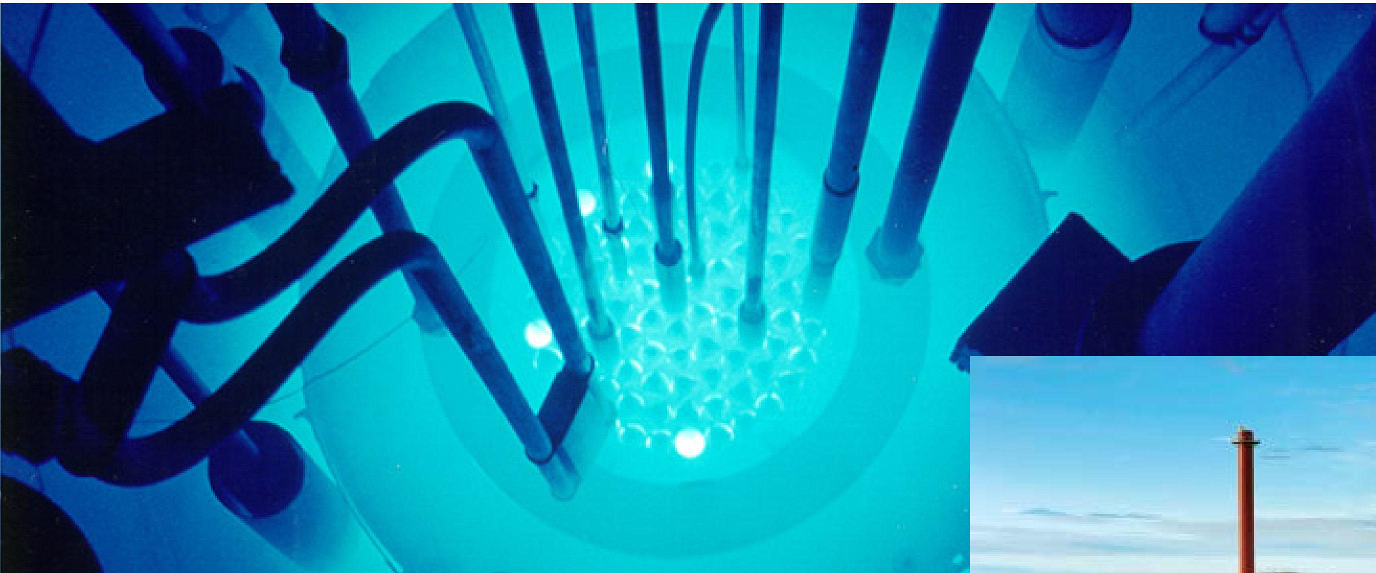
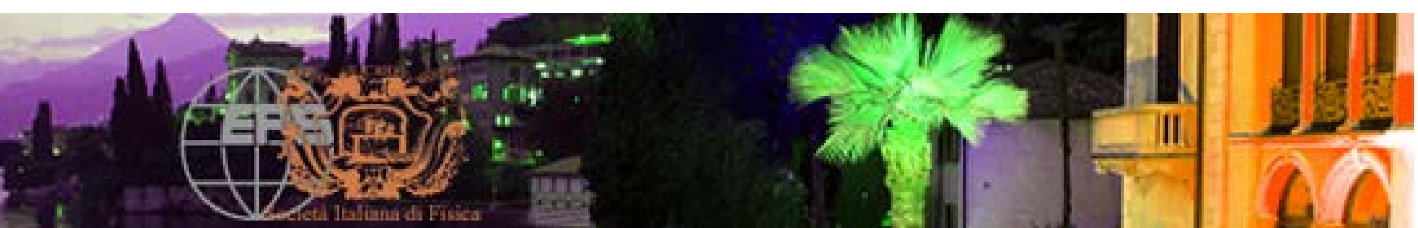
Energy from nuclear fission



M. Ripani
INFN Genova, Italy

Joint EPS-SIF International School on Energy 2014



Plan

- ✓ Figures about nuclear energy worldwide
- ✓ Safety
- ✓ Reaction products
- ✓ Radioactive waste production
- ✓ Fuel resources
- ✓ Fuel cycle
- ✓ Generation IV
- ✓ Fast systems
- ✓ ADS
- ✓ The European Roadmap
- ✓ Lead-based systems
- ✓ Waste processing and fuel cycle

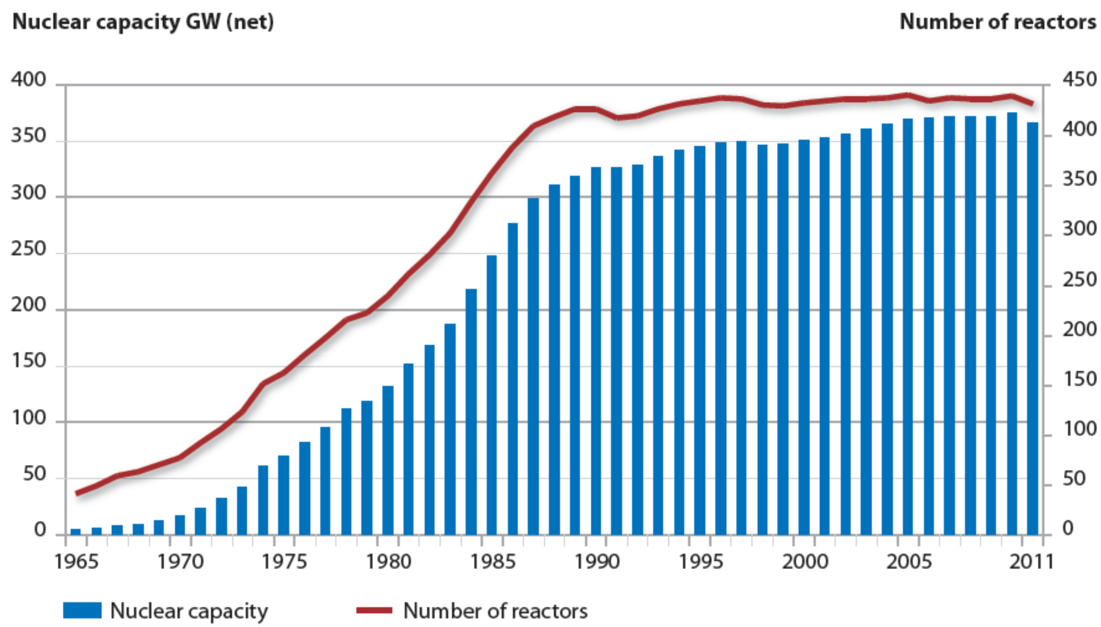
Nuclear energy today in the world

	In operation		Under construction	
	No. of reactors	Capacity (MW)	No. of reactors	Capacity (MW)
Argentina	2	935	1	692
Armenia	1	375	—	—
Belgium	7	5 927	—	—
Brazil	2	1 884	1	1 245
Bulgaria	2	1 906	—	—
Canada	18	12 604	—	—
China	16	11 816	26	26 620
Chinese Taipei	6	5 018	2	2 600
Czech Republic	6	3 766	—	—
Finland	4	2 736	1	1 600
France	58	63 130	1	1 600
Germany	9	12 068	—	—
Hungary	4	1 889	—	—
India	20	4 391	7	4 824
Iran	1	915	0	0
Japan	50	44 215	2	2 650
Mexico	2	1 300	—	—
Netherlands	1	482	—	—
Pakistan	3	725	2	630
Republic of Korea	21	18 751	5	5 560
Romania	2	1 300	—	—
Russian Federation	33	23 643	10	8 188
Slovak Republic	4	1 816	2	782
Slovenia	1	688	—	—
South Africa	2	1 830	—	—
Spain	8	7 567	—	—
Sweden	10	9 326	—	—
Switzerland	5	3 263	—	—
Ukraine	15	13 107	2	1 900
United Kingdom	18	9 953	—	—
United States	104	101 465	1	1 165
Total	**435**	**368 791**	**63**	**60 056**

Nuclear generating capacity in operation and under construction (end 2011)

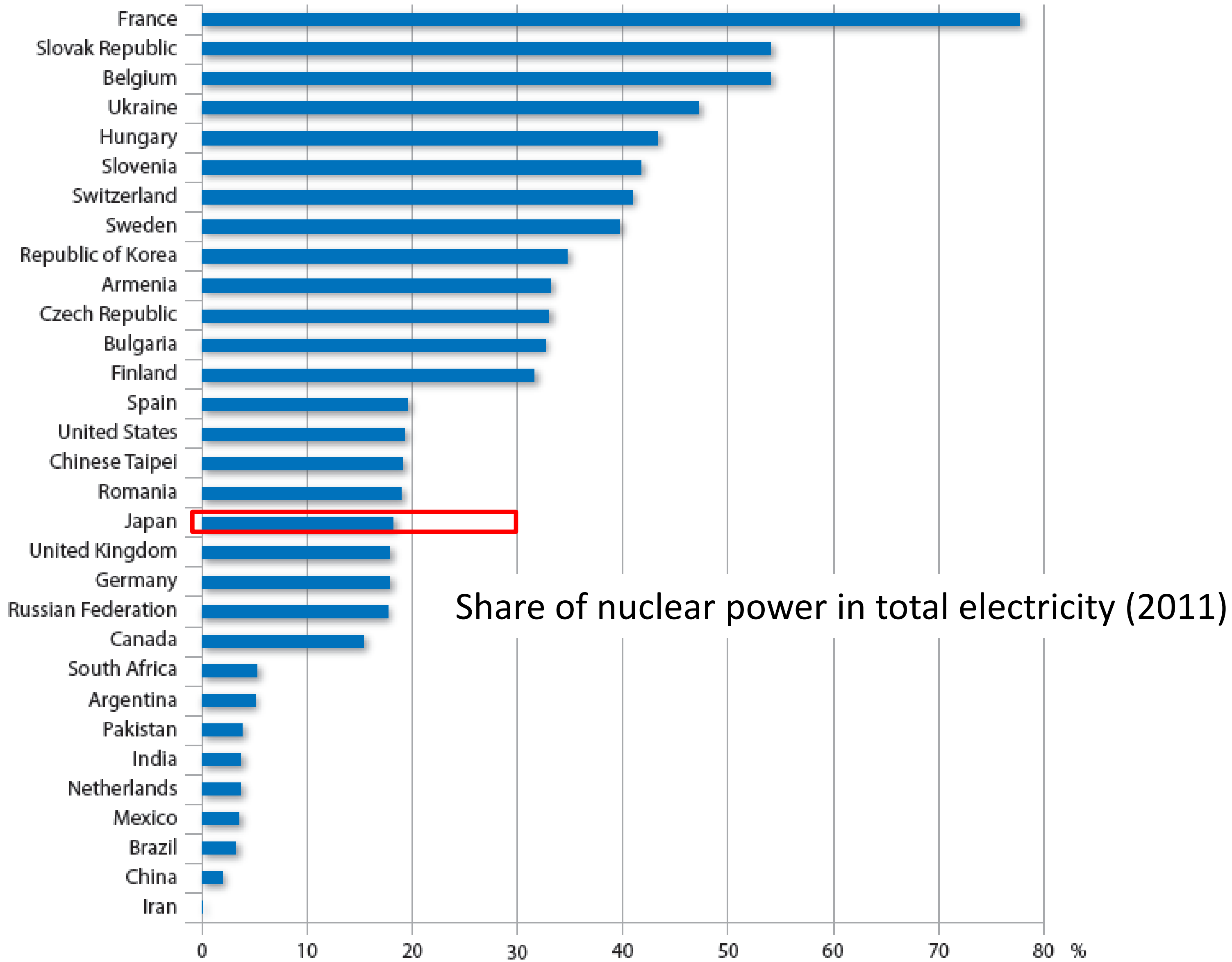
Source: IAEA Power Reactor Information System (PRIS).

Worldwide nuclear generating capacity and number of operating reactors (1965-2011)



Source: IAEA Power Reactor Information System (PRIS).

