IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Nuclear Power Technology Evolution

Frederik Reitsma
Nuclear Power Technology Development Section
Department of Nuclear Energy

Joint IAEA-ICTP Workshop on the Physics and Technology of Innovative High Temperature Nuclear Energy Systems

Presentation Aim

To provide an overview of the evolution of nuclear power technology

Presentation Objectives

By the end of this session, participants should be able to:

- Recall the early history of nuclear physics
- Recall the early reactor developments
- Explain the four generations of reactors and their main differentiating factors
- Summarize the key design and safety features of reactors in operation today

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Early Reactor Development

Reactor ‘Generations’

Characteristics of reactors in operation

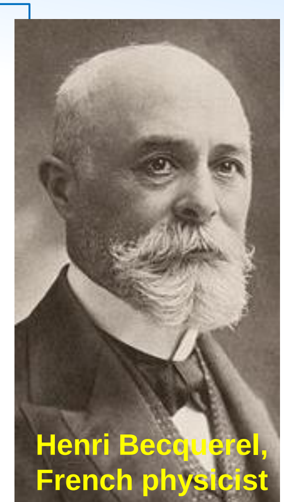
Briefly on NUCLEAR Discoveries…

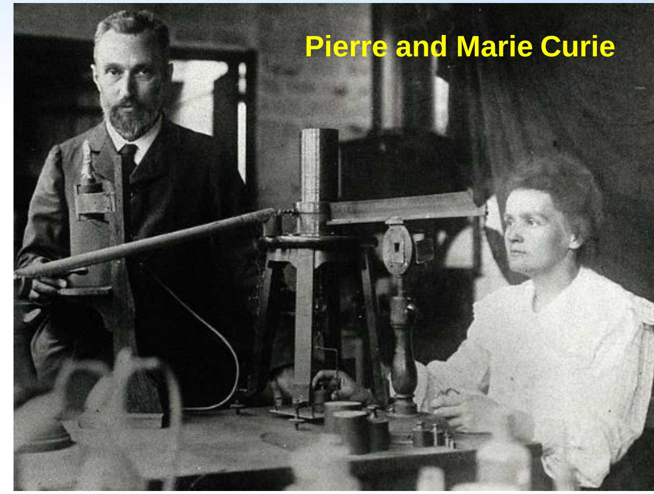
IAEA

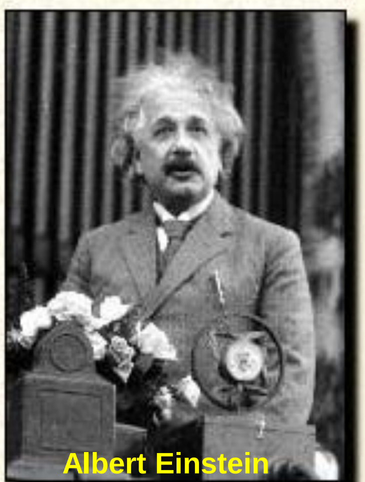
1896 - Antoine Henri Becquerel discovered radioactivity in uranium

1902 - Marie and Pierre Curie isolated a radioactive metal called radium

1905 - Albert Einstein published his theory of relativity. If somehow we could transform mass into energy, it would be possible to "liberate" huge amount of energy.



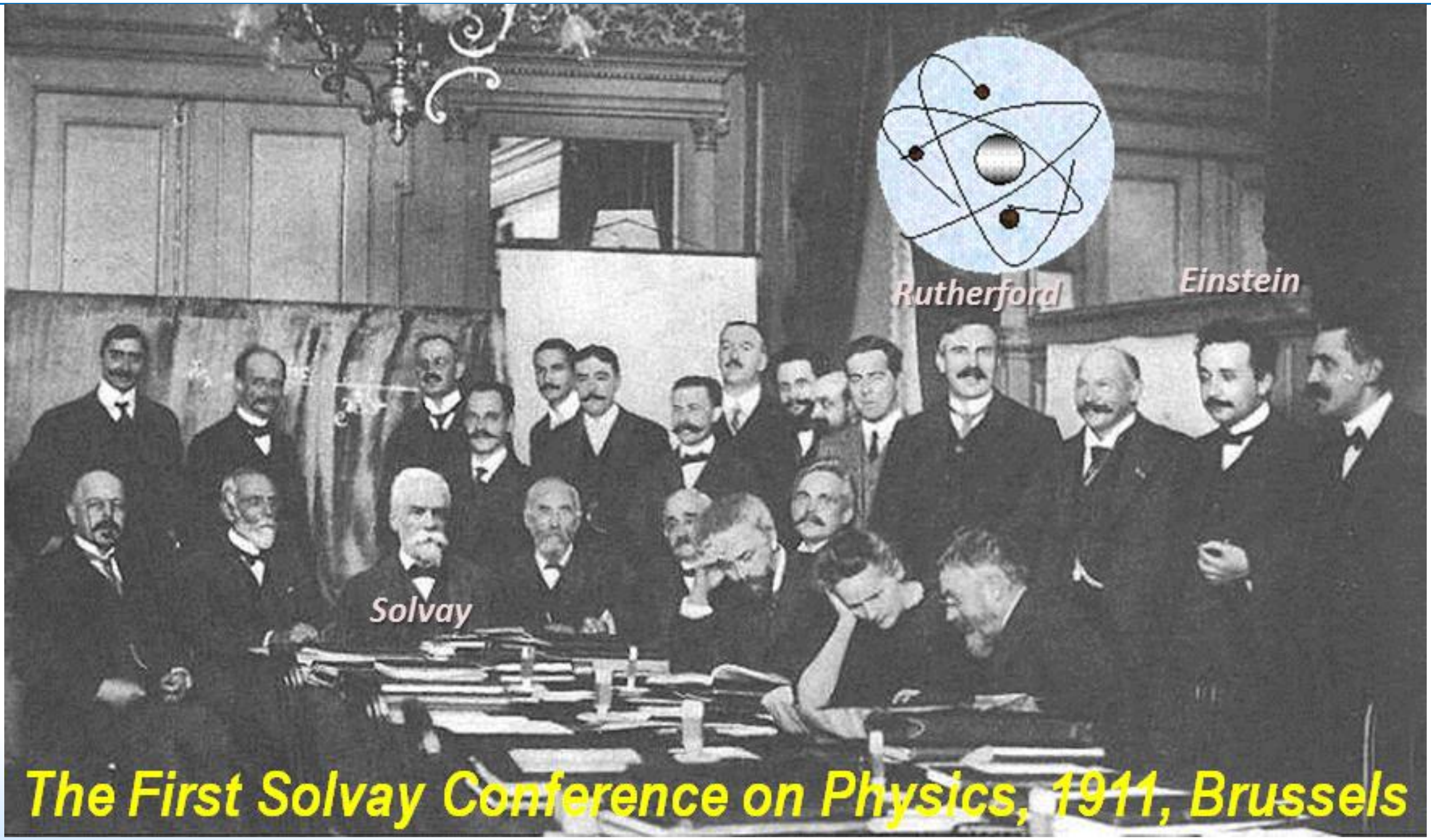




"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation E is equal to m c-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned above. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

Briefly on NUCLEAR Discoveries…

1911 – 20's - Ernest Rutherford and Niels Bohr described more precisely the structure of an atom.



Briefly on NUCLEAR Discoveries…

Fermi discovers nuclear fission

1934 – The Italian **Enrico Fermi** disintegrated heavy atoms by spraying them with neutrons. He didn't realise that he had achieved nuclear fission.

1938 - Otto Hahn and Fritz Strassman in Berlin did a similar experiment with uranium and were able to verify a world-shaking achievement.

- They had split an atom – *but did not understand the outcome of their experiments → **Lise Meitner** to coin the word "**nuclear fission**"*
- They had produced nuclear fission.
- They had transformed mass into energy→ E = mc2

33 years after Einstein had said it could be done.

Enrico Fermi (1901–1954)

Lise Meitner um 1946

Lise Meitner und Otto Hahn im Labor, Kaiser-Wilhelm-Institut für Chemie, 1913

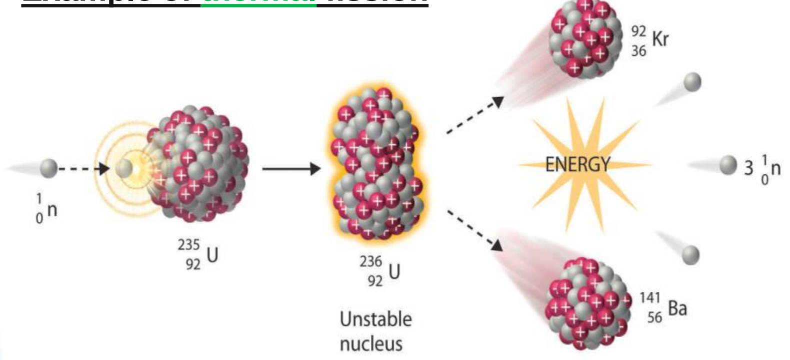
Neutron Induced Nuclear Fission

Fission is the splitting of something into smaller parts.

Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts (lighter nuclei) called fission products.

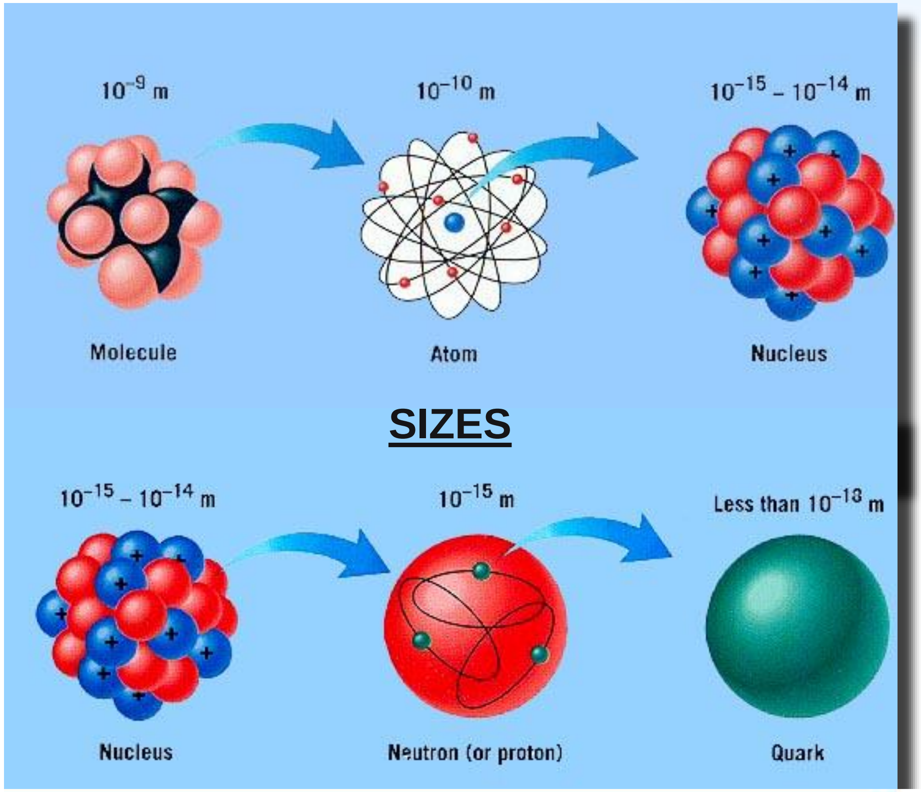
Often free neutrons and photons (in the form of gamma rays) are produced in addition to releazed energy, and split nuclei. These fission neutrons can then be utilised to induce still further fission neutrons, thereby causing a chain of fission events

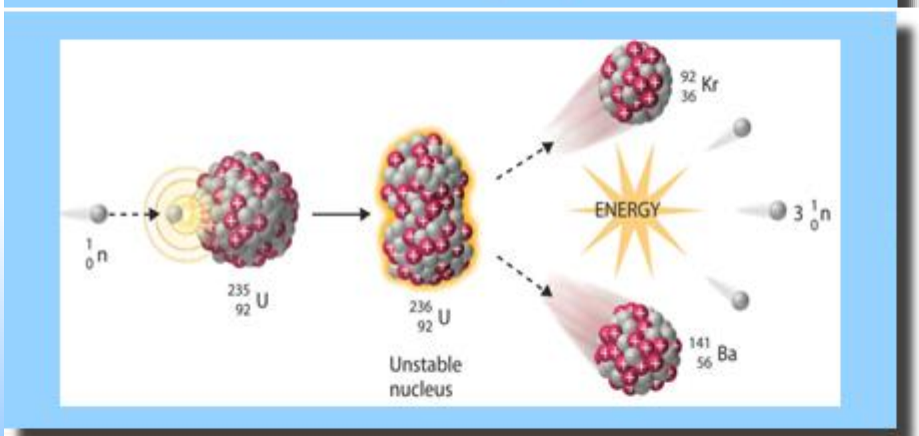
Example of thermal fission



Otto Hahn and Lize Majtner 1913

Neutron Induced Nuclear Fission





<u>Neutron is electrically neutral</u>

→Does not interact with electrons

→Interacts with the nucleus

<u>Nucleus is very small</u>

→Probability of neutron interaction is small

→Thus neutron travels long distances

Probability of neutrons interacting with nuclei defined as microscopic cross section

→ Neutron energy

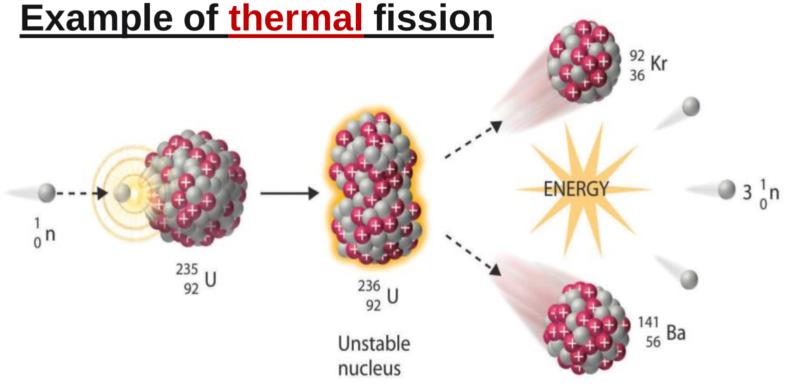
→ Type of a nucleus

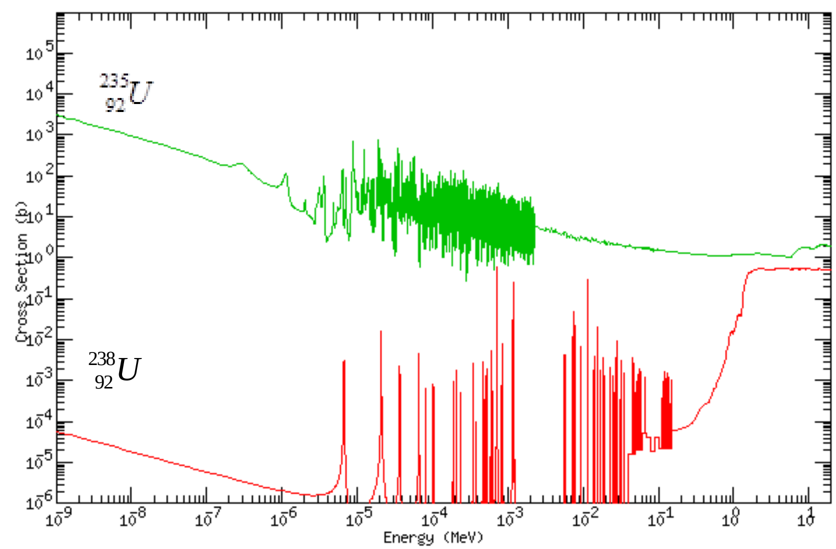
Fission occurs for nuclides above iron. Neutron is absorbed to form an unstable compound nucleus which the split / fission

For these nuclides, the Binding Energy increases (energy released) if a heavy nuclide splits (or fissions) to form two light ones.

