Design of nuclear plants

Reactor technology
Lecture 1

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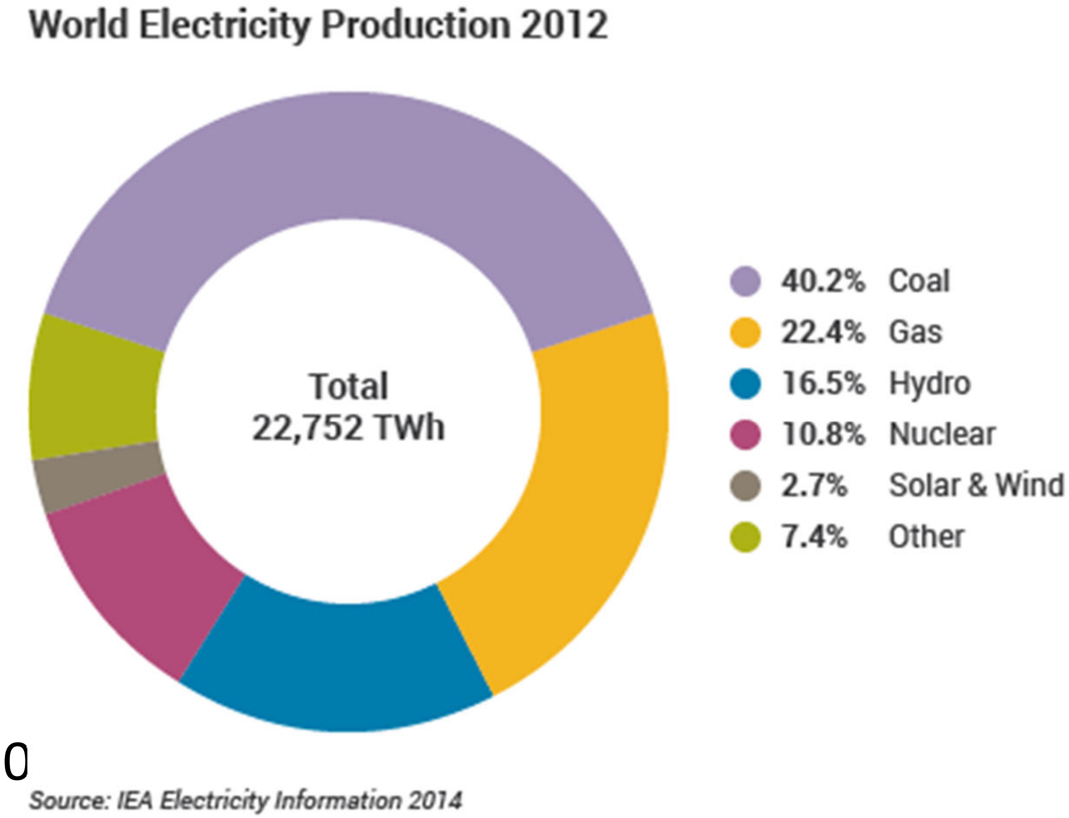
	4. Containment systems
	5. Cooling of NPPs
	6. BWR, PHWR, other types
	7. exotic reactors (fast breeders, etc.)

Nuclear energy at present

- Share of nuclear in electricity production
  (2011 -> 2014):

world	16%	→	11%
EU	35%	→	27%
Hungary	36%	→	53%

- 448 NPP units operate worldwide
- 57 units under construction
- Design lifetime of most units expires between 2015 and 2030



Source: IEA Electricity Information 2014

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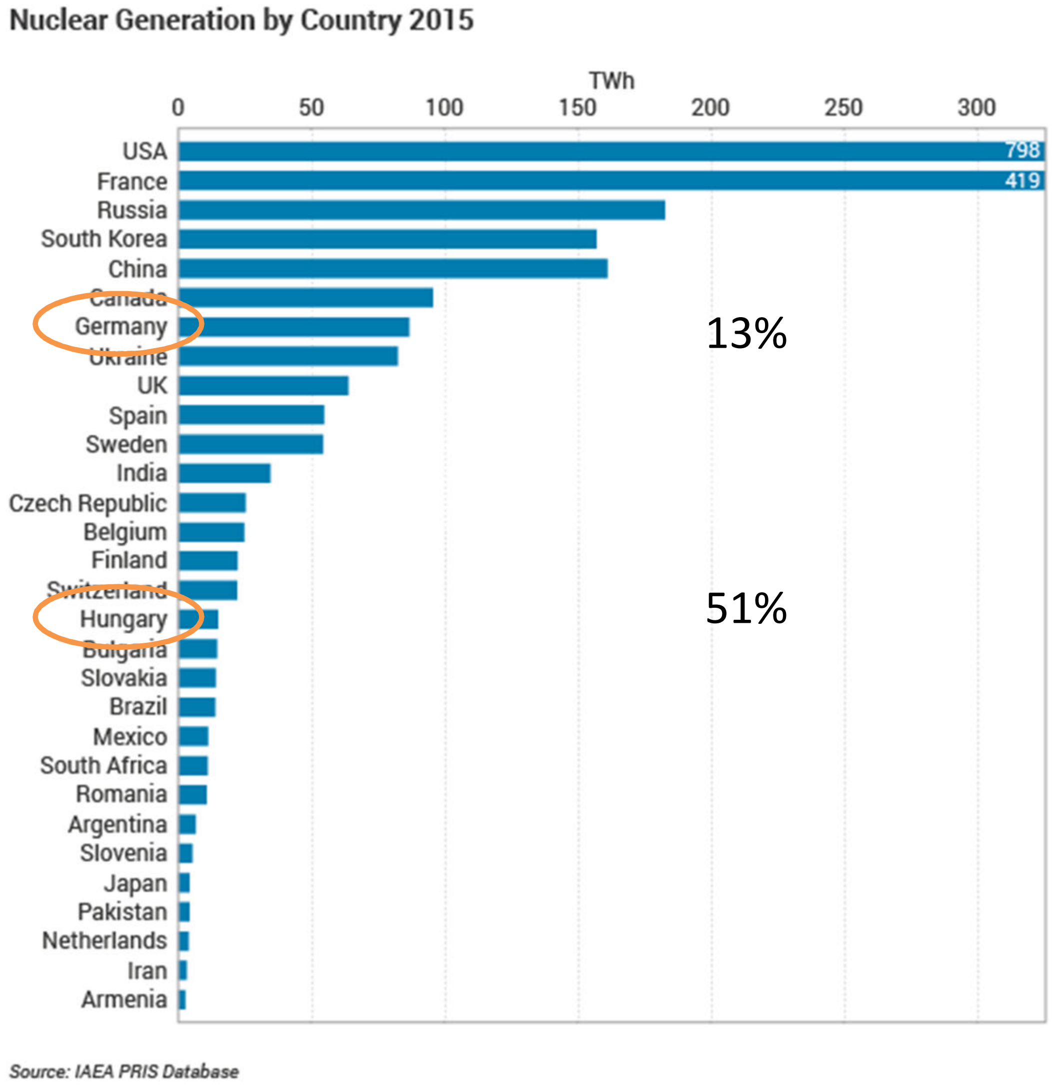


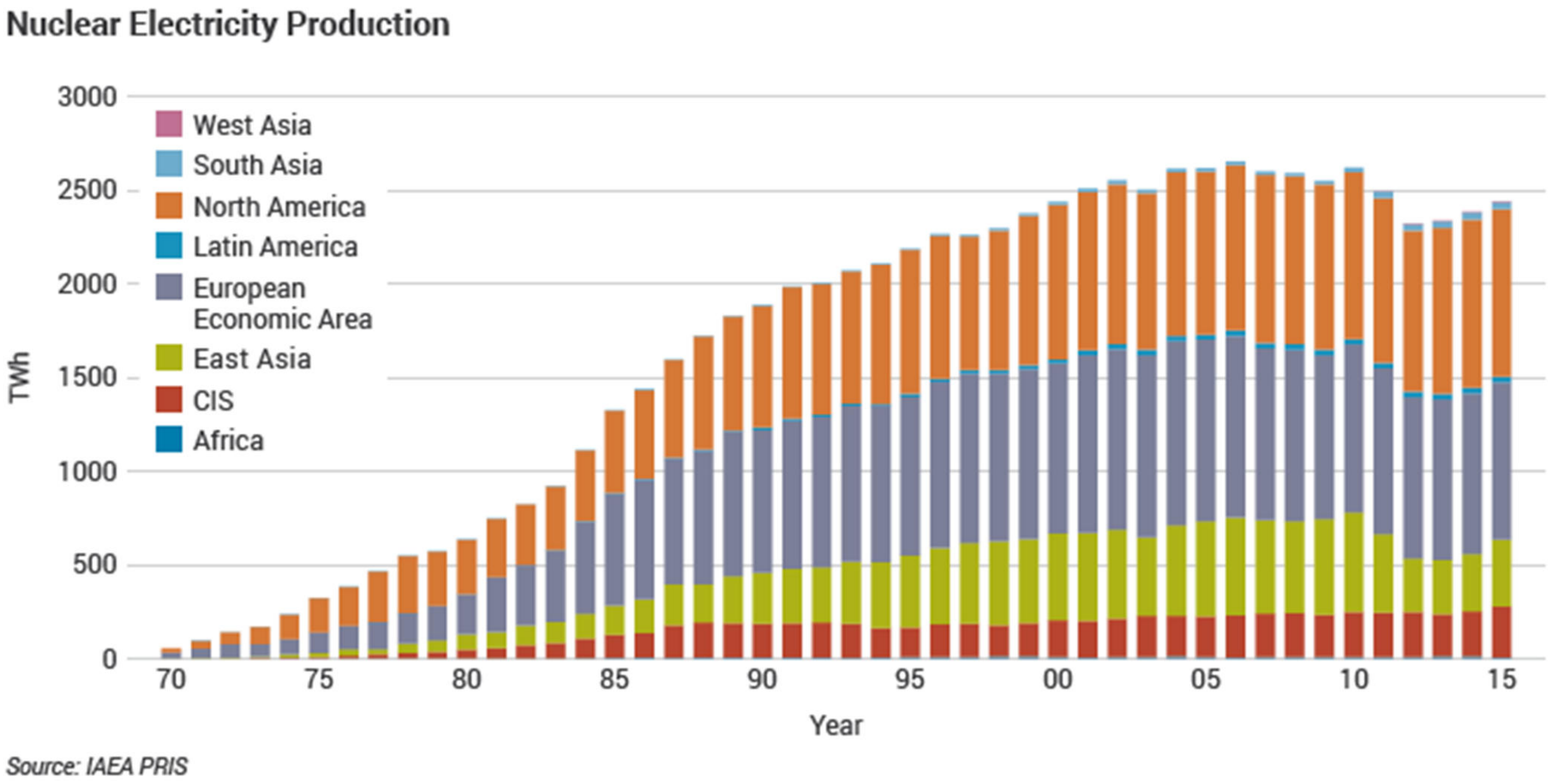
Nuclear Generation by Country 2015

13%

51%

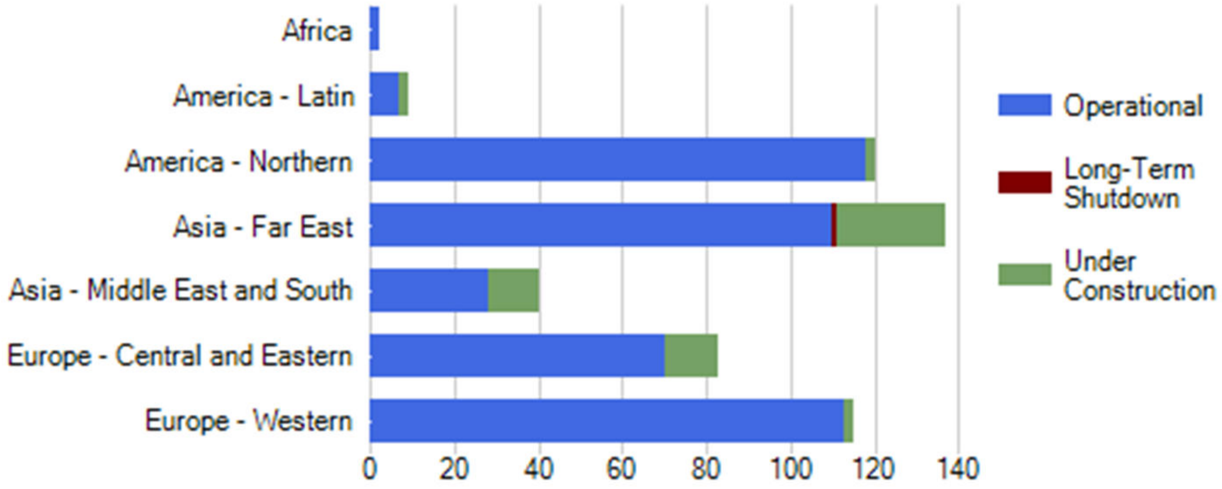
Source: IAEA PRIS Database

Trends in nuclear industry

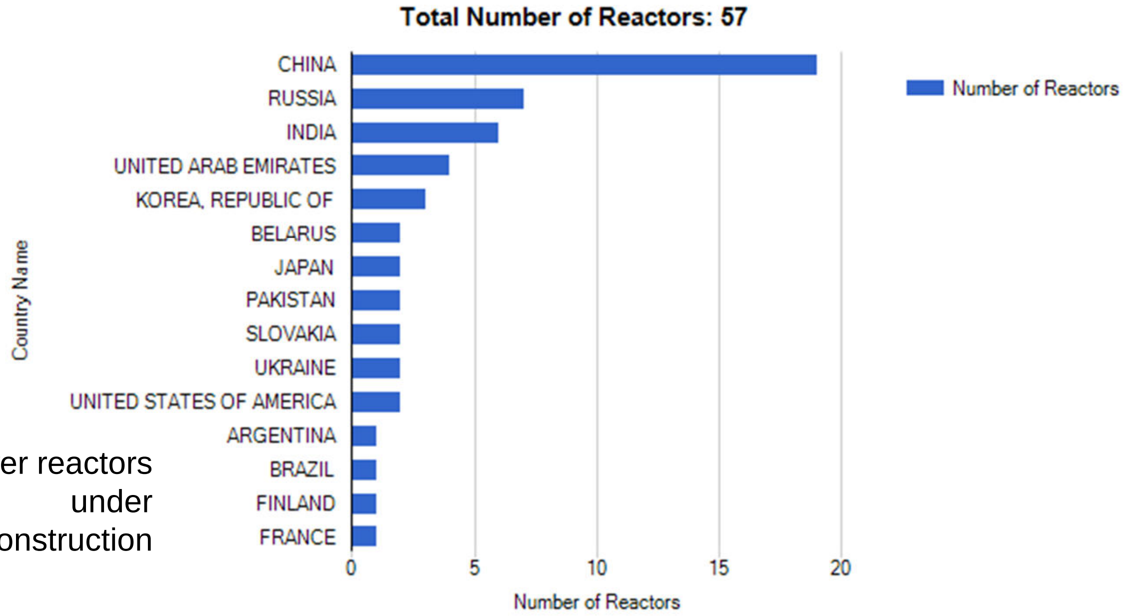


Source: WNA

Trends in nuclear industry



Source: IAEA



Power reactors under construction

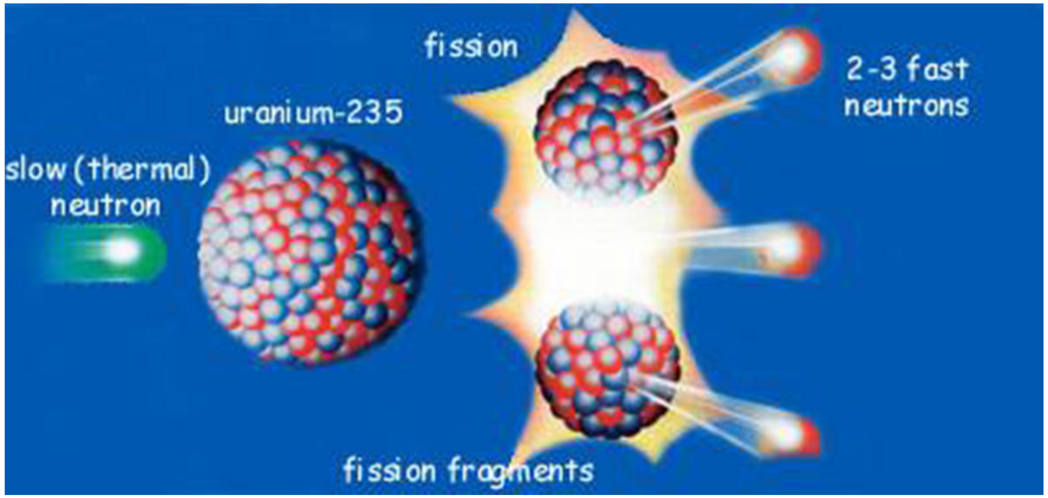
BASICS OF NUCLEAR TECHNOLOGY

Nuclear fission

- In certain isotopes, spontaneous or induced fission of the nucleus can occur
  - Induced fission: effect of bombardment of thermal neutrons
- Uranium isotopes in nature

$^{234}U_{92}$ (0.006%) $^{235}U_{92}$ (0.714%) $^{238}U_{92}$ (99.28%)

- Enrichment for nuclear power reactors <5% (U-235)

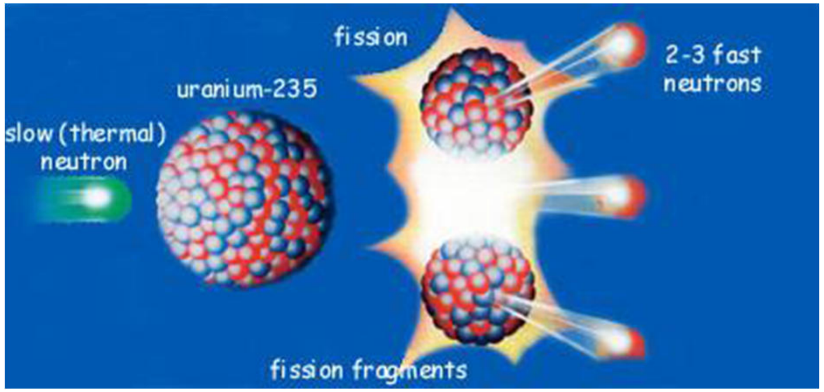


Source: NPP Paks, IAEA

Nuclear fission

- U-235: fission generated by thermal neutrons can take place
- In average, 2.4 fast neutrons are produced in every fission
  - A small part of these neutrons are delayed (for U-235: β=0.64%), with a maximum release time of 60 s (prompt neutrons: up to 10^{-14} s)
  - Delayed neutrons are extremely important in control of the chain reaction

Source: NPP Paks, NRC



ENERGY DISTRIBUTION FOR FISSION INDUCED BY THERMAL NEUTRONS

Source	Energy MeV
Fission product kinetic energy	168
Neutron kinetic energy	5
Fission gammas (instantaneous)	5
Fission gammas (delayed)	6
Fission product betas	7
Total available as heat	191
Neutrino energy (not available as heat)	11
TOTAL	202

Nuclear fission

- For different neutron-nucleus interactions:
- Microscopic cross section for nuclear reactions (for one given nucleus, and for 1 unit of neutron flux)

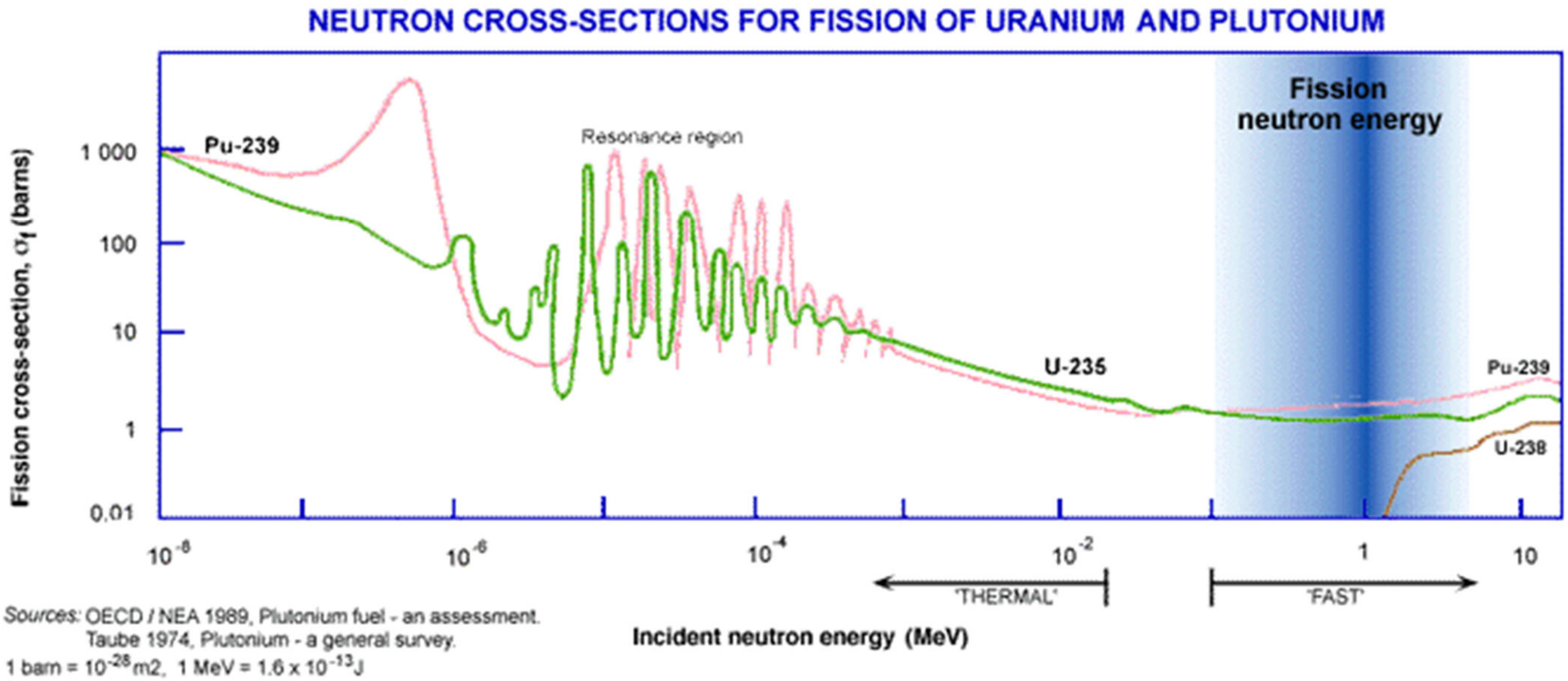
$$\sigma_t = \sigma_s + \sigma_a = \sigma_{elastic} + \sigma_{inelastic} + \sigma_{fission} + \sigma_{capture}$$

