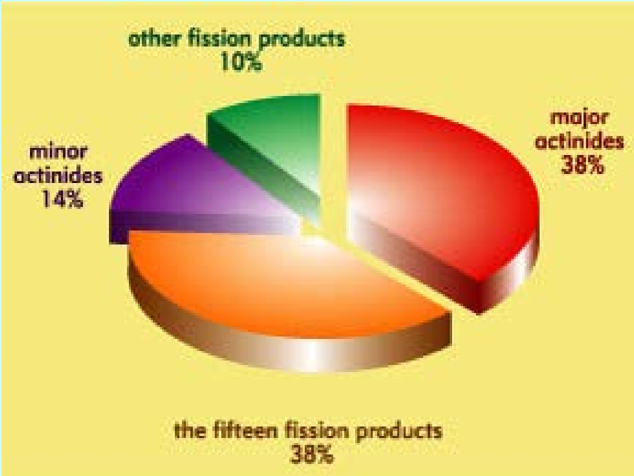

Module 02
Nuclear Engineering Overview

Status 1.3.2017

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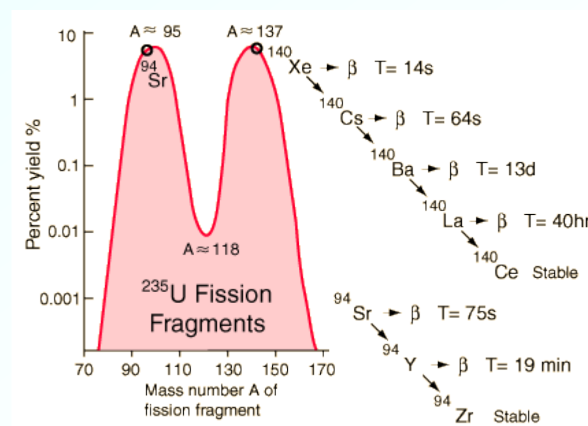

Application of Nuclear Reactors

- **Research reactors**: use neutrons for basic and applied research (normally no power production)
- **Nuclear power plants** (NPP): use thermal energy produced by fission process to produce electricity (process heat, district heating is also possible)
- **Propulsion reactors**: Aircraft carriers, submarines, ice breakers, satellites

(see www.world-nuclear.org/info/info.htm)

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Reactor Physics Repetition

- Natural Uranium : 99.28% U-238, 0.72% U-235
- Depleted Uranium: U-235 < 0.72%
- Low enriched Uranium (LEU): 0.72% < U-235 < 20%
- Medium enriched Uranium (MEU): 20% <U-235 <70%
- High enriched Uranium (HEU): 70% <U-235 <93%
- Nuclear Power Plants use U_{nat} or LEU or sometimes MOX (mixed UO_2 and PuO_2)
- German NPP consumed 25 to of Pu between 1966 to 2005 in MOX fuel (Atomwirtschaft 12/06)
- Research Reactors use LEU to HEU, gradual conversion from HEU to LEU to prevent proliferation
- Nuclear weapons use HEU or weapons grade Pu

Reactor Physics Repetition

- Thermal fission of U-235 results in ca. 2.5 fast neutrons and ca. 207 MeV of thermal energy per fission
- (200 MeV=3.2×10^{-11}J $\longrightarrow$ 1g U-235 approx. 1 MWd)
  - 167 MeV fission products
  - 5 MeV prompt gamma radiation
  - 5 MeV prompt neutrons (99.36%)
  - 13 MeV beta and gamma decay
  - 10 MeV neutrinos
  - 7 MeV delayed neutrons (0.64%)

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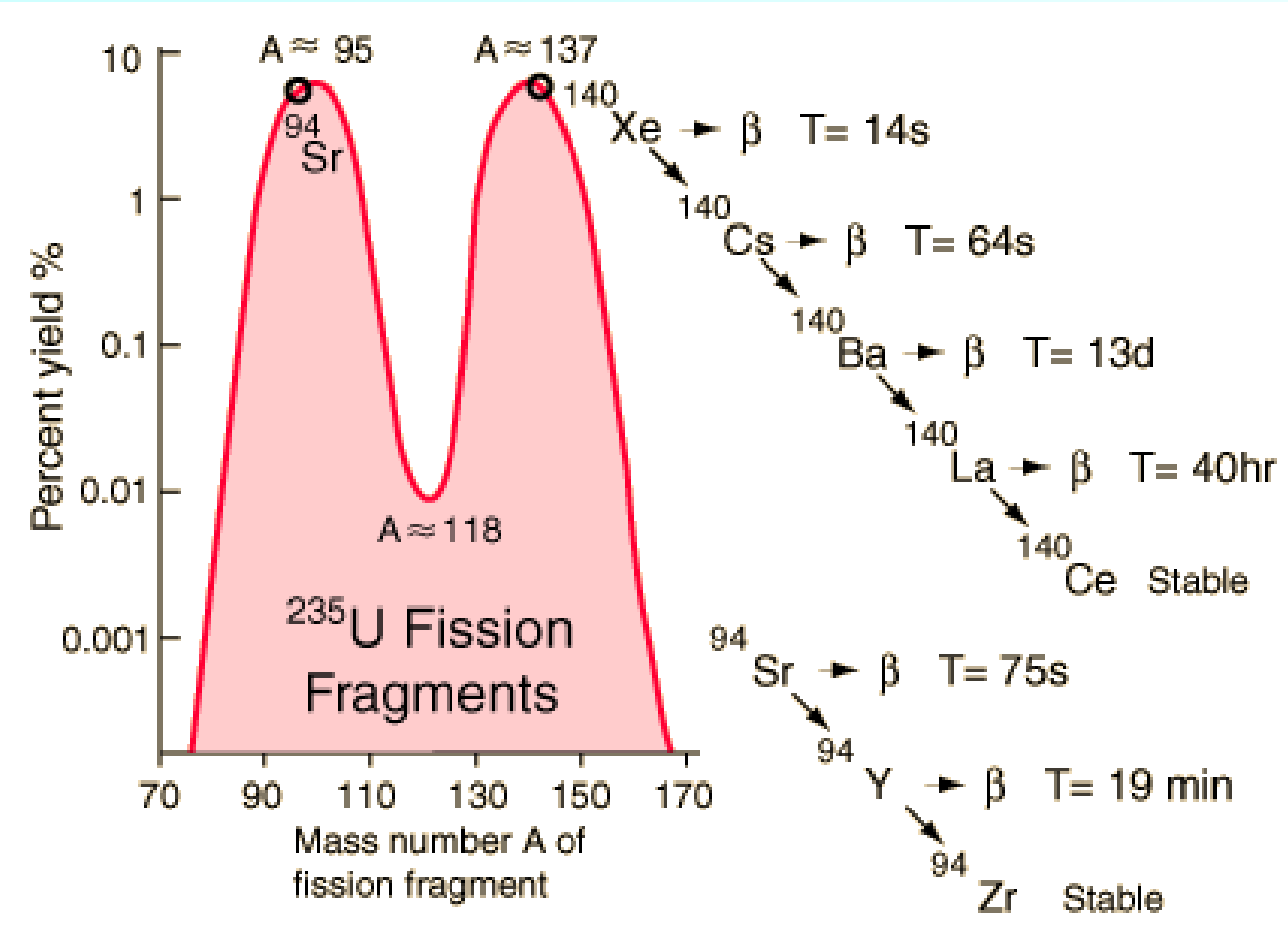
Mass Distribution of Fission Products



Reactor Physics Repetition

- **Prompt neutrons**: Production within 10^{-12} s after fission. They are slowed down by collision with (light) moderator nuclei (H_2O, D_2O, C), diffuse and some neutrons are absorbed again in U-235

- Such a cycle is described with the **four factor equation:**
- $\mathbf{k_\infty = \varepsilon . p . f . \eta}$

  ε … fast fission factor

  p … resonance escape probability

  f … thermal utilization factor

  η ... reproduction factor

- **Delayed neutrons**: Production time after fission from seconds to about one minute, only 0.64% of all neutrons are delayed but very important for the time behaviour of a reactor. A reactor is slightly subcritical with thermal neutrons and only delayed neutrons add up to criticality.