Share of electricity

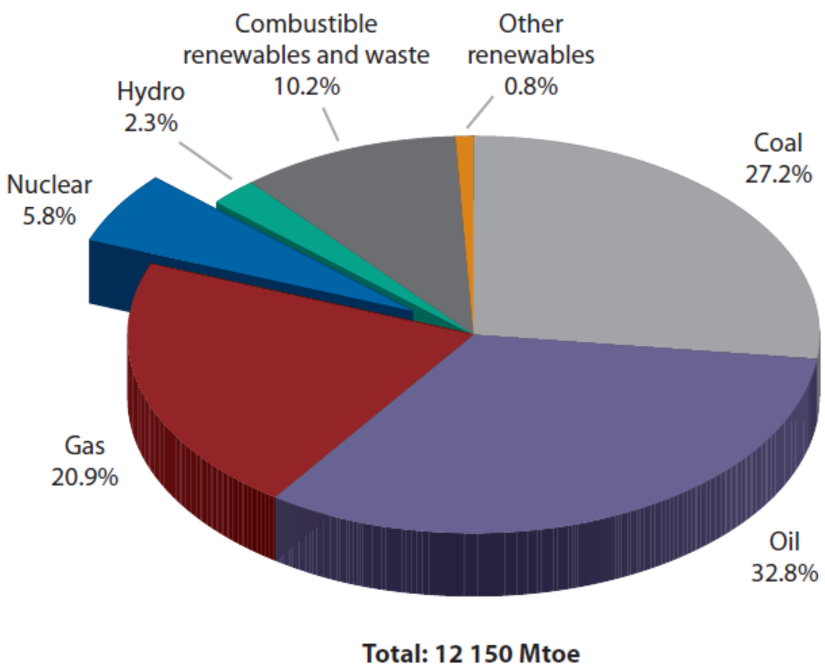


Source: IAEA Power Reactor Information System (PRIS).

Nuclear energy in the worldwide perspective

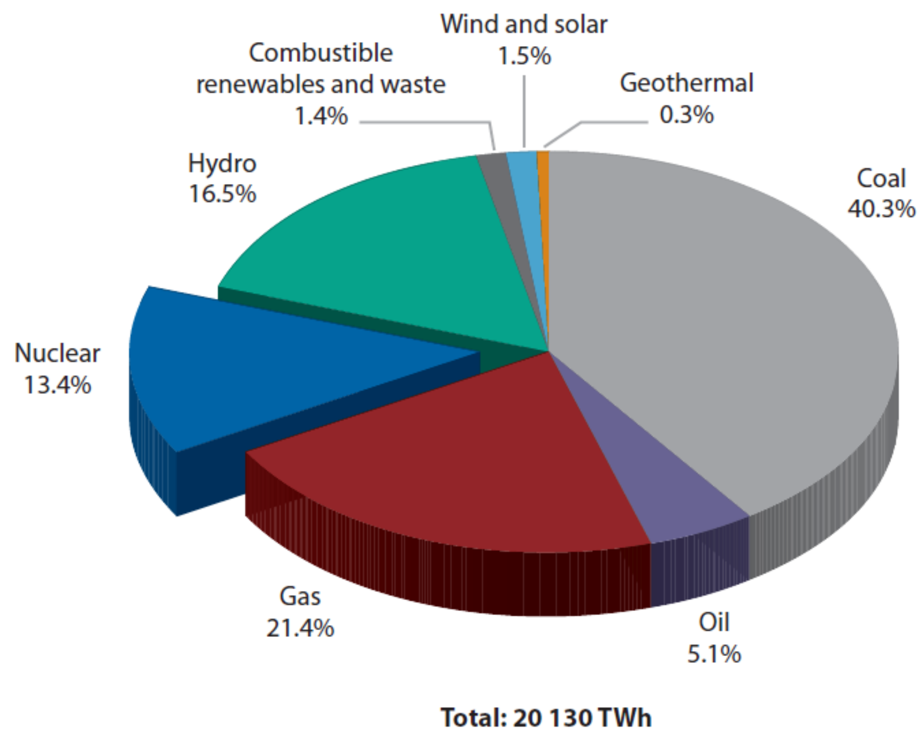
World primary energy demand (2009)

Source: IEA, Key World Energy Statistics, 2011

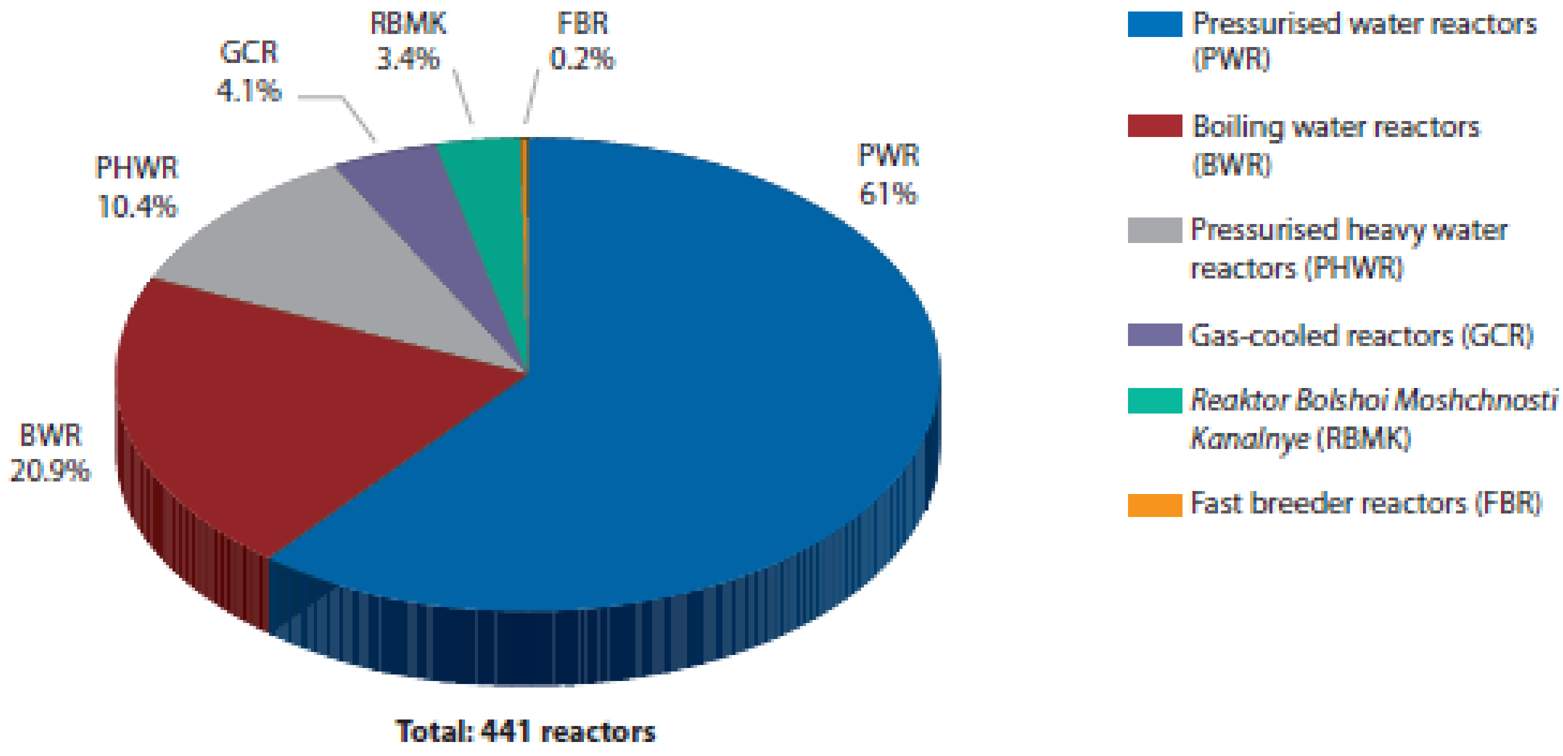


World electricity generation (2009)

Source: IEA, Electricity Information, 2011



Reactor types in use worldwide (end of 2010)