  - Where t: total, s: scattering, a: absorption
  - Unit: barn (10^{-24} cm^2)
- Macroscopic cross section (for a given material):

$$\Sigma_t = \sum_i n_i \sigma_{ti}$$

  - Where i is for all nuclei, n_i: number of nuclei by unit volume
  - Unit: 1/cm

Nuclear fission



Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6×10^{-13} J

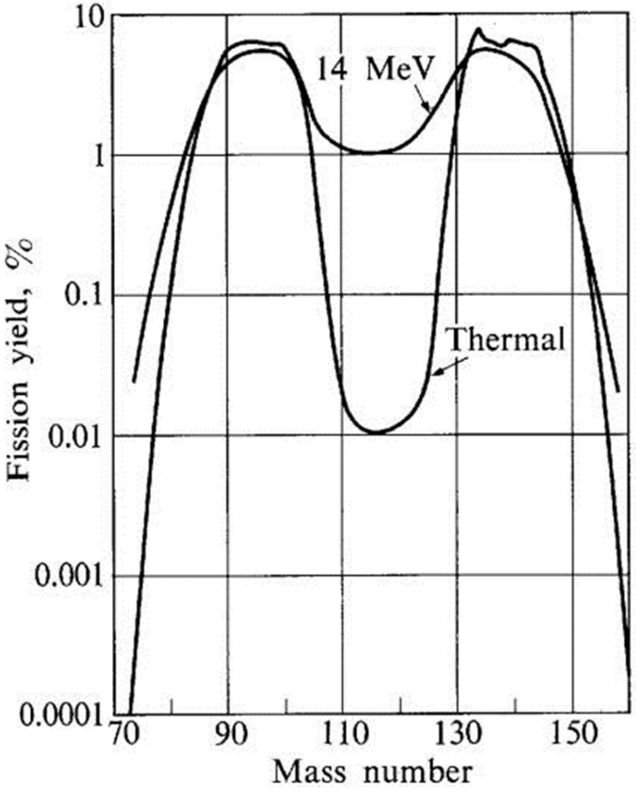
- Production of Pu-239 in thermal reactors:

$$ {}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} $$

$$ {}_{92}U^{239} \xrightarrow[23\,\text{min}]{\beta^-} {}_{93}\mathrm{Np}^{239} \xrightarrow[2.3\,day]{\beta^-} {}_{94}Pu^{239} $$

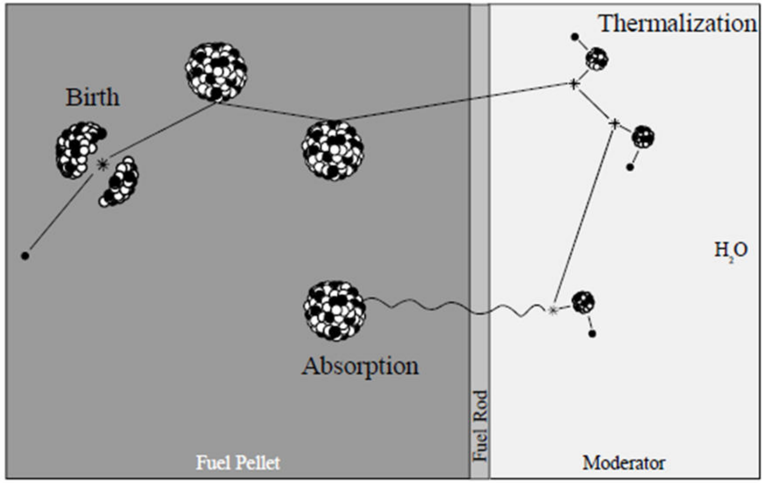
Nuclear fission

- Fission fragments, fission products
- A typical fission reaction:
- ${}_{0}n^{1} + {}_{92}U^{235} \longrightarrow ({}_{92}U^{236})^{*} \longrightarrow {}_{38}Sr^{90} + {}_{54}Xe^{144} + 2n$
- Fission yield
- Important fission products:
  - I-133, Sr-90, Cs-137 etc.
- (+ don't forget the trans-uranium isotopes!)

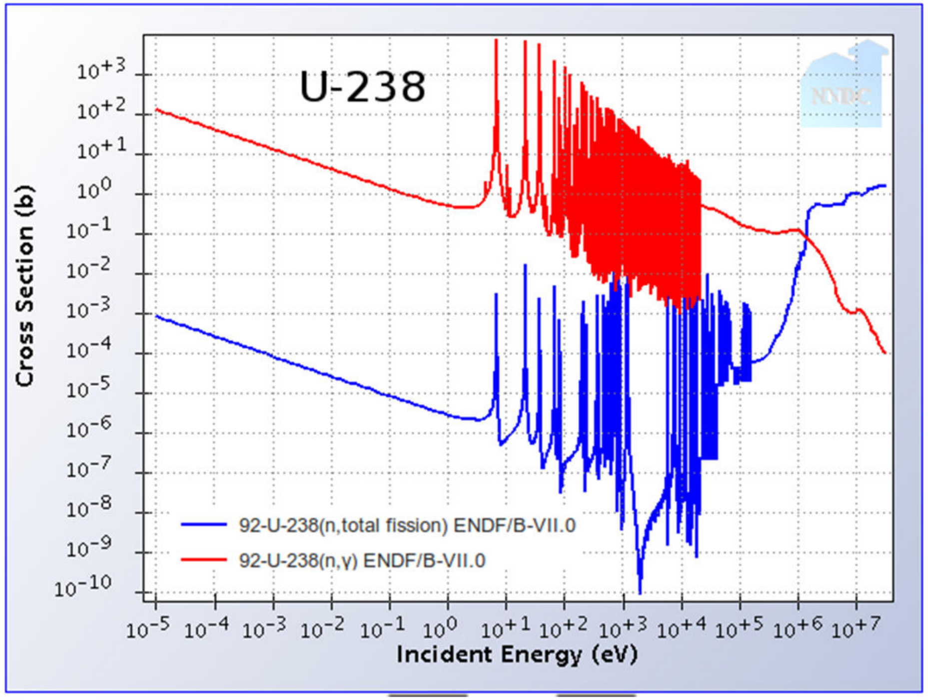


Nuclear fission

- Neutrons can be thermalized (slow down by scattering) and cause further fission
- Moderator materials
- Requirement: to reach thermal energy without being absorbed (by U-238 OR by the moderator itself)
  - > Having as few collision as it is possible



Neutron Life Cycle



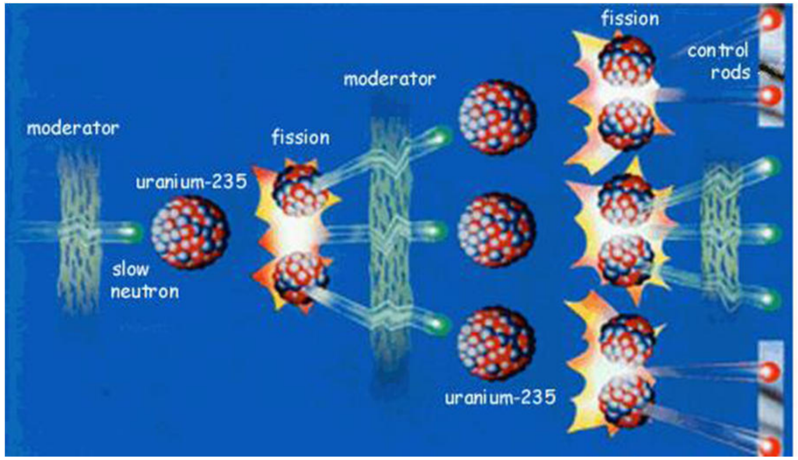
Moderator materials

Moderator parameters	H_2O	D_2O	Graphite
moderation path length [cm]	5.74	10.93	19.7
neutron absorption cross section [barn]	0.66	0.0026	0.0045

- Advantages and disadvantages of different materials
- Deuterium or graphite moderator: operation possible with natural uranium
- For H2O moderator enrichment of U-235 is necessary

Nuclear fission

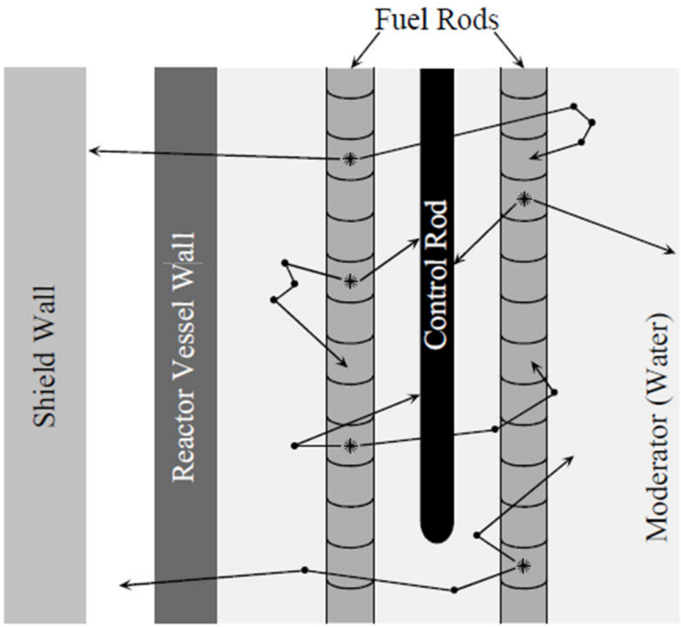
- Chain reaction
  - Series of fission becomes self-sustaining
  - Multiplication factor: k_{eff}
  - Reactivity: $\rho=(k-1)/k$
  - Critical, subcritical, supercritical chain reaction

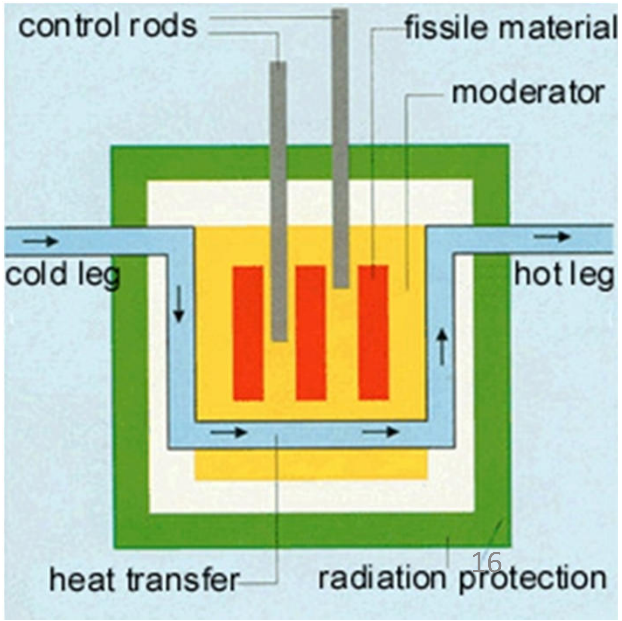


Nuclear reactors

Source: NPP Paks, NRC

- Neutrons in nuclear fuel
  - Scattering (slow down)
  - Absorption
  - Escape
  - Fission generation
- Thermal nuclear reactors
  - Fuel – fissile material, usually U or Pu (or MOX)
  - Moderator – with good slowdown parameters + small absorption (H_2O, D_2O, C)
  - Reactivity control – neutron absorbing material (B, Cd)
  - Cooling (H_2O, D_2O, CO_2, He)
  - Radiation protection (concrete, water, boric acid, etc.)





Why is nuclear safety so important?

- Specific risks of nuclear reactors (compared to other plant types):
  - Large amount of fissile material in the core
  - Large quantity of radioactive materials in the core
  - Significant energy release for a long time after shut down.

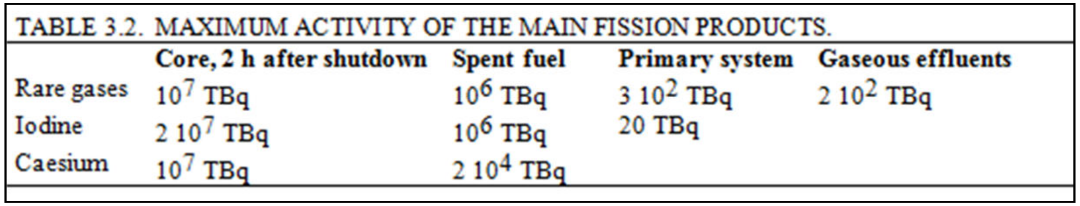
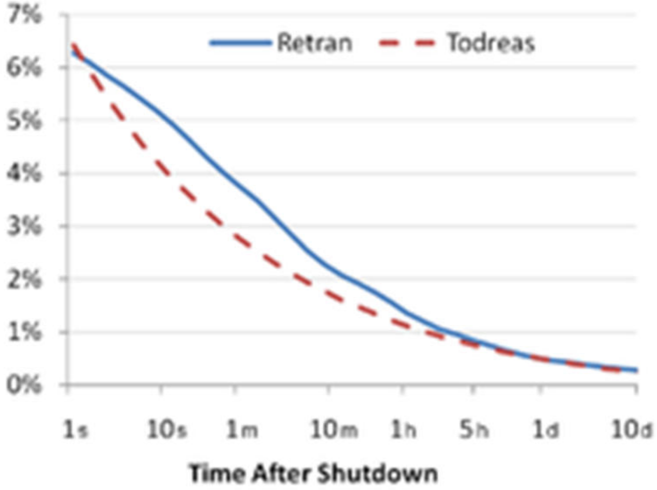


TABLE 3.2. MAXIMUM ACTIVITY OF THE MAIN FISSION PRODUCTS.

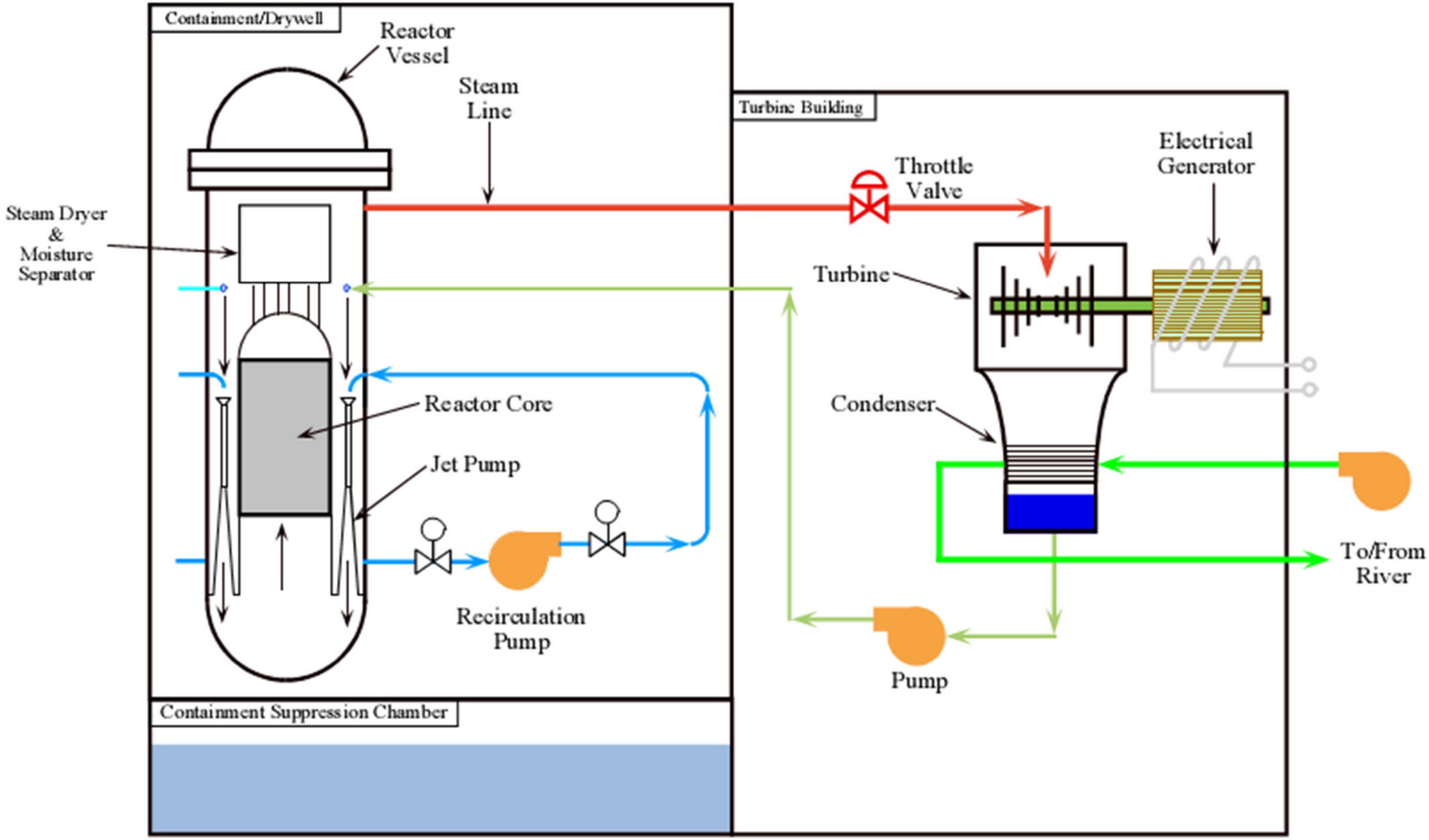
	Core, 2 h after shutdown	Spent fuel	Primary system	Gaseous effluents
Rare gases	10^7 TBq	10^6 TBq	$3\ 10^2$ TBq	$2\ 10^2$ TBq
Iodine	$2\ 10^7$ TBq	10^6 TBq	20 TBq	
Caesium	10^7 TBq	$2\ 10^4$ TBq		

Safety depends on appropriate confinement of radioactive materials, control of the chain reaction and efficient cooling of the core!