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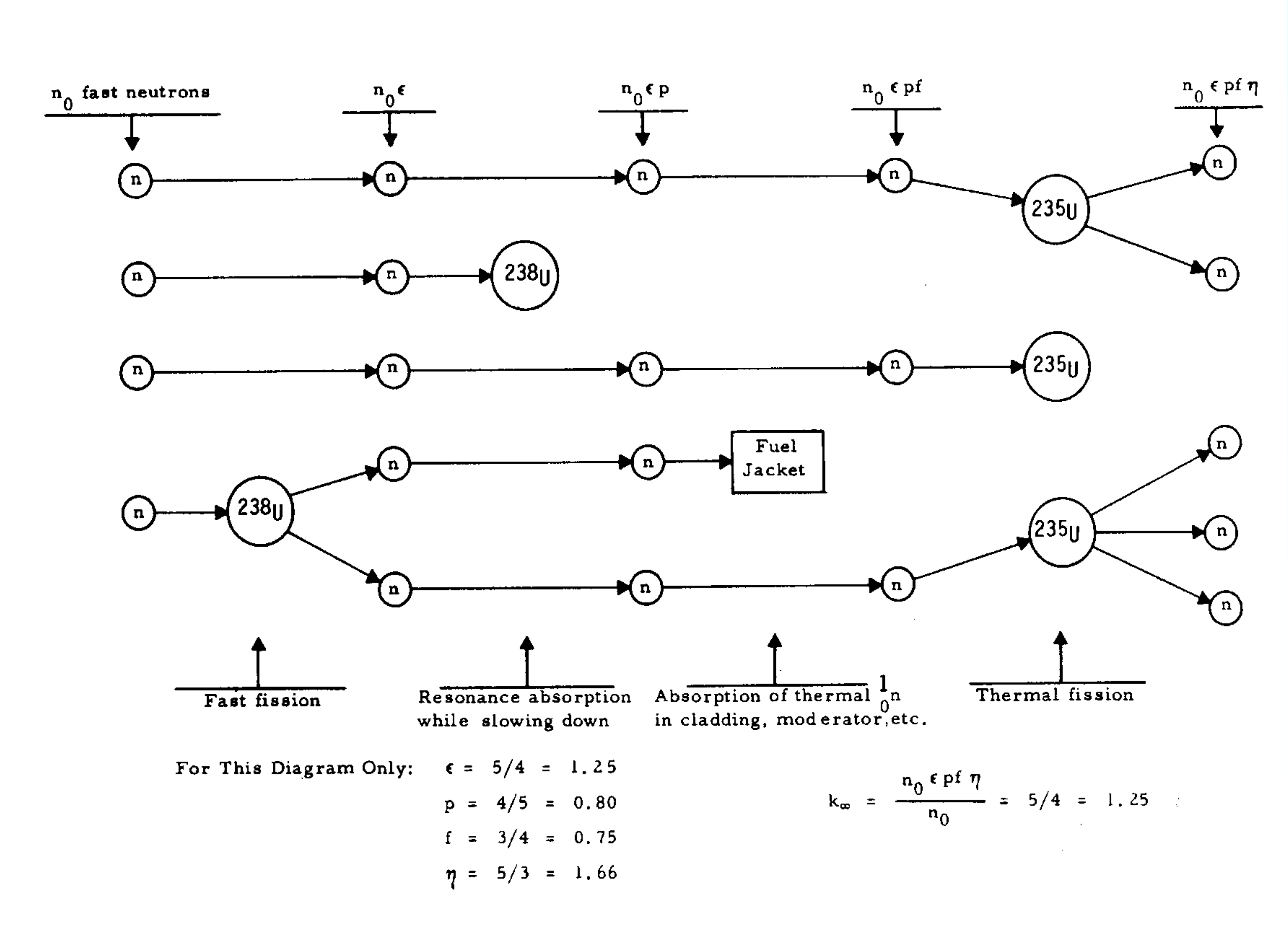
One Generation of Neutrons



Reactor Physics Repetition

- Target of reactor designers: To design a **safe and efficient** reactor under given nuclear- and material conditions. **Safe:** The reactor must have negative temperature coefficients during in any operational state i.e. increasing temperature reduces fission process - self stabilizing, negative example: Chernobyl
- **Efficient:** Minimum of material and maximum of neutron flux density
- About 6% of heat originates from fission products and transuranic elements (i.e 3000 MW_{th} NPP power after shut down 180 MW_{th} residual power), therefore heat generation continues after shut down, after core cooling is necessary for an extended period to prevent damage to the fuel or emergency core cooling (ECCS) in case of loss of coolant accident (LOCA)

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Reactor Physics Repetition

- **Reactor grade Plutonium**: NPP produce Pu nuclides through neutron capture in U-238 (approx 290kg per year), composition: 75% Pu-239, >19% Pu-240, <6% Pu-241+Pu-242, this is called reactor grade Pu. It is extracted from fuel elements during reprocessing and re-used as fuel for NPP (=MOX fuel),35 NPP in Europe use MOX, it is not usable for nuclear weapons due to high content of Pu-240

- **Weapons grade Plutonium (WPG):** composition: > 90% Pu-239, minimum mass about 10 kg pure Pu-239. It can be produced in NPP (fuel only about 3 month in the NPP) with on-load refuelling using U_{nat} as fuel (→ CANDU, RBMK), about 200 tons of WPG from military warheads available to be diluted with U-238 to produce NPP MOX fuel in France and UK

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Main Reactor Components

- **Fuel:** Usually pellets of uranium dioxide (UO_2) contained in tubes to form fuel rods. For easier handling these rods are arranged to fuel assemblies.

- **Moderator:** The moderator thermalizes the fast neutrons (about 2 MeV) produced by fission down to thermal energy (0.025 eV). Typical moderator materials are light water, heavy water, or graphite.

- **Control rods:** They contain neutron-absorbing material (such as cadmium, hafnium or borated steel), they can be moved electrically or pneumatically into and out from the core to control the fission process.

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Main Reactor Components

- **Coolant:** A liquid (H_2O, D_2O), gas (CO_2, He) or liquid metal (Na) is circulated through the core to transfer the heat from the fuel assemblies to a steam generator or sometimes directly to the turbine

- **Pressure vessel or pressure tubes:** Either a steel vessel or a series of pressure tubes containg the fuel and the primary coolant

- **Steam generator:** Component where the thermal energy is transfered from the primariy circuit to the secondary circuit where steam is produced and dried to be transfered the turbine

- **Containment:** A meter-thick concrete and steel structure to prevent the release of radioactivity to the environement in case of a serious reactor accident and to protect the reactor from external influences such as earthquake, air plane crash, tornados etc.

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Types and Materials of NPPs

REACTOR TYPE	E_N	COOLANT	FUEL – FERTILE MATERIAL				MODERATOR
			FISSILE	FERTILE	FUEL	GEOMETRY	
PRESSURIZED WATER REACTOR (PWR)	thermal	H_2O	U_{ENR}	--	UO_2	PIN	H_2O
BOILING WATER REACTOR (BWR)		H_2O	U_{ENR}	--	UO_2	PIN	H_2O
GAS COOLED GRAPHITE REACTOR (GCR)		CO_2	U_{NAT}	--	U-METALL	PIN	GRAPHITE
ADVANCED GAS COOLED GRAPHITE REACTOR (AGR)		CO_2	U_{ENR}		UO_2	PIN	GRAPHITE
HIGH TEMPERATURE GAS COOLED REACTOR (HTR)		He	U_{ENR}	TH	UO_2+TH C_2	COATED PARTICLES	GRAPHITE
LIQUID METAL COOLED FAST BREEDER REACTOR (LMFBR)	fast	Na	U+PU	U_{DEPL}	(U+PU) O_2	PIN	--