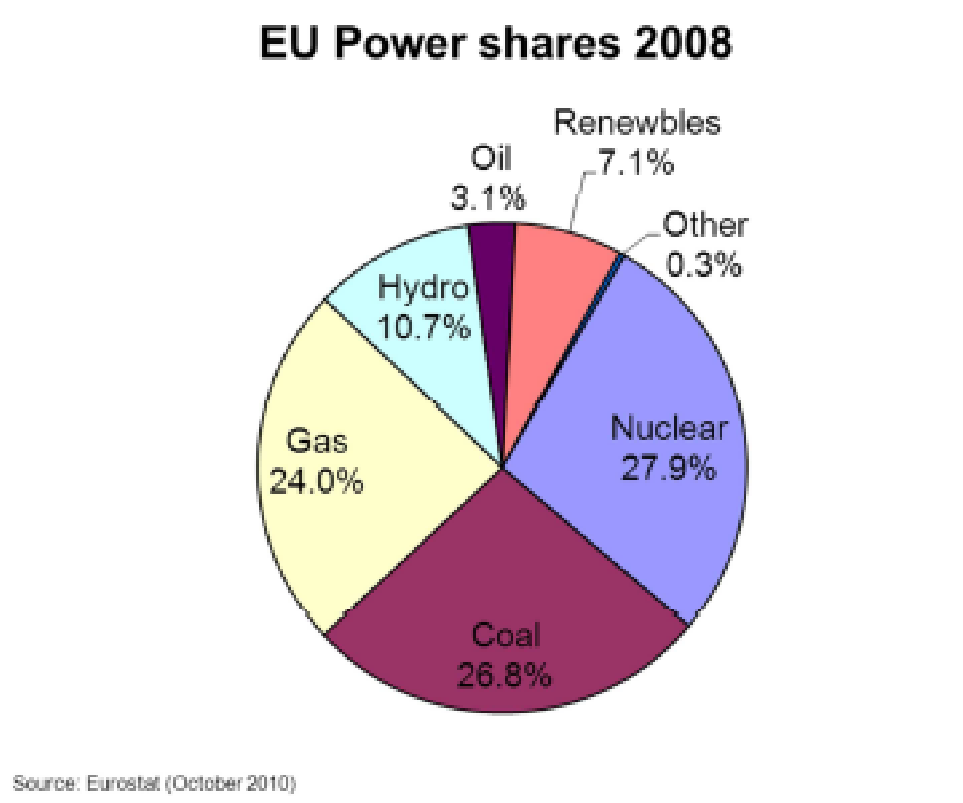


Source: Nuclear Energy Today Edition 2012, NEA/OECD

The situation in Europe

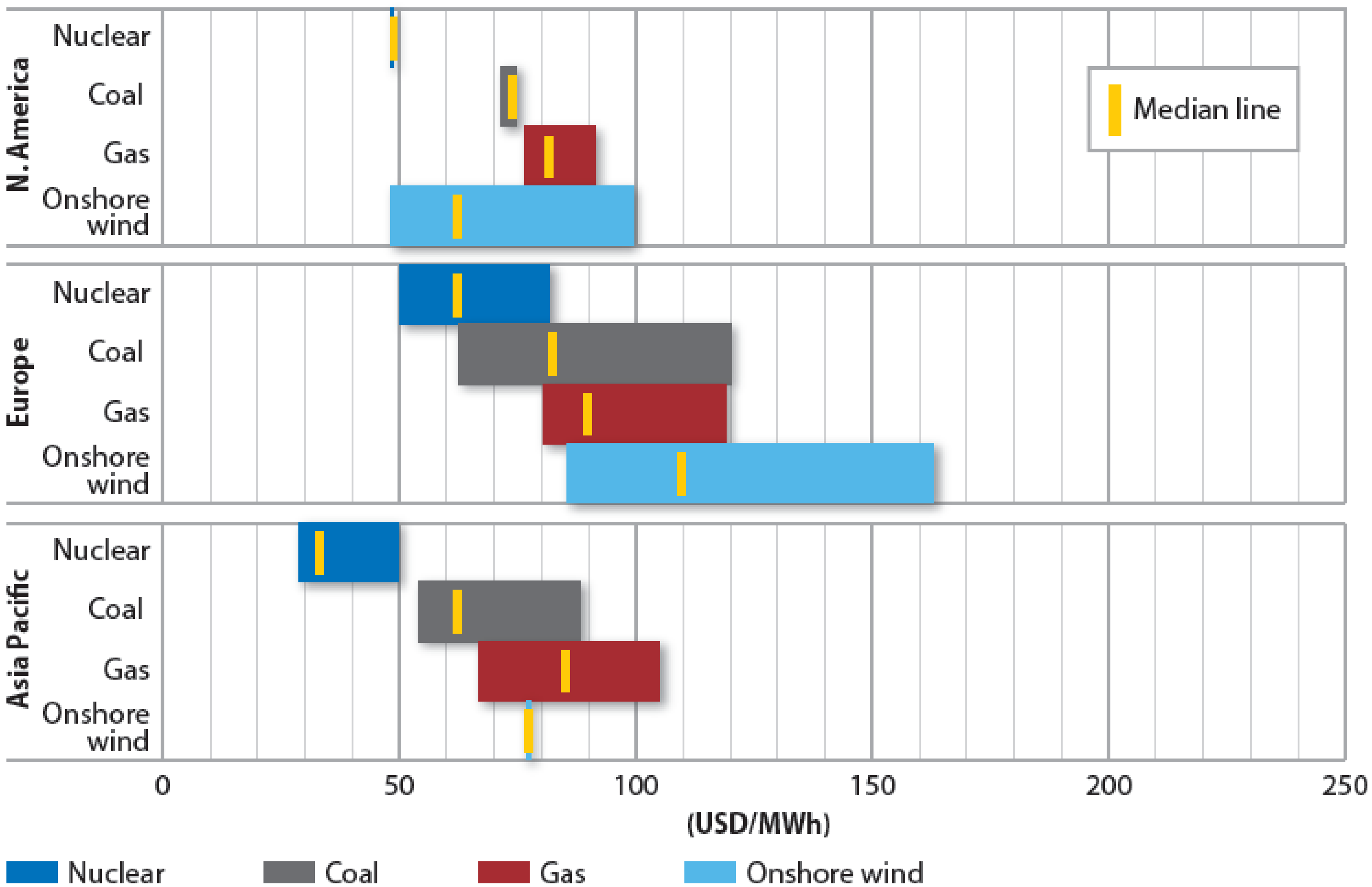
Country	Number of reactors*	Net nuclear generating Capacity (MWe)*	Nuclear share in electricity 2011*
	132 and 4 under construction	121,572	27.4%

Elaborazione European Atomic Forum - Bruxelles



Cost of electricity

Regional ranges of LCOE for nuclear, coal, gas and onshore wind power plants
(5% discount rate and carbon price of 30 USD/tonne CO2)



Source: IEA/NEA, Projected Costs of Generating Electricity, 2010

Emissions compared

The environmental impact of various energy sources is measured by looking at the release of pollutants and greenhouse gases (about 27 % of CO_2 emissions comes from electricity production).

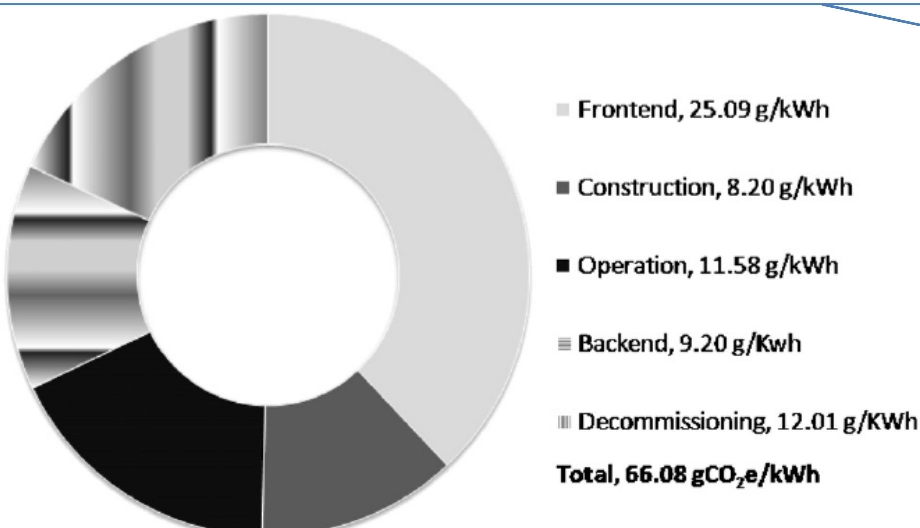
Emissions from a 1000 MWe power plant [t/year]

(Ref. Energia in Italia: problemi e prospettive (1990 - 2020) – Italian Physical Society 2008)

	CO_2	SO_2	MO_x	Polveri
Nuclear	0	0	0	0
Coal	7.500.000	60.000	22.000	1.300
Oil	6.200.000	43.000	10.000	1.600
Gas	4.300.000	35	12.000	100
Photovoltaic	0	0	0	0
Wind	0	0	0	0

Only fuel burnup

If one considers the whole plant lifetime (from fuel mining/extraction to decommissioning)

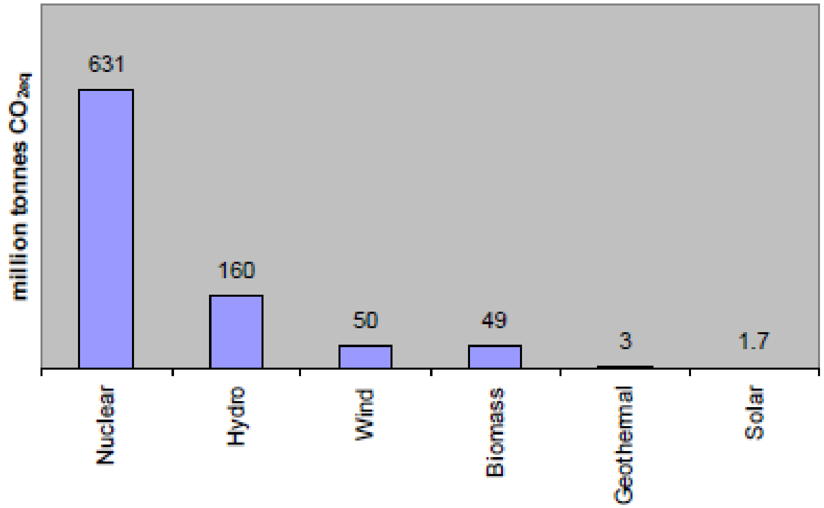


Technology	Capacity/configuration/fuel	Estimate (gCO_2e/kWh)
Wind	2.5 MW, offshore	9
Hydroelectric	3.1 MW, reservoir	10
Wind	1.5 MW, onshore	10
Biogas	Anaerobic digestion	11
Hydroelectric	300 kW, run-of-river	13
Solar thermal	80 MW, parabolic trough	13
Biomass	Forest wood Co-combustion with hard coal	14
Biomass	Forest wood steam turbine	22
Biomass	Short rotation forestry Co-combustion with hard coal	23
Biomass	FOREST WOOD reciprocating engine	27
Biomass	Waste wood steam turbine	31
Solar PV	Polycrystalline silicone	32
Biomass	Short rotation forestry steam turbine	35
Geothermal	80 MW, hot dry rock	38
Biomass	Short rotation forestry reciprocating engine	41
Nuclear	Various reactor types	66
Natural gas	Various combined cycle turbines	443
Fuel cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1050

Ref: Benjamin K. Sovacool, Energy Policy 36 (2008) 2940– 2953

Emissions compared….Europe

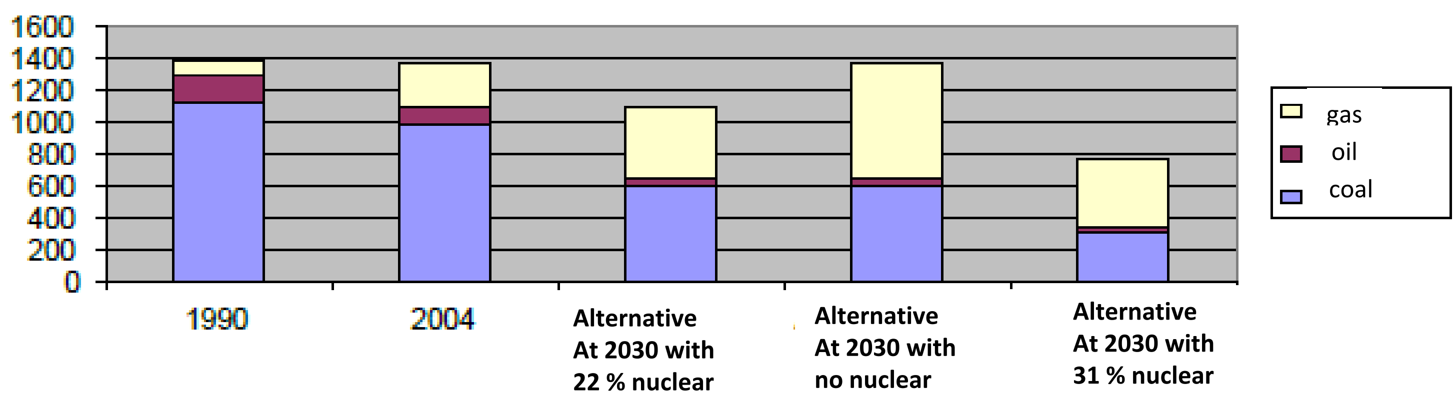
Million tonnes CO_2eq



Source: Emissions avoided in 2008 calculated using fossil fuel-emission rates from the IEA, IAEA and WEC and plant generation data from Eurostat.

Greenhouse gas emissions avoided in 2008 thanks to nuclear and renewables in Europe

The European scenario extrapolated to 2030 assuming different contributions of nuclear energy



CO_2 emissions from electricity production in the EU [Mt]. Source:World Energy Outlook 2006 - International Energy Agency

Energy consumption and emissions… the worldwide perspective

Table 2.1 • World primary energy demand by fuel and scenario (Mtoe)

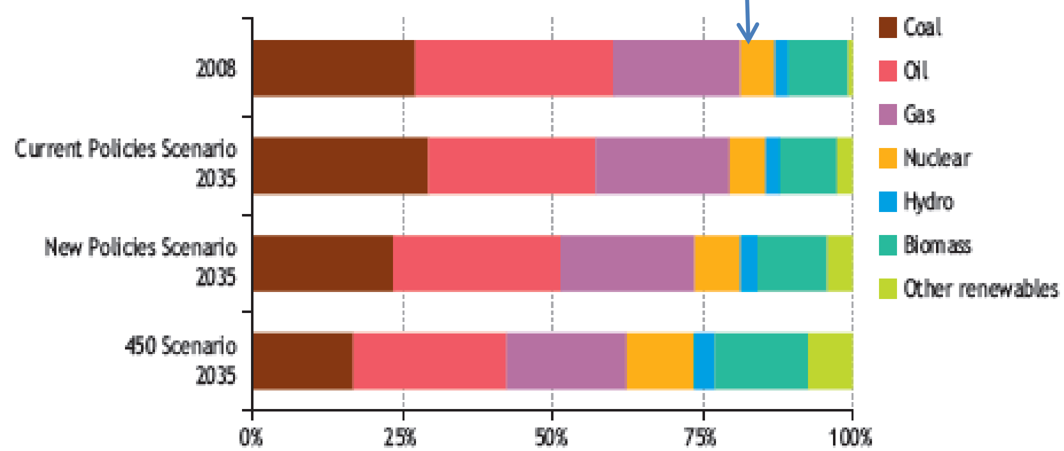
			New Policies Scenario		Current Policies Scenario		450 Scenario	
	1980	2008	2020	2035	2020	2035	2020	2035
Coal	1 792	3 315	3 966	3 934	4 307	5 281	3 743	2 496
Oil	3 107	4 059	4 346	4 662	4 443	5 026	4 175	3 816
Gas	1 234	2 596	3 132	3 748	3 166	4 039	2 960	2 985
Nuclear	186	712	968	1 273	915	1 081	1 003	1 676
Hydro	148	276	376	476	364	439	383	519
Biomass and waste*	749	1 225	1 501	1 957	1 461	1 715	1 539	2 316
Other renewables	12	89	268	699	239	468	325	1 112
Total	7 229	12 271	14 556	16 748	14 896	18 048	14 127	14 920

