Transmutation of high-level radioactive waste
Perspectives

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High level radioactive waste from nuclear power generation

Motivation for Transmutation

Transmutation Facilities and Options

European Research Infrastructures for Nuclear Data Applications

Accumulation and disposal of spent nuclear fuel in the EU

Accumulation:

Nuclear power reactors:	136*
Power:	125 $\mathrm{GW_e}$
Spent nuclear fuel	~2500 t/a

* Including Switzerland

comparison: U.S.A.
104 nuclear reactors
100 $\mathrm{GW_e}$
~ 2000 t/a

Disposal:

Reprocessing:

Separation of Uranium and Plutonium
Production of vitrified highly-radioactive waste (fission products, minor actinides)
MOX fuel elements (F,DE,BE,CH,Japan)
MOX facility Savannah River, Weapon Pu
➔ 25-45% reduction* of Pu inventory

*B. Merk, C. Broeders atw 53 (2008) 6 404

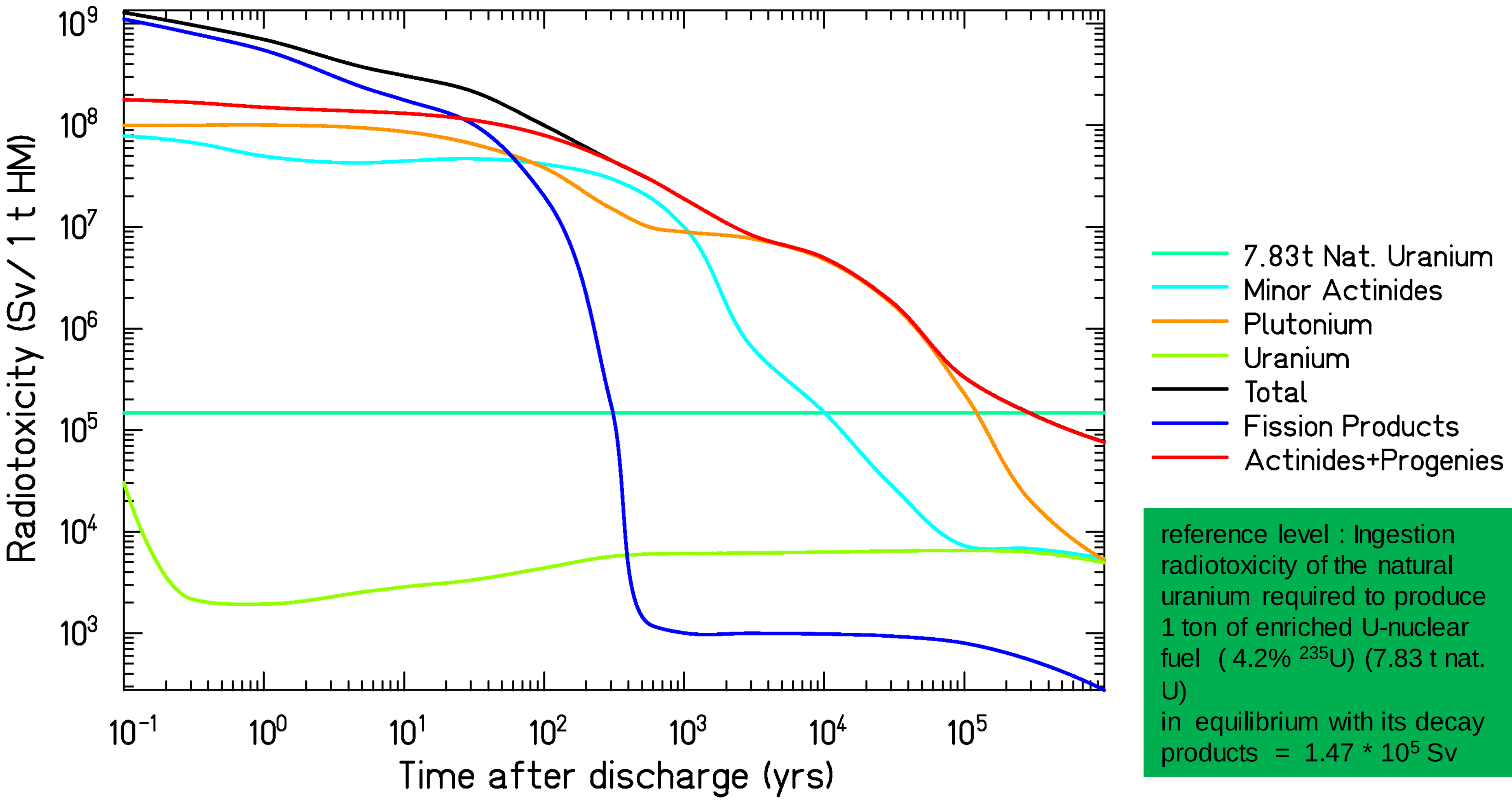
Direct final disposal:

Intermediate and final storage of spent nuclear fuel elements ca. 40 yrs.

Final repositories in deep geological formations

Power reactor data from http://www.world-nuclear.org/info/reactors.html

Radiotoxicity of spent nuclear fuel



reference level : Ingestion radiotoxicity of the natural uranium required to produce 1 ton of enriched U-nuclear fuel (4.2% ^{235}U) (7.83 t nat. U)
in equilibrium with its decay products = 1.47 * 10^5 Sv

The long-lived radiotoxicity is dominated by plutonium and minor actinides
The short-lived radiotoxicity < 60 yrs is dominated by fission products.
Not included is the different **volatility of the chemical elements** or the environmental conditions., **e.g. Cs, Sr, Tc, I, Se**

webKORIGEN SIMULATION 55 MWd/kg 4.5% UOX PWR FUEL

Final Disposal and Partition and Transmutation

Problem:
Safe disposal of highly radioactive waste for 1 000 000 years

Alternative strategy to direct disposal of spent nuclear fuel:
Partitioning of long lived actinides
Transmutation into shorter lived fission products.

➔ Direct Disposal > 1 000 000 years
➔ Transmutation of Pu ca. 10000 years
➔ Transmutation of Pu and minor actinides < 1000 years
(Long-lived Fission Fragments !)

Current Situation of the P&T Research in Germany

international agreement – Plutonium and Uranium are accounted as resource

objective:
burning of minor actinides only
- priority to Am
- limited for Cm

avoiding or limiting of the accumulation of minor actinides

European & international projects:
- regional scenario PATEROS
- iso-breeder ASTRID
- ADS facility MYRRHA

nuclear phase out decission

Germany – Plutonium, minor actinides, and Uranium are considered as waste

objective:
burning of all Plutonium and minor actinides

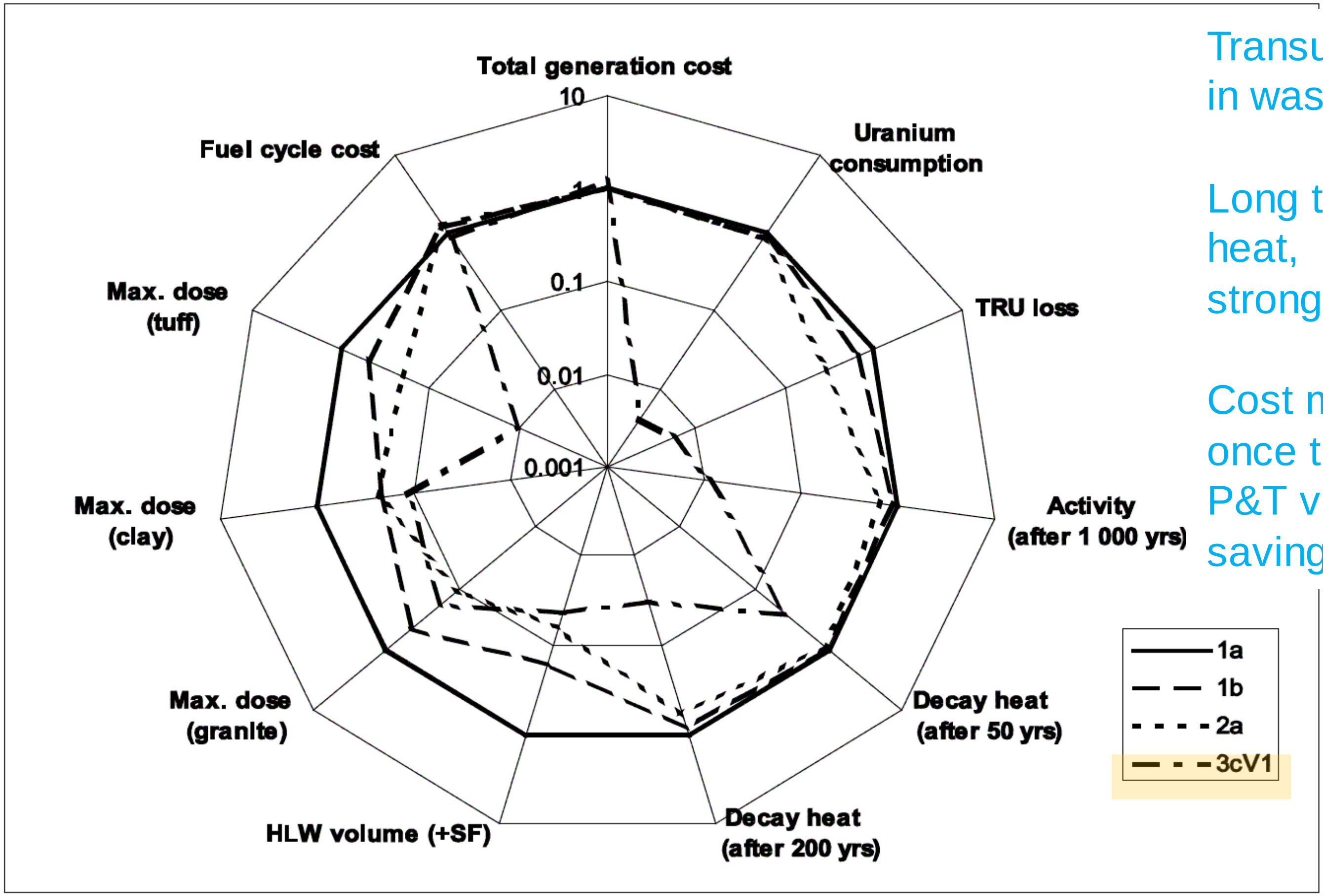
no electricity production allowed, maybe by-product, preferably:
- few facilities
- short operation span
- burning of all TRUs

significantly different design goals ➩ Germany follows a purely national strategy/concern

source:
B. Merk, HZDR

Impact of Partitioning and Transmutation

Figure 3.2. Comparison of 11 representative indicators for various fuel cycle schemes



Transuranium elements in waste strongly reduced.

Long term activity, decay heat, peak dose rate strongly reduced

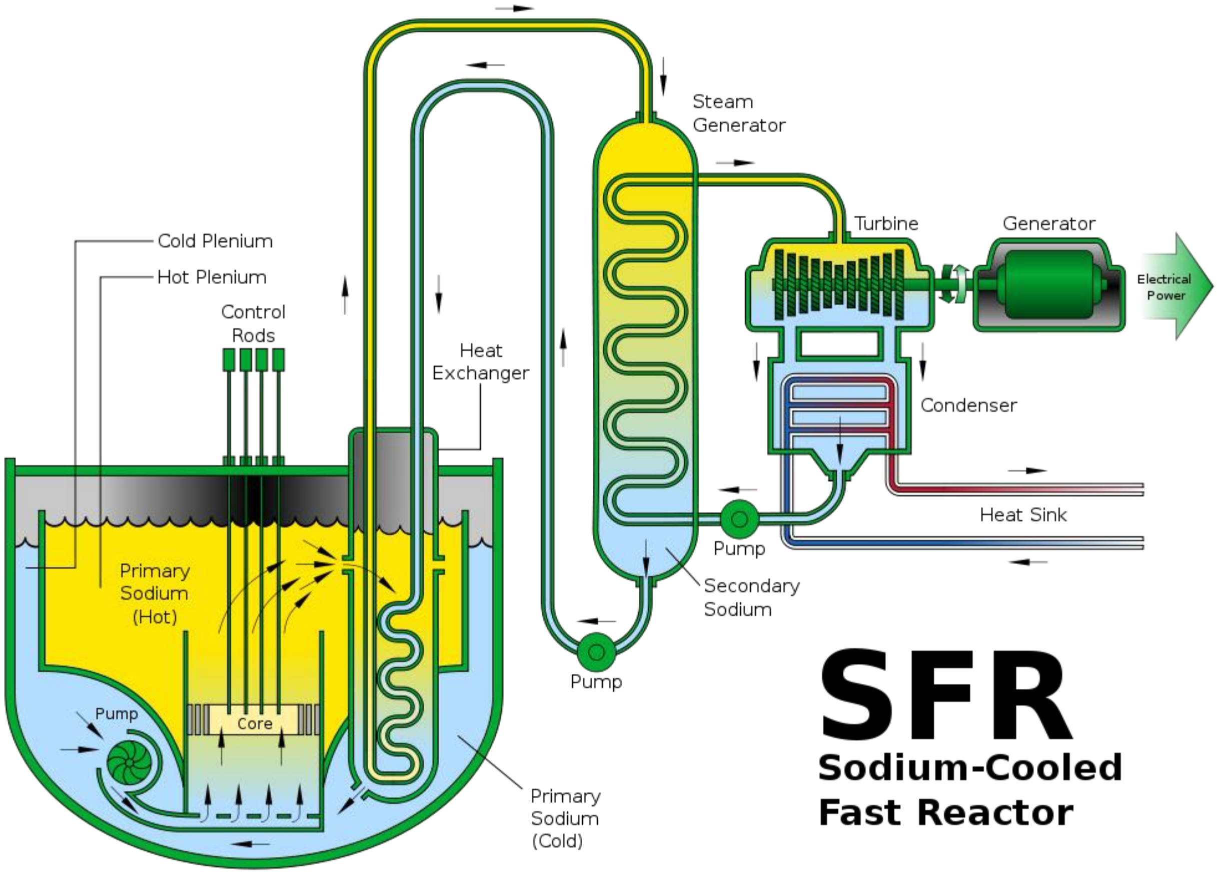
Cost might be higher than once through fuel cycle. P&T versus savings in final disposal ?

1a: once-through PWR scheme (reference); 1b: 100% PWR, spent fuel reprocessed and Pu reused once; 2a: 100% PWR, spent fuel reprocessed and multiple reuse of Pu; 3cV1: 100% fast reactors and fully closed fuel cycle.

Source: OECD/NEA, 2006 [19], Figure 1.

http://www.oecd-nea.org/science/reports/2011/6894-benefits-impacts-advanced-fuel.pdf

Sodium-cooled fast reactor



Transmutation fuel cycle:
Pu-M.A.-Zr fuel
metallic matrix
homogeneous recycling of
Pu and minor actinides
pyrometallurgical
reprocessing (on site)

SFR (ASTRID) could be operational approx. 2020 (oxide based U+Pu fuel)

Am transmutation

Homogeneous (2% Am)

Heterogeneous (10% Am, blanket)

M.A. content limited by criticality control (Doppler, delayed neutron fraction)

France: Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID)

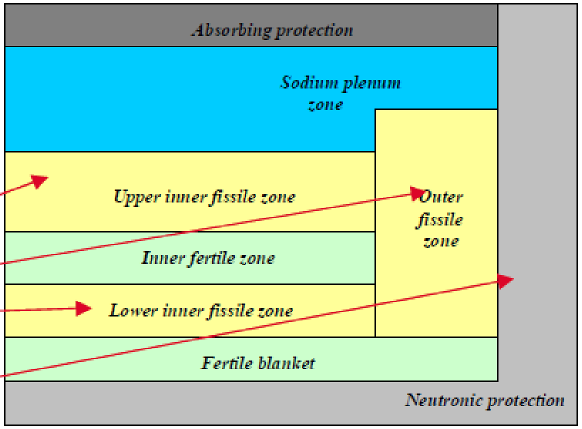
Project to start building a GEN IV reactor in 2017.

THE FRENCH 2006 PROGRAMME ACT ON THE SUSTAINABLE MANAGEMENT OF RADIOACTIVE MATERIALS AND WASTES

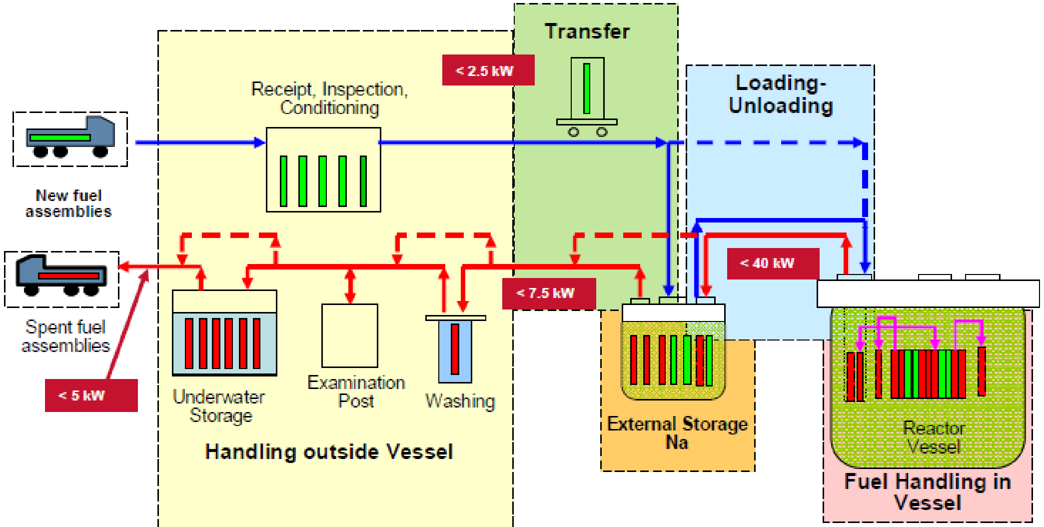
Transmutation potential in ASTRID

Assumptions

- CFV V1 Core
- Cycle of 360 EFPD
- Priority to Americium (241Am: 81%, 243Am: 19%)
- Homogeneous mode : 4 cycles
- Heterogeneous mode : 5 cycles for MABB



- Fuel handling



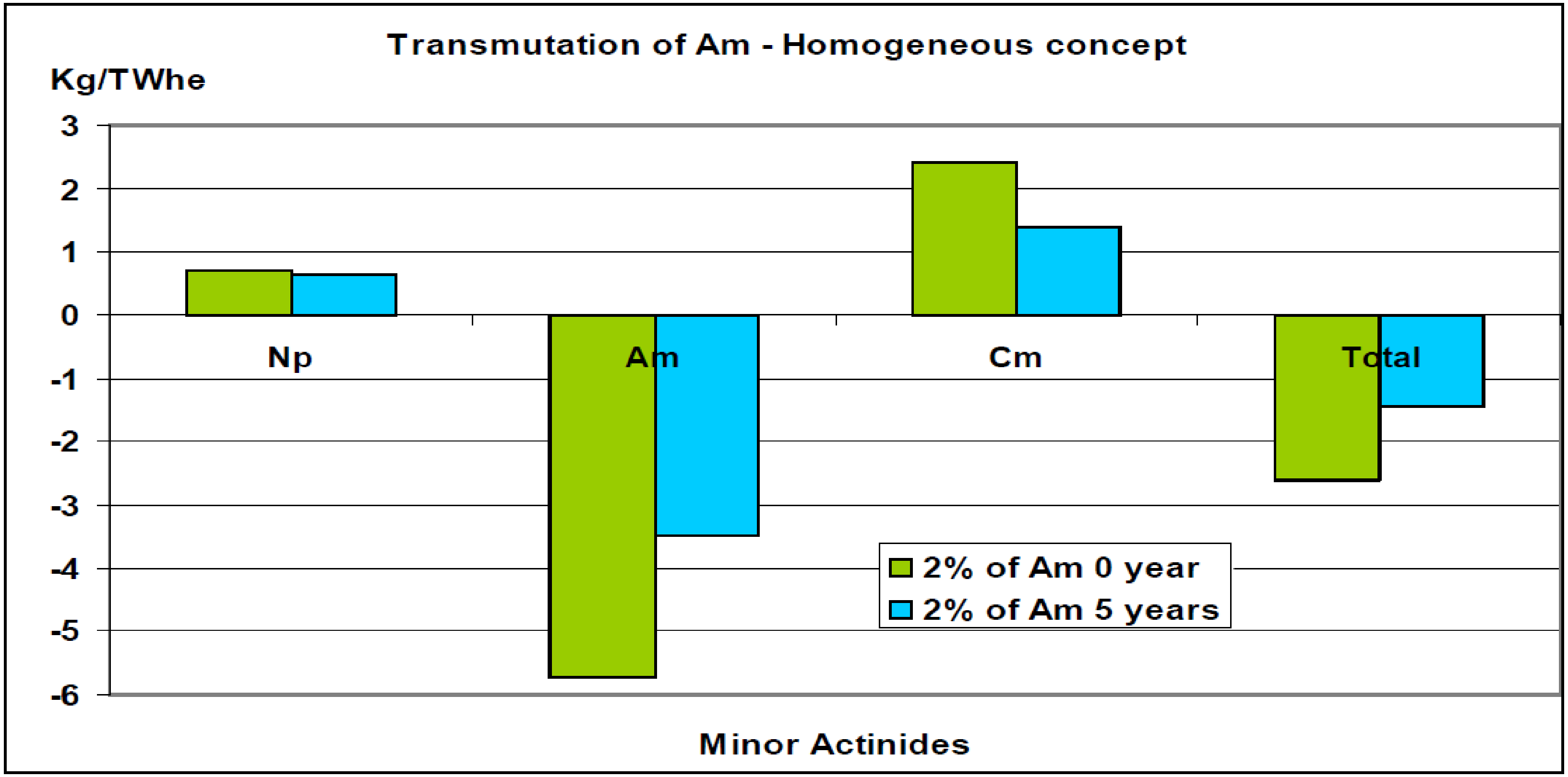
Schematic presentation of the chain of fuel handling

J.P. Grouiller, CEA

Transmutation of Am in ASTRID

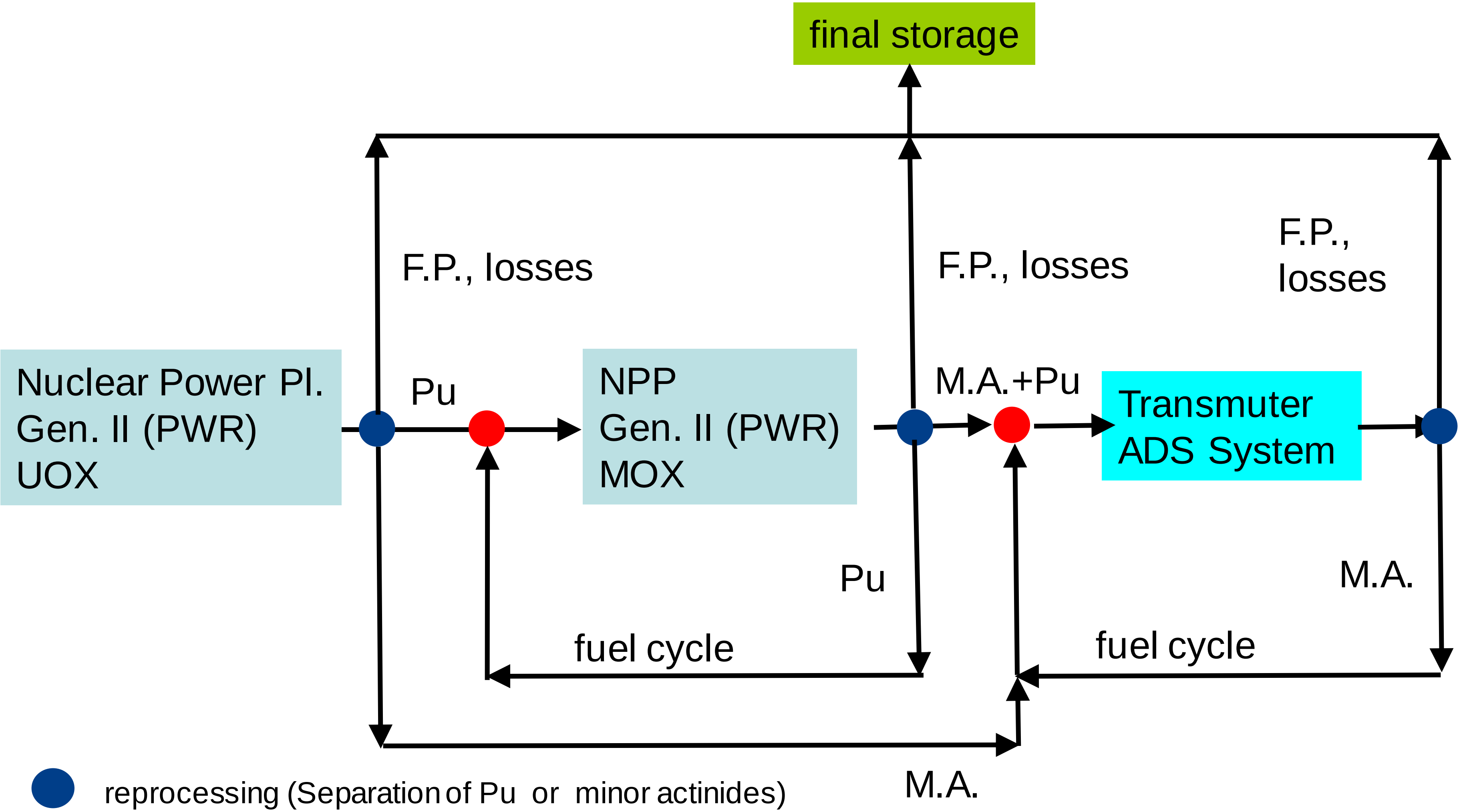
The main objective is to burn the americium produced by the standard $(U,Pu)O_2$ fuel in ASTRID ➔ Initial Am limits

- **Homogeneous mode ~ 2% of Am**



J.P. Grouiller, CEA

„Double Strata“ Concept of Transmutation



final storage

Nuclear Power Pl.
Gen. II (PWR)
UOX

F.P., losses

Pu

NPP
Gen. II (PWR)
MOX

F.P., losses

M.A.+Pu

Transmuter
ADS System

F.P.,
losses

Pu

fuel cycle

M.A.

fuel cycle

M.A.