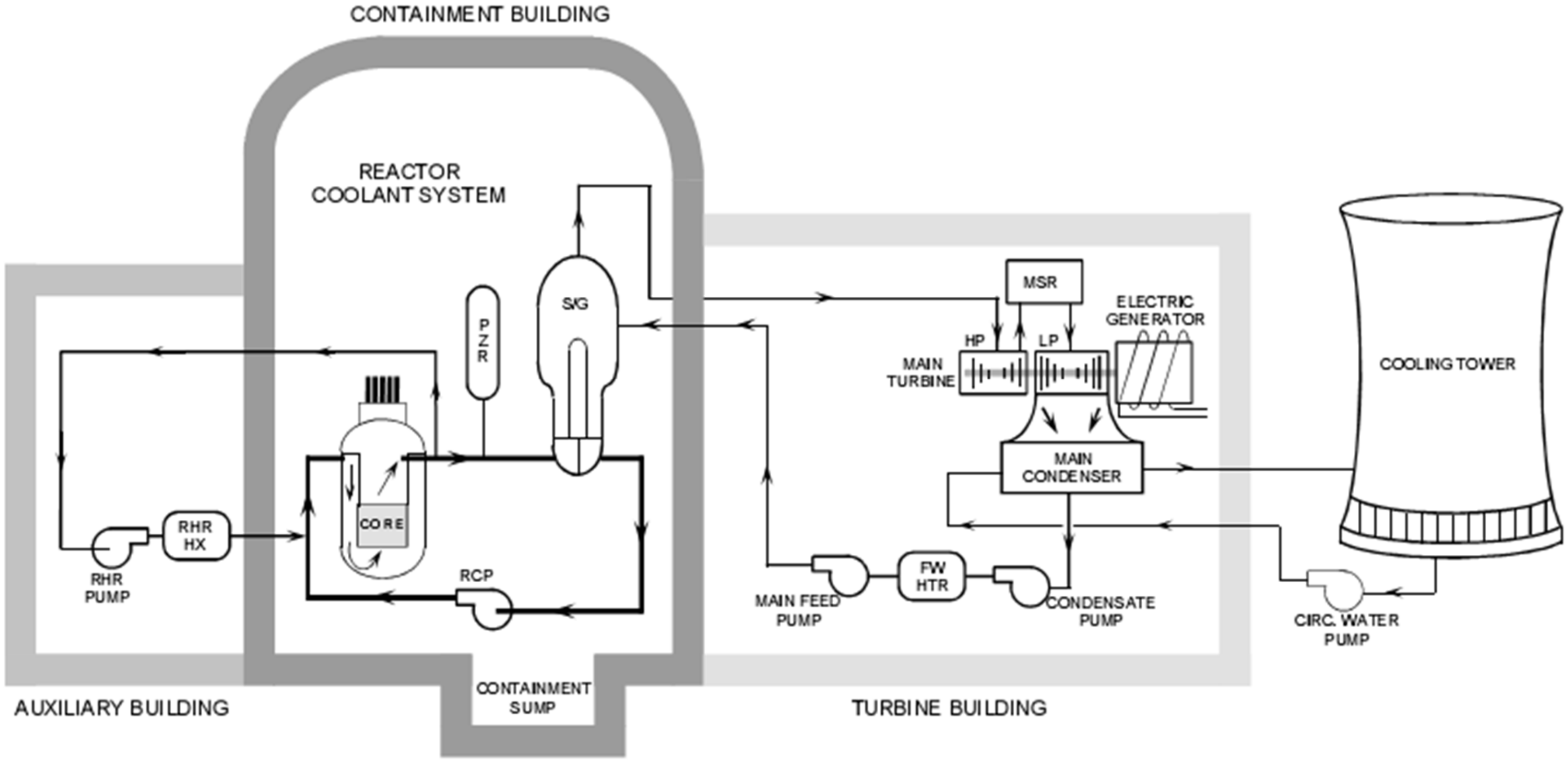
Source: Wikipedia

Boiling Water Reactor (BWR)



Source: NRC

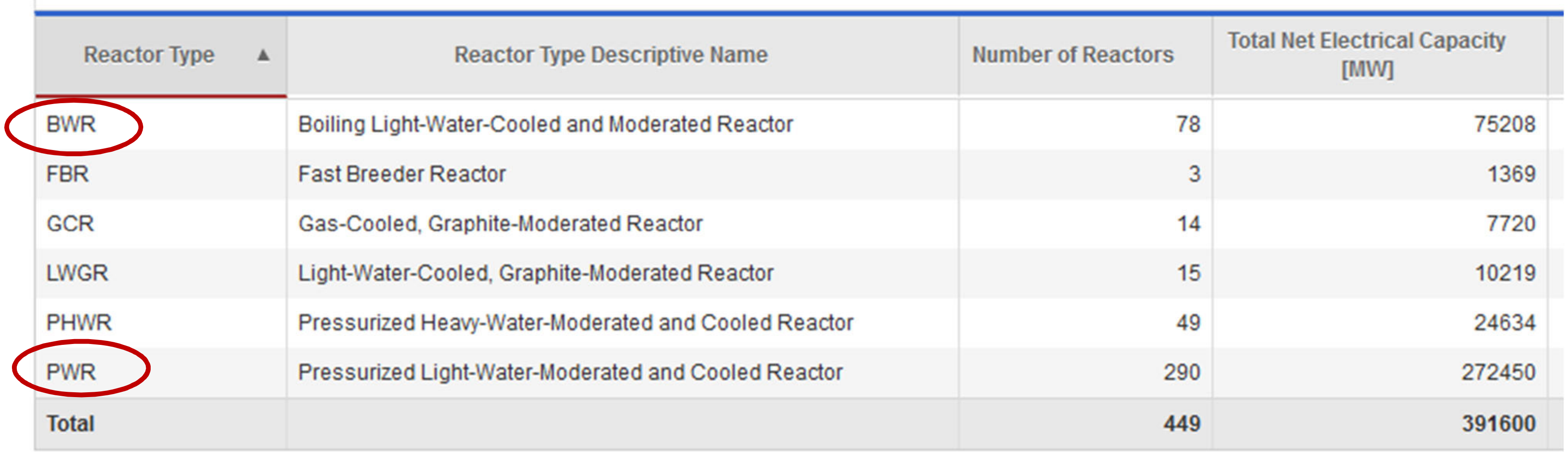
PWR design



Source: NRC

- Two cooling circuits (loop =/= circuit!)
- Primary parameters set to avoid boiling (p_{pr}: 130-160 bar, T_{pr}: 260-300^{o}C)
- Secondary circuit: classic water-steam coolant regime (Rankine-cycle at about 50-65 bar pressure)

Nuclear energy at present



Reactor Type ▲	Reactor Type Descriptive Name	Number of Reactors	Total Net Electrical Capacity [MW]
BWR	Boiling Light-Water-Cooled and Moderated Reactor	78	75208
FBR	Fast Breeder Reactor	3	1369
GCR	Gas-Cooled, Graphite-Moderated Reactor	14	7720
LWGR	Light-Water-Cooled, Graphite-Moderated Reactor	15	10219
PHWR	Pressurized Heavy-Water-Moderated and Cooled Reactor	49	24634
PWR	Pressurized Light-Water-Moderated and Cooled Reactor	290	272450
Total		**449**	**391600**

Source: IAEA

REACTOR GENERATIONS

Generations of Nuclear Energy

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

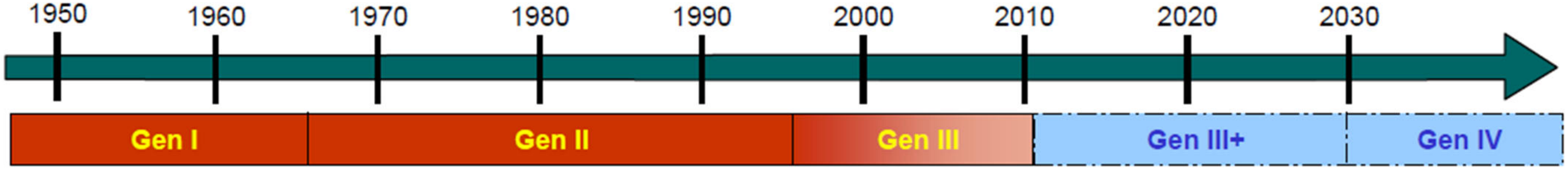
Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure



1950 1960 1970 1980 1990 2000 2010 2020 2030

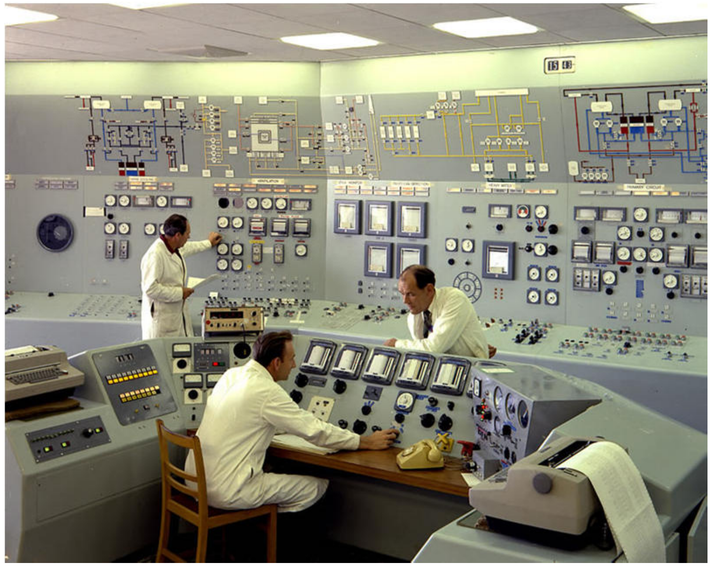
Gen I | **Gen II** | **Gen III** | **Gen III+** | **Gen IV**

Source: Gen IV Forum

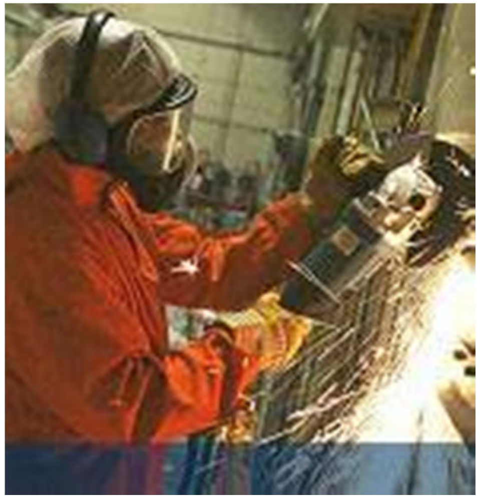
First generation NPPs

- Prototype reactors of 50s and 60s
- Low unit capacity (<250 MW)
- Small series, rather individual reactors (except Magnox)
- Safety deficiencies (lack of containment, poor emergency cooling etc.)
- Exotic types:
  - FBR – Fermi I
  - GCR – Magnox
  - HWGCR - Monts D'Arree
  - SGHWR – Winfrith

FBR –	Fast Breeder Reactor
GCR –	Gas Cooled Reactor
HWGCR –	heavy water gas cooled reactor
SGHWR –	steam generating HWR



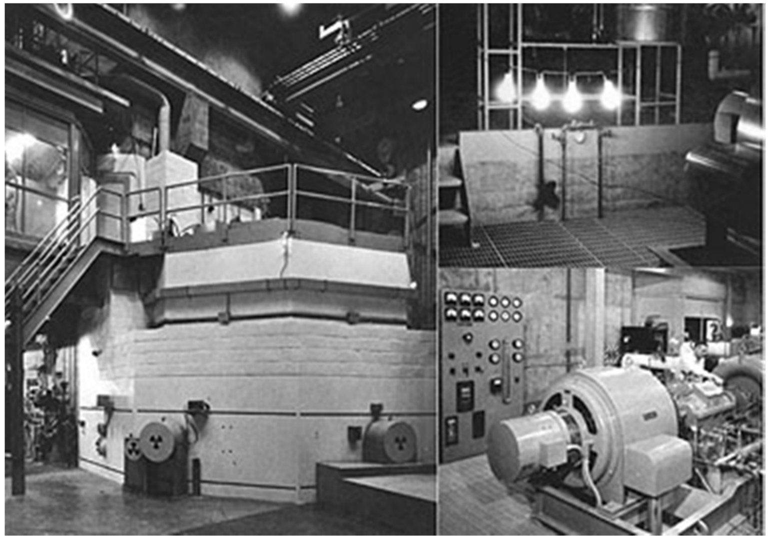
Control room of Winfrith SGHWR (1967-90, 100 MWe)



Decommissioning of Winfrith SGHWR

First generation NPPs

- **EBR (Experimental Breeder Reactor)**
- Licensed in 1951 – the first electricity generating reactor of the world, but not an NPP
- Fast reactor
- Fuel: uranium enriched to 94%
- Coolant: liquid Na-K

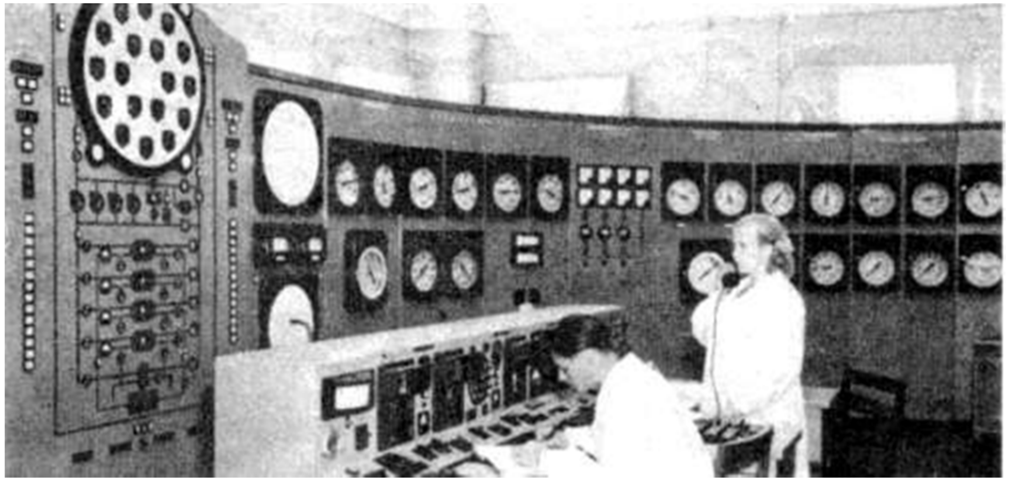


Source: INL

- P_{th}=1400 kW, P_e=200 kW.
- Supplied the lighting of a building of National Reactor Testing Station

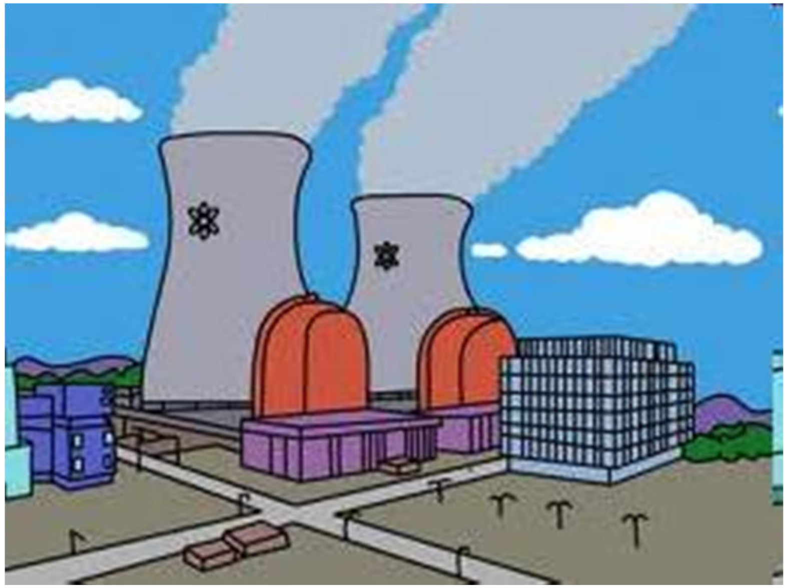
First generation NPPs

- 27 July, 1954: **Obninsk NPP** connected to the grid
- Ancestor of later RBMK reactor type
  - Graphite moderated, channel-type, boiling water reactor
- 5 MW P_e
- Shutdown in 2002



Second generation NPPs

- Most of the operating NPPs
- Commercial types, with large series
- Mainly light water (LWR: BWR/PWR) or heavy water (PHWR) reactor types
- Developed from the operational experiences of first generation reactors (the safe, economical types were kept)
- Same standardization can be observed, but the units have more non-series parameters



LWR – Light Water (cooled and moderated) Reactor
BWR – Boiling Water Reactor
PWR – Pressurized Water Reactor
PHWR – Pressurized Heavy Water Reactor

A typical Generation II NPP: Paks NPP, VVER-440

- VVER-440/V213
- Paks NPP: 4 Units, with an electric output of 500 MW (per unit)
- Connected to the grid:
  - unit 1: December 28, 1982,
  - unit 2: September 6, 1984,
  - unit 3: September 28, 1986,
  - unit 4: August 16, 1987.

- Originally planned lifetime: 30 years
- Now a lifetime-extension program is in progress (+20 years)

Table 1-1: Main technological parameters of the units

Parameter	Value
Thermal power of reactor	1,485 MW
Primary coolant volume flow rate	42,000 m^3/h
Primary pressure	123 bar
Primary circuit cold leg temperature	267 °C
Primary circuit hot leg temperature	299.5 °C
Shutdown boric acid concentration	13.5 g/kg
Fresh steam pressure	46 bar
Fresh steam mass flow rate	2,940 t/h
Fresh steam temperature	255 °C

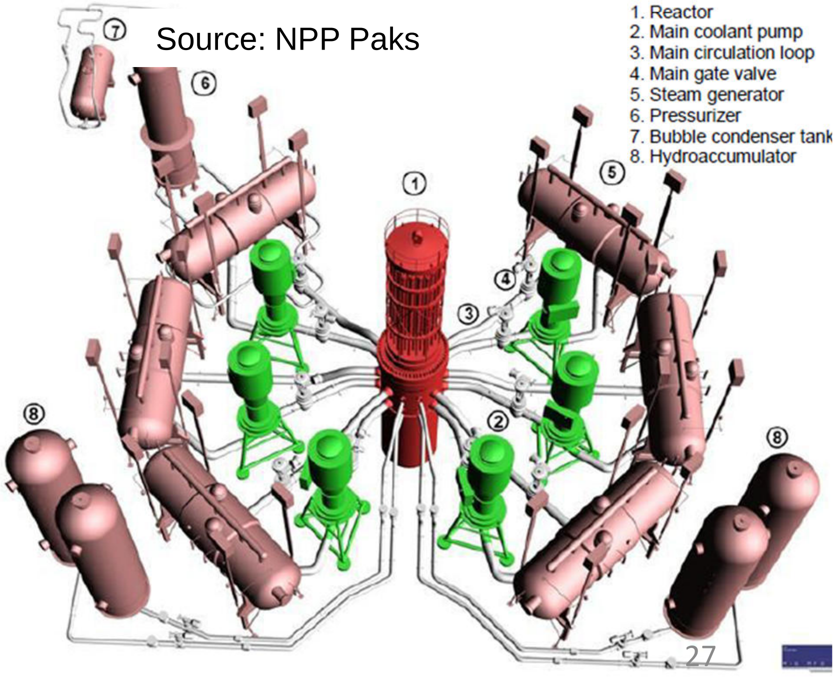
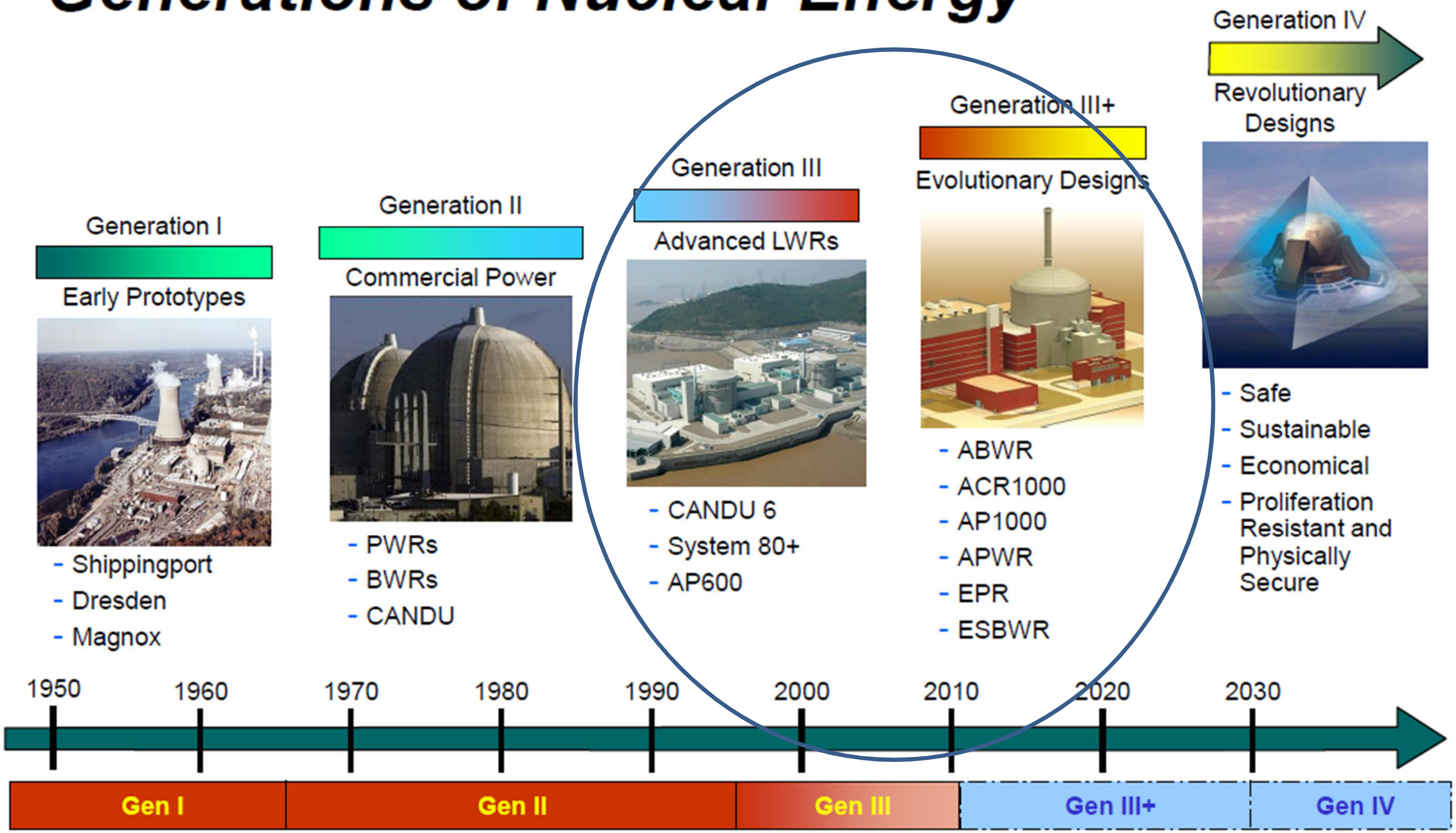