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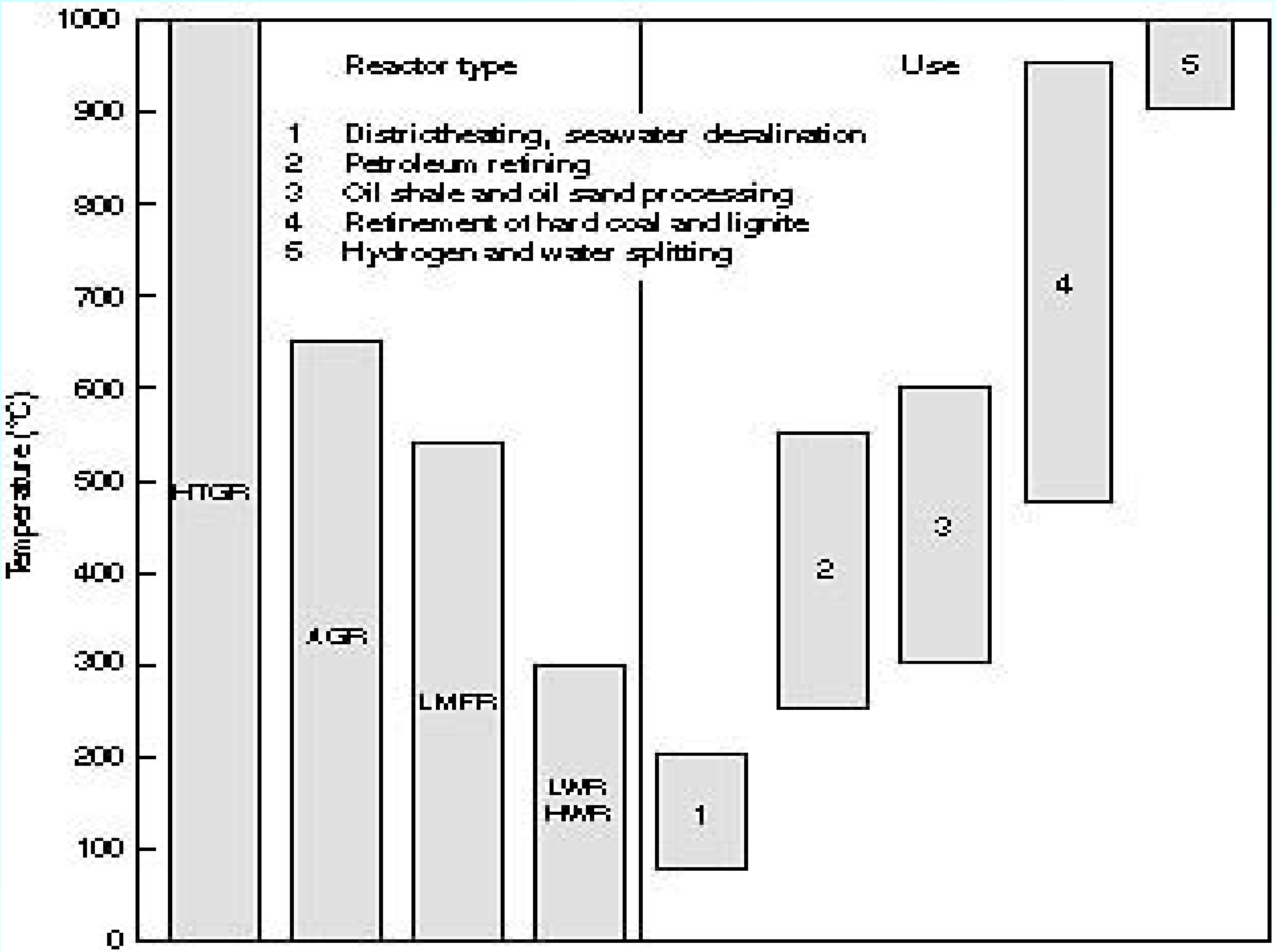
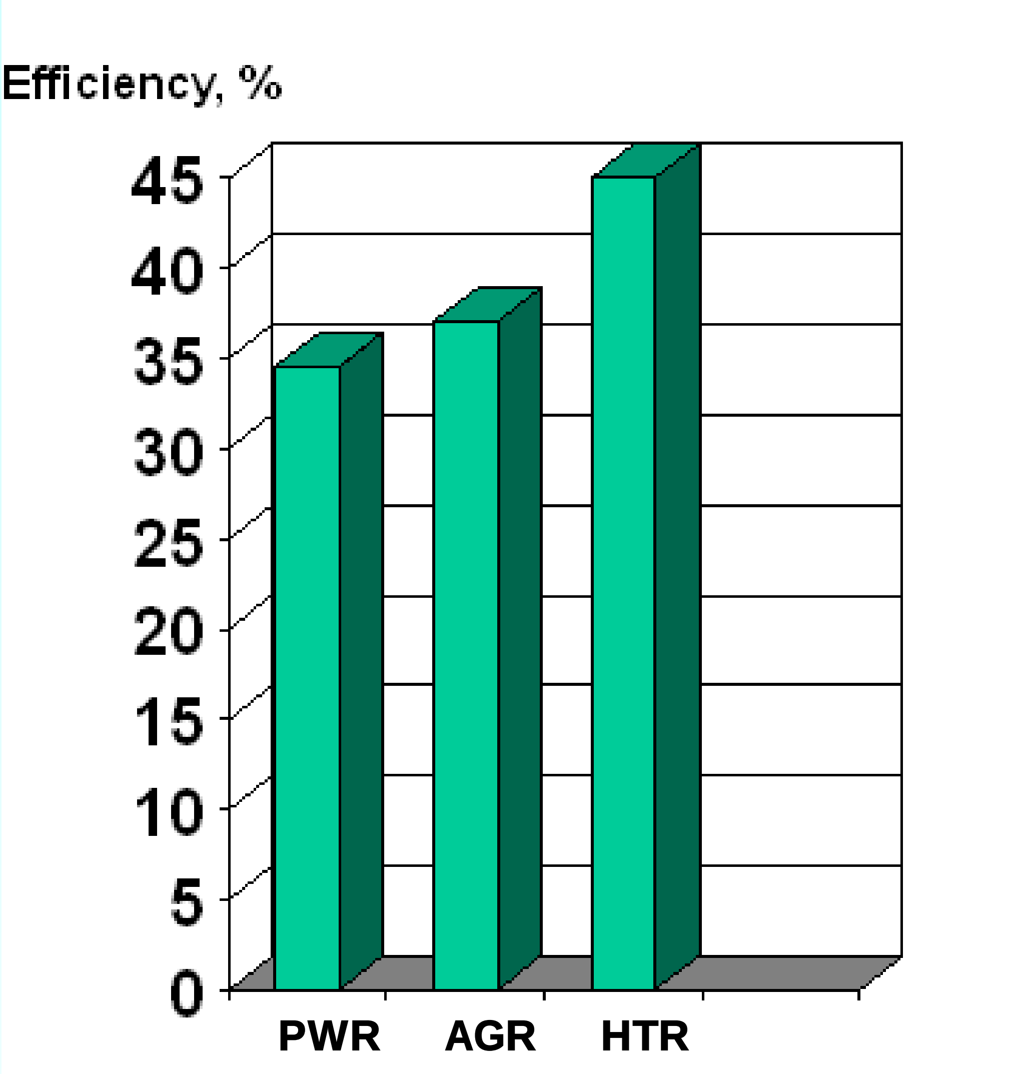
Operating Temperatures of NPPs



Efficiency of PWR, AGR, HTR



Physical Properties of Fuel Materials

Fuel	UO_2	U-Metal
Density at 20 °C (g/cm^3)	10.96	19.05
Metal density at (g/cm^3)	9.66	---
Melting point (°C)	2800	1132
Max. operation temperature (°C)	1800	660
Burn up achievable GWd/ton of metal	55 (thermal reactor) 60 (fast reactor)	5 (thermal reactor) 20 (fast reactor)

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Physical Properties of Coolants

	Temp.	Press.	Spec. heat	Density	Heat conduct.	ΔT +	$\Sigma_{a\ th}$
	^{o}C	bar	$J\ ^{o}C^{-1}g^{-1}$	$g\ cm^{-3}$	$J\ s^{-1}cm^{-1}\ ^{o}C^{-1}$	^{o}C	cm^{-1}
He	400	50	5.23	.00364	$2.7 \cdot 10^{-3}$	380	0
CO_2	400	50	1.14	.03859	$0.5 \cdot 10^{-3}$	380	$2.08 \cdot 10^{-6}$
H_2O (liqu)	300	150	5.48	.726	$6.3 \cdot 10^{-3}$	30	$1.6 \cdot 10^{-2}$
D_2O (liqu)	300	150	5.48			30	$2.2 \cdot 10^{-5}$
Na (liqu)	400	1	1.28	.857	.71	180	$1.19 \cdot 10^{-2}$

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Physical Properties of Cladding Materials

Material	Magnox	Zircaloy-2	Stainless steel AGR	Stainless steel LMFBR
Composition	.25 - .4% Al .02 – .4% Ca .002 - .1% Be balance Mg	1.5% Sn .1 % Cr .15% Fe .05% Ni balance Zr	14.5 -15.5% Cr 14.5 – 15.5% Ni 1.0 – 1.4% Mo 3 - .55% Ti balance Fe	15.5 – 17.5% Cr 12.5 -14.5% Ni 1.5% Mo ≥1. % Nb ≤ .85% V
Absorption cross section for n_{th} (E-24cm^2)	.0072	.0023	2.9	2.9
Density g/cm^3	1.74	6.6	8	8
Melting point ^oC	680	1850	1440	1440
Max. operational temp. ^oC	ca. 480	ca. 360	ca. 780 in gas	750 in sodium

Some Definitions

Research Reactors : $\mathbf{MW_{th}}$ = thermal power production
Nuclear Power Plants: $\mathbf{MW_{e}}$ = electric power production

$$MW_e = \eta .\ MW_{th}$$

η = thermodynamic efficiency for LWR approx. 0.34 or 34%

$\mathbf{MW_e}$ **gross** = overall electric power production

$\mathbf{MW_e}$ **net** = gross power production less internal power consumption for pumps, heaters etc. difference is about 5-6%

