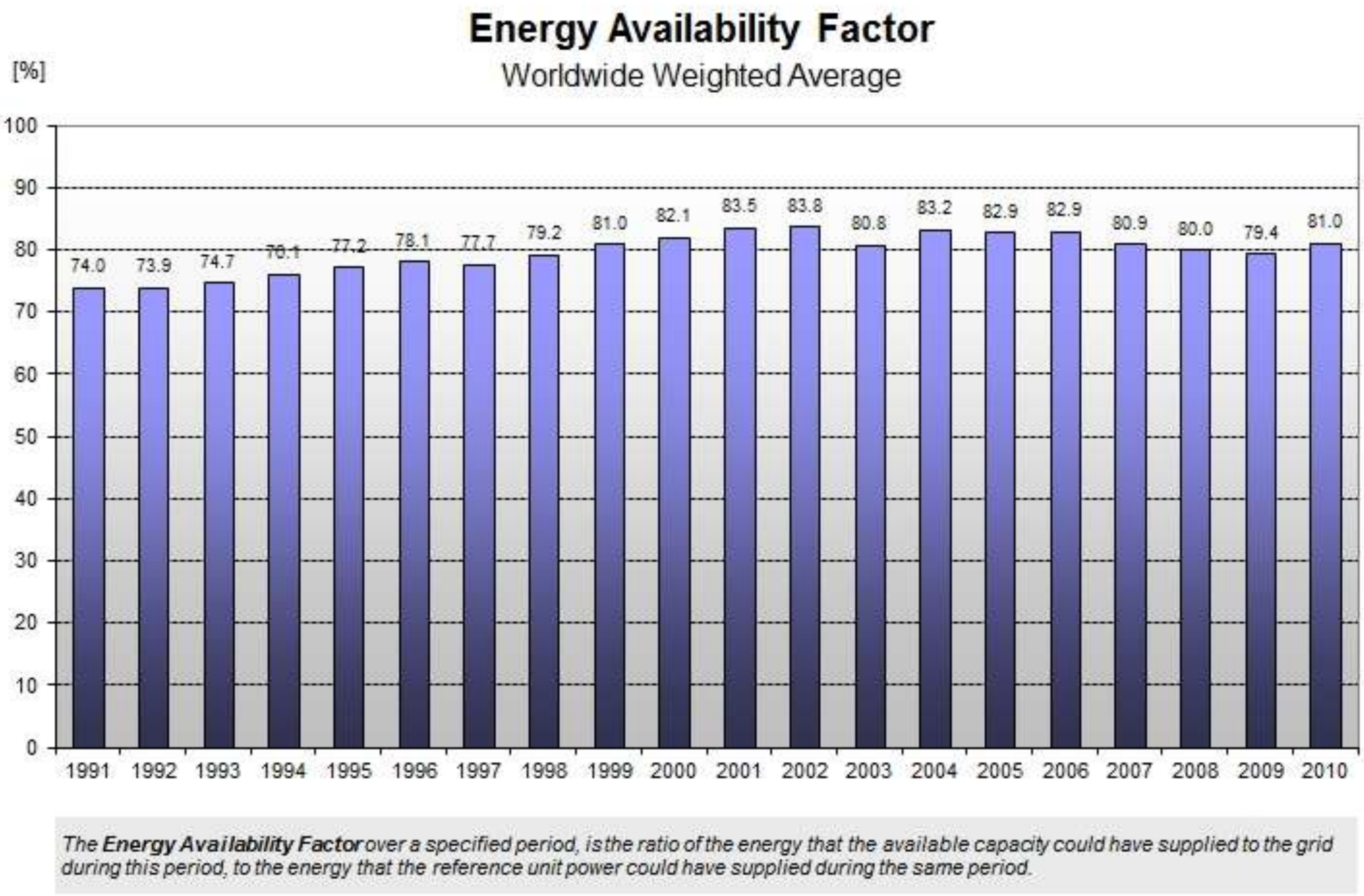


Source: U.S. Energy Information Administration

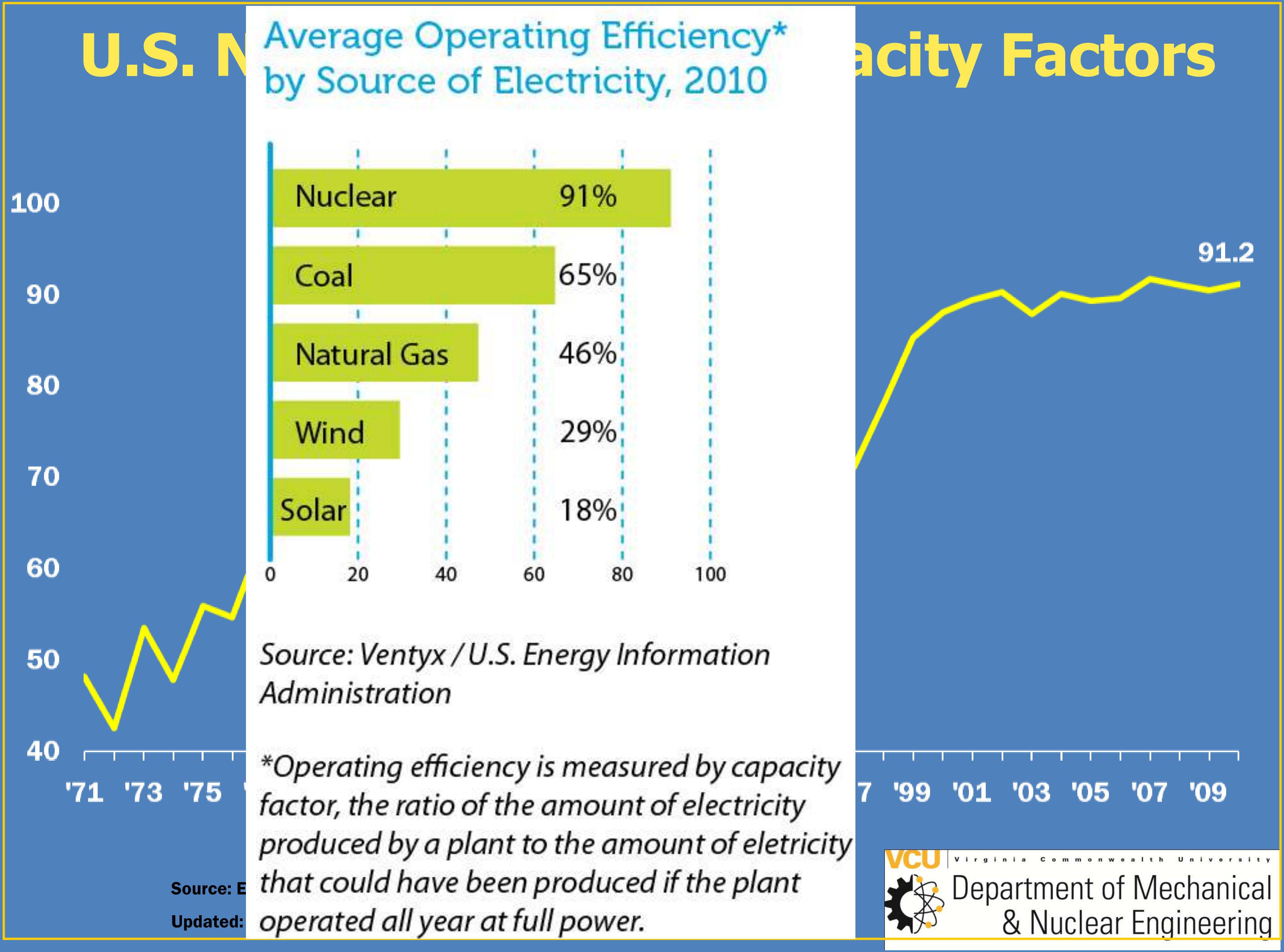
Sources of Emission-Free Electricity 2010



Availability Factors



Source: PRIS, IAEA, 01/2012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'75
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'05
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'09
Source: E
Updated:
Average Operating Efficiency*
by Source of Electricity, 2010
Nuclear 91%
Coal 65%
Natural Gas 46%
Wind 29%
Solar 18%
0
20
40
60
80
100
Source: Ventyx / U.S. Energy Information Administration
*Operating efficiency is measured by capacity factor, the ratio of the amount of electricity produced by a plant to the amount of eletricity that could have been produced if the plant operated all year at full power.
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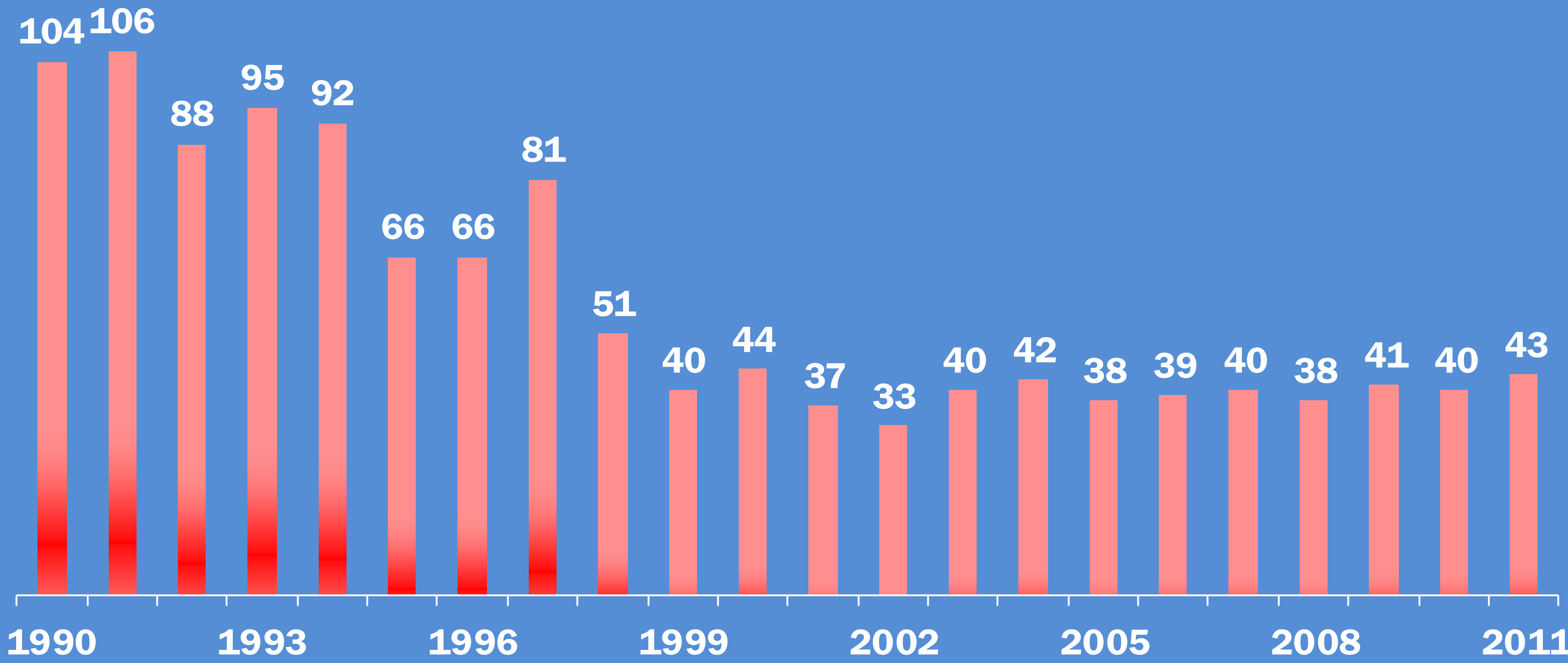
U.S. Nuclear Refueling Outage Days

Average



Source: 1990-98 EUCG, 1999-2011 Ventyx Velocity Suite / Nuclear Regulatory Commission

Updated: 3/12

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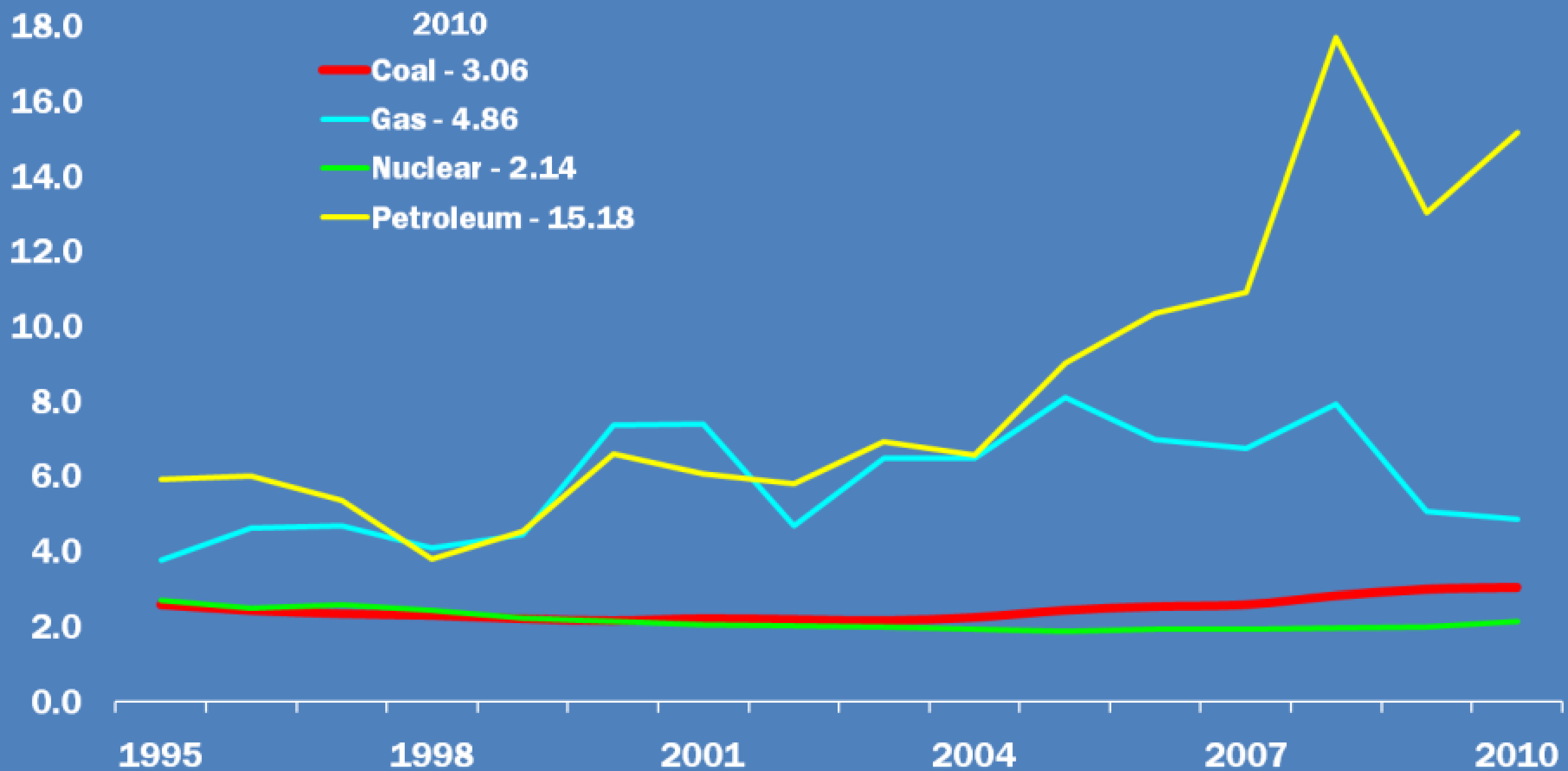
U.S. Electricity Production Costs

1995-2010, *In 2010 cents per kilowatt-hour*



Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated.

Source: Ventyx Velocity Suite
Updated: 5/11

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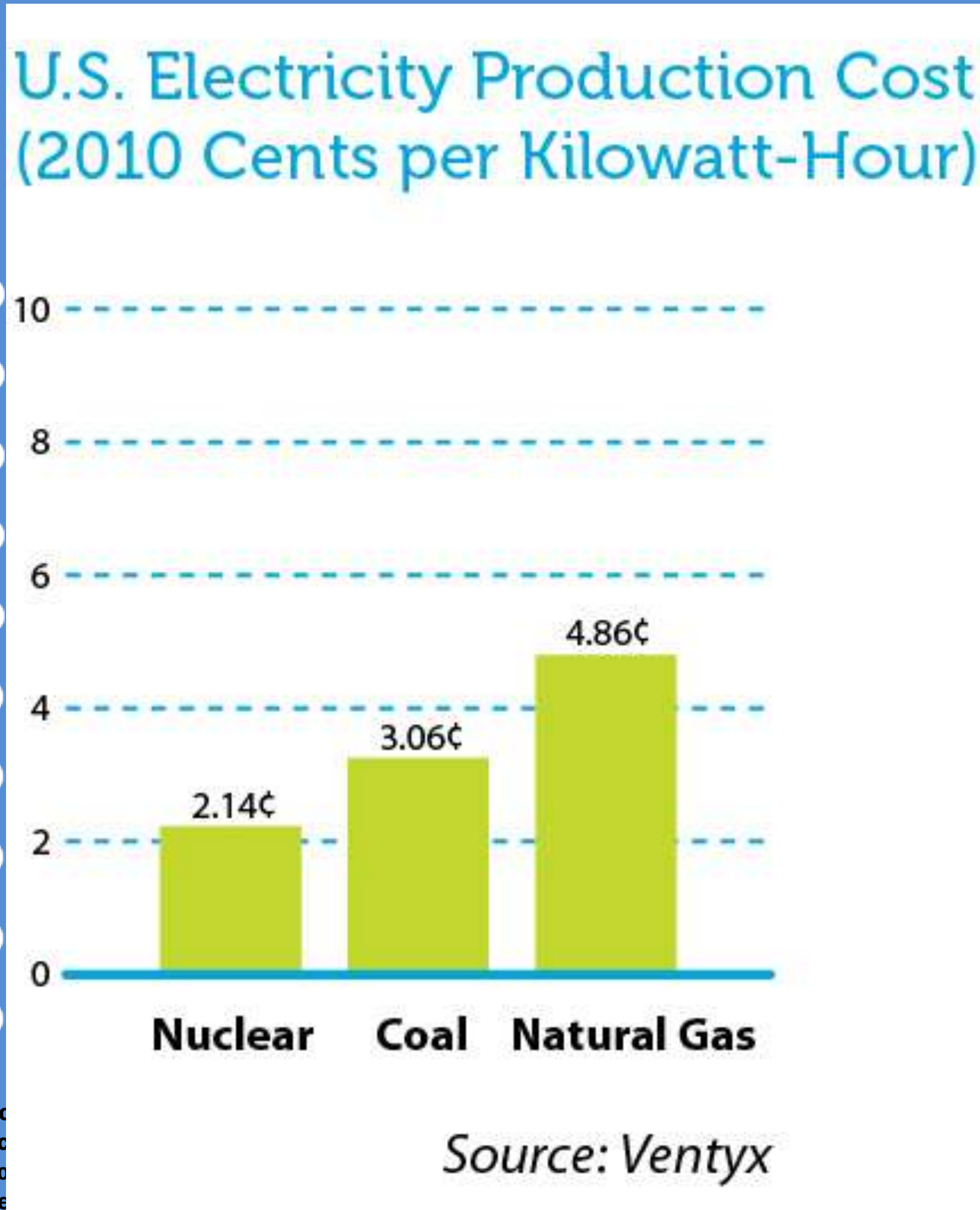
ction Costs

kilowatt-hour



Nuclear Power is the only form of electricity production whose price includes the cost of waste management and plant decommissioning.

Produc ... ude
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Source
Updated: 5/11

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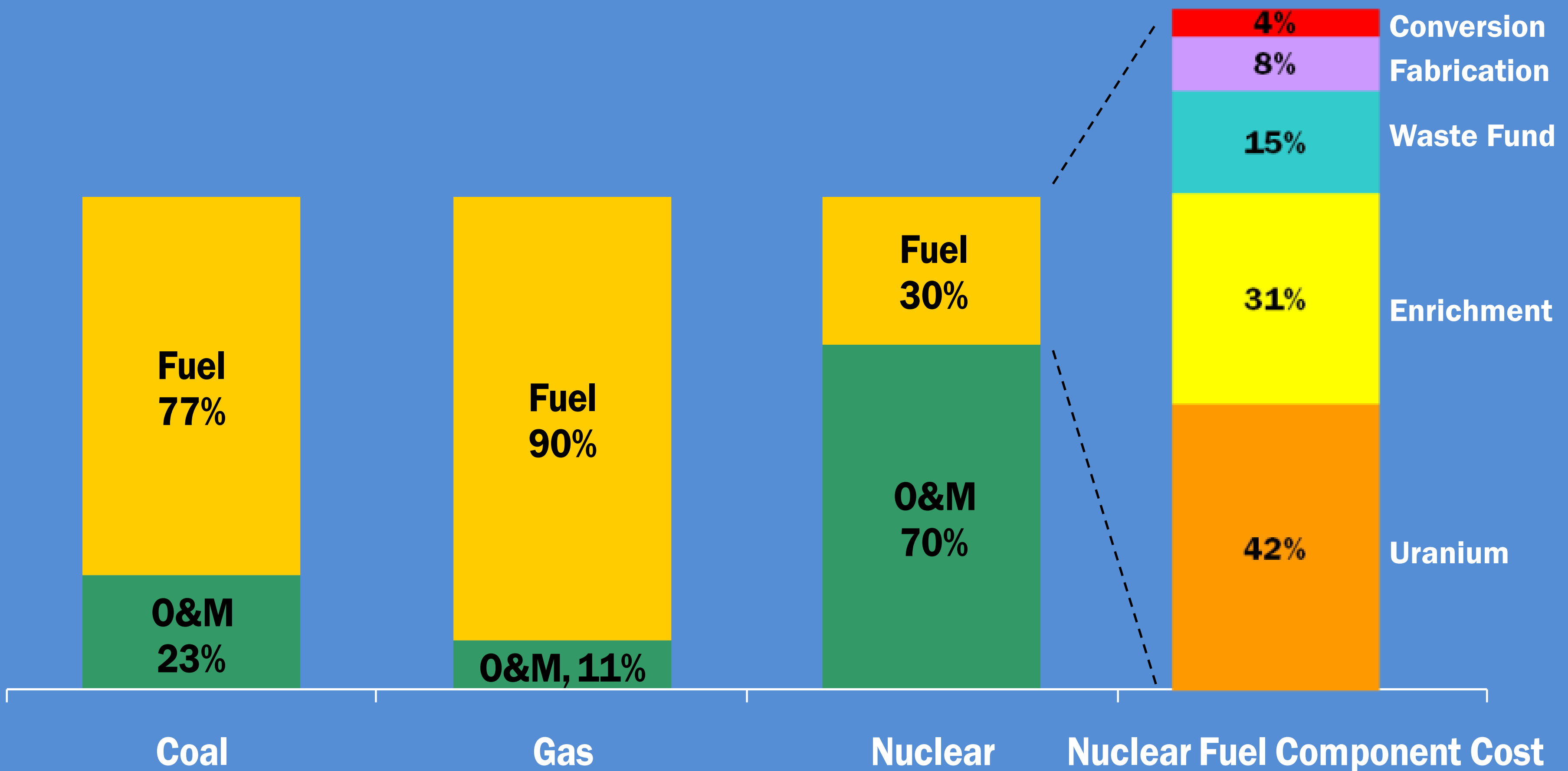
Fuel as a Percentage of Electric Power Production Costs

2010



Source: Ventyx Velocity Suite; Energy Resources International, Inc.
Updated: 5/11

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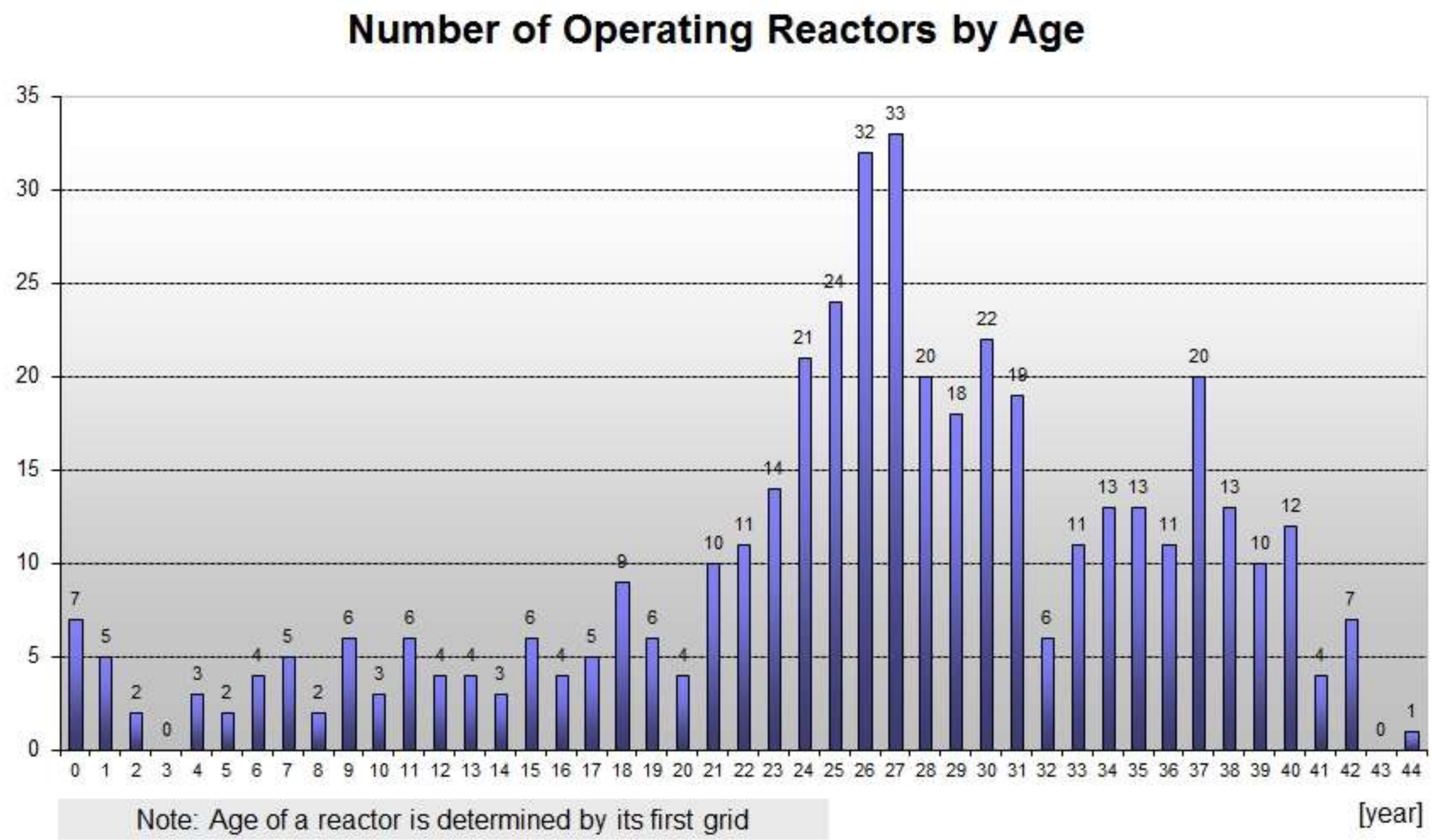
Age of the current fleet