Neutron Induced Thermal Nuclear Fission in Heavy Nuclei

Example of thermal fission





Microscopic cross sections (probability of neutrons inducing fission)

Neutrons created after fission are fast neutrons (high energy)

Thermal fission requires slow neutrons → moderator (light nuclei) required to slow fast neutrons

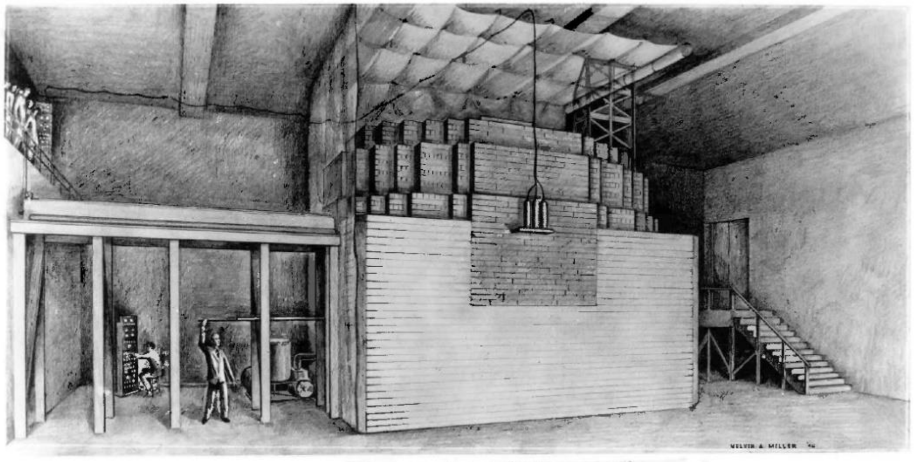
Fast fission requires fast neutrons → reactor excludes light nuclei in the core

Thermal Nuclear Reactors

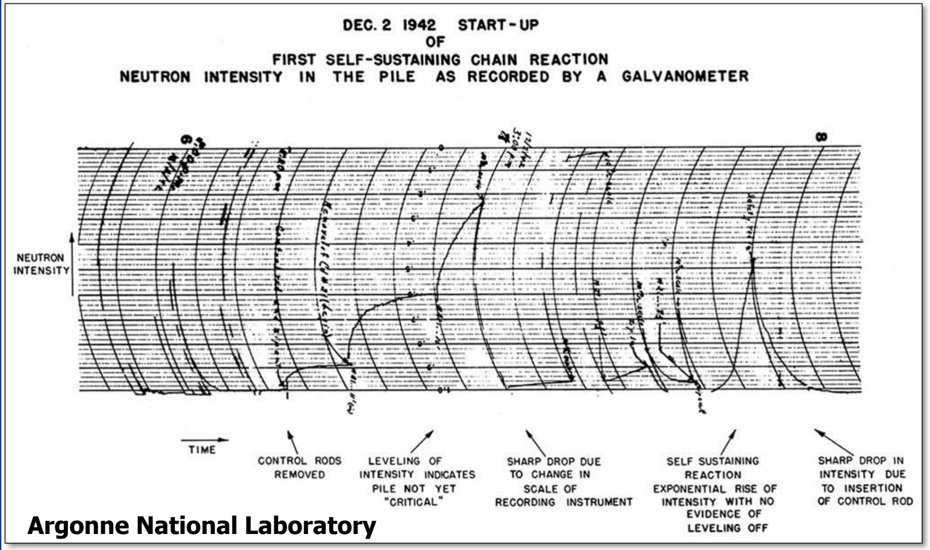
Fast Nuclear Reactors

Chicago Pile-1 Experiment led by Enrico Fermi

- Multiple options were explored as part of the Manhattan Project, one of which was the creation of a plutonium fission bomb. It was decided to attempt the construction of nuclear reactors for plutonium production.
- The first reactor consisted of stacked graphite blocks with uranium oxide cylinders (fuel) and cadmium sheets (control rods) inserted into holes in the graphite. This success was followed by the construction of additional experimental reactors.
- On December 2, 1942, Chicago Pile-1 reached criticality.



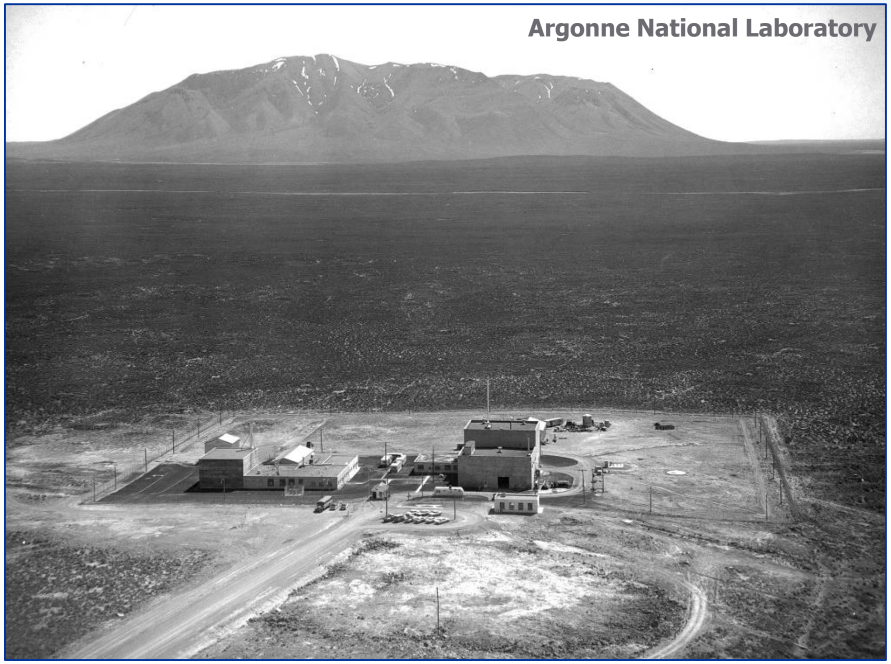
Argonne National Laboratory



Argonne National Laboratory

https://www.ne.anl.gov/About/reactors/early-reactors.shtml

Experimental Breeder Reactor I (EBR-1)



- EBR-1, the first liquid-metal cooled fast reactor, was built at Argonne National Laboratory–West (now Idaho National Laboratory) with the primary purpose of demonstrating breeding of fissile material.
- On December 20, 1951, EBR-1 generated the first usable electricity from nuclear energy to power a series of four lightbulbs. The reactor later supplied 200 kW to power its own building. Experiments in 1953 successfully demonstrated a breeding ratio >1.

https://www.ne.anl.gov/About/reactors/frt.shtml

The unfortunate introduction of the world to the power of the nucleus ...

The Manhattan Project

- August 2, 1939, Albert Einstein wrote a letter to the American President, Franklin D. Roosevelt that it should be possible to set up nuclear chain reactions in a large mass of uranium... lead to the construction of bombs... and urging him to begin a nuclear program without delay (an action he regretted deeply later)
- Roosevelt gave note that a atomic weapon should be investigated
- For the next six years scientists, engineers, generals, government officials joined hands in the Manhattan Project-a massive enterprise to produce an atomic bomb.
- The USA government spent more than $2 billion constructing a number of special research laboratories, hiring scientists and engineers, and building thirty-seven installations in nineteen states and Canada.

Dropping the bomb/The Second World War

- The development of the bomb continued and on August 6, 1945, the Enola Gay, an American airplane, dropped the first atomic bomb ever used in warfare on Hiroshima, Japan, eventually killing over 140,000 people.
- On August 9, 1945, the United States drops a second atomic bomb, this time on the Japanese city of Nagasaki. The drop is one mile off target, but it kills 75,000 people.

Unfortunately nuclear power must still operate under this cloud today

Early Civilian Use

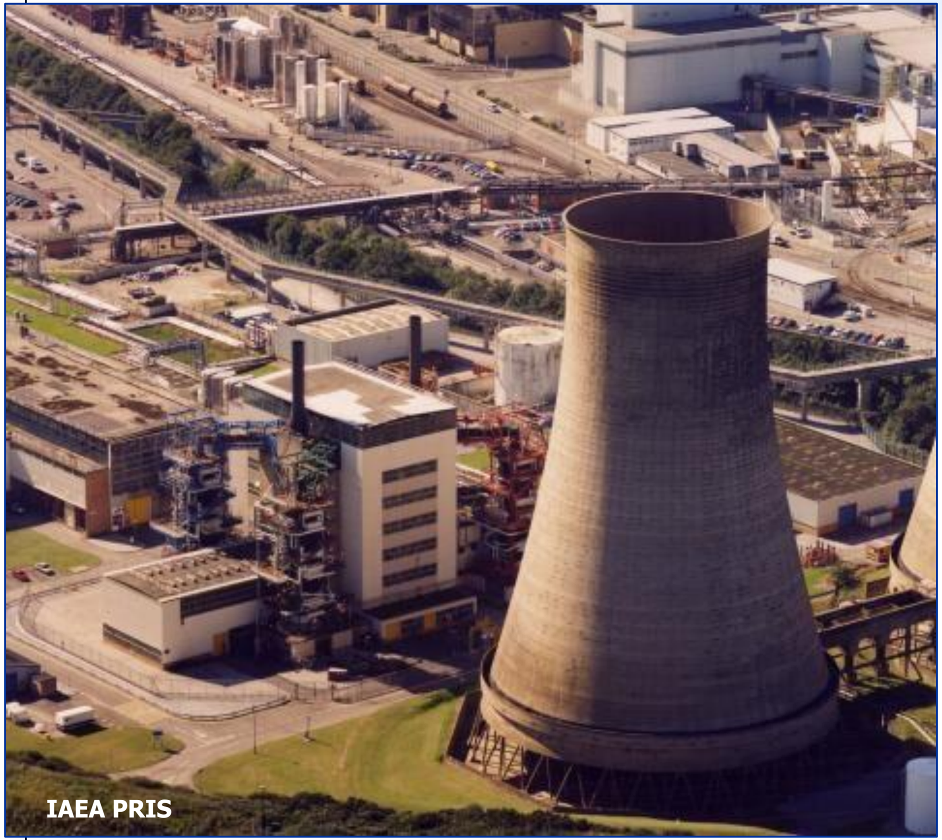
On June 27, 1954, AM-1 Obninsk Nuclear Power Plant in the Soviet Union became the first reactor connected to an electrical grid and supplied 5 MW of power.

BORAX-III, an experimental BWR, was constructed with a turbine generator in order to produce 2000 kW of electricity. On July 17, 1955, BORAX-III became the first nuclear reactor to generate electricity for an entire city by providing power to the reactor facilities and the nearby town of Arco, Idaho, USA (population ~1000).

https://www.ne.anl.gov/About/reactors/lwr3.shtml#fragment-3

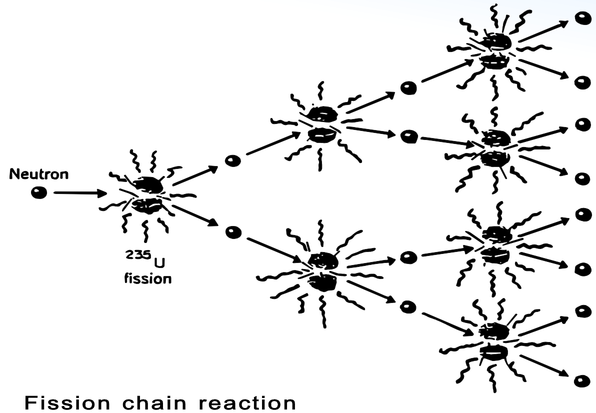
Commercial Power

- On August 27, 1956, Calder Hall Nuclear Power Station in the United Kingdom, consisting of four 60 MW magnox reactors (natural uranium fueled, graphite moderated, CO_2 gas-cooled), became the first industrial-scale power plant.
- In the following decades, hundreds of industrial-scale power plants of various designs and different materials were constructed in countries around the world.



Nuclear Power Plant Engineering

Nuclear Power Plant Engineering is the discipline that takes us from:

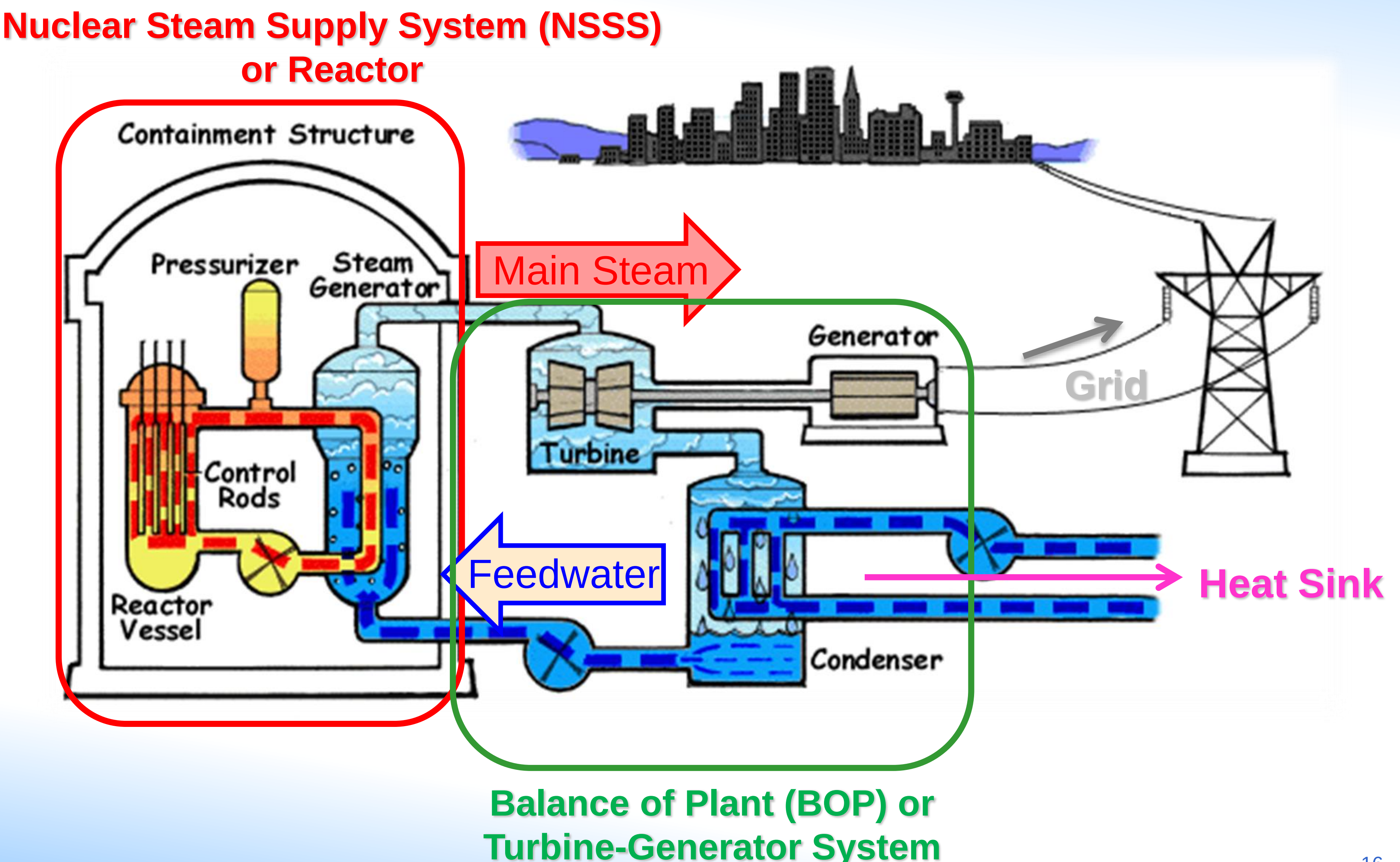


Fission chain reaction

to

The aim is to harness the energy released in the nuclear fission process in a safe and economical way, while containing the radioactive fission products and ensuring their isolation from the environment.