% of nuclear in 2020 in various scenarios
New policies: 6.6% (+35% produced energy with respect to 2008)
Current policy: 6.1% (+28% produced energy with respect to 2008)
450: 7.1 % (+40% produced energy with respect to 2008)

Nuclear share in 2008: 5,8%

New Policies Scenario: A scenario that anticipates future actions by governments to meet the commitments they have made to tackle climate change and growing energy insecurity.
450 Scenario: A scenario presented in the World Energy Outlook, which sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2.
Current Policies Scenario: A scenario in the World Energy Outlook that assumes no changes in policies from the mid-point of the year of publication (previously called the Reference Scenario)

Figure 2.2 • Shares of energy sources in world primary demand by scenario



IEA - World energy outlook 2010

The emission scenarios

Figure 13.2 • World energy-related CO_2 emissions by scenario

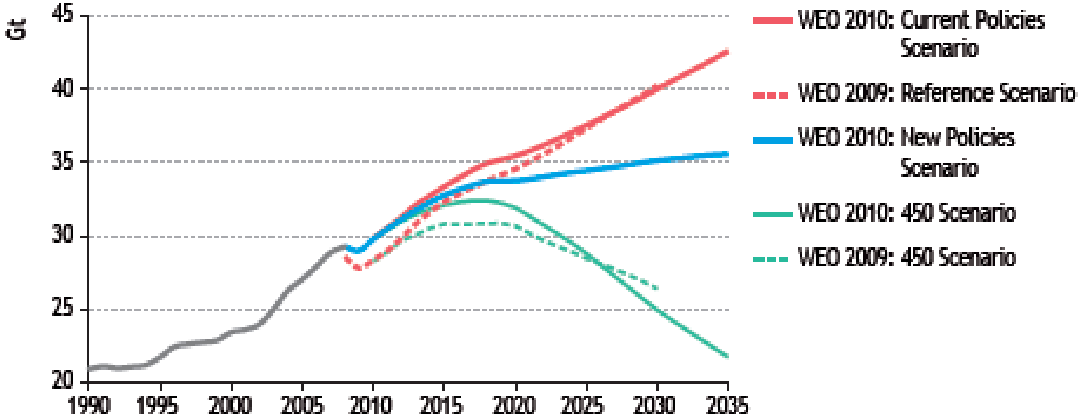
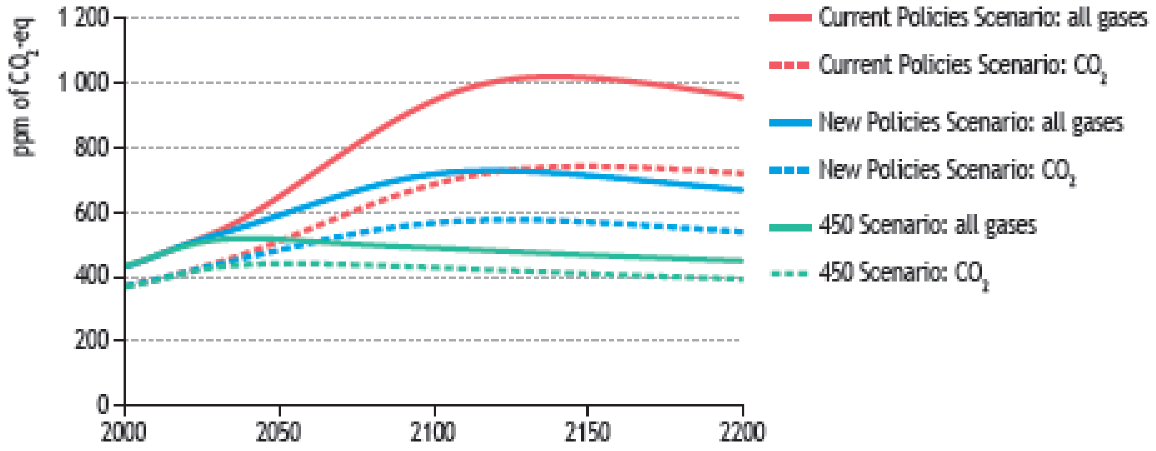


Figure 13.3 • Greenhouse-gas concentration trajectories by scenario



IEA - World energy outlook 2010

Safety

Generation II plants in operation in the world → safety upgrades may be requested for some of the following the post-Fukushima "stress tests" and the recommendations that will be issued by the relevant nuclear regulatory authorities

Generation III/III+ reactors currently under construction

→ safety upgrades are expected to address lessons learnt from the Fukushima Daiichi accident

→ may be more limited as **these reactors have incorporated design features that apply passive safety features and consideration of severe accident mitigation**

These designs are characterised by:

• explicit consideration of severe accidents as part of an extended design condition;

• effective elimination of some severe accident sequences by inherent safety features using passive systems;

• significant reduction or elimination of radioactive releases even in the unlikely case of severe accidents;

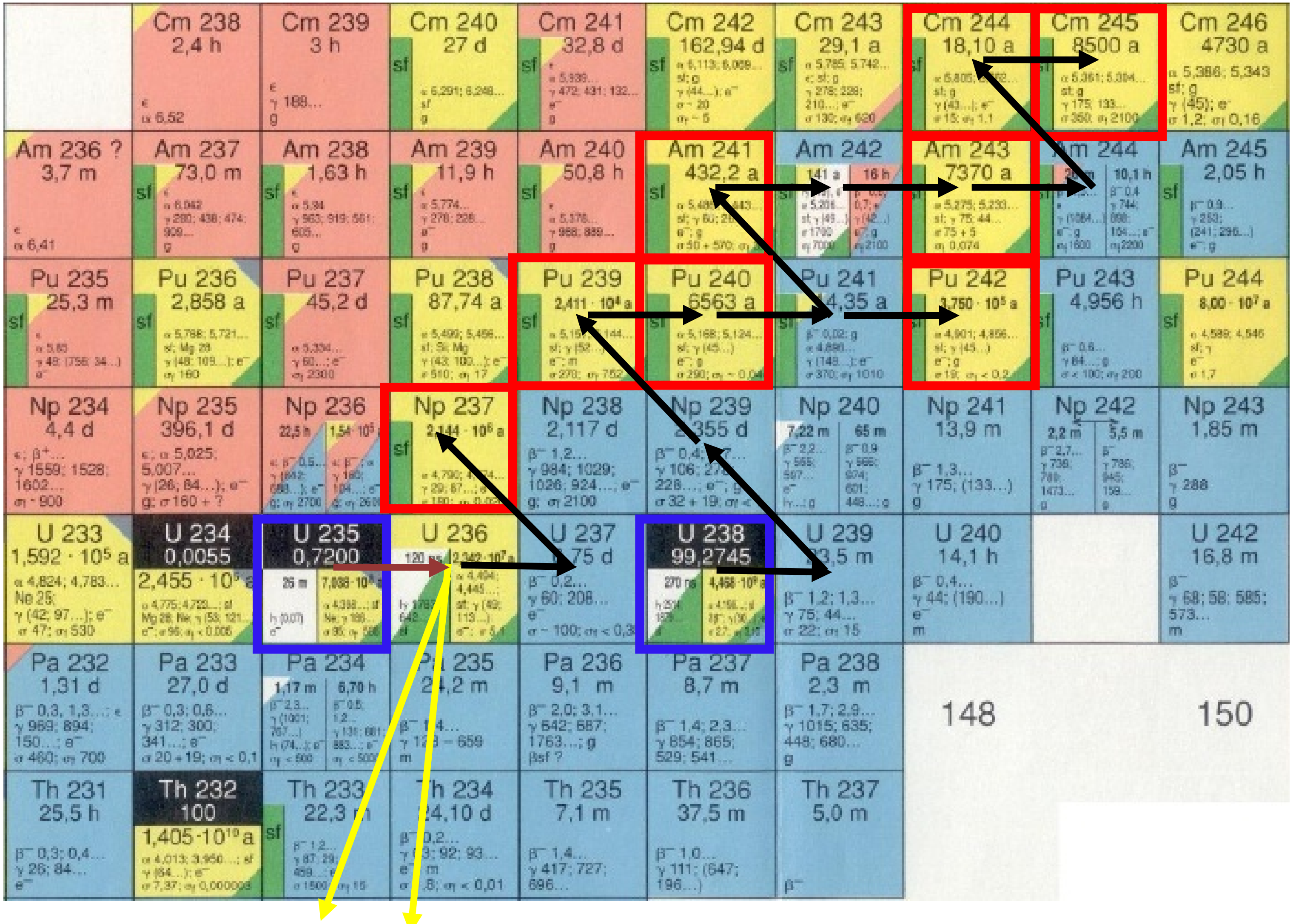
• improved operability and maintainability by extensive use of digital technology;

• reduction in system complexity and the potential for human error.

All of these features, if successfully implemented, could result in less need for extensive onsite and off-site protective measures, such as evacuation plans for the public, and would represent further improvements over the current safety posture

Source: Nuclear Energy Today Edition 2012, NEA/OECD

Long lifetime radioactive waste production (1 GW$_e$ LWR)



$^{244,\,245}$Cm
1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP
76.2 Kg/yr

LLFP=Long Life Fission Products

Transuranics = Minor Actinides + Pu

How long will U resources last ?

As an example, fuel fabrication for a big nuclear power plant with 1000 MWe production, requires about 160.000 Kg natural U per year

→ In the current scheme with about 400 reactors and 369.000 Mwe capacity, "conventional" (cheap) reserves would last for another 80 years (maybe less if average reactor power will increase)

→ Should nuclear power increase as in some of the above scenarios, we should think about (more expensive) resources like phosphates (doable) or U from sea water (still under study)

→ Switching to fast reactors/Thorium cycle would increase availability to a few 100/few 1000 years

	million tons uranium
Australia	1.14
Kazakhstan	0.82
Canada	0.44
USA	0.34
South Africa	0.34
Namibia	0.28
Brazil	0.28
Russian Federation	0.17
Uzbekistan	0.12
World total (conventional reserves in the ground)	4.7
Phosphate deposits	22
Seawater	4 500

Lifetime of uranium resources (in years) for current reactor technology and future fast neutron systems (based on 2006 uranium reserves and nuclear electricity generation rate)

	Identified resources	Total conventional resources	Total conventional and unconventional resources
Present reactor technology	100	300	700
Fast neutron reactor systems	> 3 000	> 9 000	> 21 000

Source: OECD/NEA, Nuclear Energy Outlook, 2008

Uranium resources

Need to produce new fuels
non-natural with fertilization factor
(ratio produced fuel/burnt fuel) ≥ 1