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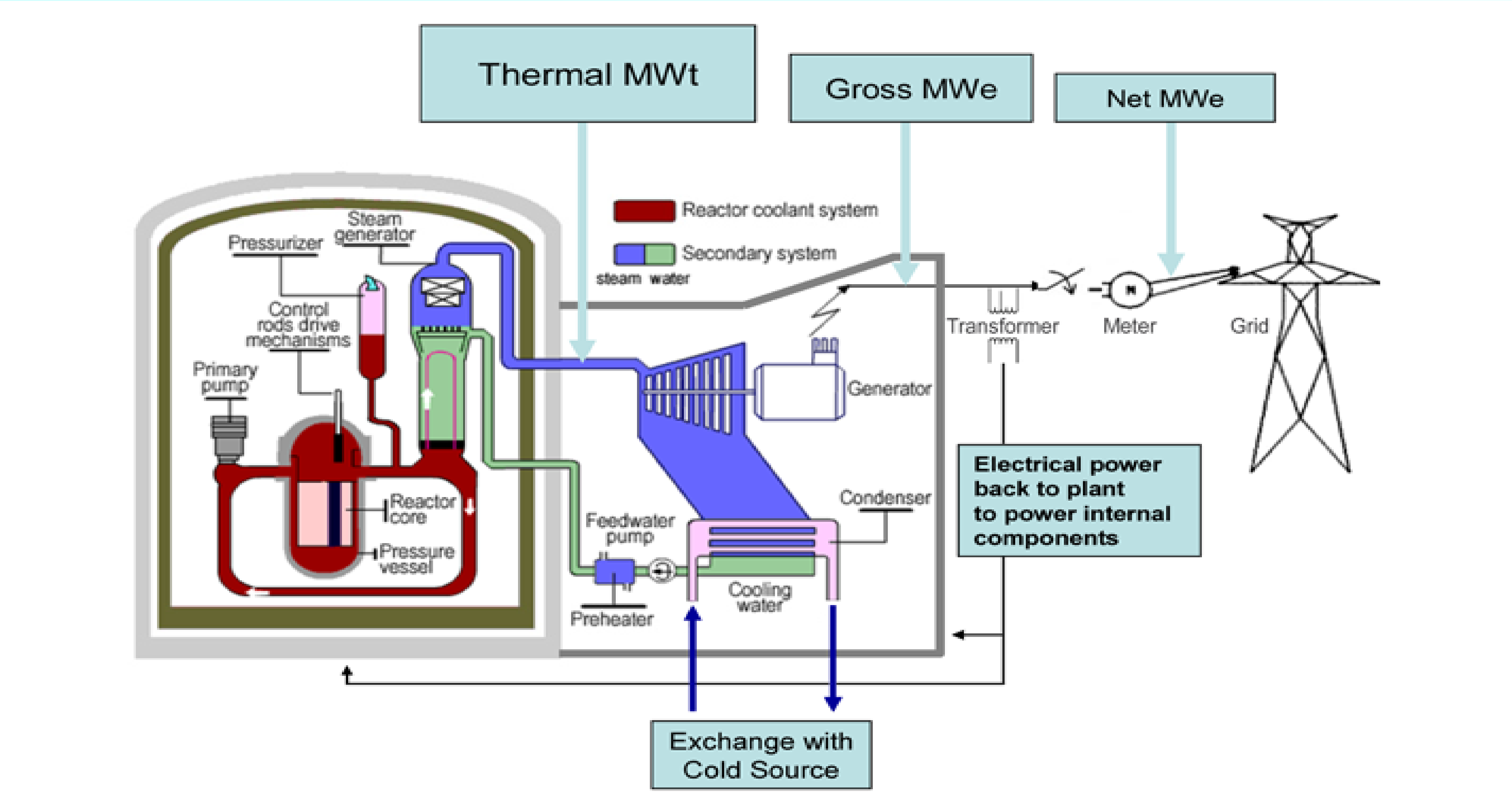
NPP Power Defintions



Some Definitions

Capacity - Availability – Power Production

- NPP operates about 8000h/y with an availability of up to 90%
- **Burn-up**: Measure of thermal energy released by nuclear fuel relative to its mass, typically Gigawatt days per ton (GWd/tU)
- **Availability**: The time a reactor spends on-line (=operating) in a period (usually a year) expressed in percentage of total period (8760 h), presently the availabilty factor for modern LWR is about 85-90%
- **Fissile material**: Uranium and Plutonium nuclides which are fissioned by thermal neutrons (U-235,Pu-239, Pu-241) – U and Pu nuclides with uneven mass number
- **Fertile material**: Thorium and Uranium nuclides which are transformed into fissile material (Th-232, U-238) – Th and U nuclides with even mass number

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Nuclear power plants in commercial operation (2015)

Status 31.12.2015 ATW 2016, p 271

Reactor type	Main Counties	Number	GWe net	Fuel	Coolant	Moderator
Pressurised Water reactor (PWR)	US, France Japan, Russia	270	257,8	Enriched UO_2	water	water
Boiling Water reactor (BWR)	US, Japan, Sweden	91	81,9	Enriched UO_2	water	water
Gas-cooled Reactor (Magnox & AGR)	UK	16	9,7	Enriched UO_2	CO_2	graphite
Pressurised Heavy Water reactor 'CANDU' (PHWR) D2O-DWR	Canada	45 1	21,5	Natural or Enriched UO_2	Heavy water	Heavy water
Light Water Graphit reactor (RBMK)	Russia	15	11,4	Enriched UO_2	Water	graphite
Liquid Metal Fast Breeder Reactor (LMFBR)	Japan, Russia	2	0,7	PuO_2 & UO_2	Liquid sodium	none
	Total	442	388			

Updated State of NPPs Worldwide

Status 31.12.2015 ATW 2016 p 271

- NPP in operation : 442 in 31 countries
- Net power: 388 GWe
- Net energy production: 2 628 TWh
- NPP under construction: 65 NPPs with total capacity of 69 GWe net in 15 countries (such as ARG-1,BELRUS-2, BRA-1,China-24,FIN-1,F-1, India-6,JAP-2, KOR-5,PAK-2, RUS-9, SK-2, Taiwan-2, USA-5, UAE-3)
- NPP under planning worldwide: 125 units in various planning stages in 25 countries such as China>30,
  Russia>30, IND>6, TR 5