Typical Configuration of Nuclear Power Plants



IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Early Reactor Development

Reactor ‘Generations’

Characteristics of reactors in operation

Reactor Classification

- Reactors is typically classified by:
  - the energy range of the neutron contributing most to the fission process
  - it materials or specific conditions of the design
  - power conversion used
  - and more recently the generation or time of design of the reactor

Energy range

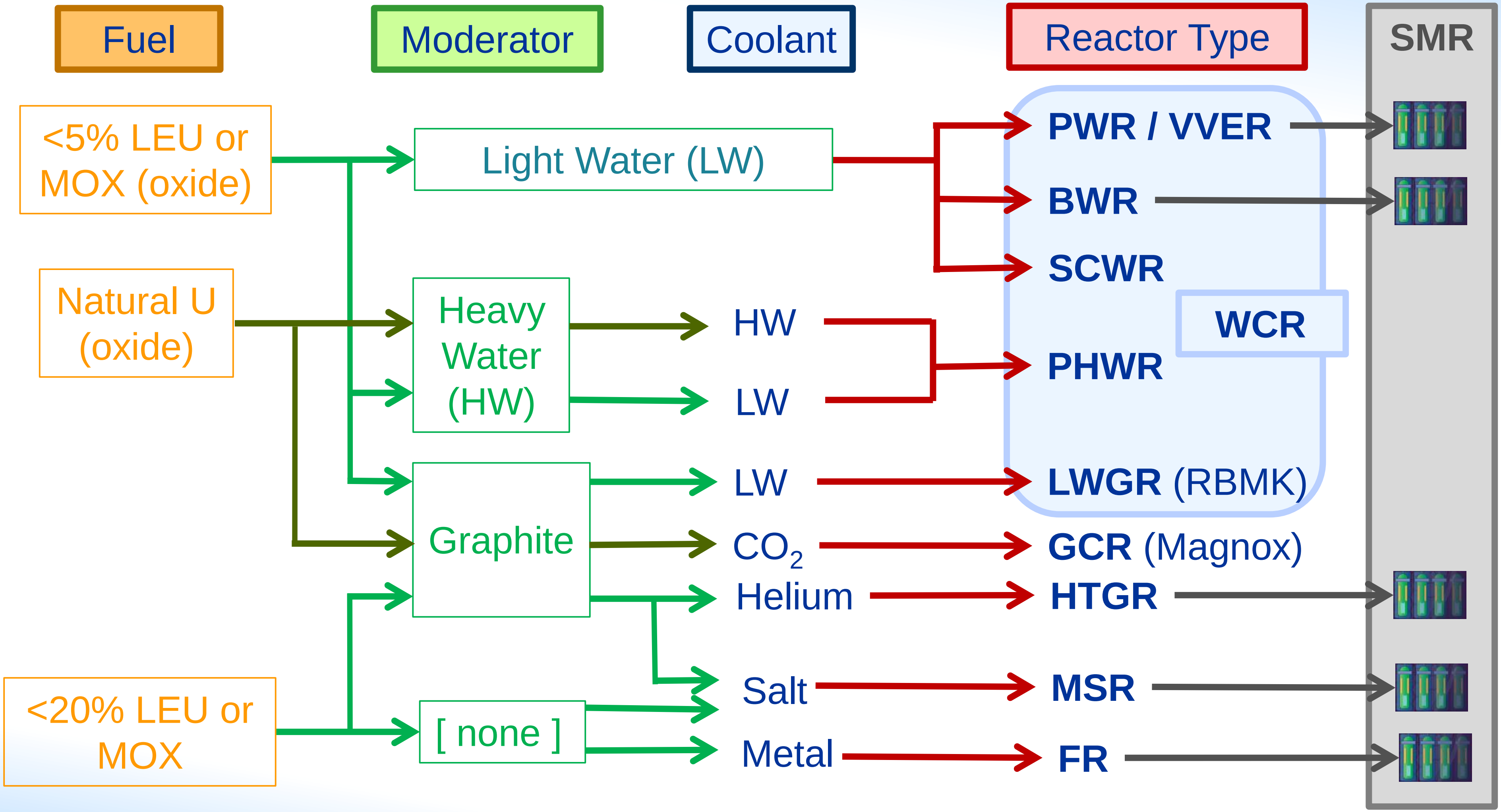
- Neutrons are classified as thermal, epithermal and fast by reactor physicists.
  - Thermal: E < 1 eV (often 0.625 eV is also used for LWRs)
  - Epithermal: 1eV < E < 50 kEV
  - Fast: 50 keV < E < 20MeV
- The light water reactors (PWRs, BWRs) are thermal since the fission caused by thermal neutrons are contributing just about all of the energy.
- These reactors typically have large cores and need to use slightly enriched U-235 with the slowing down of neutrons to thermal energy (moderation) caused by water.
- In a similar way fast reactors relies on fissions from fast neutrons.

Reactor Classification

Materials

- The coolant material (and state) is often use to name reactor types. The Pressurised Water Reactor (PWR - water coolant kept under pressure to prevent boiling) and Boiling Water Reactor (BWR - the water coolant is allowed to boil in the reactor to create steam to drive the turbine) is two common examples.
- The CANDU (Canadian Deuterium Uranium) is another example where use is made of natural uranium as fuel and deuterium playing the role of moderator and coolant.
- The gas-cooled reactors also typically include the term "gas-cooled" in its name even though the coolant (carbon-dioxide, helium) or the fuel (Magnox referring to the clad alloy, pebble-bed) may differ substantially.
- Some names use a combination of the material and neutron energy range such as the "liquid metal fast reactor“

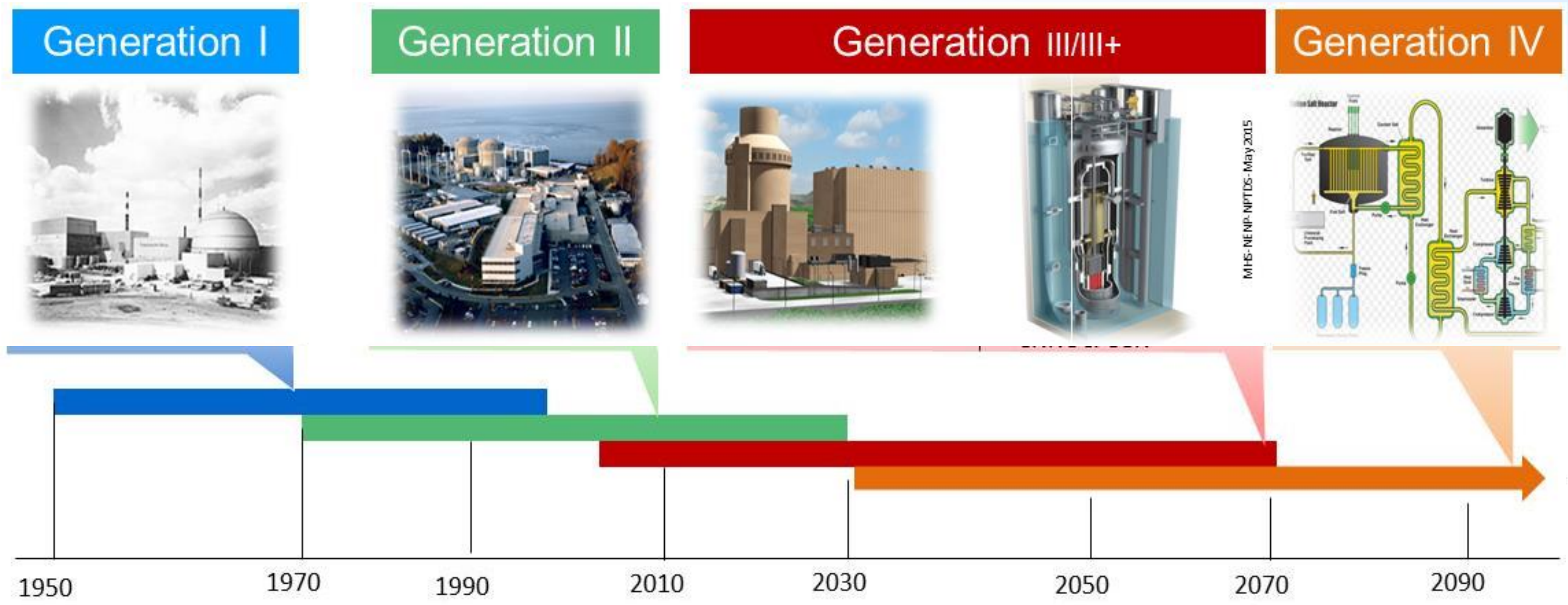
Illustration of Reactor Types



MOX: mixed-oxide containing any combination of U, Pu and Th oxides

FR includes SFR and LFR

Reactor Classification



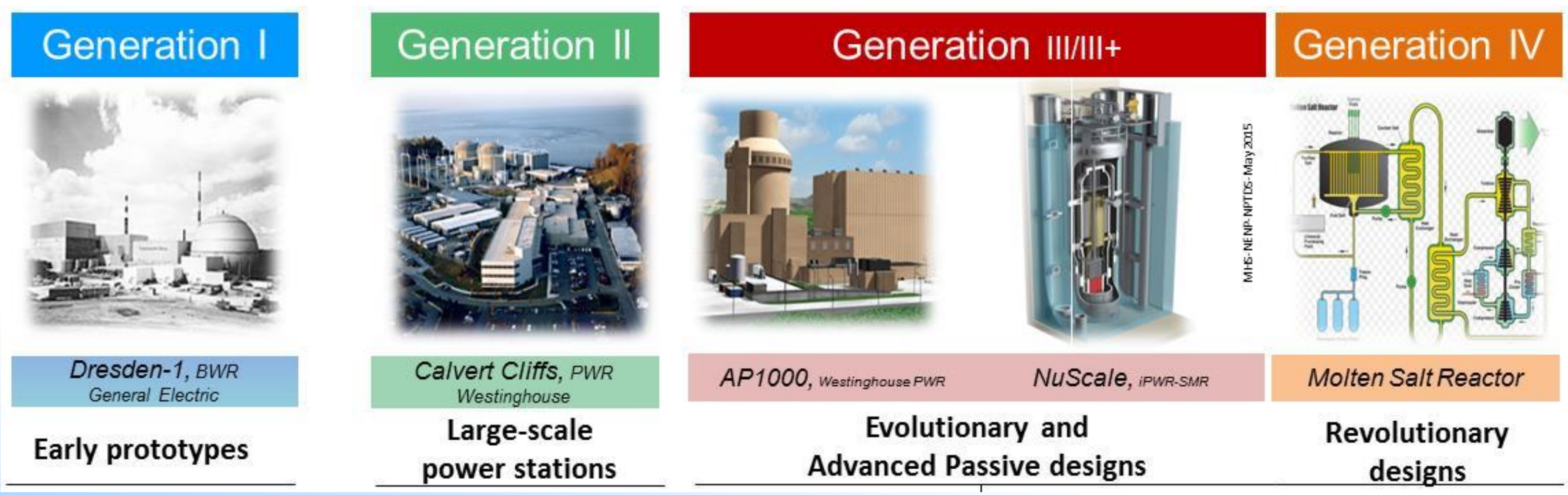
Time of development, IAEA terminology and common ‘generation’ scheme:

- Early prototype and demonstration plants (Generation I).
- Commercial Power Reactors (Generation II).
- Advanced reactors, may be ‘evolutionary’ (Generation III/III+) or ‘innovative’ (Generation IV).

Generation Differentiating Factors

The key factors characterizing the development and deployment of nuclear power reactors:

- Cost effectiveness
- Safety (notably active vs. passive systems)
- Security and non-proliferation
- Grid preparedness and adaptability
- Commercialization roadmap
- Fuel and fuel cycle



Reactor Deployment Timeline: Early Prototype Reactors

Early prototype reactors may or may not be full commercial scale and are intended to demonstrate:

- performance,
- reliability,
- safety systems,
- economics.

A demonstration plant will typically generate electrical power and/or process heat for industrial applications at some limited scale.

Early Prototype reactors provided the technical basis for the currently operating reactor fleet.

Generation I

Dresden-1, BWR
General Electric

Early prototypes

- **Calder Hall** GCR
- **Douglas Point** PHWR/CANDU
- **Dresden-1** BWR
- **Fermi-1** SFR
- **Kola 1-2** PWR/VVER
- **Peach Bottom 1** HTGR
- **Shippingport** PWR

Reactor Deployment Timeline: Commercial Power Reactors

Commercial power reactors use highly reliable reactor power plant designs, are built to full scale and intended solely for commercial use in the generation of electricity and/or process heat for industrial applications.

These commercial power reactors make up the majority portion of the currently operating reactor fleet.

Nuclear accidents in these commercial power reactors have motivated significant developments in safety.