🔵 reprocessing (Separation of Pu or minor actinides)

🔴 fuel element production

Accelerator Driven Systems (ADS)

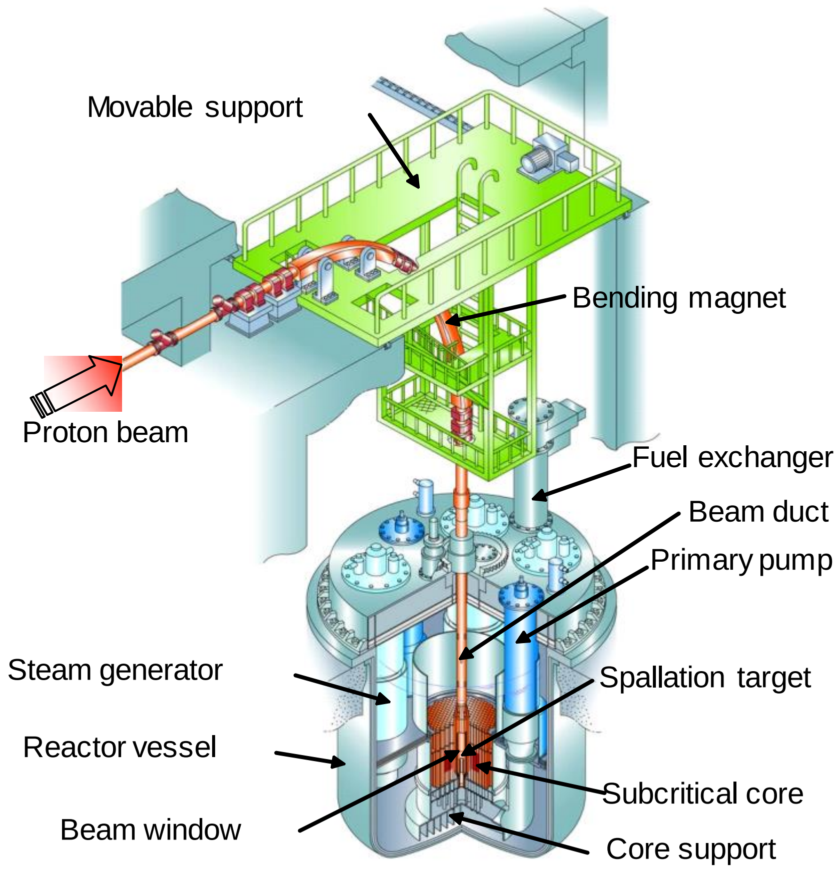


Figure: Hiroyuki OIGAWA
EURATOM PARTRA Cluster Meeting Karlsruhe
Feb. 2008

- Accelerator driven intense thermal neutron source, C.D. Bowman 1992,
  Energy Amplifier, C. Rubbia, 1995

- subcritical neutron multiplication
  number of neutron generations $1/(1-k_{eff})$
  thermal power: 400 MWt
- Highest Performance-proton-accelerator
  800 MeV ca. 10 mA beam current
  8 MW- beam power
- Liquid metal cooling Pb, Pb/Bi oder Na
- Criticality controlled by spallation neutrons
  ca. 15-30 n / proton

Challenges:

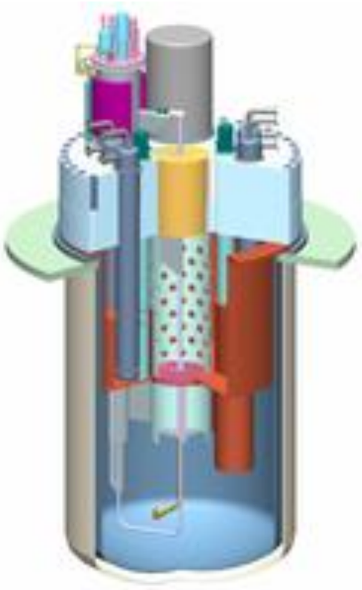
Reliability of the accelerator
(Linac, Cyclotron)

Development of the spallation target (window?)

EUROTRANS Projekt KIT (J. Knebel) ➔ XT-ADS

Myrrha project, SCK.CEN, Mol Belgium

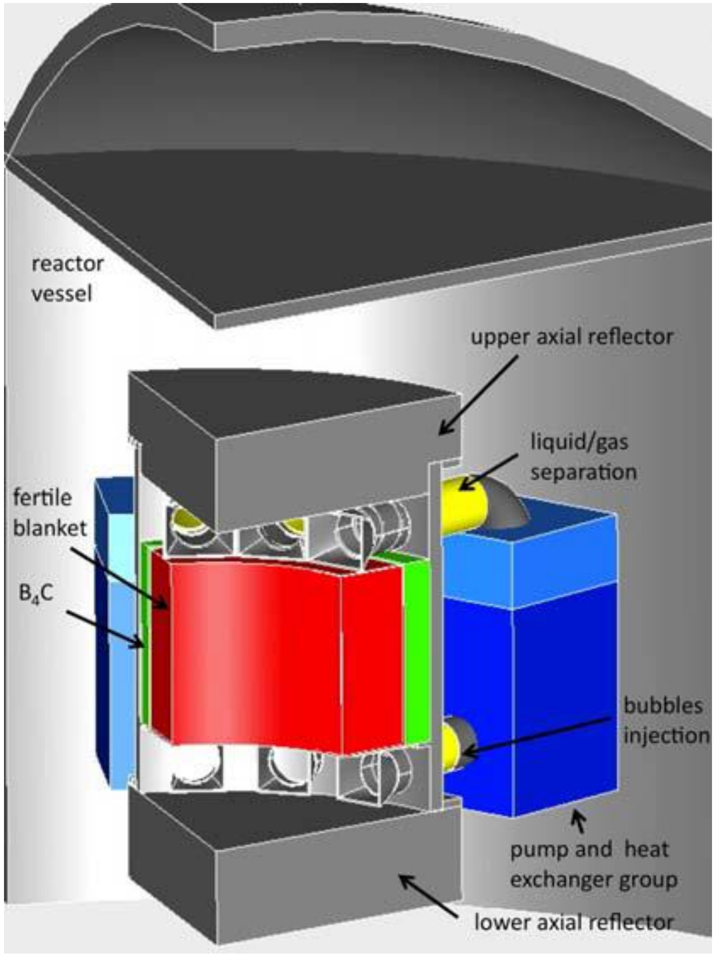
Myrrha: **Multi-purpose hYbrid Research Reactor for High-tech Applications**



- Experimental Accelerator Driven System
  Power 65-100 MW_{th}
  $k_{eff} = 0,95$
- No dependence of criticality on the delayed neutron fraction
- Proton beam
  600 MeV, 4 mA
- Cooling + Spallation target material Pb+Bi
- Mixed oxide fuel U + Pu
- 04.03.2010 Belgian Government pledges 40% of the total cost (= 400 M€; 60 M€ grant from 2010-2014)
- Experimental operation from 2023

H. A. Abderrahim, International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)

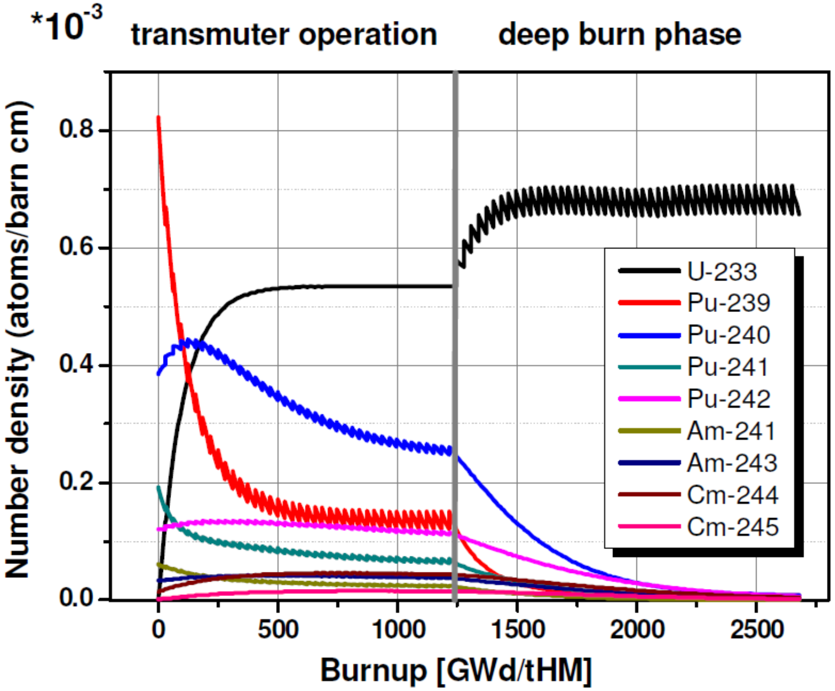
Molten Salt Fast Reactor (MSFR)

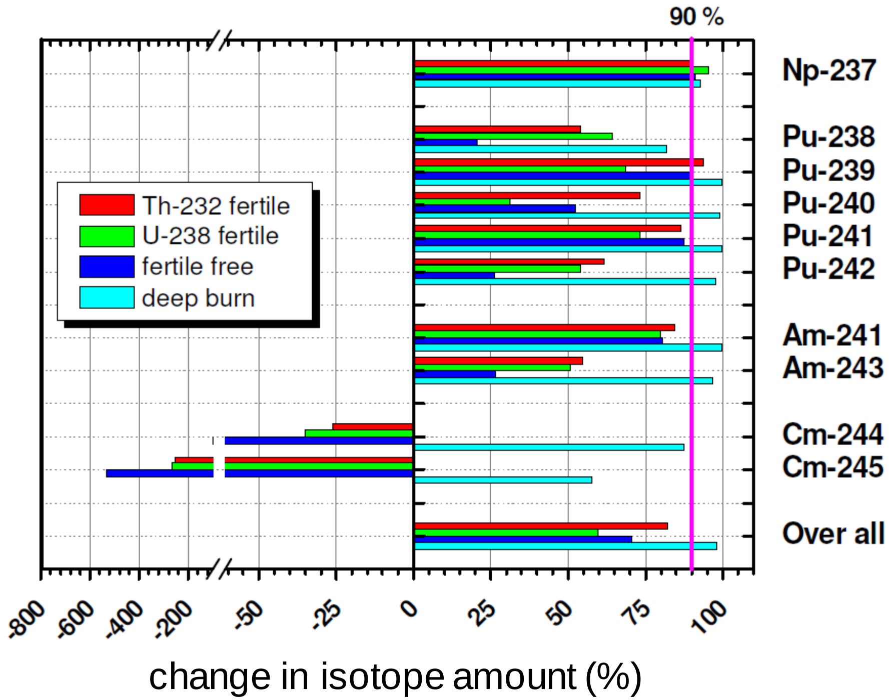


Strategic Research Agenda Annex MSFR
EVOL reference: 3000 MWth, 18 m^3 salt
T = 750 °C, cycle time: 4 s

- Molten Salt Reactor Experiment (ORNL, 1965-1969) thermal spectrum
- Based on Thorium fuel cycle
  ^{232}Th breeding ➔ ^{233}U (fissile)
- large negative temperature and void coefficients
- molten salt fuel:
  ^{7}LiF + (Th,U,Pu,M.A.)F_4 eutectic
  $T_{melt} > 565$ °C
- no radiation damage constraint on obtainable fuel burn-up
- no solid fuel fabrication and transports to reprocessing
- Structural materials neutron irradiation and corrosion resistance at high T
- Fuel salt chemistry and online reprocessing
- R&D Challenges FP7-EVOL project

MSFR transmutation potential

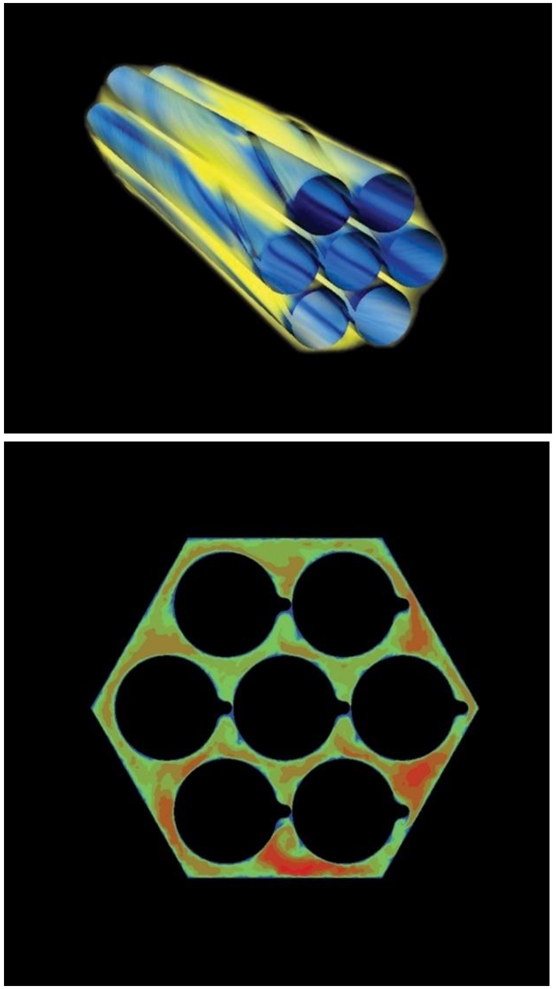




P&T scenario for the german phase out of nuclear power
49 yrs operation with TRU feed from PWR operation e.g. Germany
58 yrs deep burn phase (feed from ^{233}U bred from ^{232}Th)
90% transmutation efficiency
„last transmuter problem“ does not occur here
Residual uranium can be sold to nuclear power generating countries

B. Merk, International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios (FR13)

Simulation and Development of transmutation systems



source: Argonne National Laboratory
IBM BlueGene/P Supercomputer

- Reactor design with modern supercomputers
- Detailled thermohydraulic neutron-transport coupled simulations in realistic geometry
- Fundamental simulation of the processes on the atomic level in parts of the reactor core

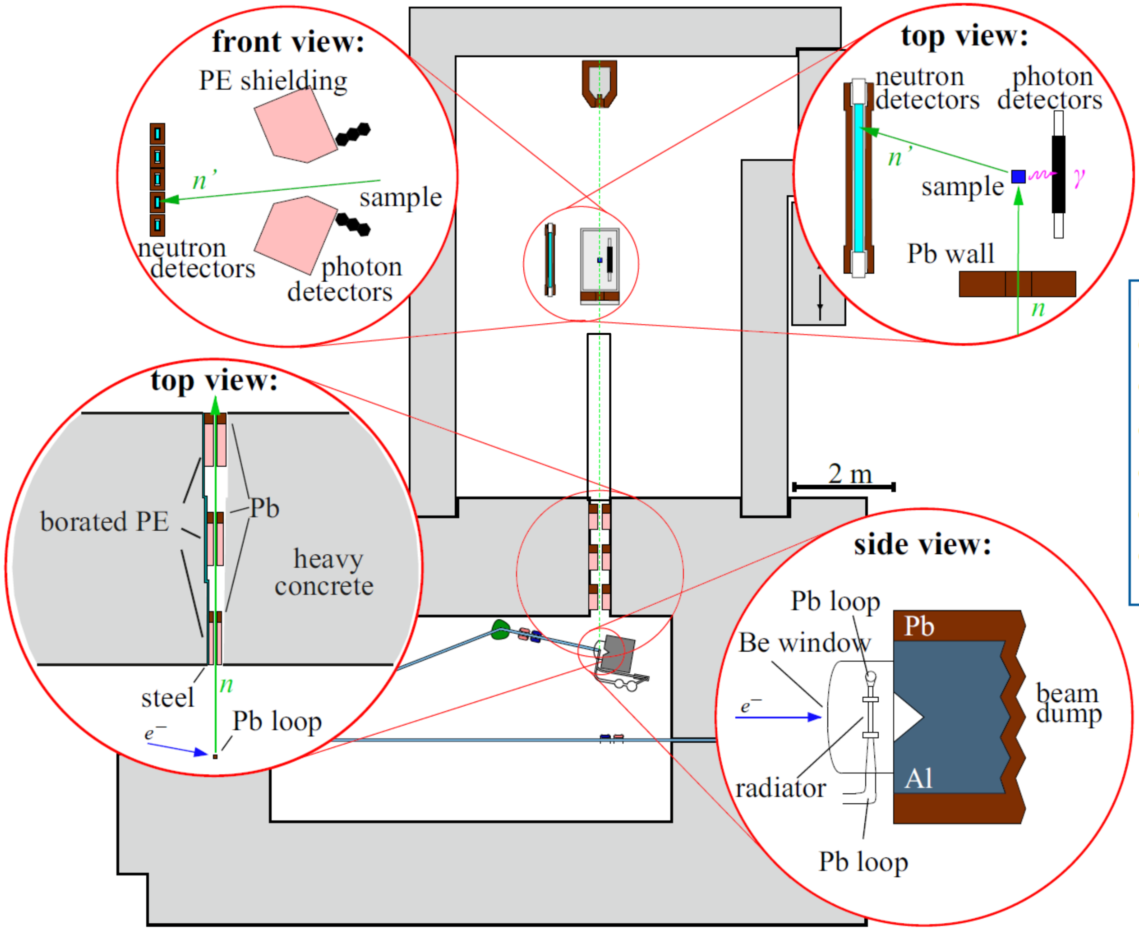
- **Requirement: precise nuclear data for neutron induced reactions**

ERINDA Facilities

15 ERINDA Partners:

1. **Time of flight facilities for fast neutrons:**
   - nELBE (HZDR, Dresden); n_TOF (CERN, Geneva); GELINA(IRMM, Geel)
2. **Charged-Particle Accelerators**
   - production of quasi-monoenergetic neutrons
     electrostatic accelerators at Bordeaux, Orsay, Bukarest, Dresden
   - Neutron reference fields at PTB Braunschweig, NPL Teddington
   - Cyclotrons at Rez, Jyväskylä, Oslo, Uppsala neutron energy range up to 180 MeV
   - Pulsed Proton Linear Accelerator at Frankfurt
3. **Research reactor**
   - Budapest, Rez cold neutron beam, PGAA

Photoneutron Source nELBE



Floor plan of the new nELBE neutron source and low scattering experimental hall.