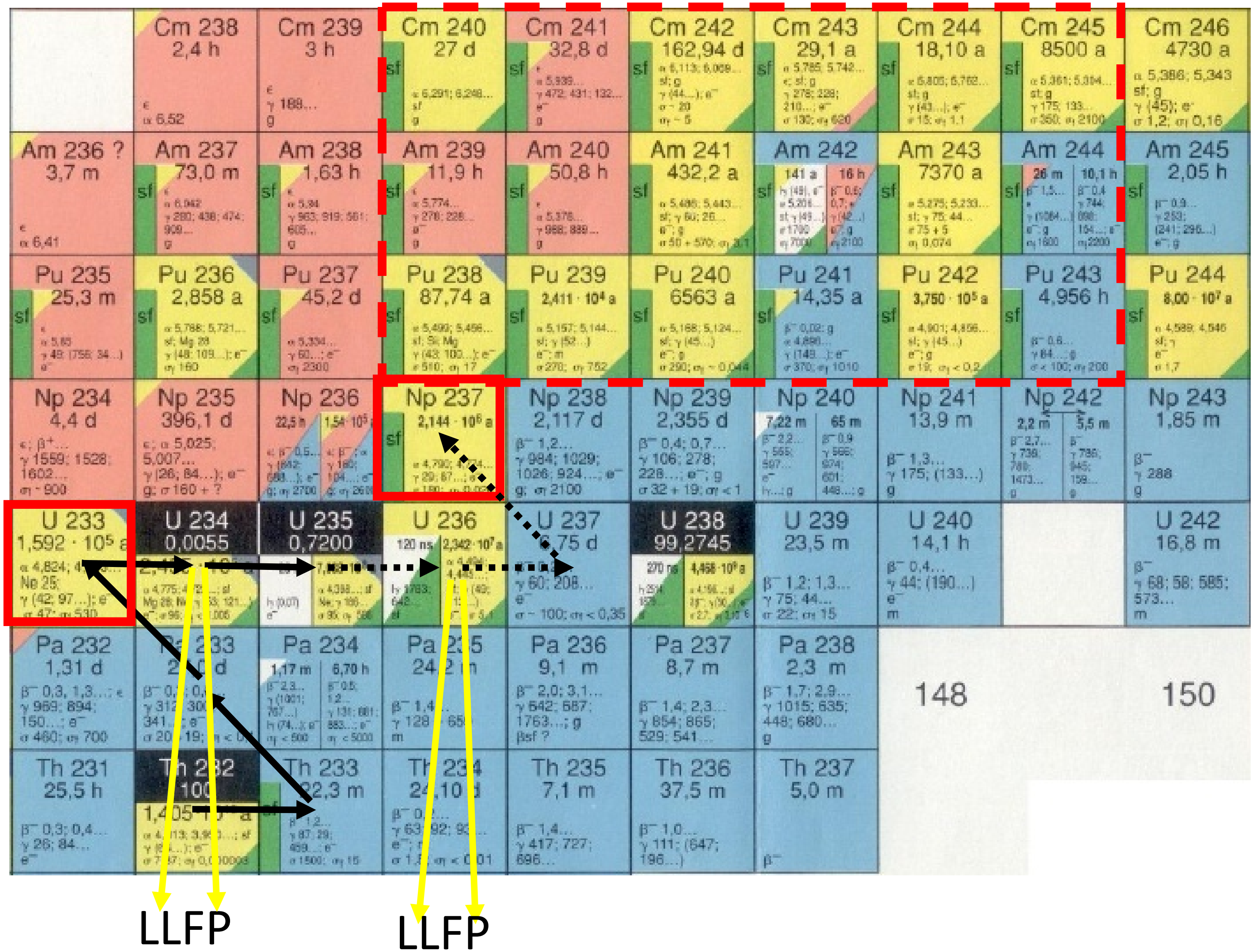
$^{238}U\ (n,\gamma) \rightarrow {}^{239}U \rightarrow {}^{239}Np \rightarrow {}^{239}Pu$ (fissile)
$^{232}Th\ (n,\gamma) \rightarrow {}^{233}Th \rightarrow {}^{233}Pa \rightarrow {}^{233}U$ (fissile)

Advantageous in the fast chain reaction
(number of produced neutrons per absorbed neutron>2)

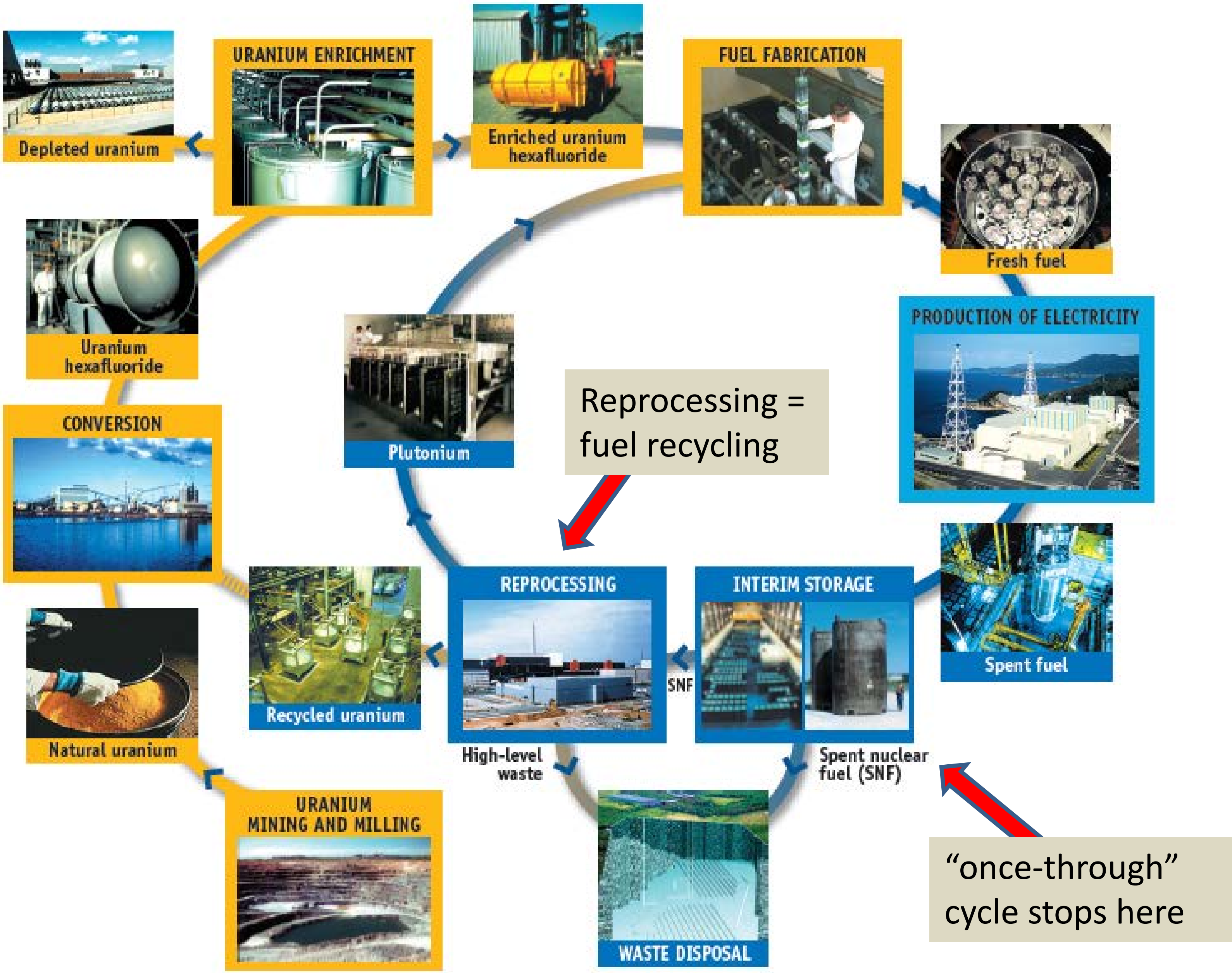
- Conversion of ^{238}U in fissile material (Pu^{239}) in fast reactors would allow to increase by 60 the quantity of produced energy starting from natural U

- The possibility of producing energy from Thorium in the cycle $Th^{232} \rightarrow U^{233}$ would enormously increase fuel availability and would reduce the waste (less production of Transuranic elements)

The thorium cycle



The nuclear fuel cycle



IAEA Scheme for Classification of Radioactive Waste (2009)

1. Exempt waste (EW) – such a low radioactivity content, which no longer requires controlling

2. Very short-lived waste (VSLW) – can be stored for a limited period of up to a few years to allow its radioactivity content to reduce by radioactive decay. It includes waste containing radionuclides with very short half-lives often used for research and medical purposes

3. Very low level waste(VLLW) – usually has a higher radioactivity content than EW but may, nonetheless, not need a high level of containment and isolation. Typical waste in this class includes soil and rubble with low levels of radioactivity which originate from sites formerly contaminated by radioactivity

4. Low level waste (LLW) - this waste has a high radioactivity content but contains limited amounts of long-lived radionuclides. **It requires robust isolation and containment for periods of up to a few hundred years and is suitable for disposal in engineered near-surface facilities**. It covers a very broad range of waste and may include short-lived radionuclides at higher levels of activity concentration, and also long-lived radionuclides, but only at relatively low levels of activity concentration

5. Intermediate level waste (ILW) – because of its radioactivity content, particularly of long -lived radionuclides, it requires a greater degree of containment and isolation than that provided by near surface disposal. **It requires disposal at greater depths, of the order of tens of metres to a few hundred metres**

6. High level waste (HLW) – this is waste with levels of activity concentration high enough to generate significant quantities of heat by the radioactive decay process or waste with large amounts of long-lived radionuclides that need to be considered in the design of a disposal facility for such waste. **Disposal in deep, stable geological formations usually several hundred metres or more below the surface is the generally recognized option for disposal**

Often surface and deep repository are designed together and comprise additional infrastructures, such as to form a High-Tech Campus

Nuclear waste management

Indicative volumes (m^3) of radioactive waste produced annually by a typical 1 000 MWe nuclear plant, for once-through cycle and with reprocessing of spent fuel

Waste type	Once-through fuel cycle	Recycling fuel cycle
LLW/ILW	50-100	70-190
HLW	0	15-35
Spent Fuel	45-55	0

Source: OECD/NEA, Nuclear Energy Today, 2012

- **Most** of the reactors operative in the **world today** are **thermal spectrum reactors**
  - 265 PWRs, 92 BWRs, 48 CANDU, 18 AGRs, 15 LGR and only one LMFBR
- Currently dominant **open fuel cycle,** in which uranium fuel is irradiated, discharged and replaced with new uranium fuel, has resulted in the gradual **accumulation of large quantities** of highly radioactive or fertile materials in the form of **Depleted Uranium**, **Plutonium**, **Minor Actinides** (MA) **and Long-Lived Fission Products** (LLFP)
- ~**2500 tons** of spent fuel are produced **annually in the EU** containing ~**25 tons of Pu,** ~**3.5 tons of MAs** (Np, Am, and Cm) and ~**3 tons of LLFPs** (Tc, Cs and I)
- In **EU spent fuel is reprocessed** and some of the separated products have already been **utilized** in the form of **MOX** (Mixed Pu/U Oxide) fuels, but not yet in sufficient quantities to significantly slow down the steady accumulation of these materials in storage. Also Japan implemented reprocessing

Nuclear waste transmutation/incineration

Transmutation (or nuclear incineration) of radioactive waste

↓

Neutron induced reactions that transform **long-lived** radioactive isotopes into **stable** or **short-lived** isotopes.