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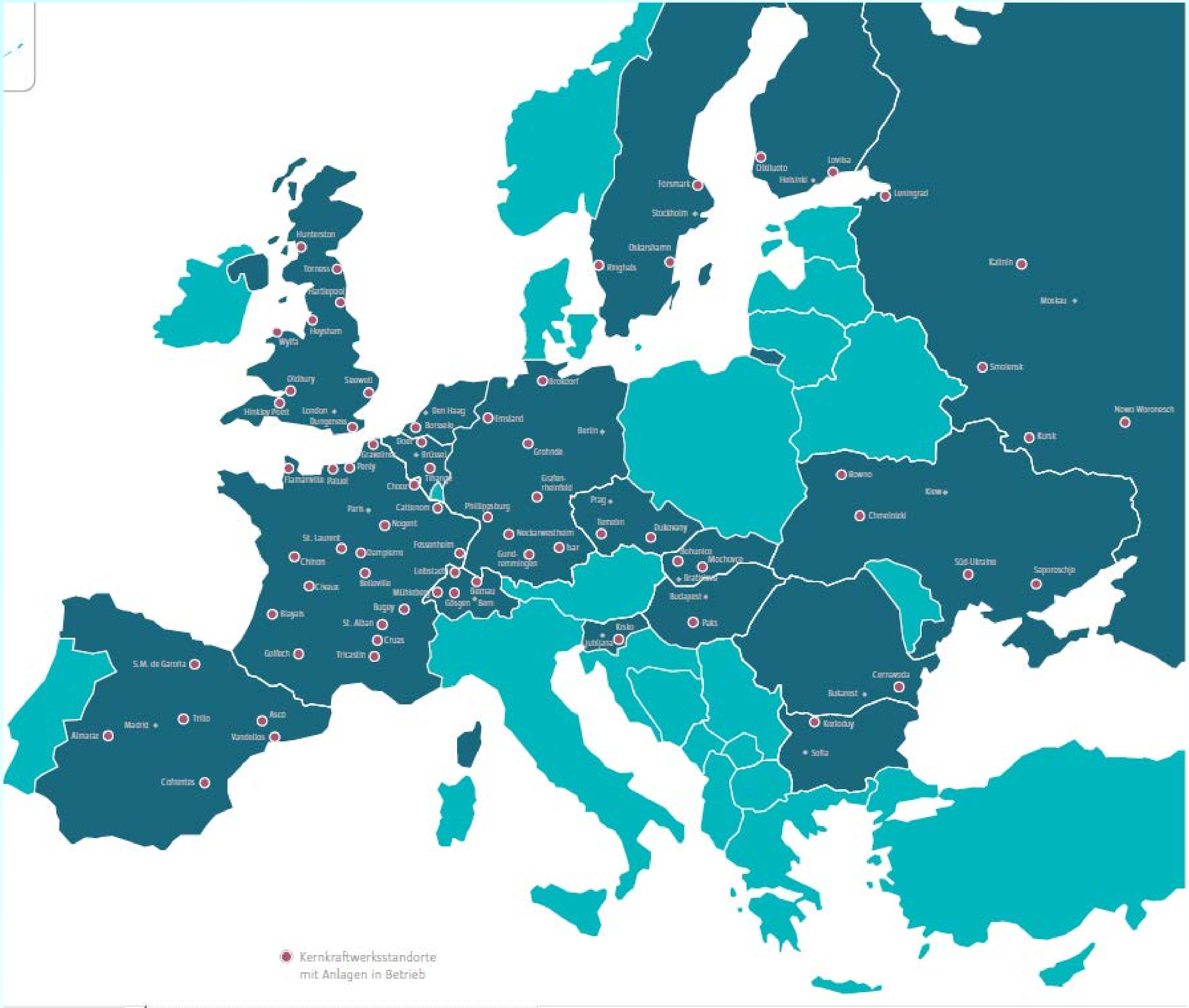
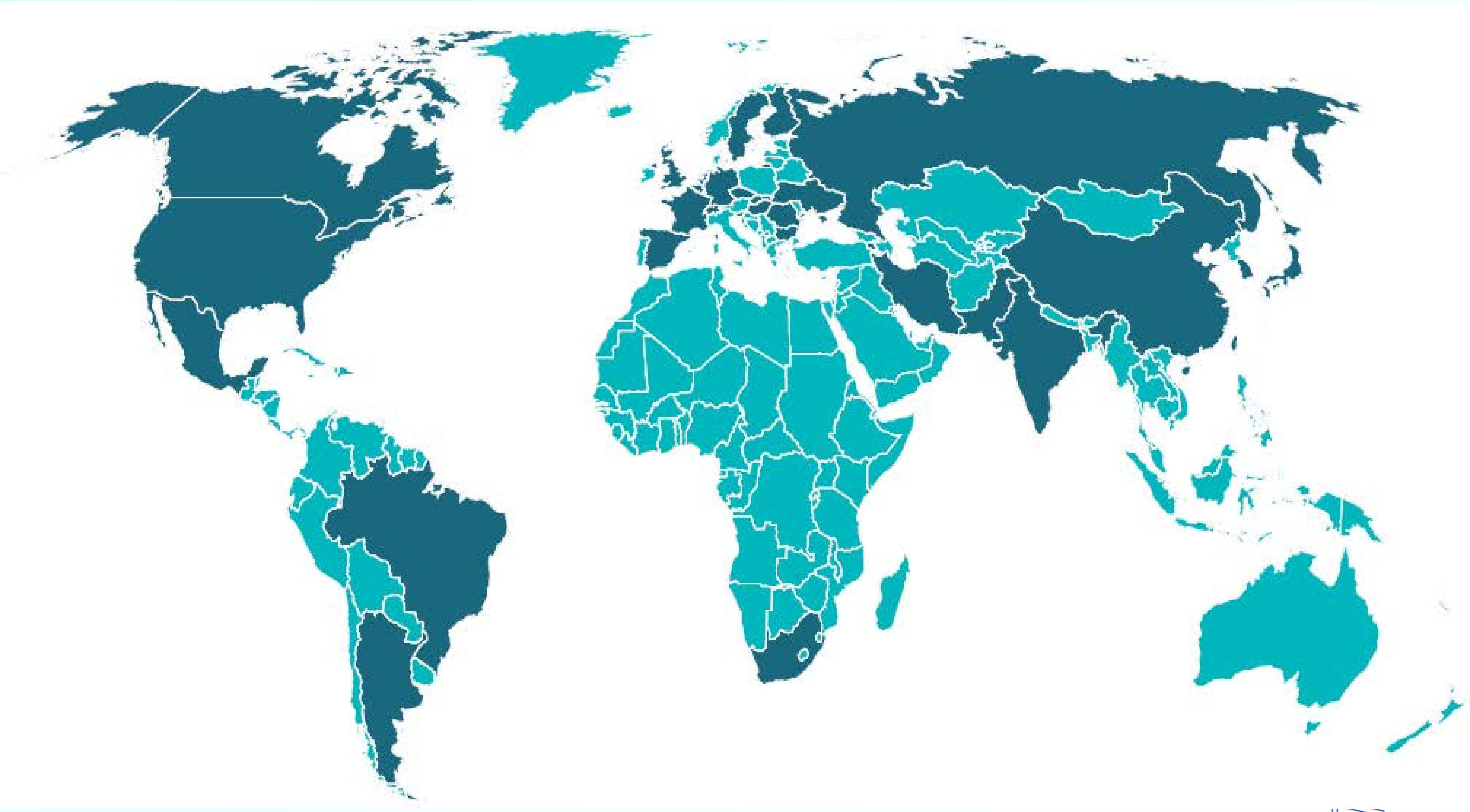
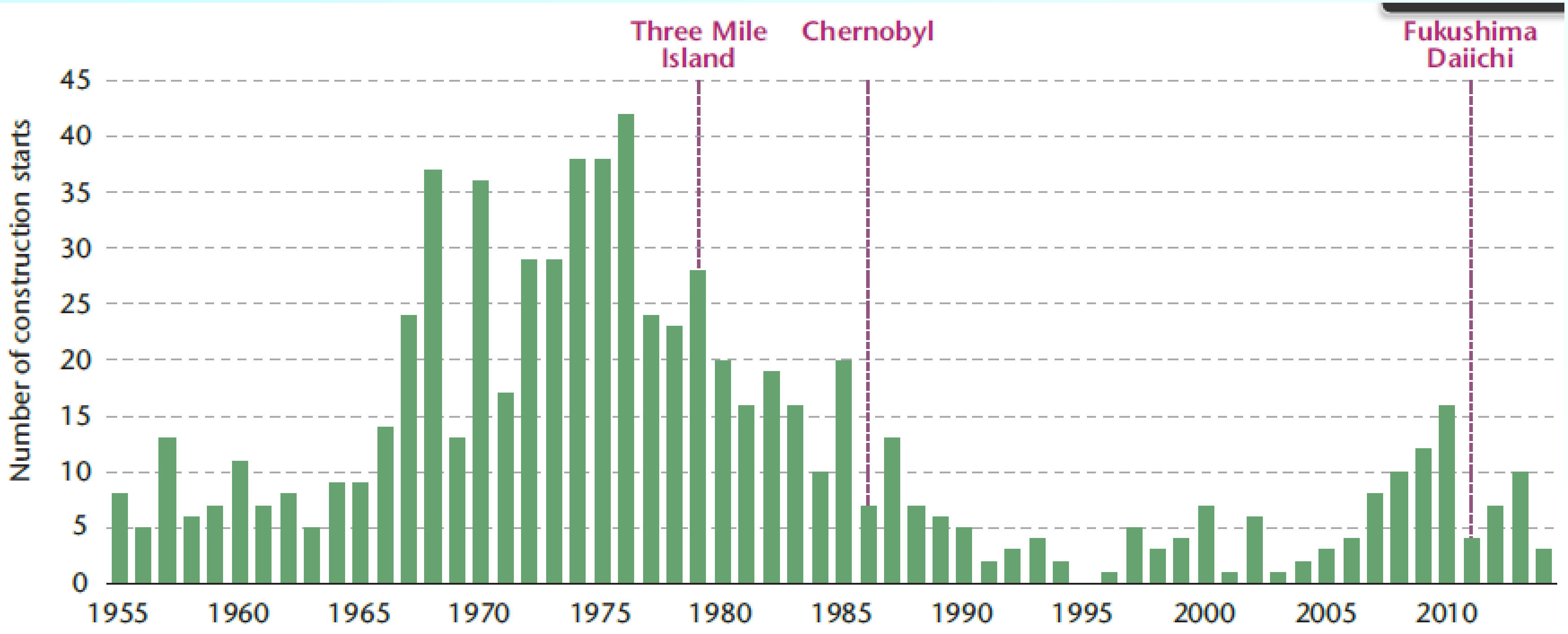
Present State of NPPs in Europe



Worldwide State of NPPs



Reactor types under construction 2014



Source: IAEA Power Reactor Information System (PRIS).

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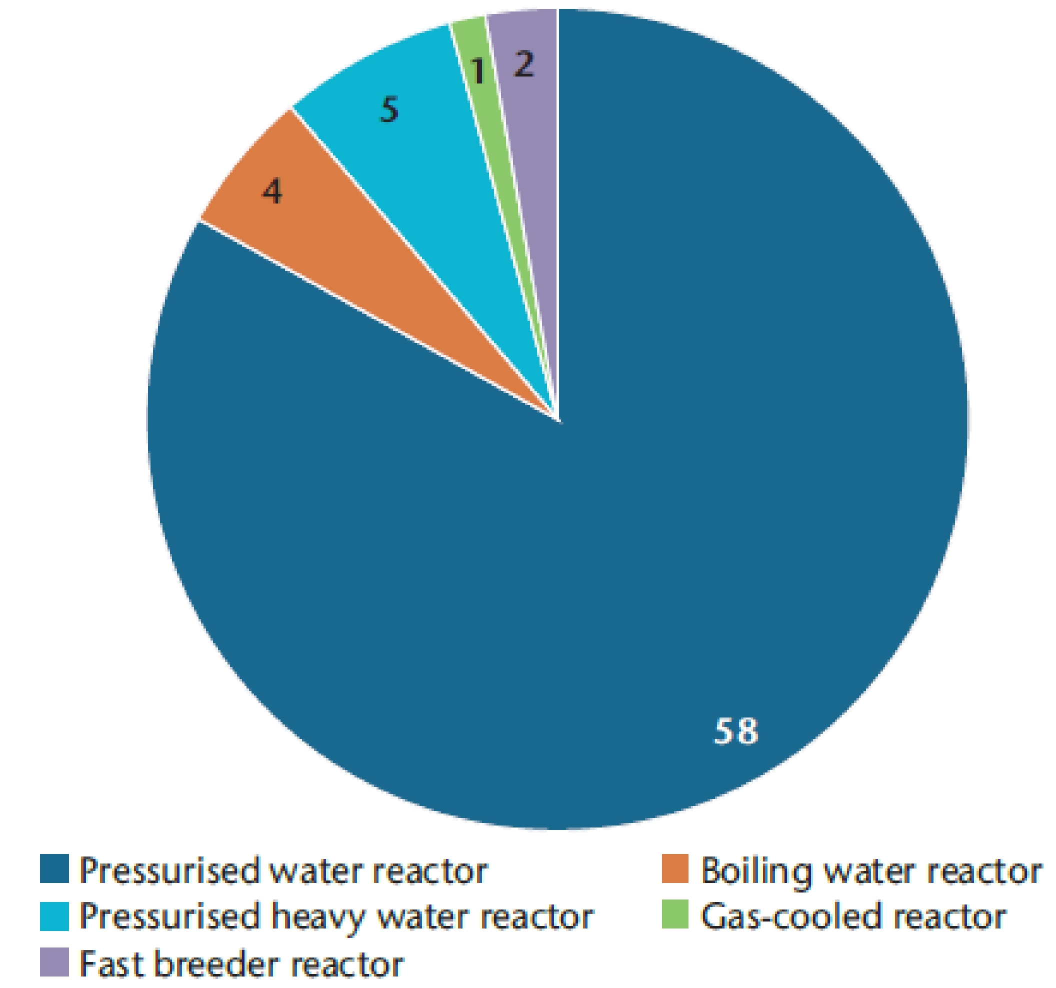
Reactor construction starts since 1995