Source: NPP Paks

Figure 1-6: Arrangement of main equipment in the primary circuit

Generation III nuclear plants

Generations of Nuclear Energy



Generation I

Early Prototypes

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Advanced LWRs

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Generation III+

Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV

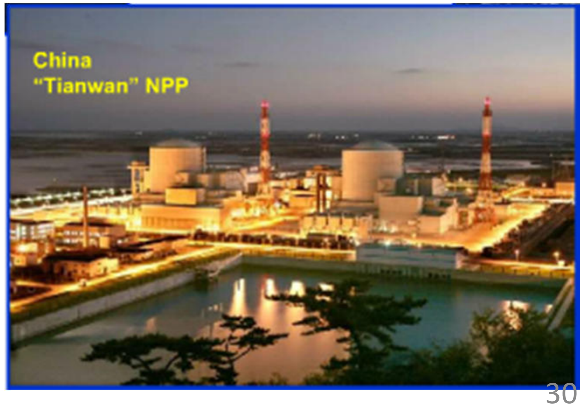
Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

Source: Gen IV Forum

Generation III NPPs

- Advanced reactors, being deployed between 2000 and 2030
- Developed from Gen II designs (evolutionary and innovative types)
- Tendency of development:
  - Economically more competitive types
    - decreasing of construction costs.
    - Simplification, standardization, modular construction, large unit size, shorter construction period, etc.
  - Improvement of safety
    - decreasing the probability and consequences of accidents.
    - Development of active and passive safety systems.
  - Non-proliferation objects
    - with engineering or administrative means
  - Sustainable development

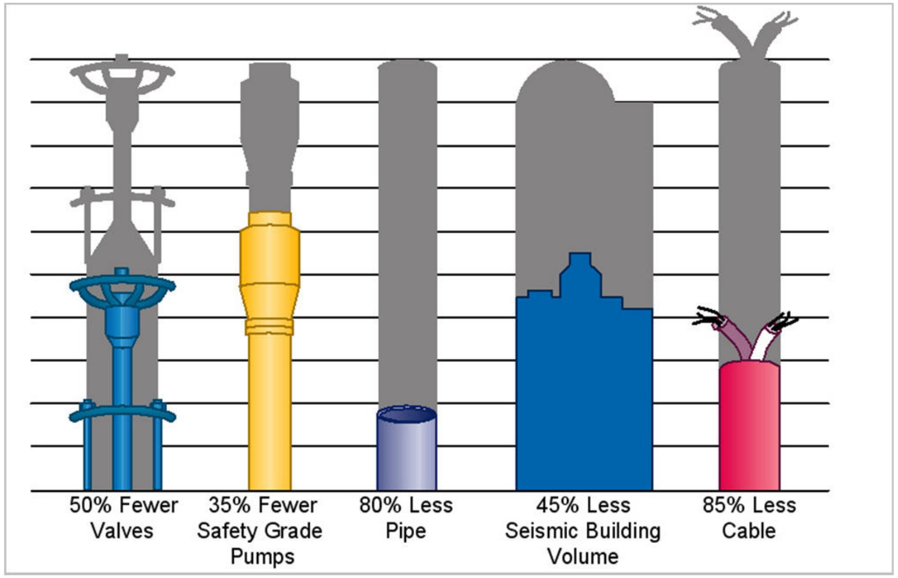


Generation III NPPs

- **Economic competitiveness**
  - At nuclear: the **45-75%** of generating costs are construction costs.
  - At coal this ratio is 15-40%.
  - Nuclear investments are capital-demanding because of the high construction costs and long construction period
  - Investors have to take long rate of return into account
  - Costs can be cut back with cogeneration (district heat, hydrogen production, sea water desalination)

Means for competitiveness (examples):

- Unit size increase, construction time decrease
- Standardization, serial products
- More units per sites
- Modularization
- Passive systems
- Reducing the number of components



AP1000 – Source: Westinghouse

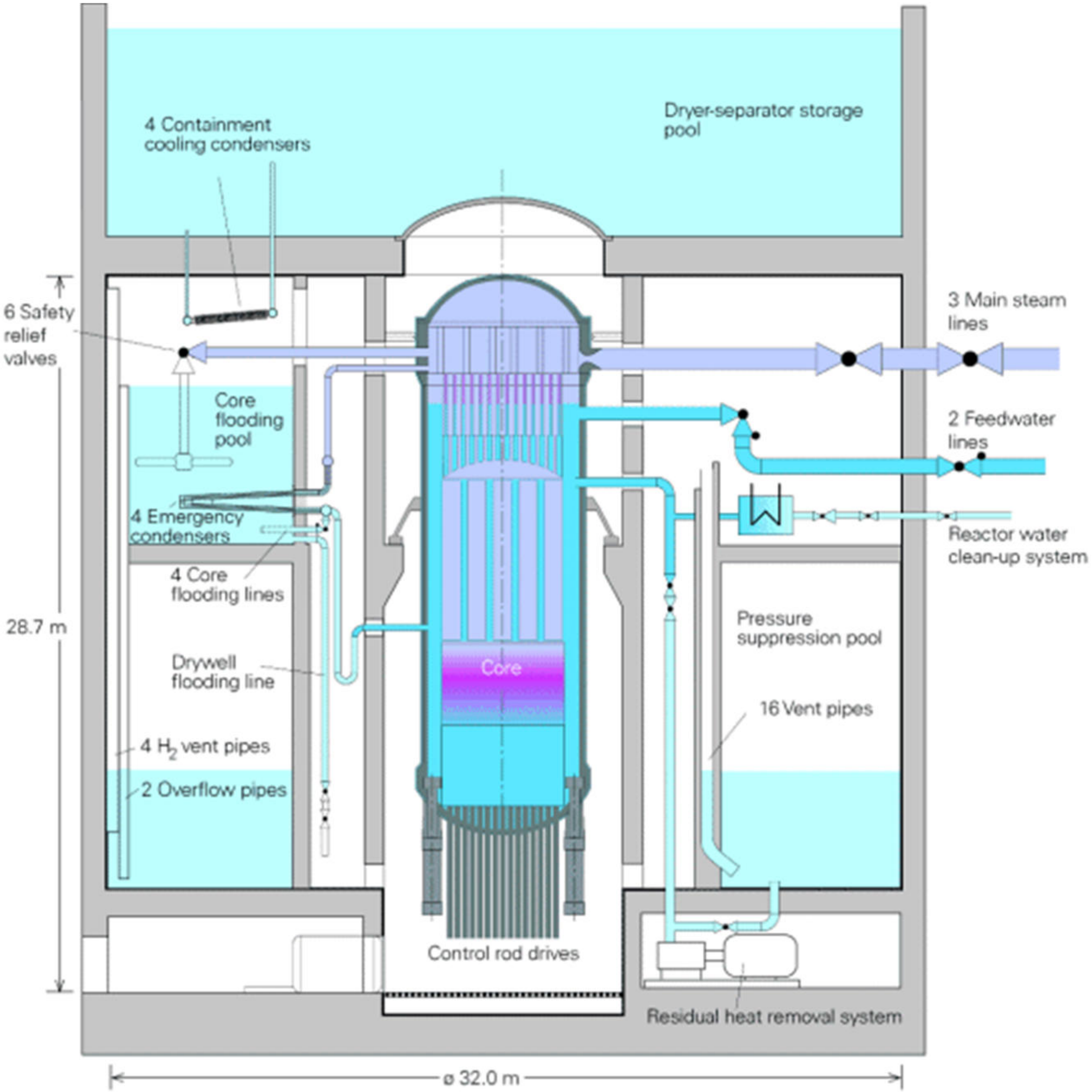
Generation III NPPs

IAEA requirements: INSAG-12, 1999:

- For operating plants, the CDF target is 10^{-4} /year. (The probability of considerable off-site release could be reduced by an order with emergency procedures.)
- **For new NPPs the CDF target is 10^{-5} /year**
- For new NPPs only limited consequences are allowed

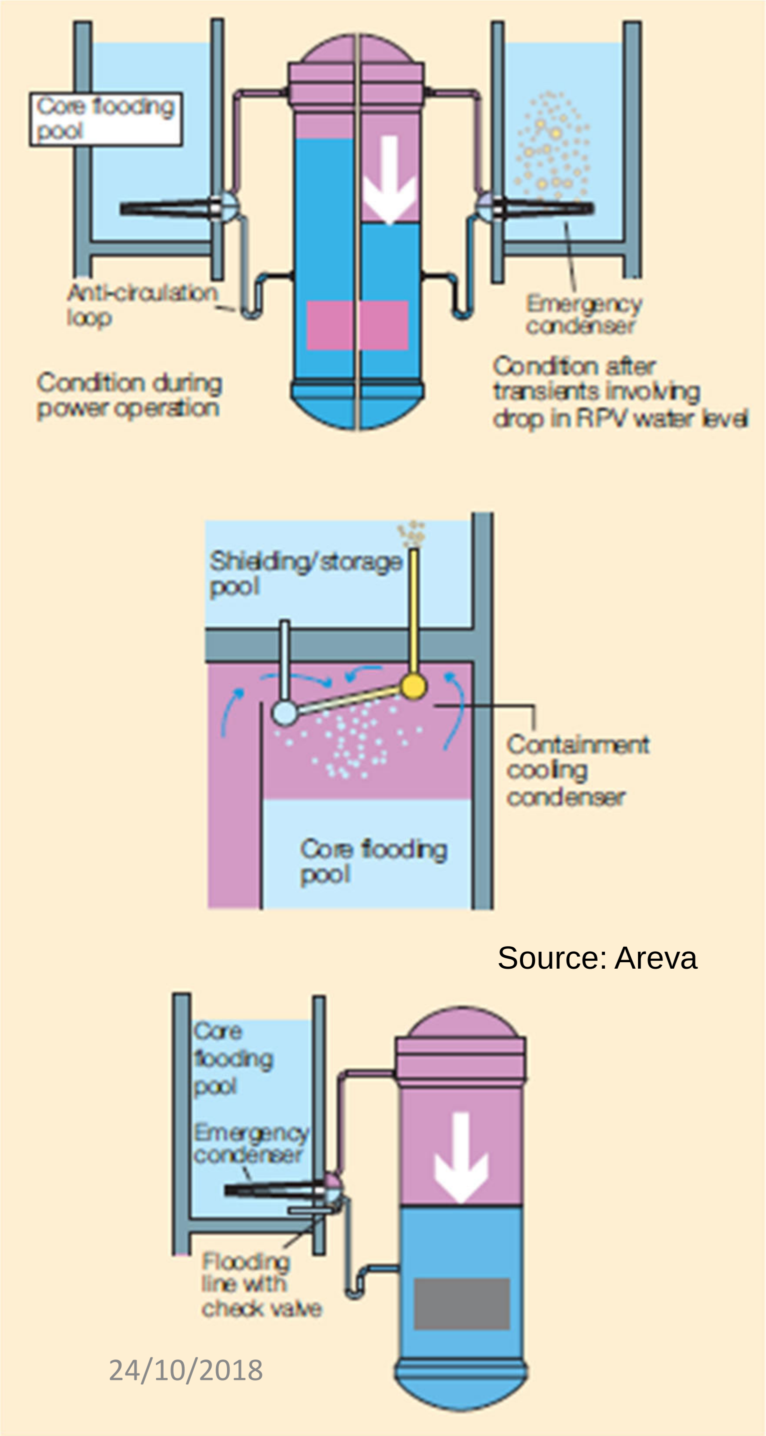
- Safety improvement
  - Objective:
    - **To decrease the probability and consequences of accidents**
    - **To eliminate the possibility of large off-site release**
      (maintaining the hermetic containment)
  - Means: advanced active and passive safety systems, reducing the **core damage frequency (CDF) and large release frequency (LRF)**
- **Passive safety systems**
  - Based on physical processes, operating without outer action or energy sources
  - Heat removal from primary circuit and containment by processes driven by gravity, natural circulation and compressed (high pressure) gas
  - Heat sink: evaporation pool or air cooling
- Other engineering tools
  - Larger water volumes (pressurizer, steam generator), lower power density, negative reactivity coefficients -> **larger margins and time constraints**
  - **Reliable, redundant and diverse systems** with **physical separation**
  - More robust **containments**, defense against external risks (double wall containment)
  - Management of severe accidents (corium cooling + handling)

Passive safety of Generation III



Passive systems of Kerena by Areva (former SWR-1000 of Siemens-Framatome)

Passive safety of Generation III



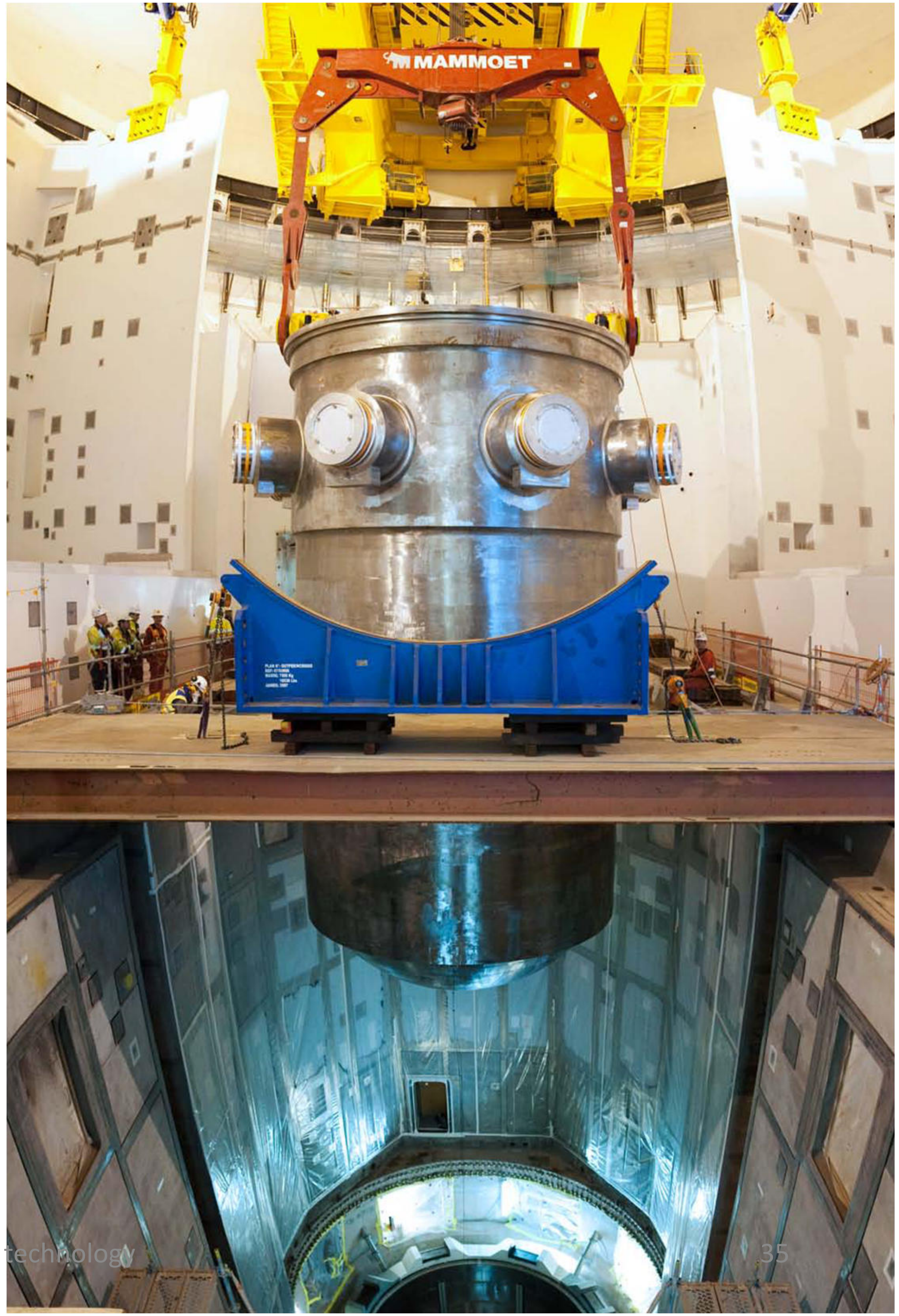
Source: Areva

- Example: SWR-1000: advanced boiling water reactor
- P_{el}=1250 MW
- Passive safety systems
  - Emergency condensers
  - Containment cooling condenser
  - (Core flooding system)

An example for passive safety systems: the former SWR-1000 of Siemens-Framatome (now Kerena)

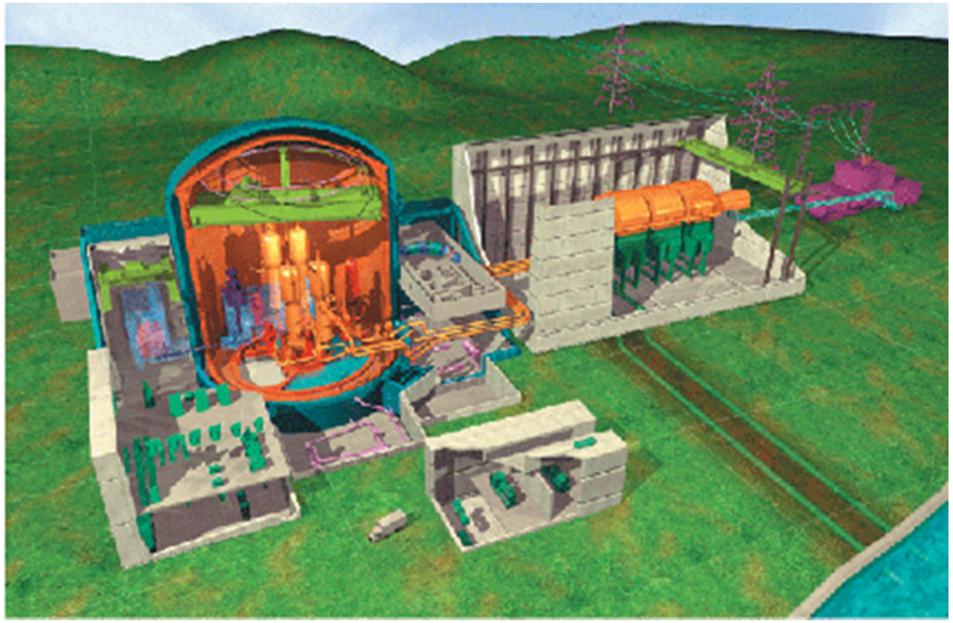
Generation III at present

- Operating Gen3 units at present:
  - ABWR: 2 units in Japan – temporary shut down
  - APR-1400: Shin Kori 3 (Korea)
  - VVER-1200: Novovoronezh-II-1 (Russia), Leningrad II-1 (Russia)
  - EPR: Taishan
  - AP1000: Sanmen-1, 2, Haiyang-1, 2 (China)
- Under construction:
  - ABWR
    - Taiwan: Lungmen-1, -2
    - Japan: Shimane-3
  - EPR
    - Finland: Olkiluoto-3
    - France: Flamanville-3
    - China: Taishan-1 and -2
  - APR-1400
    - South-Korea: Shin-Kori-4
    - United Arab Emirates
  - AP-1000
    - China: Sanmen-1, 2, Haiyang-1, 2
    - USA: Vogtle-3 and 4, Virgil C. Summer -2 and -3
  - VVER-1200
    - Russia: LNPP-2, NVNPP-2
    - Belarus: Astravets
  - ACPR1000, Hualong One
    - Yangjiang, Hongyanghe, Tianwan, Fuqing, Fangchenggang