Research Programme:
Investigation of fast neutron induced reactions of relevance for nuclear transmutation and nuclear safety

See Poster Toni Kögler PR65

Characteristic parameters:

• repetition rate:	101 or 202 kHz
• flight path:	5 - 11 m
• source strength:	ca. $1.6\cdot10^{11}$ n/s
• intensity @ target:	ca. $2.5\cdot10^{4}$ n/cm^{2}s
• energy range:	10 keV - 10 MeV
• energy resolution:	< 1 %

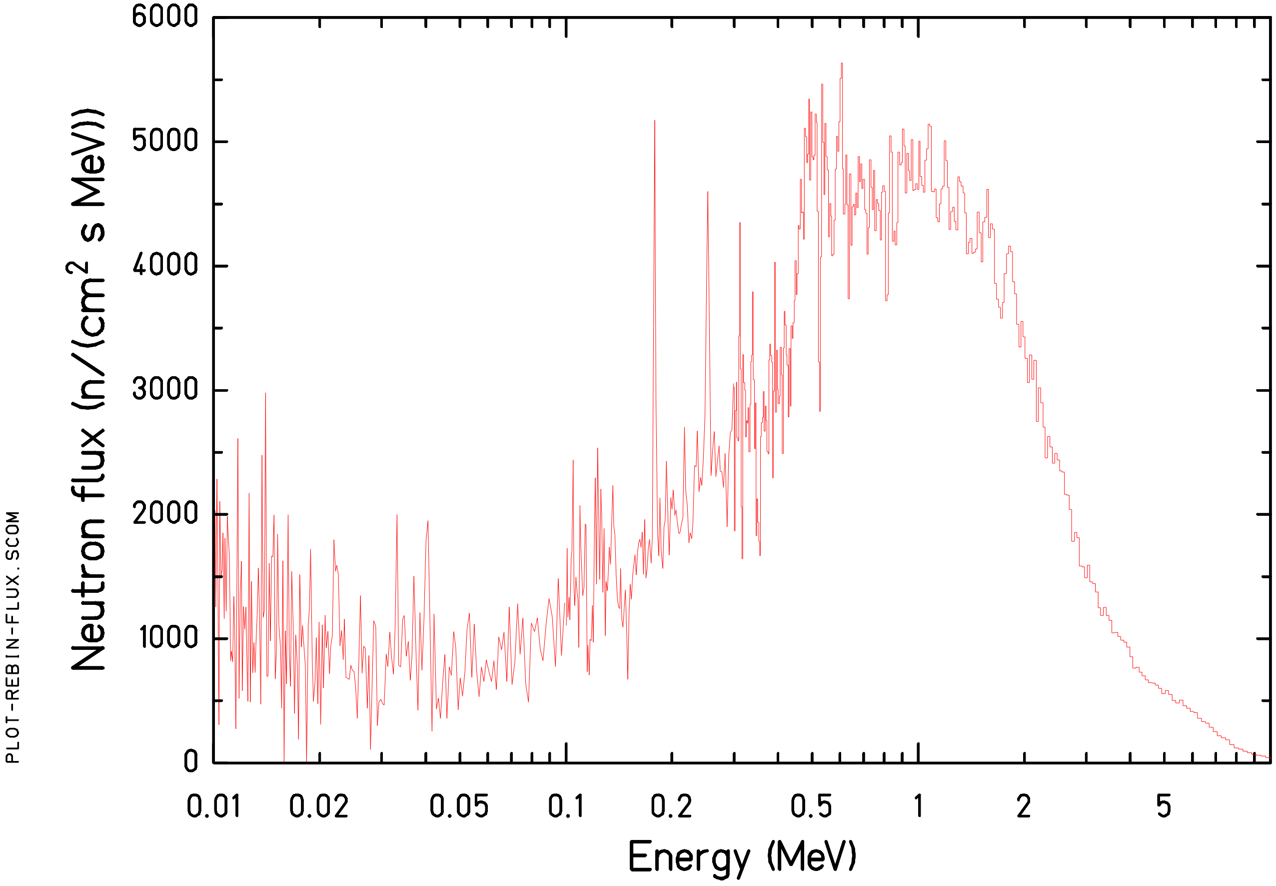
The only photo neutron source at a superconducting accelerator in the world.

Project at KAERI
T.Y. Song et al., Journal of the Korean Physical Society, Vol. 59, No. 2, (2011) 1609

nELBE double time-of-flight experiment HZDR Dresden

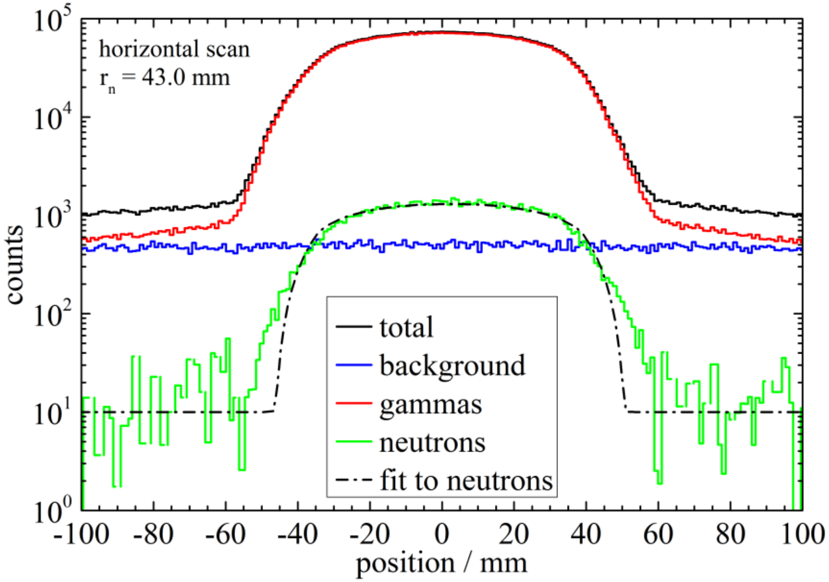
LaBr$_3$ test set up ➔ angular distribution

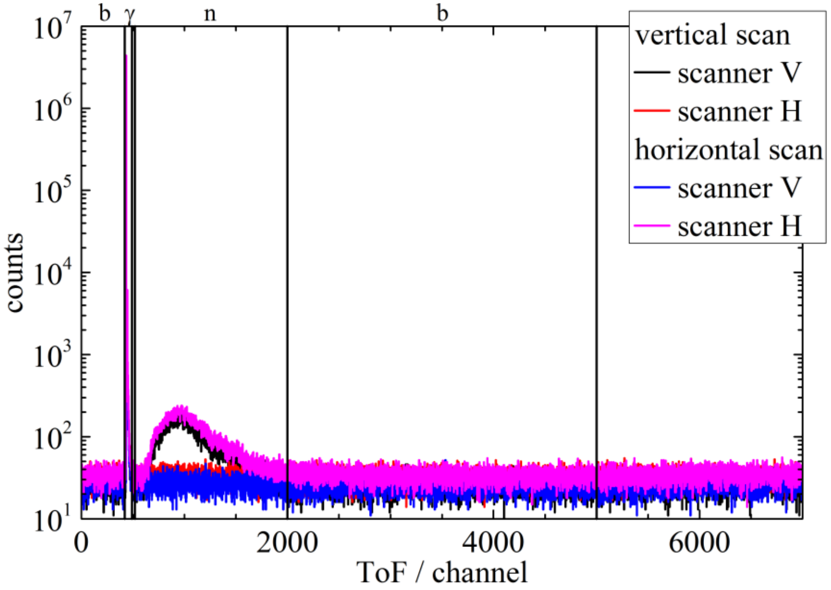
nELBE neutron spectrum



live time : 15 h I_{e-} = 6 μA, E_{e-} = 31 MeV
Flight path 815 cm
Absorption dips : 78,117, 355, 528, 722, 820 keV ^{208}Pb scatttering resonances
Emission peaks: 40,89,179, 254, 314, 605 keV near threshold photoneutron emission
In ^{208}Pb (strong capture resonances of ^{207}Pb)

Time of flight beam profile

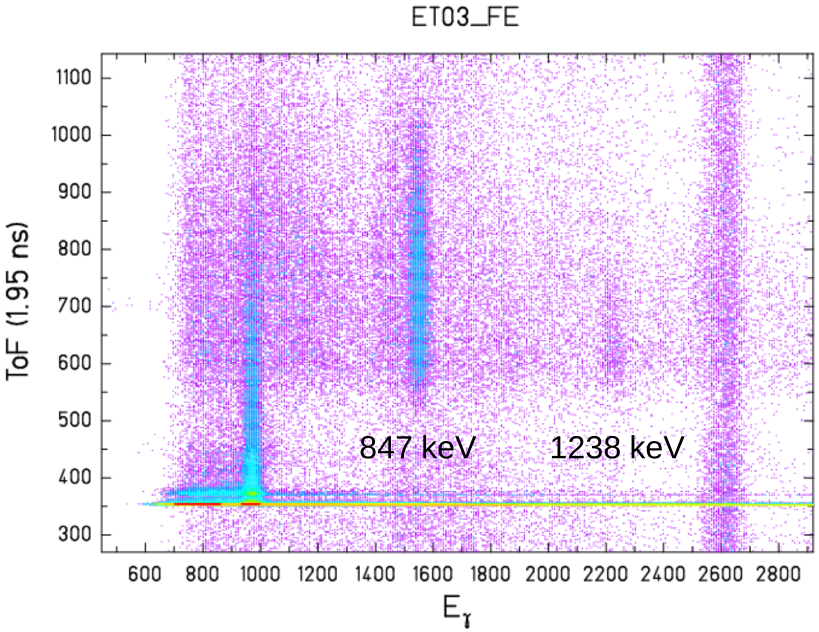




Neutron and Bremsstrahlung profile measured
with plastic scintillator moved through the beam.

Time of flight gate to separate neutrons and bremsstrahlung

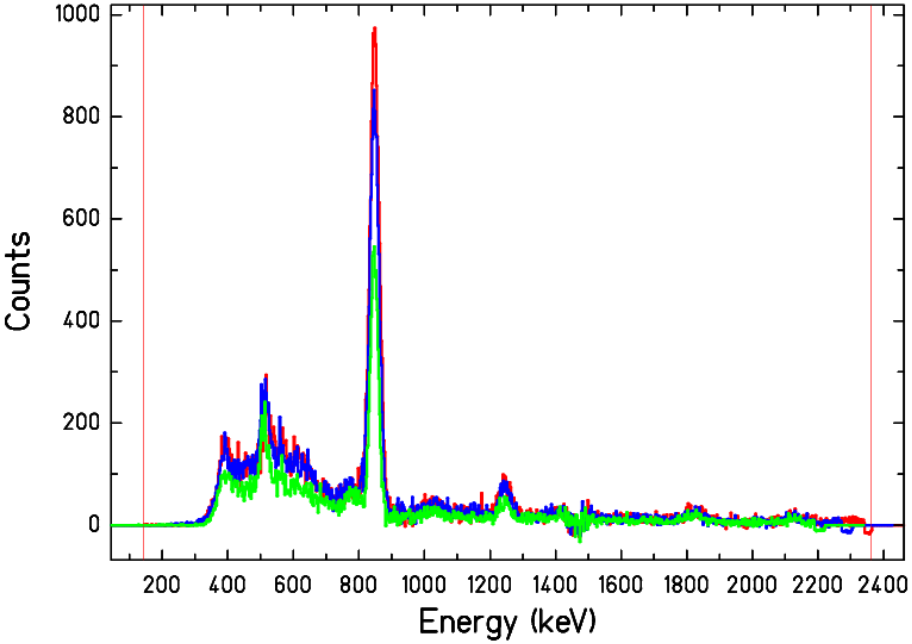
56Fe(n,n‘γ) $LaBr_3$ spectra



847 keV 1238 keV

Time of flight vs. energy (uncalibrated)

$LaBr_3$ Energy spectrum
(Target out background subtracted +
Time of flight gate for neutrons)



Summary and Outlook

- Fast neutrons are decisive for the transmutation of long-lived actinide nuclei into mostly short-lived fission fragments.
- The time for final storage can be reduced to an historical time scale (< 1000 yrs) by partitioning and transmutation.
- For the design of transmutation systems (fast reactors, ADS) precise nuclear data for fast neutron reactions are required
  e.g. (n,n'γ) (n,tot) und (n,f) with radioactive targets.
- The nELBE neutron time-of-flight facility at HZDR Dresden is dedicated to neutron-induced reaction studies in the fast neutron range.
- nELBE is a partner in the EURATOM FP7 ERINDA and CHANDA projects
  Transnational access is supported. External users are very welcome.

TRAKULA

ERINDA
European Research Infrastructures for Nuclear Data Applications

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

DRESDEN concept

HZDR

Ende der Vortragsfolien

Data needs for fast reactors and ADS

NEA Working Party on International Nuclear Data Evaluation Co-operation (WPEC) subgroup 26

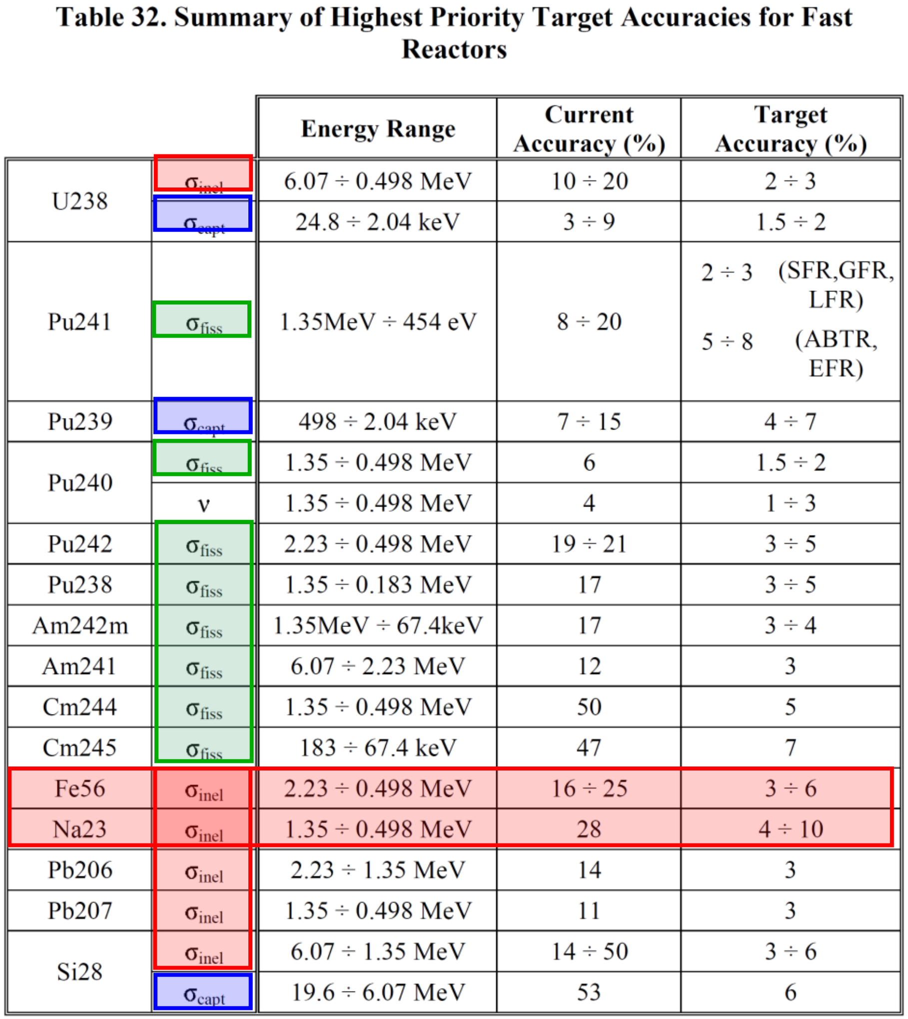


Table 32. Summary of Highest Priority Target Accuracies for Fast Reactors

		Energy Range	Current Accuracy (%)	Target Accuracy (%)
U238	σ_{inel}	6.07 ÷ 0.498 MeV	10 ÷ 20	2 ÷ 3
	σ_{capt}	24.8 ÷ 2.04 keV	3 ÷ 9	1.5 ÷ 2
Pu241	σ_{fiss}	1.35MeV ÷ 454 eV	8 ÷ 20	2 ÷ 3 (SFR,GFR, LFR) 5 ÷ 8 (ABTR, EFR)
Pu239	σ_{capt}	498 ÷ 2.04 keV	7 ÷ 15	4 ÷ 7
Pu240	σ_{fiss}	1.35 ÷ 0.498 MeV	6	1.5 ÷ 2
	ν	1.35 ÷ 0.498 MeV	4	1 ÷ 3
Pu242	σ_{fiss}	2.23 ÷ 0.498 MeV	19 ÷ 21	3 ÷ 5
Pu238	σ_{fiss}	1.35 ÷ 0.183 MeV	17	3 ÷ 5
Am242m	σ_{fiss}	1.35MeV ÷ 67.4keV	17	3 ÷ 4
Am241	σ_{fiss}	6.07 ÷ 2.23 MeV	12	3
Cm244	σ_{fiss}	1.35 ÷ 0.498 MeV	50	5
Cm245	σ_{fiss}	183 ÷ 67.4 keV	47	7
Fe56	σ_{inel}	2.23 ÷ 0.498 MeV	16 ÷ 25	3 ÷ 6
Na23	σ_{inel}	1.35 ÷ 0.498 MeV	28	4 ÷ 10
Pb206	σ_{inel}	2.23 ÷ 1.35 MeV	14	3
Pb207	σ_{inel}	1.35 ÷ 0.498 MeV	11	3
Si28	σ_{inel}	6.07 ÷ 1.35 MeV	14 ÷ 50	3 ÷ 6
	σ_{capt}	19.6 ÷ 6.07 MeV	53	6

➔ fast neutron spectrum

➔ U,Pu + minor actinides
structural & coolant materials

- neutron induced fission
- neutron capture
- neutron inelastic scattering

➔ $^{56}\mathrm{Fe}\,(n,n'\gamma)\,^{56}\mathrm{Fe}$

ERINDA
European Research Infrastructures for Nuclear Data Applications

EURATOM

The ERINDA project aims for a coordination of European efforts to exploit up-to-date neutron beam technology for novel research on advanced concepts for nuclear fission reactors and the transmutation of radioactive waste.

- *EU contribution 1 MEUR*
- *Transnational access (2500 hours of beam time, 2876 h distributed in 25 Exp.)*
- *Supporting Scientific Visits (8 weeks)*
- *Scientific workshops (4):*

Kick-off meeting at HZDR Dresden January 27-28, 2011
1st ERINDA Progress Meeting and Scientific Workshop
January 16-18, 2012, NPI Řež, Prague, Czech Republic
2nd ERINDA Progress Meeting and Scientific Workshop
January 8-11, 2013, University of Jyväskylä, Finland

Final ERINDA Progress Meeting and Scientific Workshop
October 1-3, 2013,CERN, Geneva Switzerland

FP7 support action, transnational access, www.erinda.org

DRESDEN concept

HZDR

Possible Benefits of Partitioning and Transmutation of SNF

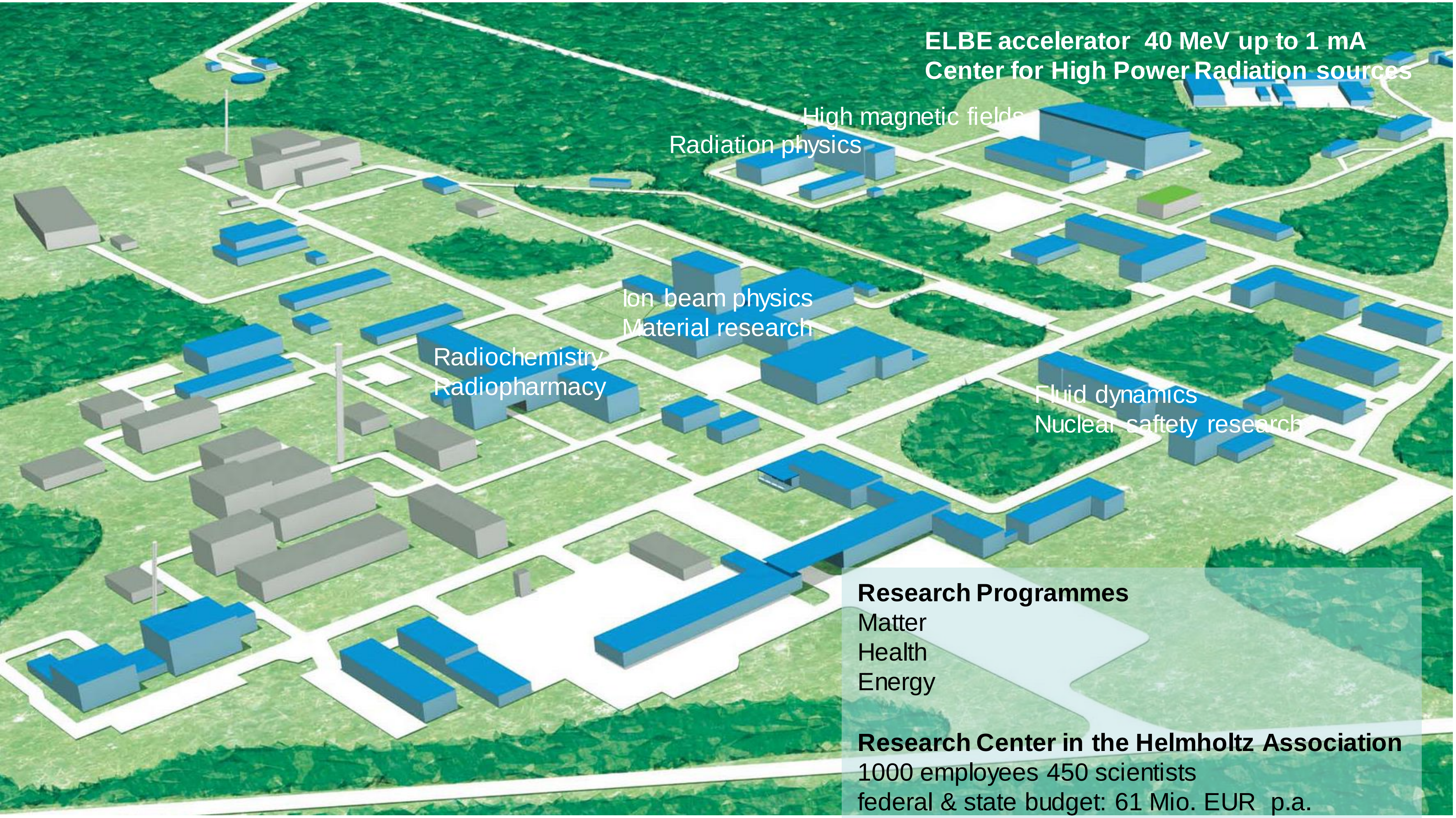
- In nuclear waste management:
  - Radiotoxicity of the disposed high level waste
  - Peak dose rate from a final disposal site
  - Long-term decay heat
  - Waste form, volume and mass
  - uncertainty in future geological development, human intrusion…

  ➔ Reduction of the burden on the required final repositories

- Additional benefits from closed nuclear fuel cycle (e.g. using fast reactors and reprocessing (partitioning) of spent nuclear fuel)

  References:
  Advanced Nuclear Fuel Cycles and Radioactive Waste Management OECD NEA Paris (2006)
  EURATOM FP6 RED-IMPACT 2007
  Potential Benefits and Impacts of Advanced Nuclear Fuel Cycles with Actinide Partitioning and Transmutation Nr. 6894 OECD NEA Paris (2011)

Helmholtz-Zentrum Dresden-Rossendorf



Research Programmes
Matter
Health
Energy

Research Center in the Helmholtz Association
1000 employees 450 scientists
federal & state budget: 61 Mio. EUR p.a.