Generation II

Calvert Cliffs, PWR
Westinghouse

Large-scale power stations

- **Bruce** (PHWR/CANDU)
- **Calvert Cliffs** (PWR)
- **Flamanville** 1-2 PWR
- **Fukushima** II 1-4 BWR
- **Grand Gulf** BWR
- **Kalinin** PWR/VVER
- **Kursk** 1-4 LWGR/RBMK
- **Palo Verde** PWR

Safety Argument – Generation of reactors

- Another definition used to define the minimum standards required for Generation-III (sometimes III+) is to show that it includes significant enhancements from the lessons learned from 3 major events:

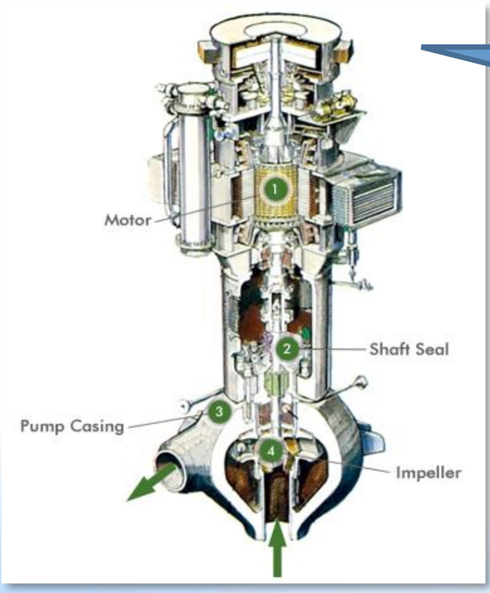
(1)	Three Miles Island (1979) Core meltdown accident	Limit the risk of a new Three miles Island to < 1 reactor over every 100 years all over the world from 1 every 10 years for Generation II
(2)	Chernobyl (1986) Dispersal of radioactive material	Eliminate the risk of experiencing consequences on populations similar to the Chernobyl disaster (especially limiting long term consequences)
(3)	9/11 (2001) Terrorist attack using a commercial aircraft	Ensure that a terrorist attack will not cause a severe accident in the context where more and more countries have access to the nuclear technology

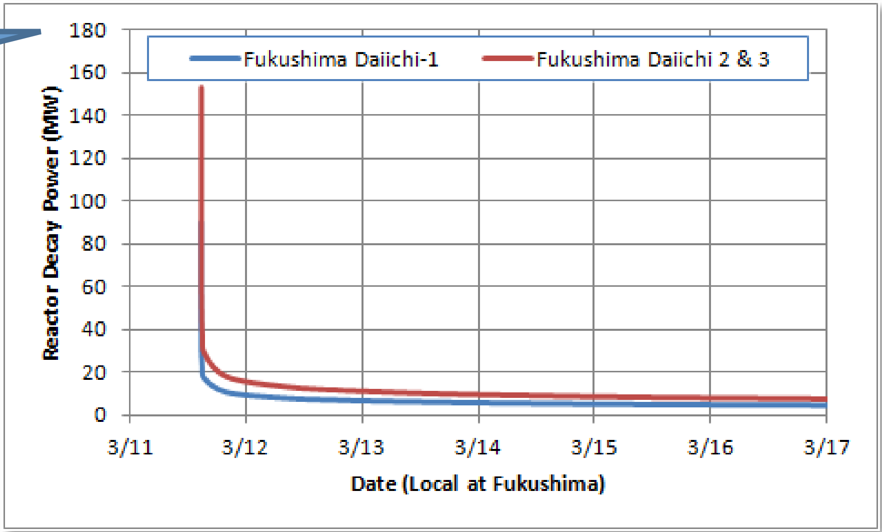
- The evaluation of designs (existing and Generation III+ and IV) against the extraordinary circumstances experienced after the earthquake and tsunami at the Fukushima site has started soon after the accidents (stress tests and design evaluations).

Important Safety Issues - WCRs

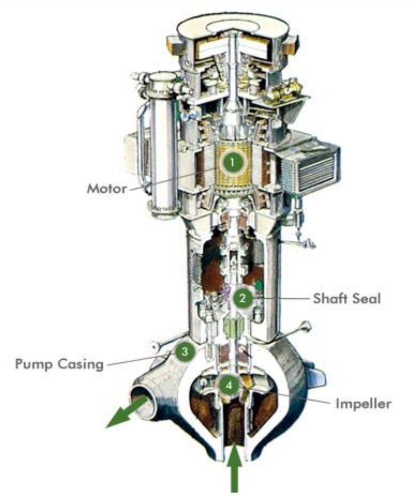
Managing Decay Heat

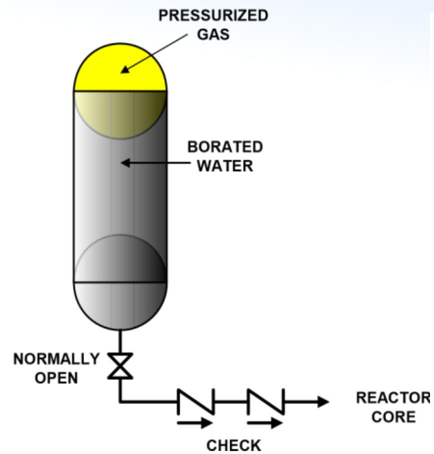
– Large WCRs have between 10-160 MW of decay heat that needs to be managed after the reactor shutdown (fission reactions stopped)
– Needs the water coolant to remove heat to prevent meltdown
– Historically, electrically driven pumps have been used to circulate coolant for decay heat removal – today also passive means

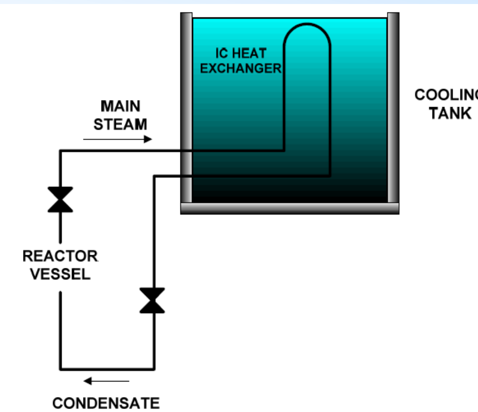




Safety Systems







Active Systems

- Widely used among current reactor fleet
- Electrically powered pumps
- Electrically operated valves
- Systems that **require operator action** or **external power sources** to function
- Back up diesel generators

Passive Systems

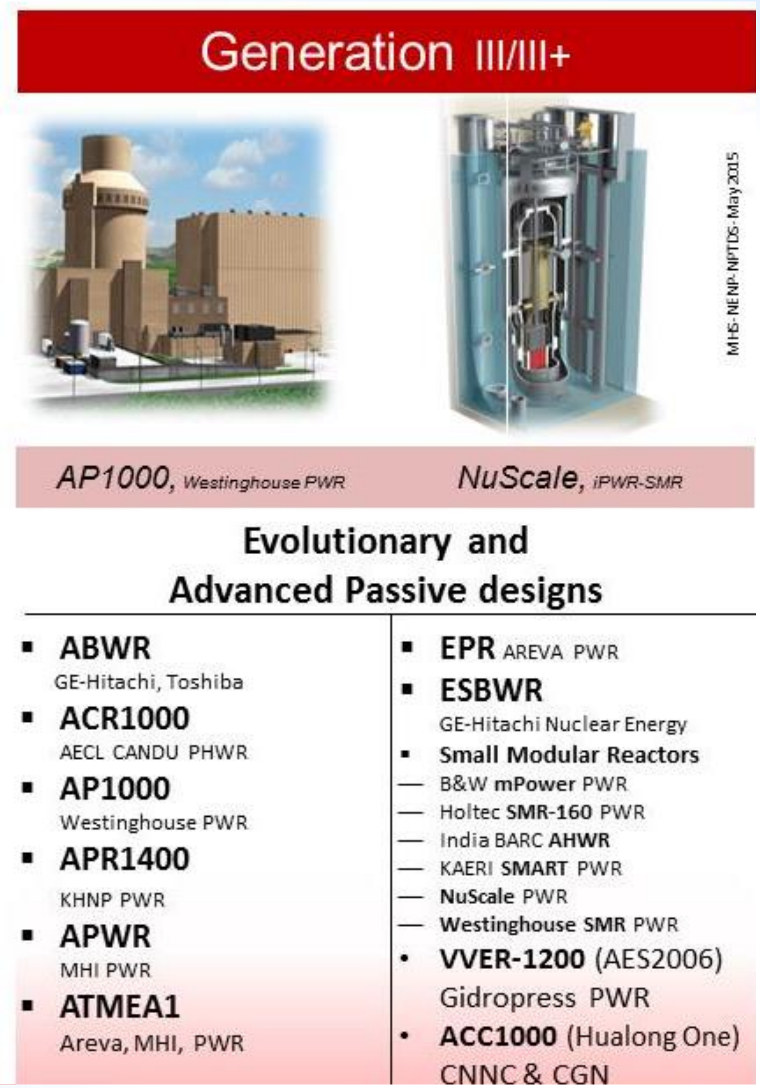
- Wholly or in part operated by **natural forces** such as gravity, pressure differences, phase changes or natural heat convection
- Require **limited or no operator action** to function
- Charged accumulators and valves that fail in safe-mode

Reactor Deployment Timeline: Advanced Reactors (Evolutionary)

Evolutionary reactors achieve improvements over previous designs through small to moderate modifications, and may, for example, include:

- Redundant systems
- Increased application of passive safety systems
- Significant improvements to containment

A few reactors are currently operating, with several more under construction.

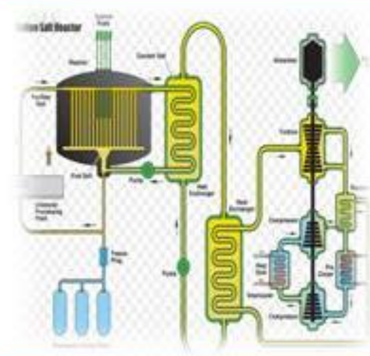


Reactor Deployment Timeline: Advanced Reactors (Innovative)

Innovative reactors incorporate radical conceptual changes from the currently operating reactor fleet and may require a prototype or demonstration plant before commercialization.

Many innovative reactor concepts utilize new materials or different neutron energy ranges from current reactors (as in GFR, LFR, MSR), while others operate in greatly different parameter ranges (as in SCWR, VHTR).

Generation IV



Molten Salt Reactor

Revolutionary designs

- **GFR** Gas-cooled Fast reactor
- **LFR** Lead-cooled fast reactor
- **MSR** Molten salt reactor
- **SFR** Sodium-cooled fast reactor
- **SCWR** Supercritical water cooled reactor
- **VHTR** Very high temperature reactor

Where to Find the Most Up-to-Date Information about Nuclear Power Reactors?

IAEA | PRIS Power Reactor Information System

World Statistics | Country Statistics | Publications | Glossary | About PRIS

PRIS

The Database on Nuclear Power Reactors

The Power Reactor Information System (PRIS), developed and maintained by the IAEA for over five decades, is a comprehensive database focusing on nuclear power plants worldwide. PRIS contains information on power reactors in operation, under construction, or those being... READ MORE »

Registered User ENTRY | How to Register

SHORTCUTS

Select Country

Select Reactor

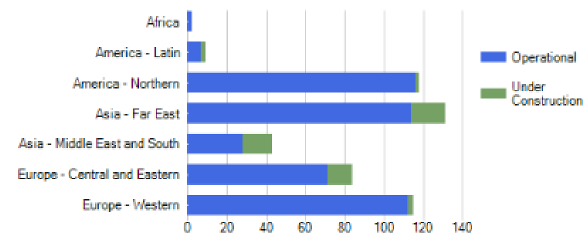
- 2019: Nuclear Power Reactors in the...
- 2018: Operating Experience with NPP...
- PRIS STATISTICS – User's Manual

OVERVIEW

Current Status:

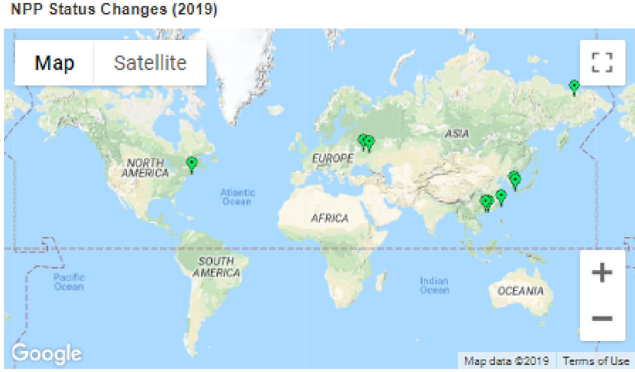
450	NUCLEAR POWER REACTORS IN OPERATION
399 706	MW_e TOTAL NET INSTALLED CAPACITY
52	NUCLEAR POWER REACTORS UNDER CONSTRUCTION
52 704	MW_e TOTAL NET INSTALLED CAPACITY
18 146	REACTOR-YEARS OF OPERATION

Regional Distribution of Nuclear Power Plants (Click on the chart for more statistics)



HIGHLIGHTS

NPP Status Changes (2019)



Year: 2019

New connections to the grid	
NOVOVORONEZH 2-2	(1114 MW(e), PWR, RUSSIA) on 1 May
SHIN-KORI-4	(1340 MW(e), PWR, KOREA,REP.OF) on 22 April
TAISHAN-2	(1660 MW(e), PWR, CHINA) on 23 June
YANGJIANG-6	(1000 MW(e), PWR, CHINA) on 29 June
Permanent shutdowns	
BILIBINO-1	(11 MW(e), LWGR, RUSSIA) on 14 January
CHINSHAN-2	(604 MW(e), BWR, TAIWAN,CHINA) on 16 July
GENKAI-2	(529 MW(e), PWR, JAPAN) on 9 April
PILGRIM-1	(677 MW(e), BWR, USA) on 31 May
Construction starts	
KURSK 2-2	(1115 MW(e), PWR, RUSSIA) on 15 April

Status Change Trends

Construction Starts | First Grid Connections | Permanent Shutdown

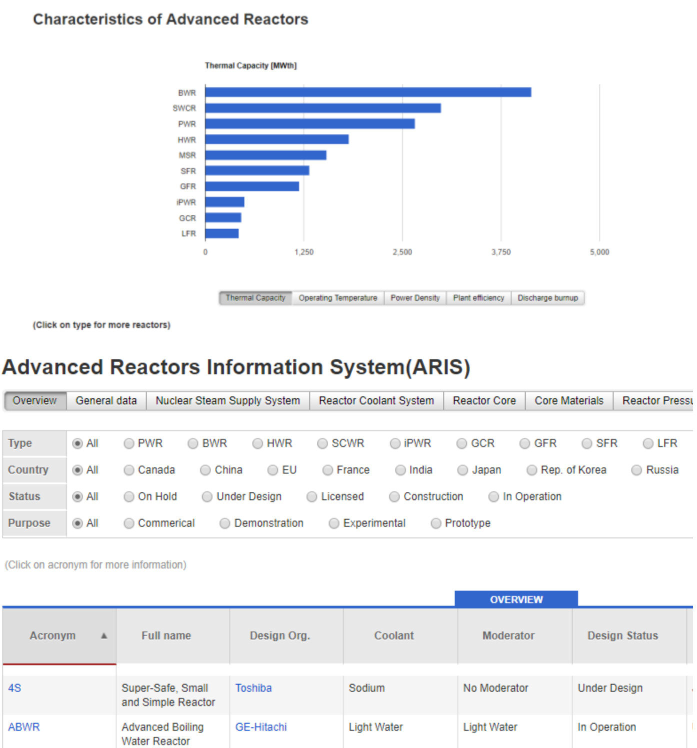
Above data are from the PRIS database. Last update on 2019-08-18