Source: PRIS, IAEA, 01/2012

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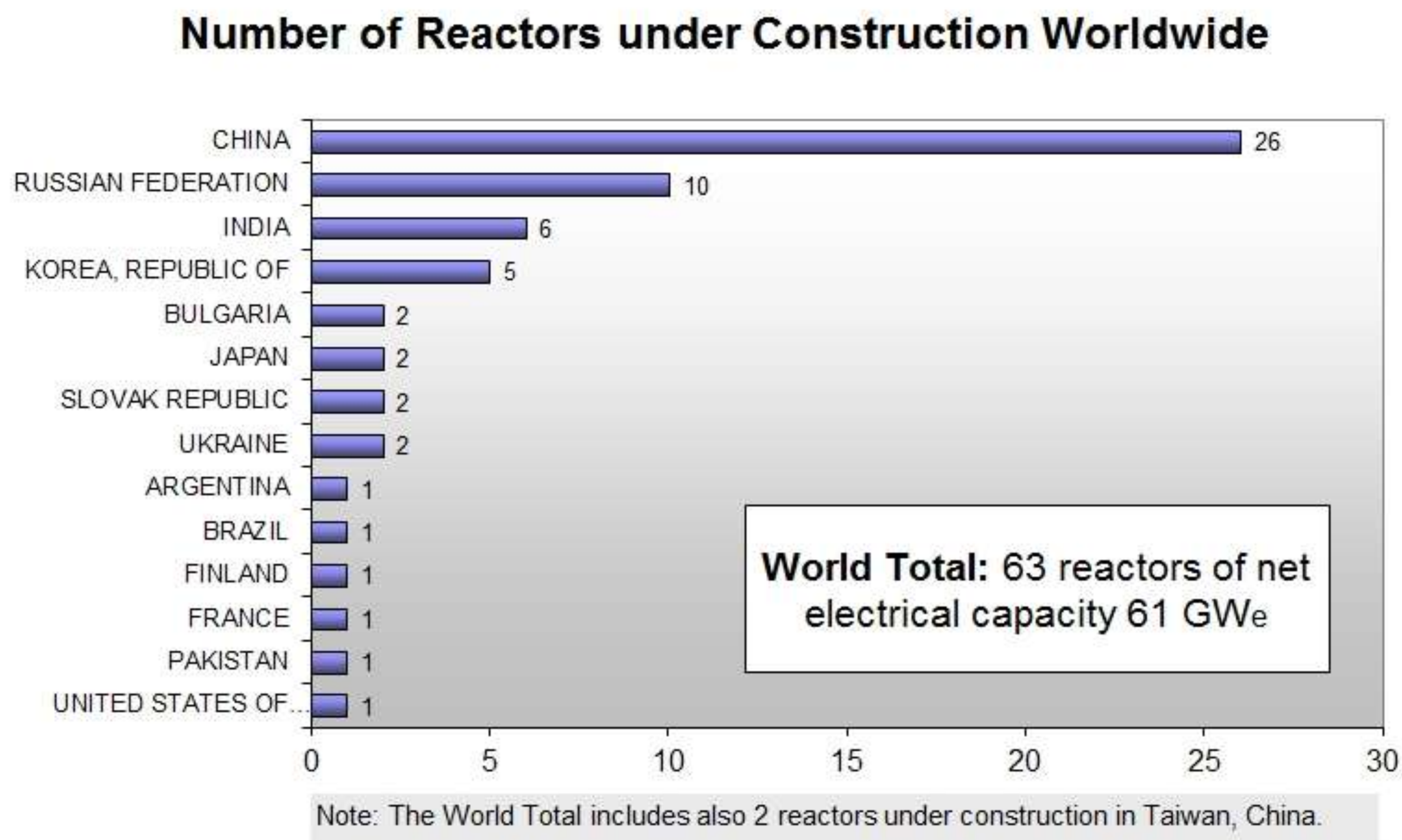
Reactors Currently under Construction



Source: PRIS, IAEA, 01/2012

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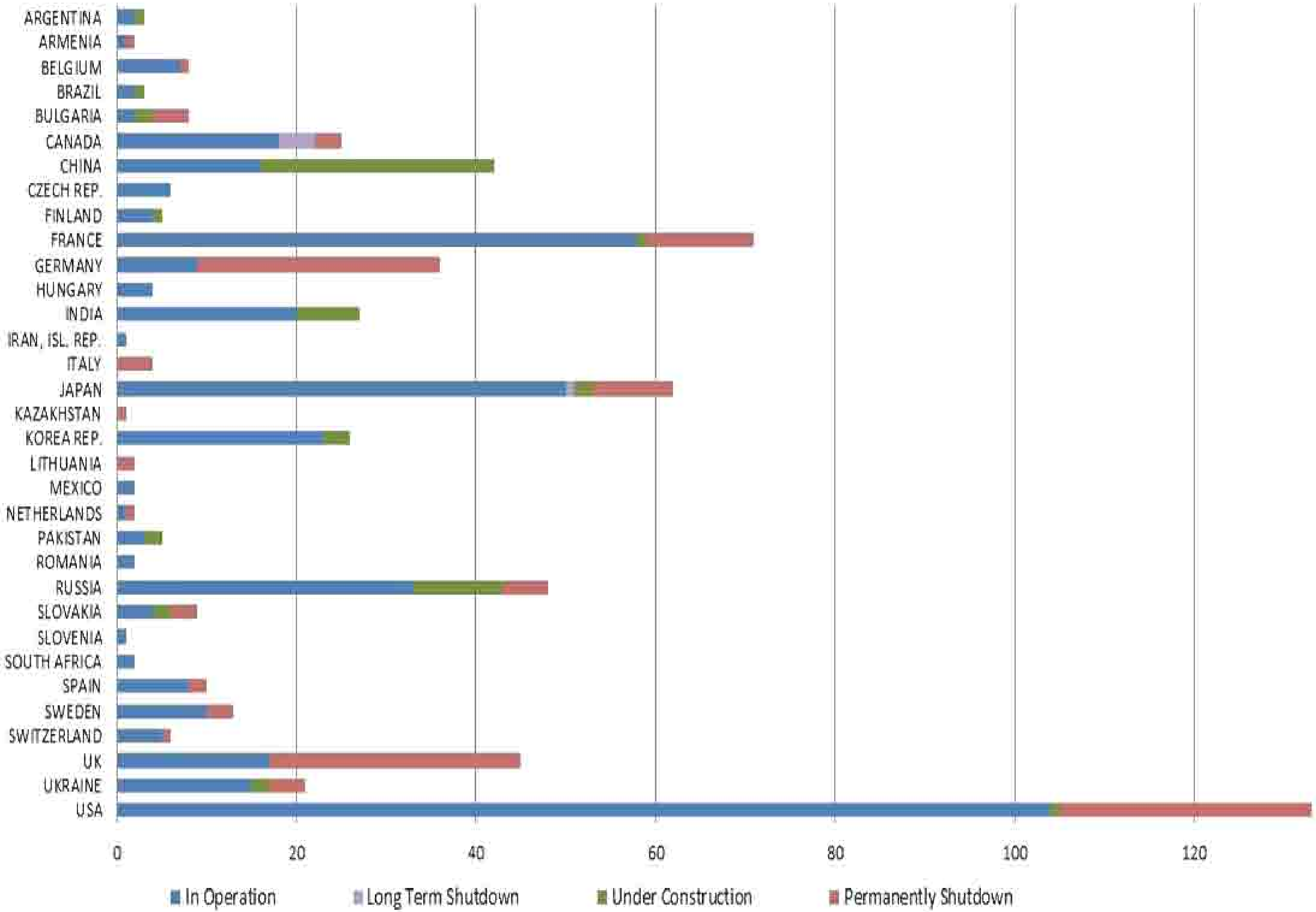
Reactors Currently under Construction

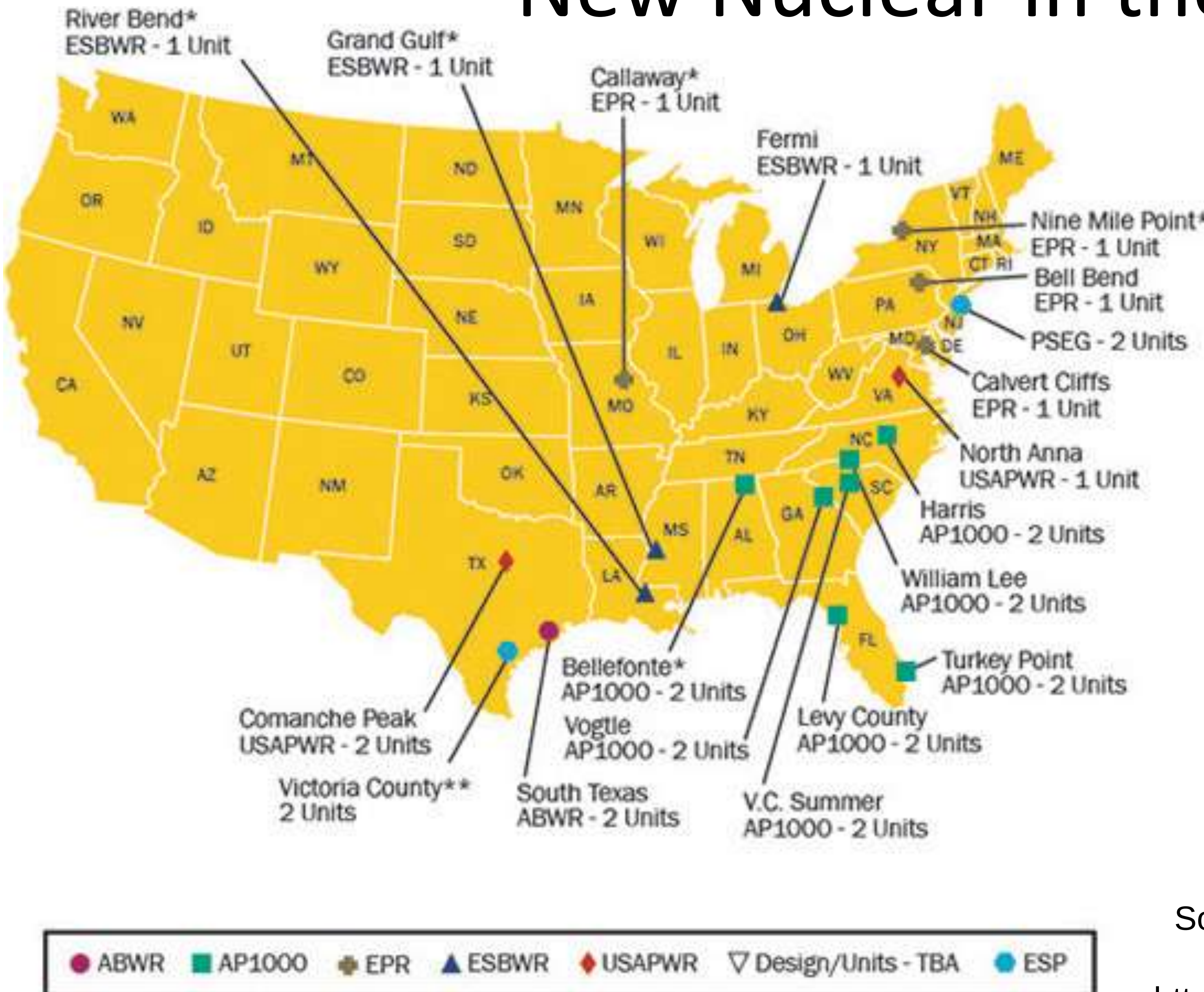
Under Construction		
Type	**No. of Units**	**Total MW(e)**
BWR	4	5,250
FBR	2	1,274
LWGR	1	915
PHWR	4	2,582
PWR	52	51,011
Total:	**63**	**61,032**

Source: PRIS, IAEA, 08/2011

Number of Power Reactors by Country and Status



New Nuclear in the US

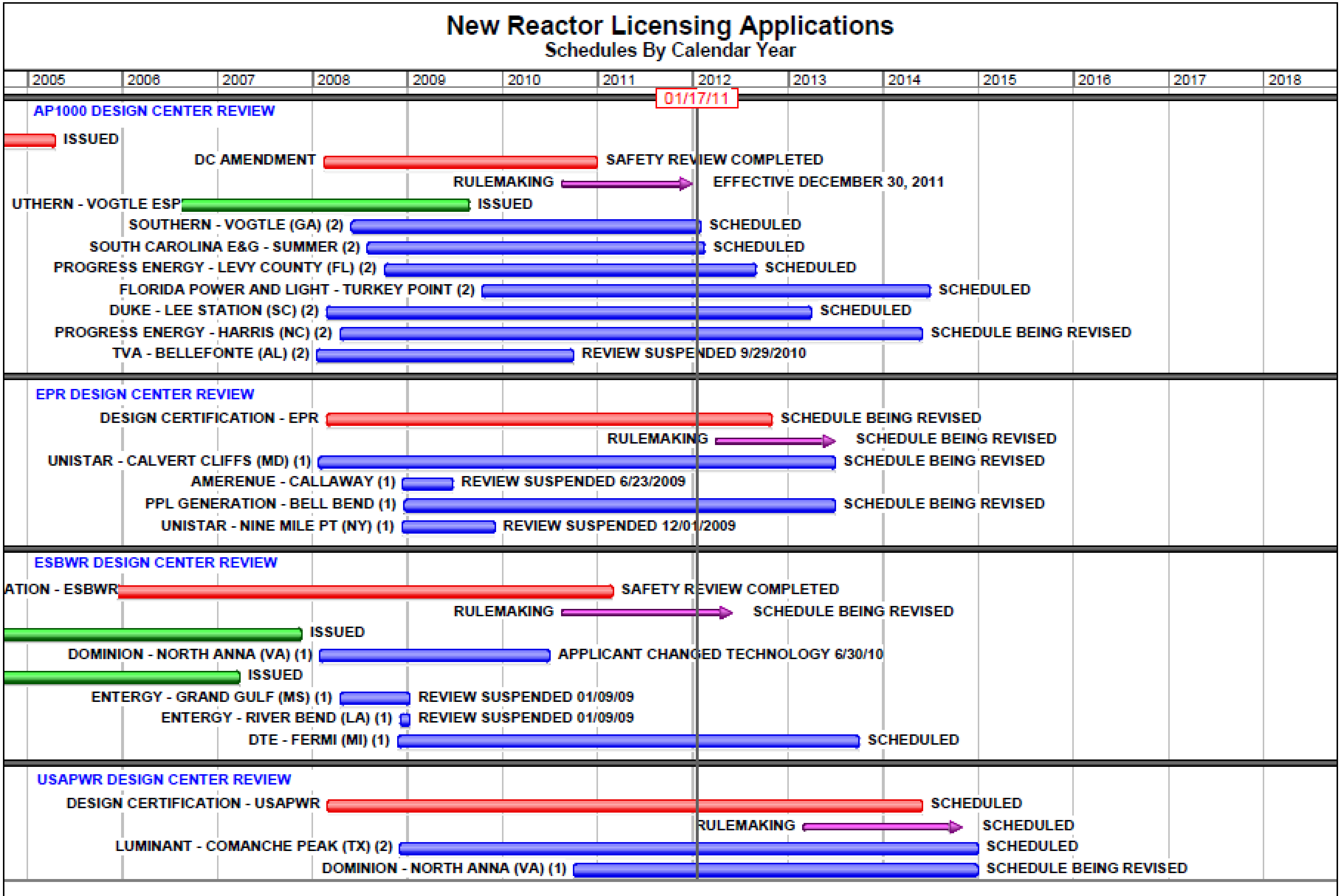


*Review Suspended by Applicant

** COL Application Amended by Applicant to ESP on 03/25/2010

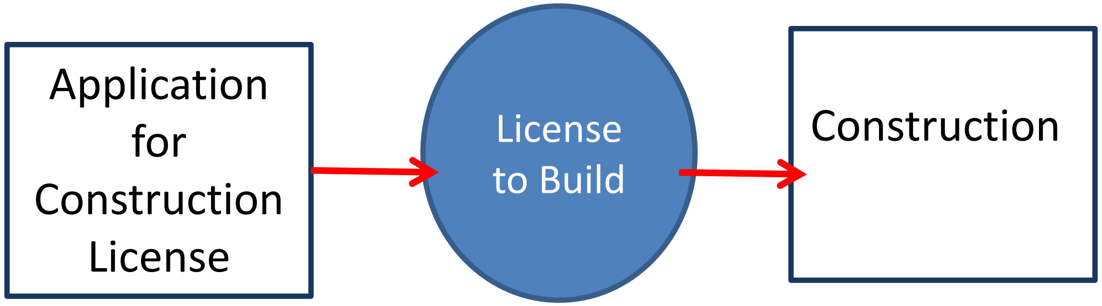
Source: US NRC
08/2011
http://www.nrc.gov

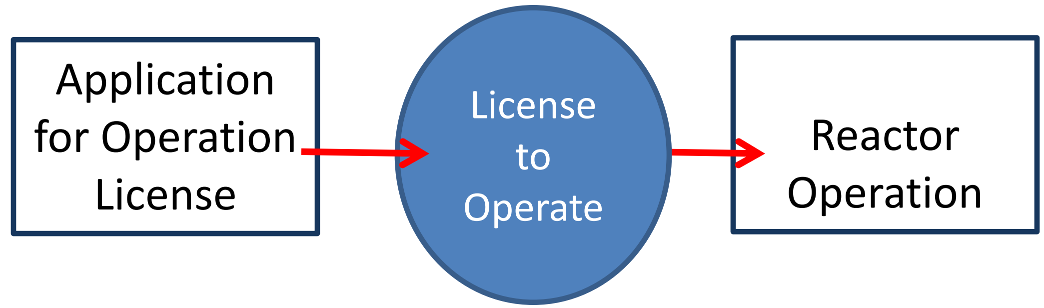
New Nuclear in the US



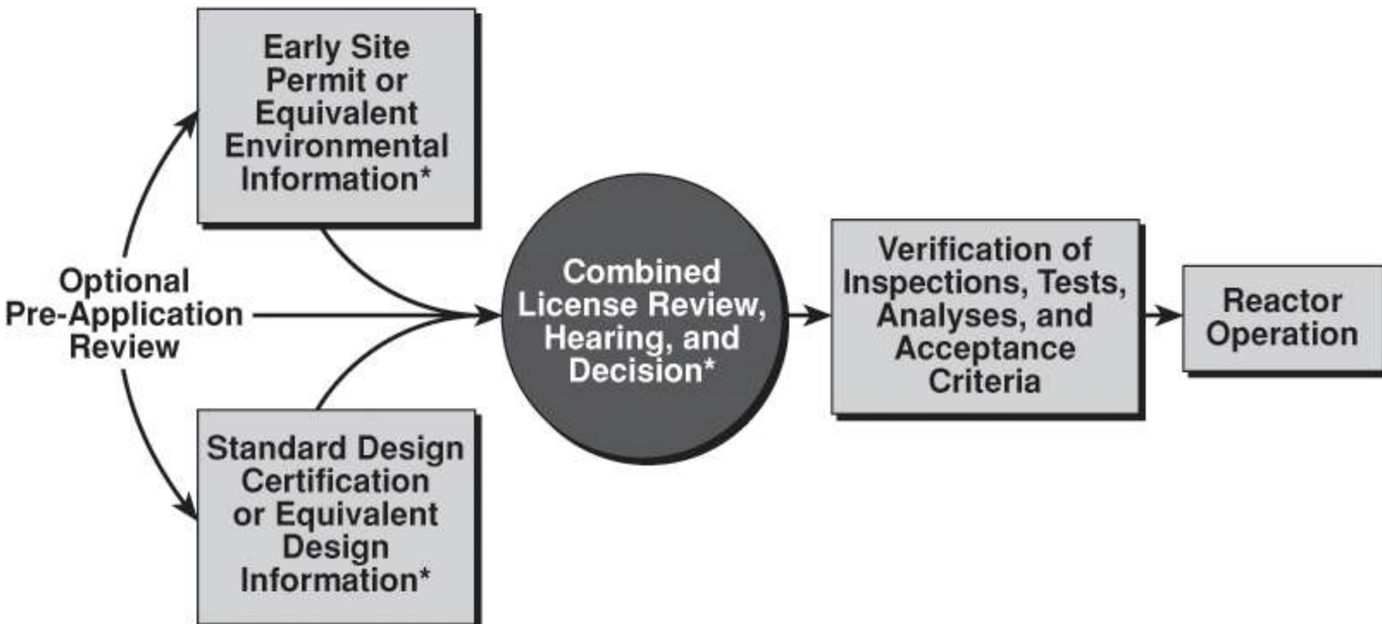
Source: US NRC, 02/2012

Two Step Licensing (Part 50)





One Step Licensing (Part 52)



US NRC Design Certification

- Toshiba ABWR → December 2011
  - GE-Hitachi ABWR under review
- Westinghouse AP-1000 → December 2011
- GE-Hitachi ESBWR → Expected May 2012

world nuclear news

Energy & Environment | New Nuclear | Regulation & Safety | Nuclear Policies | Corporate | Explorat

ABWR

02 November

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AP1000

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Approval

09 February 2012

American safety
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Nuclear Regulator

Workers stand in the
(Image: Southern)

The review work
in a confirmatory
licence, while cha
licence issued on
recommendations developed in response to the Fukushima accident in

Regulator OKs the start of Summer

02 April 2012

Two AP1000 reactors at the VC Summer plant in South Carolina are to be the second US new-build project to receive combined construction and operation licences (COLs) after receiving the final regulatory go-ahead.

Four of the US Nuclear Regulatory Commission's (NRC's) five commissioners voted that the NRC staff's review of South Carolina Electric & Gas (SCE&G) and Santee Cooper's application for the units was "adequate" for the necessary regulatory safety and environmental findings, clearing the way for the NRC's Office of New Reactors (NRO) to issue the COLs. The COLs should be issued within the next two weeks, in the culmination of a process that began with the submission of the COL application in March 2008.

Artist's impression of Summer units 2 and 3 (Image: NRC)

The NRC has imposed two conditions on the COLs. The first condition requires inspection and testing of squib valves, which are important components of the reactors' passive cooling system. Secondly, the NRC has directed that strategies must be developed to respond to extreme natural events resulting in the loss of power at the new reactors. The NRC has also directed the NRO to issue an order requiring enhanced, reliable used fuel instrumentation, and a request for information on emergency plant staffing, alongside the COLs.

The regulator's announcement was greeted with enthusiasm by SCANA

Related Stories

- Agreement on Summer cost overruns
- Approval for first nuclear new build in America
- Final days of Summer licensing
- SCG&E orders two AP1000s for South Carolina

WNA Links

- Nuclear Power in the USA

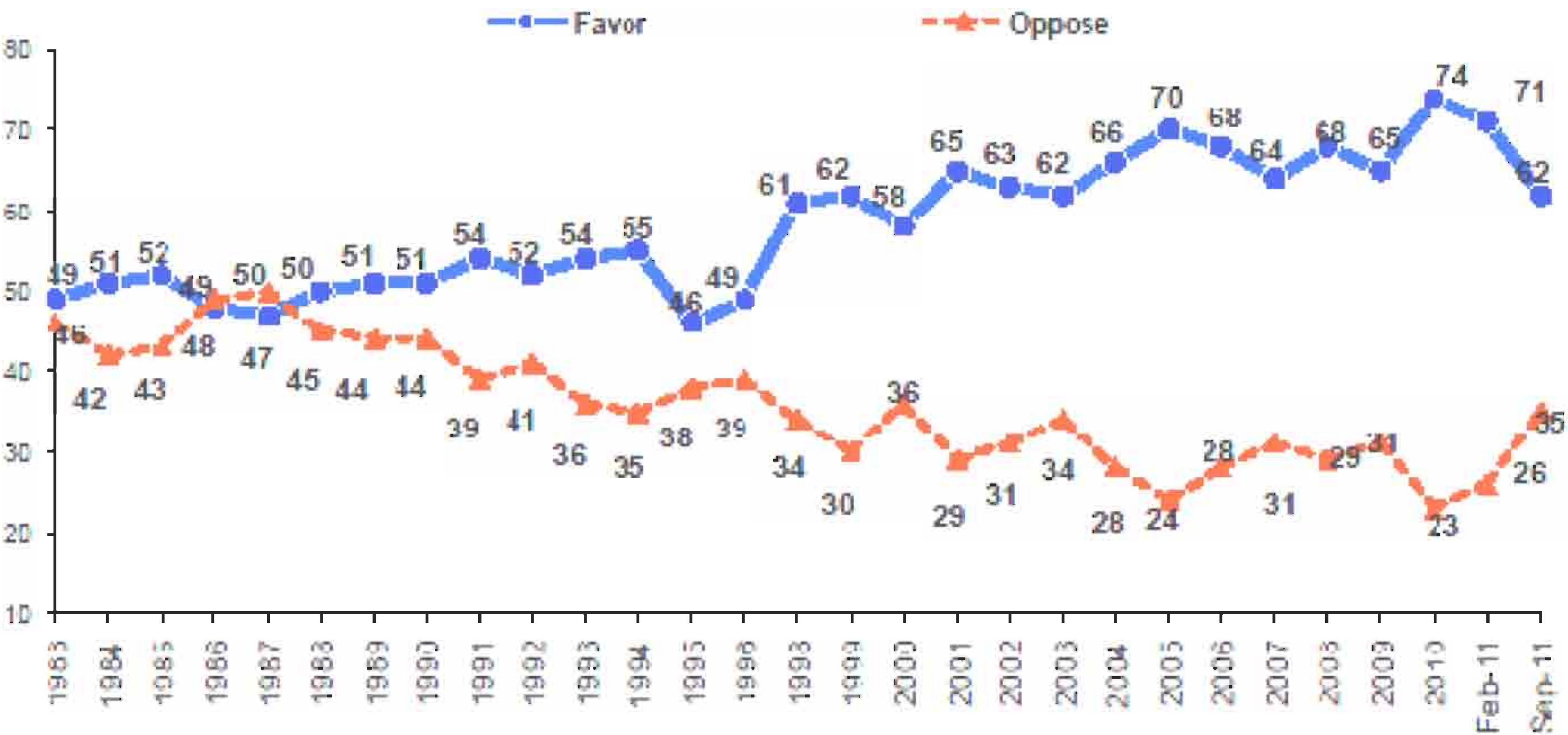
Related Links

- Nuclear Regulatory

Misperceptions: Support for Nuclear Energy is Often Underestimated

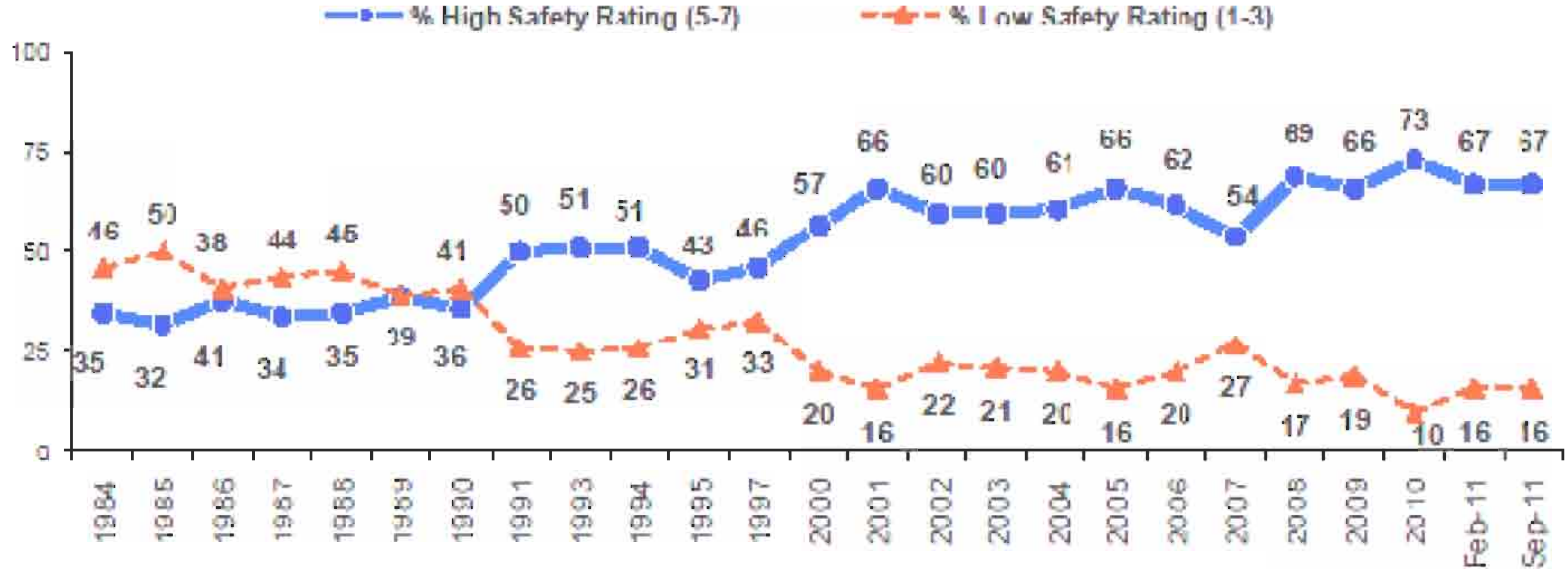
Percent Who Favor and Oppose Nuclear Energy: Annual Averages 1983 to 2010

"Overall, do you strongly favor, somewhat favor, somewhat oppose, or strongly oppose the use of nuclear energy as one of the ways to provide electricity in the United States?"