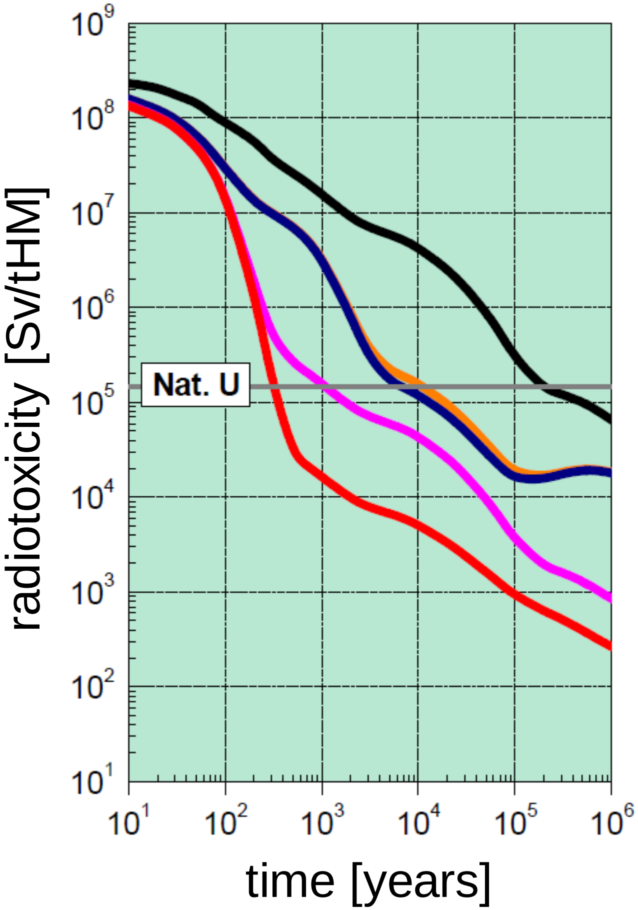
Sustainable use of nuclear power in the future

- Closed nuclear fuel cycle
  - Partitioning: Reprocessing of plutonium + minor actinides
  - Fuel element production with plutonium + minor actinides
  - Transmutation e.g. in an accelerator driven system
  - Final disposal of fission products and small amounts of actinides for a historical time frame (< 1000 Jahre)

➔ efficient use of fissile material (Pu,^{238}U,^{235}U)
(in a thermal spectrum only 0.7% (^{235}U) of the natural uranium undergoes fission)

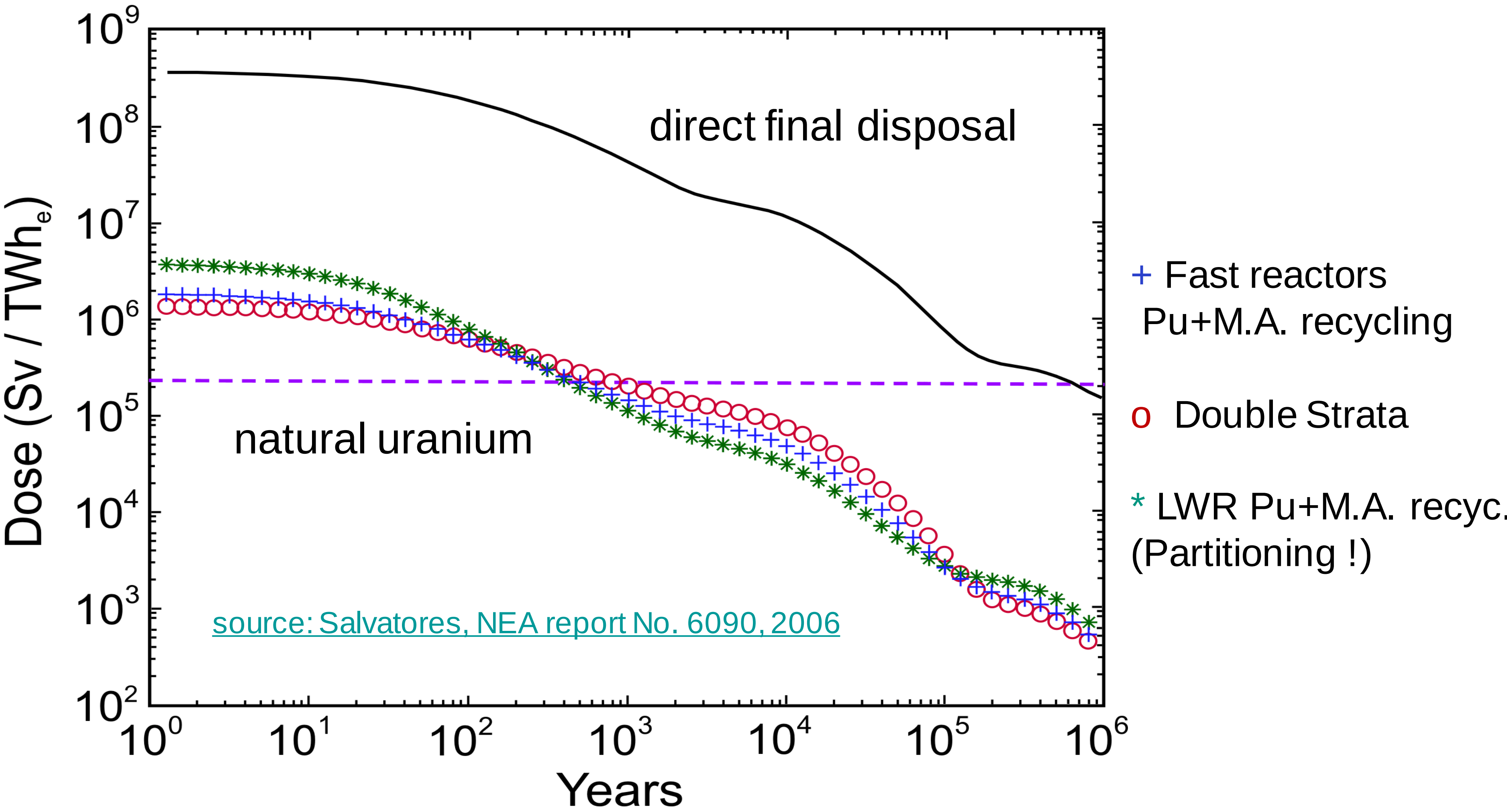
Partitioning efficiency

Partitioning	Radiotoxicity reduced to the level of natural uranium (years)
none	200000
99.0% Pu	11300
99.9% Pu	6500
99.0% Pu, MA	1100
99.9% Pu, MA	320



Source: Klaus Gompper, INE, Karlsruhe

Transmutation of spent nuclear fuel



source: Salvatores, NEA report No. 6090, 2006

➔ Reduction of radiotoxicity by a factor ≈100. Final storage for approx. 1000 years

Highly radioactive waste from german nuclear power plants

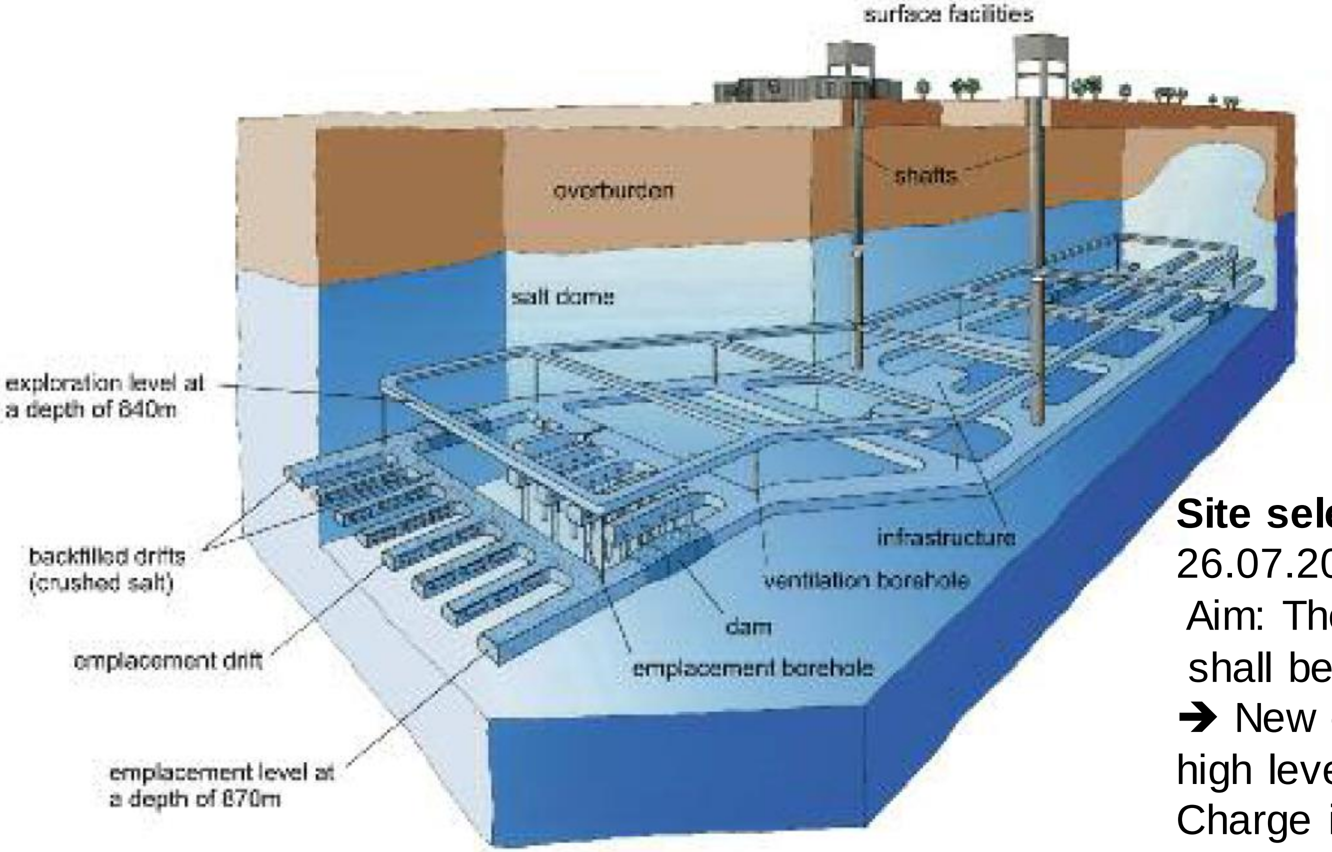
- **01.07.2005** Ban of reprocessing of irradiated nuclear fuel (atomic energy act)
- **31.12.2010** 13.471 t HM as **spent fuel elements**
  of which 6.670 t HM have been reprocessed
- **06.08.2011** Atomic energy act amended to phase out nuclear power in Germany
  Estimate: additional 6801 t HM until all nuclear power plants will be shut down (01.01.2022)

Quantity	PWRUOX	PWRMOX	BWRUOX	BWRMOX	**Total SF**	HLW
Total (t)	5350	773	3470	246	**9840**	215.0
U (t)	5060	702	3310	227	**9290**	0.7
Pu (t)	51.7	34.3	32.9	7.95	**127**	0.2
Np (t)	3.6	0.234	2.16	0.0497	**6.04**	2.9
Am (t)	4.6	4.96	3.48	1.17	**14.2**	3.6
Cm (t)	0.23	0.226	0.148	0.0644	**0.669**	0.1

Source: M. Salvatores, et al., NFCSim Scenario Studies of German and European Reactor Fleets, 2004

SF = spent nuclear fuel
HLW = (Fission Products, minor actinides,…) (high level waste)

Final Disposal Repository Project: Gorleben Salt Dome



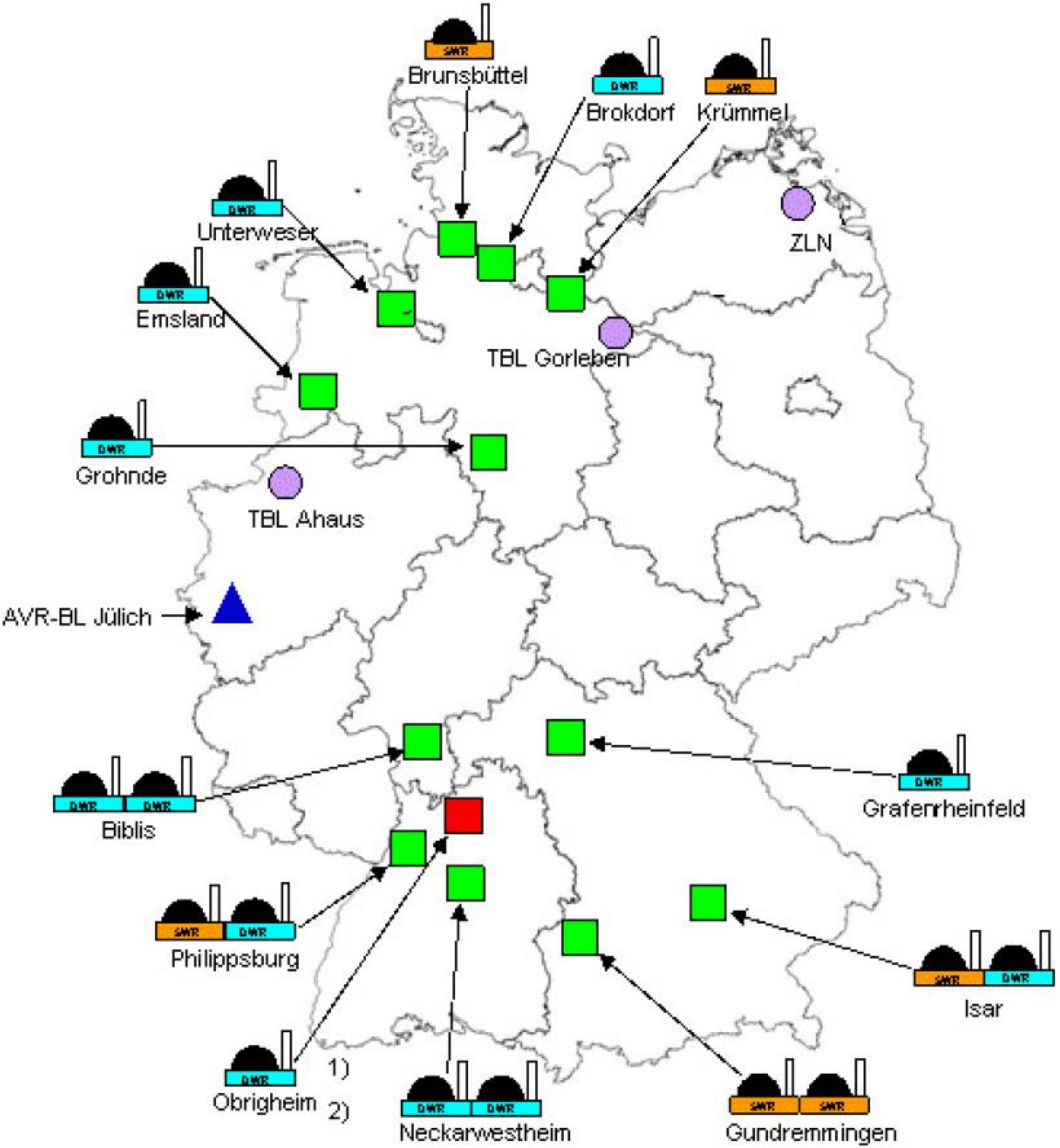
Site selection federal law:
26.07.2013
Aim: The site selection process shall be concluded by 2031.
➔ New commission on *storage* of high level waste
Charge includes:
Alternatives to direct final disposal
Report due 31.12.2015

Final disposal site in Germany is not fixed.

Direct disposal of spent fuel elements
Pollux-10-Containers (Load 5.4 tSM, Total weight 65 t)
➔ 2120 Pollux-10 Containers
(+ 906 Pollux-9 Containers for vitrified waste)

Source:
http://www.grs.de/endlagersicherheit/gorleben/ergebnisse
http://www.bmwi.de/English/Redaktion/Pdf/final-disposal-of-high-level-radioactive-waste,property=pdf,bereich=bmwi,sprache=en,rwb=true.pdf

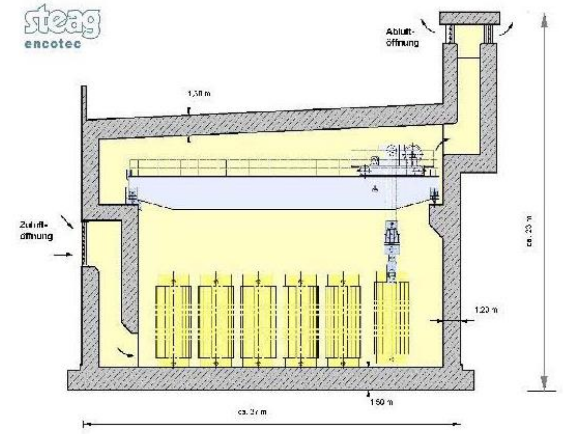
Interim Storage for heat producing radioactive waste and irradiated fuel elements in Germany



On site interim storage at all
12 nuclear power plant locations

Additional storage sites at:
Ahaus, Gorleben, Jülich, Greifswald

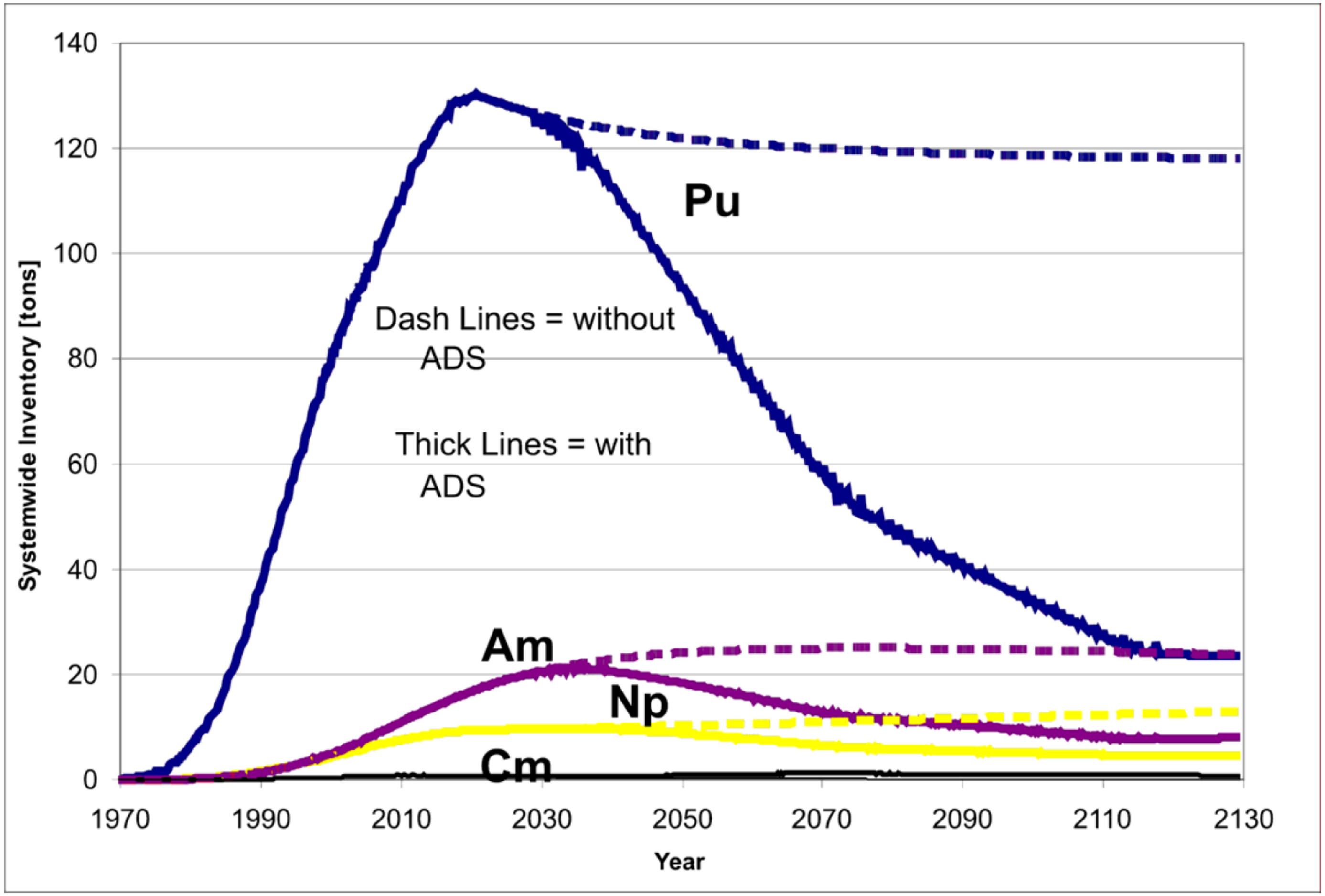
Licence for 40 years
dry storage in CASTOR containers
steel-reinforced concrete facilties
wall thickness ≅1.2 m



STEAG-Designed Building

http://www.bfs.de/de/transport/publika/flab18062003

Transmutation study for Germany (ADS based)



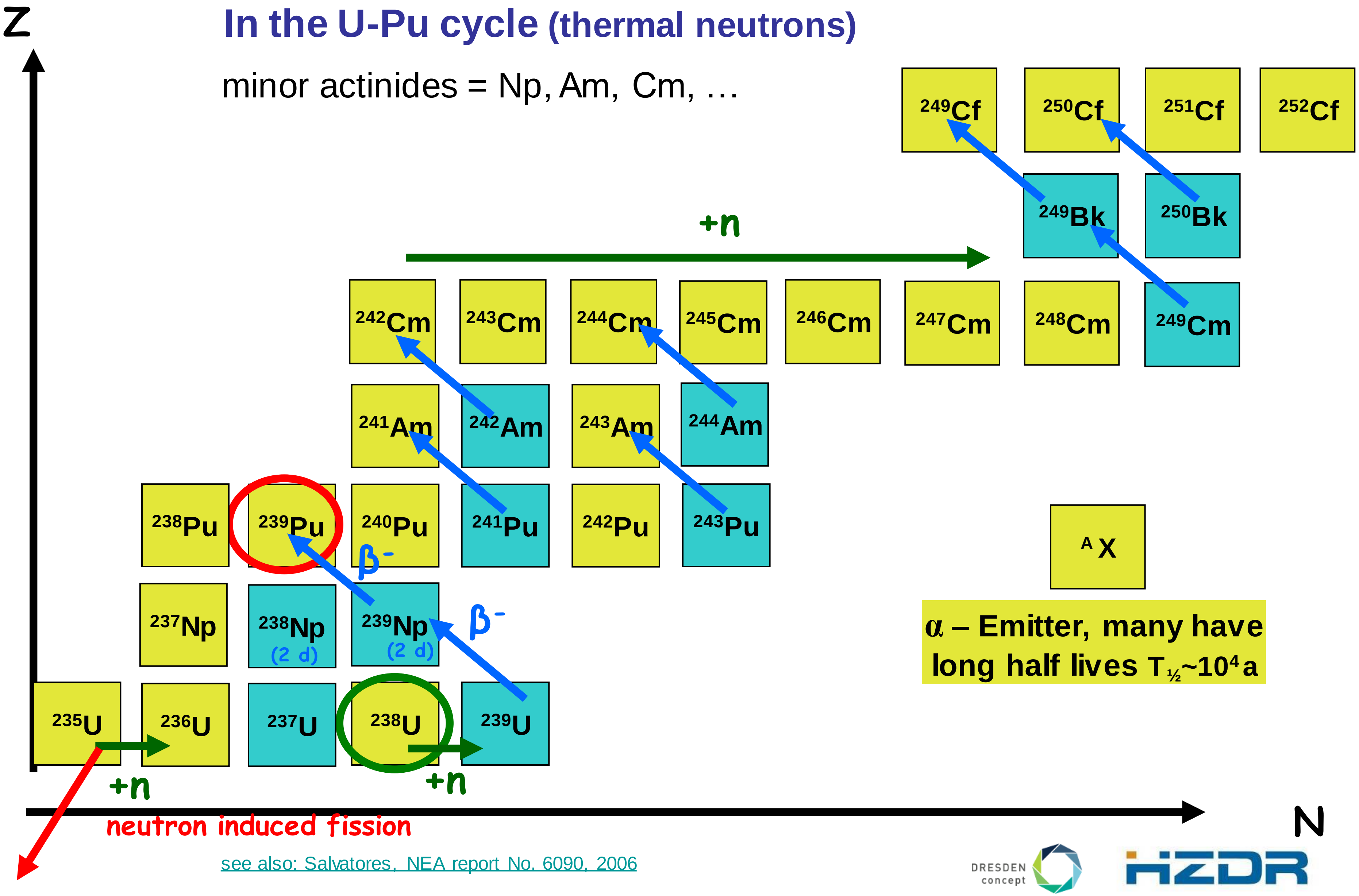
Begin: 2030
1st Generation:
8 ADS Transmuter
(840 MWth)
2nd Generation:
3 ADS Transmuter