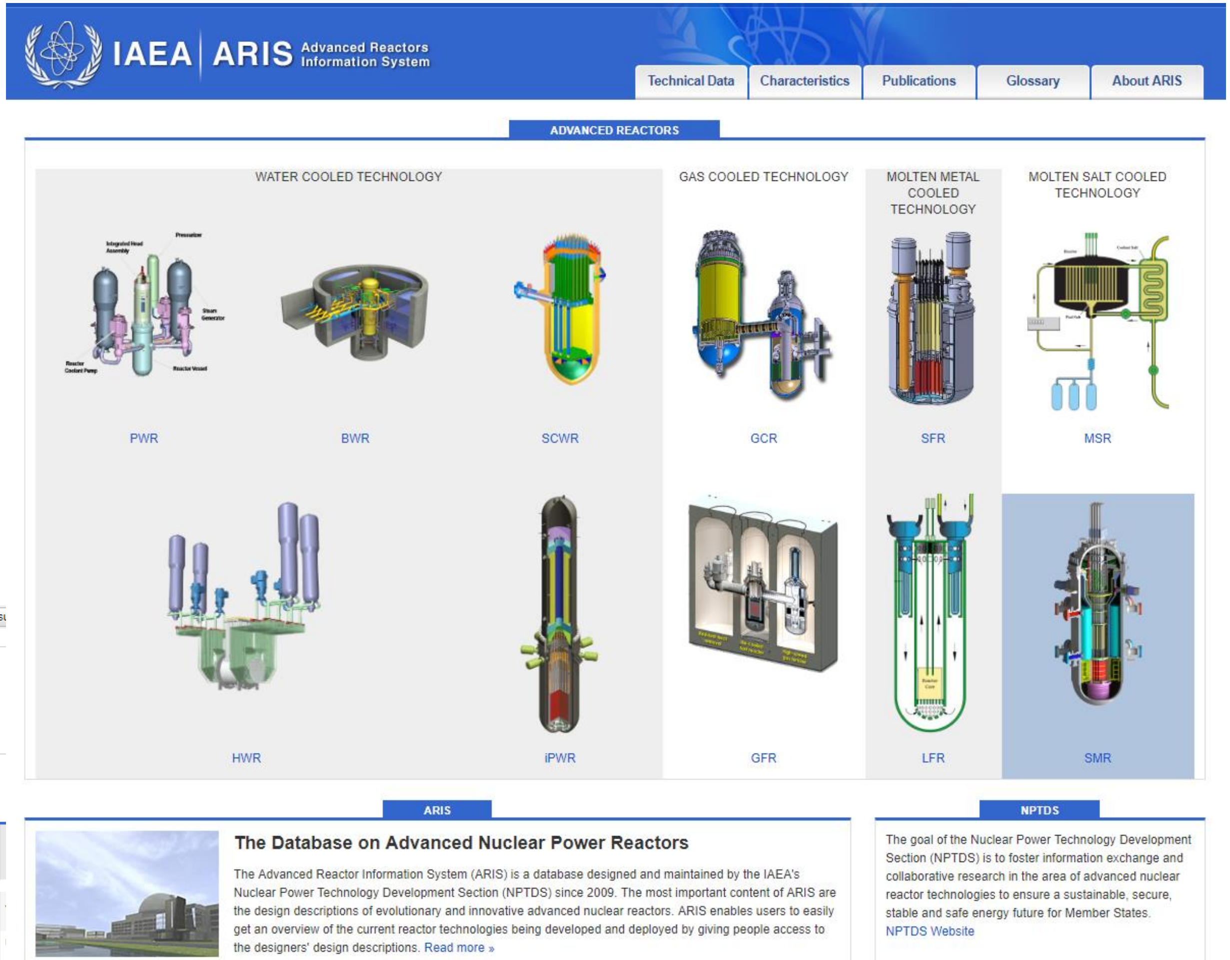
ARIS - Advanced Reactors Information System

IAEA

Database

ARIS enables users to easily get an overview of the current reactor technologies being developed and deployed by giving people access to the designers' design descriptions





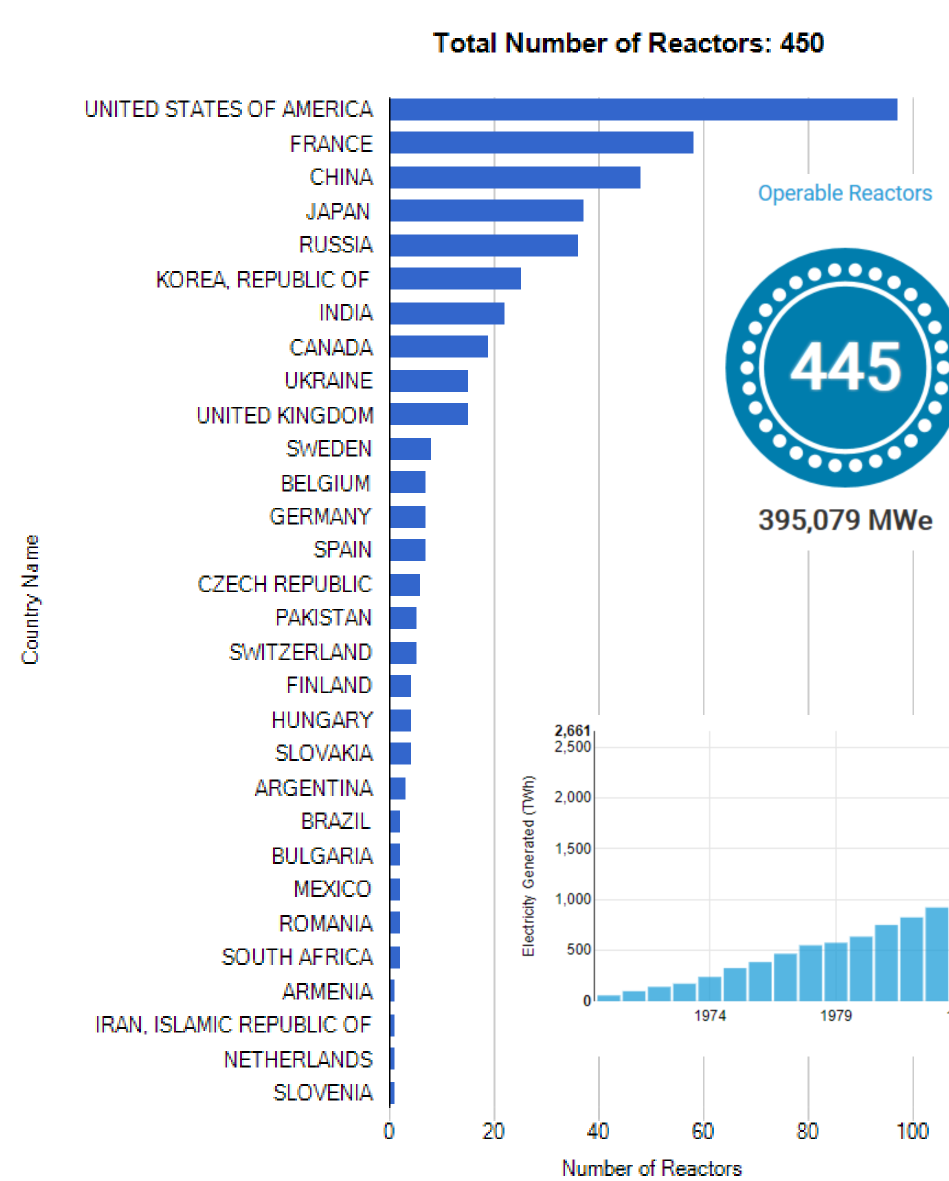
IAEA
International Atomic Energy Agency
Atoms for Peace and Development

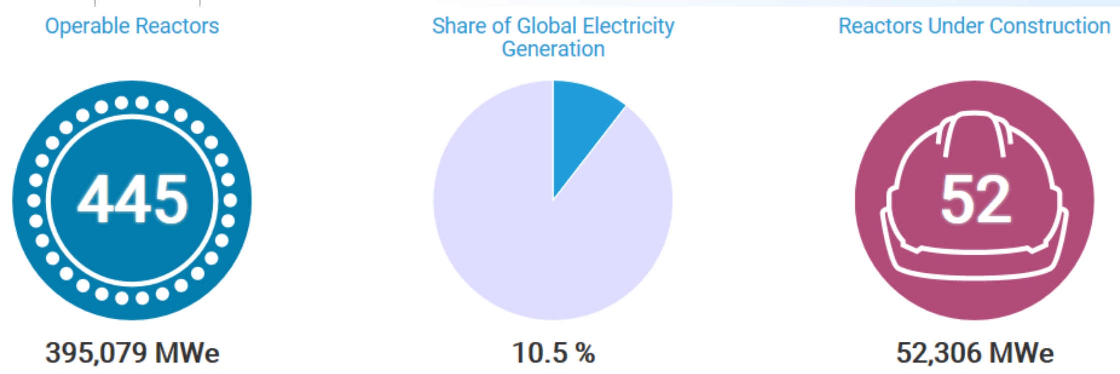
Early Reactor Development

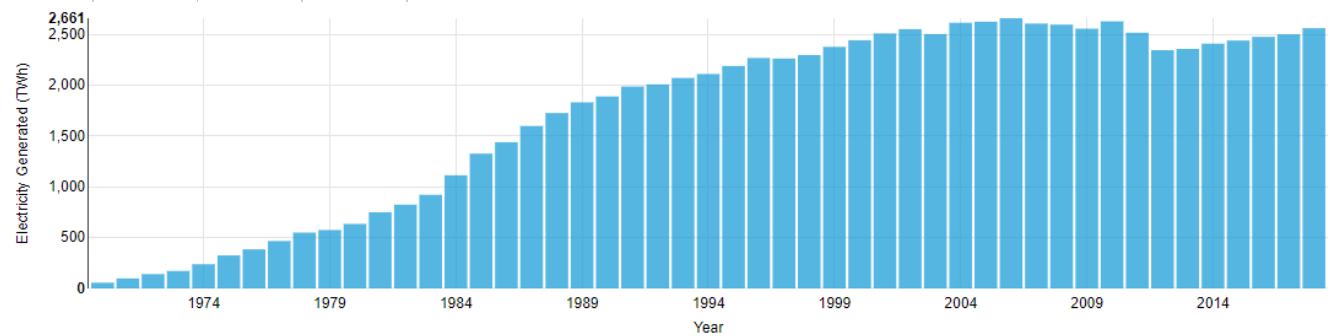
Reactor ‘Generations’

Characteristics of reactors in operation

Nuclear Power in the World: *Today*





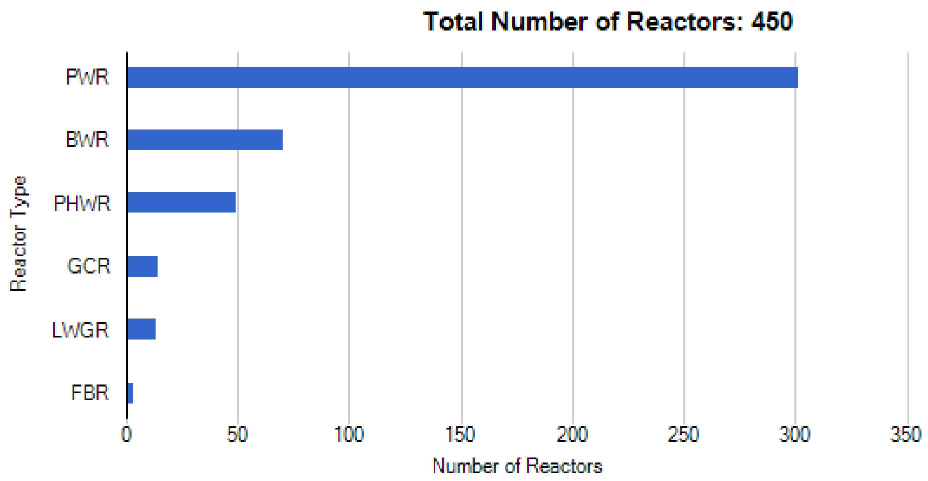


2,563 TWh: global electricity generation from nuclear energy in 2018

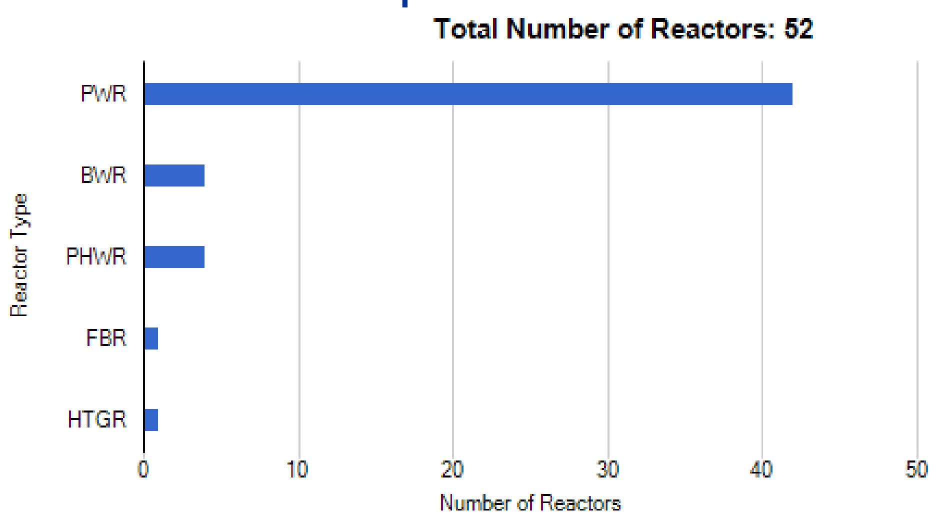
Sources: IAEA PRIS Database (update on 2019-08-19) https://www.iaea.org/PRIS/home.aspx
World Nuclear Association http://www.world-nuclear.org/information-library/facts-and-figures/reactor-database.aspx

NPPs Today

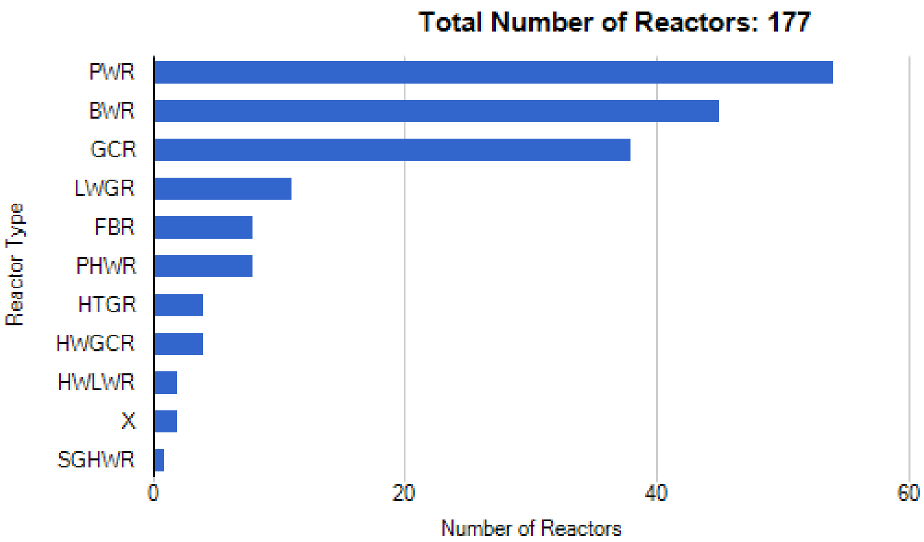
Operating power reactors



Under construction power reactors



Permanent shutdown power reactors



Source: IAEA PRIS Database (update on 2019-08-19) https://www.iaea.org/PRIS/home.aspx