Transmutation reactions

Long-Lived Fission Fragments (LLFF)

^{151}Sm, ^{99}Tc, ^{121}I, ^{79}Se …

↓

neutron **capture** (n,γ)

n + ^{99}Tc (2.1x10^{5} y) → ^{100}Tc (16 s) → ^{100}Ru

Pu and Minor Actinides

^{240}Pu, ^{237}Np, $^{241,243}Am$, $^{244,245}Cm$, …

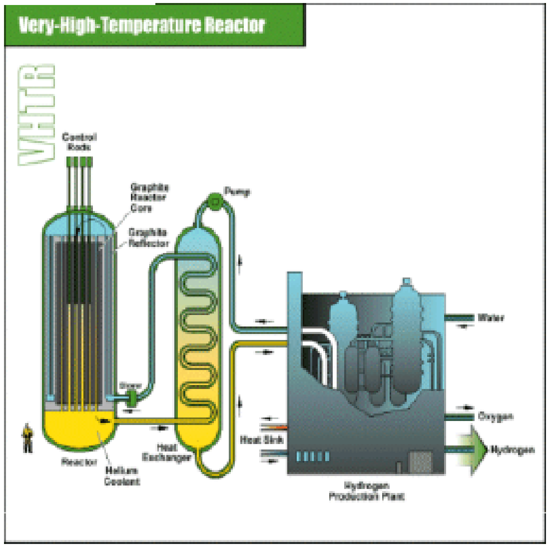
↓

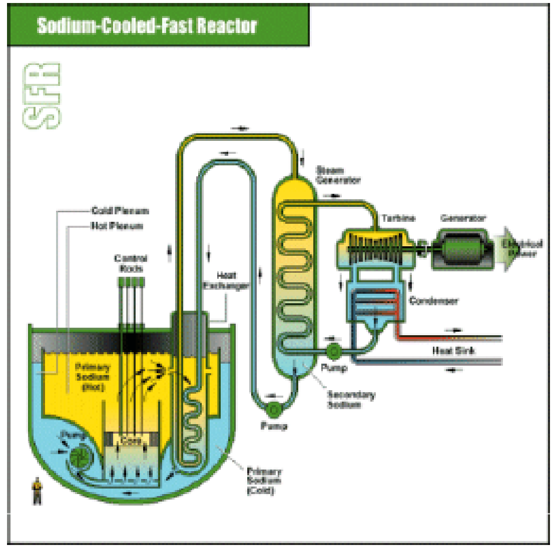
neutron-induced **fission** (n,f)

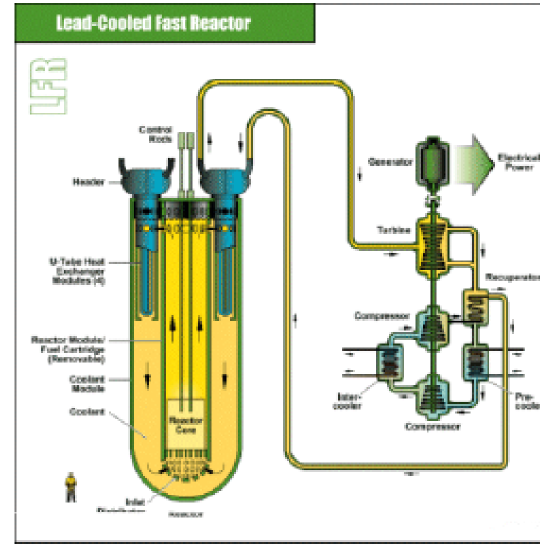
neutron **capture** (n, γ)

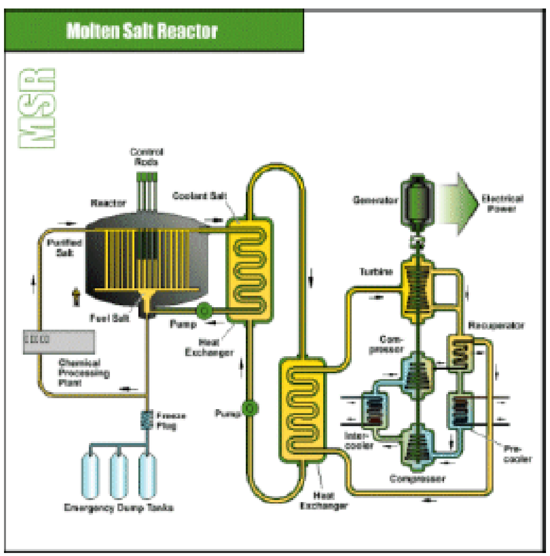
Generation IV

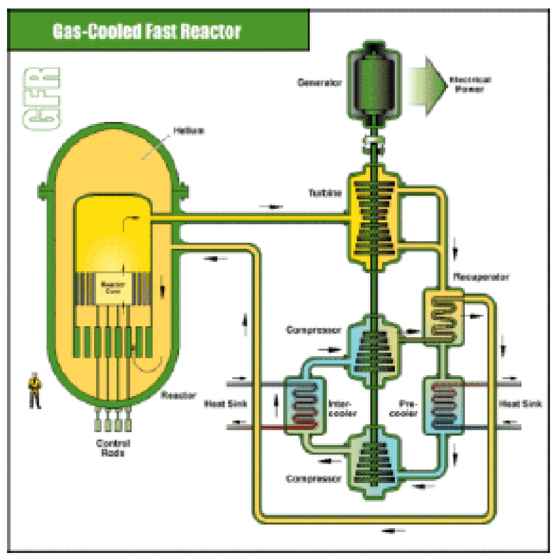
Six conceptual nuclear energy systems were selected by the Gen. IV International Forum (GIF) for collaborative R&D

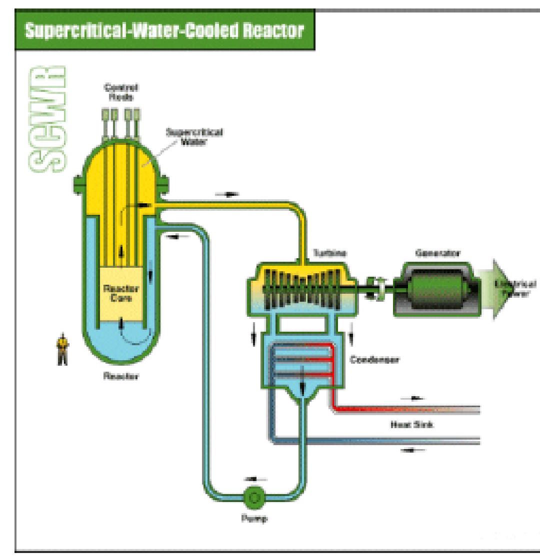










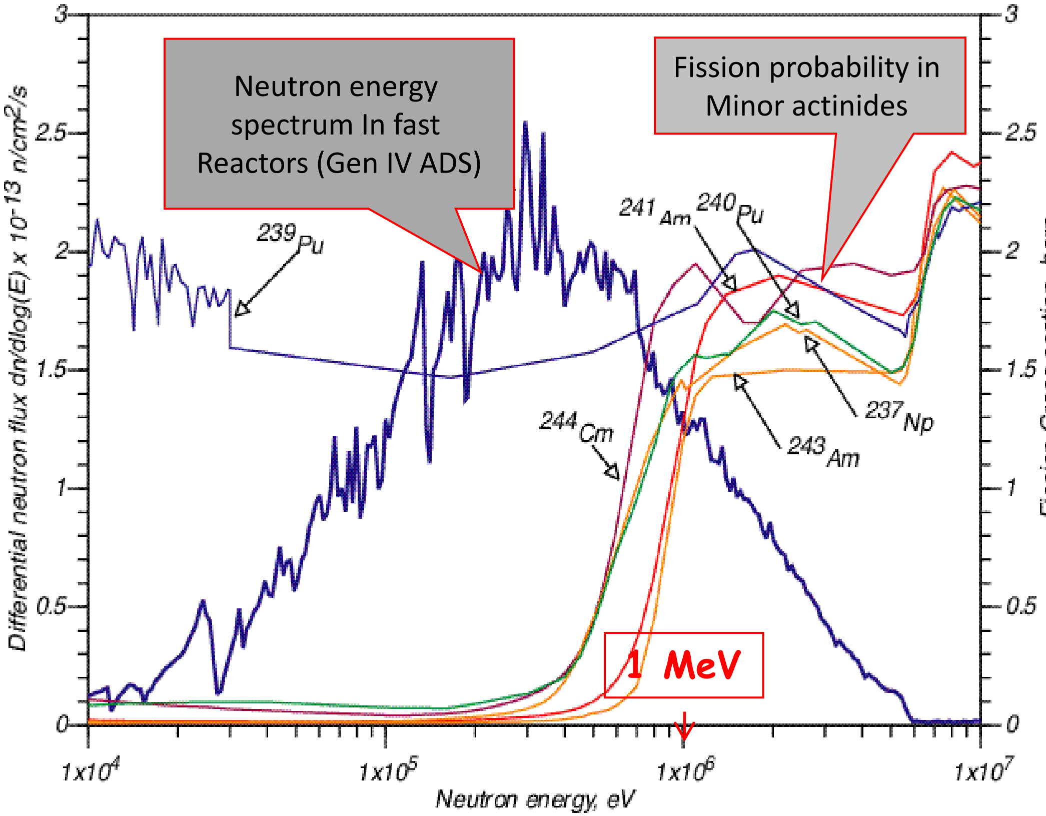


Fast spectrum systems

Apart for ^{245}Cm, minor actinides are characterized by a **fission threshold** around the **MeV**.

In order to transmute actinides, need **fast neutrons → minimal moderation** in intermediate medium → (cooling) medium must be **gas, sodium, lead**, etc.

➔ Such isotopes can be burnt in **fast reactors or in fast Accelerator Driven Systems (ADS)** (neutron spectrum from 10 keV to 10 MeV)

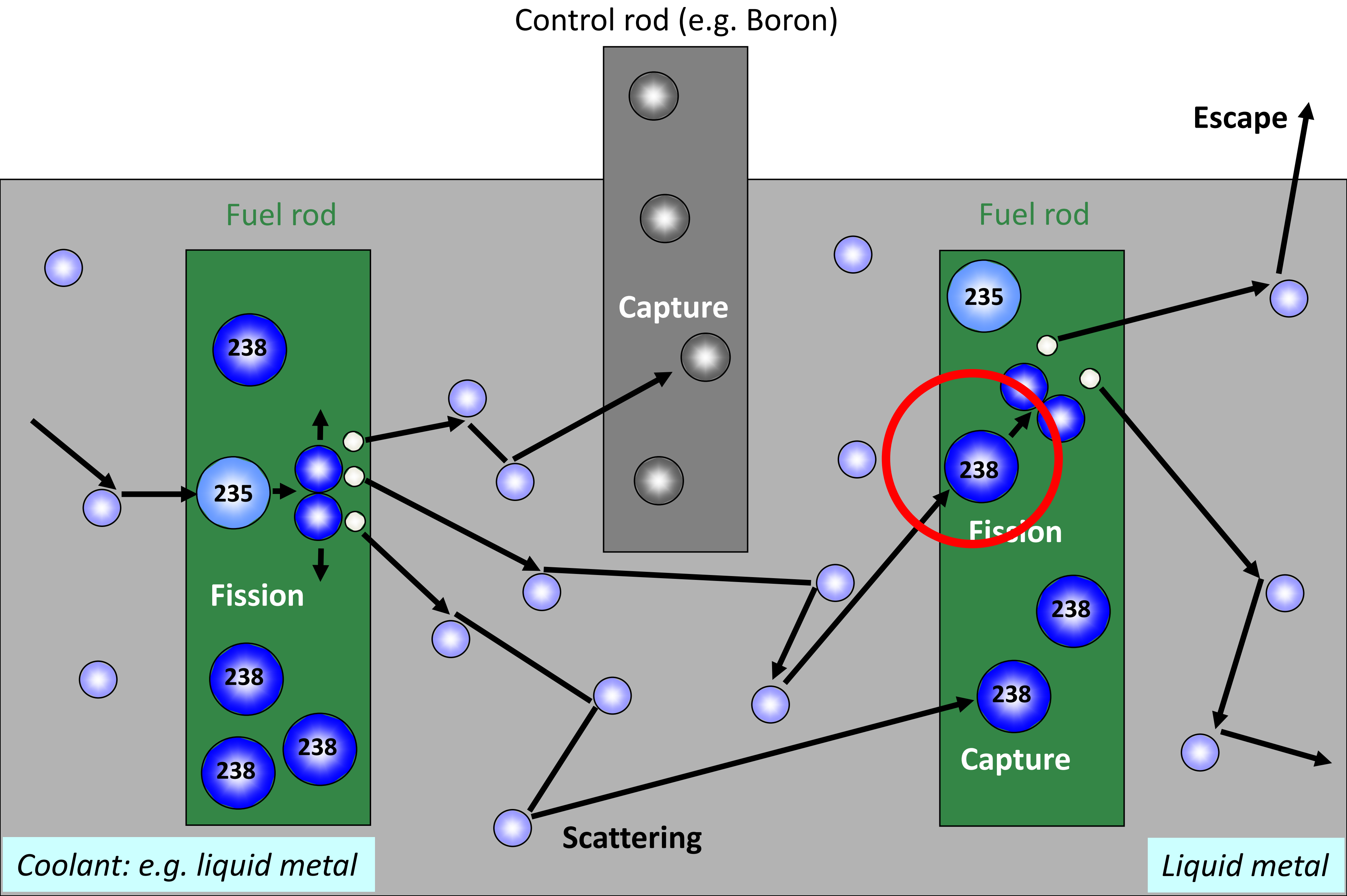


Delayed neutron fraction from FF, e.g.: ^{235}U = 0.65 % ^{241}Am = 0.113 %

In **ADS delayed neutrons** emitted by FF are **less important** for the reactor control: **fast ADS** can therefore be fueled with almost any Transuranic element and burn them

Fast ADS → good candidates as transmuters of high activity and long lifetime (thousands of years) Generation III reactor waste into much shorter lifetime fragments (few hundred years), to be stored in temporary surface storage.
But further R&D is still needed

The fast reactor



Lead as coolant ?