Perceived Safety of Nuclear Power Plants Annual Averages Until 2011

"Thinking about the nuclear power plants that are operating now, how safe do you regard these plants? Please think of a scale from "1" to "7," where "1" means "very unsafe" and "7" means "very safe." The safer you think they are, the higher the number you would give."



Types of Nuclear Reactors Coolant

- **Water Cooled Reactors**
  - Light Water Cooled (BWR, PWR)
  - Heavy Water (PHWR, CANDU type)
- **Gas Cooled Reactors**
  - CO_2 (GCR)
  - Helium (HTGR)
- **Liquid Metal Cooled Reactors**
  - Sodium
  - Lead or Lead-Bismuth
- **Molten Salt Reactors**
  - Fluorides (LiF)
  - Chlorides (NaCl – table salt)
  - Fluoroborates (NaBF4) + others
  - Mixtures (LiF-BeF2),
  - Eutectic compositions (LiF-BeF2 (66-33 % mol))

Types of Nuclear Reactors
Moderator

- Light Water Moderated
- Heavy Water Moderated
- Graphite Moderated
- Non-moderated

Types of Nuclear Reactors Neutronic Spectrum

- Thermal Reactors
- Epithermal Reactors
- Fast Reactors

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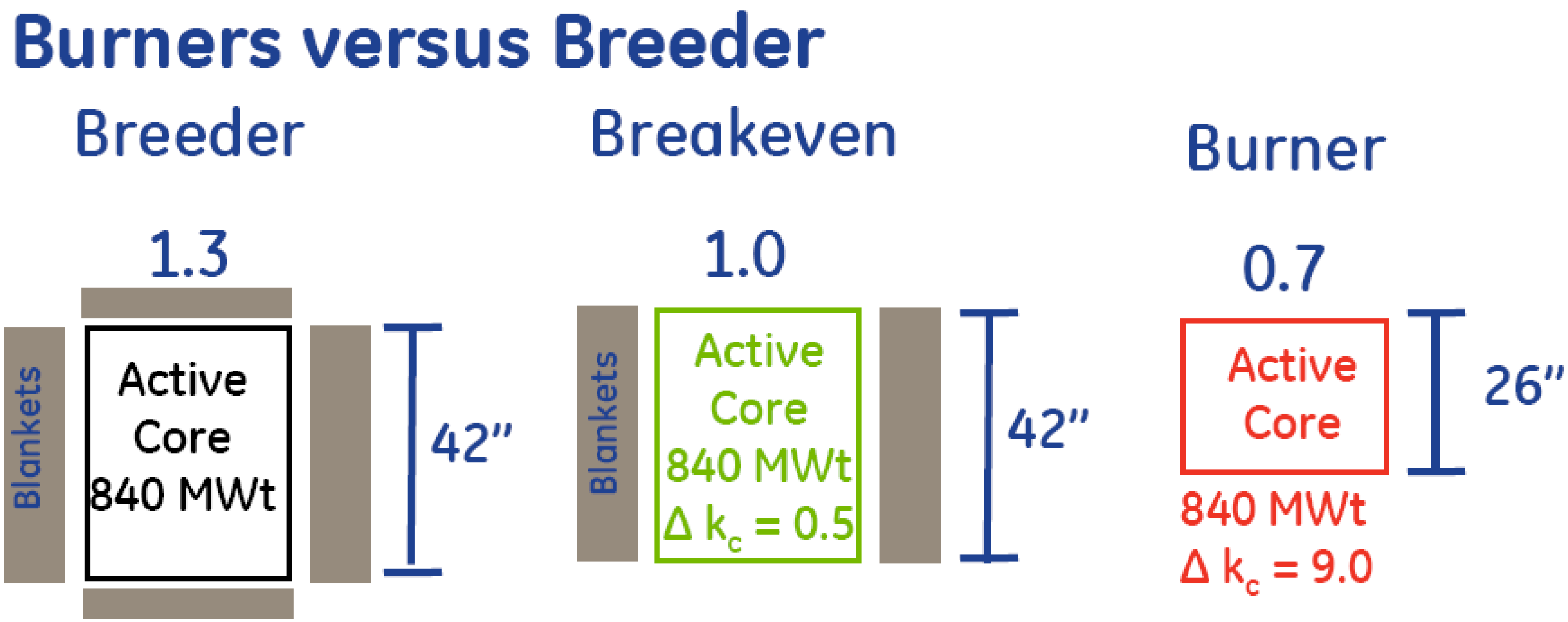
Types of Nuclear Reactors
Fuel Type

- **Solid Fuel**
  - Fuel pins
  - Fuel pebbles

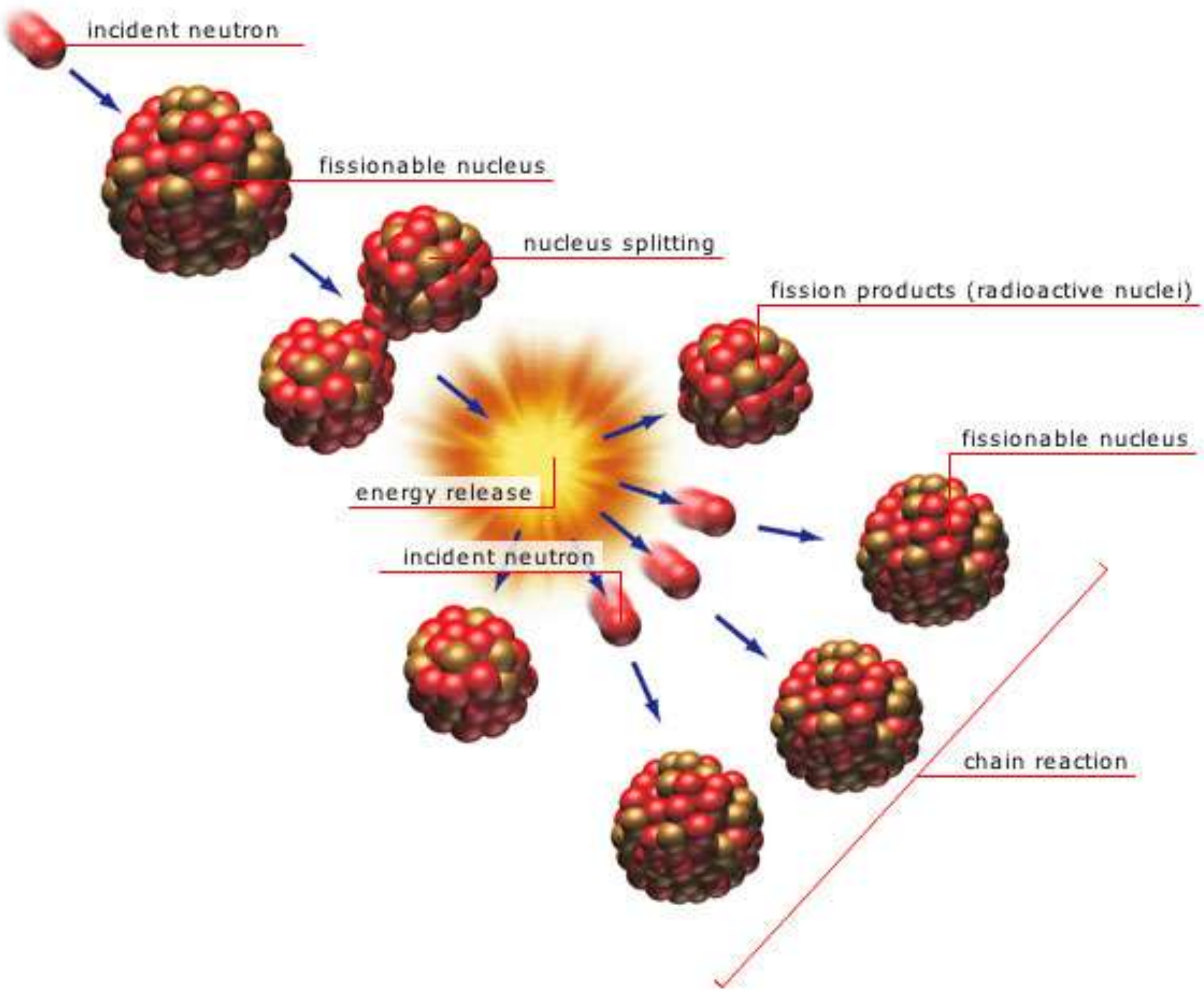
- **Liquid Fuel**
  - Solved in the coolant

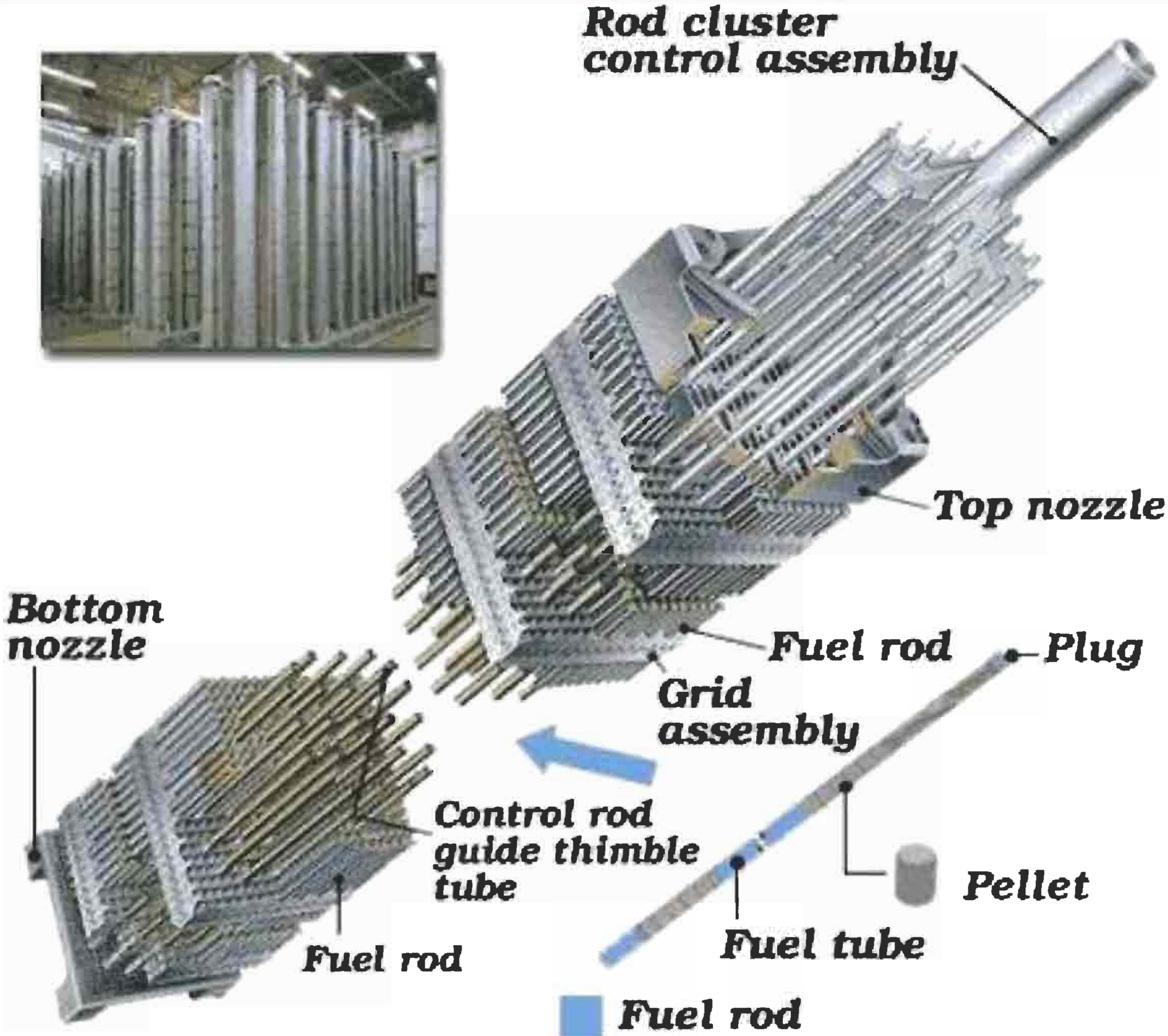
Types of Nuclear Reactors
Conversion Rate

- **Burners**
- **Breeders**



Nuclear Fission




Rod cluster control assembly
Top nozzle
Bottom nozzle
Fuel rod
Plug
Grid assembly
Control rod guide thimble tube
Pellet
Fuel tube
Fuel rod
Fuel rod

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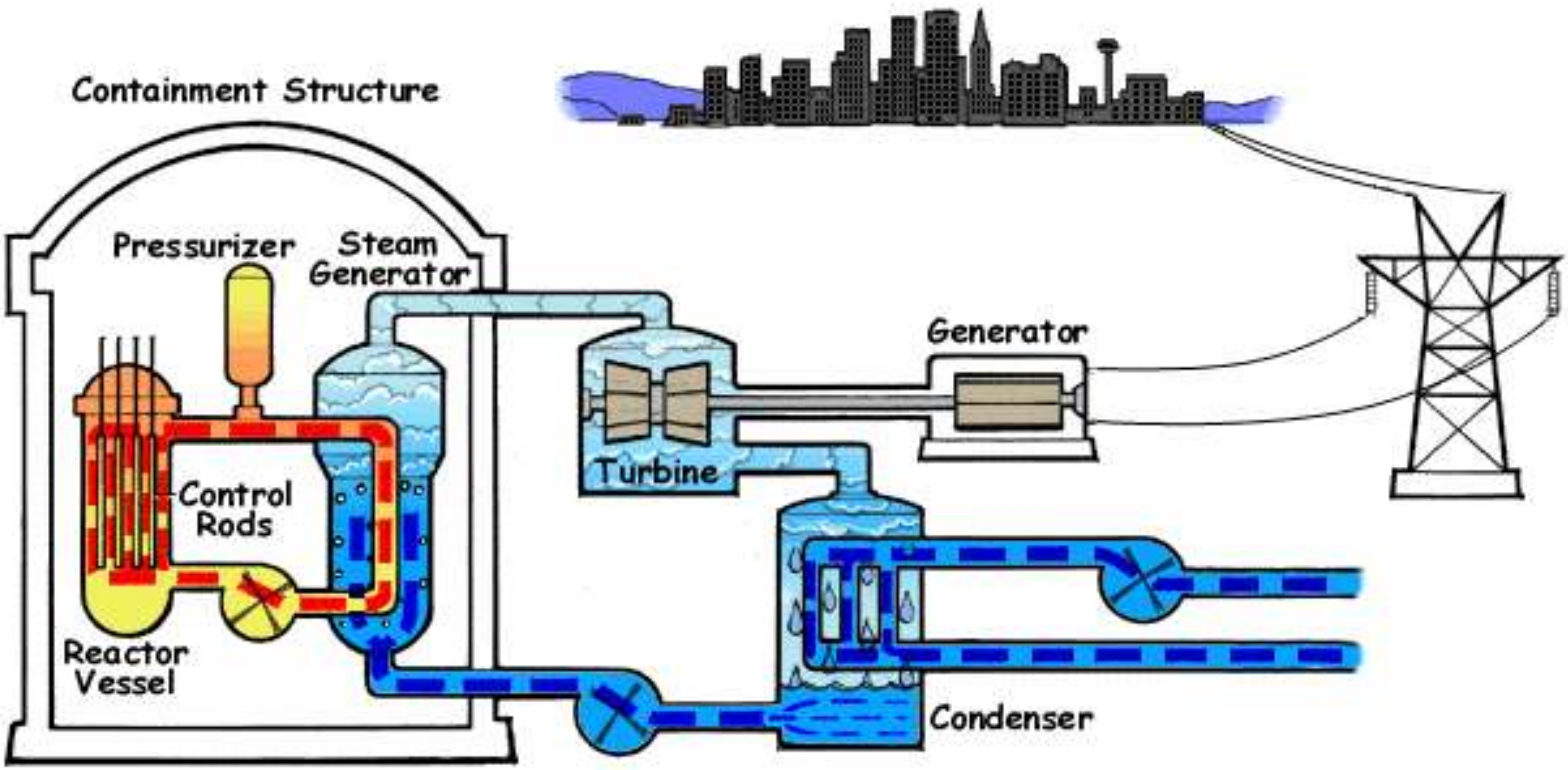
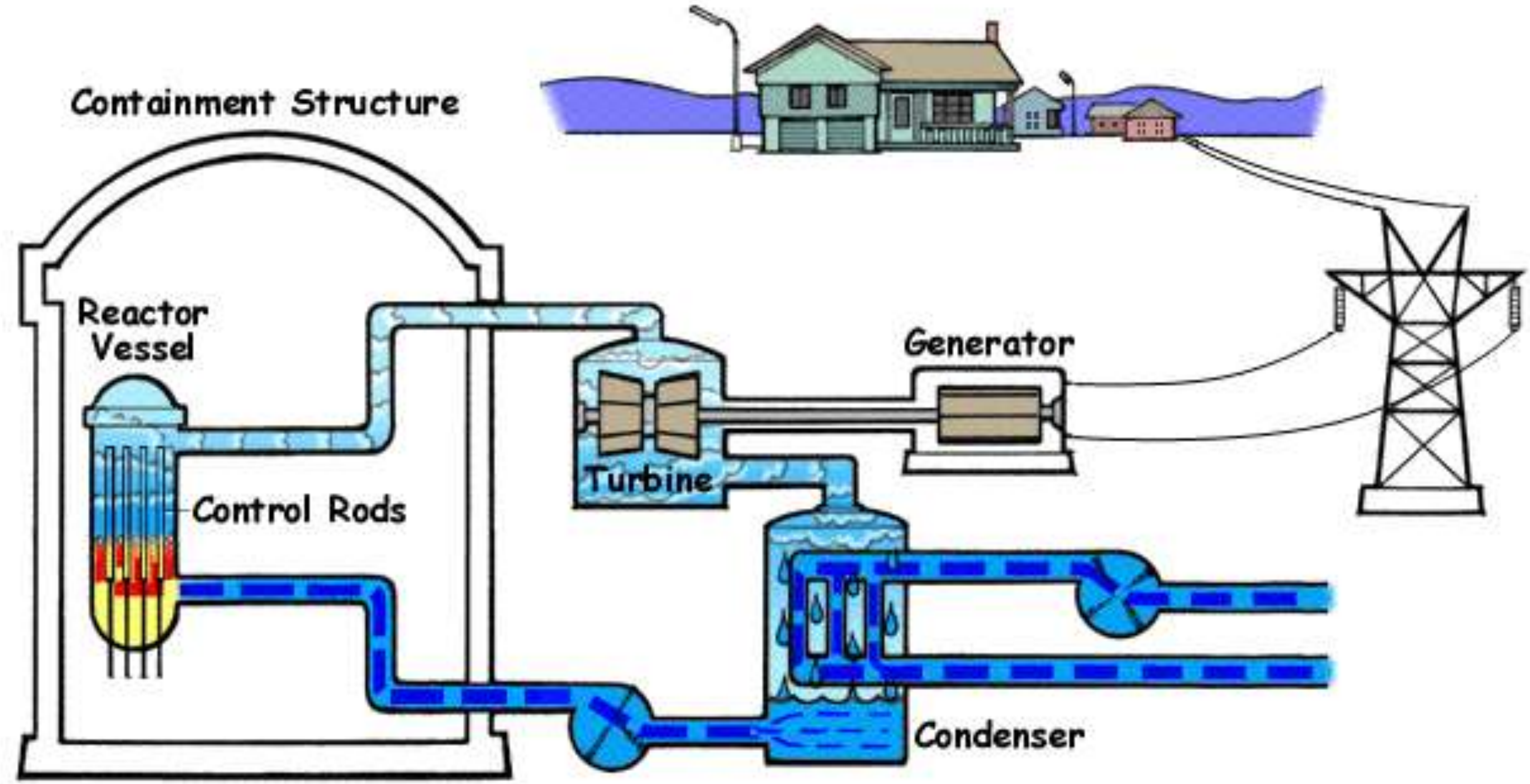
Pressurized Water Reactor (PWR)

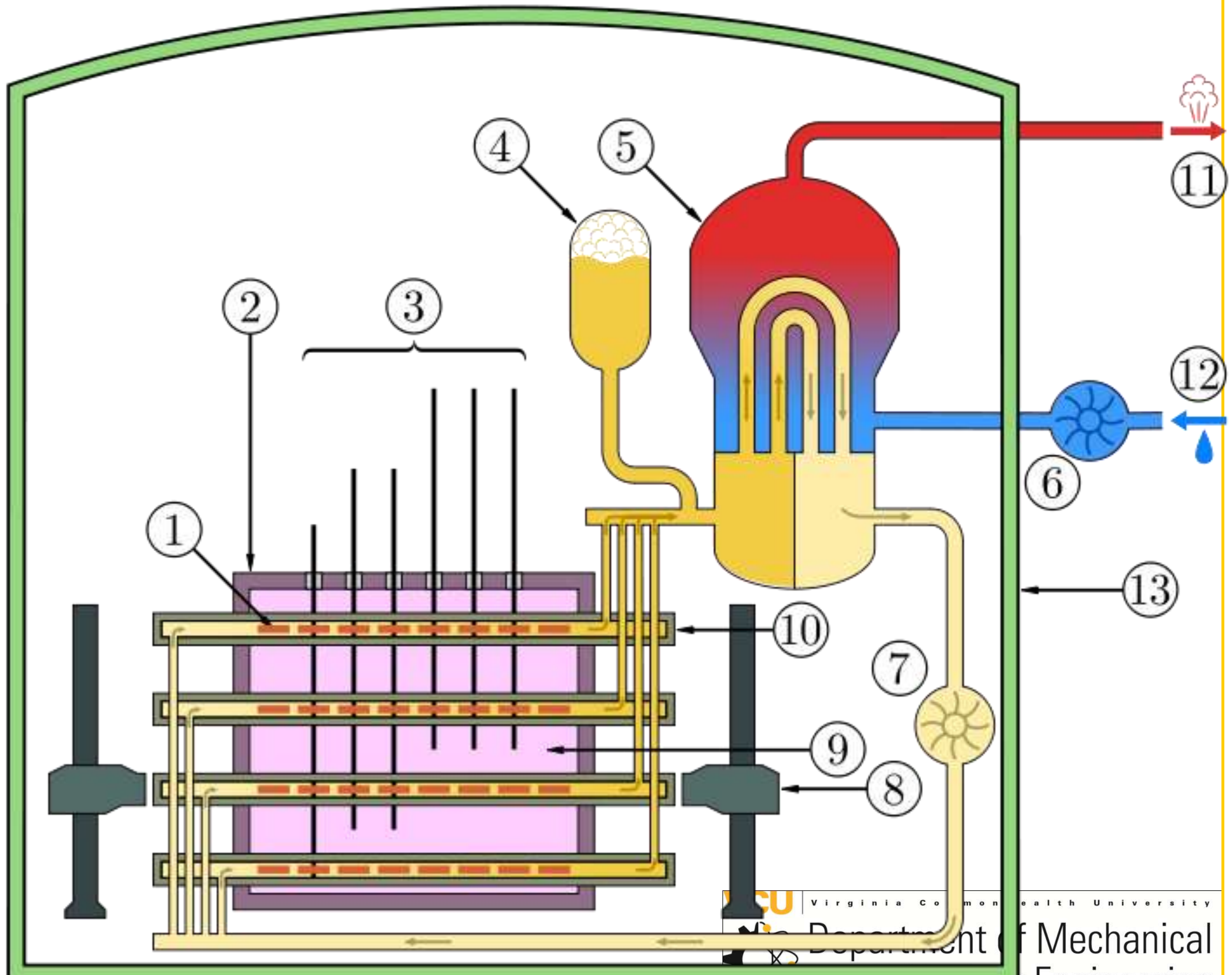


Boiling Water Reactor (BWR)

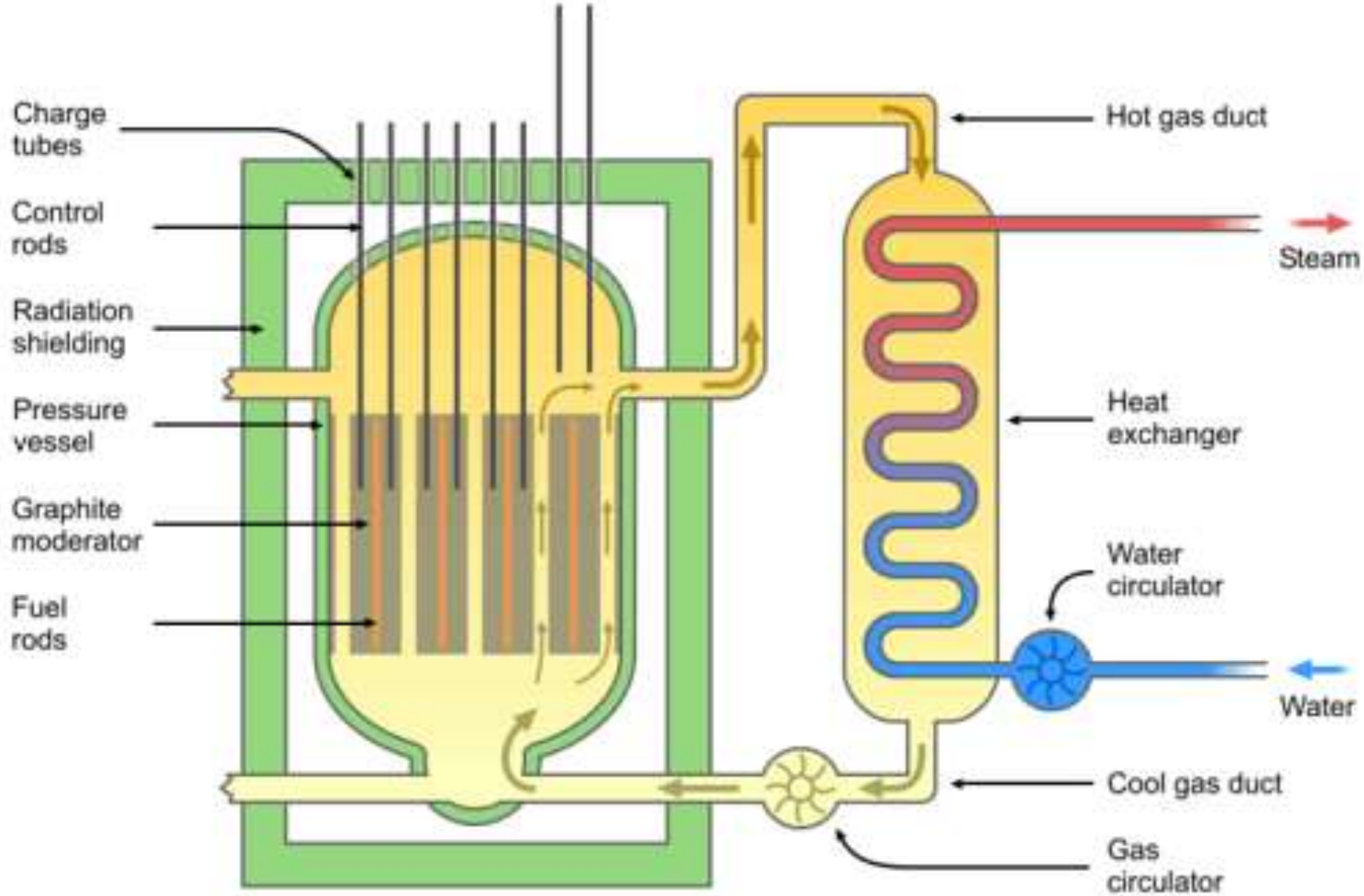


Pressurized Heavy Water Reactor (PHWR)