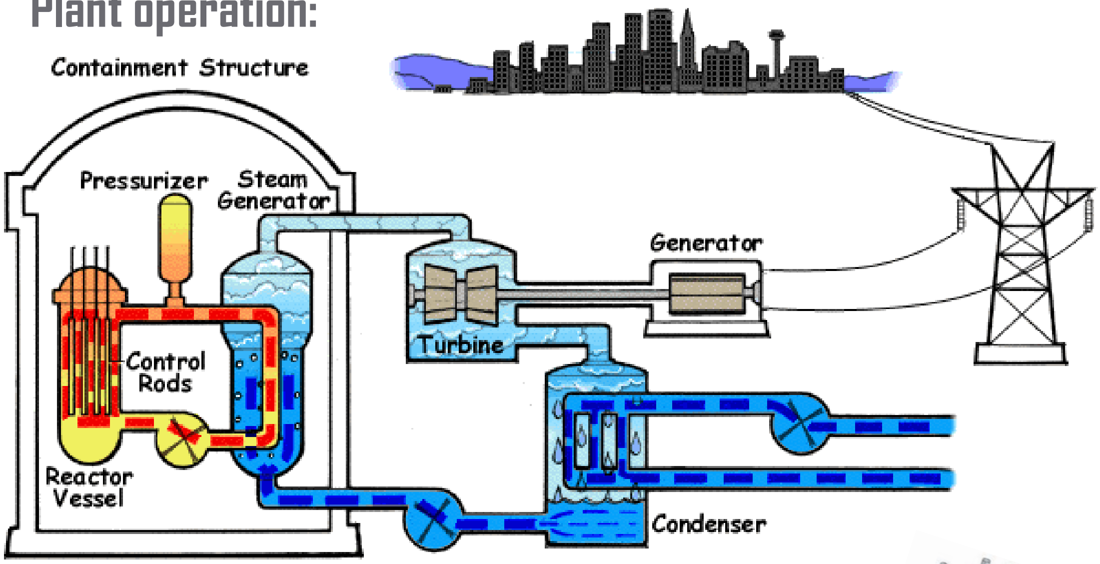
Main reactor designs relevant to power generation (past and today in operation)

- The Pressurized Water Reactor (PWR)
- The VVER design
- The Boiling Water Reactor (BWR)
- The CANDU design
- The RBMK design
- Gas cooled reactors

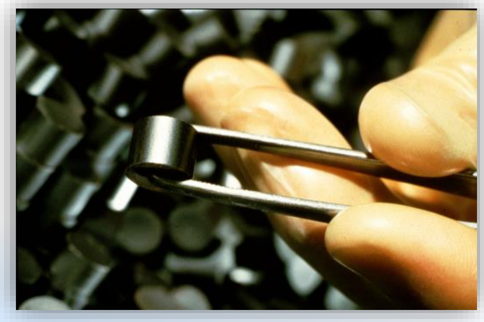
- Operating fast reactors covered as part of Generation-IV

PWR Technology

Plant operation:

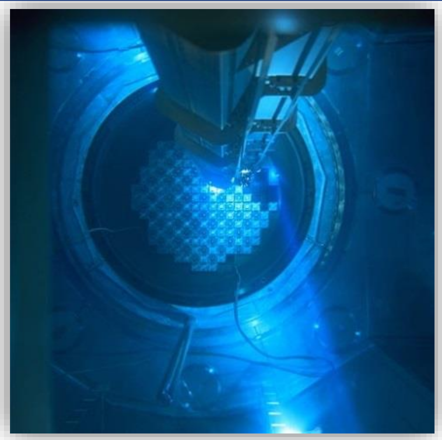


- **Most common** thermal reactor technology
- Moderator: **light water**
  Important safety feature (increase in temperature causes water to "expand" reducing probability of neutron thermalization which reduces new fissions thus reduces reactivity (called negative temperature coefficient of reactivity)
- Coolant: **light water**
  Primary loop: coolant is under ~ 15.5MPa (water remains liquid despite high temperature)

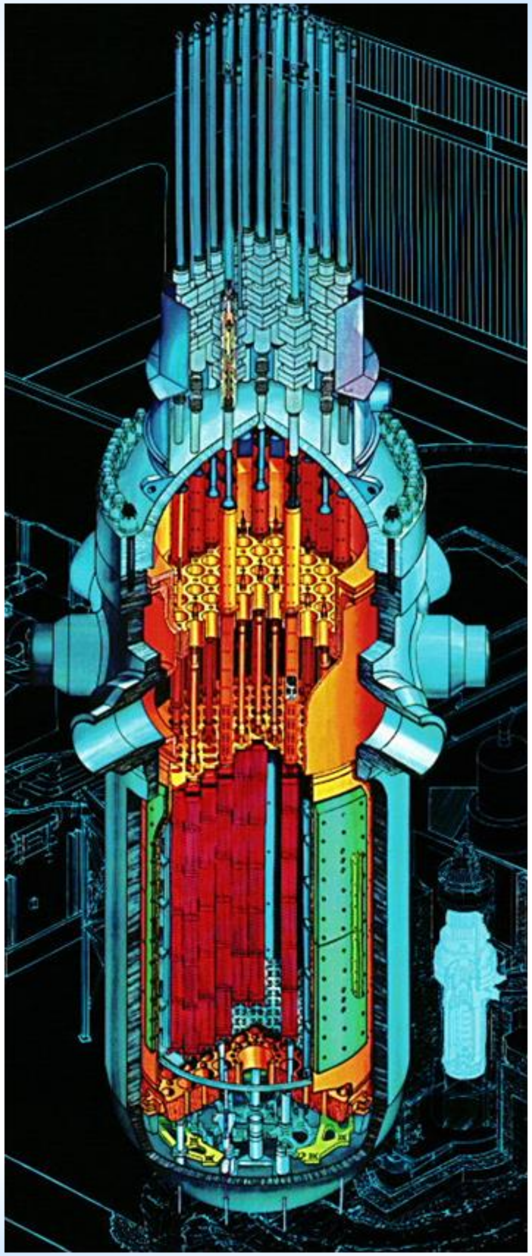


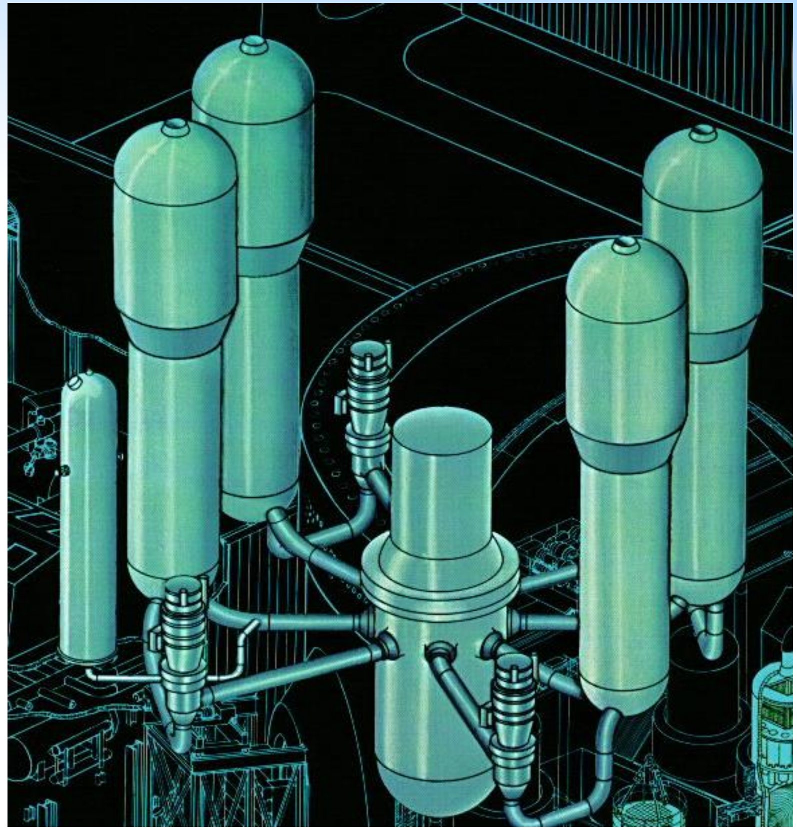
Fuel pellet (enriched UO_2)

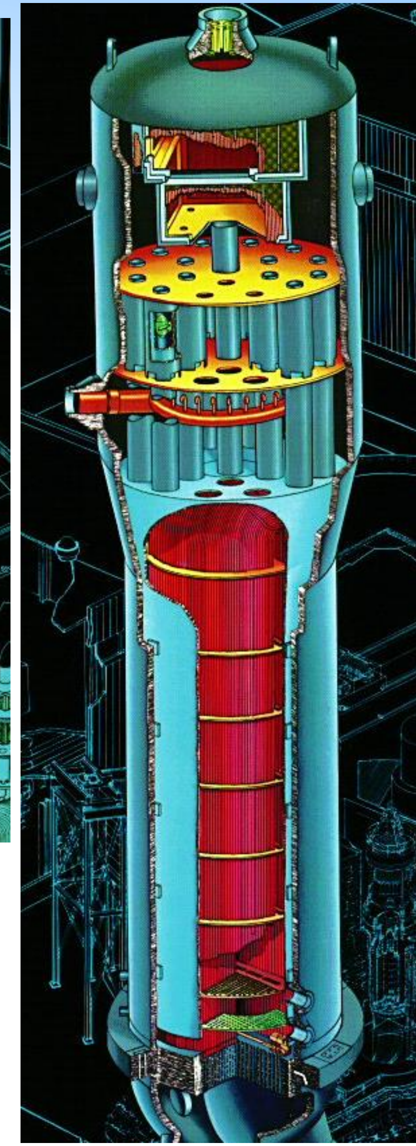
Fuel assembly

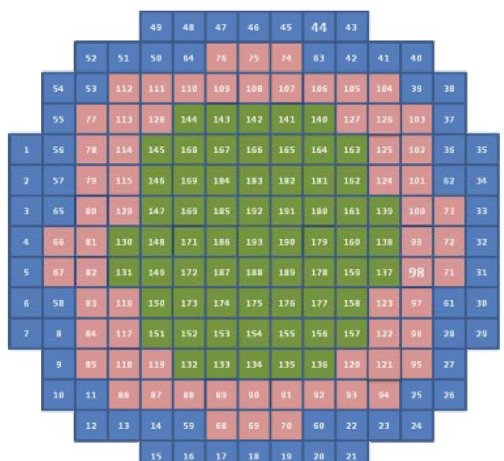


Reactor core





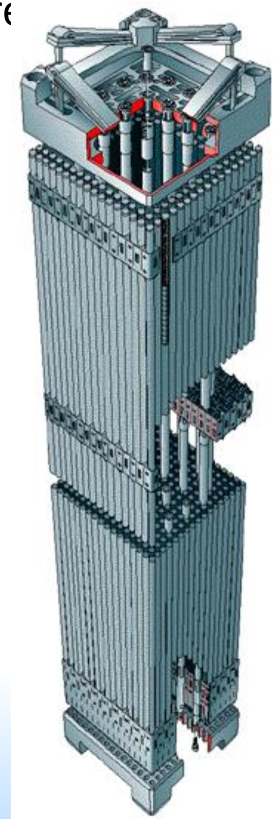


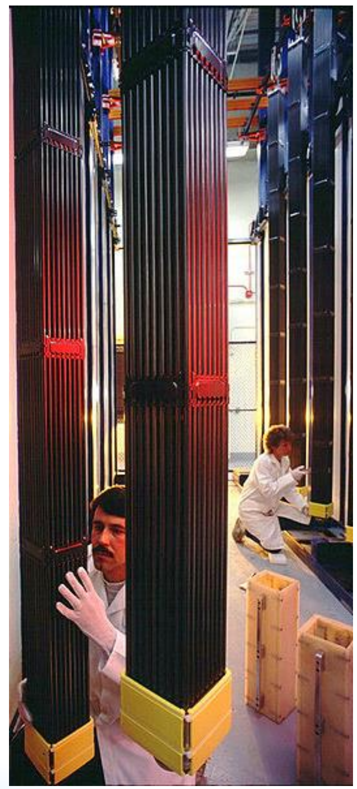

49 48 47 46 45 44 43
52 51 50 64 76 75 74 63 42 41 40
54 53 112 111 110 109 108 107 106 105 104 39 38
55 77 113 128 144 143 142 141 140 127 126 103 37
1 56 78 114 145 168 167 166 165 164 163 125 102 36 35
2 57 79 115 146 169 184 183 182 181 162 124 101 62 34
3 65 80 129 147 169 185 192 191 180 161 139 100 73 33
4 66 81 130 148 171 186 193 190 179 160 138 99 72 32
5 67 82 131 149 172 187 188 189 178 159 137 98 71 31
6 58 83 116 150 173 174 175 176 177 158 123 97 61 30
7 8 84 117 151 152 153 154 155 156 157 122 96 28 29
9 85 118 119 132 133 134 135 136 120 121 95 27
10 11 86 87 88 89 90 91 92 93 94 25 26
12 13 14 59 68 69 70 60 22 23 24
15 16 17 18 19 20 21

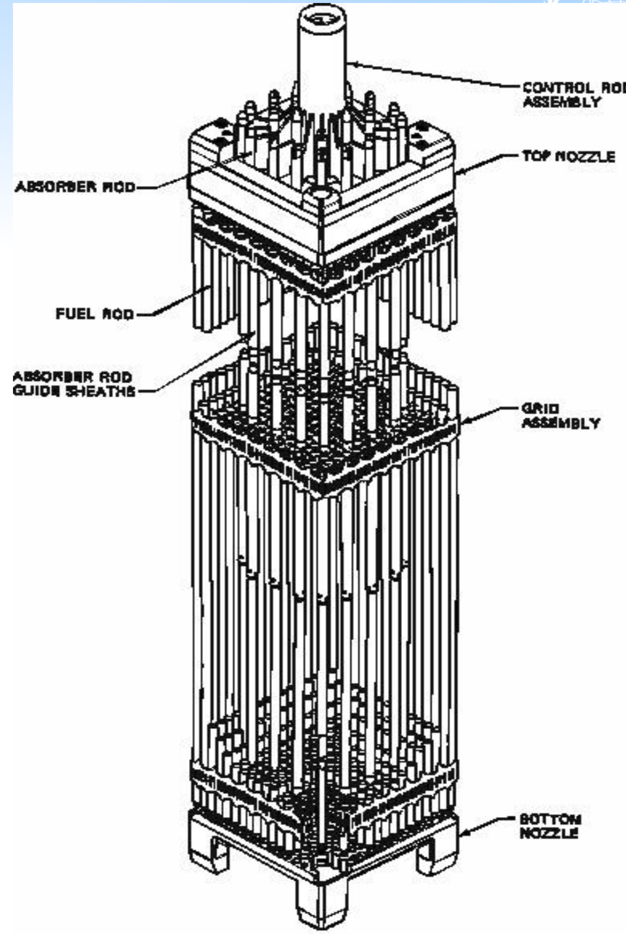
PWR fuel

PWR Fuel Element

- The PWR fuel element is about 3.6 m in height and has a square radial dimension of 21.4 cm. The fuel rod (pin) locations are on a 1.26 cm pitch and are arranged in a 17x17 array. This implies that there are in excess of 45 000 pin locations in a typical PWR core





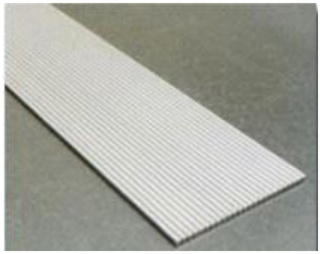


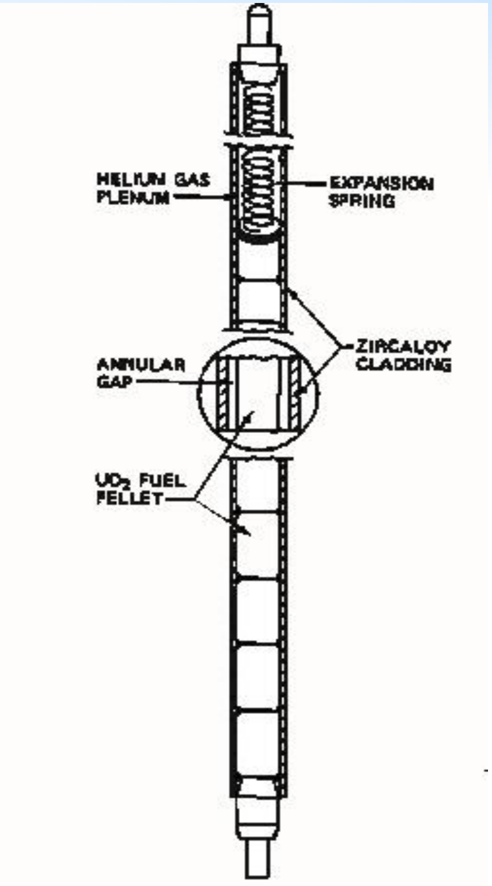
Fuel and control rod assembly of a PWR (Westinghouse Electric Corp.).