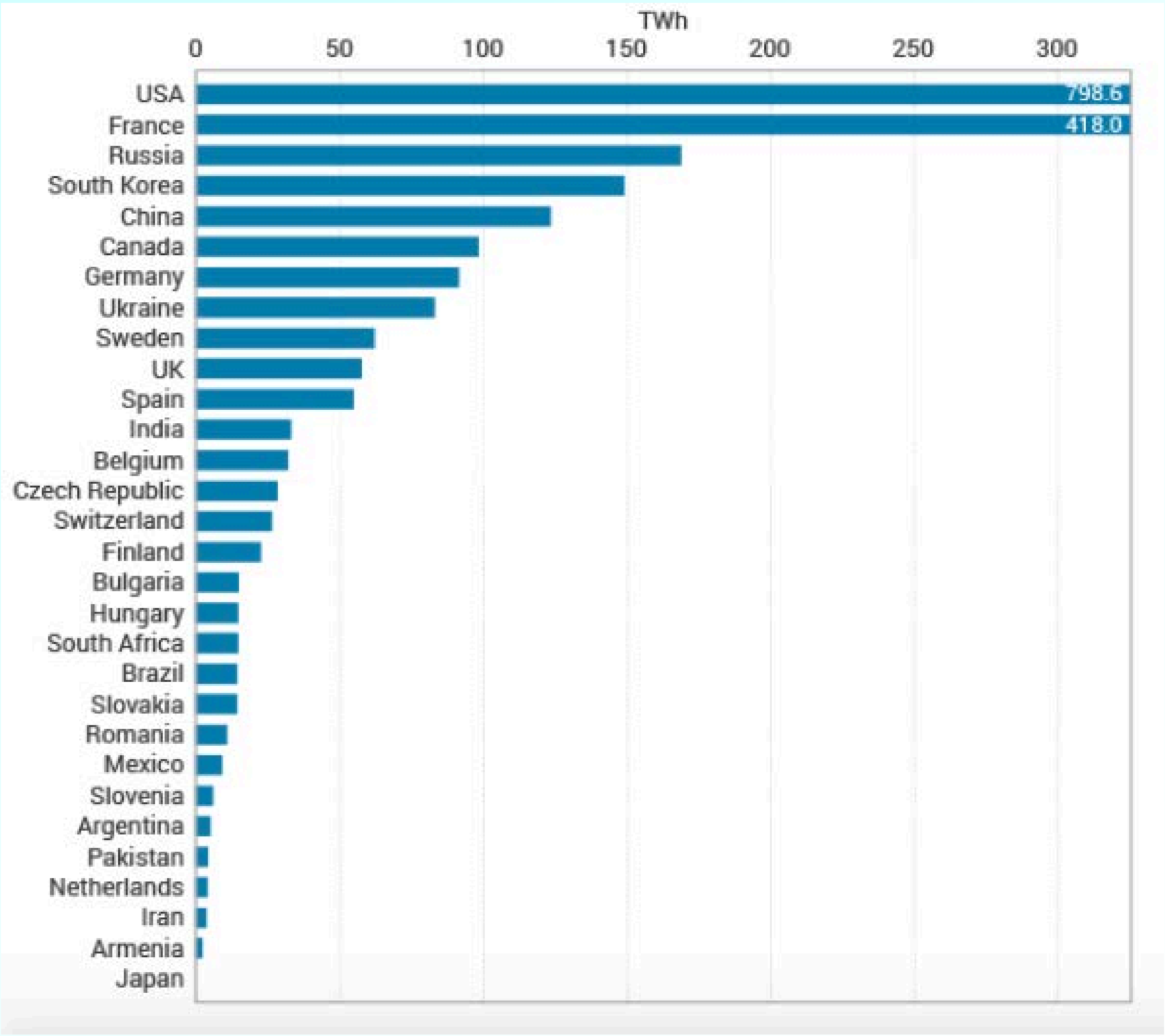
Source: IAEA/PRIS.

Examples of Generation 3 reactor designs

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
AREVA	France	EPR	PWR	1 600	0	4 (Finland, France, China)
AREVA/MHI	France/ Japan	ATMEA	PWR	1 100	0	0
CANDU Energy	Canada	EC6	PHWR	700	0	0
CNNC-CGN	China	Hualong-1	PWR	1 100	0	0
GE Hitachi – Toshiba GE Hitachi	United States/ Japan	ABWR ESBWR	BWR BWR	1 400-1 700 1 600	4 (Japan) 0	4 (Japan, Chinese Taipei) 0
KEPCO/KHNP	Korea	APR1400	PWR	1 400	0	7 (Republic of Korea, United Arab Emirates)
Mitsubishi	Japan	APWR	PWR	1 700	0	0
ROSATOM	Russia	AES-92, AES-2006	PWR	1 000-1 200	1	10 (Russia, Belarus, China, India)
SNPTC	China	CAP1000, CAP1400	PWR	1 200-1 400	0	0
Westinghouse/ Toshiba	United States/ Japan	AP1000	PWR	1 200	0	8 (China, United States)

*: As of 31 December 2014.

Nuclear Generation by Country 2014



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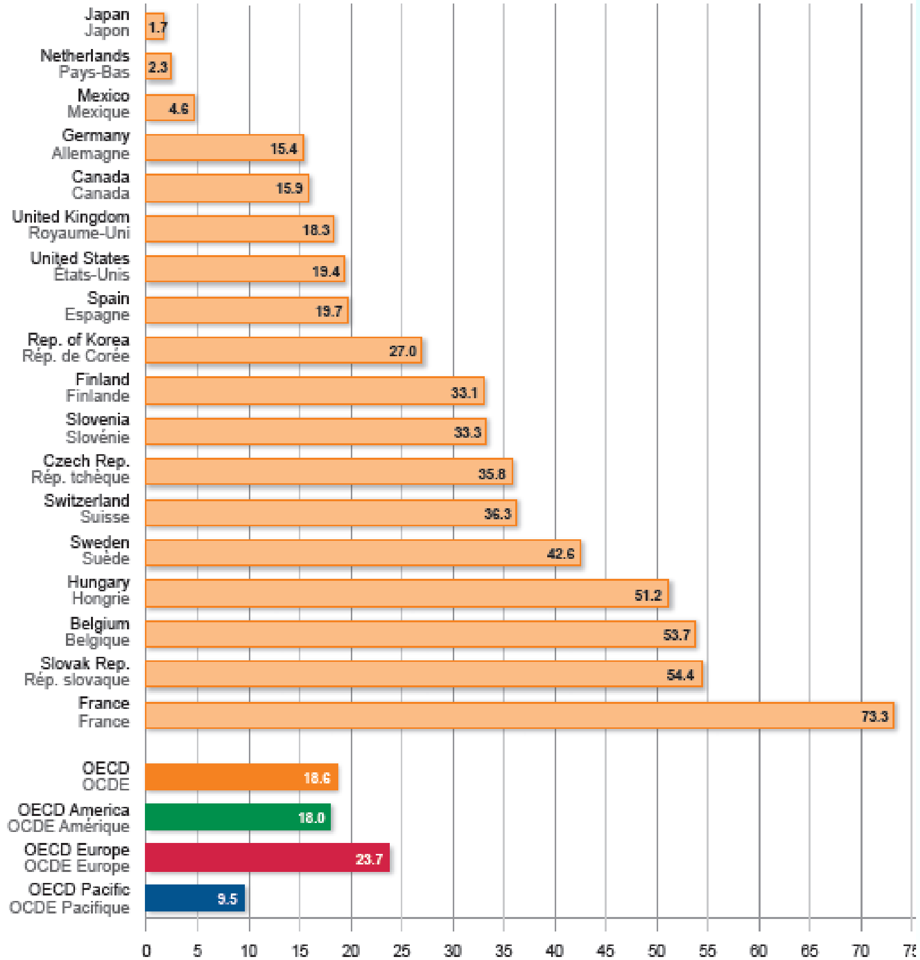
1. Nuclear capacity and electricity generation

1. Puissance et production d'électricité d'origine nucléair

Figure 1.1: Nuclear power share of total electricity production in OECD countries (2013)

Figure 1.1 : Part de l'énergie nucléaire dans la production d'électricité dans les pays de l'OCDE (20



StatLink www.oecd-nea.org/pub/7197/F1-1.xlsx

Typical Fuel Requirement for a 1000 MW_e PWR per Year

Mining:	**20 000 tonnes of 1% uranium ore**
Milling:	**230 tonnes of uranium oxide concentrate (with 195 t U)**
Conversion	**288 tonnes UF6 (with 195 t U)**
Enrichment	**35 tonnes UF6 (with 24 t enriched U) – balance is 'tails'**
Fuel fabrication	**27 tonnes UO_2 (with 24 t enriched U)**
Reactor operation	**7000 million kWh or 7 TWh of electricity**
Spent fuel	**27 tonnes containing 240kg plutonium, 23 t uranium (0.8% U-235), 720kg fission products, also transuranics**