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



Gas Cooled Reactor

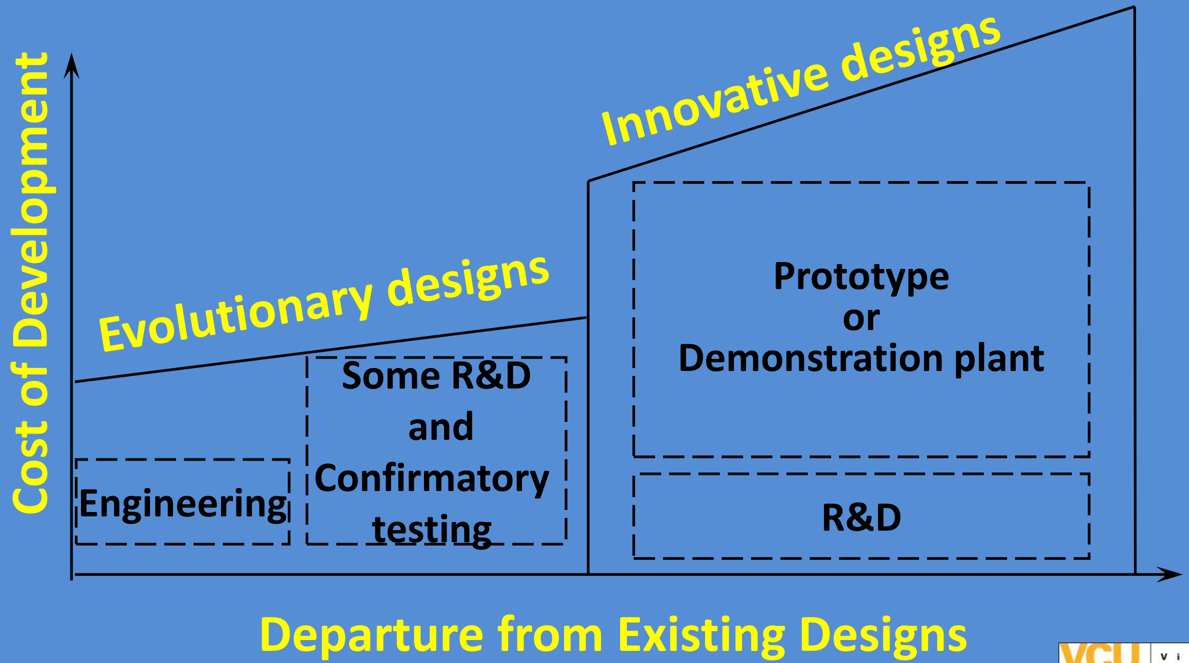


Advanced Reactor Designs

(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



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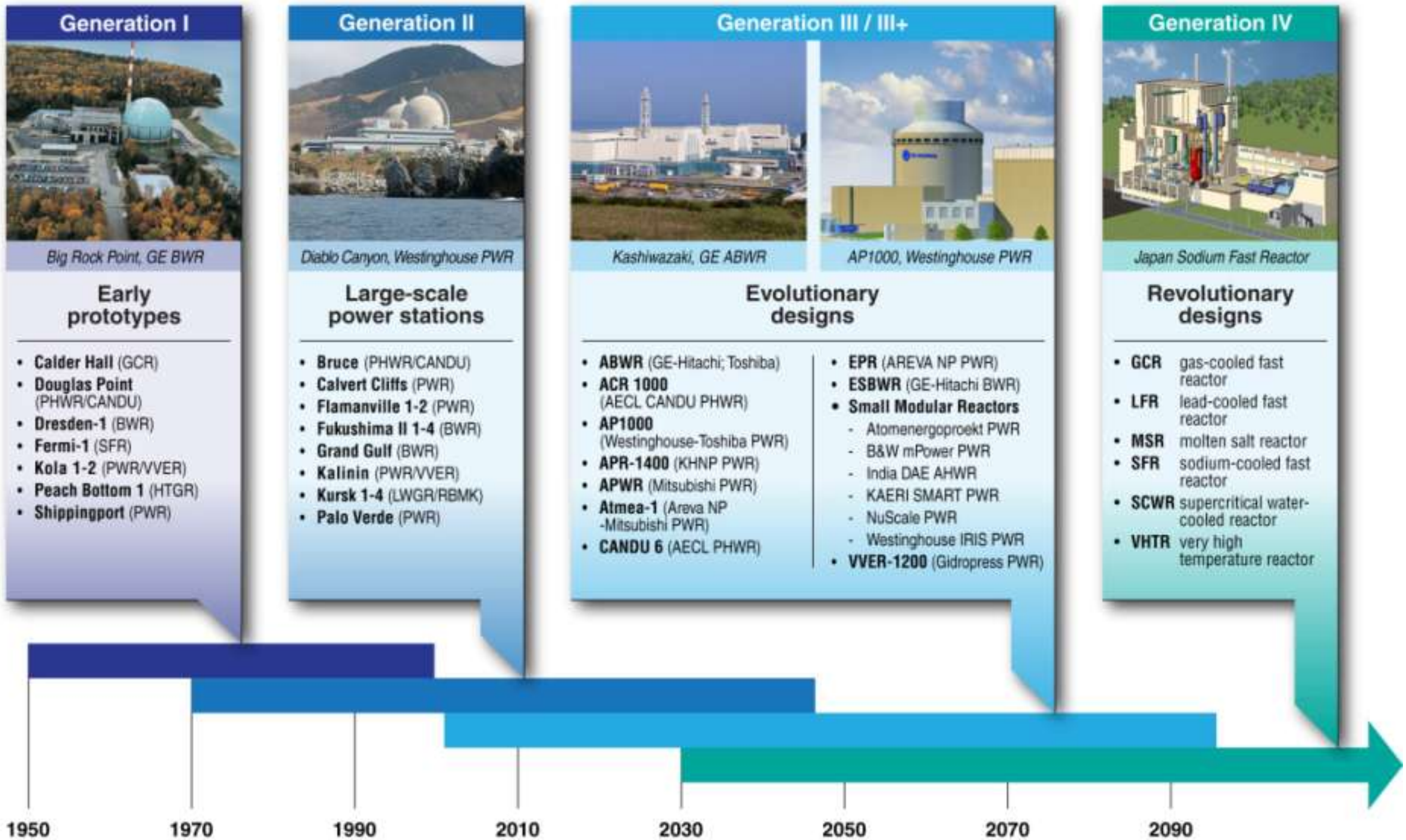
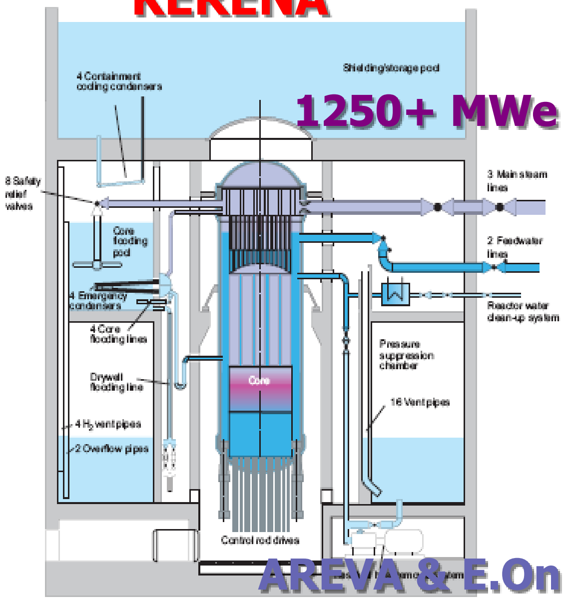
Another classification…



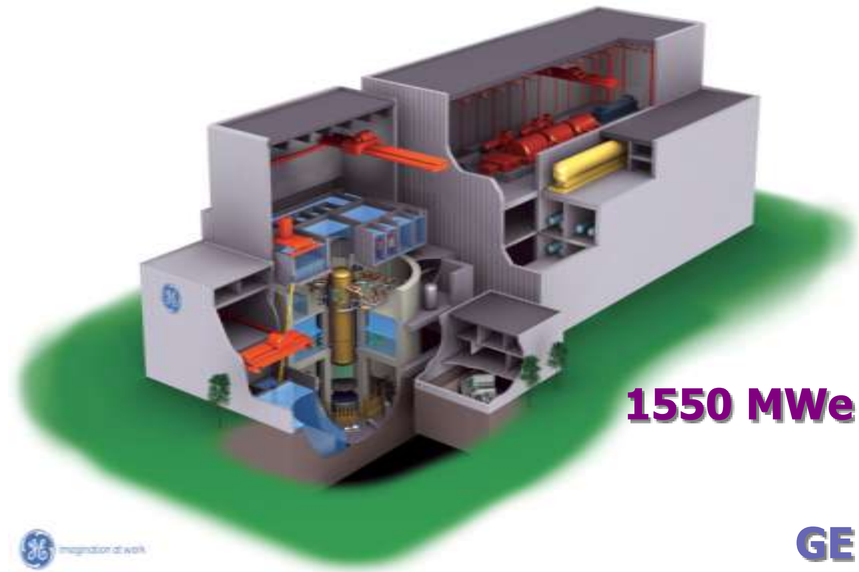
Global Trends in Advanced Reactor Design

- **Cost Reduction**
  - Standardization and series construction
  - Improving construction methods to shorten schedule
  - Modularization and factory fabrication
  - Design features for longer lifetime
  - Fuel cycle optimization
  - Economy of scale → larger reactors
  - Affordability → SMRs
- **Performance Improvement**
  - Establishment of user design requirements
  - Development of highly reliable components and systems, including "smart" components
  - Improving the technology base for reducing over-design
  - Further development of PRA methods and databases
  - Development of passive safety systems
  - Improved corrosion resistant materials
  - Development of Digital Instrumentation and Control
  - Development of computer based techniques
  - Development of systems with higher thermal efficiency and expanded applications (Non-electrical applications)

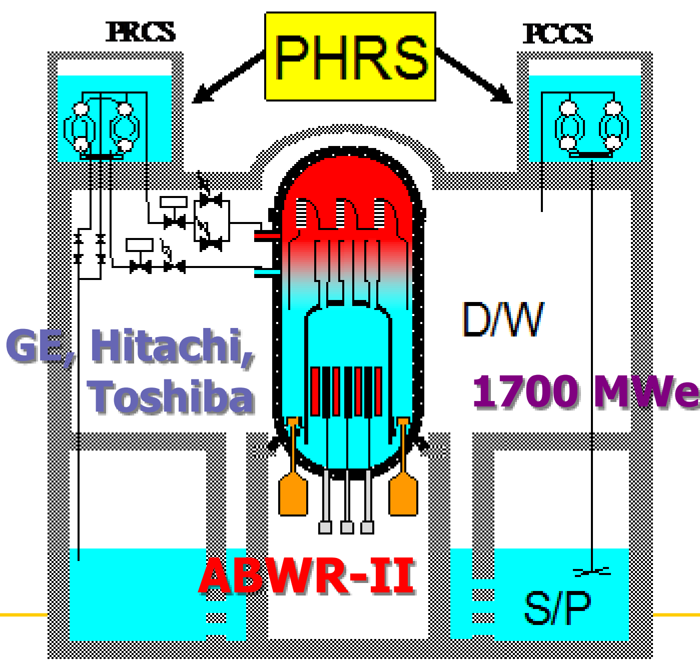
KERENA



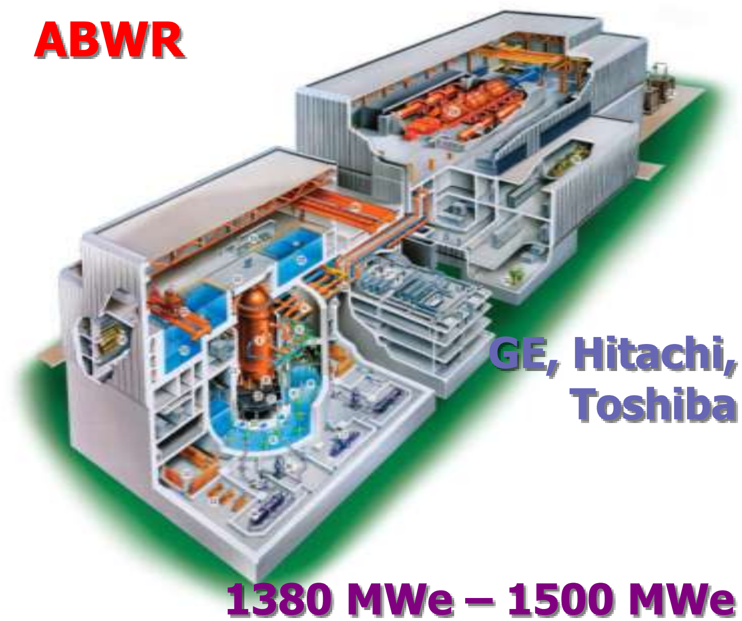
ESBWR



Boiling Water Reactors (BWR)

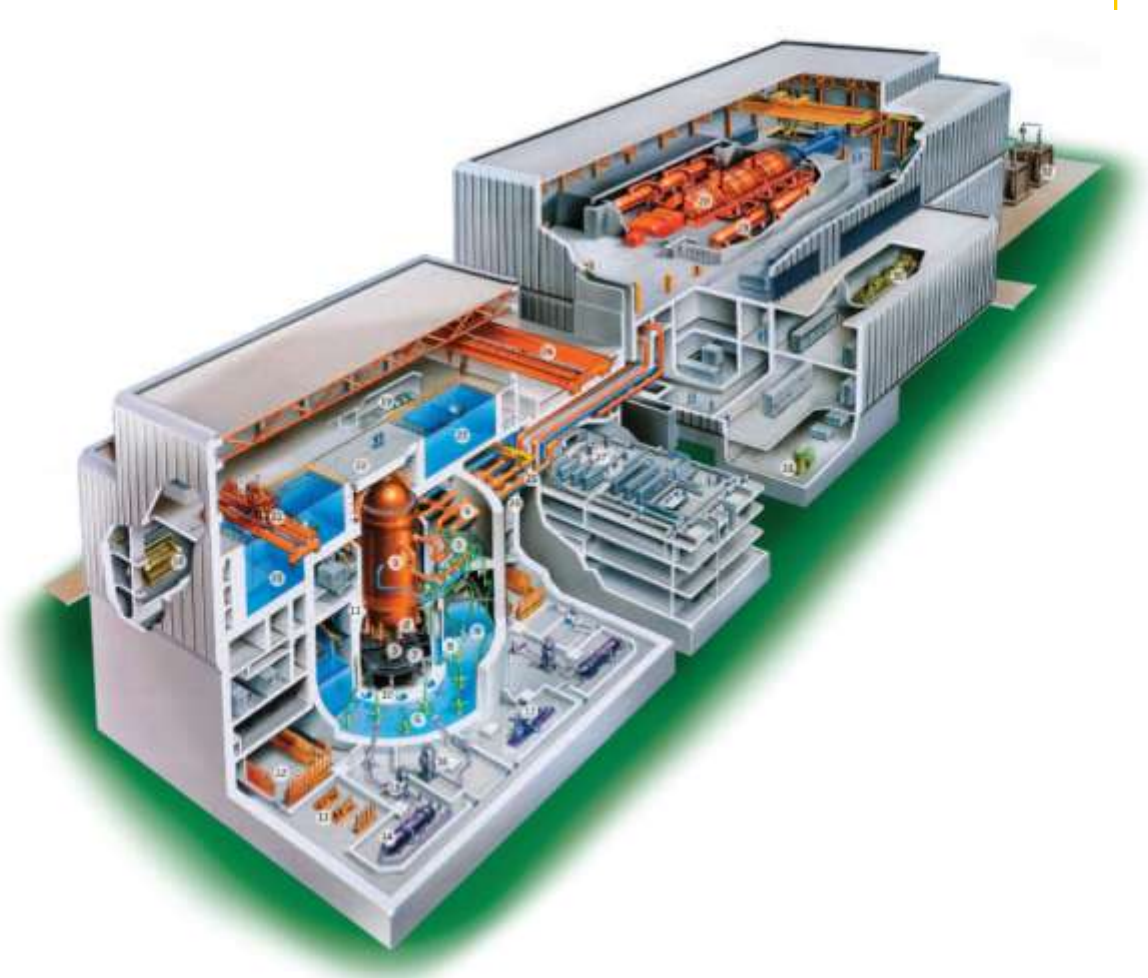


ABWR



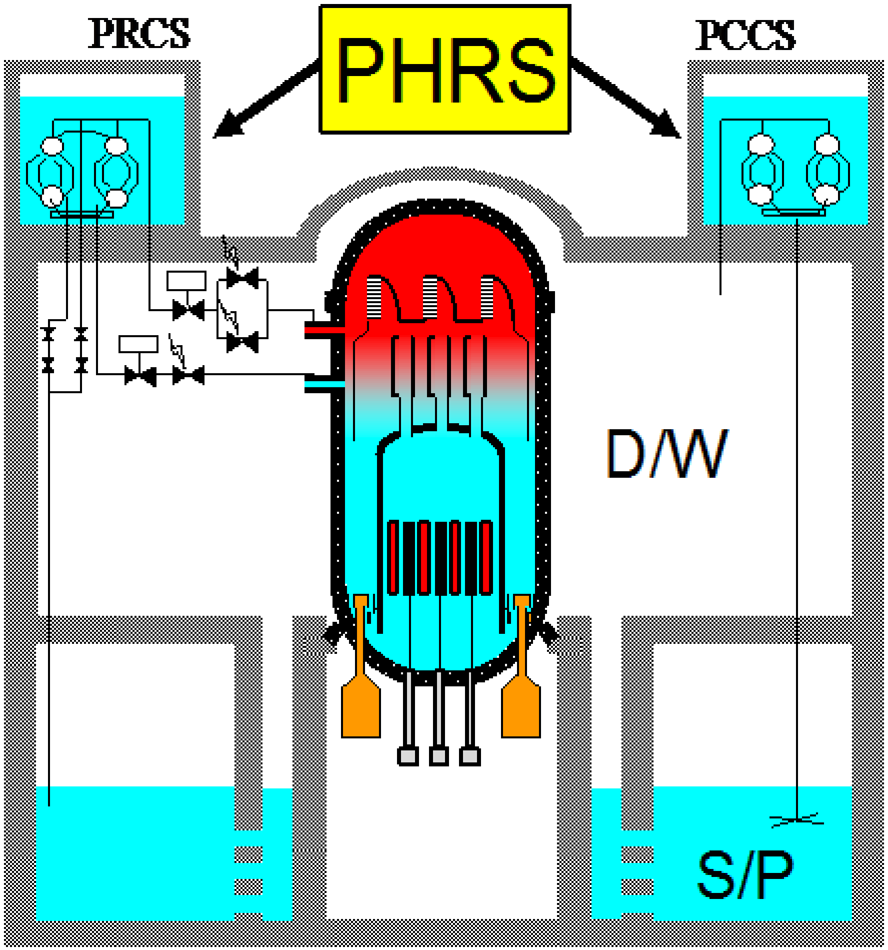
Advanced Boiling Water Reactor (ABWR)

- 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)



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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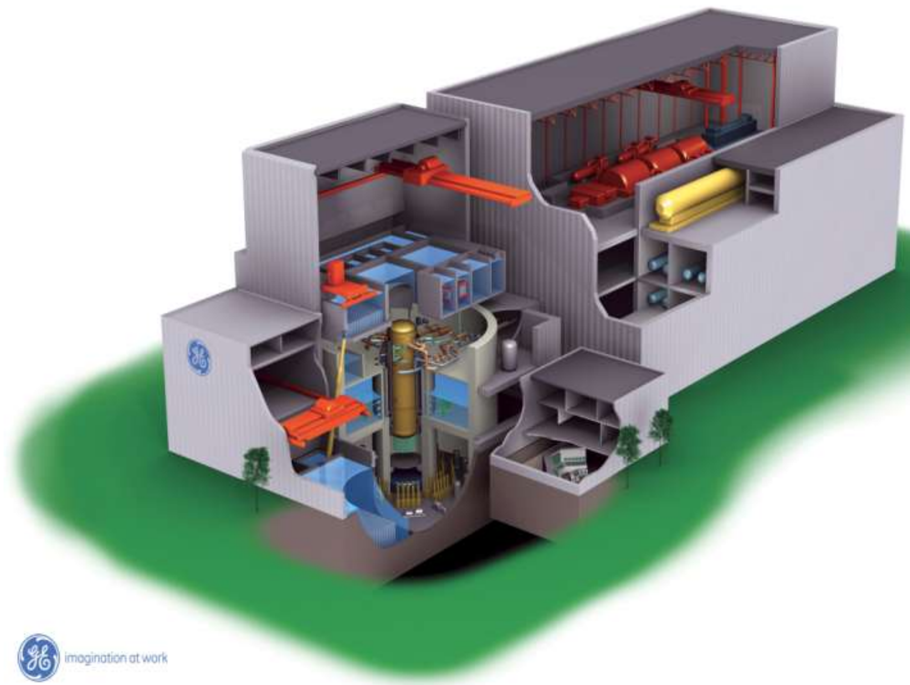
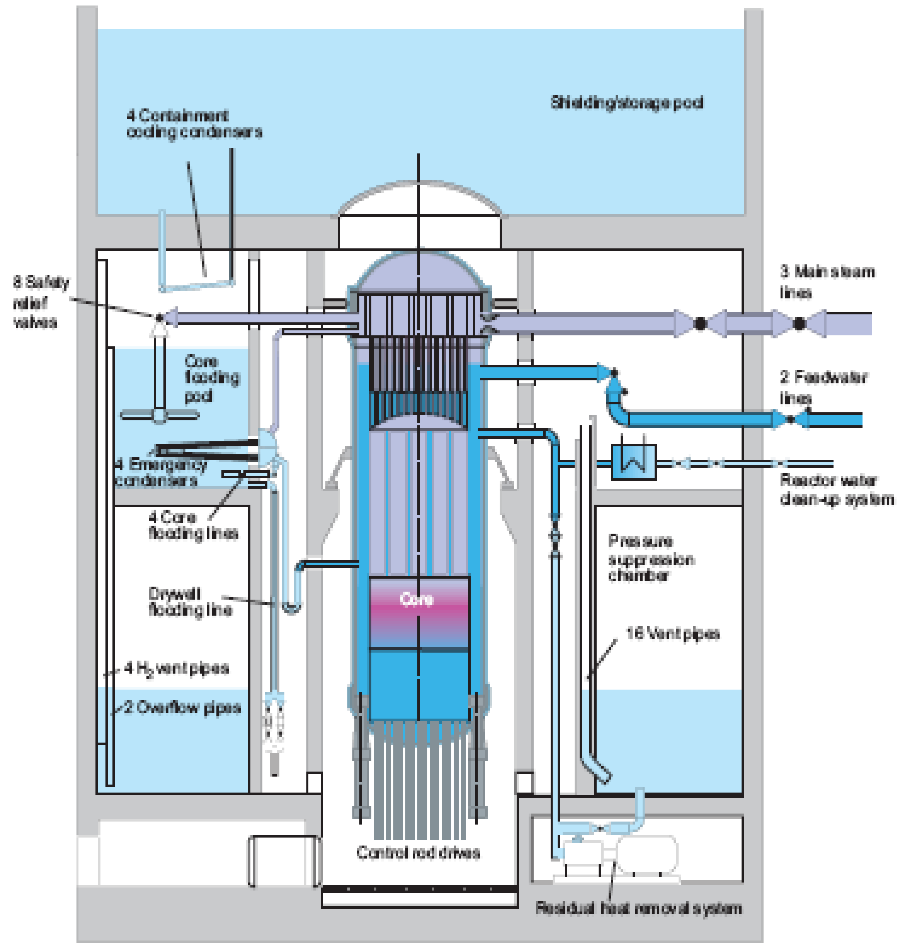
ESBWR

- 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 – expected approval 06/2012
- 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



KERENA = SWR-1000

- AREVA & E.On
- Reviewed by EUR
- 1250+ MWe
- Uses internal re-circulation pumps
- Active & passive safety systems
- Offered for Finland-5
- Gundremingen reference plant
- New systems verified by test (e.g. FZ Jülich test of isolation condenser)



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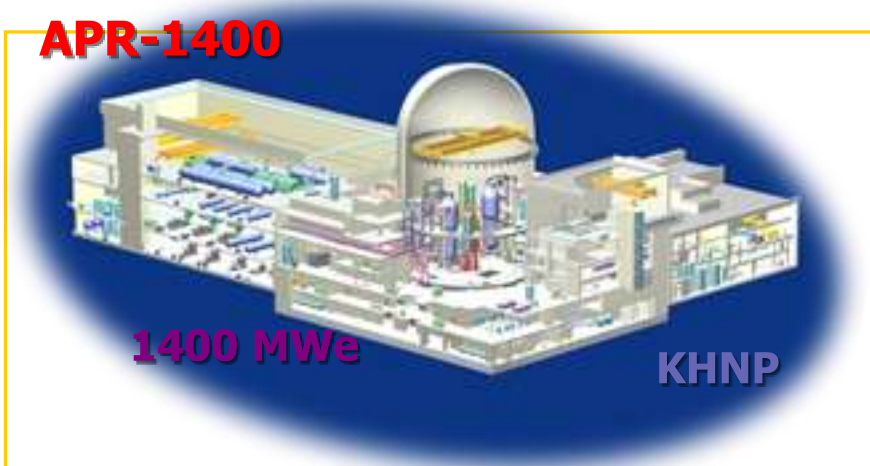
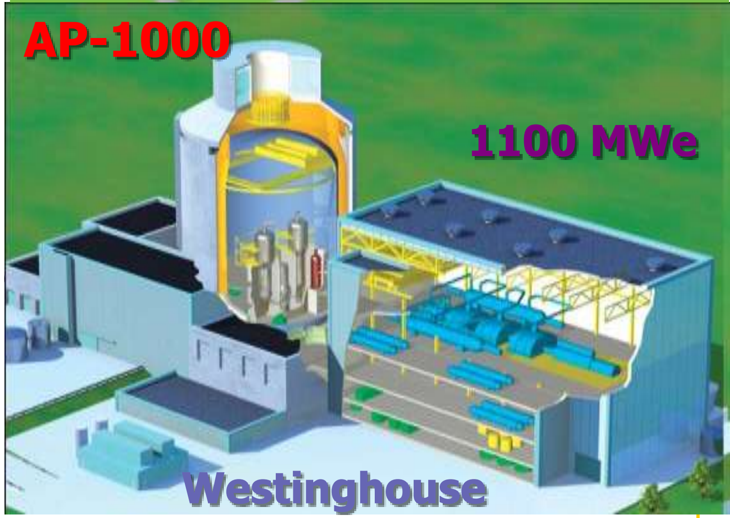