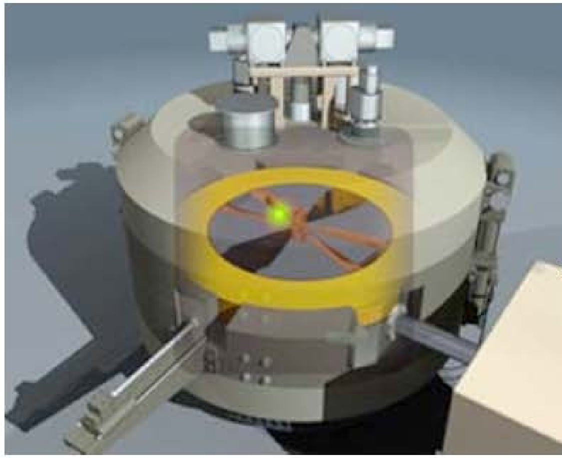
Why Lead as the Coolant for ADS and LFR ?

AnsaldoNucleare
A Finmeccanica Company

- Lead does **not react with water or air**
  - ✓ Possibility to eliminate the intermediate loop; SGU installed inside the Reactor Vessel
  - ✓ Need R&D on effects of water-lead interaction in case of SGTR accident
  - ✓ Less stringent requirements on reactor leak tightness
- Lead has very **high boiling point**
  - ✓ Reduced core voiding risk (Lead boiling point is 1745°C)
- Lead has a **higher density** than the oxide fuel
  - ✓ No need for core catcher to face core melt (molten clad and fuel float)
  - ✓ No risk of re-criticality in case of core melt
- Lead is a **low moderating** medium and has **low absorption** cross-section.
  - ✓ No need to have a very compact Fuel Assemblies (FA can have fuel rods spaced large apart; Core pressure loss drastically reduced in spite of the higher density of lead resulting in lower pumping power and higher natural circulation capability)
- Lead has a very **low ^{210}Po** production
- Lead is compatible with existing **clad material T91**
  - ✓ Operation over long irradiation period and under Oxygen control up to 500°C
  - ✓ More margins with surface coating up to 550-600 °C

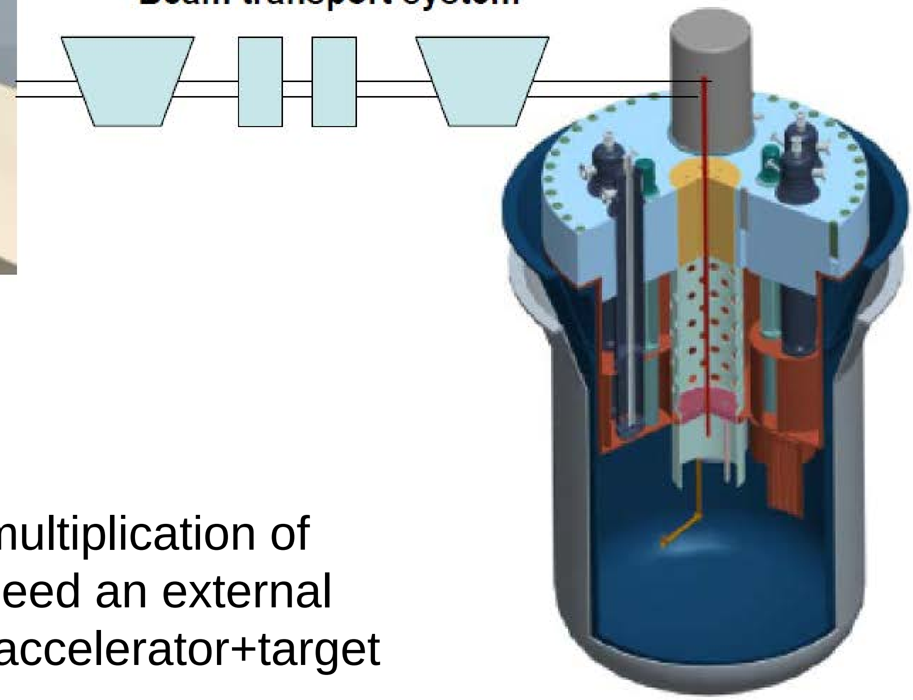
Courtesy of L. Mansani, Ansaldo Nucleare SpA, Italy

ADS: a 3-component infrastructure

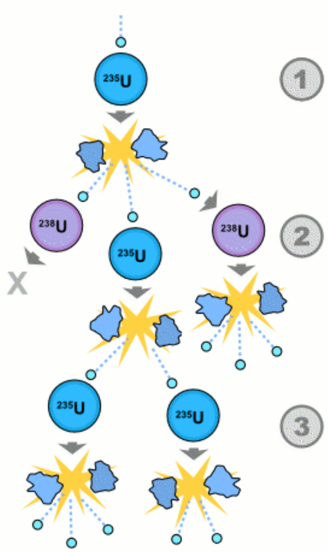


Proton accelerator

Beam transport system



Subcritical reactor



In ADS, effective multiplication of neutrons is < 1 → need an external neutron source → accelerator+target

The maximum thermal power P_{th} from the subcritical reactor is limited (and controlled !) by the input beam power P_{beam}

The neutron source

✓ Accelerated protons impinging on a thick target are the typical way to produce neutrons

✓ Accelerators today are capable of providing about 1 GeV proton energy with around 1 mA average current → a MW beam !

✓ At this energies, the process occuring on heavy nuclei (Fe,W,Pb,…) is **spallation** → e.g. in Pb about 20 neutrons/proton are produced at 1 GeV proton energy

Accelerator requirements

- High neutron production rate (proton or deuteron beams)
- High beam power (high energy E_p and/or current i_p)
- Very high stability (for high-power ADS):very few beam trips during long running times
- Minimal electric power consumption P_{plug}: i.e. optimal P_{plug} /P_{beam} ratio (from 4 to 25 in existing accelerators)

Most of these requirements are more severe than in conventional research accelerators and require, at least for high power ADS, a special design

The European roadmap

Fast Neutron Reactors in the frame of the European Sustainable Nuclear Industrial Initiative (ESNII)

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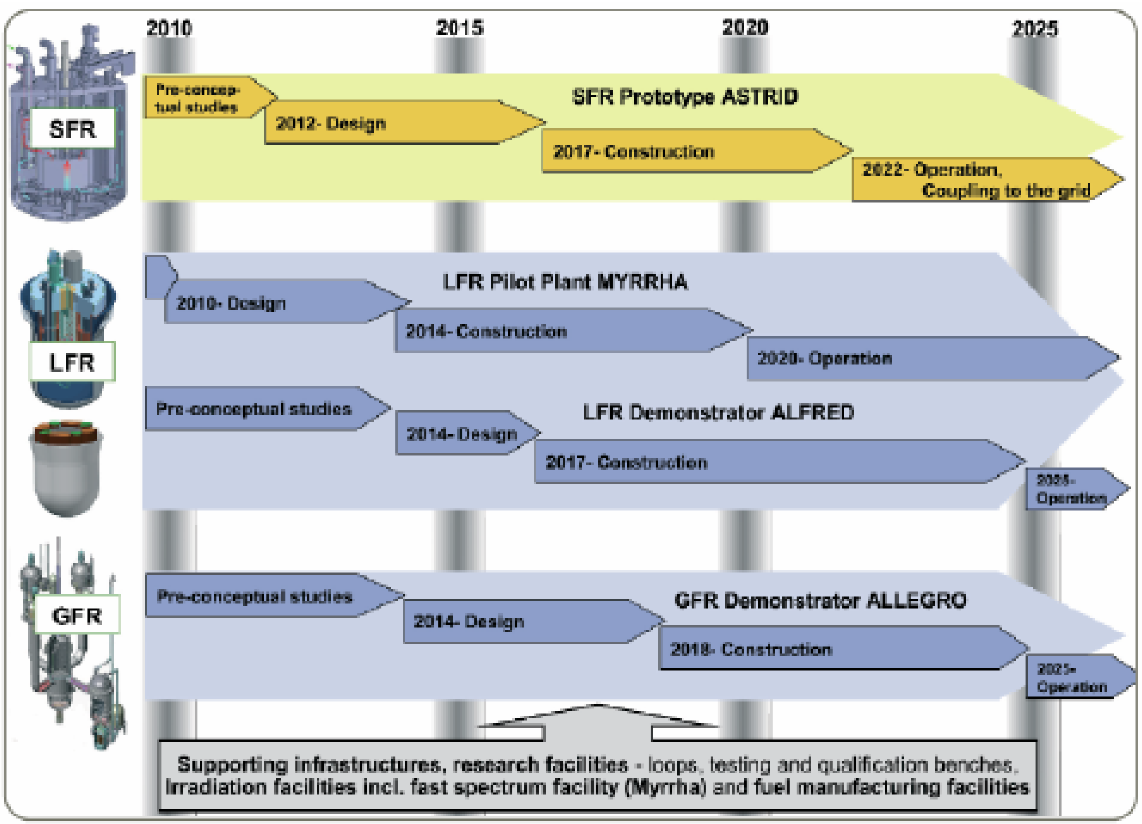
ESNII Roadmap



ADS are envisaged as dedicated facilities for transmuting large amounts of MA in a concentrated approach

ADS technology development has considerable synergy with the R&D required for FNRs and in particular for LFR

ADS is not considered as a potential energy production system (economic reasons), but as a fast neutron irradiation and testing tool which can support the development of FNRs

European Lead Fast Reactor (LFR)/ADS Activities

Accelerator

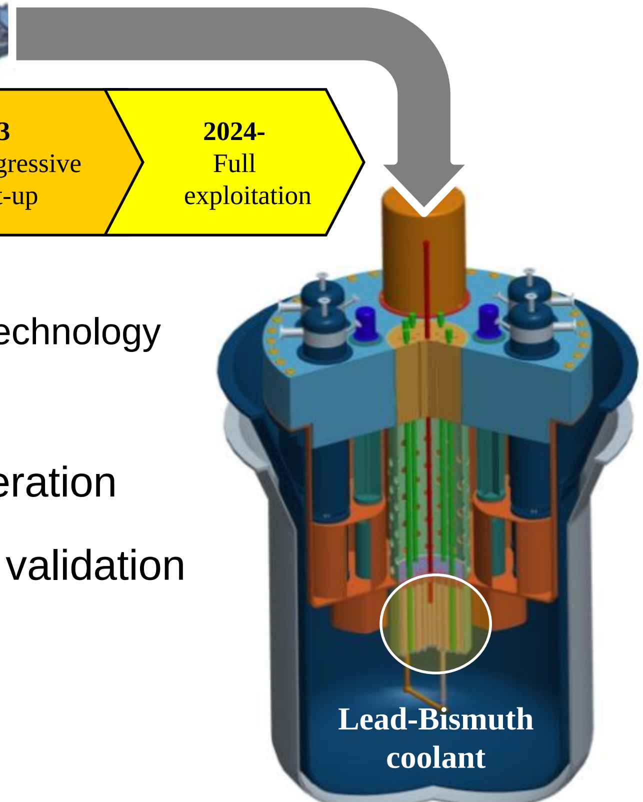
(600 MeV - 4 mA proton)

Reactor

Subcritical mode - 65 to 100 MWth

MYRRHA
project schedule

2010-2014	2015	2016-2018	2019	2020-2022	2023	2024-
Front End Engineering Design	Tendering & Procurement	Construction of components & civil engineering	On site assembly	Commissioning	Progressive start-up	Full exploitation