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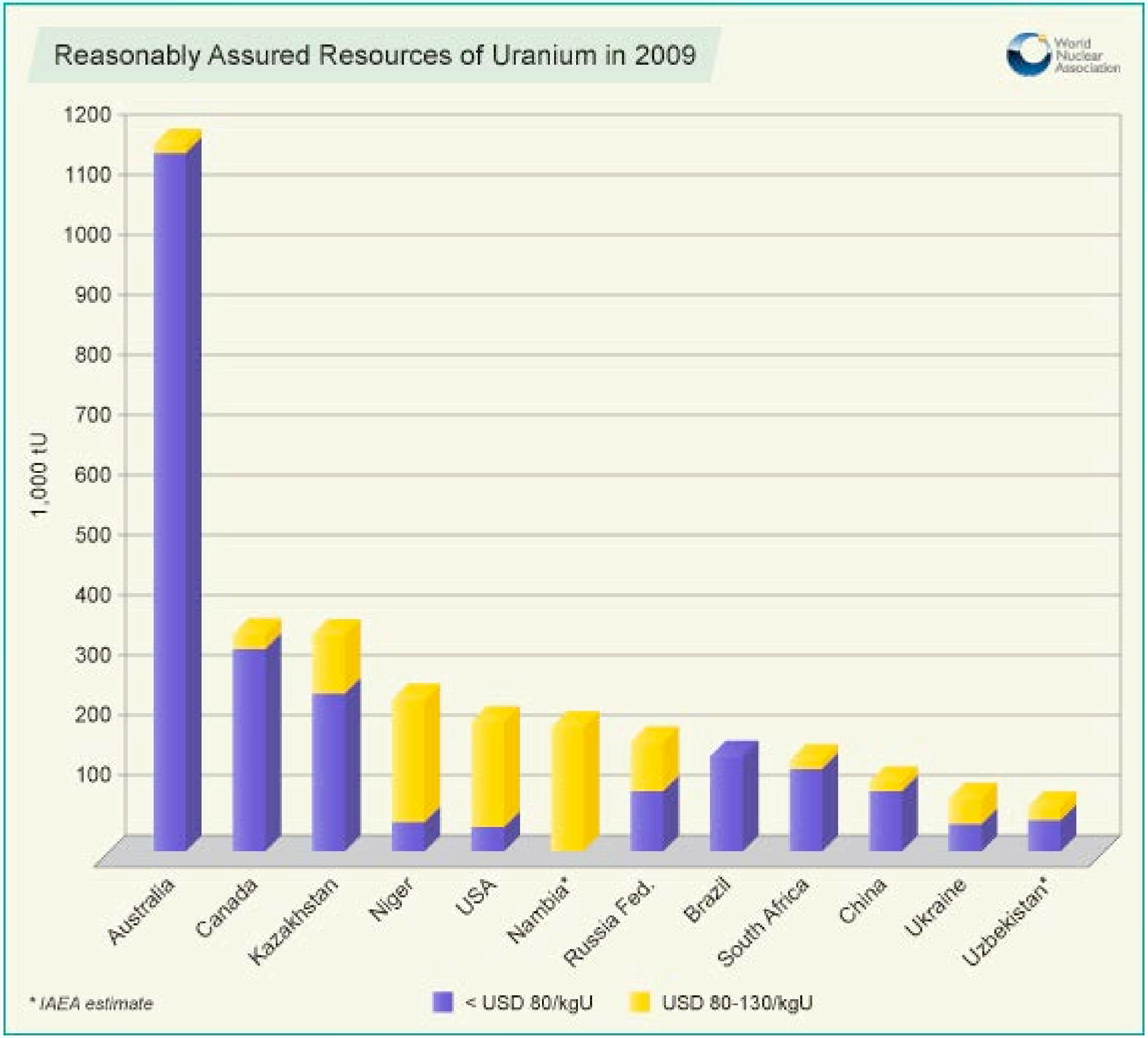
Uranresources in 2009



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Uranium Situation Worldwide

- Uranium demand 2015 56 000 tons/year
- **Primary uranium** (about 35 000 tons) from mines in Canada (30,5%), Australia (22,2%), Kasachstan, Niger, Russian Federation, Namibia
- **Secondary uranium** from disassembled weapons
- NPP will increase, uranium price presently at 22 US$/lb The present worldwide reserves of 7,641 Mio t U are sufficient to cover the needs for the next 135 years even for high nuclear scenario
- (ATW 2017/1)

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Uranium Situation Worldwide

- U_3O_8 („yellow cake“) produced from uranium mineral, 2.6 lb U_3O_8= 1kg U=22 US$/lb U_3O_8
- Without U recyling or input from weapons U reserves for about 70 years
- MOX = Depleted Uranium from enrichment mixed with 5% Pu (weapons grade) is equivivalent to 4,5% enriched uranium for NPP use
- In Europe 35 NPP‘s are operating on MOX
- This is the optimal way to consume the avilable stock of Pu

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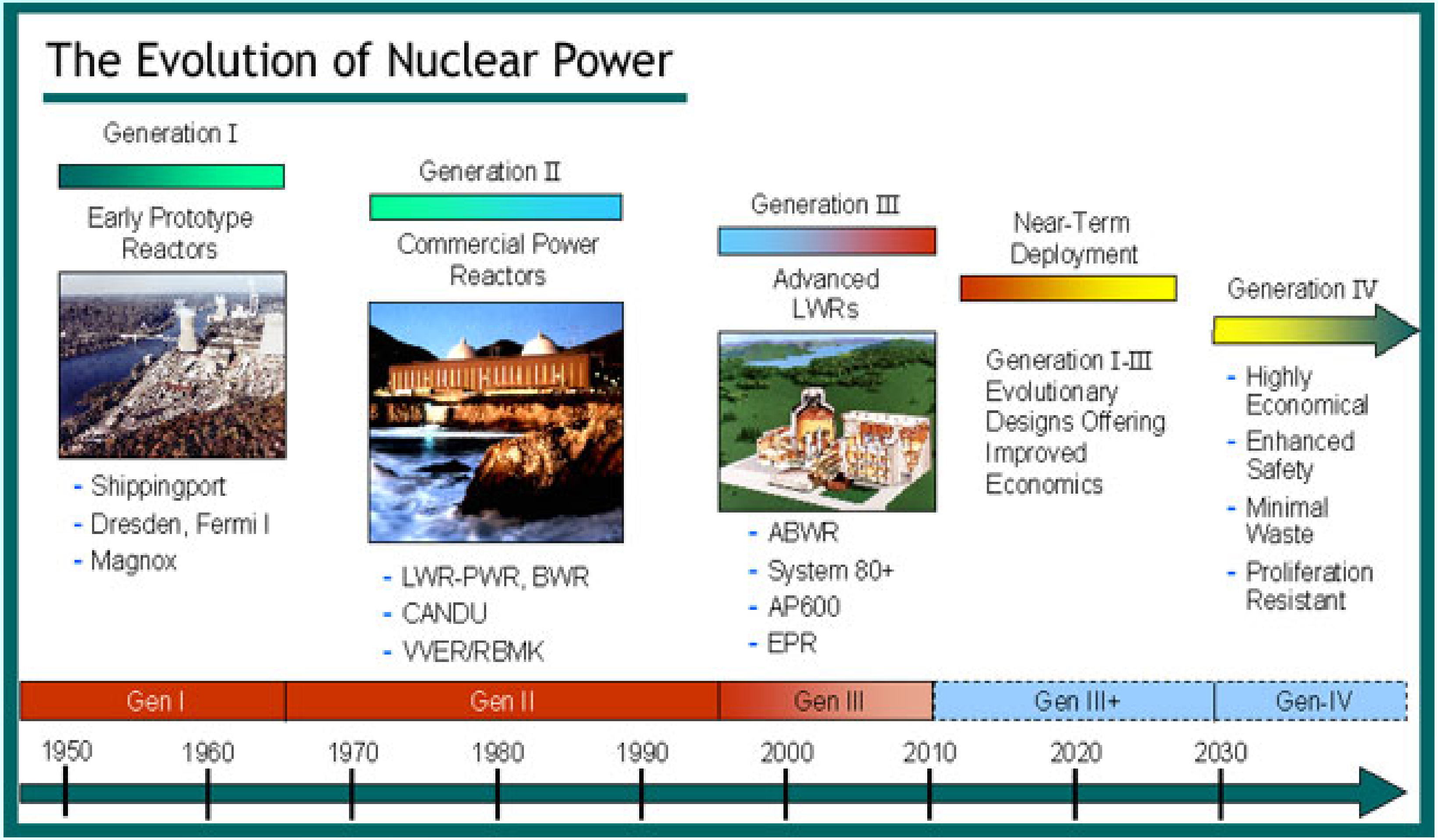
Military Warheads as a Source of Nuclear Fuel

- Weapons-grade uranium and plutonium surplus to military requirements in the USA and Russia is being made available for use as civil fuel.
- Weapons-grade uranium is highly enriched, to over 90% ^{235}U (the fissile isotope). Weapons-grade plutonium has over 93% ^{239}Pu and can be used, like reactor-grade plutonium, in fuel for electricity production.
- Highly-enriched uranium from weapons stockpiles is displacing some 10,600 tonnes of U_3O_8 production from mines each year, and meets about 13% of world reactor requirements.