APR-1400
1400 MWe
KHNP

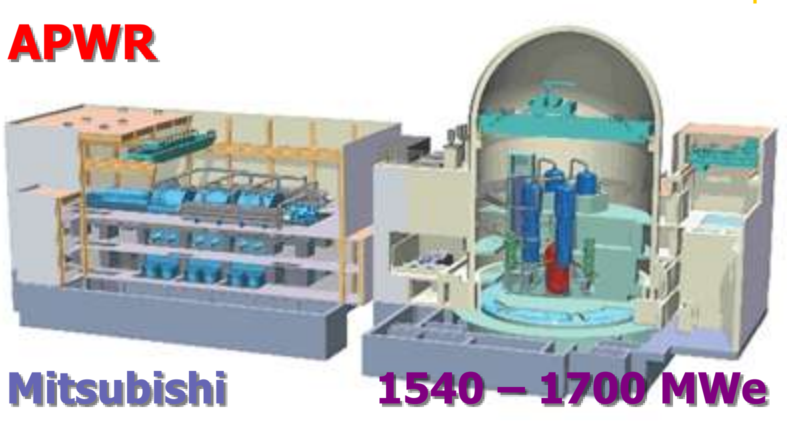

WWER-1000/1200
Gidropress
1000– 1200 MWe


ATMEA
AREVA+Mitsubishi
1100 MWe

Water Rea

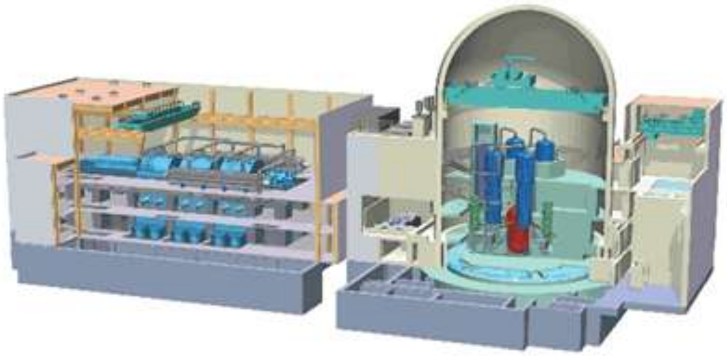

AP-1000
1100 MWe
Westinghouse


EPR
AREVA
1600+ MWe


APWR
Mitsubishi
1540 – 1700 MWe

Advanced Pressurized Water Reactor (APWR)

- Mitsubishi Heavy Industries & Japanese utilities
- 2x1540 MWe APWRs planned by JAPC at Tsuruga-3 & -4 and 1x1590 MWe APWR planned by Kyushu EPC at Sendai-3
  - 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 (advanced Accumulator)
  - Full MOX cores
  - 39% thermal efficiency
  - Selected by TXU for Comanche Peak 3 and 4
- 1700 MWe "EU-APWR" to be evaluated by EUR



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, Finland (operation by 2012?)
  - Flamanville-3, France (operation by 2012)
  - Taishan-1 and 2, China (operation by 2014-2015)
- Planned for India
- U.S.NRC is reviewing the US EPR Design Certification Application

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EPR

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 2010
  - Core catcher and passive SG secondary side heat removal to atmosphere

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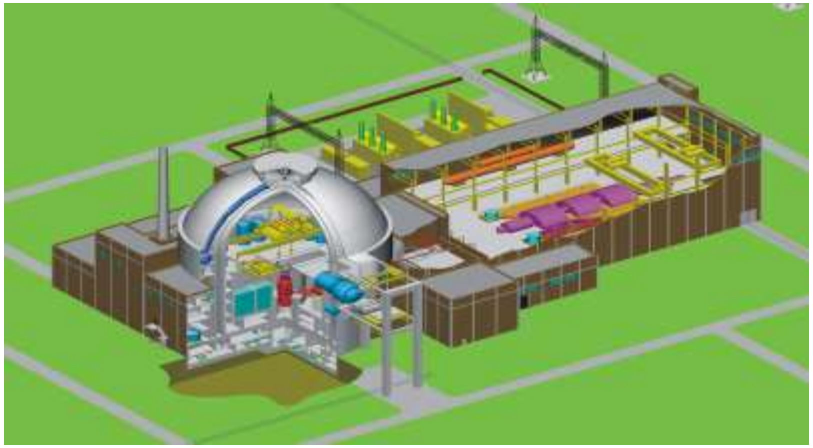
WWER-1200

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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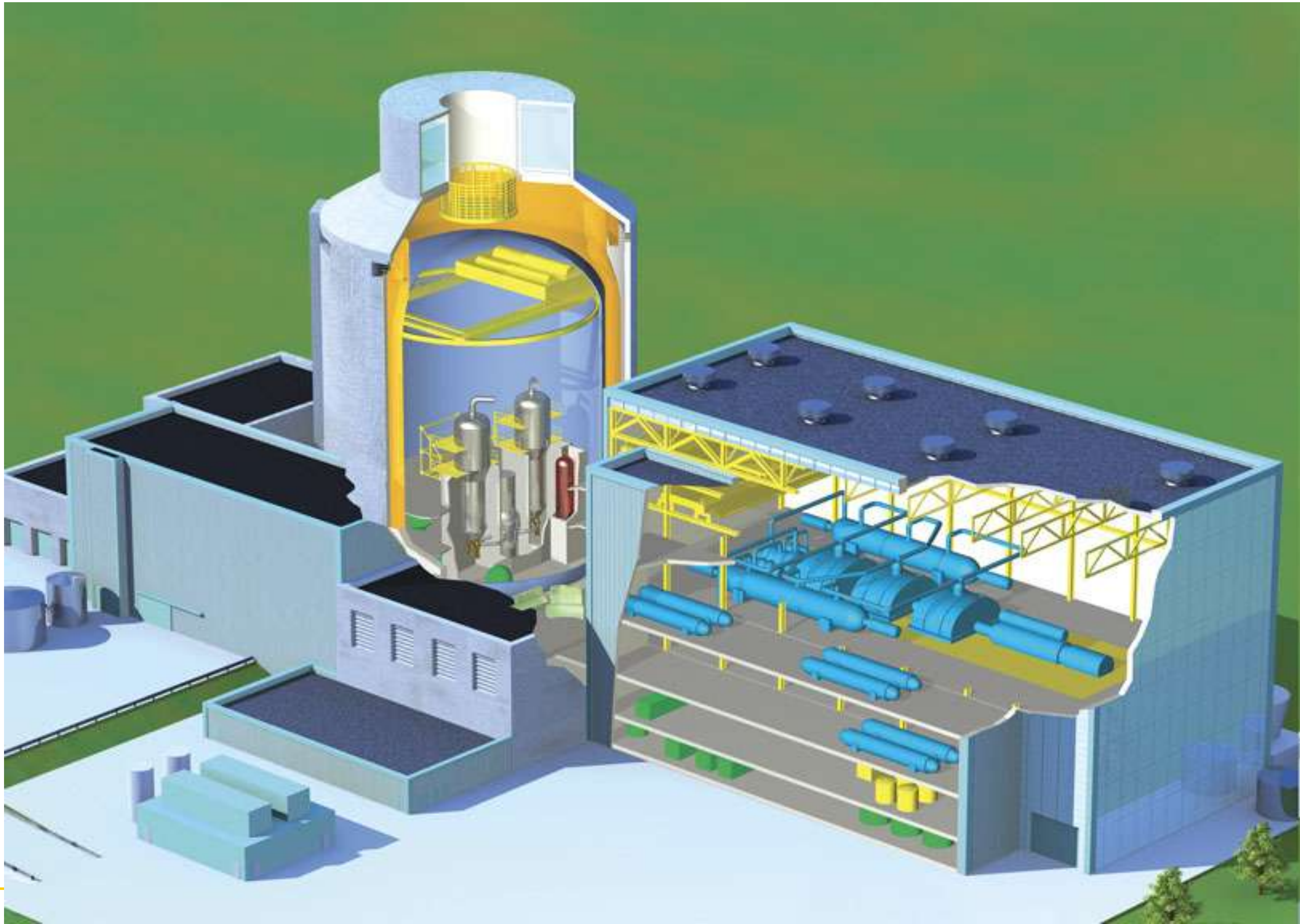
APR-1400

- 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
- 4 units to be built in UAE

AP-600 and AP-1000

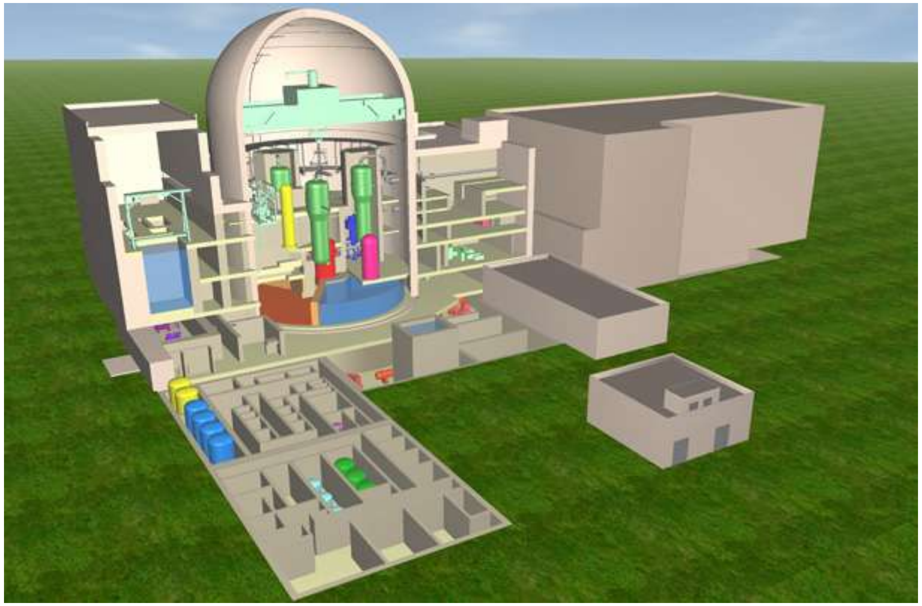
- Westinghouse
- AP-600:
  - Late 80's–developed to meet URD
  - 1999 - Certified by U.S.NRC
  - Key developments:
    - passive systems for coolant injection, RHR, containment cooling
    - in-vessel retention
    - new systems verified by test
- AP-1000:
  - pursues economy-of-scale
  - applies AP-600 passive system technology
  - Certified by U.S.NRC (12/2011)
  - 4 units under construction in China
    - Sanmen & Haiyang: 2013 – 2015
  - Contract for 2 units in US
    - Plant Vogtle
    - VC Summer
    - Proposed in several other sites in US

AP-1000



ATMEA1

- 1100 MWe, 3 loop plant
- Combines AREVA & Mitsubishi PWR technologies
- 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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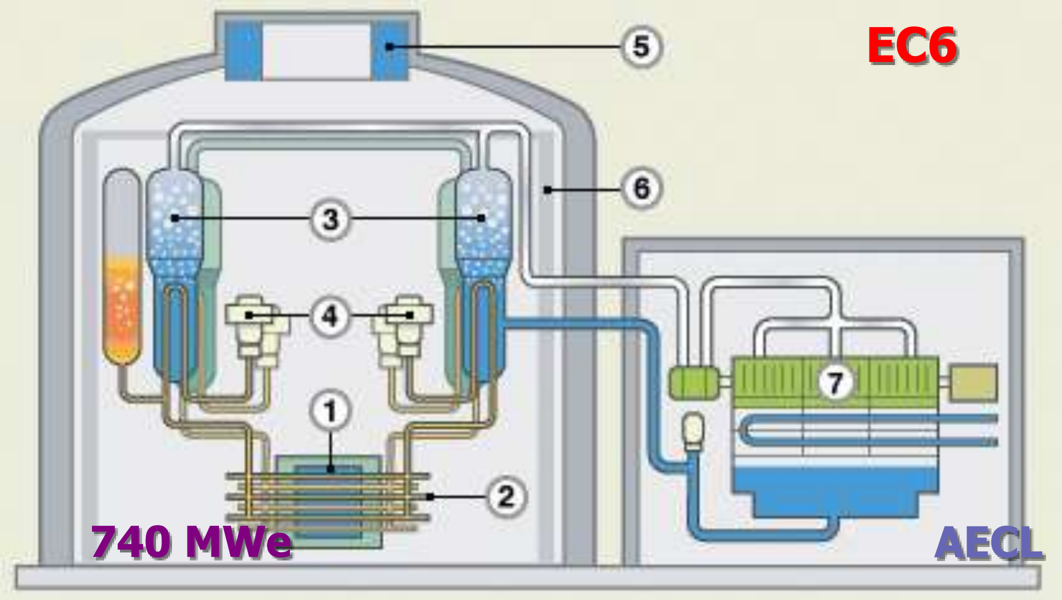
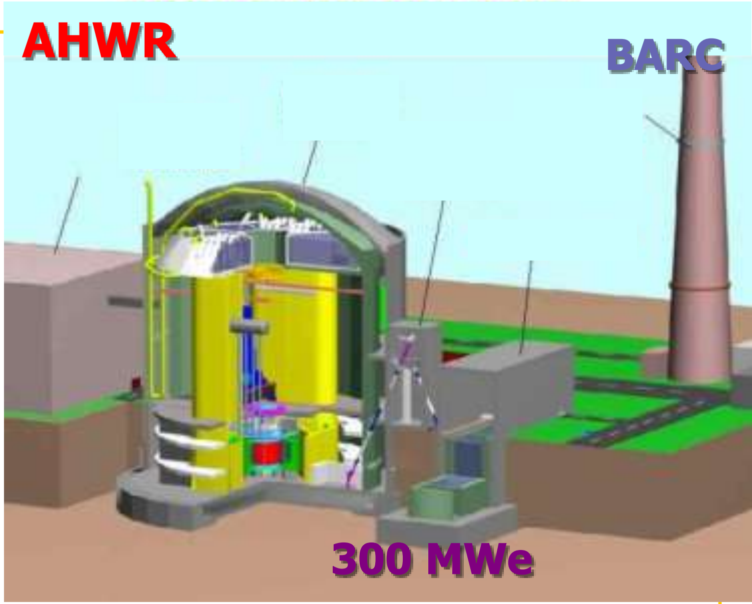
Chinese advanced PWRs CPR (CGNPC) and CNP (CNNC)

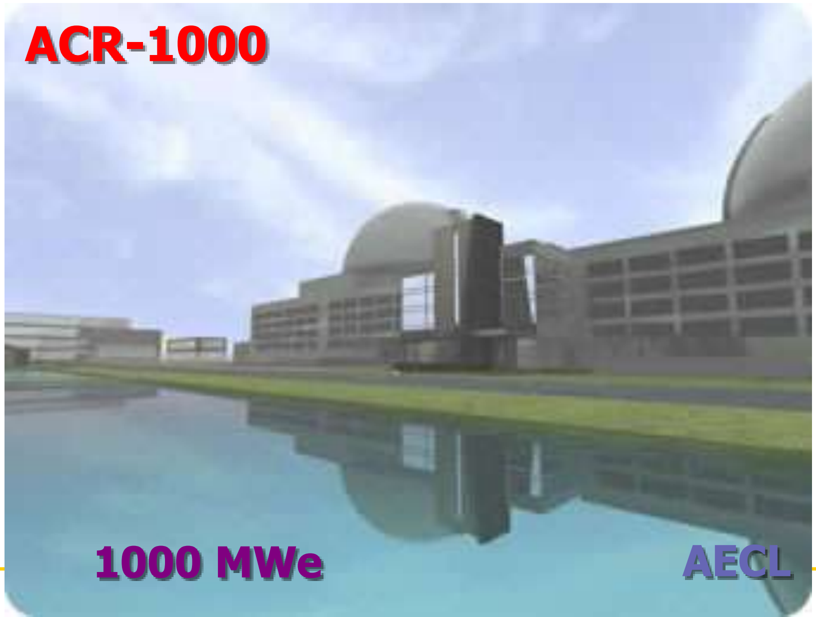
- CPR-1000
  - Evolutionary design based on French 900 MWe PWR technology
  - Reference plant: Lingau-1&2 (NSSS Supplier: Framatome; commercial operation in 2002)
  - Lingau-3&4 are under construction (with > 70% localization of technology; NSSS Supplier: Dongang Electric Corporation);
  - Now a Standardized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

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

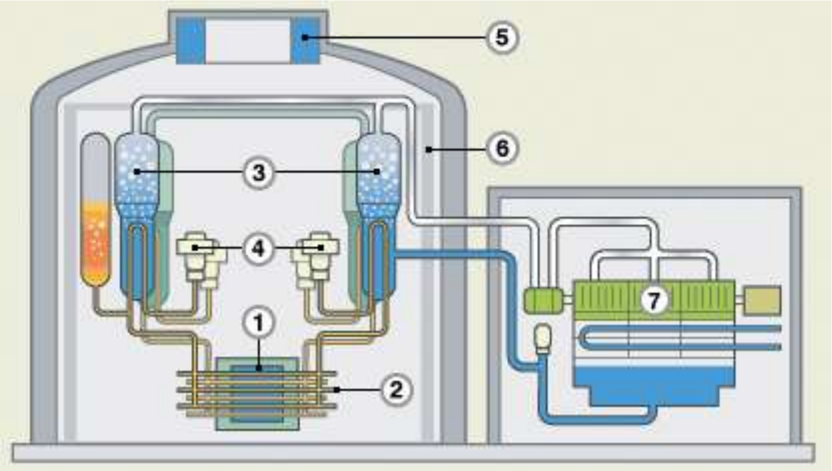


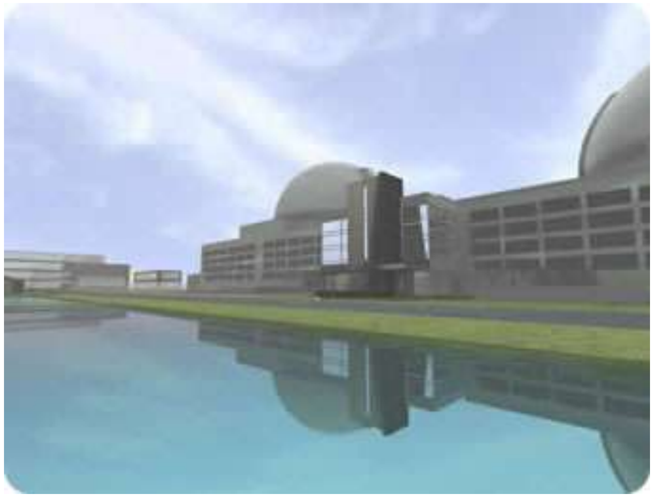


Heavy Water Reactors (HWR)



ACR-700 & ACR-1000

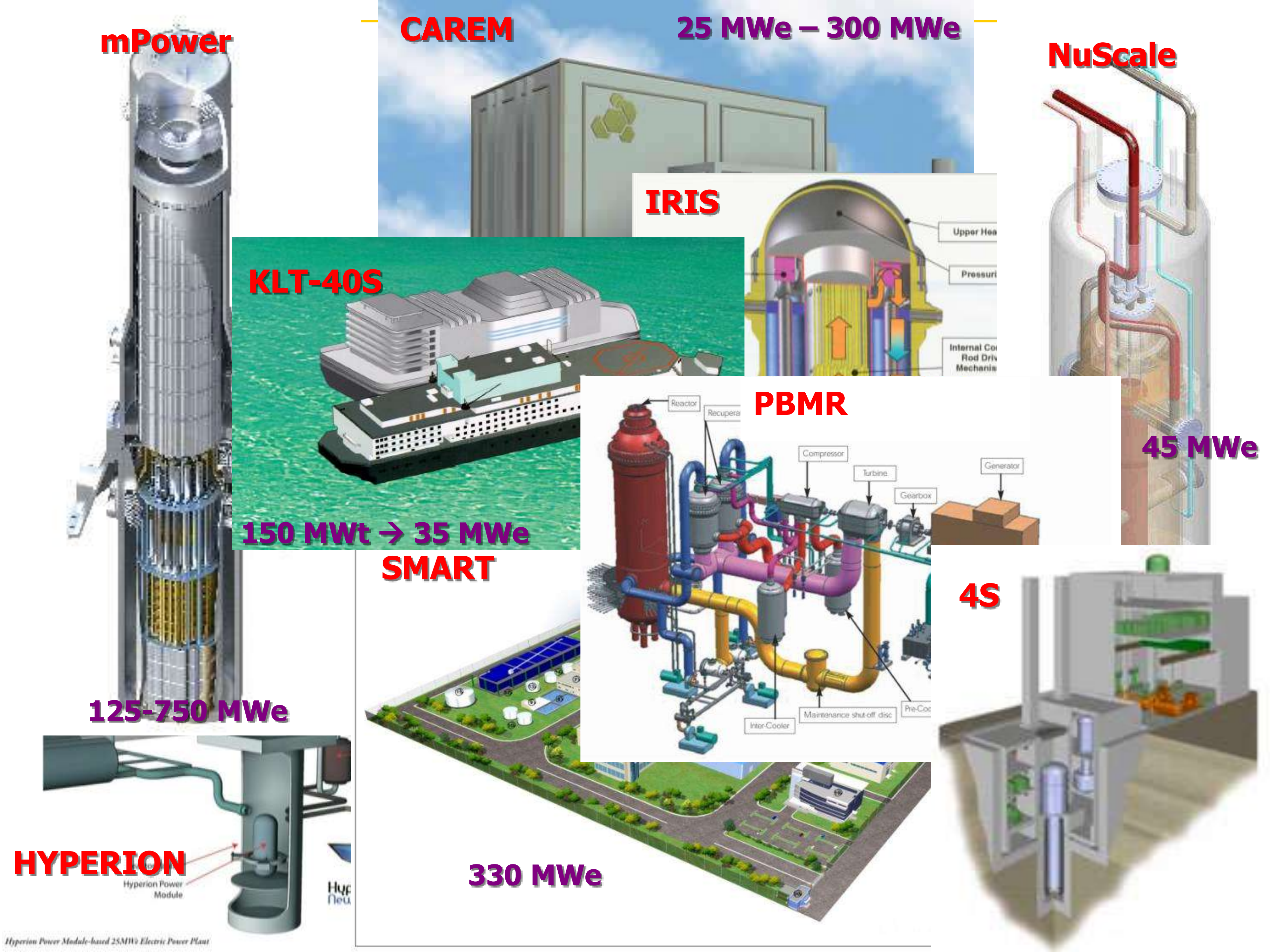




- AECL
- 740 MWe Enhanced CANDU-6
- 1200 MWe Advanced CANDU reactor
- 284 / 520 horizontal channels
- Low enriched uranium– 2.1%,
- 60 yr design life
- Continuous refueling
- Combination of active and passive safety systems
- CNSC has started “pre-project” design review
- Energy Alberta has filed *an 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

India’s HWR

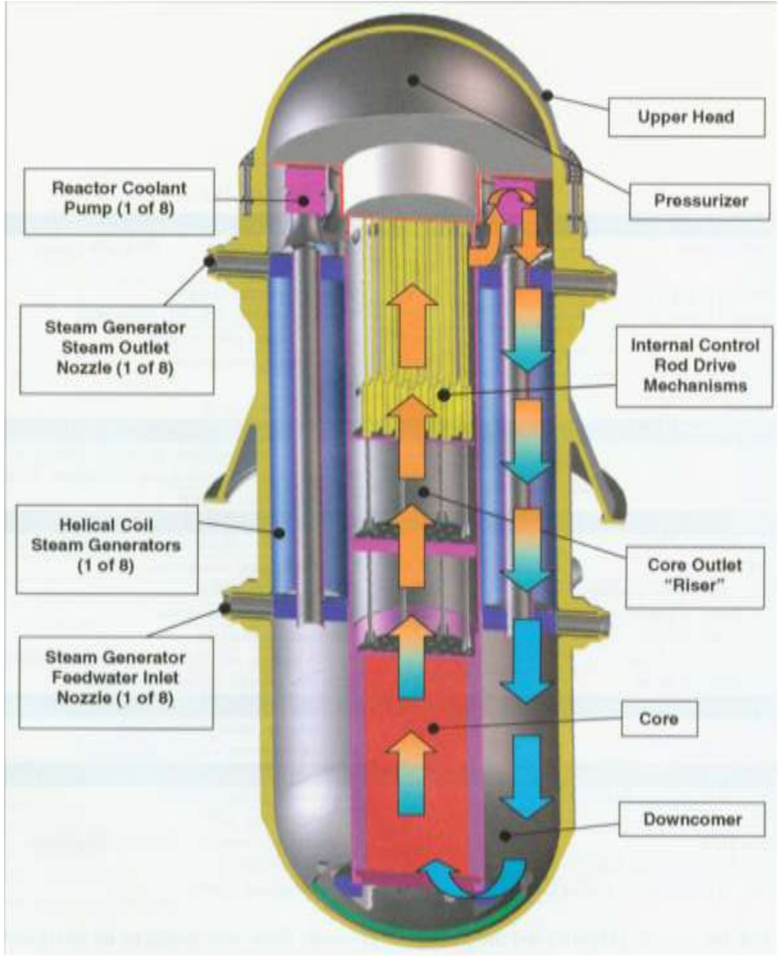
- 540 MWe PHWR [evolution from current 220 MWe HWRs]
  - » Nuclear Power Corporation of India, Ltd.
  - » First units: Tarapur-3 & -4 connected to grid (2005 & 6)
- 700 MWe PHWR [further evolution – economy of scale]
  - » NPCIL
  - » Regulatory review in progress
  - » Use of Passive Decay Heat Removal System; reduced CDF from PSA insights
  - » Better hydrogen management during postulated core damage scenario
  - » First units planned at Kakrapar & Rawatbhata
- 300 MWe Advanced HWR
  - » BARC
  - » for conversion of Th232 or U238 (addressing sustainability goals)
  - » vertical pressure tube design with natural circulation



mPower
CAREM
25 MWe – 300 MWe
NuScale
IRIS
Upper Hea
Pressuri
KLT-40S
PBMR
Reactor
Compressor
Turbine
Gearbox
Generator
Inter-Cooler
Maintenance shut-off disc
45 MWe
150 MWt → 35 MWe
SMART
4S
125-750 MWe
HYPERION
Hyperion Power Module
330 MWe
Hyperion Power Module-based 25MWe Electric Power Plant

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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SMART

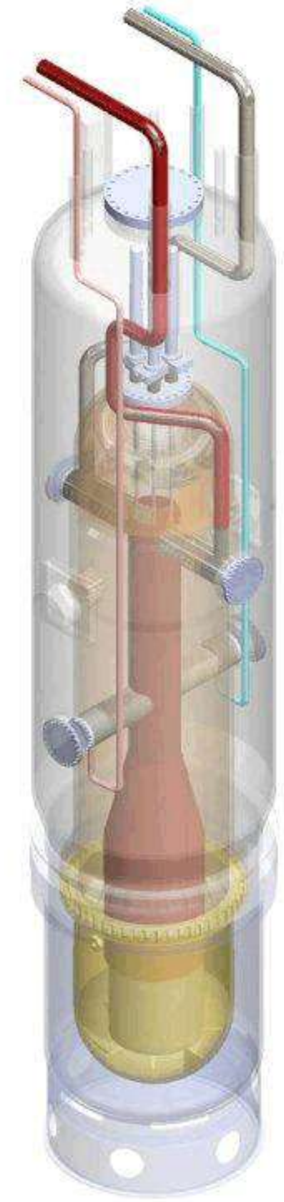
- Korea Atomic Energy Research Institute
- 330 MWe
- Used for electric and non-electric applications
- Integral reactor
- Passive Safety

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 under development
- Prototype planned for 2012 in Argentina's Formosa province

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.