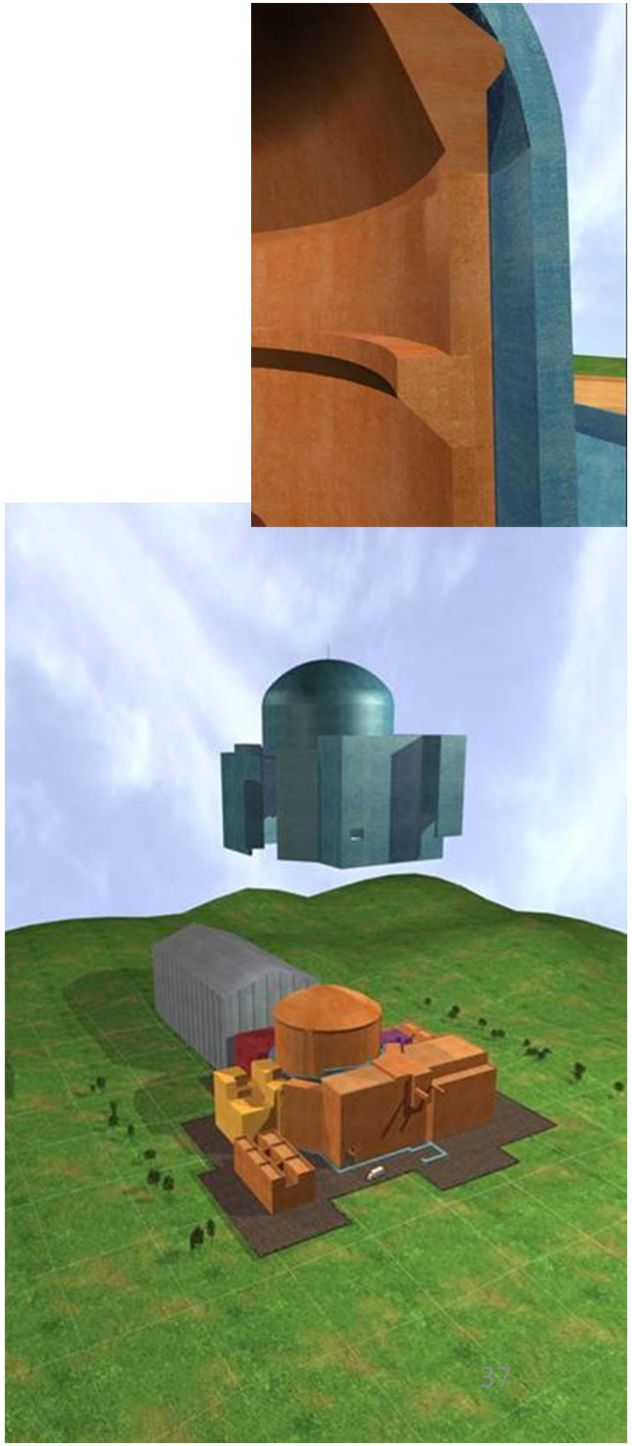
EPR

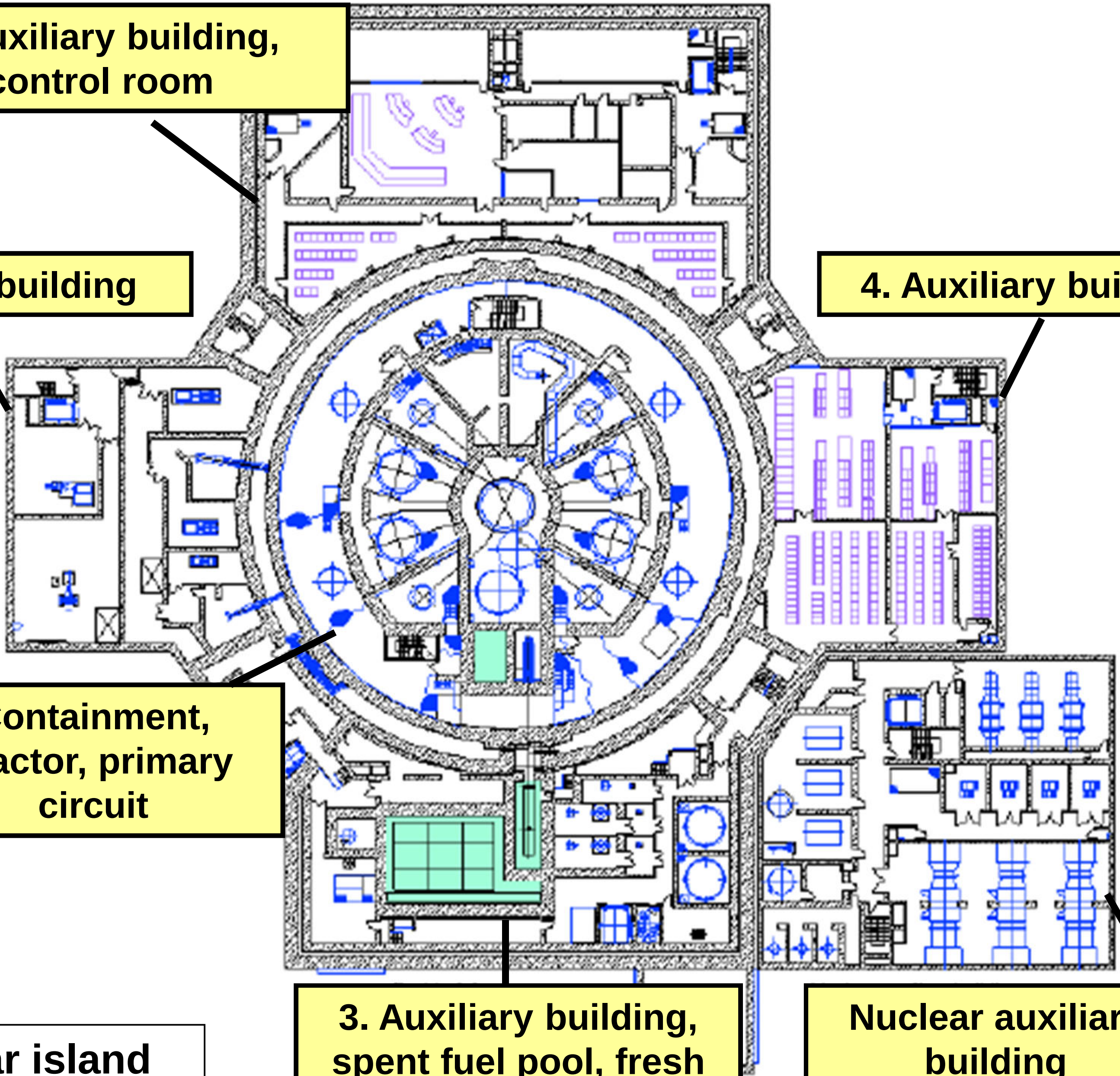
- EPR – European Pressurized Water Reactor
- At the moment:
  - 4 units under construction (2 in China, 1 in Finland, 1 in France)
- Generation III, evolutionary design developed on the basis of the French N4 and the German Konvoi types
- PWR
- Thermal power:
  ~4500 MW
- Electric output:
  ~1600-1650 MW
- Efficiency:
  36-37% (2nd generation PWRs: ~ 33%)



EPR

- Primary circuit:
  - Operational pressure: 154 bar
  - Input/output temperature: 296/327 °C
  - 4 primary loops
- Secondary circuit:
  - Operational pressure: 78 bar
  - Fresh steam temperature: 290 °C
  - 1 HP + 3 LP turbine
- Double wall hermetic containment, designed to withstand the crash of a large passenger airplane





2. Auxiliary building, control room

1. Auxiliary building

4. Auxiliary building

Containment, reactor, primary circuit

3. Auxiliary building, spent fuel pool, fresh fuel storage

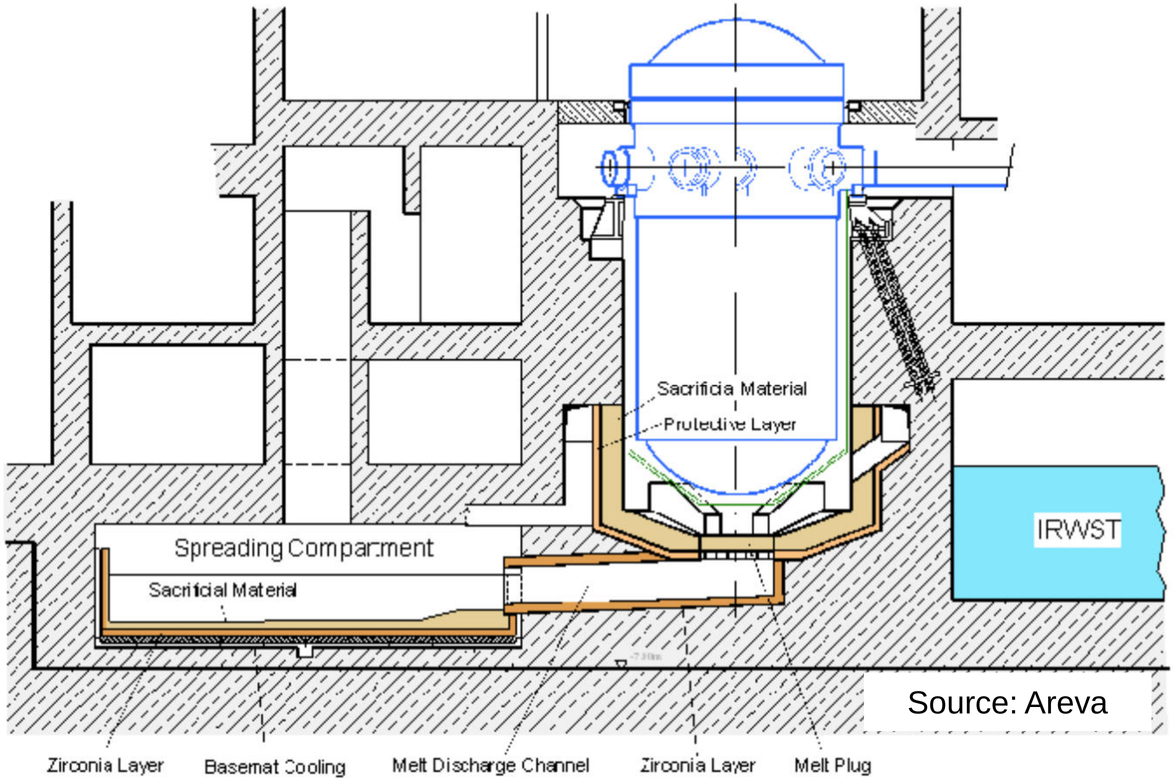
Nuclear auxiliary building

The nuclear island

Source: Areva

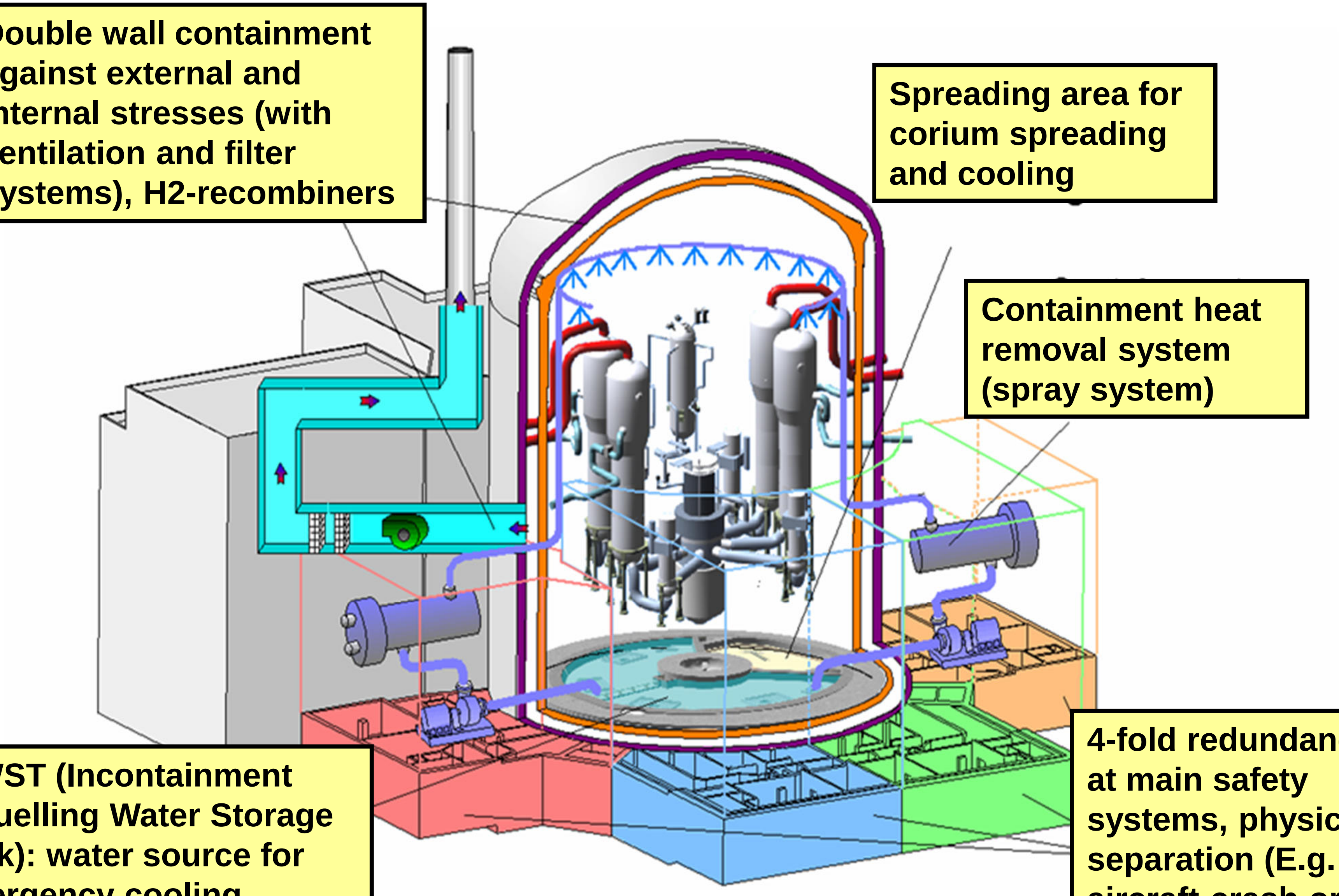
EPR safety systems

- Safety philosophy: to prevent off-site consequences with:
  - Improving accident prevention systems.
  - Tools: simplification, physical separation, reducing the possibility of human failure
- Decrease the consequences of severe accidents – tools: containment cooling, corium catching and cooling, cooling of basemat from below
- **CDF: 10^{-6} / year**, frequency of large release is even lower
- 6 m thick concrete basemat
- Double wall containment, the outer wall covers the 2. and 3. auxiliary buildings as well



Source: Areva

Corium spreading area



Double wall containment against external and internal stresses (with ventilation and filter systems), H2-recombiners

Spreading area for corium spreading and cooling

Containment heat removal system (spray system)

4-fold redundancy at main safety systems, physical separation (E.g. for aircraft-crash or fire)

IRWST (Incontainment Refuelling Water Storage Tank): water source for emergency cooling systems and for corium cooling in severe accidents

Source: Areva

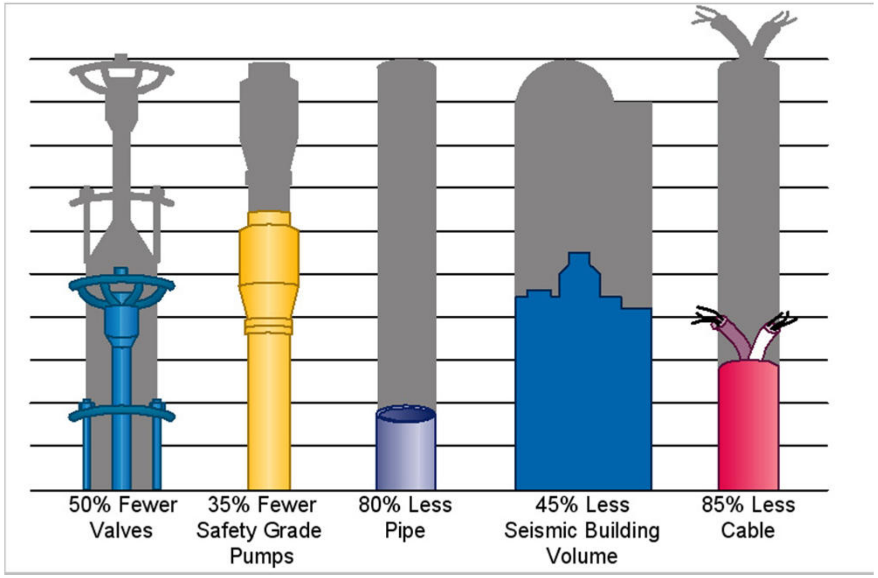
Olkiluoto-3, the first EPR unit

- December 2003: Owner TVO selected the AREVA EPR™ design to be built at Olkiluoto
  - Turn-key contract: **3.2 billion** euro
- Original plan: start of construction in 2004, start of commercial operation in **2009** (5 years construction time).
  - July 2005: Start of construction, first concrete pouring
  - June 2010: Installation of the reactor pressure vessel in the reactor building
  - November 2011: Installation of heavy components of the primary cooling system complete

- Now: start of commercial operation in ~~2015 or 2016~~ **2018**, costs **~8 billion** euro
- Various problems including project-coordination, dialogue with authority, quality problems

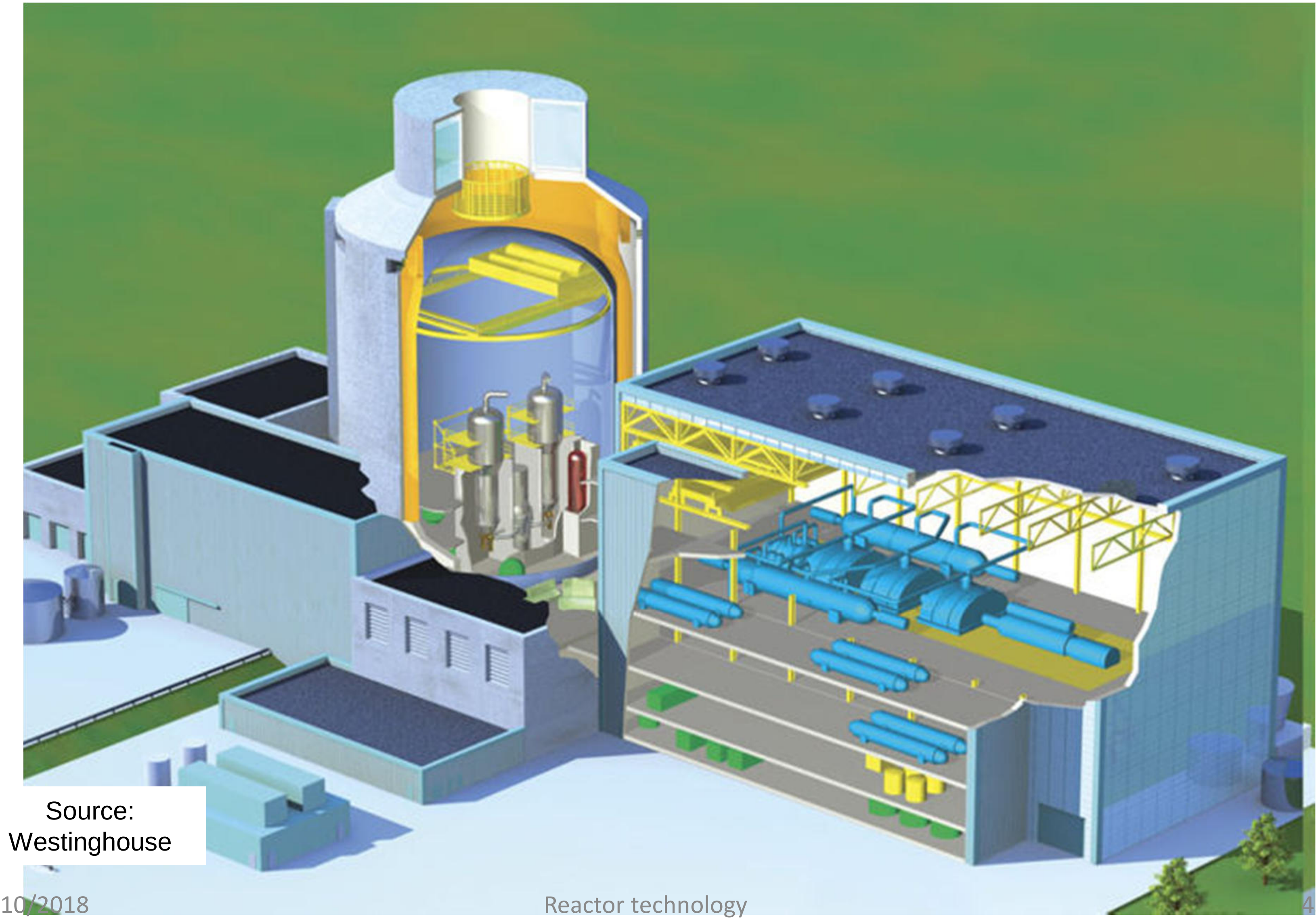
AP1000

- AP1000 – Advanced Passive Plant, Westinghouse
- Under construction:
  - 2 Units at Sanmen NPP, China (February 2008)
  - 2 Units at Haiyang NPP, China (July 2008)
  - 2 Units at Vogtle NPP, USA (February 2012)
  - 2 Units at Virgil C Summer (March 2012)
- PWR with two loops
- Electric output: 1117 MWe
- Passive safety systems
  - Simplified systems with less component than present PWRs
- NRC design certification in 2005
- **CDF=5,09x10^{-7} / year** according the PSA analysis
- Modular construction (transport by rail or by ship)
- Planned construction time: 36 months (☺)
- 18 month campaign
- 60 years planned lifetime