PWR fuel

PWR Fuel Rod

- A typical fuel rod may have an outside diameter of 0.94 cm, a cladding thickness of 0.0572 cm, a pellet diameter of 0.819 cm and a pellet-cladding gap of 0.0082 cm. Fuel enrichments are 1.8%, 2.4%, 3.1% and 3.25% at start-up and initial cycles.



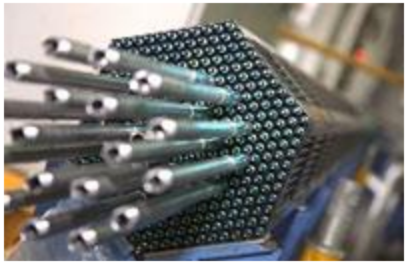


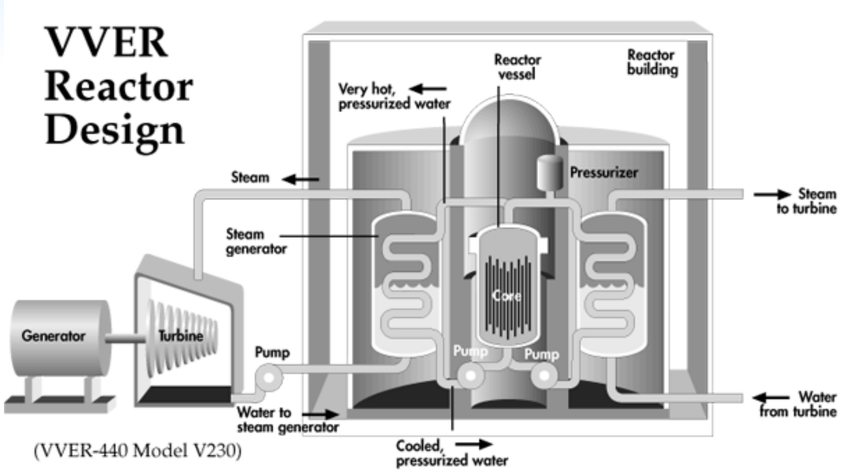
Uranium dioxide fuel rod

- UO2 pellets are loaded into a Zircaloy-tube. Then a pellet-hold-down spring is inserted from one end, and end plugs are pressed into place at both ends. Top and bottom end plugs are alternately welded to the fuel tube. Helium gas is pressurized through a vent hole in the top end plug and the vent hole is then seal-welded.

The VVER design

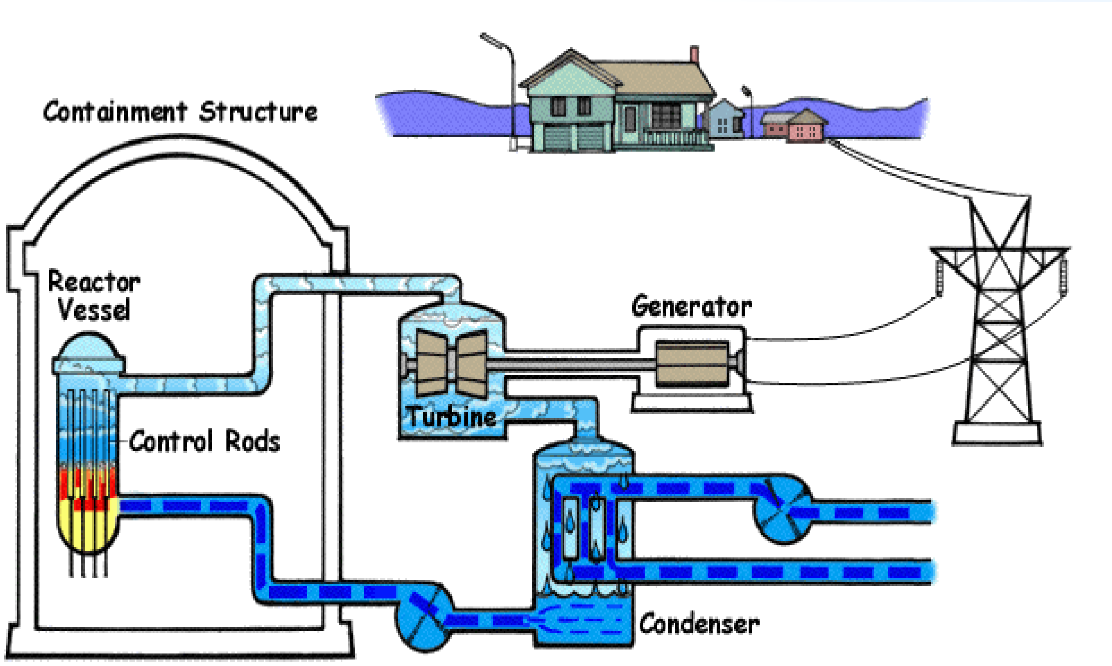
- The VVER is the Russian version of the Pressurised Water Reactor (PWR).
- Fuel different with hexagonal pitch

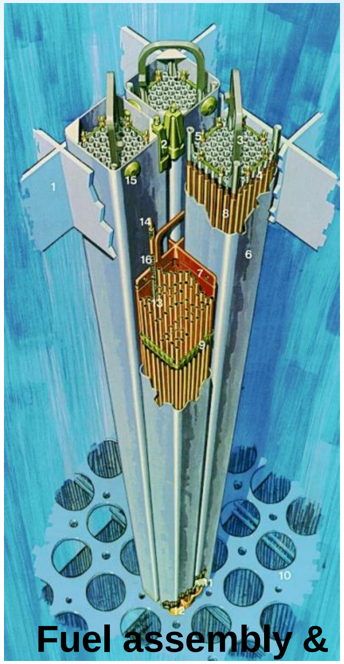




- A major difference between western designed PWRs and the VVERs is that the latter have horizontal steam generators. The older VVERs have isolation valves in the reactor coolant loops and accident localisation compartments.
- Water passing on the outside of the steam generator tubes is heated and converted to steam. The steam passes to the Turbine as in the Pressurised Water Reactor. The Turbine drives the Generator similar to the Pressurised Water Reactor plants. Steam in the VVER design is not expected to be radioactive.
- The older VVER 440 design includes accident localisation zones and a confinement rather than a true containment. Loviisa 1 and 2 are the exceptions which do have the western-style containment. The VVER 1000 has a traditional containment.

BWR Technology



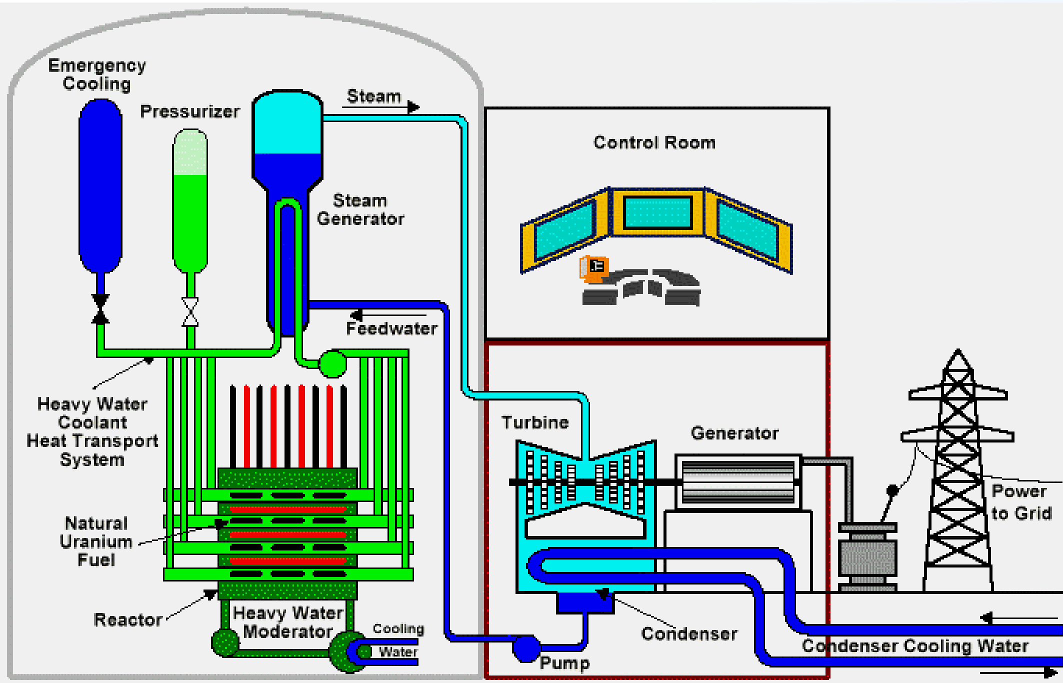


Fuel assembly & Cruciform control rods

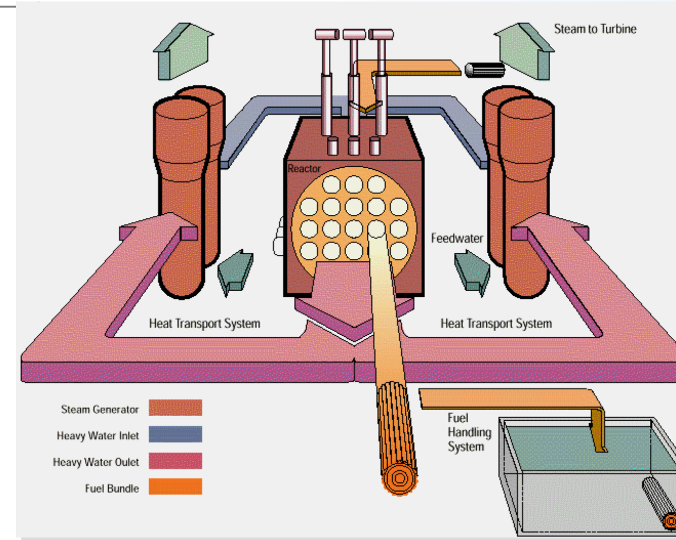
- Second most common power reactor type
- Water: coolant & moderator
- Fission generates heat that causes cooling water to boil producing steam
- Steam separators in the upper part of the reactor remove water from the steam
- Steam drives the turbines directly: direct-cycle
- Cooling water is at low pressure, ~ 7.6 Mpa (it boils in the core at ~ 285 C)
- The Control Rods, used to shutdown the reactor and maintain an uniform power distribution across the reactor, are inserted from the bottom by a high pressure hydraulically operated system

Pressurized Heavy Water Reactor (PHWR)

…also known as CANDU



- Better neutron economy
- On-line refuelling



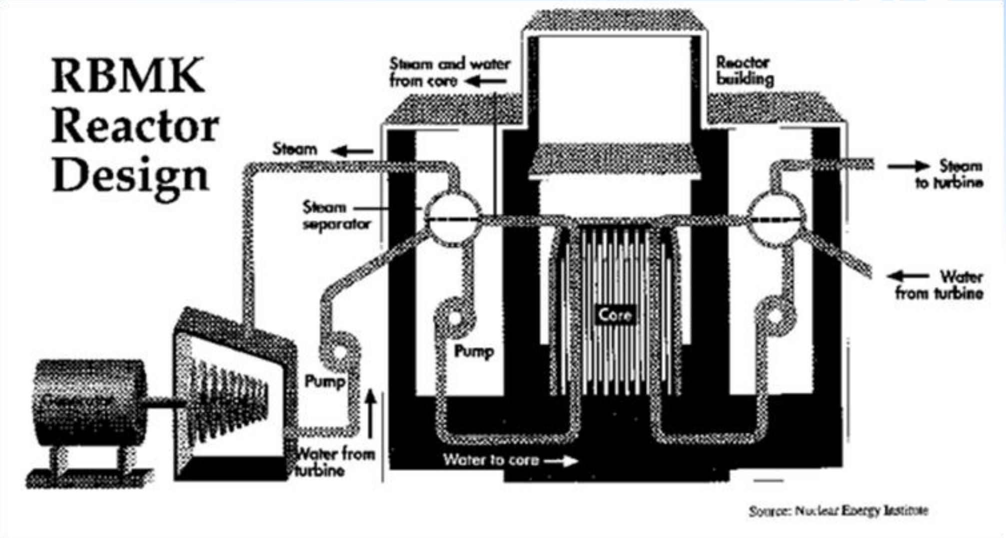
- Moderator: heavy water →
- Fuel: natural uranium (no enrichment)
- Pressure-tube design: pressure tubes within calandria (380 – 480 tubes assembles a reactor)

The CANDU Bruce Nuclear Generating Station is the largest nuclear power plant in the world by net operating capacity

Qinshan Phase III units 1 & 2, located in Zhejiang China (30.436 N 120.958 E): Two CANDU 6 reactors, designed by Atomic Energy of Canada Limited (AECL), owned and operated by the Third Qinshan Nuclear Power Company Limited

The RBMK design

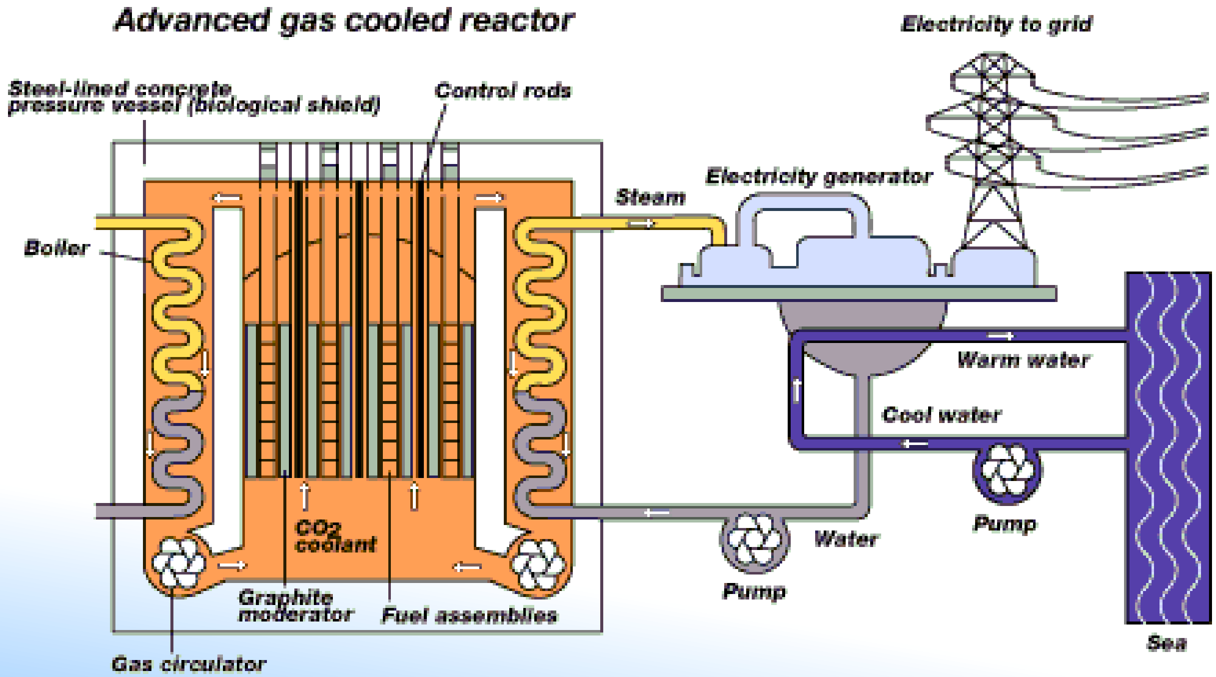
- The RBMK is unique in that it has a graphite moderator with fuel tubes and coolant tubes passing vertically through the graphite.
- The coolant tubes carry water at high pressure.
- As with the CANDU design, these reactors can be refuelled on-line.