Conversion of weapons material into NPP fuel

	Weapons 1987	Weapons 2003	Reduction
Russia	32 900	6 527	26 373 (ca 80%)
USA	24 000	5 000	19 000 (ca 79%)
Total	56 900	11 527	45 373

Evolution of Nuclear Power Plants



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Number of NPP decreases
Nuclear Energy output increases

- Higher availability
- Higher licensed power
- Longer fuel cycle
- Extended life time

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Looking backwards and forewards

- Average **availability** increased between 1991 and 2004 from 75.7% to 85.3%
- Good **experience** allowed life time extension of NPPs from 40 to 60 years
- Many NPPs uprated the power from **100% up to 108%**
- Fuel cycles increased by optimization from 12 months up to **24 months**

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World Oldest Nuclear Reactor

- **Where:** Oklo in Gabon
- **When:** 2 billion years ago
- **How many reactors:** at least 17
- **How long:** 2 million years of operation
- **Power:** approx. 20 kW_{th}
- **Natural reactor requirements**:
  - higher enrichment of U: U-235 concentration in U_{nat} at that time was 3.7 percent (today 0.7)
  - low concentration of neutron absorbers
  - high concentration of a moderator: clean water
  - penetrated Uranium mine
  - critical size to sustain the fission reaction
  - at least 4 tons of U-235 fissioned
  - Approx. 100 billion of kWh produced (= 3 years production of a 1300 MWe NPP)
- **Fission products:** 5.4 tons plus 1.5 tons Plutonium produced

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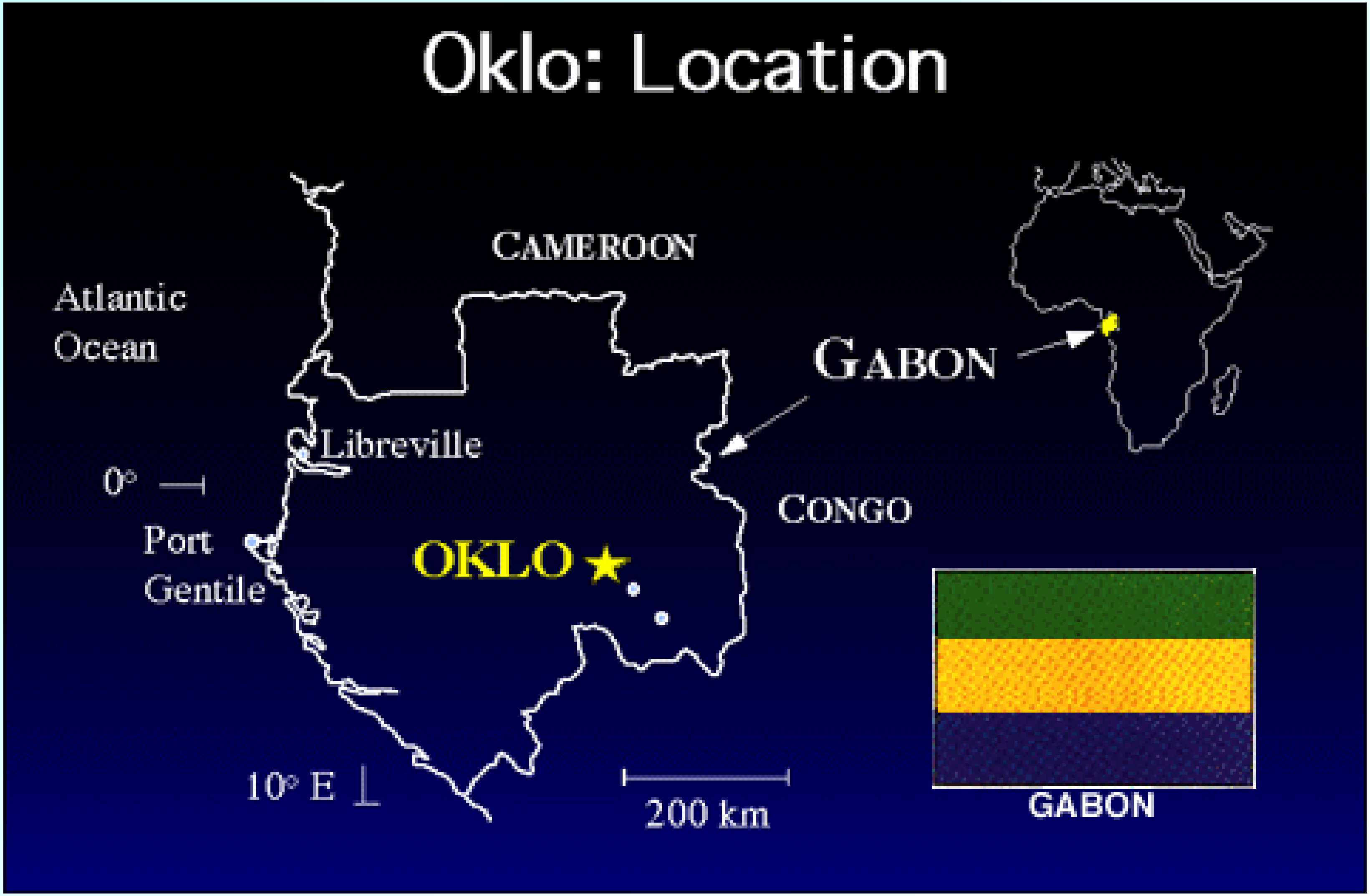
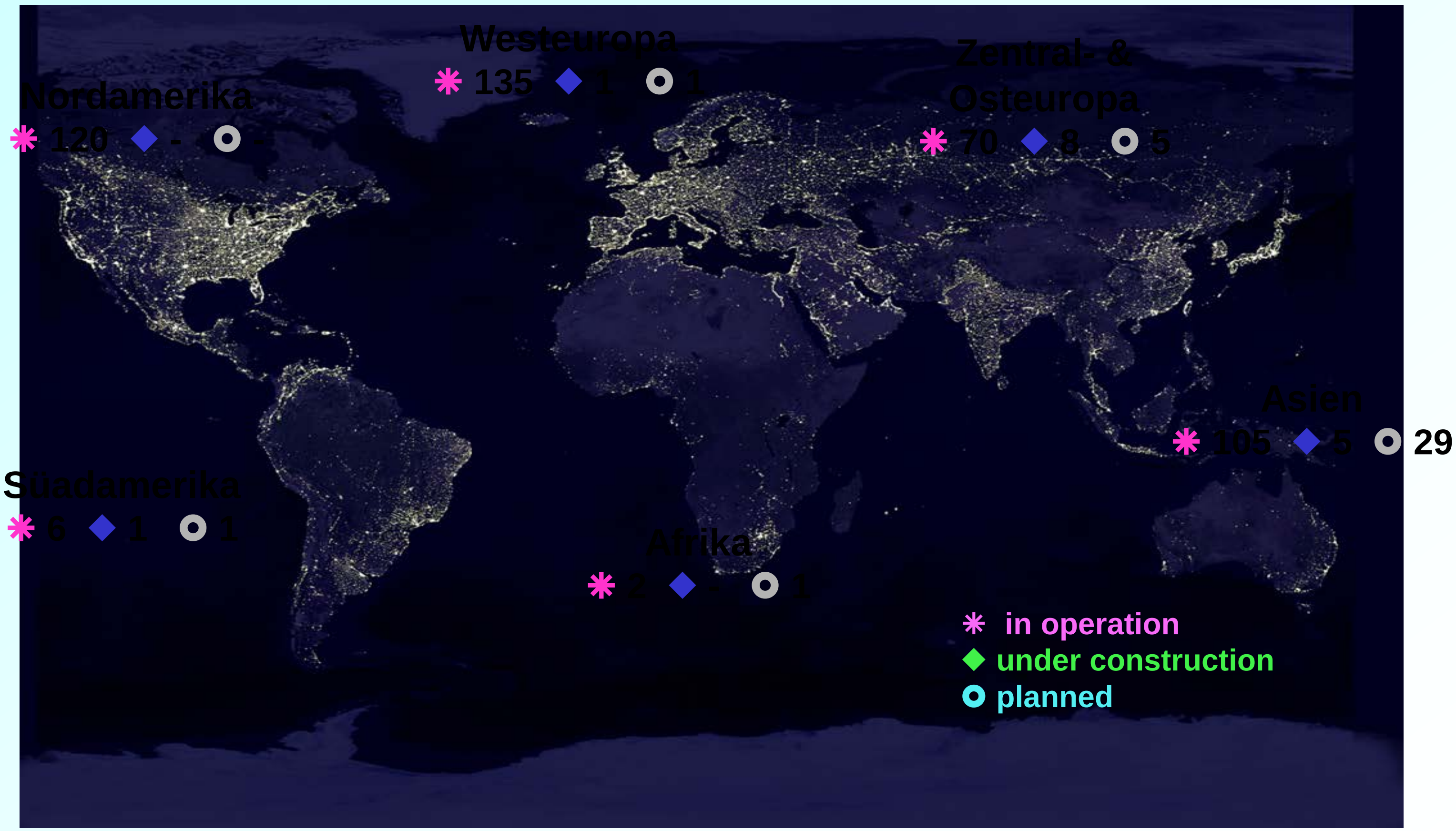
World Oldest Nuclear Reactor



- www.curtin.edu.au/curtin/centre/waisrc/OKLO/index.shtml

Nuclear Power Plants World Wide
August 2007



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References

- www.iaea.org
- www.world-nuclear.org/info/inf32.html (very good overview)
- OECD/NEA and IAEA "*Uranium 2009: Resources, Production and Demand*
- OECD/NEA Nuclear Energy Data 2014