AP1000 – Source: Westinghouse

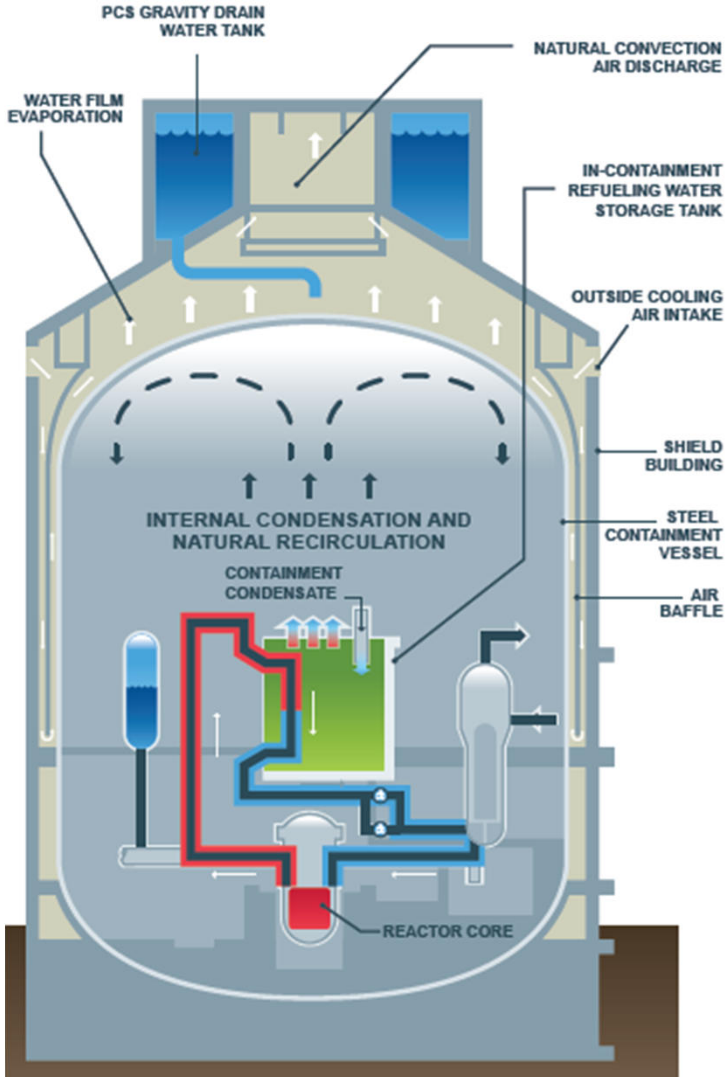
AP1000



Source:
Westinghouse

AP1000

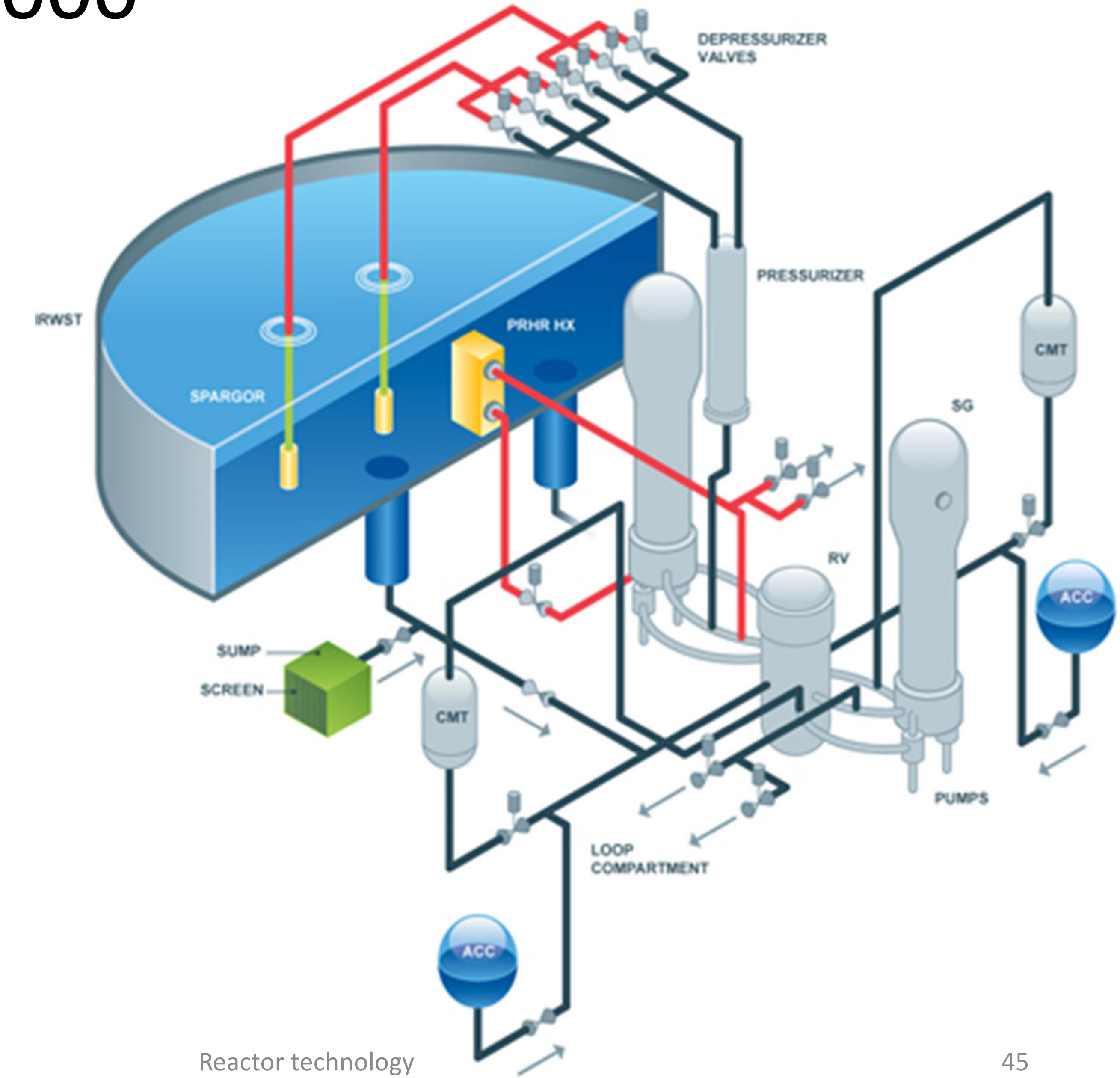
- **Passive safety systems**: no operator action is necessary in the first 72 hours of a DBA (including SBO)
- Passive core cooling system for LOCA, remanent heat removal, automatic depressurization and coolant injection
- **Passive Containment Cooling System**
- Main control room emergency habitability system – for 11 people for 72 hours
- Containment isolation – 60% less penetration



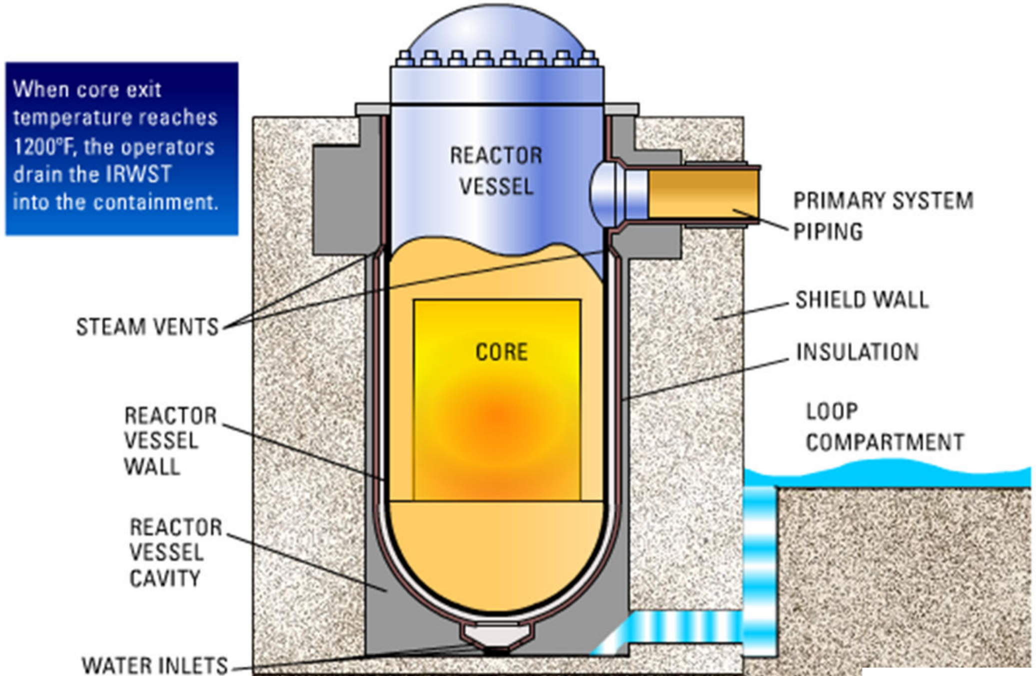
Source: Westinghouse

AP1000

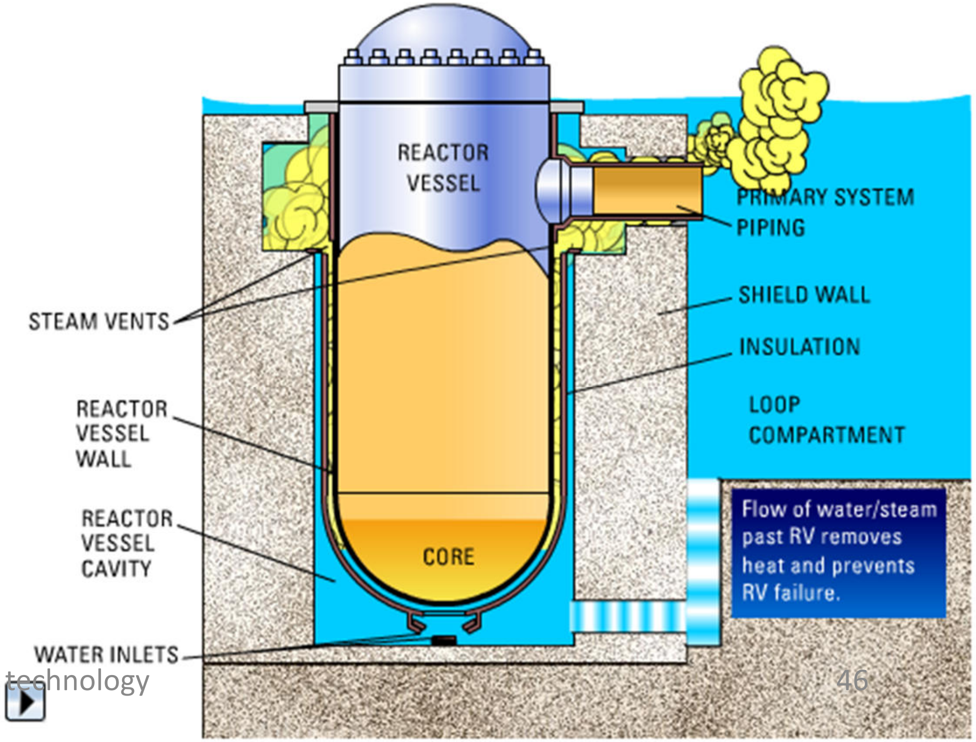
- Passive safety systems



AP1000 pressure vessel outer flooding



- Severe accident management: preventing RPV failure in case of core melting (outer RPV flooding system)



AP1000 - Vogtle

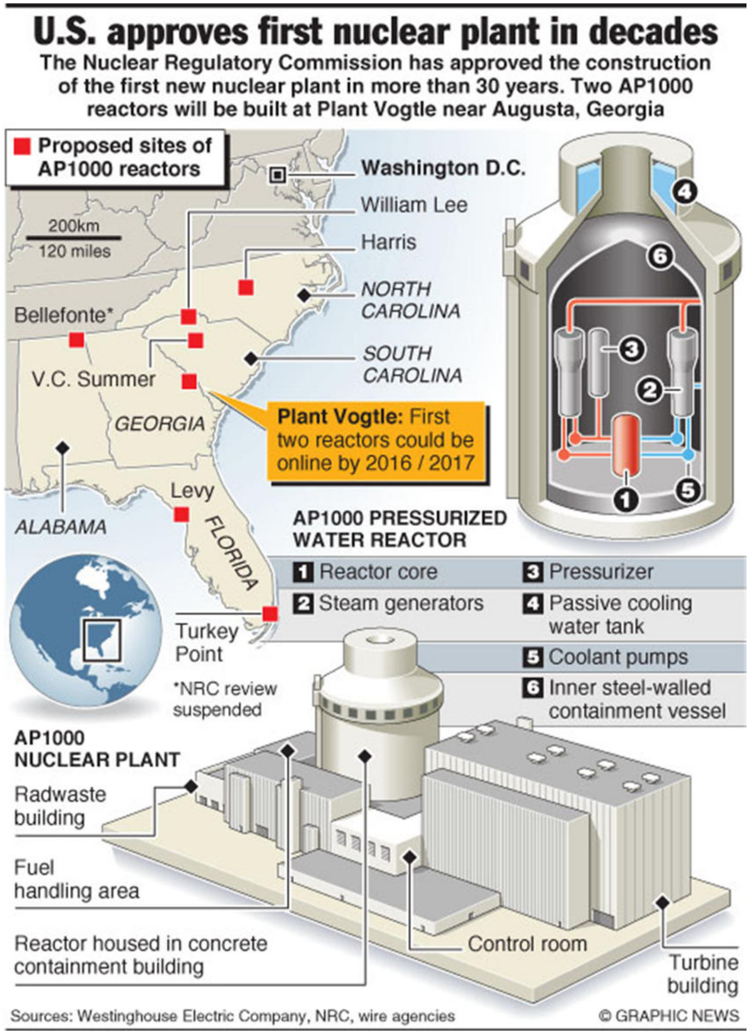
- USA: last construction license was issued in 1978
- New licensing system (separated design assessment and site permit, combined construction and operation license) no combined license issued until 2012
- February 2012: NRC issued combined license for Southern Company for the construction of two AP1000 units at the Vogtle site, where 2 PWR units are operating (votes 4:1)
- According to the schedule, the new units could start in ~~2016-2017 2017-2018~~ 2019-2020

Original

Cost:	4.8 bn $
Completion	2016/2017

Revised

Cost:	5.045 bn $
Completion	2019/2020



U.S. approves first nuclear plant in decades

The Nuclear Regulatory Commission has approved the construction of the first new nuclear plant in more than 30 years. Two AP1000 reactors will be built at Plant Vogtle near Augusta, Georgia

Plant Vogtle: First two reactors could be online by 2016 / 2017

*NRC review suspended

Sources: Westinghouse Electric Company, NRC, wire agencies

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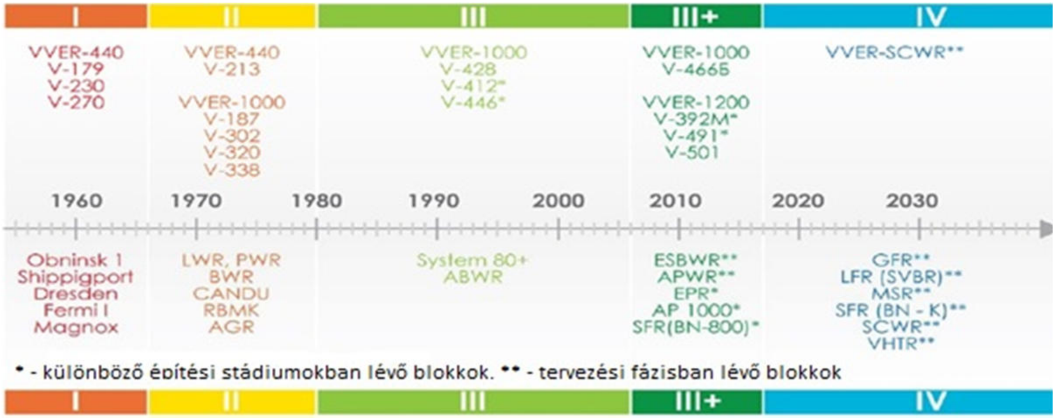
VVER-1200

- Gidropress
- PWR
- Based on VVER-1000 (AES-91 and AES-92) models
  - AES-91: Tianwan
  - AES-92: Kudankulam
- Generation III+
- Nominal gross power: 1200 MW
- 60 years lifetime for the main equipment
- Load following capability
- **CDF < 6x10^{-7} /reactor.year**
- LRF (Large release frequency) < 10^{-7} /reactor.year


Kudankulam NPP

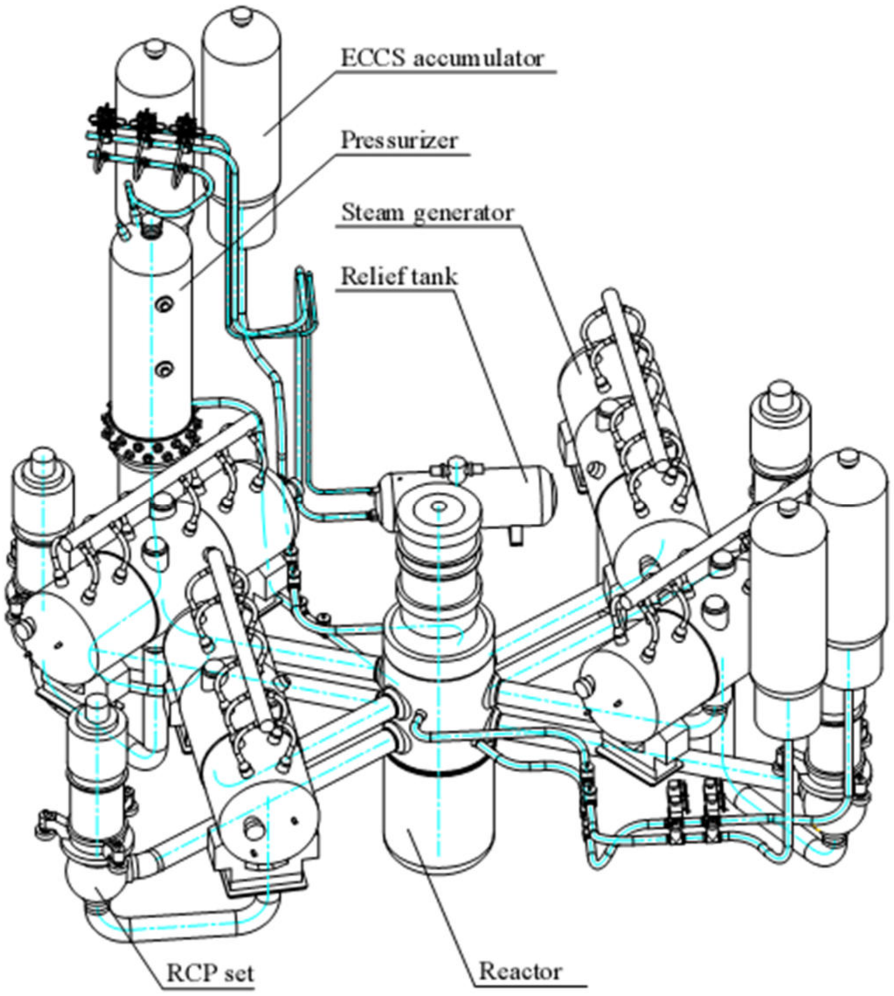


Reaktor generációk

VVER-1200 (AES 2006)

- Models (same parameters, different safety solutions):
  - **V392M** – developed by the Moscow design institute (in operation and under construction in Novovoronezh)
  - **V491** – developed by the St. Petersburg design institute (under construction in the Leningrad-II NPP, in Belarus NPP~~, in Baltic NPP~~), planned at Paks NPP

Operational parameters	
Efficiency	33,9%
Pressure of primary circuit	162 bar
Temperature of primary coolant	298-328 °C
Steam pressure	68 bar
Steam temperature	283 °C
Initial enrichment	4,79%
Burnable poison	Gd2O3



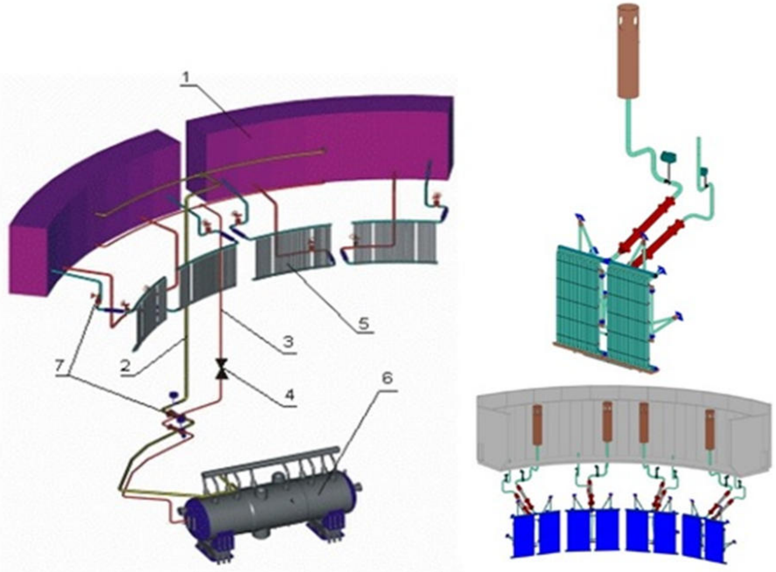
VVER-1200 V491 safety systems

- Application of European Utility Requirements and safety philosophy (DBC, DEC conditions)
- Designed to resist external hazards (e.g. wind, tornado, snow pressure, seismic effects – 0.25 g maximal PGA)
- Active systems: 4x100% redundancy, physical separation
- Passive safety systems

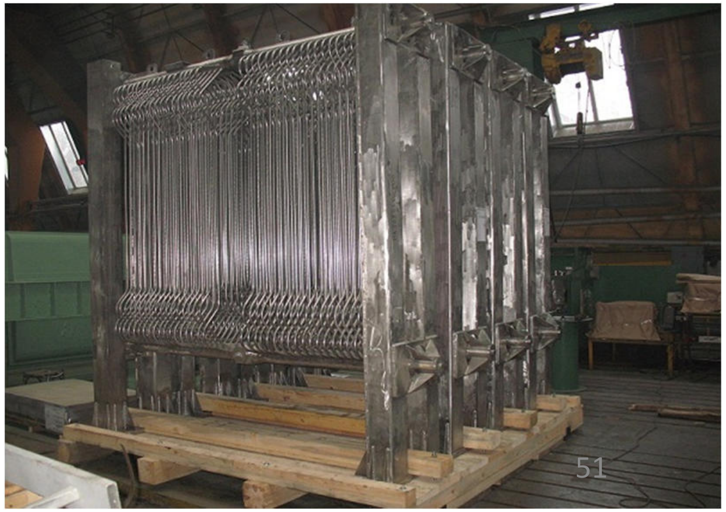
Four branches of the active safety systems