- A The RBMK reactor has a huge graphite block structure as the Moderator that slows down the neutrons produced by fission.
- Passing through the Reactor Core are 1661 vertical tubes of about 87mm diameter that circulate water as the Coolant to remove the heat produced by 2 sets of long Fuel Assemblies (consisting of 18 rods length-wise), which are also mounted in the vertical tubes. Fuel rods are about 15mm in diameter. The total core length is 7m+ high.
- There are 2 horizontal steam generators and 2 reactor cooling loops, with headers that then feed the pressure tubes in the reactor.

Gas cooler reactors

- The Gas Cooled Reactor was one of the original designs.
  - In the Gas Cooled Reactor (GCR), the moderator is graphite.
  - Inert gas, e.g. helium or carbon dioxide, is used as the coolant.
- The advantage of the design is that the coolant can be heated to higher temperatures than water.
  - As a result, higher plant efficiency (40% or more) could be obtained compared to the water cooled design (33-34%).
- Still 14 AGRs in operation in the UK today



Evolutionary PWRs

- APR-1400
- APWR
- ATMEA1
- AP-1000
- CAP-1400
- EPR
- VVER-1200

- ABWR
- ESBWR
- KERENA

Evolutionary BWRs

Evolutionary PHWRs

- EC6 and AFCR
- IPHWR-700

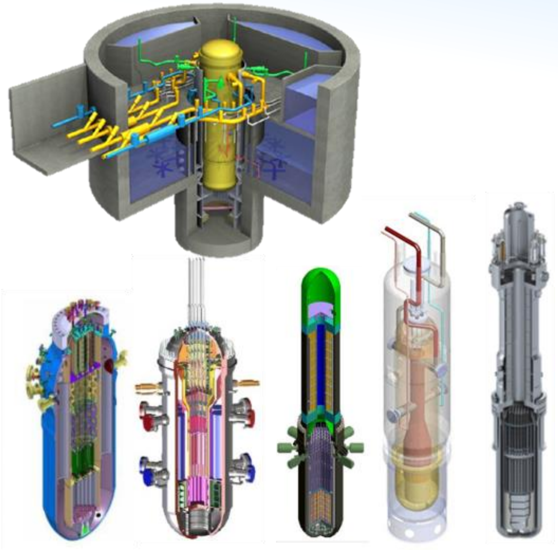
Innovative Nuclear Energy Systems

- Water Cooled Small Modular Reactors (SMR) –
- High Temperature Gas Reactors (HTGR) –
- Generation IV reactor Technology –
  - Supercritical Water Reactors (SCWR)
  - Fast Reactors (FR)
  - (Very) High Temperature Gas Reactors (VHTGR)
  - Molten Salt Reactors (MSR)

Evolutionary WCR Design Goals

Development Areas:

- Simplification
- Modularization
- High reliability systems
- *Passive safety systems*
- Further development of PSA
- Improvement of technology base
- Waste reduction



AWCR Deployed and Available Designs

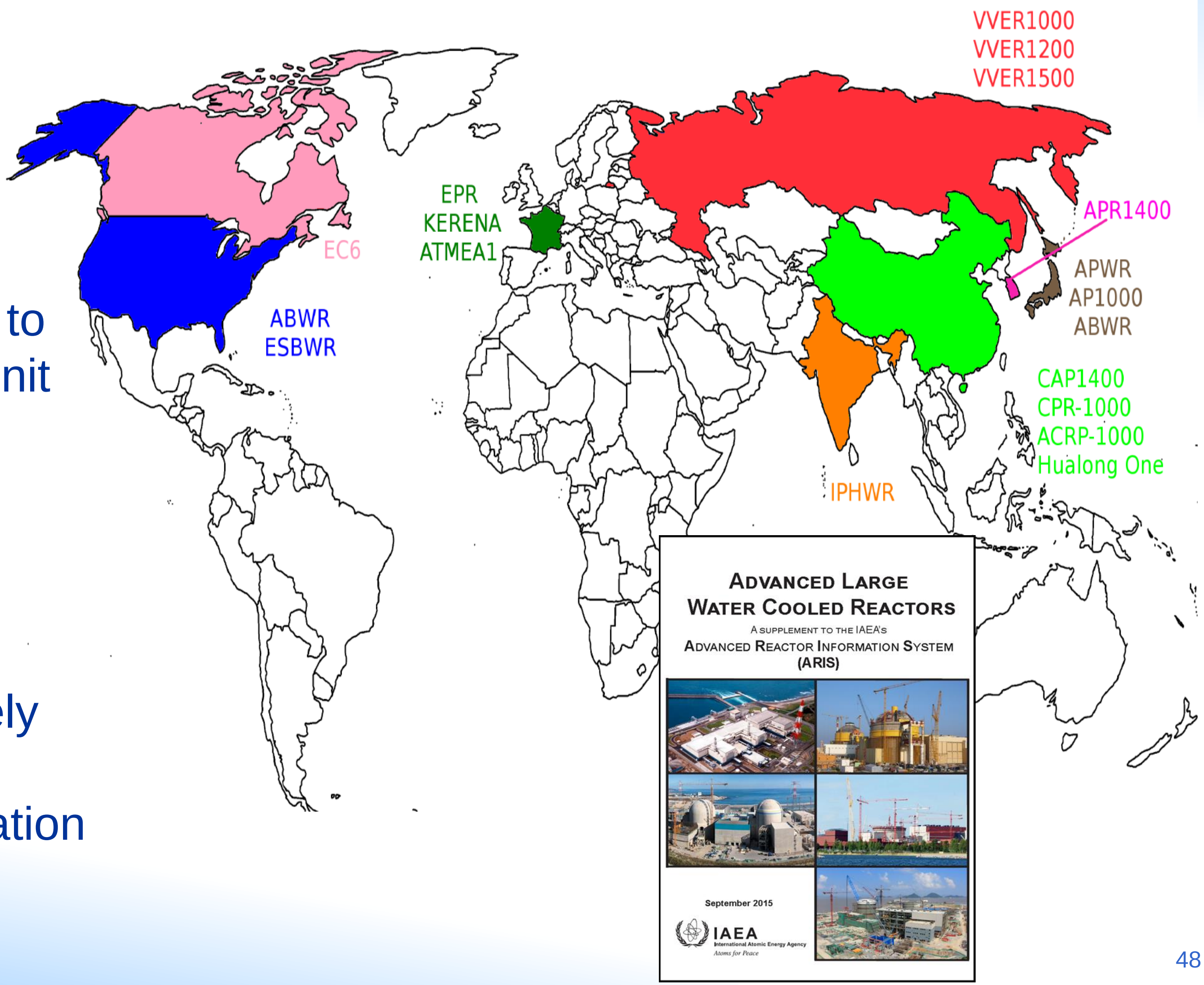
Large NPPs:

~15 designs

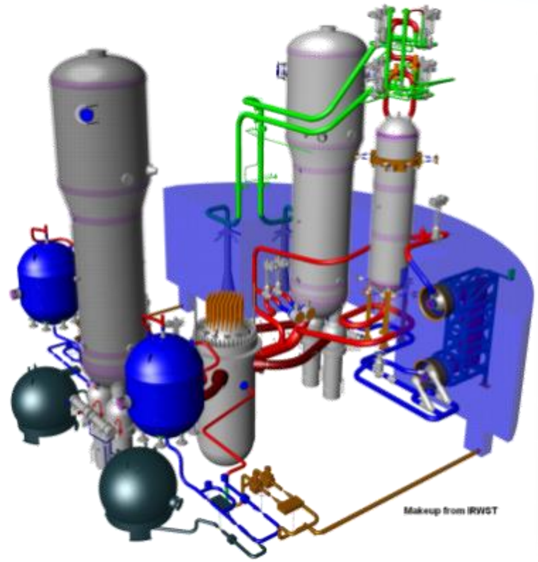
Output from 700 to 1600 MWe per unit

Water cooled, pressurized, T(out) ~ 300C

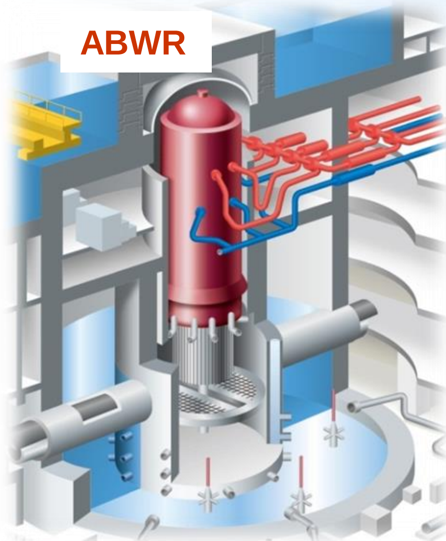
Almost exclusively designed for electricity generation



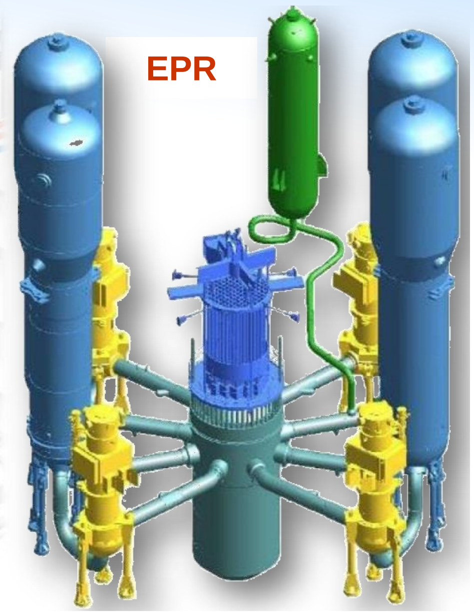
Advanced Water Cooled Reactors



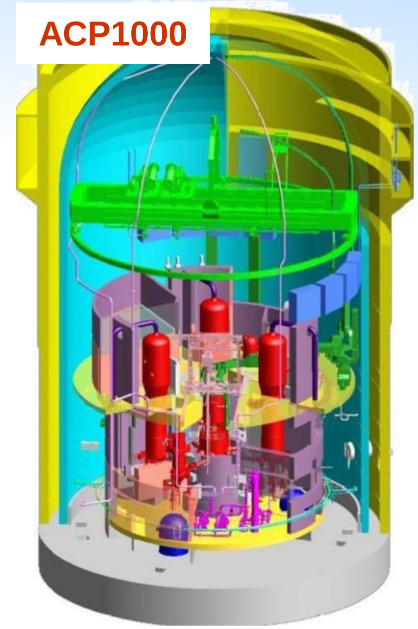
AP1000



ABWR

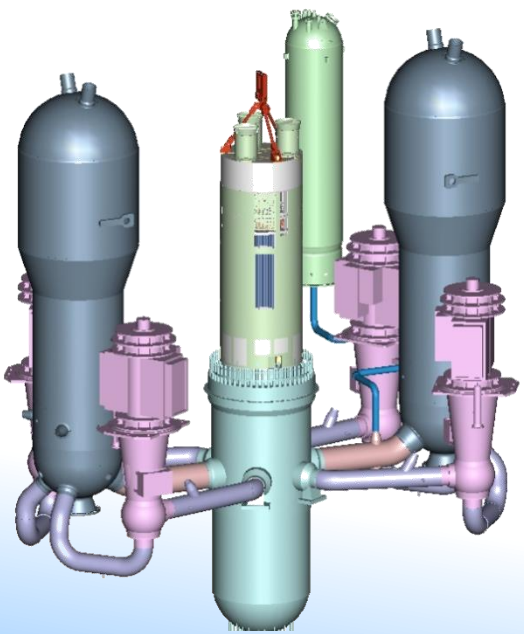


EPR

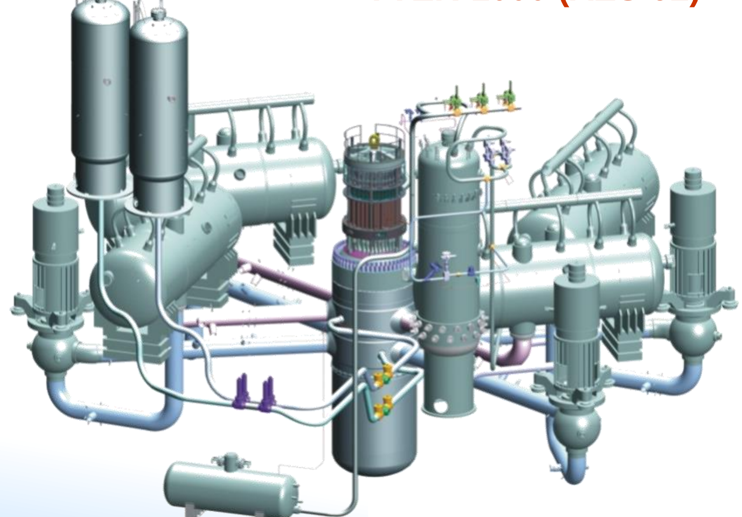


ACP1000

APR1400



VVER-1000 (AES-92)



Key Design Characteristics of Advanced (Passive) WCRs

1

Independent of AC Power

- Require no AC power to actuate /operate Engineered Safety Features;
- Only gravity flow, condensation natural circulation forces needed to safely cool the reactor core
- Passively safe shutdown the reactor, cools the core, and removes decay heat out of containment

2

Less reliance on operator action

Provides 3 to more than 7 days of reactor cooling without AC power or operator action

3

Design simplification

- Fewer number of plant systems and components
- Reducing plant construction and O&M costs

4

Incorporating lessons-learned from the Fukushima Dai-ichi nuclear accident

- Enhanced robustness to extreme external events by addressing potential vulnerabilities
- Alternate AC independent water additions in Accident Management – SBO mitigation
- Ambient air as alternate Ultimate Heat Sink
- Filtered containment venting
- Diversity in Emergency Core Cooling System

Presentation Objectives

By the end of this session, participants should be able to:

- Recall the early history of nuclear physics
- Recall the early reactor developments
- Explain the four generations of reactors and their main differentiating factors
- Summarize the key design and safety features of reactors in operation today

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

Thank you!