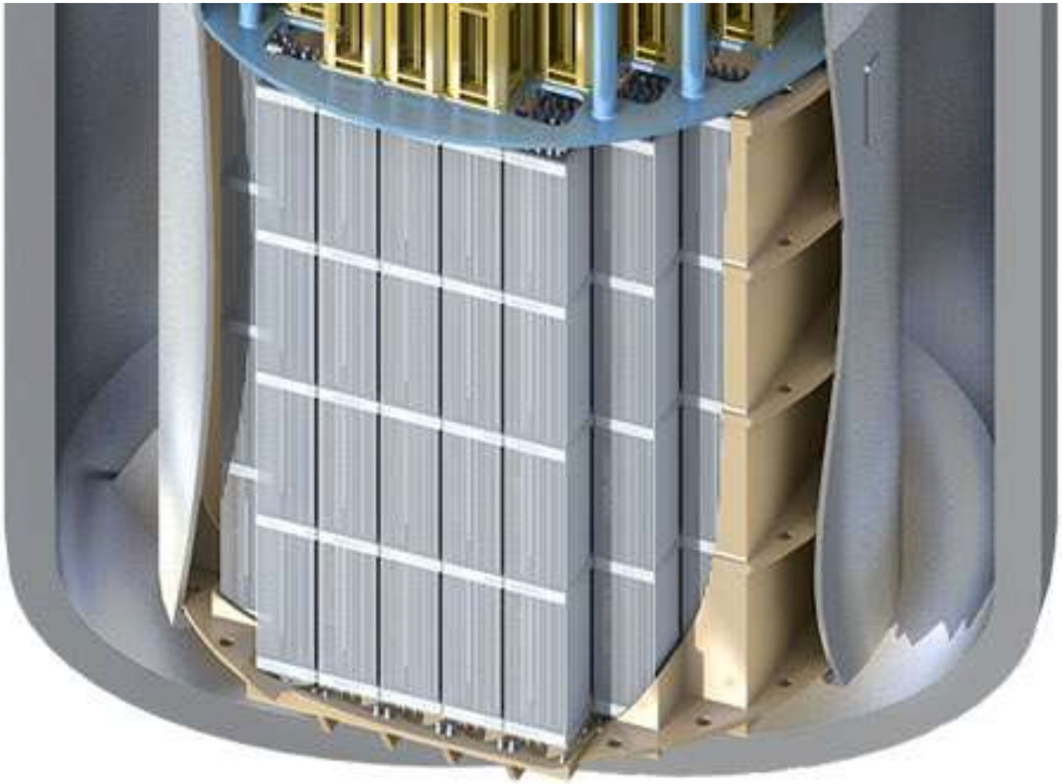


B&W mPower

- Integral reactor
- Scalable, modular
- 125 – 750 MWe
- 5% enriched fuel
- 5 year refueling cycle
- Passive safety
- Lifetime capacity of spent fuel pool

cal
ing

mPower – Reactor Core



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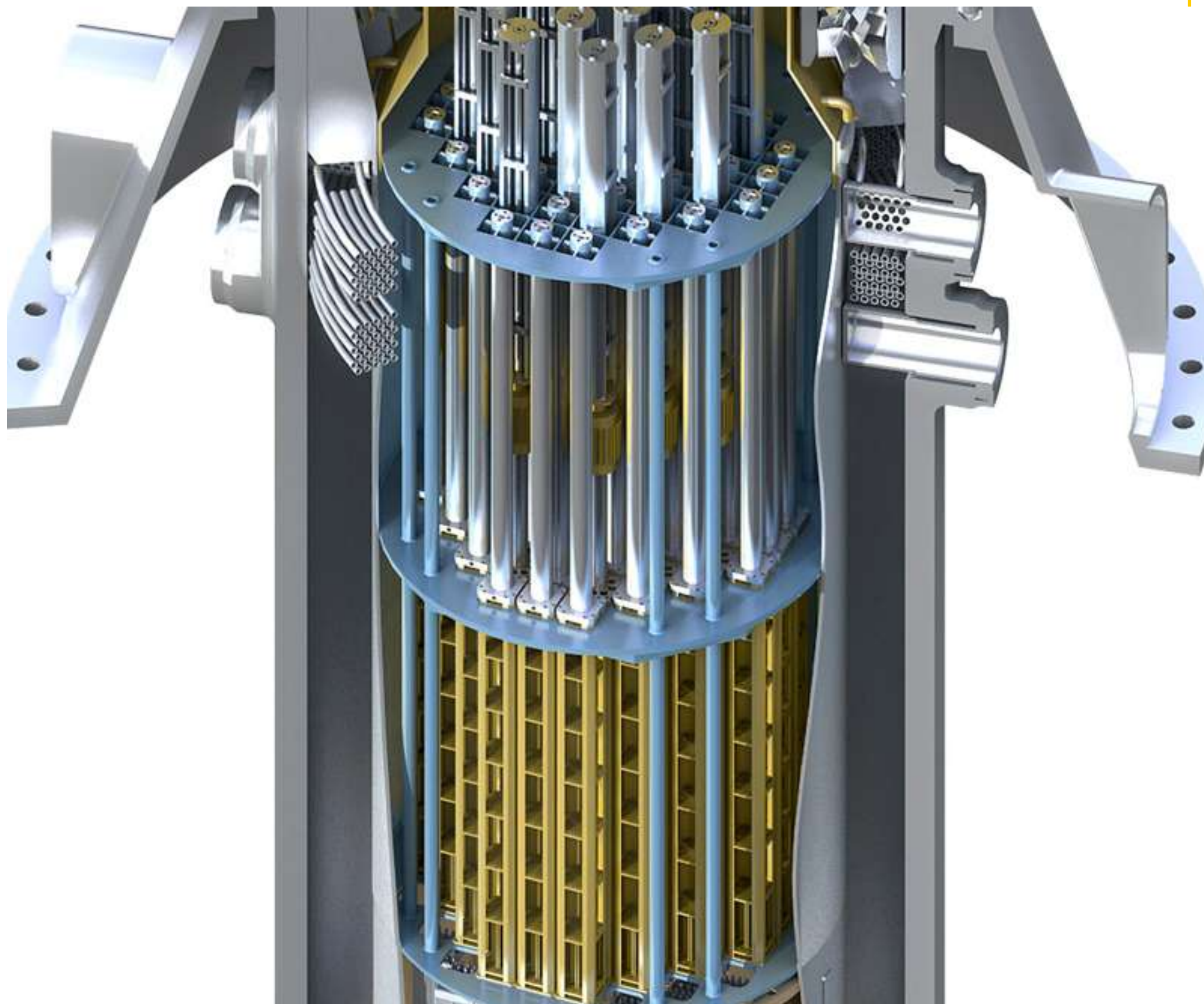
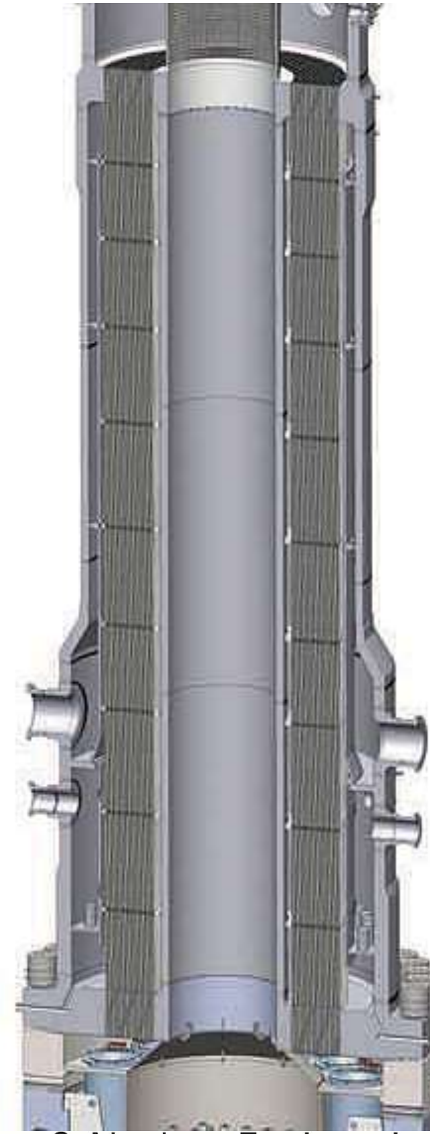
mPower – CRDMs



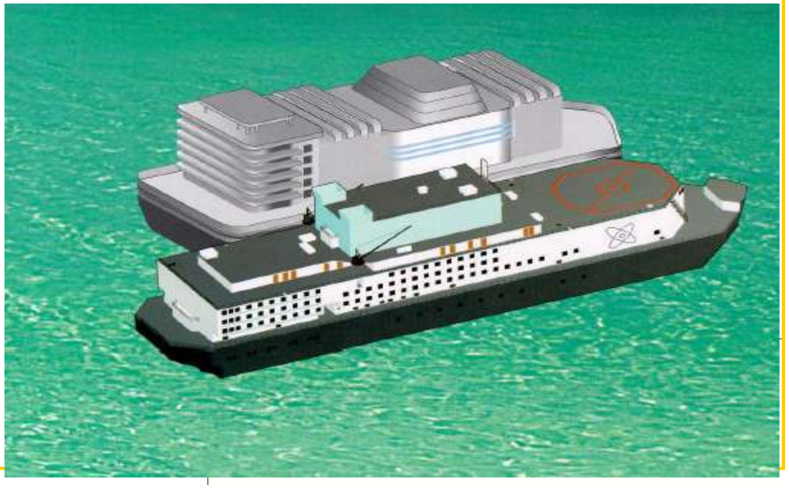
mPower – Steam Generator



mPower – Pressurizer

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)

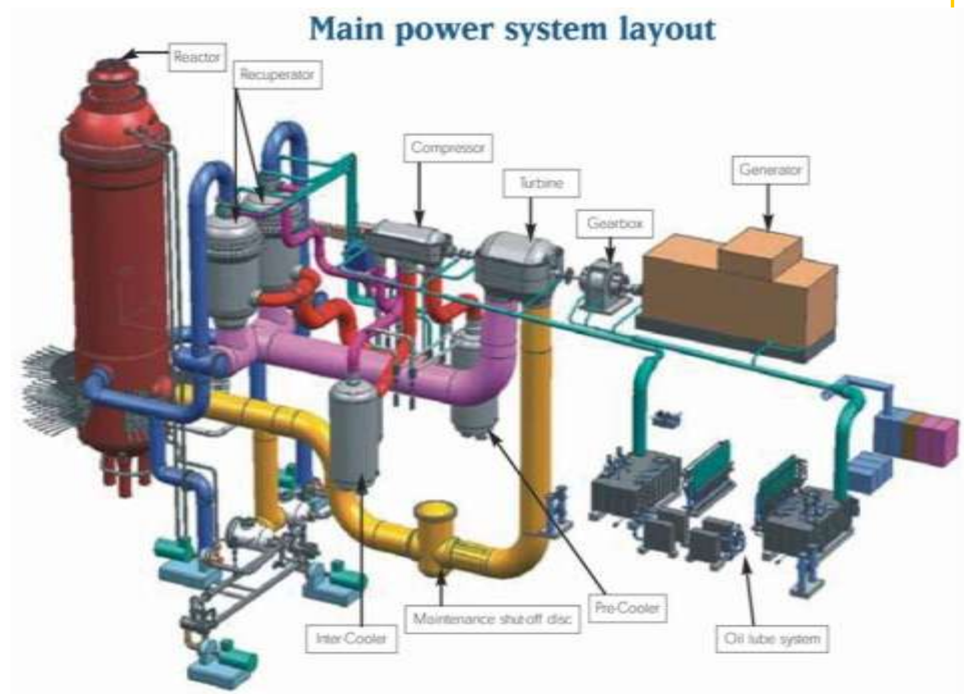


4S (Super Safe, Small and Simple)

- Toshiba & CRIEPI of Japan
- 50 MWe
- Sodium Cooled Fast Reactor
- 10 – 30 year refueling period
- Submitted for US NRC Pre Application Review
- Proposed for Galena, Alaska

PBMR (Pebble Bed Modular Reactor)

- ESKOM, South Africa Government, Westinghouse
- Project currently mothballed
- Helium Gas Cooled
- 165 MWe
- Electrical and non-electrical applications



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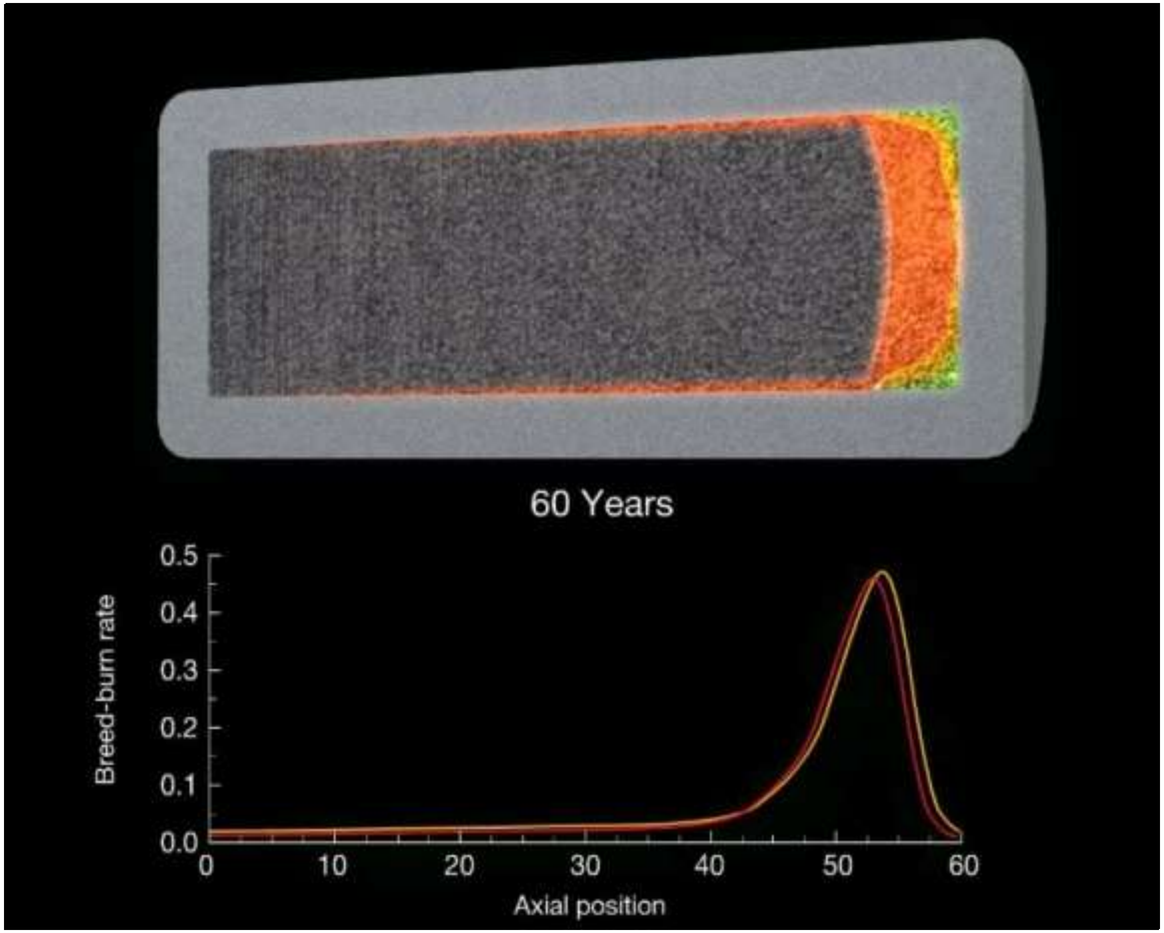
Travelling Wave Reactor



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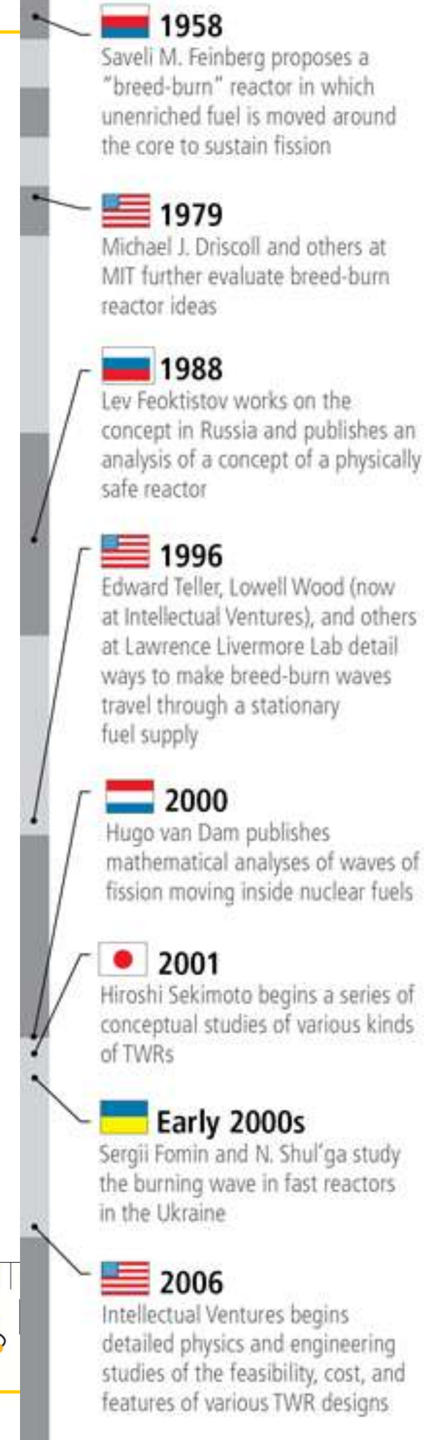
Travelling Wave Reactor Concept

- A reactor that breeds its own fuel
- The fission reaction takes place in a small area of the reactor and moves to where the fissionable fuel is being created.
- Breed-and-burn

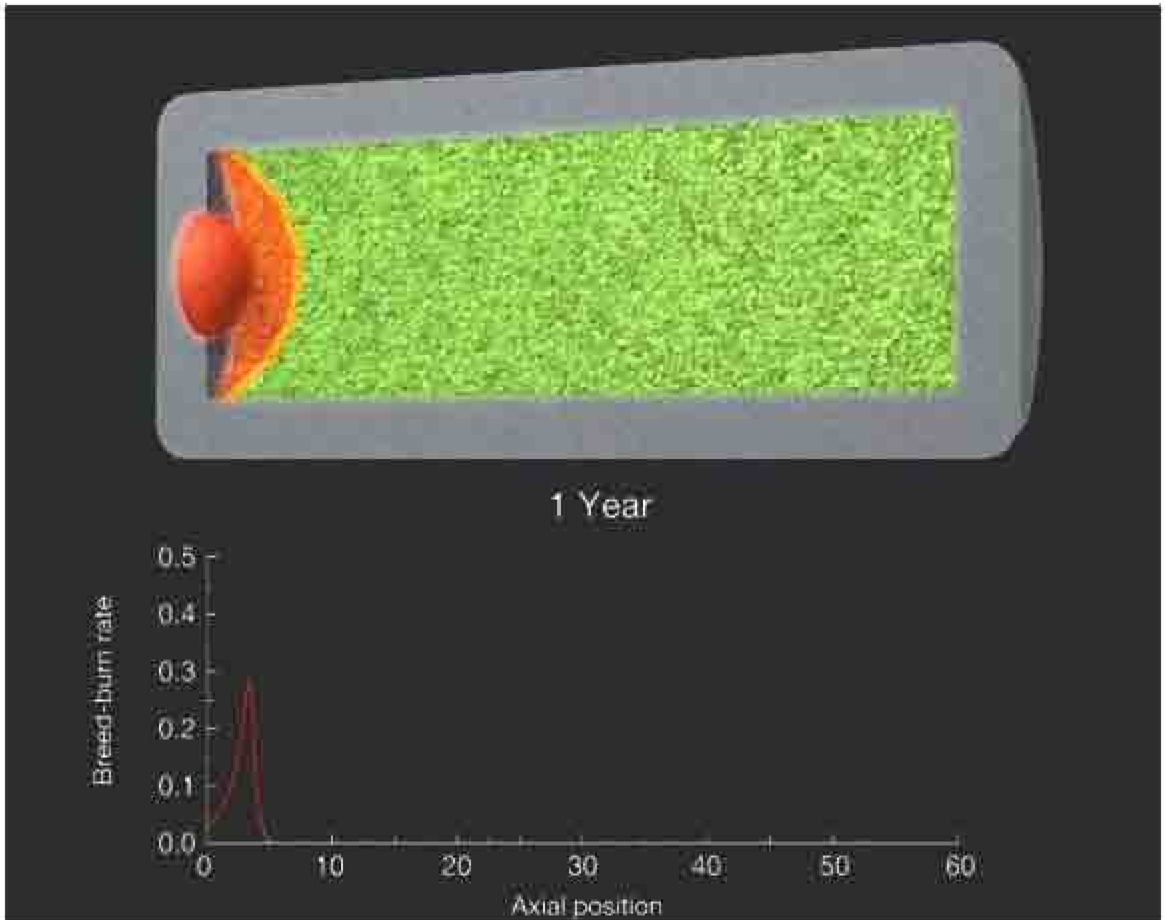


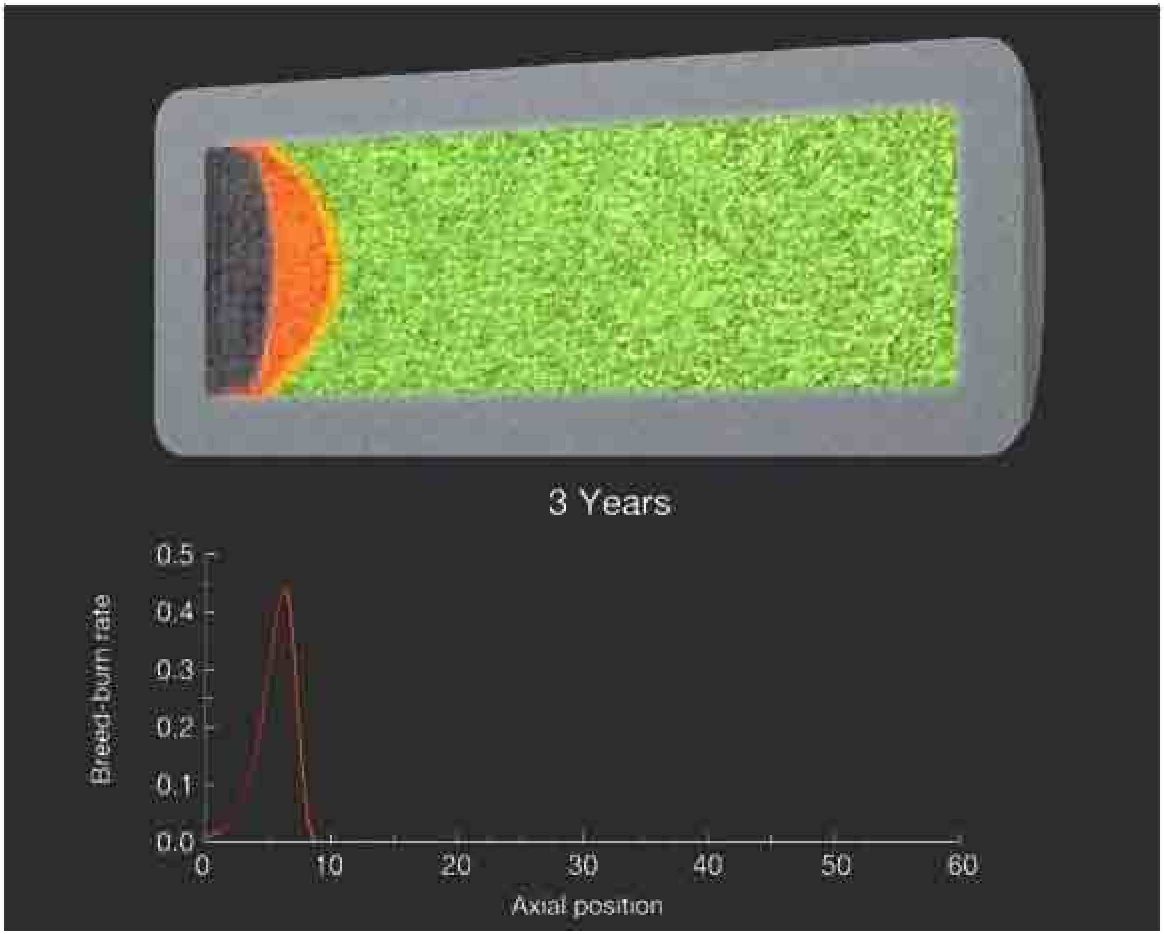
Concept

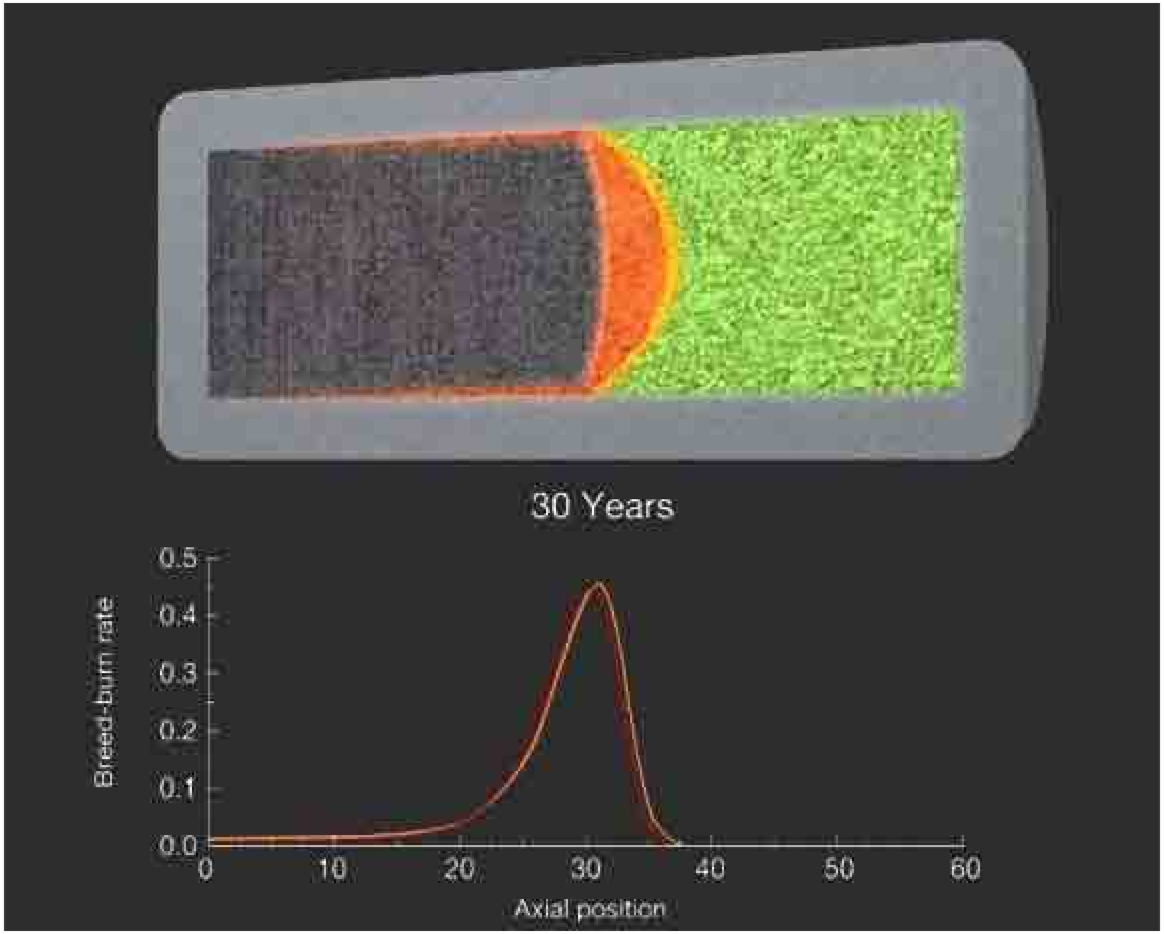
- Fast reactor

$$^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + \beta \rightarrow {}^{239}_{94}\mathrm{Pu} + \beta$$