VVER-1200 V491 safety systems

- Active safety systems (ECCS, CS, emergency boron injection system, residual heat removal system, emergency feedwater system, etc.)
- Localization systems
  - Double wall cylindrical containment made of pre-stressed concrete,
  - Steel cladding (liner) on the inner surface of the internal wall
  - Leakage rate: 0.2% for 24 hours
  - P_d: 5 bar T_d: 150 ^{o}C
- Passive systems (BDBA)
  - Hydroaccumulator (59 bar)
  - Passive containment heat removal
  - Passive SG cooling
    - Experimental and numerical tests
  - Passive autocatalytic H-recombiners (1000 kg H2)



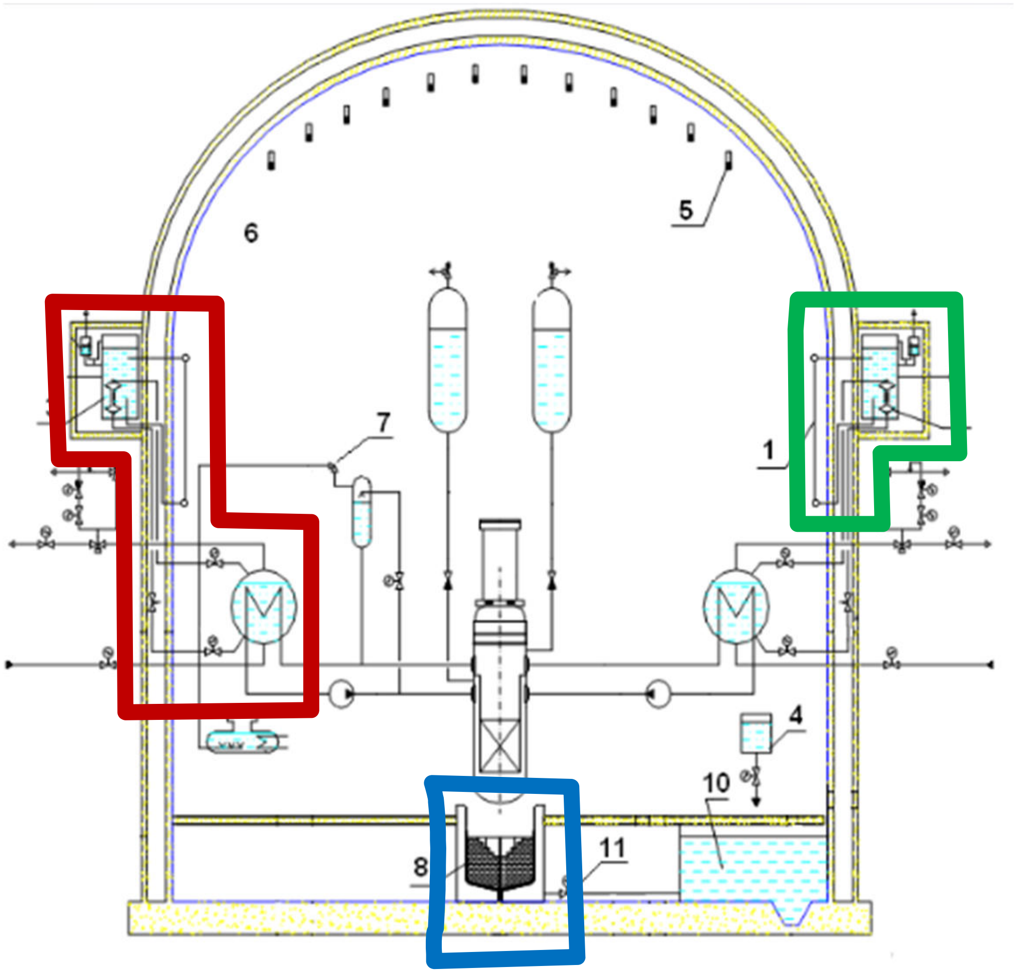
Passive SG cooling system



Heat exchanger of PHRS-SG

VVER-1200 / V491

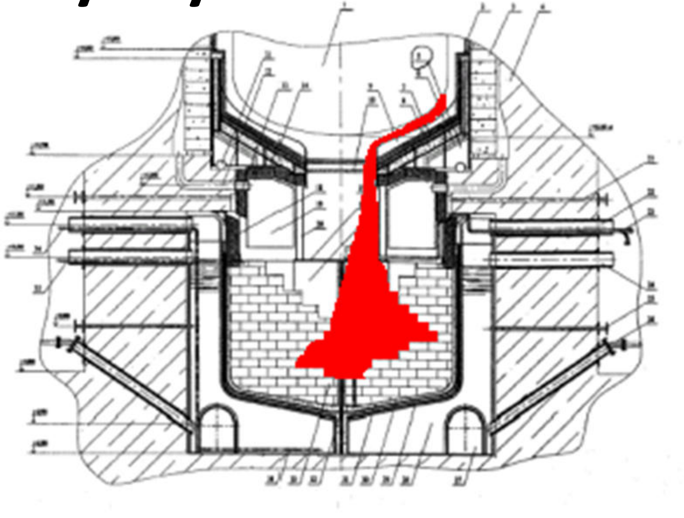
1- passive containment cooling system
2- passive heat removal system (PHRS SG)
3- PHRS tank
4- emergency chemical addition
5- hydrogen recombiner
6- hydrogen monitoring transmitter
7- pressurizer safety valve
8- core catcher
9- SPF water supply
10- borated water tank
11- core catcher closing valve



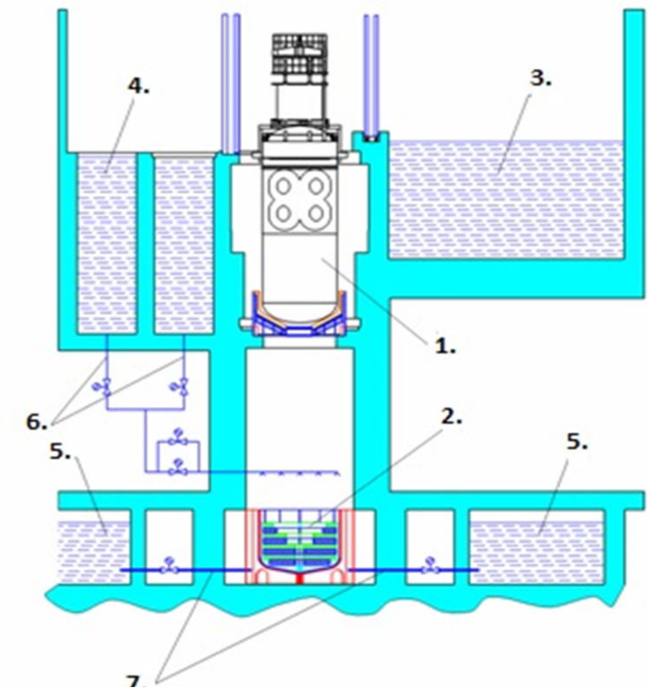
Source: Atomstroyeksport

VVER-1200 V491 safety systems

- Severe accident management: core catcher – introduced in Tianwan NPP
  - Large size core catcher to minimize the corium thickness
  - Preventing re-criticality
  - Outer cooling with natural circulation (passive)
  - Corium can be flooded
  - Because of the thick corium layer, 1 year is necessary for full solidification
- Mass: 150 t, height: 6 m
- Al2O3-Fe2O3 mixture as sacrificial material (200 t)
- Double wall core catcher



VVER core catcher



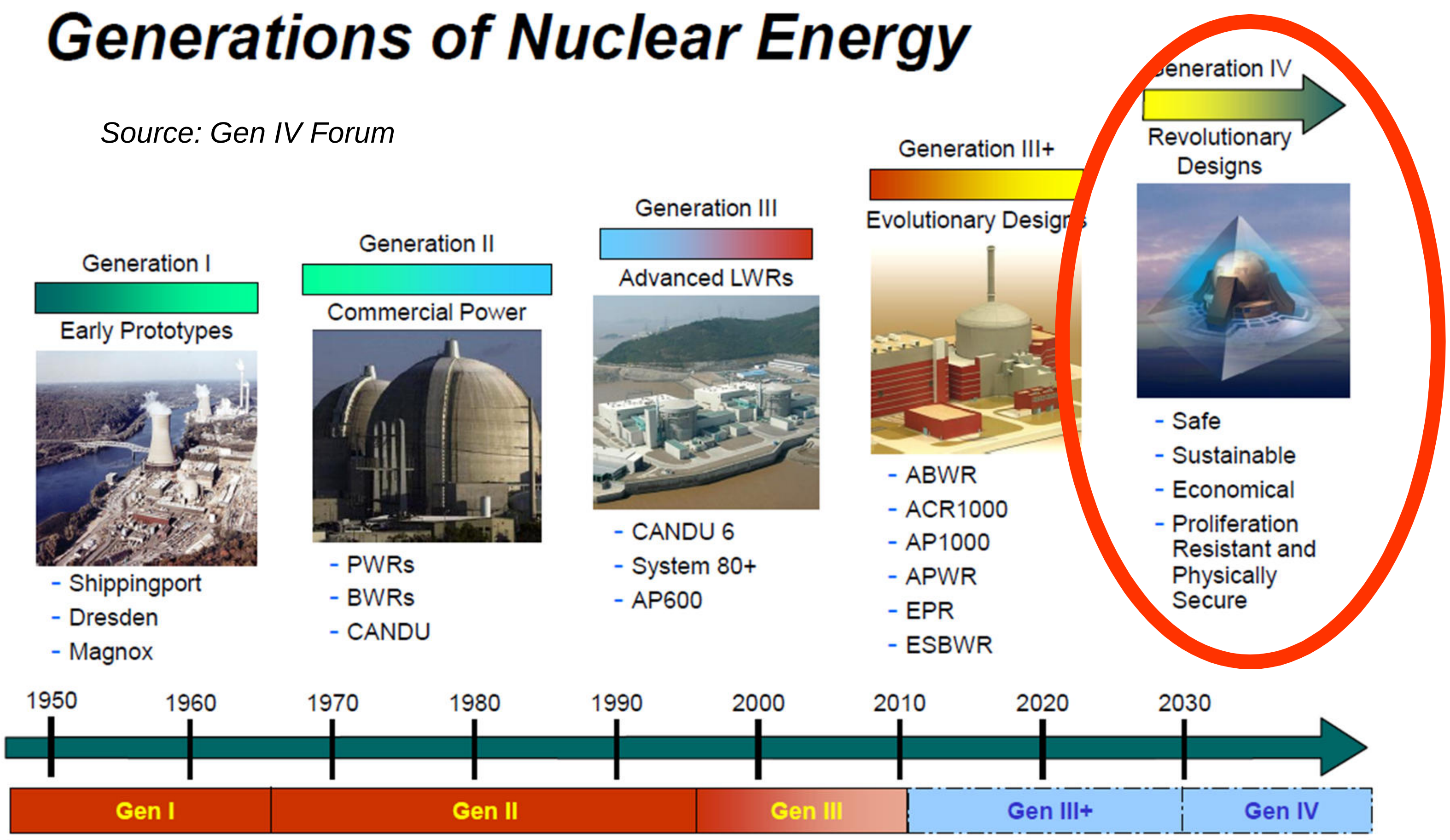
VVER-1200 V491 safety systems

- Core catcher

Installation of the core catcher at the Leningrad-II NPP (unit 1)

Sacrificial material of the core catcher

Generation IV reactors

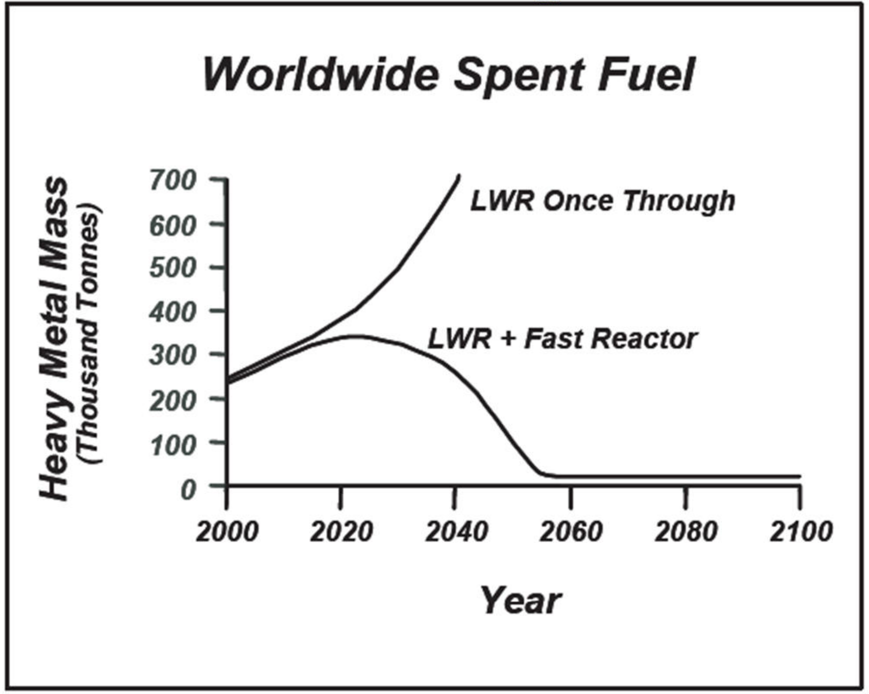

Generations of Nuclear Energy

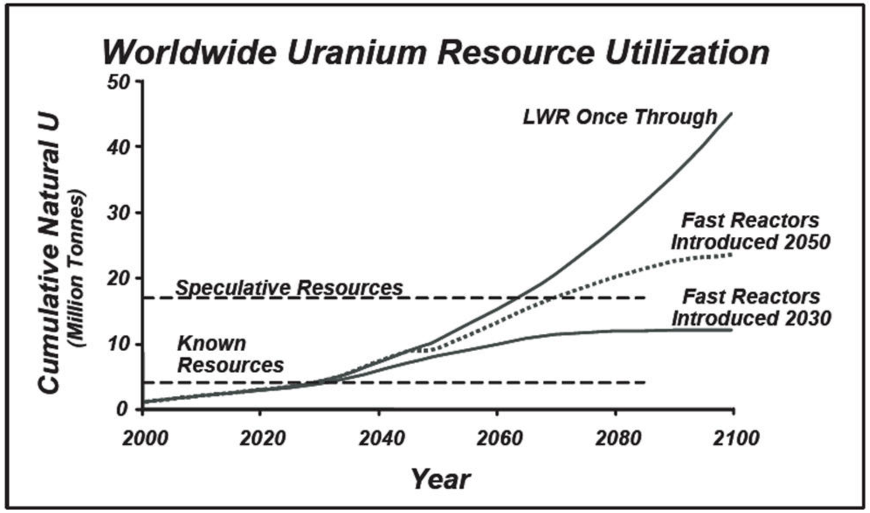
Source: Gen IV Forum

- Generation IV: reactor designs to be deployed from 2030
- Designs developed based on all operational and safety experiences
- Main goal is to ensure the sustainable electricity generation (coupled heat and electricity generation, hydrogen production, seawater desalination)

Fuel cycle and sustainability

- Expectations for **open fuel cycle** (with the present electricity generation)
  - Largest amount of waste – but still less than in case of other energy sources
  - Amount of waste is limiting the use of nuclear energy: many final disposals are necessary in the next decades
  - Most unfavorable utilization of the resources: the known resources will depleted before the end of the century

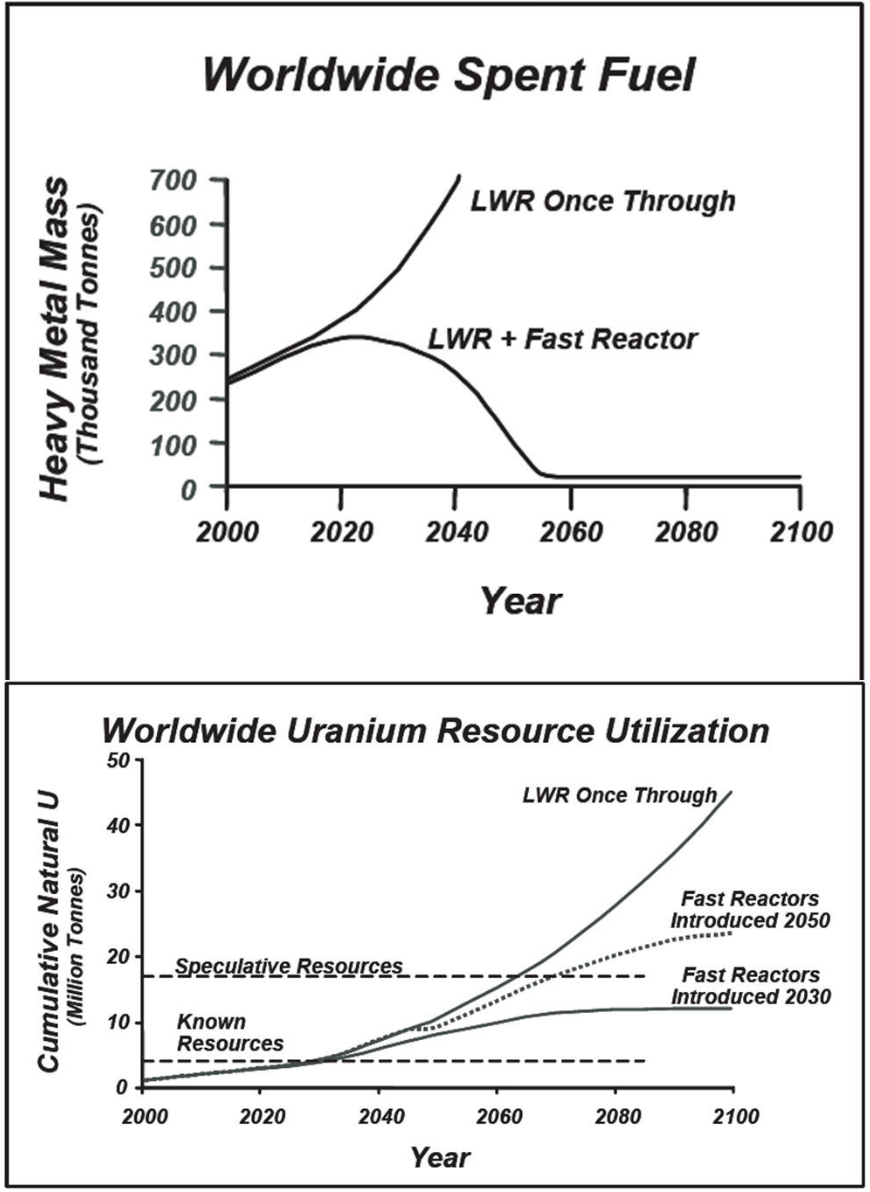




Effect of fast reactor introduction on the fuel utilization
Source: GenIV

Fuel cycle and sustainability

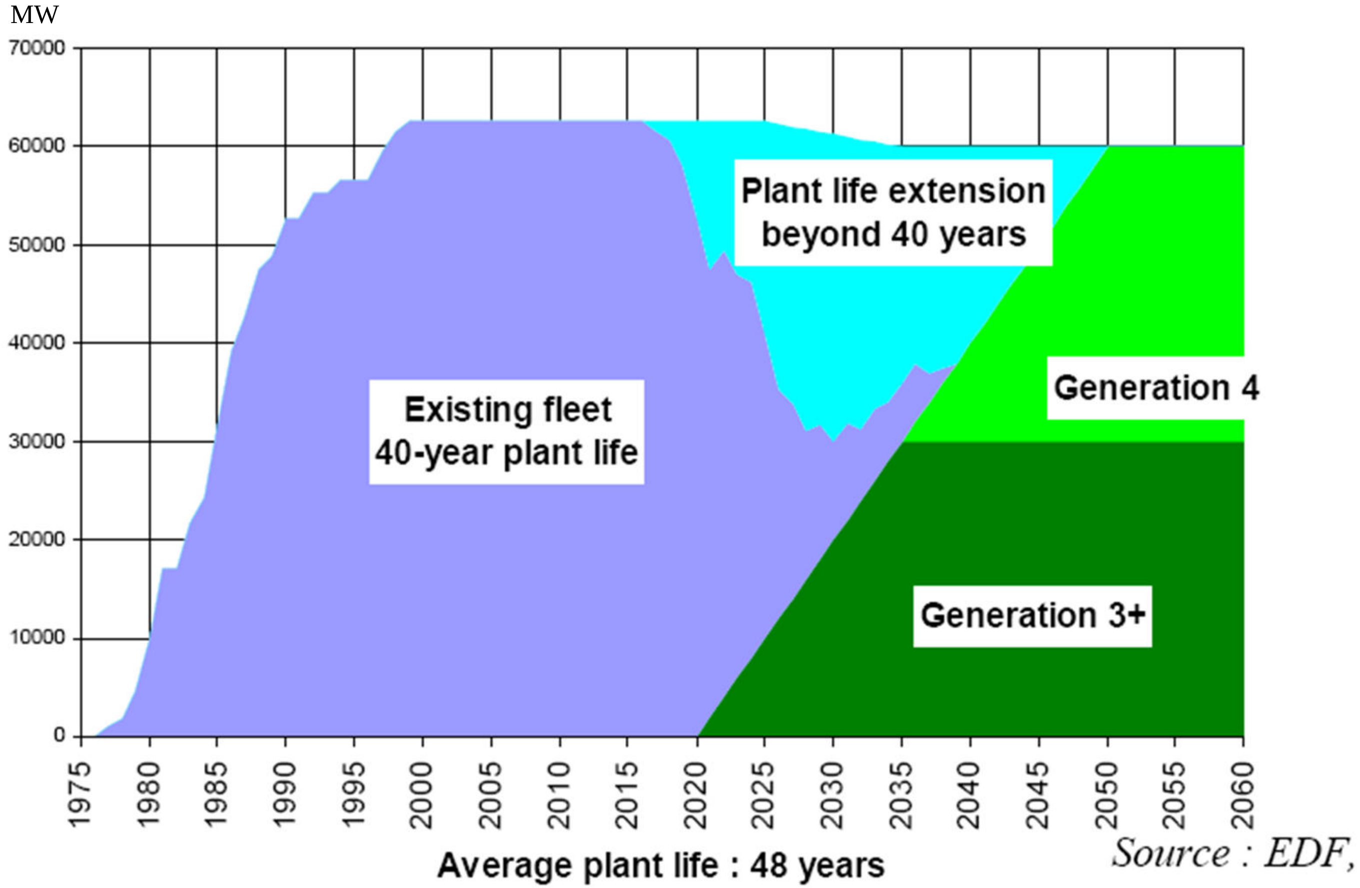
- Expectations for **closed fuel cycle** (with the present electricity generation)
  - Amount of waste can be decreased significantly
  - With the use of transmutation facilities, waste amount can be decreased by an order of magnitude
  - Different waste fractions could be managed separately
  - Problems:
    - Cost reduction
    - Proliferation risks