GUINEVERE and MYRRHA

the first two steps of the EU Road Map for the development of LFR technology

GUINEVERE

The Zero-Power facility – solid Lead – critical and sub-critical operation

Nuclear data, nuclear instrumentation, Keff measurements, code validation

Criticality reached in February 2011

Subcritical coupling performed in October 2011

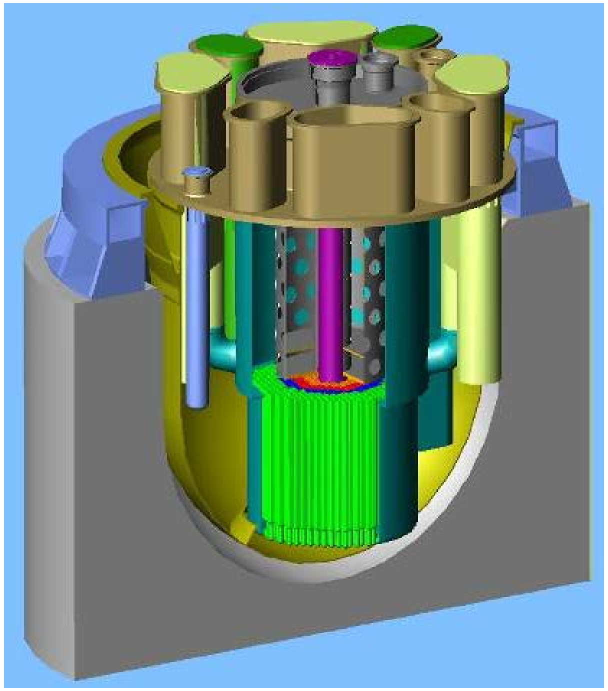
MYRRHA

(Multipurpose hYbrid Research Reactor for High-tech Applications, estimated cost - 960 M€)

European Technology Pilot Plant of LFR

European Lead Fast Reactor (LFR)/ADS Activities

ADVANCED PROJECT: EFIT
(European Facility for
Industrial Transmutation)

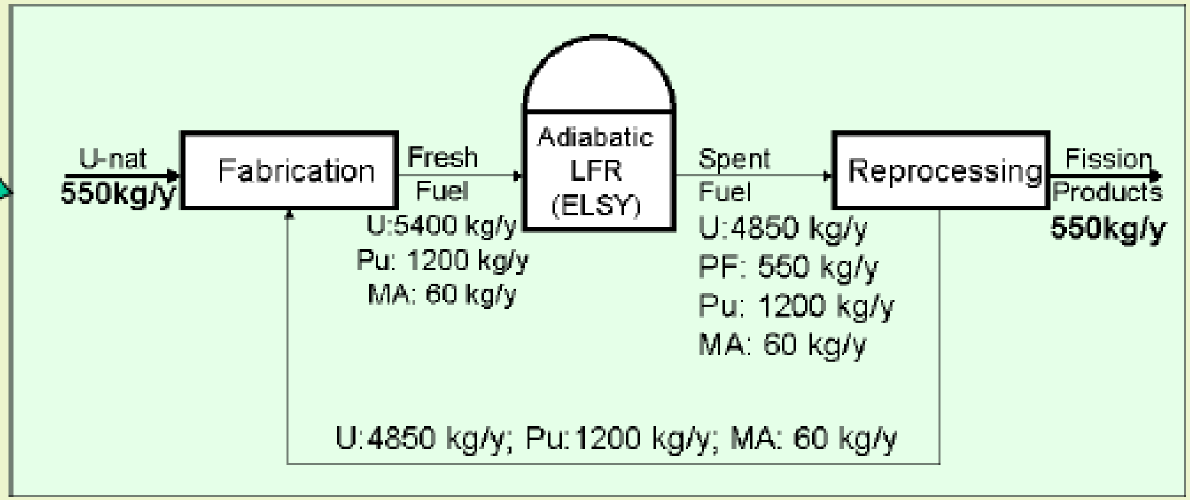


Pure lead-cooled reactor of about 400 MWth with MA burning capability and electricity generation at reasonable cost

- ⇨ EFIT shall be an effective **burner of MA**
- ⇨ EFIT will be loaded with **U-free fuel** containing MA
- ⇨ EFIT will **generate electricity** at reasonable cost
- ⇨ EFIT will be **cooled by pure lead** (a cooled gas option is also studied)

Fast Reactor Fuel cycle: an example

Theoretical equilibrium fuel cycle
for 1500 MW_{th} LFR (ELSY-type)

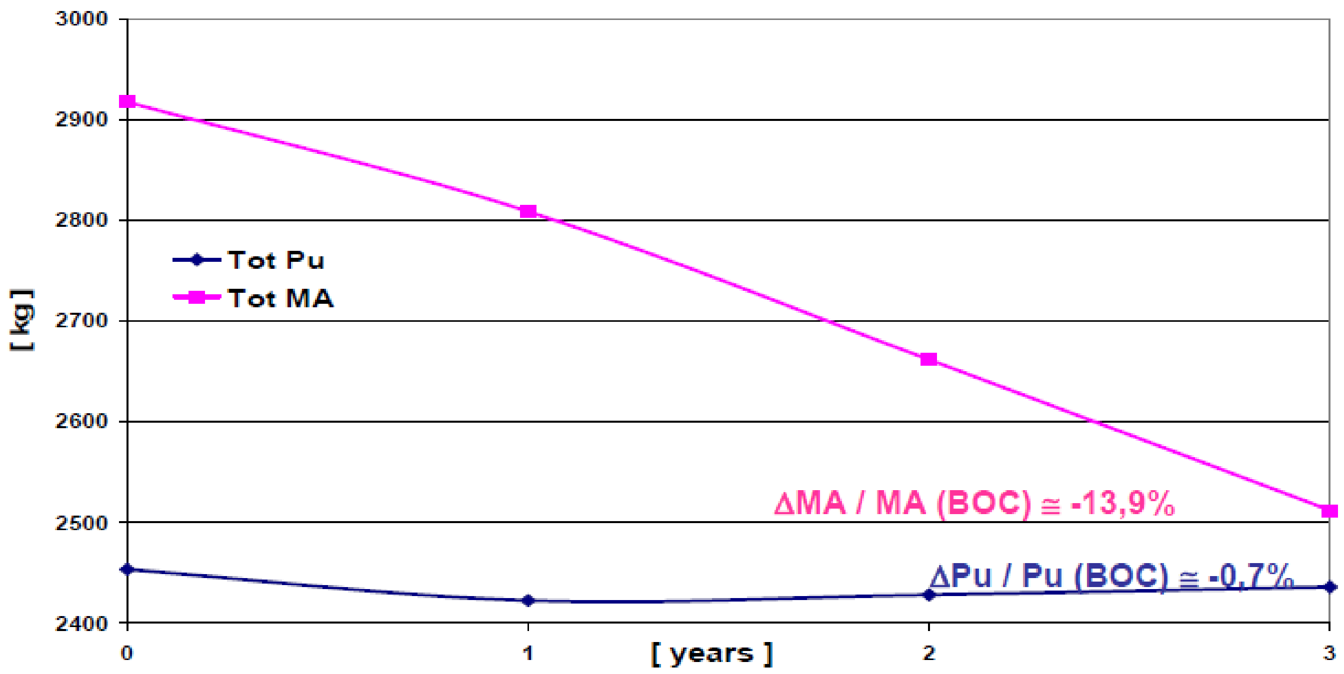


Considering 0.5% losses in the reprocessing:

- **in the waste there are also: 25 kg/y U, 6 kg/y Pu , 0.3 kg/ MA; fed U must be 580 kg/y**

Example of ADS performance

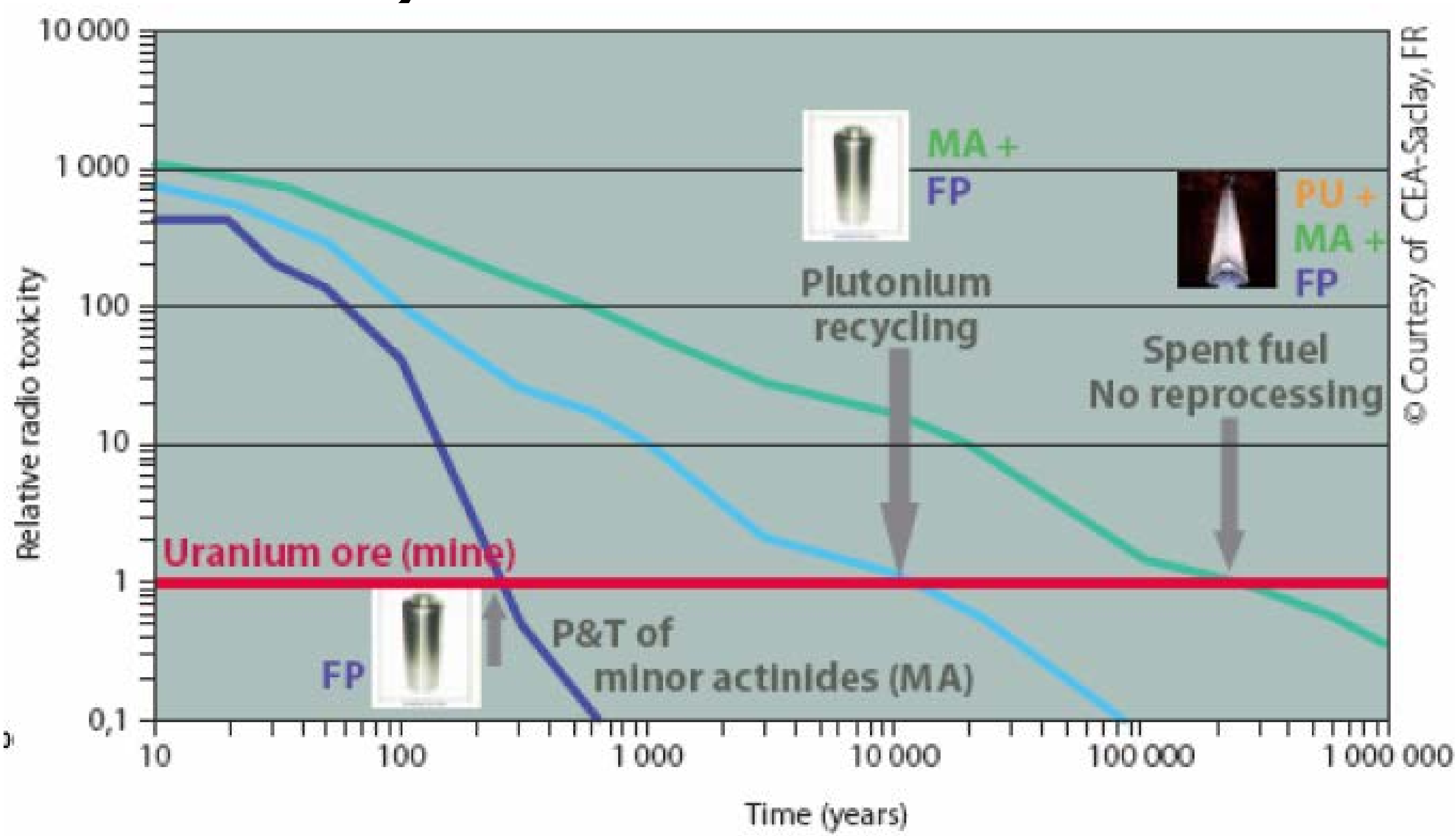
- ✓ Main design missions of EFIT are effective transmutation rate of the Minor Actinides (MA) and effective electric energy generation
  - ❑ Fuelled with only MA (Uranium free fuel)
  - ❑ CER-CER (Pu,Am,Cm)O2-x – MgO
  - ❑ CER-MET (Pu,Am,Cm)O2-x – 92Mo
- ✓ Minimize the burn-up reactivity swing without burning and breeding Pu



BU → -40,17 kg (MA) / TWh

-1,74 kg (Pu) / TWh

Fuel cycle and transmutation



Moreover, since in the new reactors the fuel may include non-separated actinides, the proliferation issue (use of Pu to make weapons) would be mitigated

Radiotoxicity=
Activity (how much radioactivity from the material, measured e.g. in Becquerel=decays/sec)
x Dose per Bq (equivalent dose per activity, measures the biological damage, measure in Sievert)
1 Sievert = 1 Joule/Kg (after correction depending on radiation type)

Thank you for your attention !