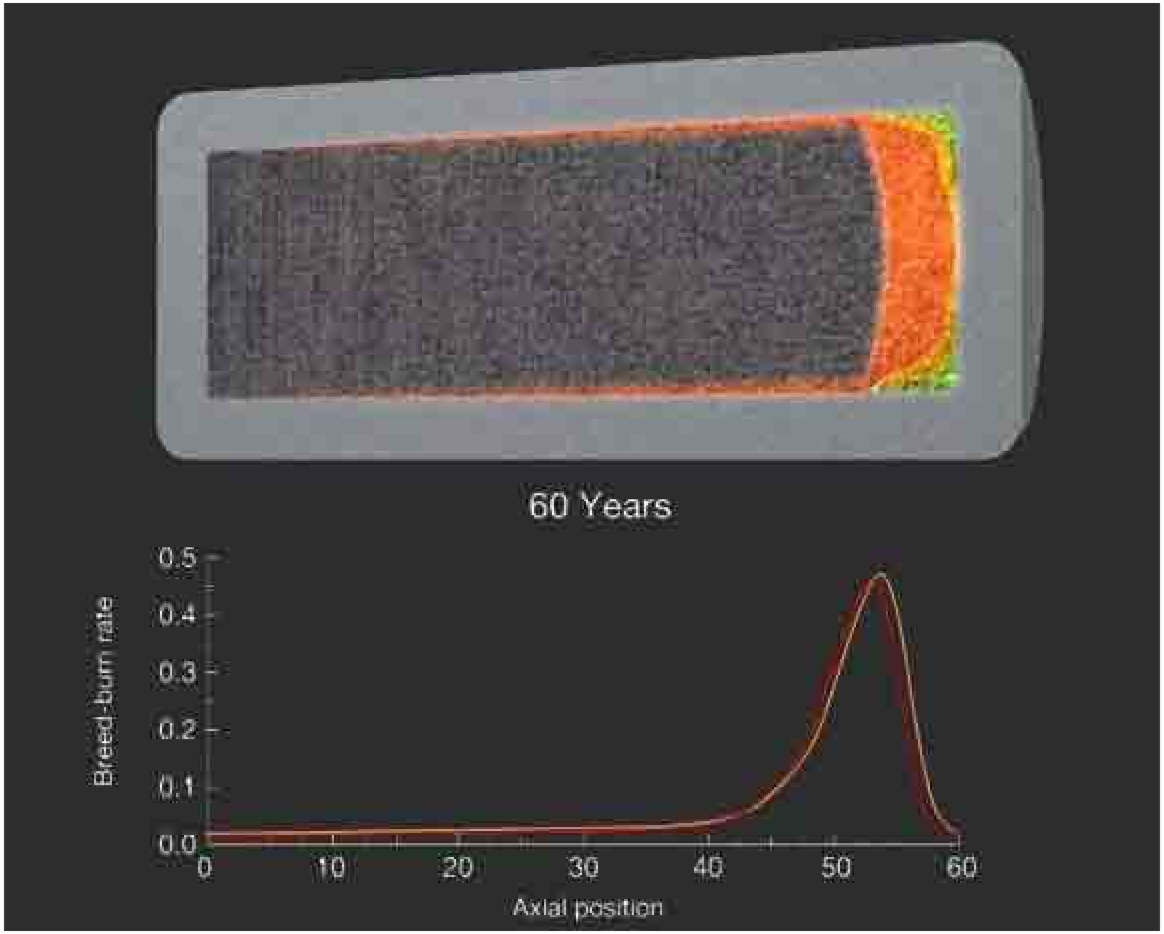
- Uses depleted Uranium (from mining tails)
  - Metallic fuel
  - projected global stockpiles of depleted uranium could sustain 80% of the world's population at U.S. per capita energy usages for over a millennium.
  - Needs a small amount of 10% enriched Uranium to start the reaction
  - Fertile fuel: natural Uranium, Thorium, spent fuel
- Sodium cooled
- Used fuel could be reprocessed to be used again


1 Year
0.5
0.4
0.3
0.2
0.1
0.0
Breed-burn rate
0
10
20
30
40
50
60
Axial position


3 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
Axial position



30 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
Axial position


60 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0.0
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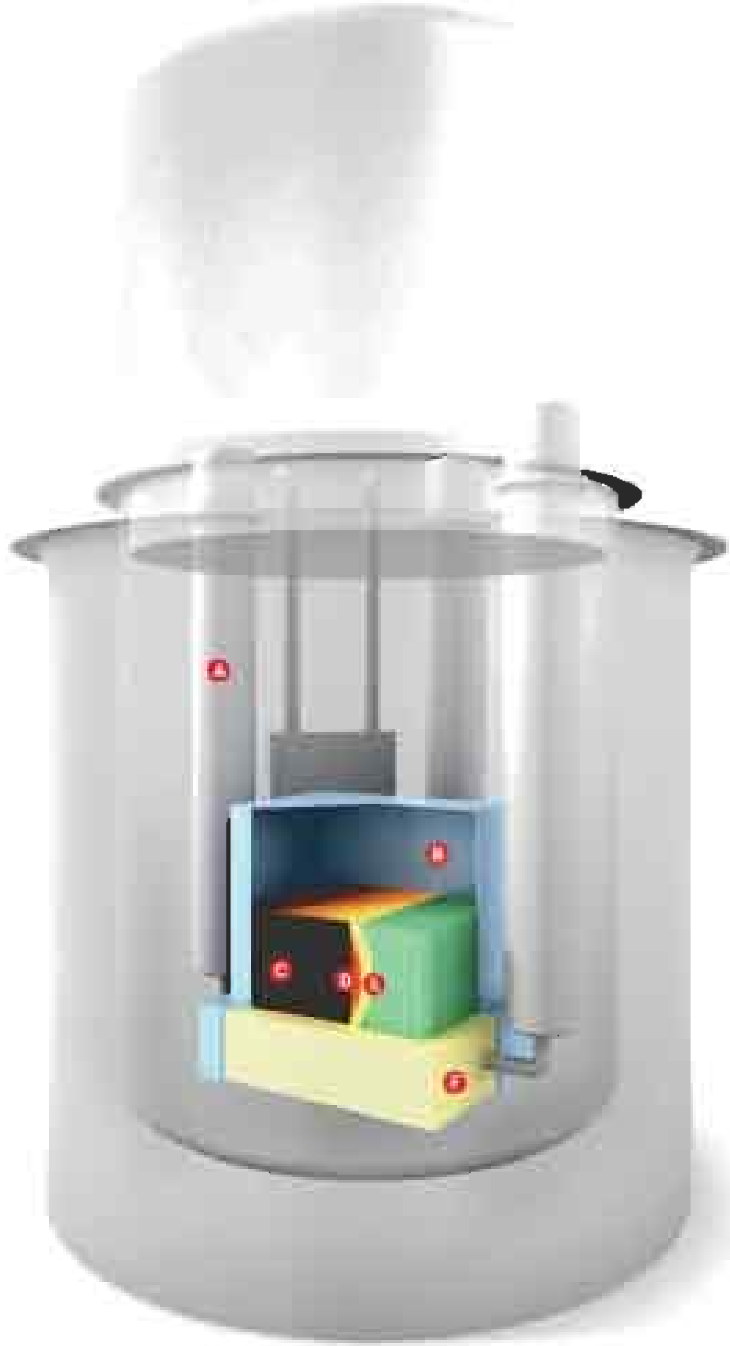
10
20
30
40
50
60
Axial position



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Standing Wave Reactor

- The wave does not move → the fuel assemblies move
- Engineering concept similar to a pool type Sodium reactors
- 40 – 60 year cycle
- Less U per kWh produced
  - Better burn-up
  - Higher thermal efficiencies

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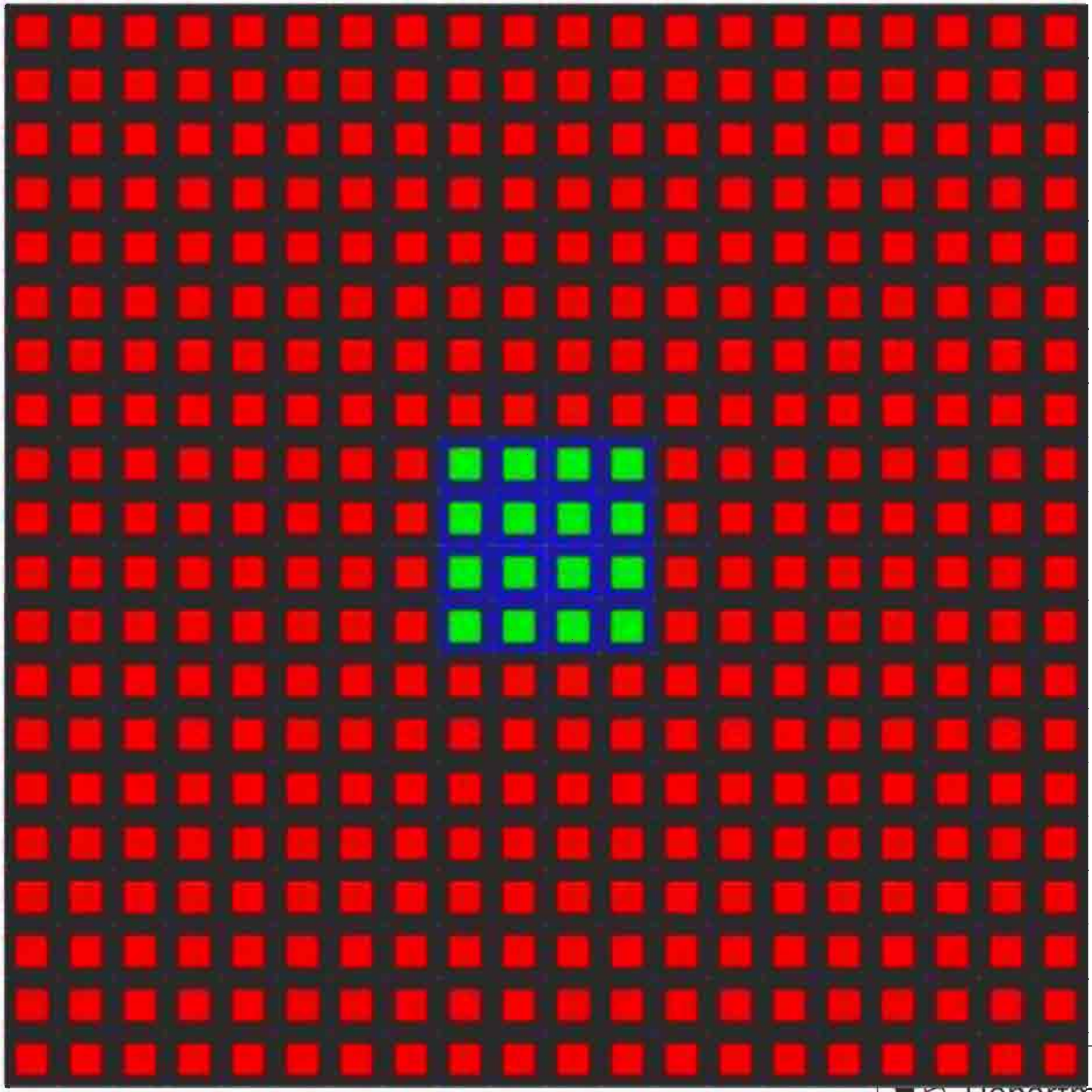

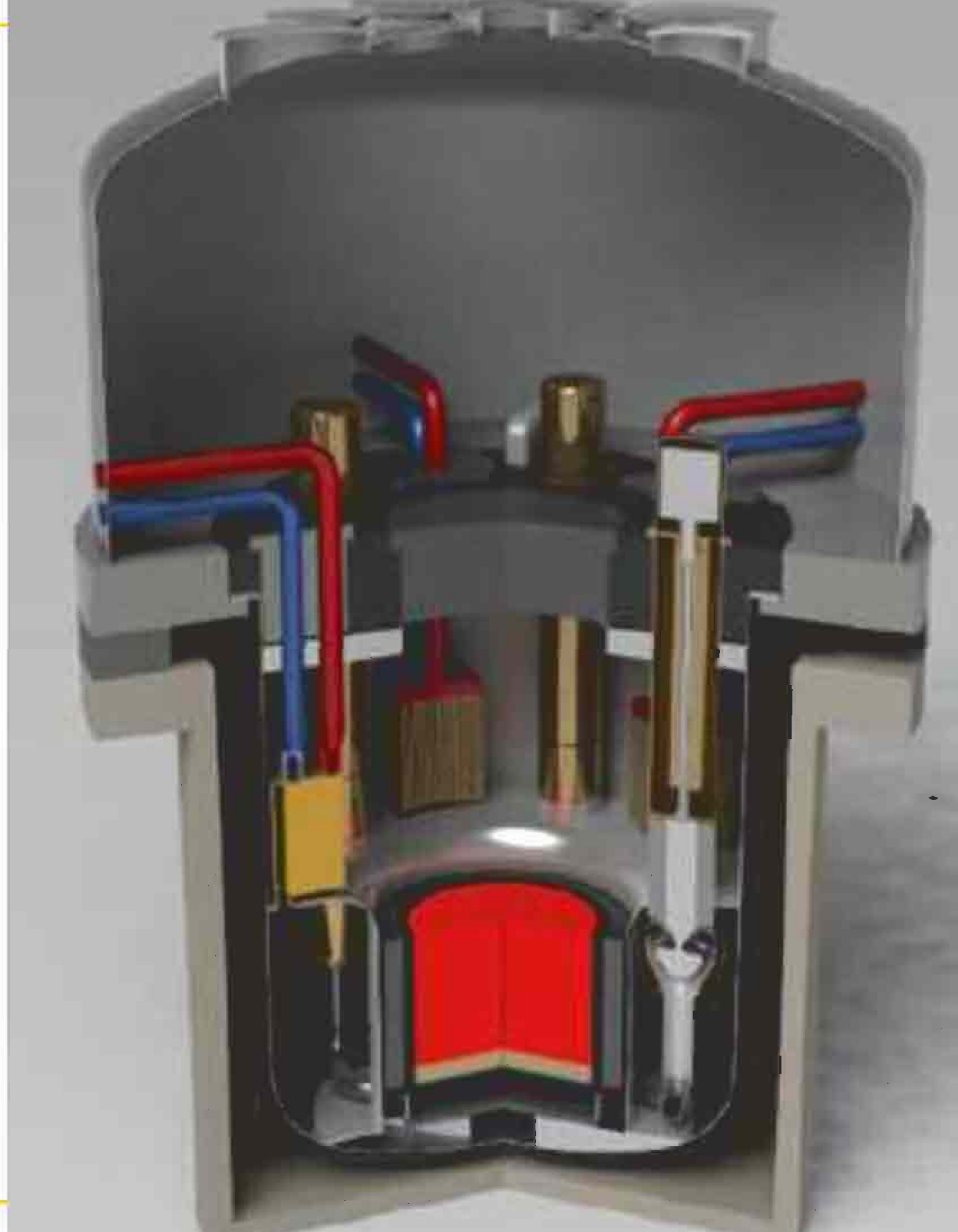

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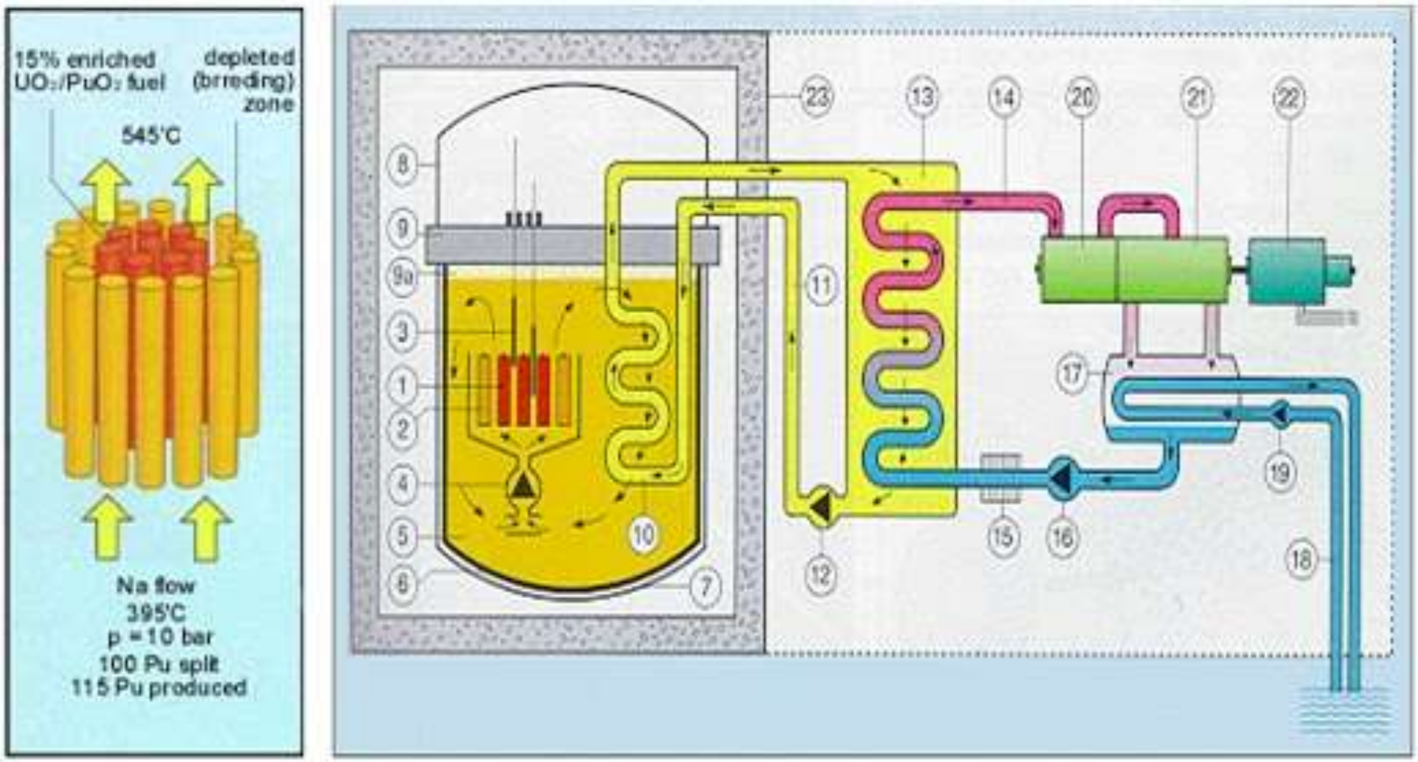
Pool Type Fast Reactor

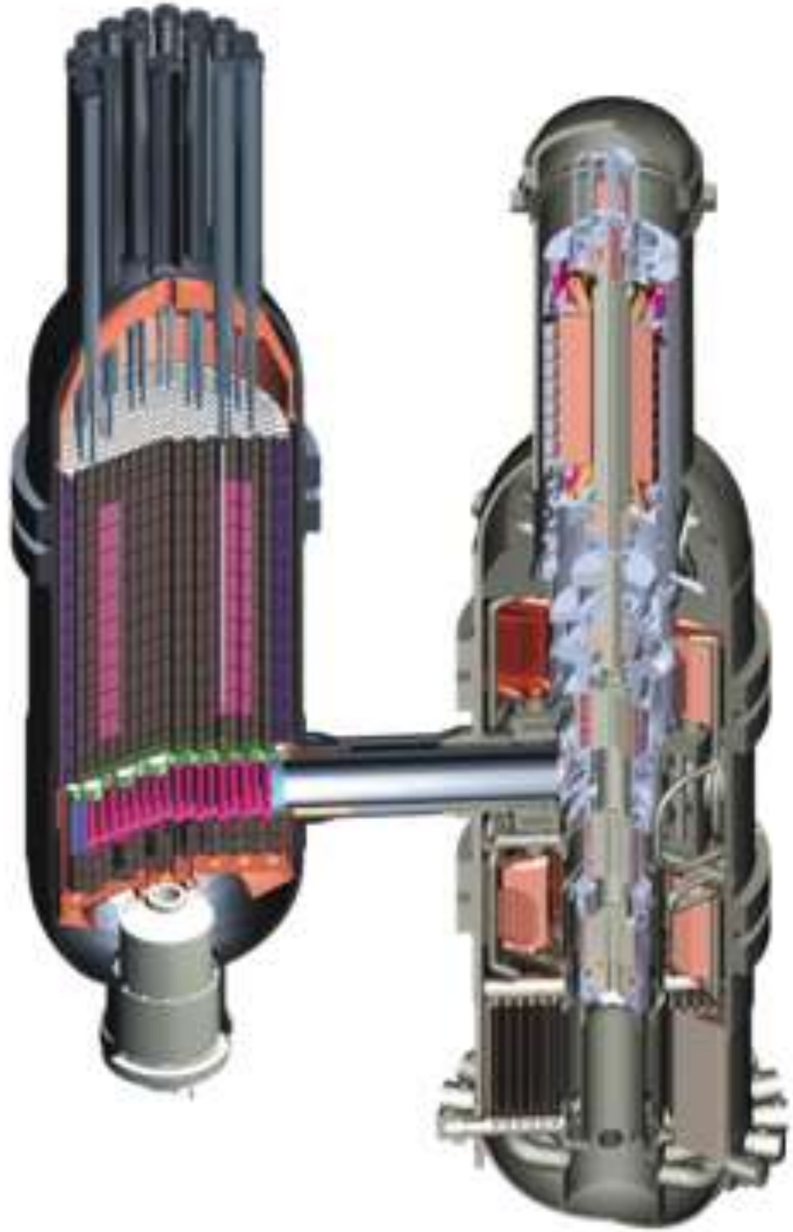


1 Fuel (fissile material)
2 Fuel (breeder material)
3 Control rods
4 Primary Na pump
5 Primary Na coolant
6 Reactor vessel
7 Protective vessel
8 Reactor cover
9 Cover
10 Na/Na heat exchanger
11 Secondary Na
12 Secondary Na pump
13 Steam generator
14 Fresh steam
15 Feedwater pre-heater
16 Feedwater pump
17 Condenser
18 Cooling water
19 Cooling water pump
20 High pressure turbine
21 Low pressure turbine
22 Generator
23 Reactor building

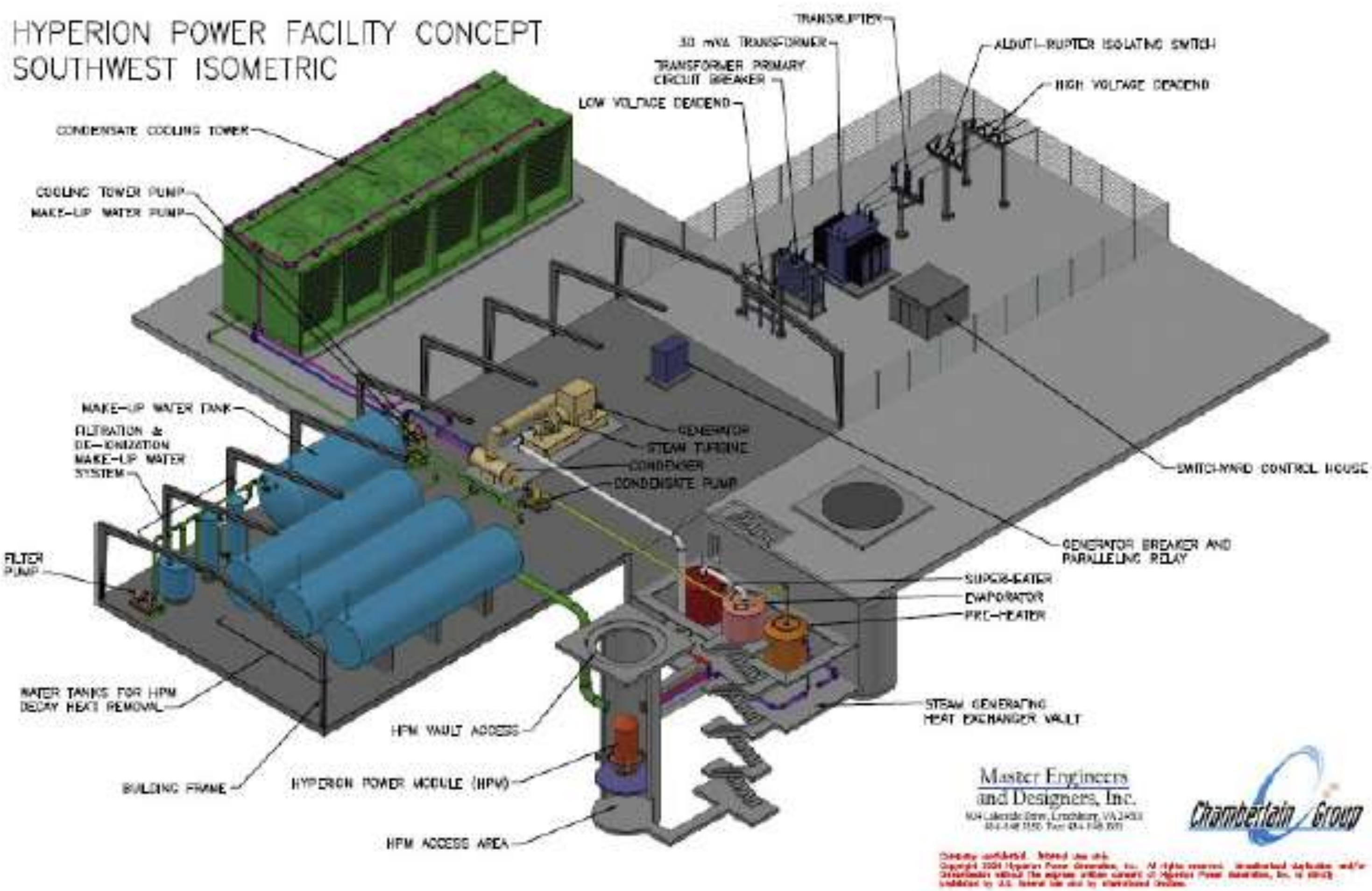
Status

- TerraPower working on all technical issues to bring the concept to a commercial-ready state
- Expect first power-producing system by 2020
- Other related concepts
  - Japanese CANDLE
  - US General Atomics Energy Multiplier Module (EM2)

EM2



Hyperion



HYPERION POWER FACILITY CONCEPT
SOUTHWEST ISOMETRIC
TRANSRUPTER
30 mVA TRANSFORMER
TRANSFORMER PRIMARY CIRCUIT BREAKER
LOW VOLTAGE DEADEND
ALDUTI-RUPTER ISOLATING SWITCH
HIGH VOLTAGE DEADEND
CONDENSATE COOLING TOWER
COOLING TOWER PUMP
MAKE-UP WATER PUMP
MAKE-UP WATER TANK
FILTRATION & DE-IONIZATION MAKE-UP WATER SYSTEM
FILTER PUMP
GENERATOR
STEAM TURBINE
CONDENSER
CONDENSATE PUMP
SWITCHYARD CONTROL HOUSE
GENERATOR BREAKER AND PARALLELING RELAY
SUPERHEATER
EVAPORATOR
PRE-HEATER
STEAM GENERATING HEAT EXCHANGER VAULT
WATER TANKS FOR HPM DECAY HEAT REMOVAL
HPM VAULT ACCESS
BUILDING FRAME
HYPERION POWER MODULE (HPM)
HPM ACCESS AREA
Master Engineers and Designers, Inc.
Chamberlain Group

GAS-COOLED REACTOR DEVELOPMENT

- More than 1400 reactor-years experience
- CO_2 cooled
  - 22 reactors generate most of the UK's nuclear electricity
  - also operated in France, Japan, Italy and Spain
- Helium cooled
  - operated in UK (1), Germany (2) and the USA (2)
  - current test reactors:
    - 30 MW(th) HTTR (JAERI, Japan)
    - 10 MW(th) HTR-10 (Tsinghua University, China)
- In South Africa a small 165 MWe prototype plant is planned
- Russia, in cooperation with the U.S., is designing a plant for weapons Pu consumption and electricity production
- France, Japan, China, South Africa, Russia and the U.S. have technology development programmes

Fast Reactor Development

- **France:**
  - Conducting tests of transmutation of long lived waste & use of Pu fuels at Phénix (shutdown planned for 2009)
  - Designing 300-600 MWe Advanced LMR Prototype "ASTRID" for commissioning in 2020
  - Performing R&D on GCFR
- **Japan:**
  - MONJU restart planned for 2009
  - Operating JOYO experimental LMR (Shutdown for repair)
  - Conducting development studies for future commercial FR Systems
- **India:**
  - Operating FBTR
  - Constructing 500 MWe Prototype Fast Breeder Reactor (commissioning 2010)
- **Russia:**
  - Operating BN-600
  - Constructing BN-800
  - Developing other Na, Pb, and Pb-Bi cooled systems
- **China:**
  - Constructing 25 MWe CEFR – criticality planned in 2009
- **Rep. of Korea:**
  - Conceptual design of 600 MWe Kalimer is complete
- **United States**
  - Under GNEP, planning development of industry-led prototype facilities:
    - Advanced Burner Reactor
    - LWR spent fuel processing