Effect of fast reactor introduction on the fuel utilization
Source: GenIV

Transition from Gen III to Gen IV

- Present: operating Generation II reactors with lifetime extension
- Generation III/III+: for replacement of the existing fleet around 2020
- Generation IV: deployment in 2030-2035

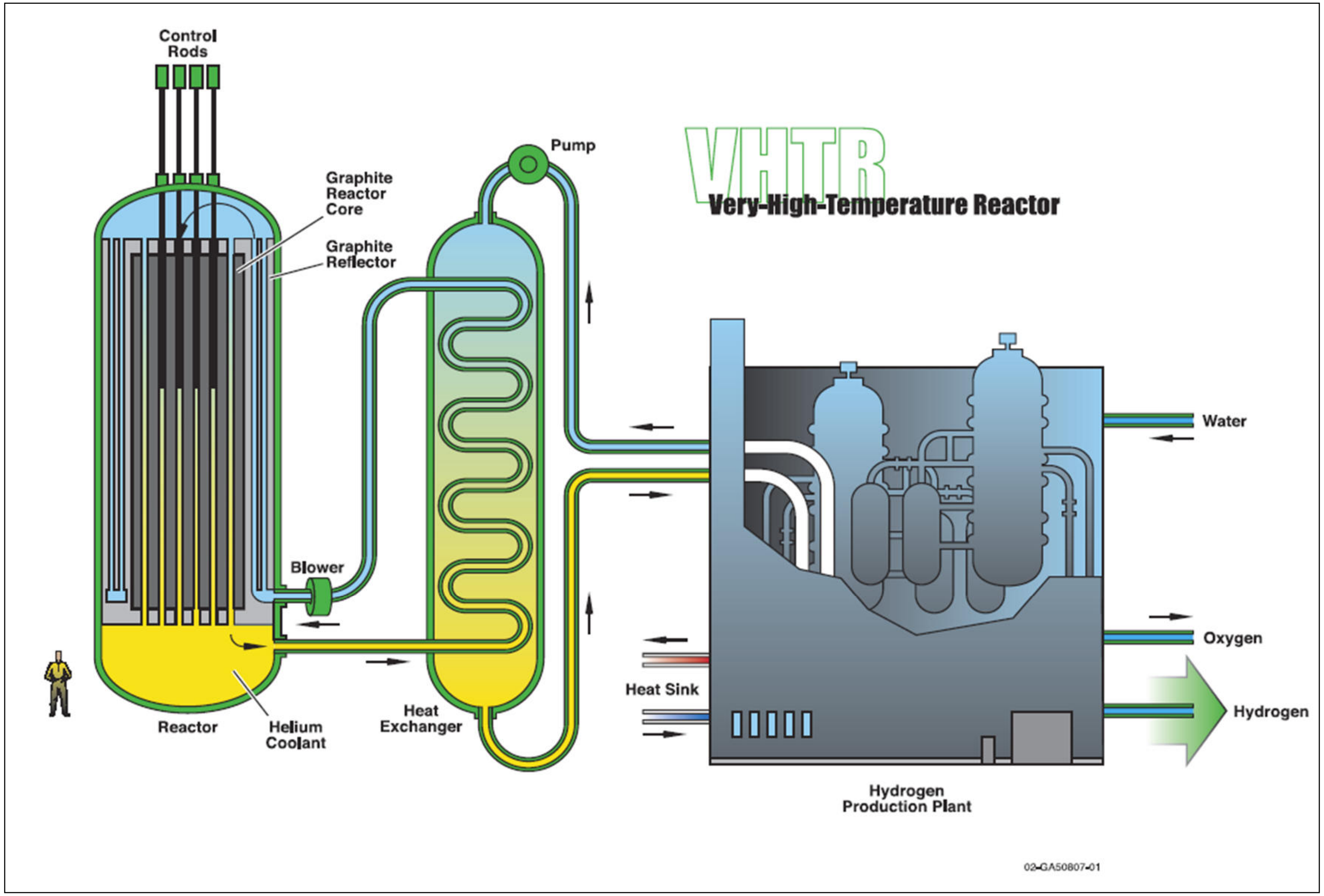


Source : EDF,

Installed capacity in France

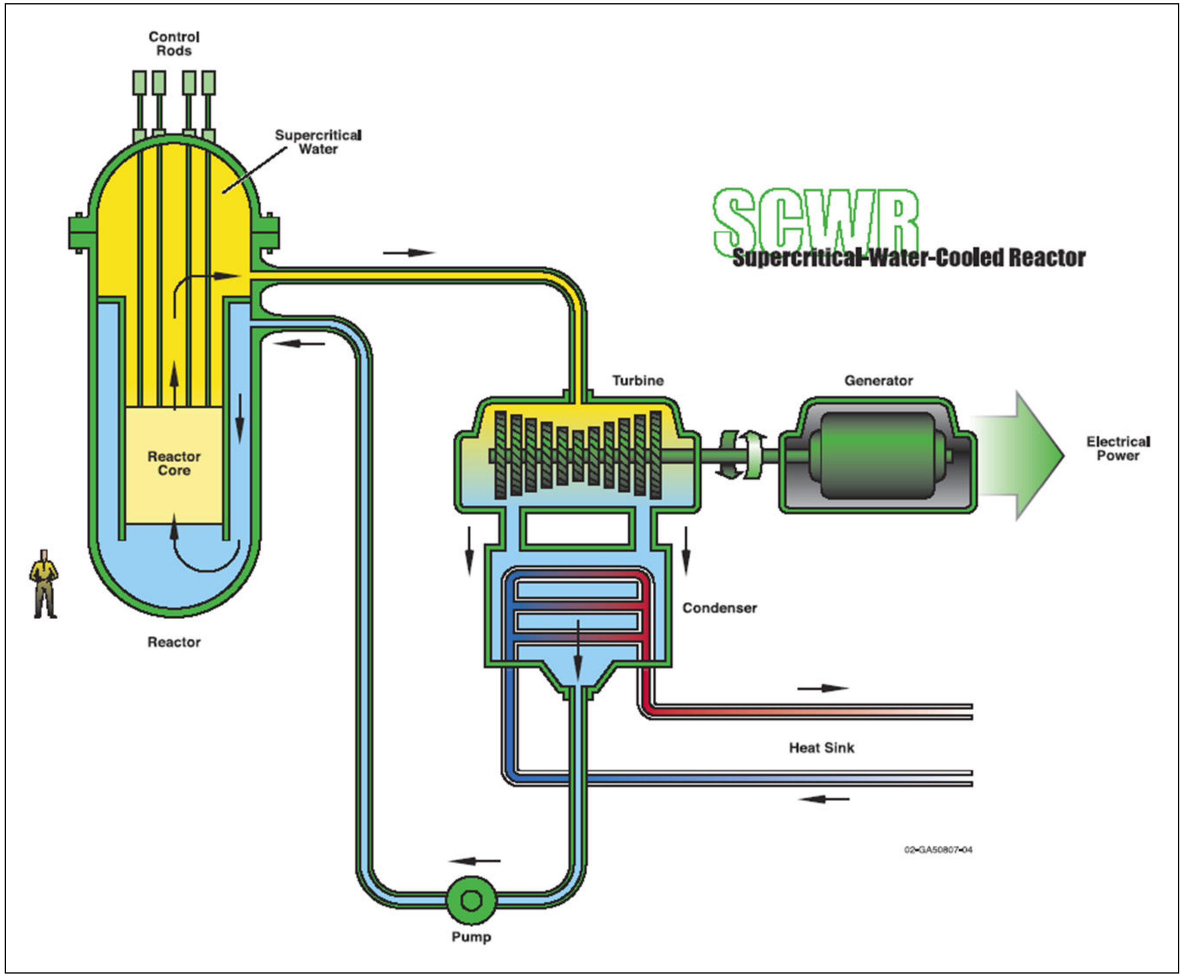
Generation IV reactors

Surce: GenIV



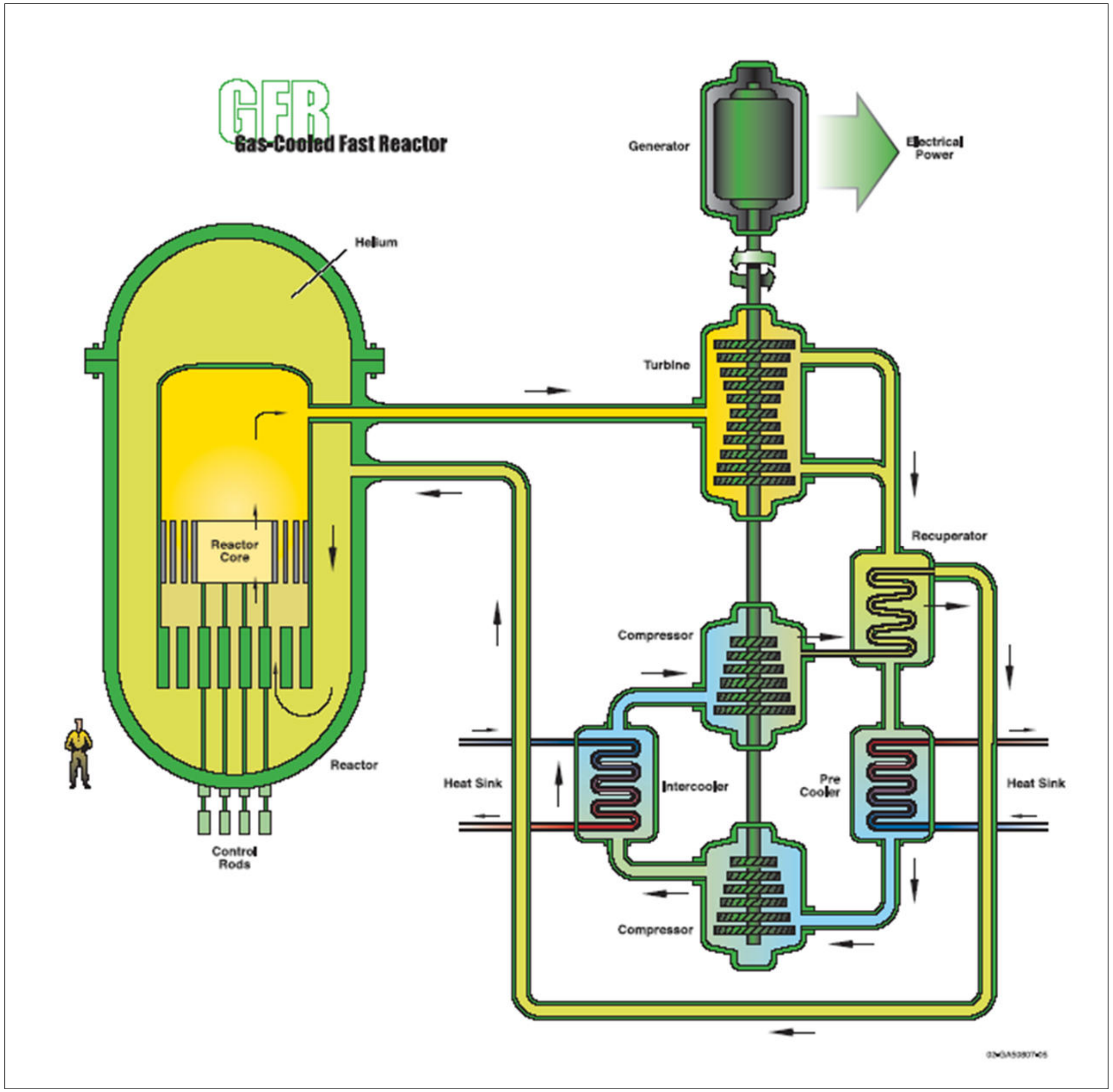
Generation IV reactors

Surce: GenIV



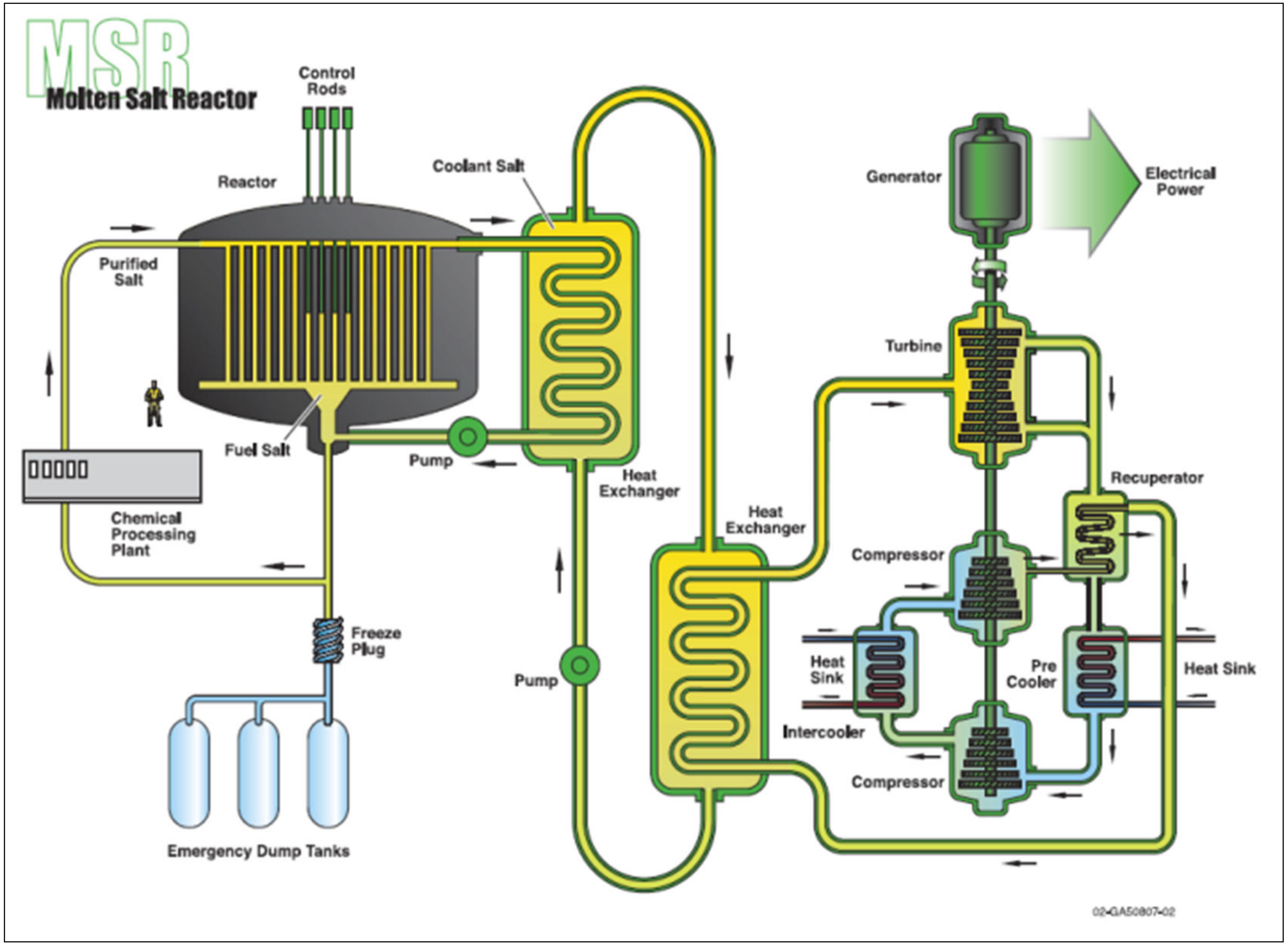
Generation IV reactors

Surce: GenIV



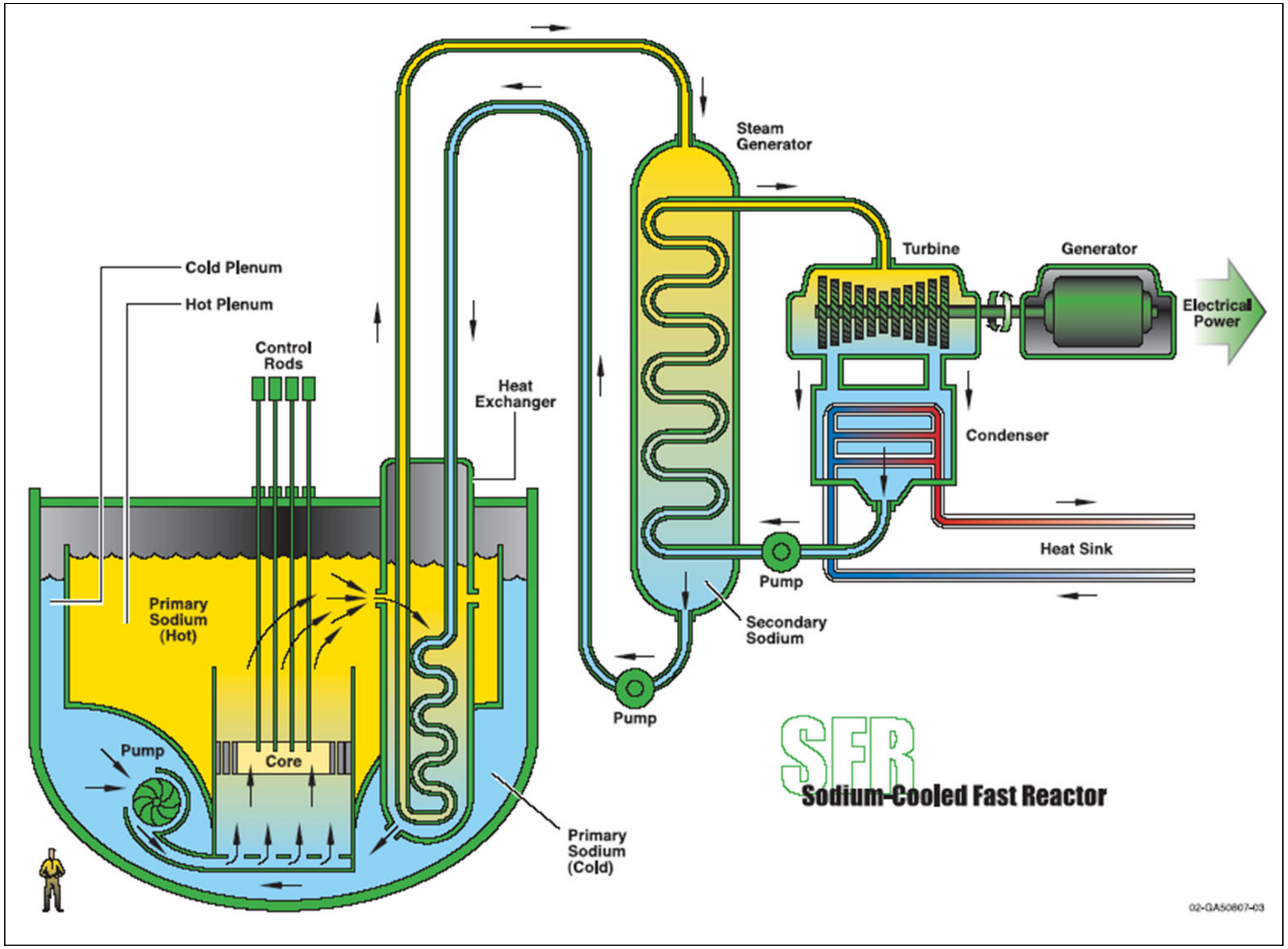
Generation IV reactors

Source: GenIV



Generation IV reactors

Source: GenIV



Generation IV reactors

Source: GenIV