Transmutation
of 100 t Pu
and minor actinides
in 100 years

Figure: M. Salvatores et al., NEA report 6194, 2009

Formation of minor actinides and Pu In the U-Pu cycle (thermal neutrons)

minor actinides = Np, Am, Cm, …



$α$ – Emitter, many have long half lives $T_{½}$~10^4 a

see also: Salvatores, NEA report No. 6090, 2006

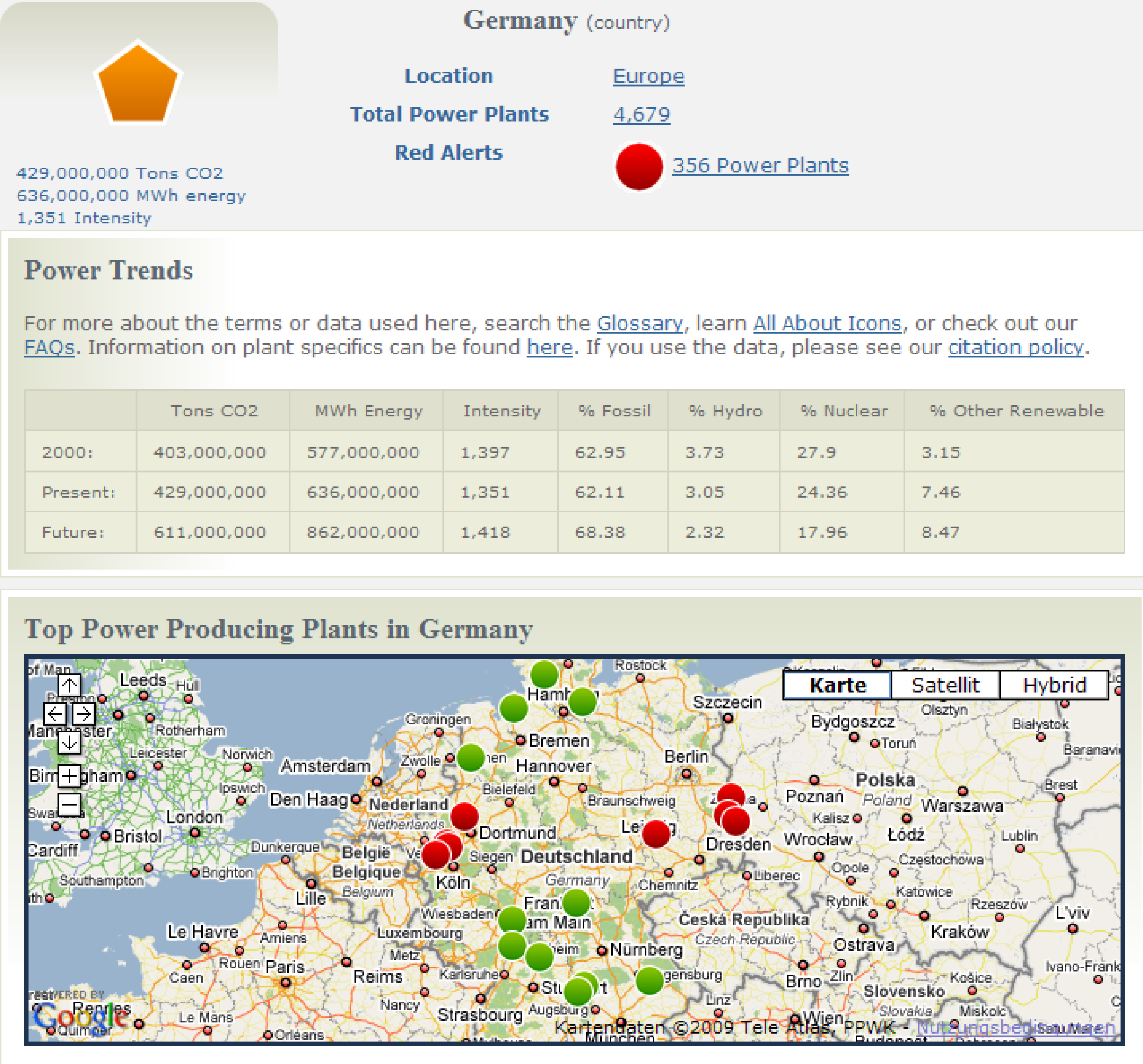
MOX facility at Savannah River

- 1999 National Nuclear Security Administration (NNSA) signed contract design, build, and operate a **Mixed Oxide (MOX) Fuel Fabrication Facility**.
- United States' program to **dispose of surplus weapon-grade plutonium**.
- Design based on AREVA's MELOX and La Hague MOX facilities in France.
- Currently being built (until 2014) at the Savannah River Site (SRS) near Aiken, SC

May 2013

http://www.moxproject.com

CO_2 emissions from power plants: Germany



Germany (country)

Location	Europe
Total Power Plants	4,679
Red Alerts	● 356 Power Plants

429,000,000 Tons CO2
636,000,000 MWh energy
1,351 Intensity

Power Trends

For more about the terms or data used here, search the Glossary, learn All About Icons, or check out our FAQs. Information on plant specifics can be found here. If you use the data, please see our citation policy.

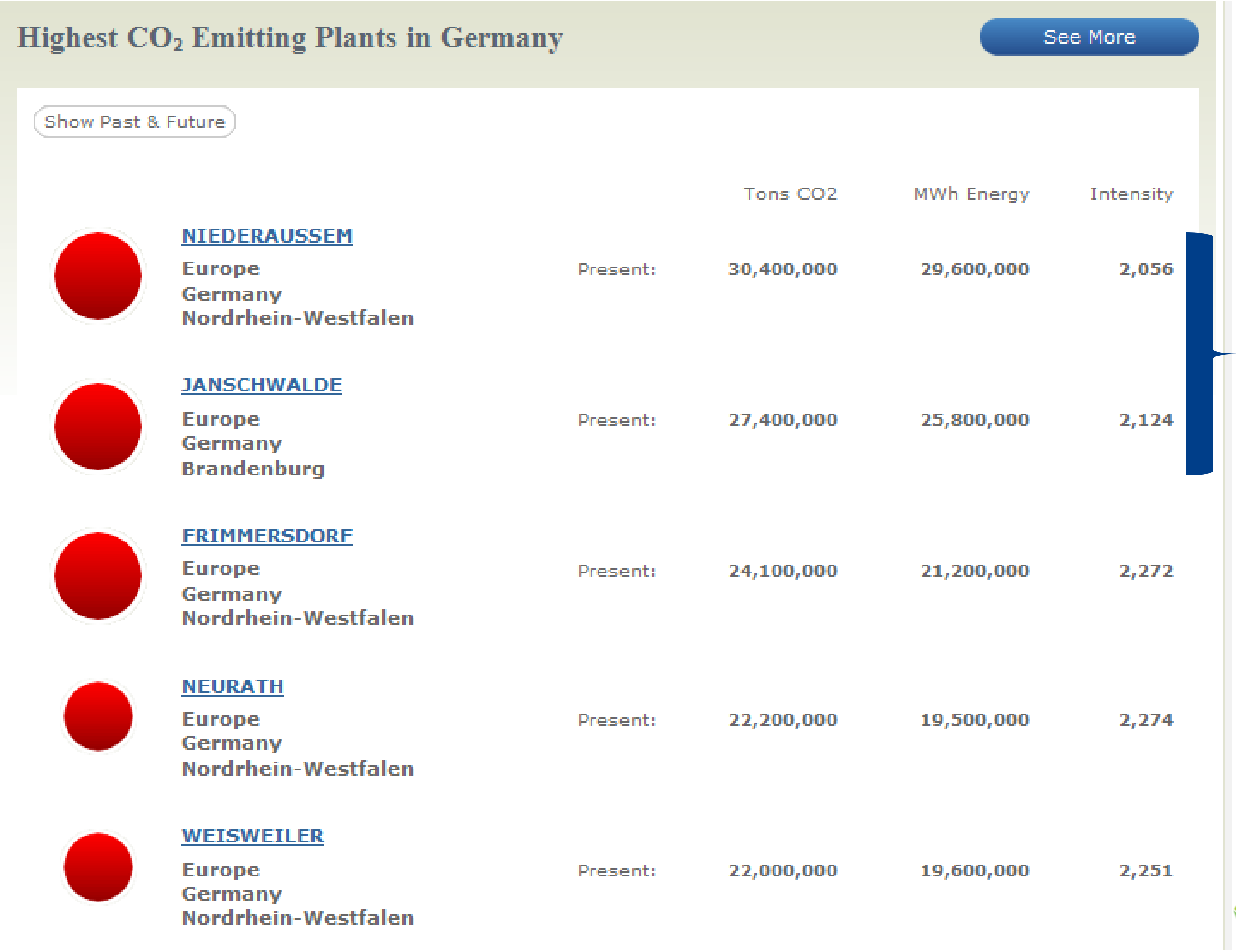
	Tons CO2	MWh Energy	Intensity	% Fossil	% Hydro	% Nuclear	% Other Renewable
2000:	403,000,000	577,000,000	1,397	62.95	3.73	27.9	3.15
Present:	429,000,000	636,000,000	1,351	62.11	3.05	24.36	7.46
Future:	611,000,000	862,000,000	1,418	68.38	2.32	17.96	8.47

Top Power Producing Plants in Germany

Electricity
636,000,000 MWh
Emissions:
429,000,000 tons CO_2

source: www.carma.org

CO_2 emissions from power plants: Germany



Highest CO_2 Emitting Plants in Germany

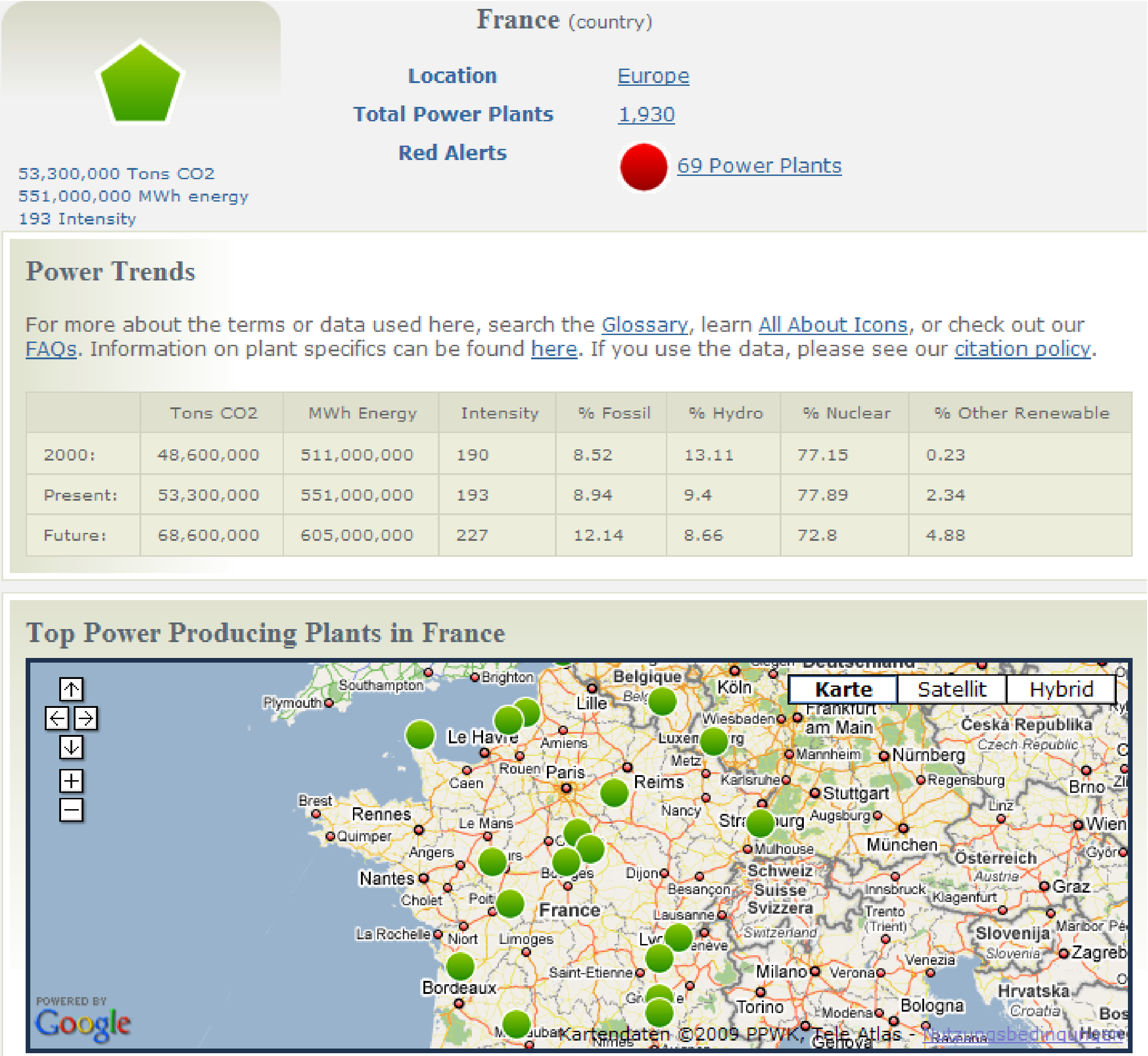
		Tons CO2	MWh Energy	Intensity
NIEDERAUSSEM Europe Germany Nordrhein-Westfalen	Present:	30,400,000	29,600,000	2,056
JANSCHWALDE Europe Germany Brandenburg	Present:	27,400,000	25,800,000	2,124
FRIMMERSDORF Europe Germany Nordrhein-Westfalen	Present:	24,100,000	21,200,000	2,272
NEURATH Europe Germany Nordrhein-Westfalen	Present:	22,200,000	19,500,000	2,274
WEISWEILER Europe Germany Nordrhein-Westfalen	Present:	22,000,000	19,600,000	2,251

In the Top Ten
Of CO_2 emitting
Power plants
worldwide

source: www.carma.org

CO_2 emissions from power plants: France

source: www.carma.org



France (country)

Location	Europe
Total Power Plants	1,930
Red Alerts	● 69 Power Plants

53,300,000 Tons CO2
551,000,000 MWh energy
193 Intensity

Power Trends

For more about the terms or data used here, search the Glossary, learn All About Icons, or check out our FAQs. Information on plant specifics can be found here. If you use the data, please see our citation policy.

	Tons CO2	MWh Energy	Intensity	% Fossil	% Hydro	% Nuclear	% Other Renewable
2000:	48,600,000	511,000,000	190	8.52	13.11	77.15	0.23
Present:	53,300,000	551,000,000	193	8.94	9.4	77.89	2.34
Future:	68,600,000	605,000,000	227	12.14	8.66	72.8	4.88

Top Power Producing Plants in France

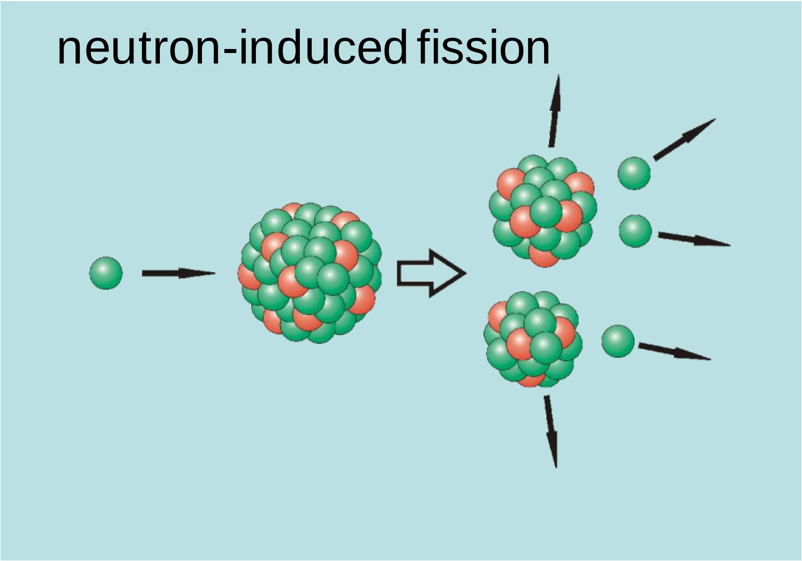
Electricity
551,000,000 MWh
Emissions
53,300,000 Tons CO_2

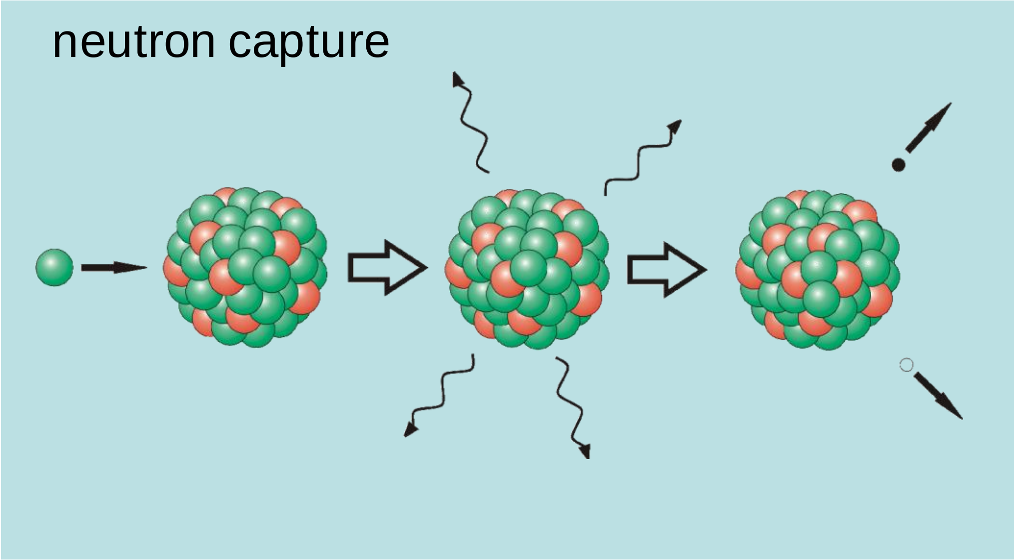
Power plants in Germany emit nearly 8 times more CO_2 than power plants in France

DRESDEN concept

HZDR

Transmutation of heavy atomic nuclei

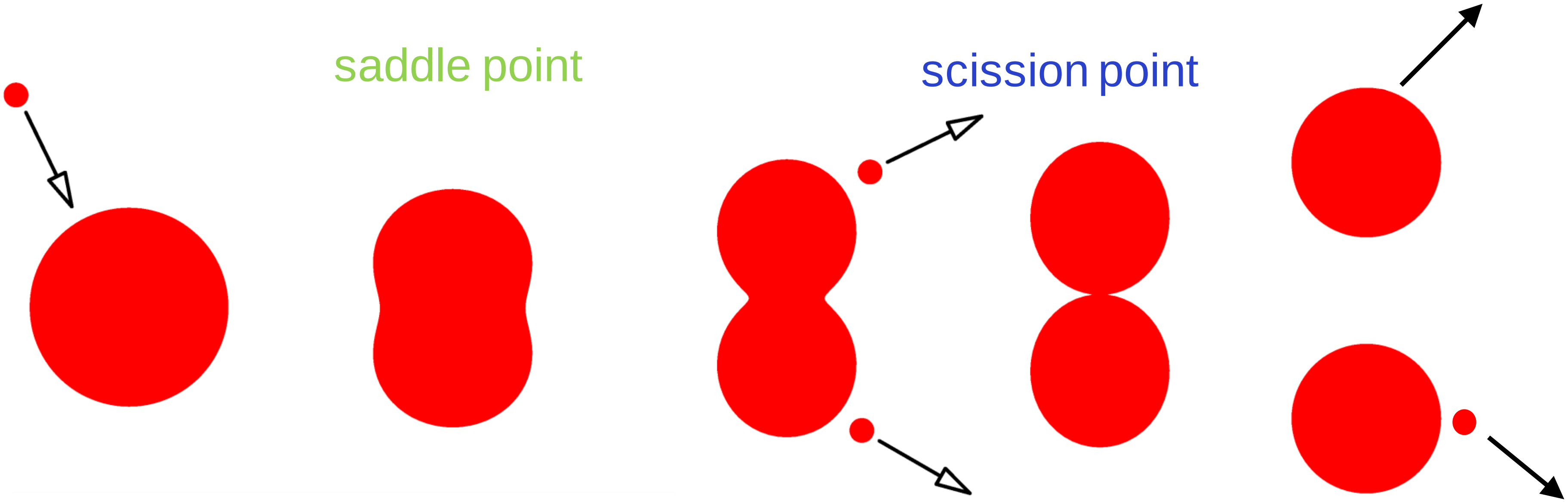


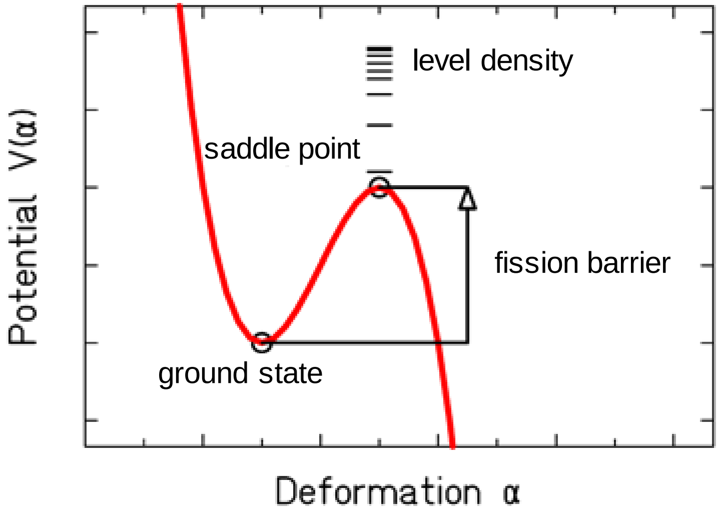


neutron bombardment ➔ Fission of heavy nuclei ➔fission products mostly short-lived

neutron bombardment ➔ neutron capture ➔ Formation of a long-lived heavy nucleus.