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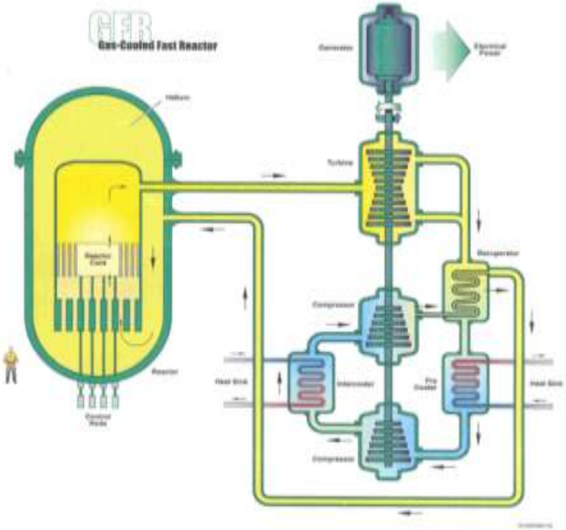

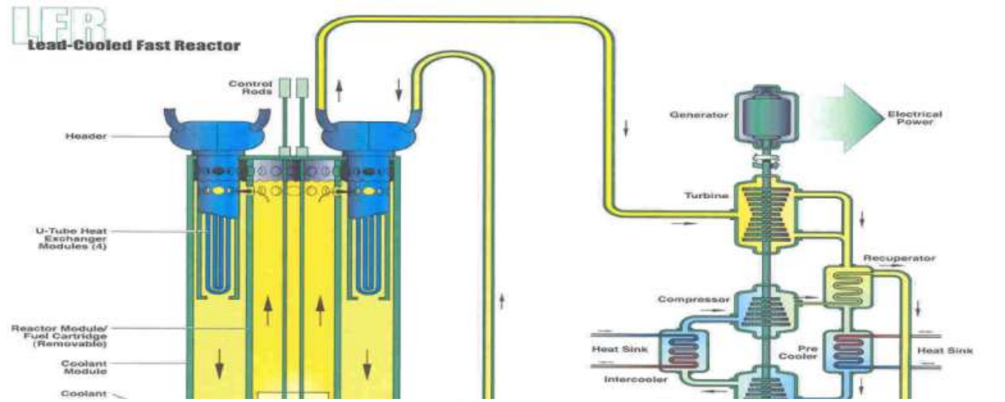

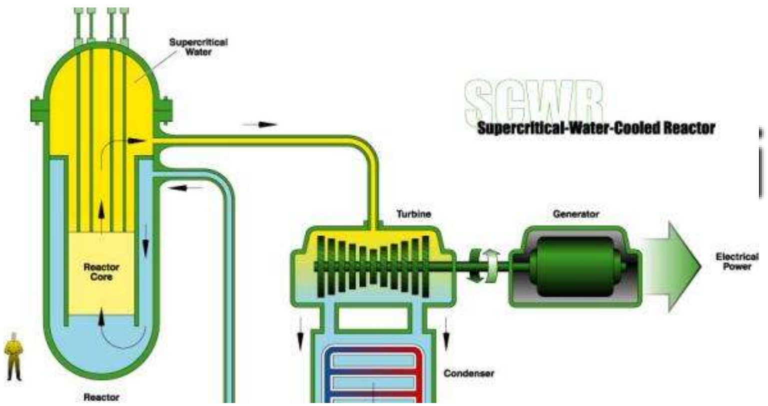

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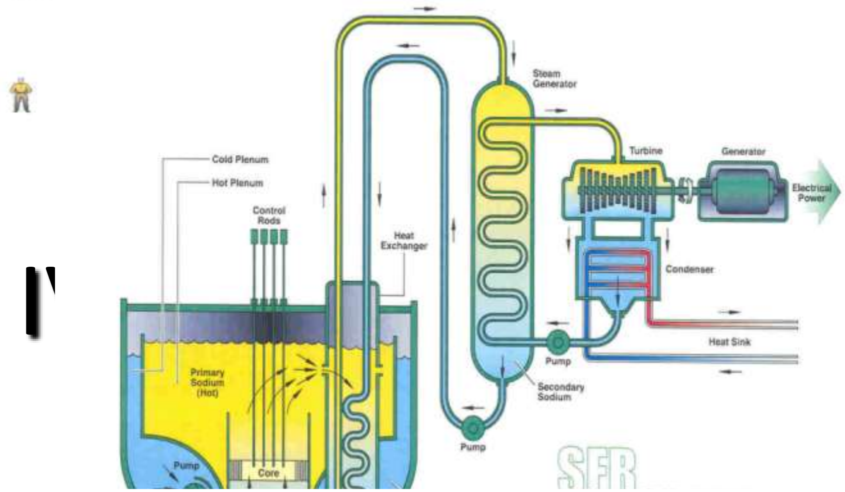

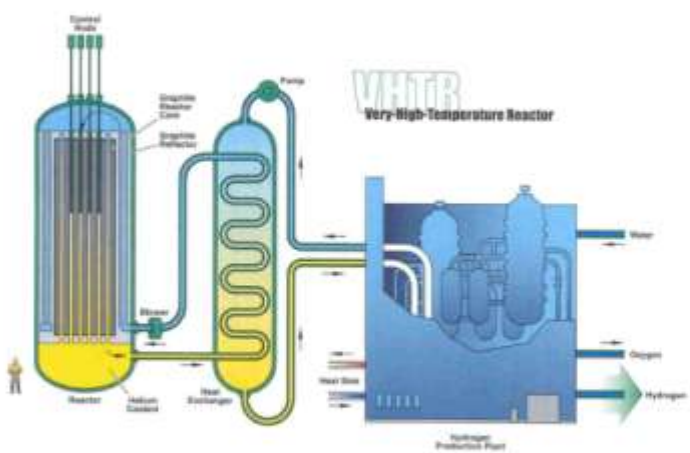

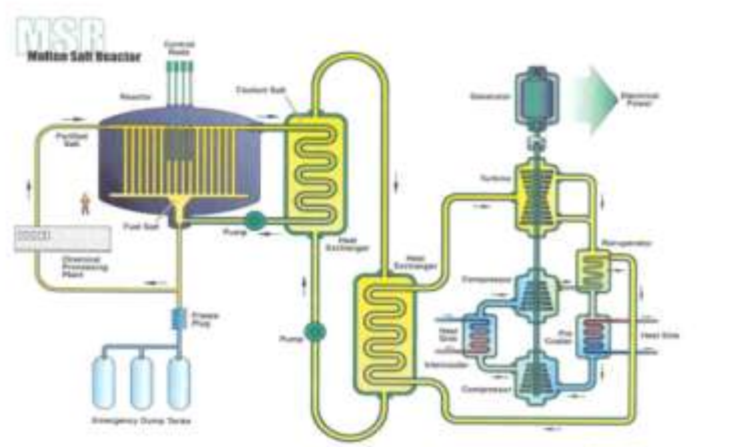

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Generation IV Reactor Designs

- 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)

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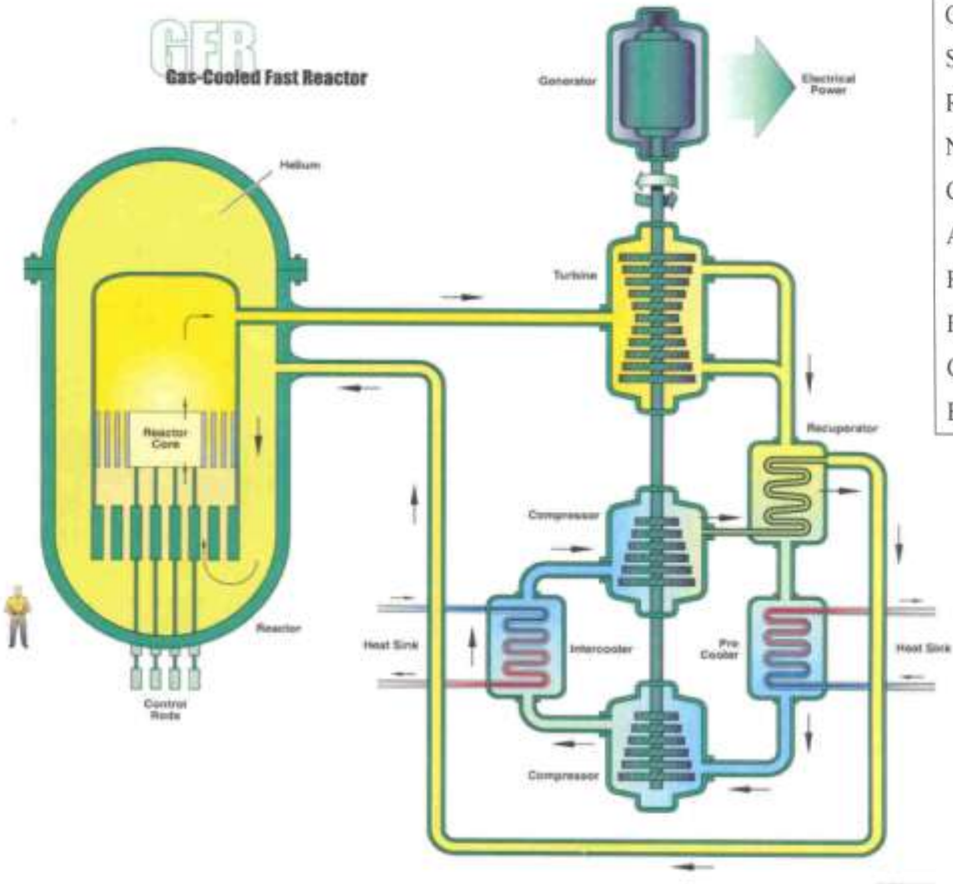
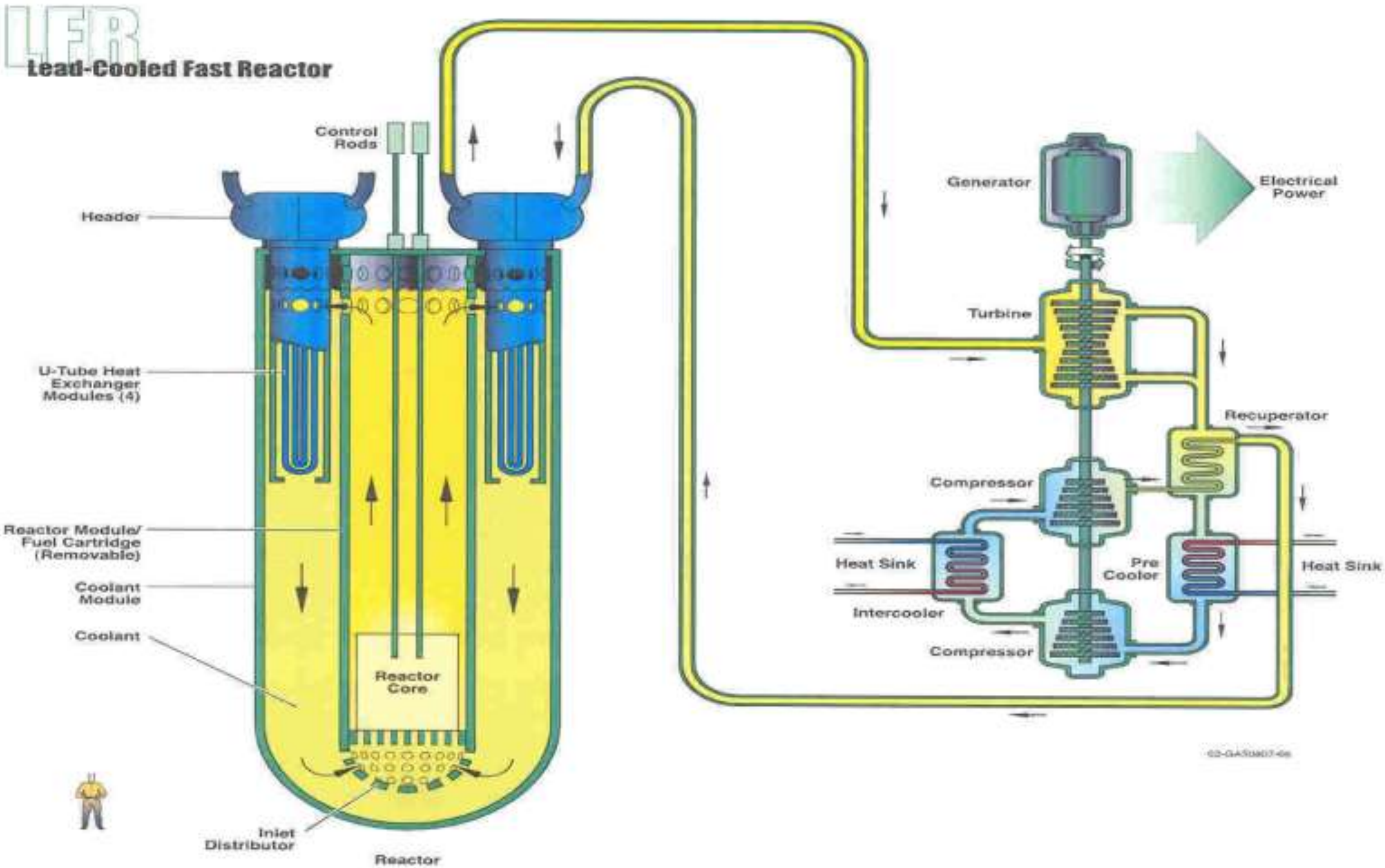
Gas Cooled Fast Reactor



Reactor parameter	Reference Value
Coolant	Helium
Spectrum	Fast
Reactor power	600 MWth
Net plant efficiency (Brayton cycle)	48%
Coolant inlet/outlet temperature and pressure	490°C/850°C at 90 bar
Average power density	100 MWth/m^3
Reference fuel compound	UPuC/SiC with about 20% Pu content
Fuel cycle	Closed
Conversion ratio	Self-sufficient
Burn up	5% FIMA

Lead Cooled Fast Reactor



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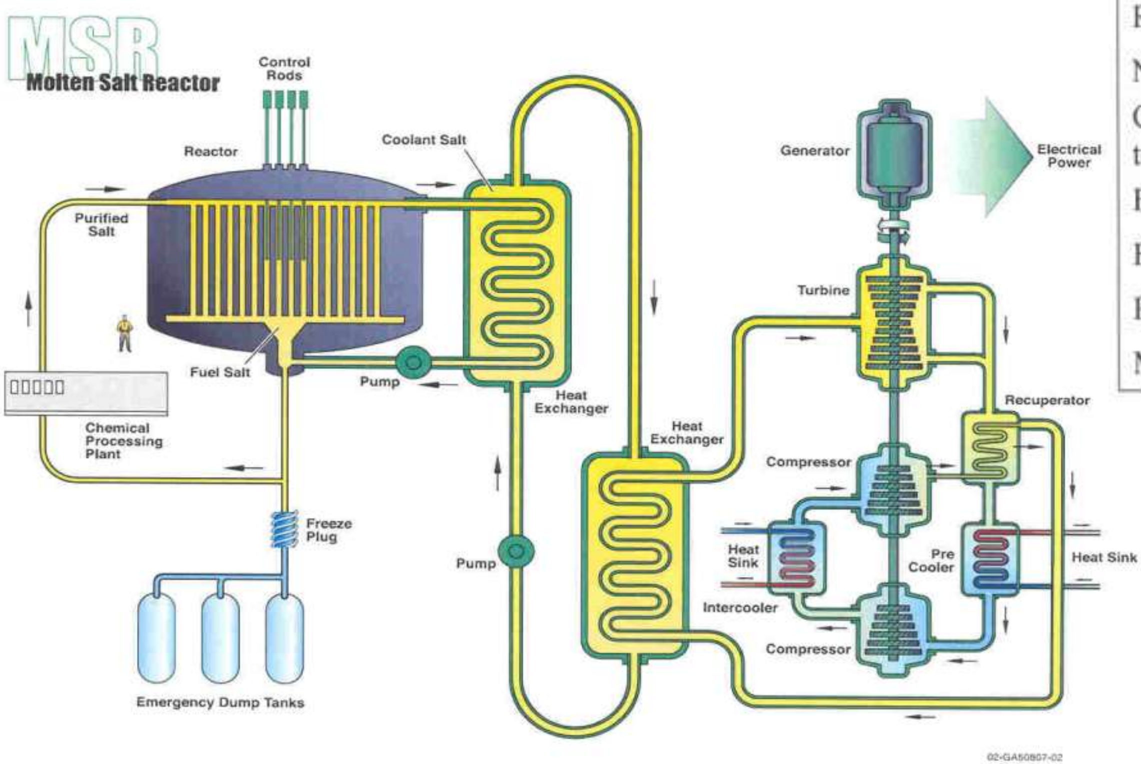
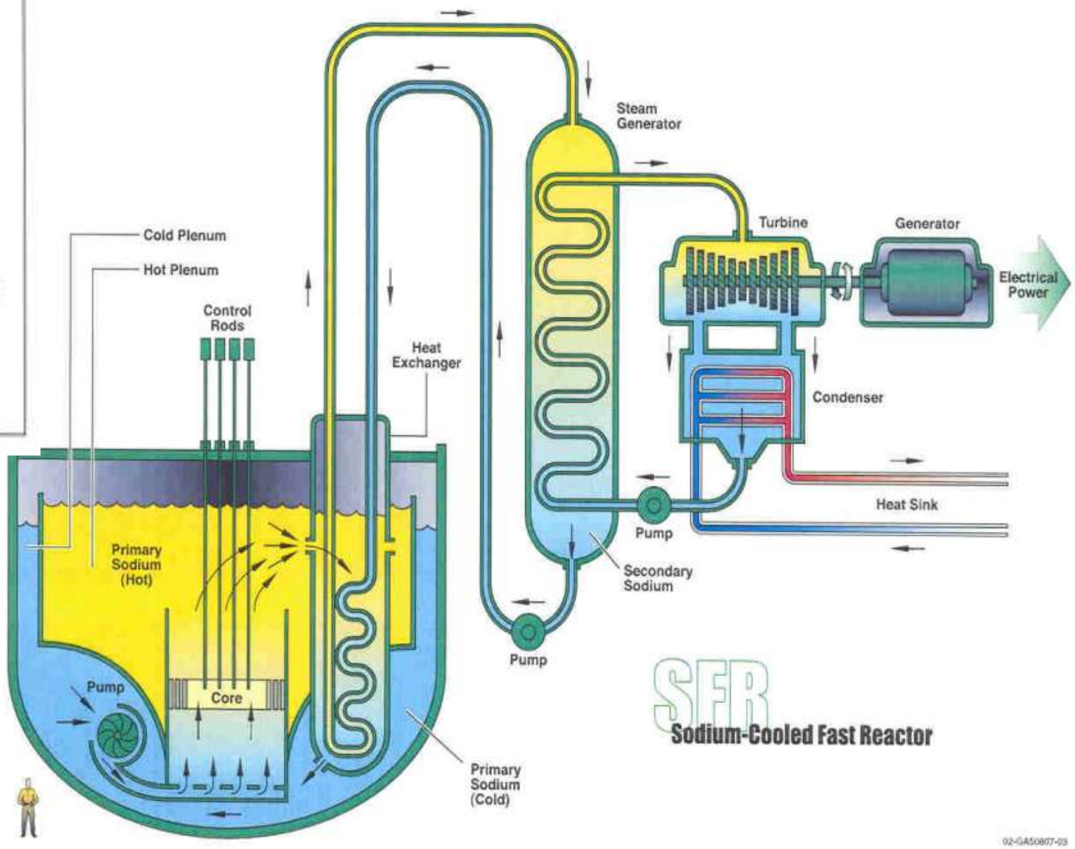
Molten Salt Reactor



Reactor parameter	Reference Value
Coolant	Molten Salt
Spectrum	Thermal
Reactor power	1000 MWe
Net plant efficiency	44 to 50 %
Coolant inlet/outlet temperature and pressure	565 - 750°C (850°C for hydrogen production)
Fuel	Uranium/Plutonium Fluoride
Fuel cycle	Closed
Power Density	22MWth/m^3
Moderator	Graphite

Sodium cooled Fast Reactor

Reactor parameter	Reference Value
Coolant	Sodium
Spectrum	Fast
Reactor power	1000-5000 MWth
Design	Pool type
Coolant outlet temperature and pressure	530-550°C, 1 bar
Fuel	Oxide or metal alloy
Fuel cycle	Closed
Average Burn-up	About 150-200 GWD/MTHM
Conversion ratio	0.5-1.30
Average Power Density	350 MWth/m^3



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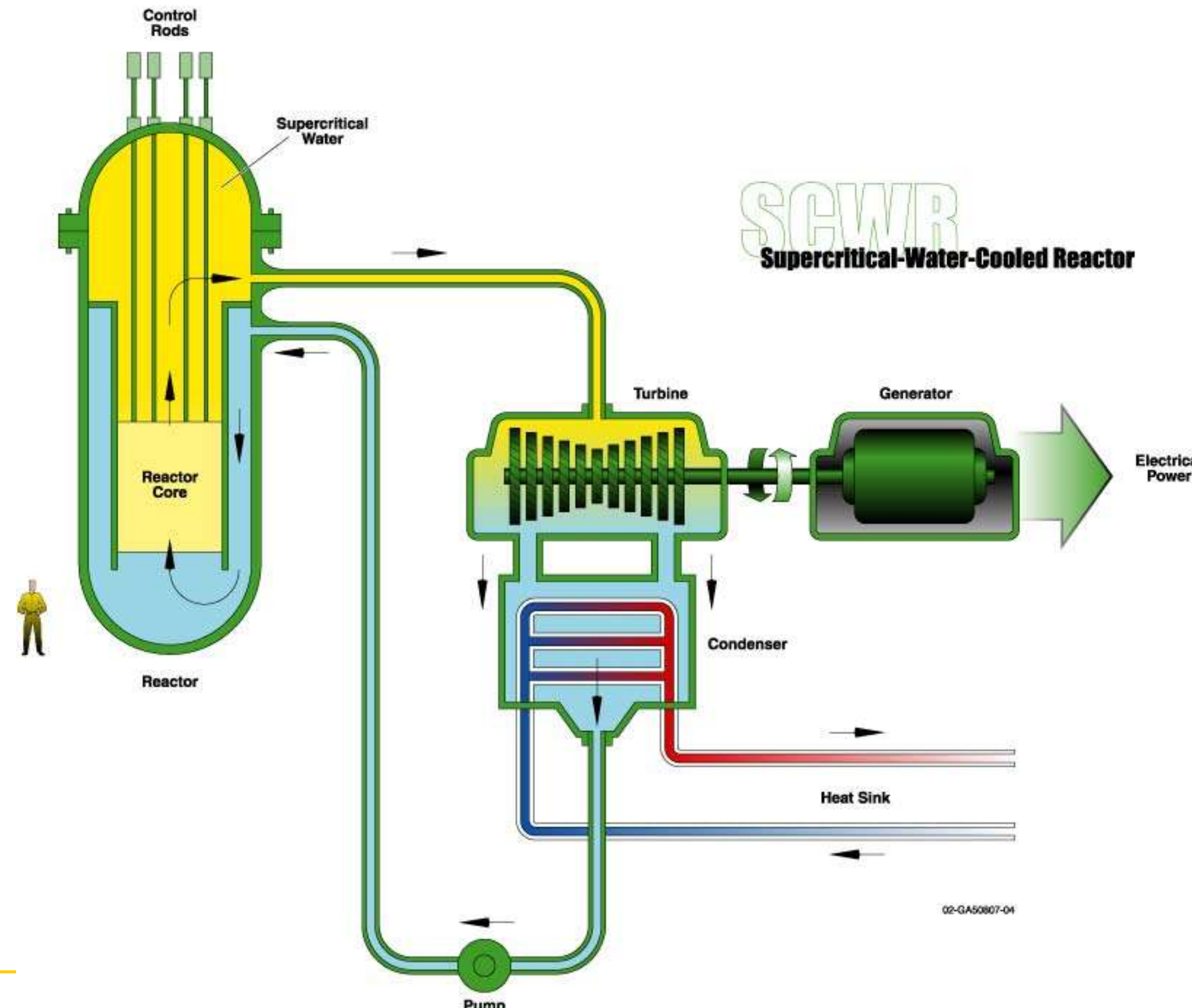
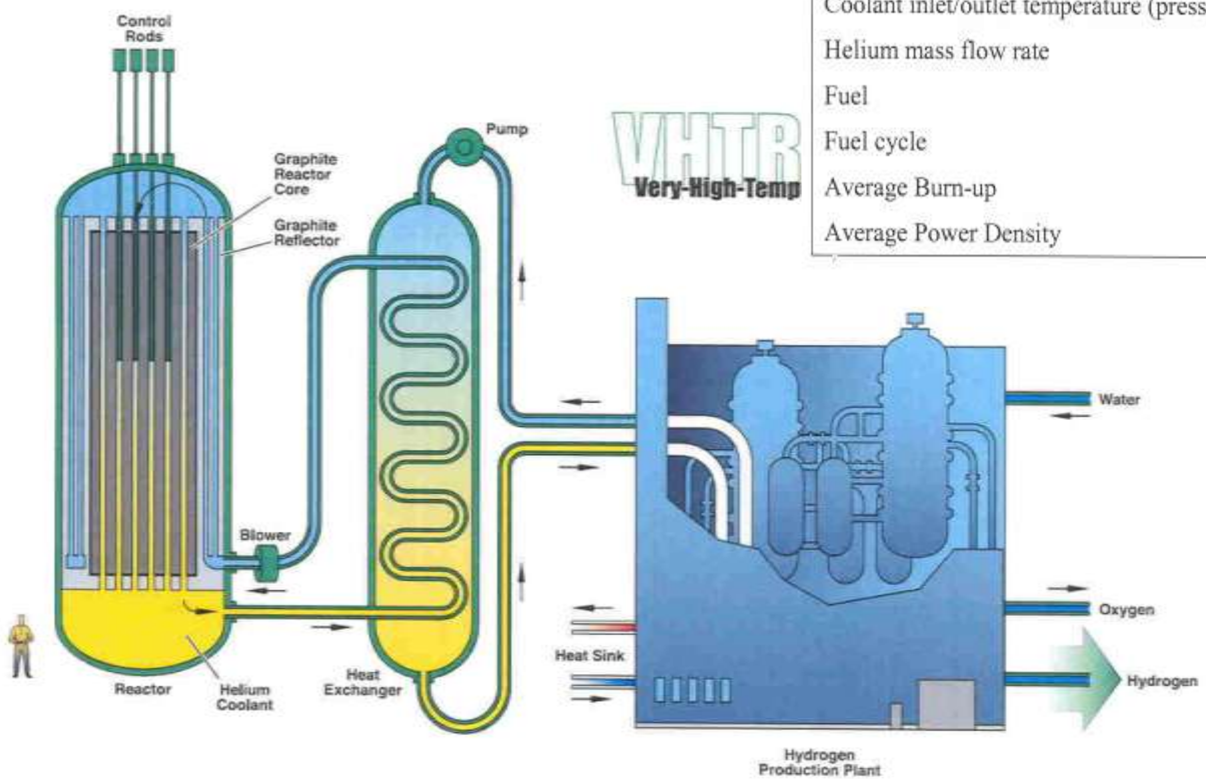
Super-Critical Water Cooled Reactor



Very High Temperature Reactor

Reactor parameter	Reference Value
Coolant	Helium
Spectrum	Thermal
Reactor power	600 MWth
Coolant inlet/outlet temperature (pressure)	640/1000°C (depending on process)
Helium mass flow rate	320 Kg/s
Fuel	UO_2 in ZrC-coated particles in blocks, pins or pebbles
Fuel cycle	Open
Average Burn-up	150-200GWD/MTHM
Average Power Density	6-10 MWth/m^3



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