Nuclear Fission induced by neutrons



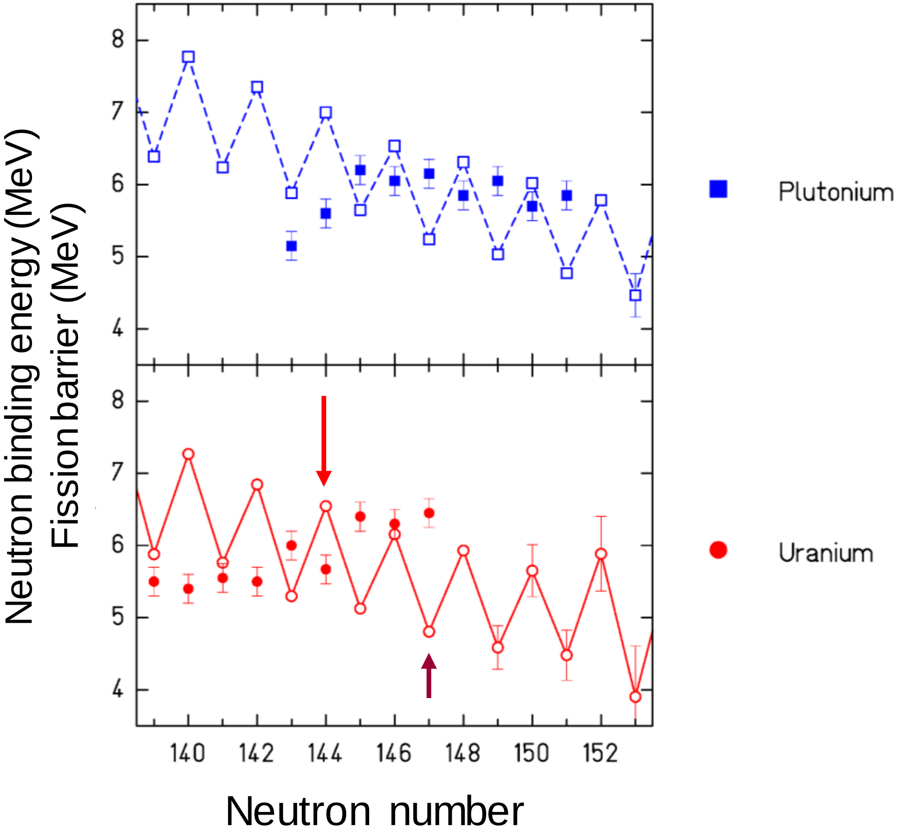


- neutron bombardment ➔ nucleus excited
- excited nucleus oscillates + deforms
ground state ➔ saddle point (N. Bohr, 1939)
- Deformations requires energy up to the
saddle point: fission barrier
- Further deformation will lead to fission
➔ Fission fragments plus neutrons

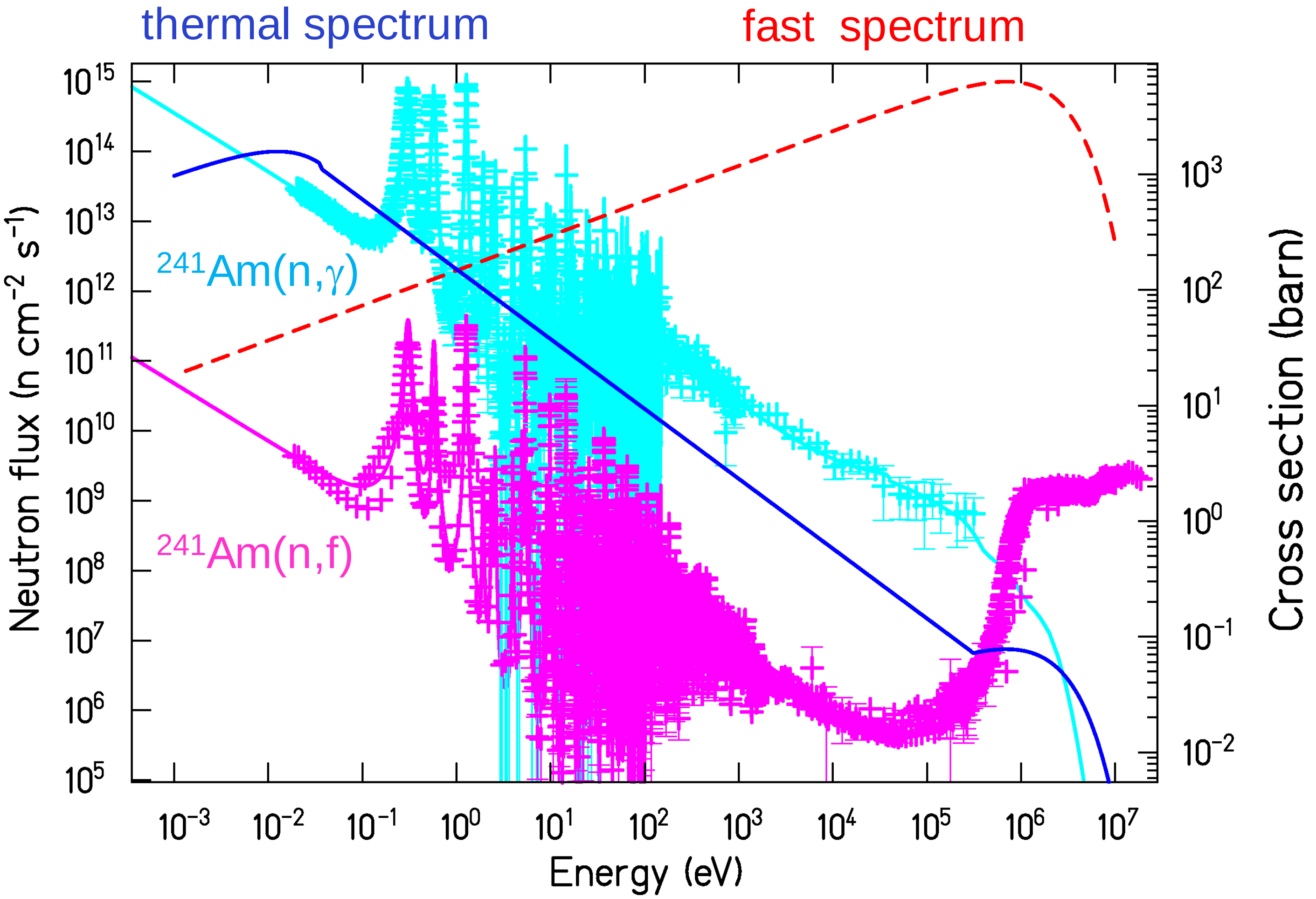
Fissility of heavy nuclei

- Neutron induced fission can occur if the excitation energy exceeds the fission barrier.
- The neutron binding energy is higher for nuclei with even number of neutrons than for nuclei with odd n
  ➔ even-odd effect
- ^{235}U + n (N = 143+1)
  Fission barrier lower than neutron binding energy ➔ Fission by low energy neutrons
- ^{238}U + n (N = 146+1)
  Fission barrier higher than neutron binding energy ➔ Fission by fast neutrons only

➔ Fast neutrons can fission all nuclei.



Neutron capture – neutron induced fission



Neutron capture is dominating fission in a thermal spectrum

Fission is more probable than capture in a fast spectrum.

^{241}Am(n,γ) JEFF-3.1 Evaluation; Exp.(EXFOR): M. Jandel (2008), G.. Vanpraet (1985), N. Shinohara (1997),…

^{241}Am(n,f) JEFF-3.1 Evaluation, Exp.(EXFOR): B. Jurado (2007), J.W.T. Dabbs (1983), H.H. Knitter (1979), P.E. Vorotnikov (1986), ….

Spent nuclear fuel from nuclear power plants worldwide

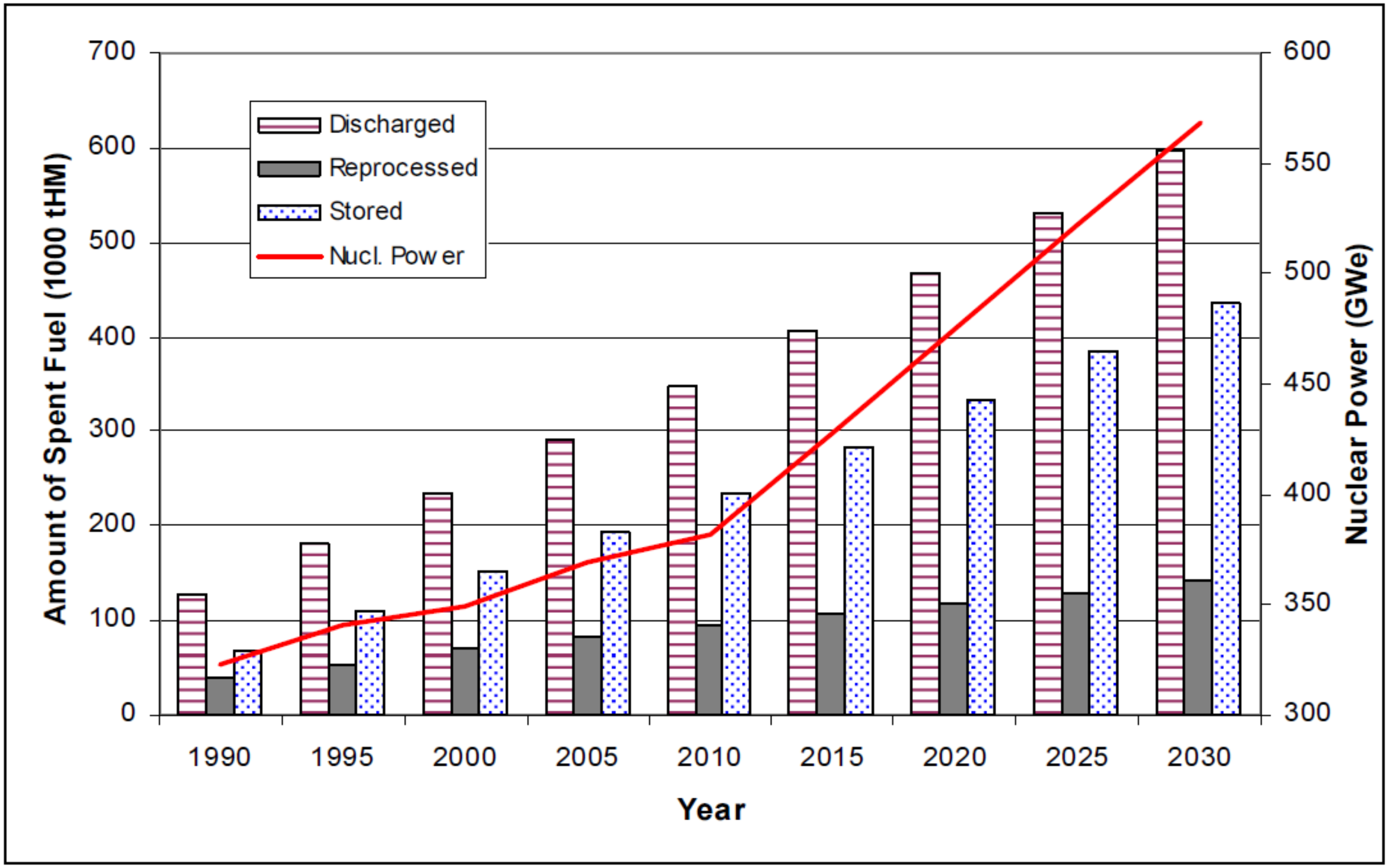
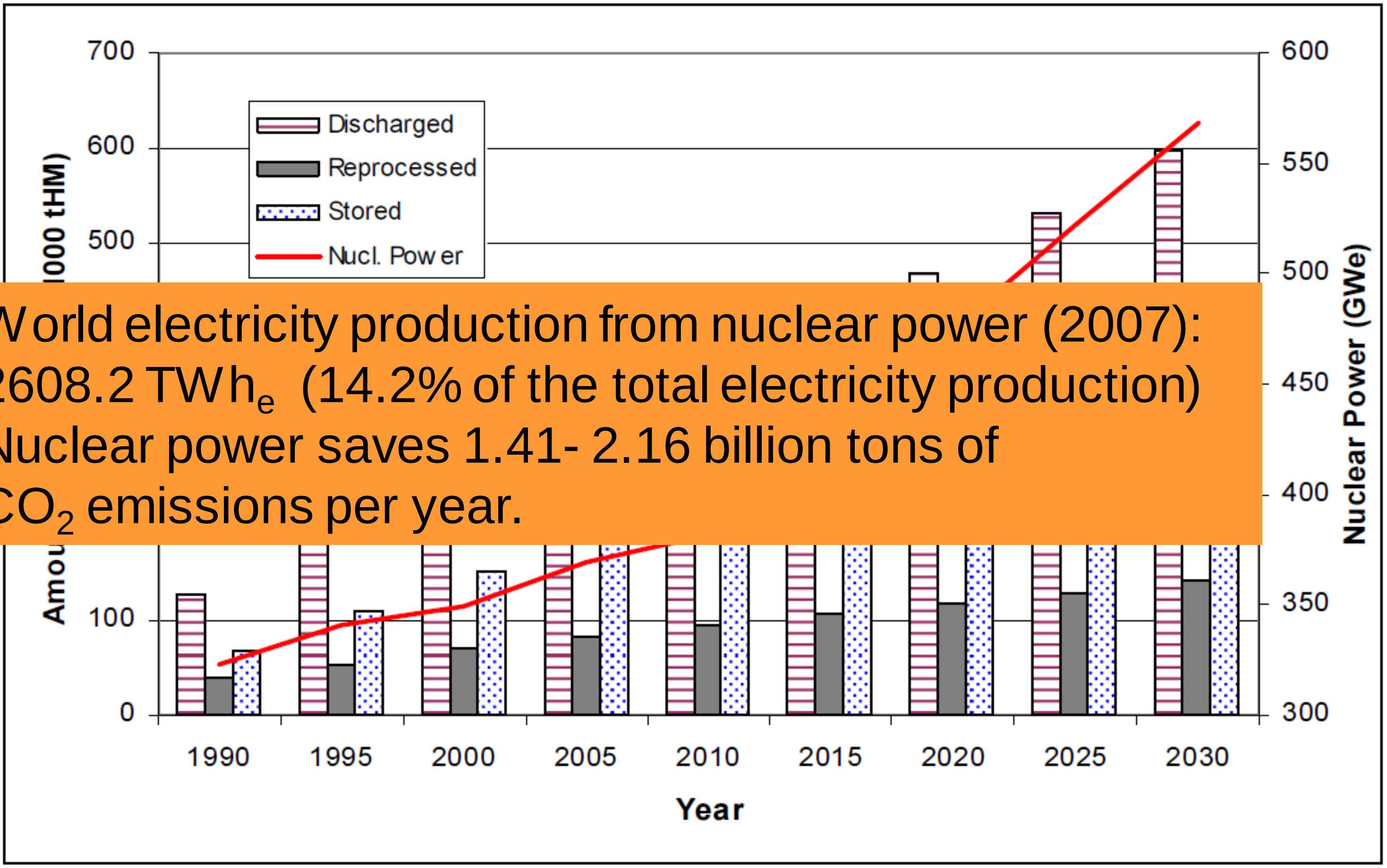


Fig. 14. Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030.

source : IAEA-TECDOC-1613, April 2009

Spent fuel from nuclear power plants worldwide

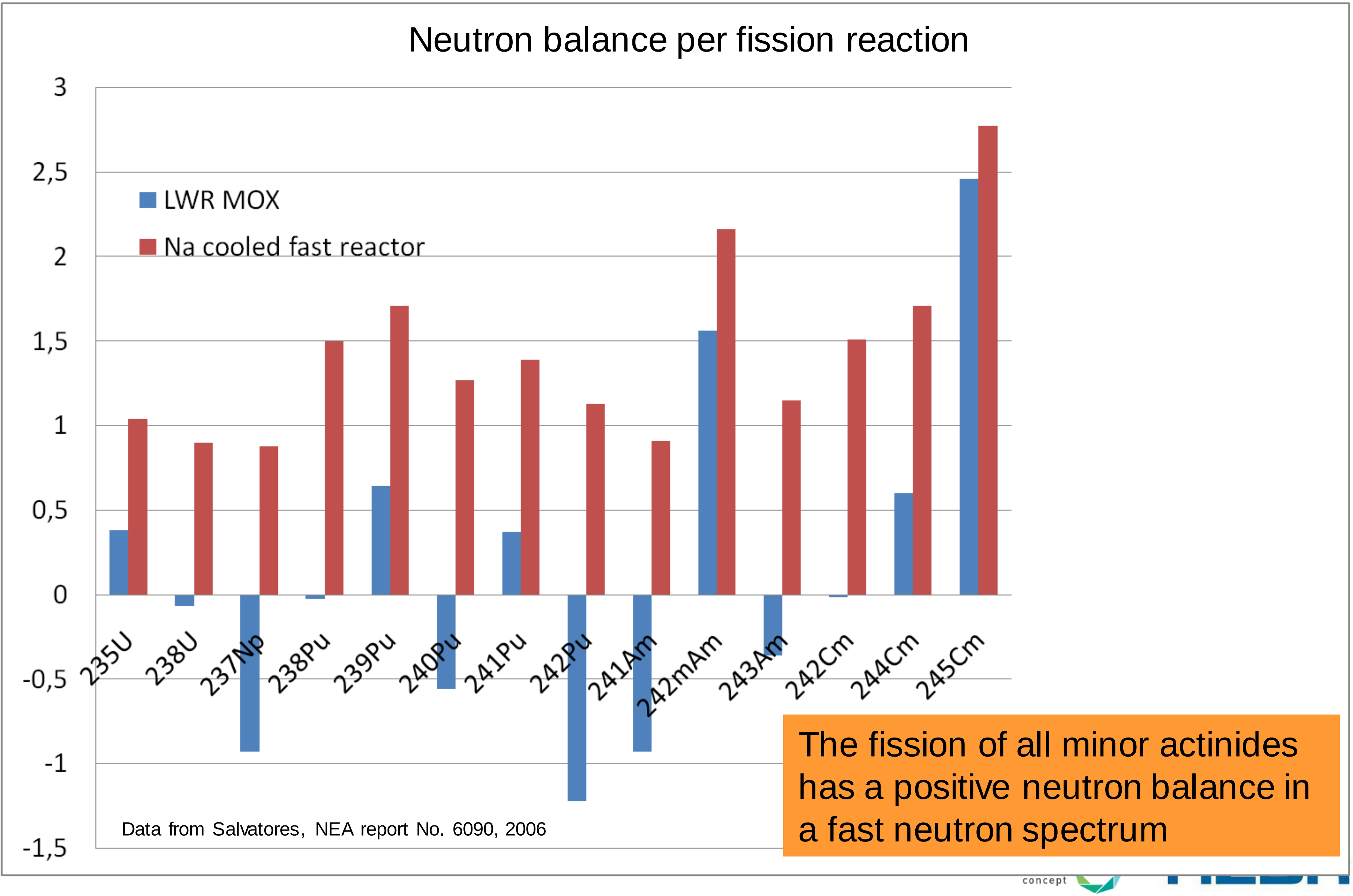


World electricity production from nuclear power (2007): 2608.2 TWh$_e$ (14.2% of the total electricity production)

Nuclear power saves 1.41- 2.16 billion tons of CO_2 emissions per year.

Fig. 14. Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2030.

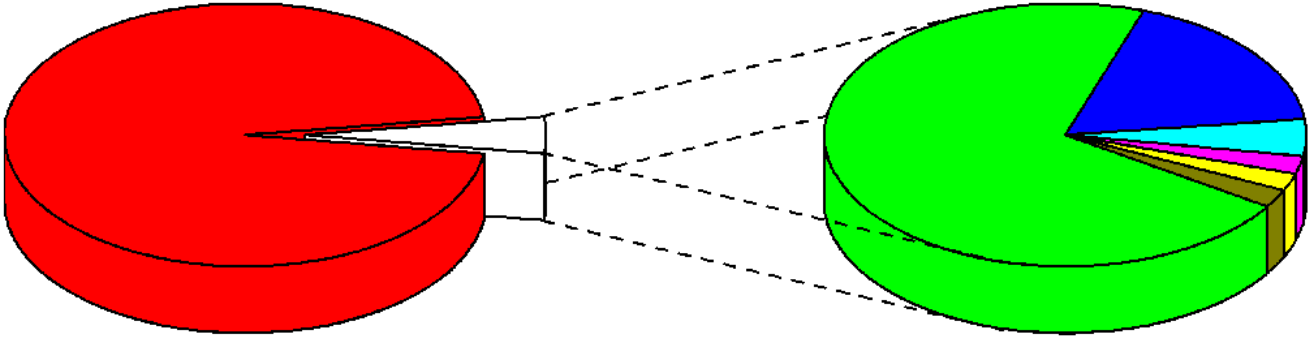
source : IAEA-TECDOC-1613, April 2009



Data from Salvatores, NEA report No. 6090, 2006

The fission of all minor actinides has a positive neutron balance in a fast neutron spectrum

Spent nuclear fuel 33 GWd/t 10 a cooling



- 🟥 Uranium (95.5 %)
- 🟩 stable fission products (3.2 %)
- 🟦 Plutonium (0.8 %)
- 🟦 short lived Cs and Sr (0.2 %)
- 🟪 minor actinides (0.1 %)
- 🟨 long lived I and Tc (0.1 %)
- 🟫 other long lived fission products (0.1 %)

1 tonne of SNF contains:
955.4 kg U
8.5 kg Pu

Minor actinides (MAs)
0.5 kg ^{237}Np
0.6 kg Am
0.02 kg Cm

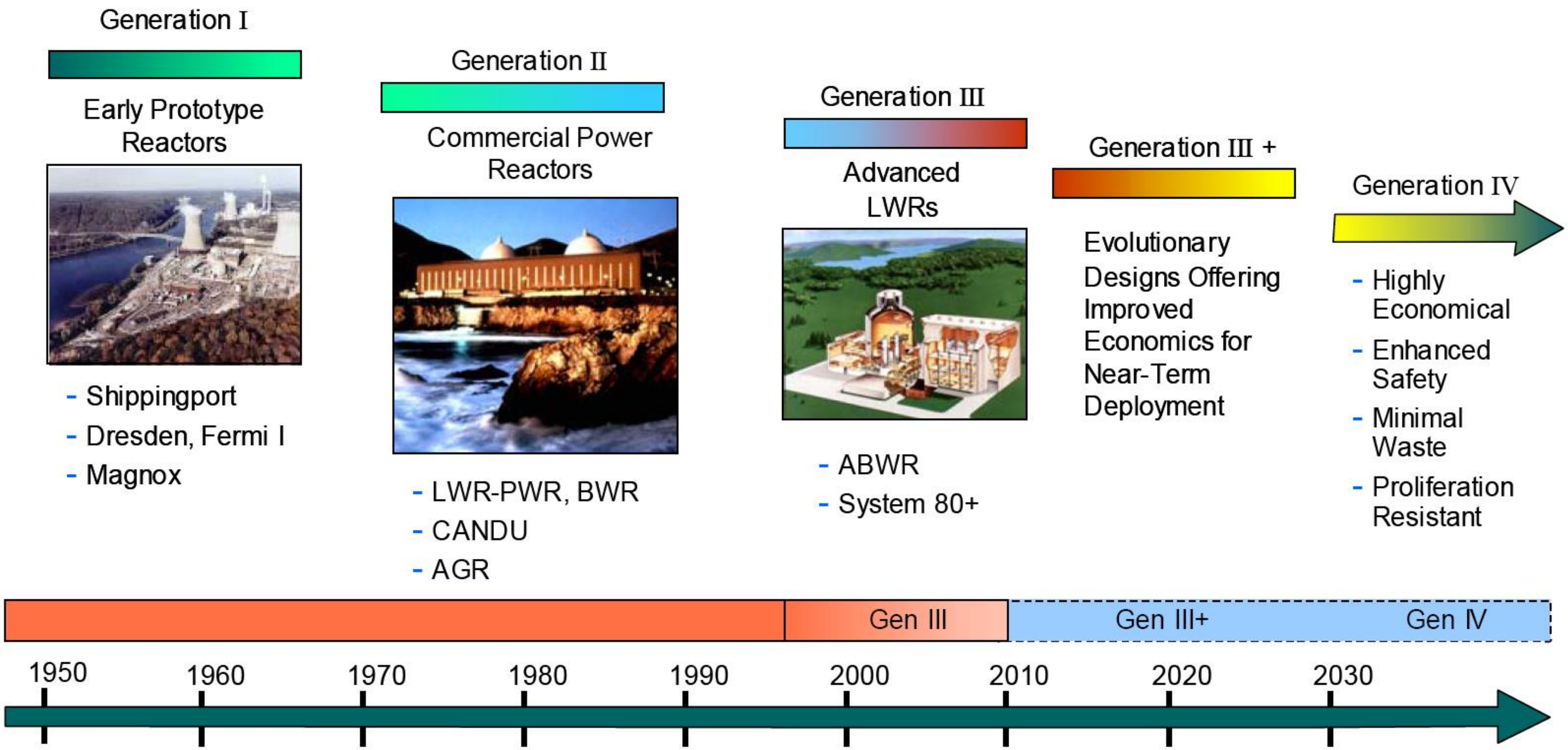
Long-lived fission products (LLFPs)
0.2 kg ^{129}I
0.8 kg ^{99}Tc
0.7 kg ^{93}Zr
0.3 kg ^{135}Cs

Short-lived fission products (SLFPs)
1 kg ^{137}Cs
0.7 kg ^{90}Sr

Stable isotopes
10.1 kg lanthanides
21.8 kg other stable

Main component: ^{238}U
Fission products and minor actinides ≈ 1 kg / t

History of nuclear power reactors



Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- AGR

Generation III

Advanced LWRs

- ABWR
- System 80+

Generation III +

Evolutionary Designs Offering Improved Economics for Near-Term Deployment

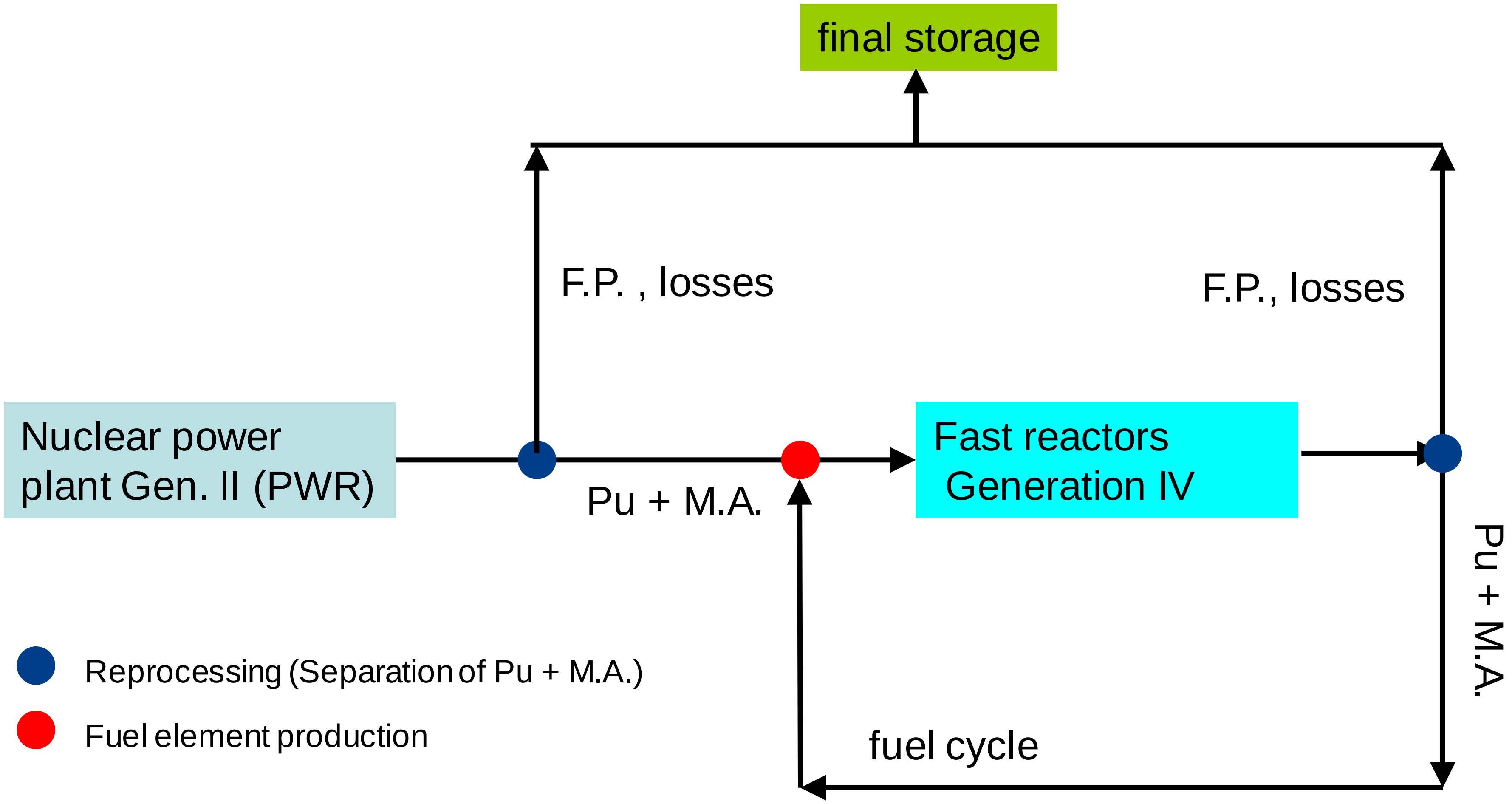
Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

A Technology Roadmap for Generation IV Nuclear Energy Systems

Currently operational power reactors are mostly generation II
(Olkiluoto 3 in construction in Finland is a
European Pressurized Water Reactor Generation III)

Sustainable Nuclear Energy: Partitioning & Transmutation



final storage

F.P. , losses

F.P., losses

Nuclear power plant Gen. II (PWR)

Pu + M.A.

Fast reactors Generation IV

Pu + M.A.

fuel cycle

● Reprocessing (Separation of Pu + M.A.)

● Fuel element production

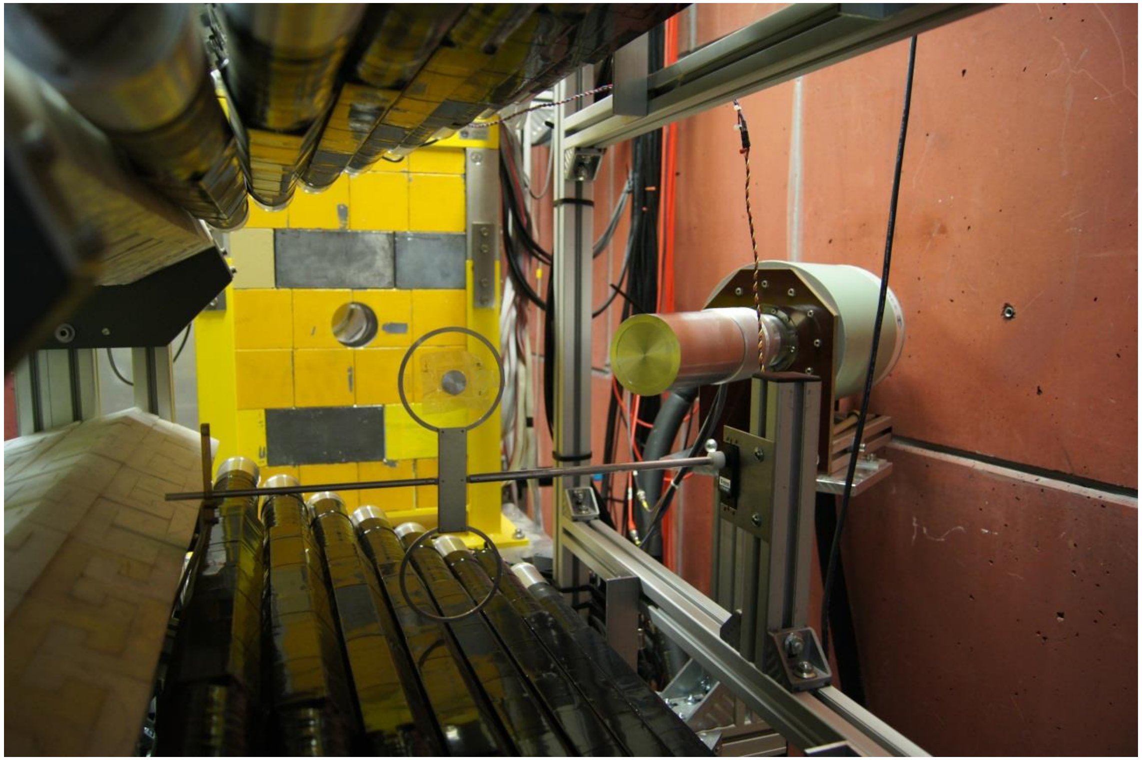
➔ Final storage of fission products(F.P.)

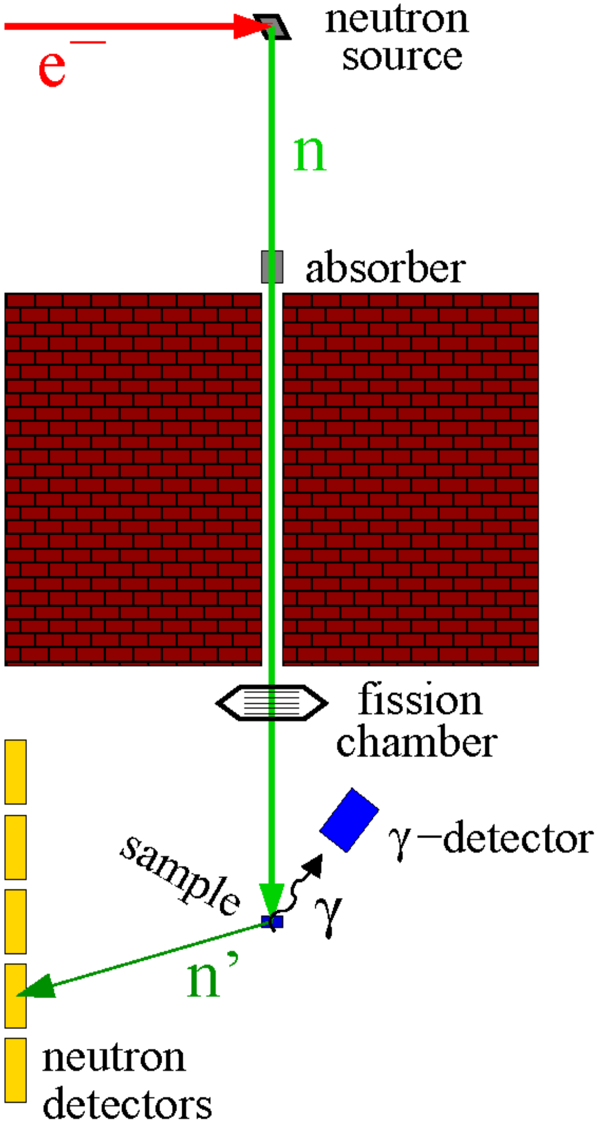
➔ No final storage of Pu + minor actinides (M.A.)

➔ homogeneous recycling of Pu + M.A. (risk of proliferation reduced)

Quelle: M. Salvatores, Physics and Safety of Transmutation Systems, NEA nuclear science report 6090, 2006

Measurements of photon production cross section ^{56}Fe(n,n'γ)





Target: cylinder of natural iron diameter 20 mm, thickness 8 mm

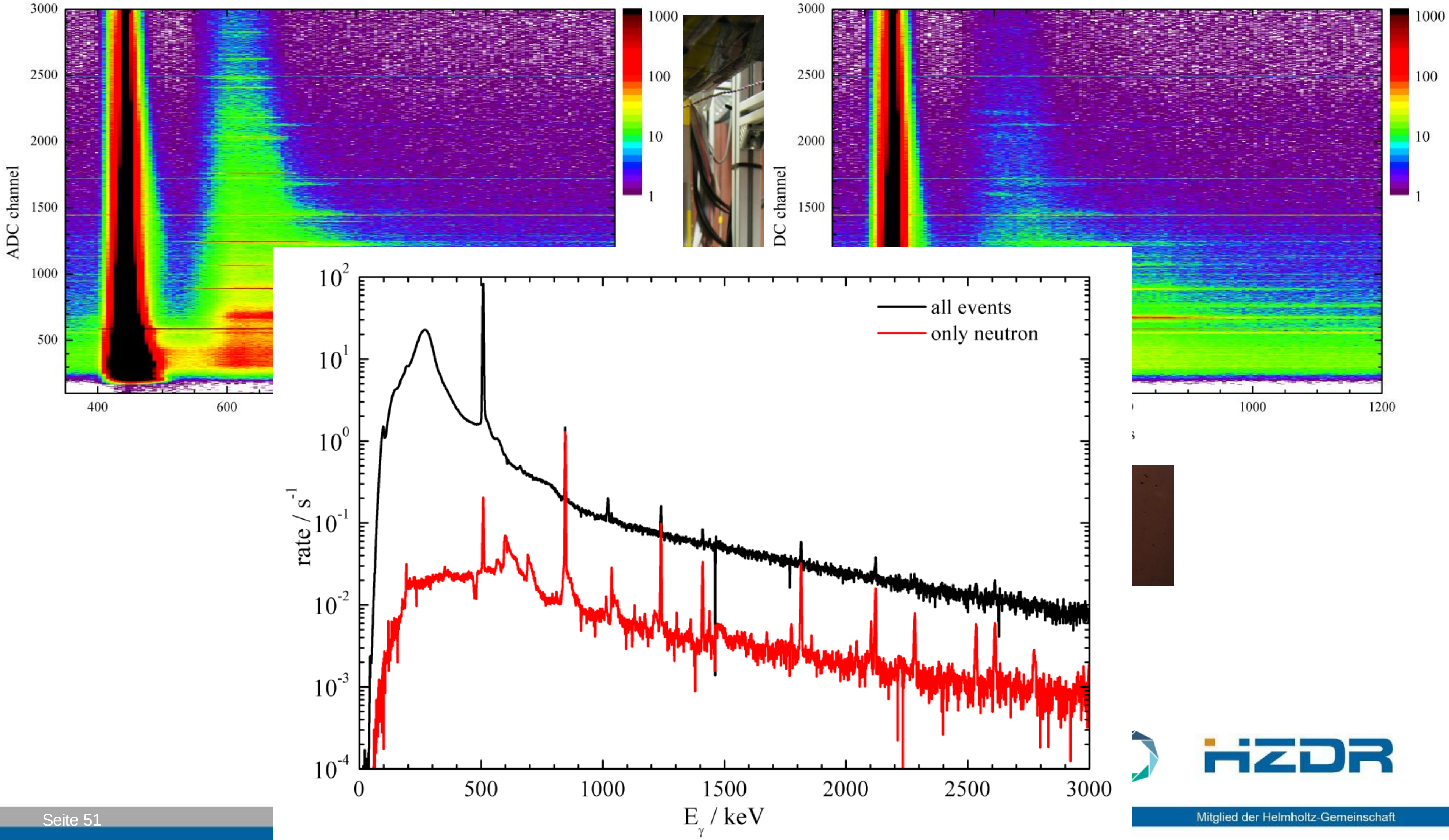
◦ HPGe detector at 125◦ to the neutron beam and a distance of 20 cm from the target

◦ Time difference between acelerator RF and signal of the HPGe detector
⇒ time-of-flight of the incident neutrons time resolution 10 ns

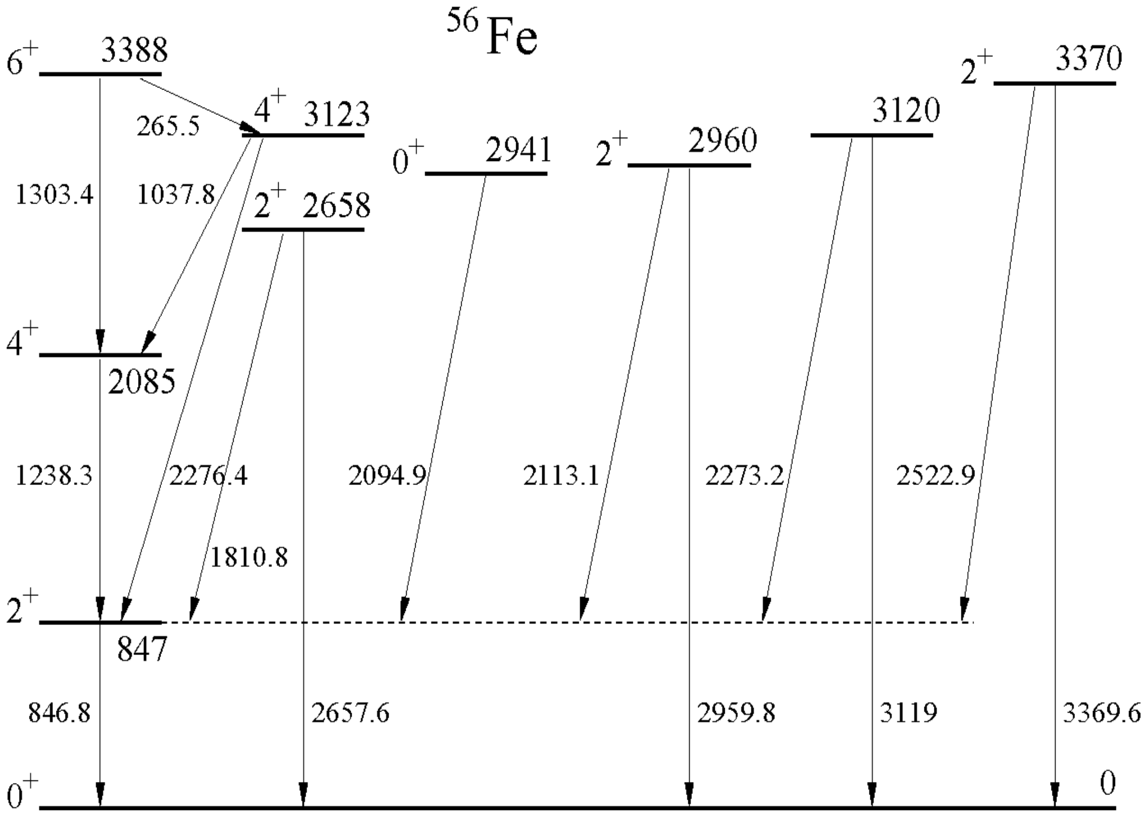
Measurements of photon production cross section

with target

without target

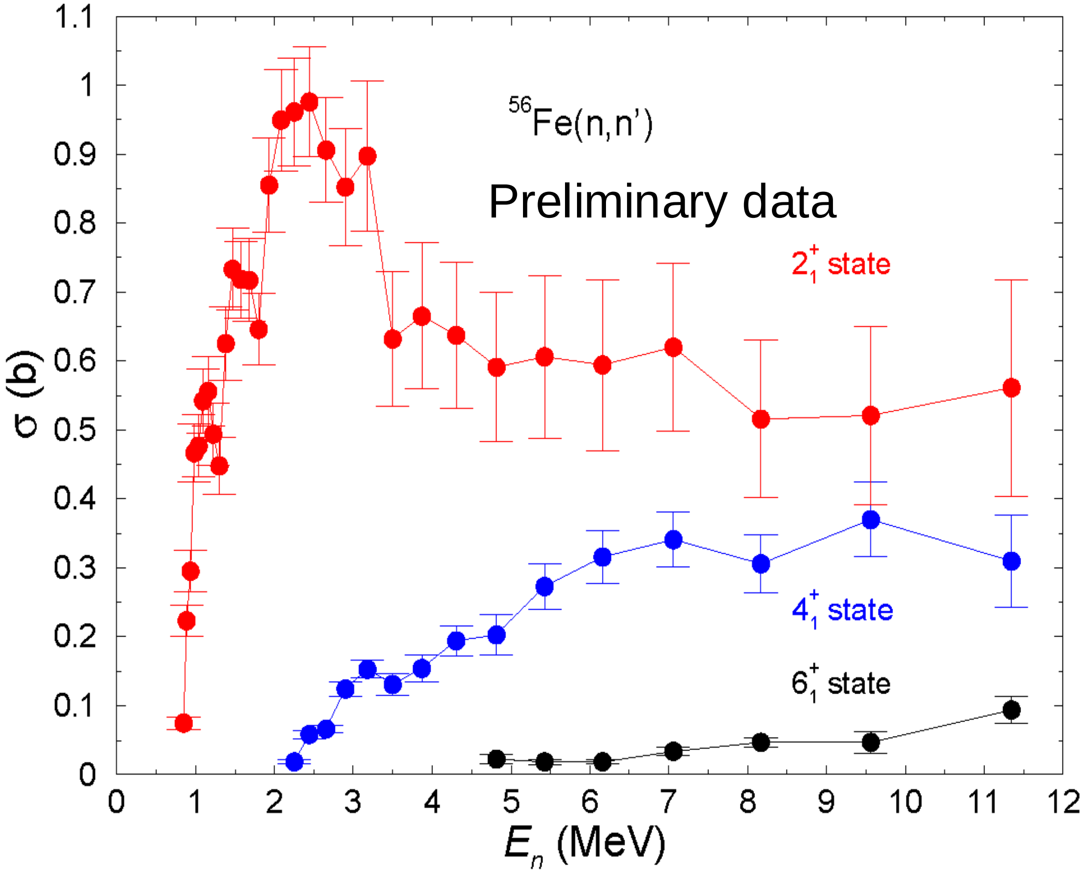


Excited states in ^{56}Fe

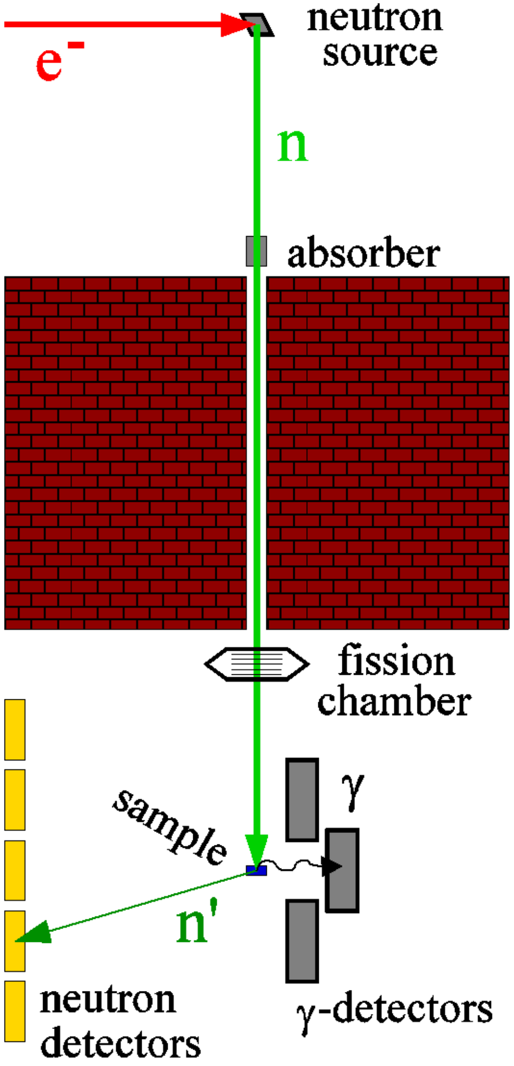


Subtraction of feeding from higher lying states

Cross section for inelastic scattering from ^{56}Fe

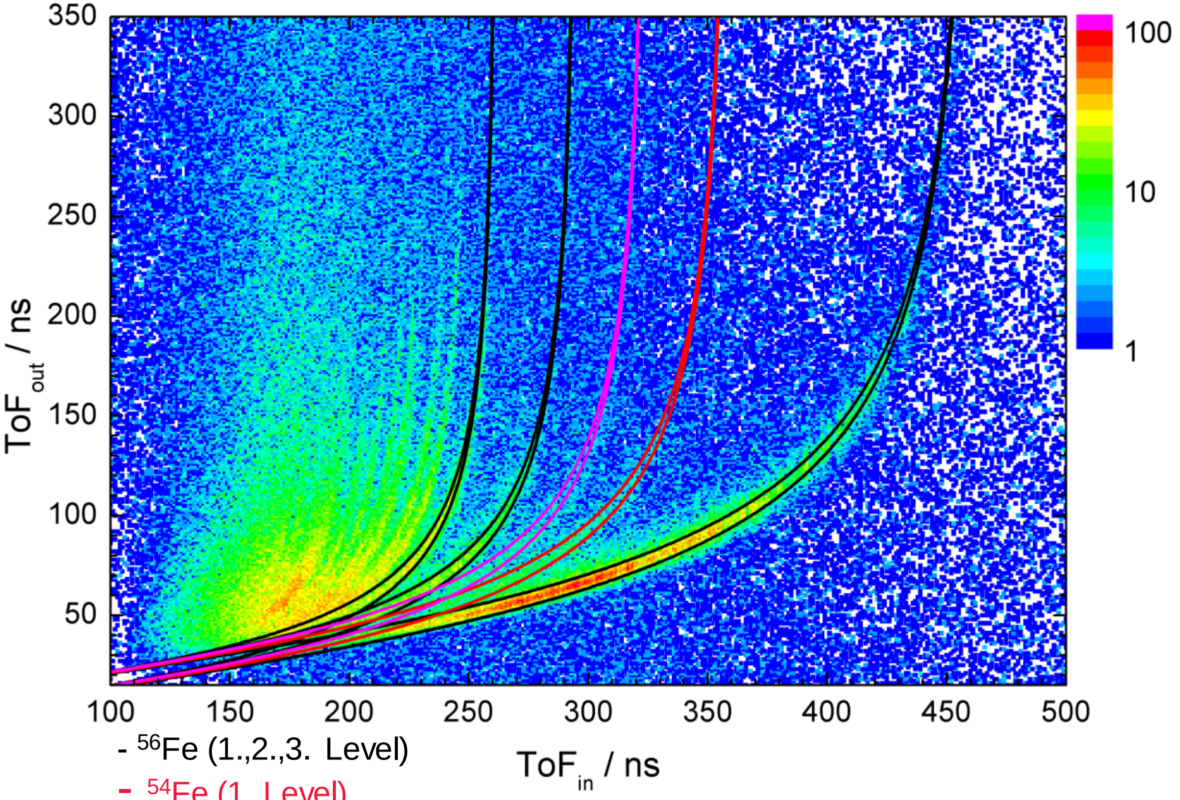


Double time of flight experiment for inelastic scattering



$$^{56}\mathrm{Fe}(n,n'\gamma)^{56}\mathrm{Fe} \quad \left\{ \begin{array}{l} ^{56}\mathrm{Fe}+n\rightarrow{}^{56}\mathrm{Fe}^{*}+n' \\ \qquad ^{56}\mathrm{Fe}^{*}\rightarrow{}^{56}\mathrm{Fe}+\gamma \end{array}\right.$$

with sample (78 h live time)



- ^{56}Fe (1.,2.,3. Level)
- ^{54}Fe (1. Level)
- ^{56}Fe double scatter 1. level

Implementation of the ERINDA project

- **Transnational Access to Large Infrastructures**
  Consortium of all relevant nuclear data facilities in Europe to meet future scientific and industrial nuclear data requests. Pool of 2500 hours of beam time for experiments in 36 months. Competence building of young scientists (< 6 yr PhD)
- **Scientific support of experiments**
  10 scientific visits (up to 8 weeks each) at the participating institutes e.g. theoretical, data analysis +simulations
- **Communication and dissemination of results**
  4 scientific workshops, annual scientific reports, public website, leaflet, poster, project presentation

Nuclear Transmutation Project

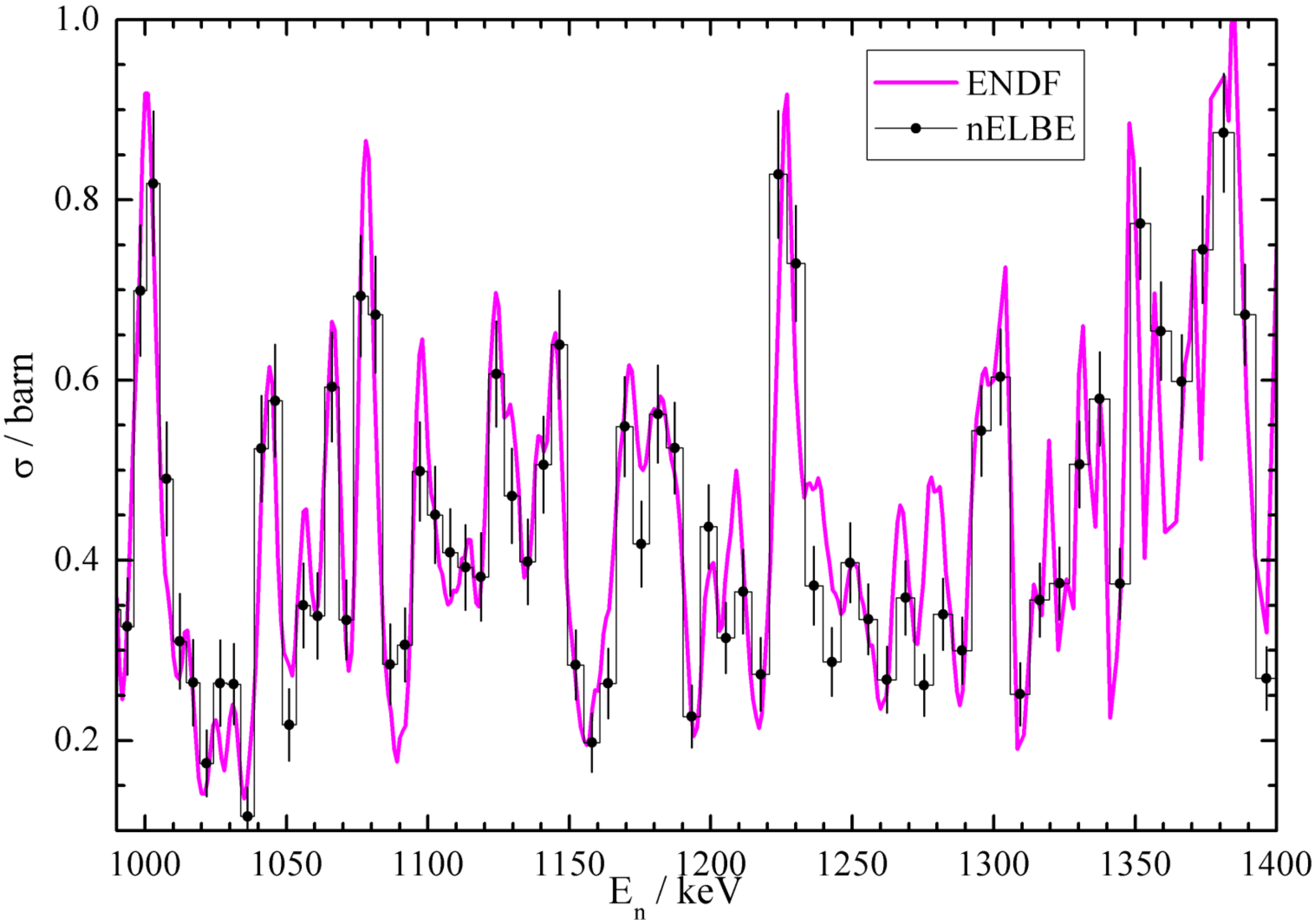
- Roland Beyer, Evert Birgersson**, Anna Ferrari, Roland Hannaske, Mathias Kempe, Toni Kögler, Michele Marta, Ralf Massarczyk, Andrija Matic, Georg Schramm

- Arnd Junghans, Daniel Bemmerer, Eckart Grosse*, Klaus-Dieter Schilling, Ronald Schwengner, Andreas Wagner

- Development of the nELBE photoneutron source together with the Institut für Sicherheitsforschung, Frank-Peter Weiss and also with IKTP, TU Dresden, Hartwig Freiesleben, Klaus Seidel through a DFG project.

* (also at IKTP Dresden)
** now AREVA, Erlangen

The ^{56}Fe(n,n'γ) cross section for the 1st excited state



Preliminary data. Normalisation ongoing.

Total neutron cross section of Tantalum and Gold

- Transmission measurement

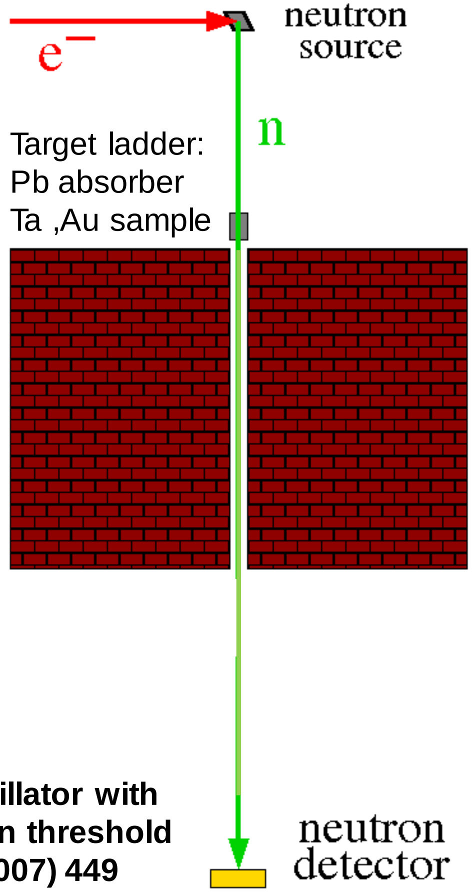
$$T = \frac{N}{N_0} = \exp(-\sigma_{tot} n_t t)$$

➔ Neutron total cross section

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} + \sigma_{n,\gamma} + \cdots$$

- Au (0.095 at/b), Ta (0.141 at/b), PbSb4 targets
- ^{197}Au(n,γ): cross section standard total cross section data are insufficient (NEA HPRL)
- Ta: component of low activation steels
- Energy range ca. 100 keV – 7 MeV

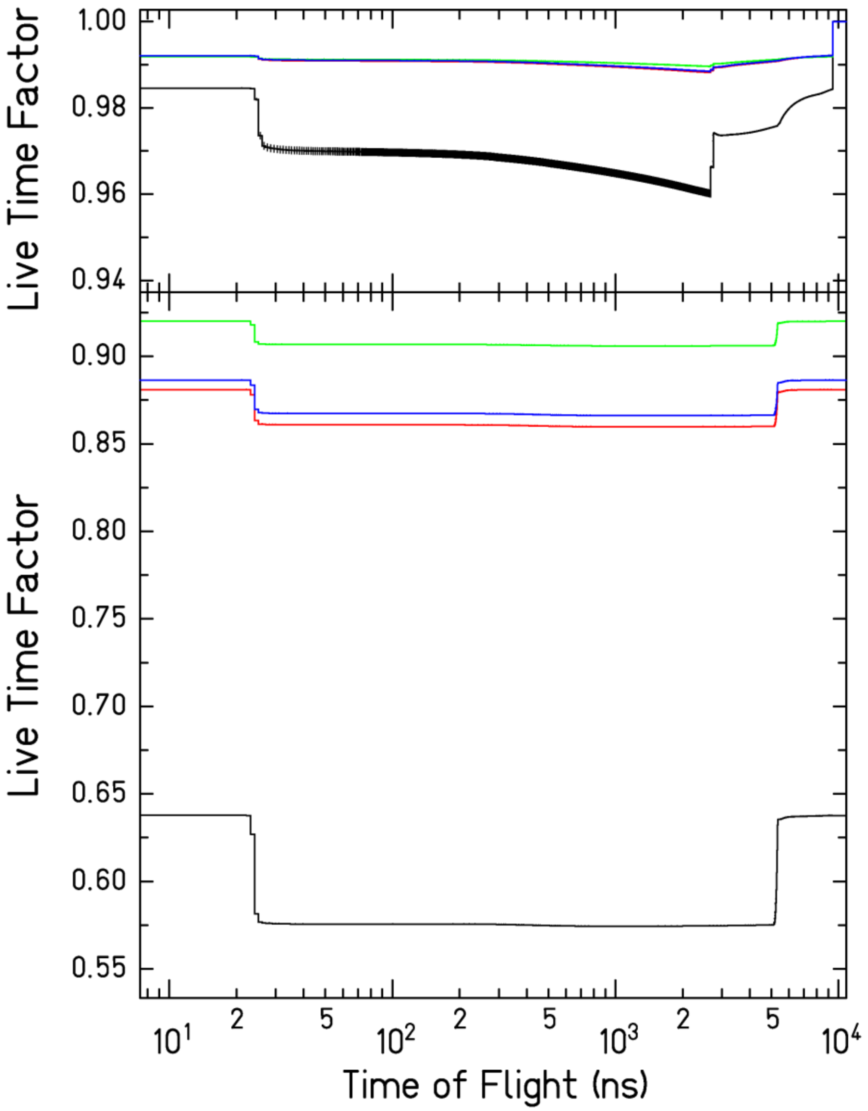
Flight path: 7.18 m
Repetition rate: 100 kHz



Target ladder:
Pb absorber
Ta ,Au sample

Plastic scintillator with low detection threshold NIMA 575 (2007) 449

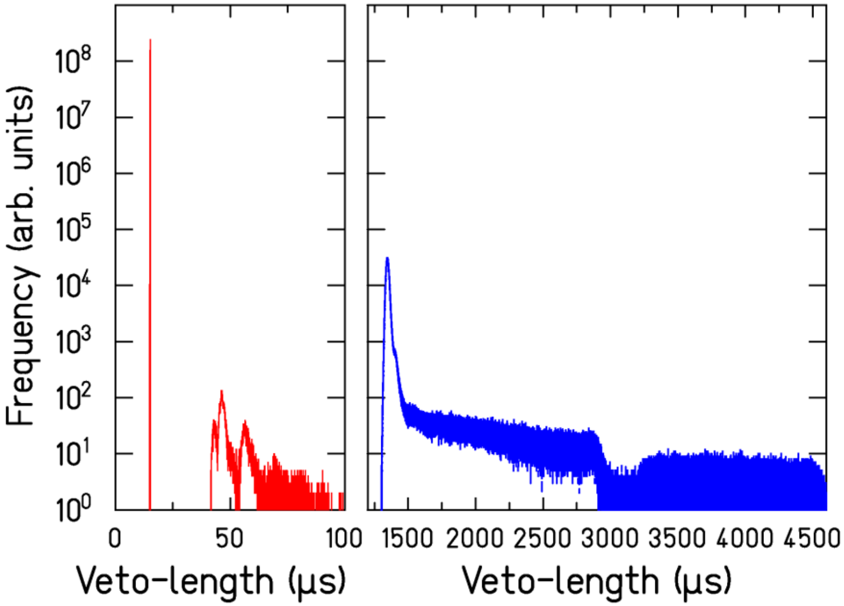
Time of flight dependent live time corrections



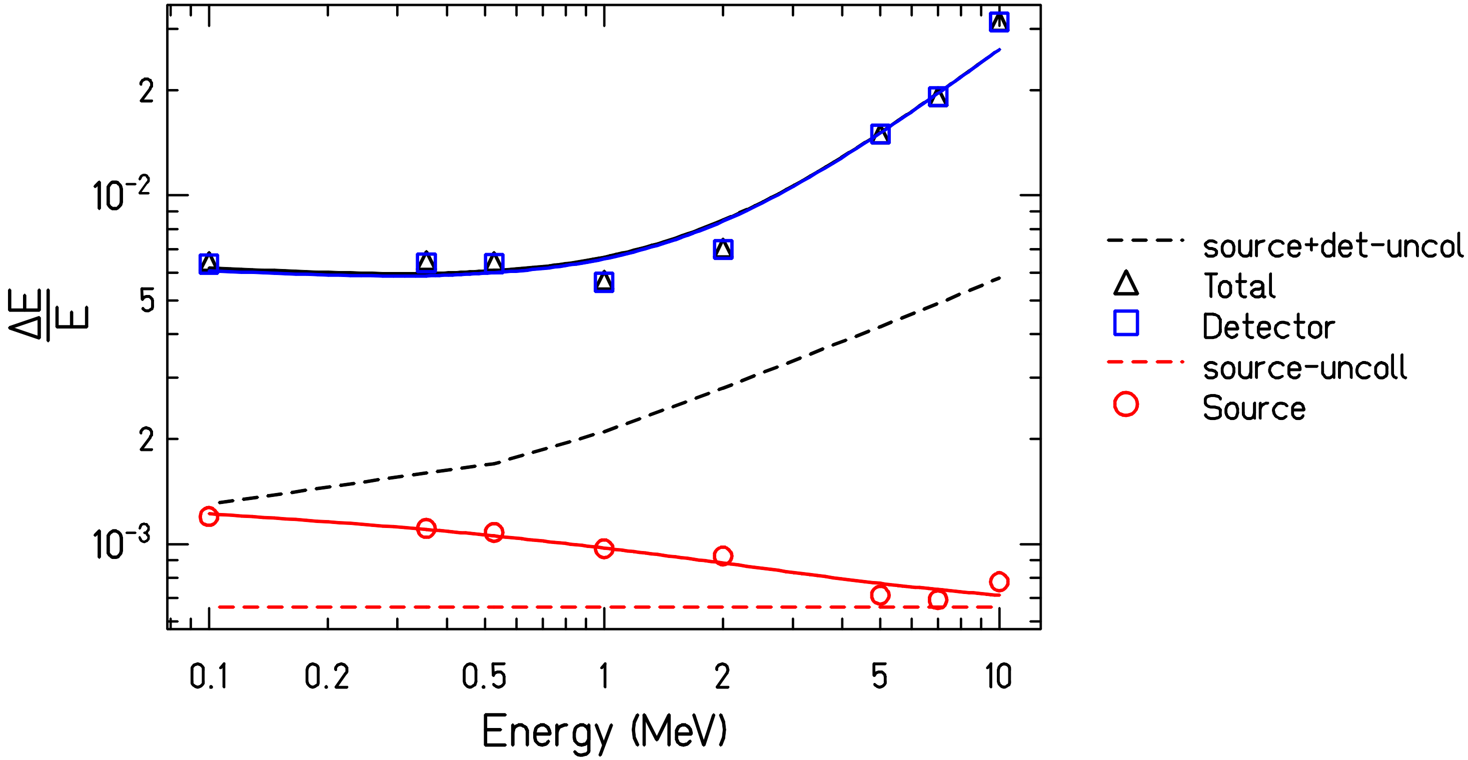
Correction due to fixed 2.7 μs
CFD singles veto length
To suppress PMT after pulses

Correction due to DAQ veto length
measured per event ≈ 15 μs

M. Moore.*Nucl. Inst. Meth. 169 (1980) 245-247*.



Energy resolution



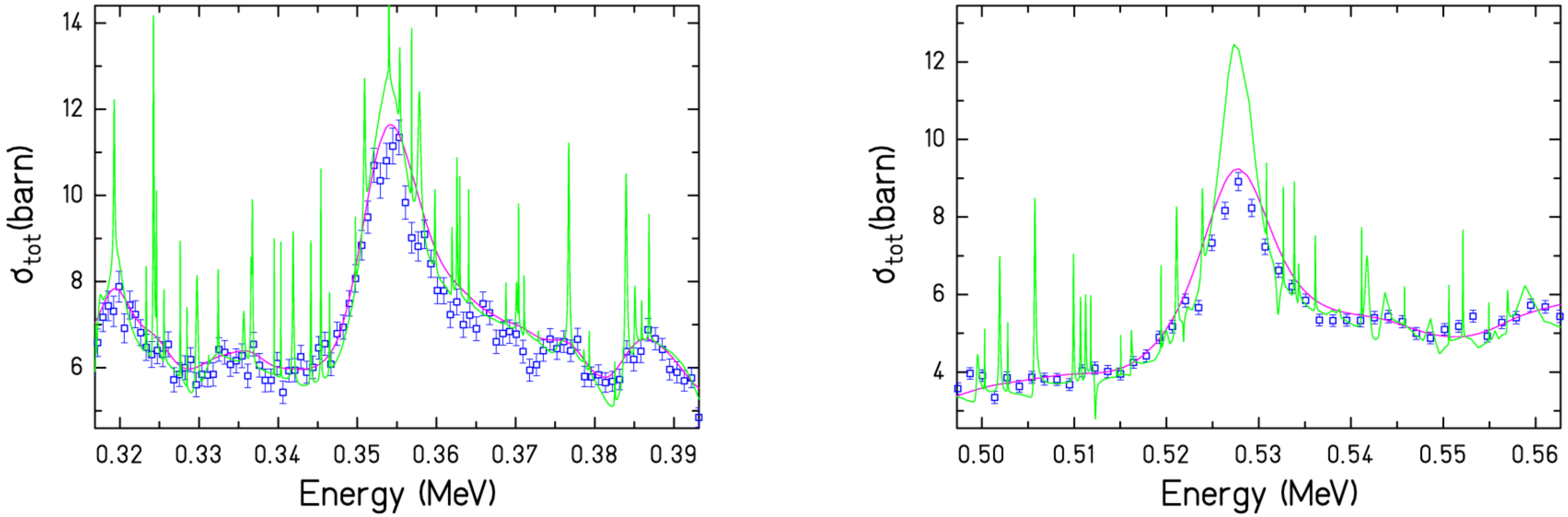
Time of flight- Energy correlation simulated with MCNP 5

Energy resolution of the photoneutron source incl. collimator ≈ 10^{-3} (1σ)

Scattering in Pb shield of the 11 mm thick plastic scintillator dominates the energy resolution

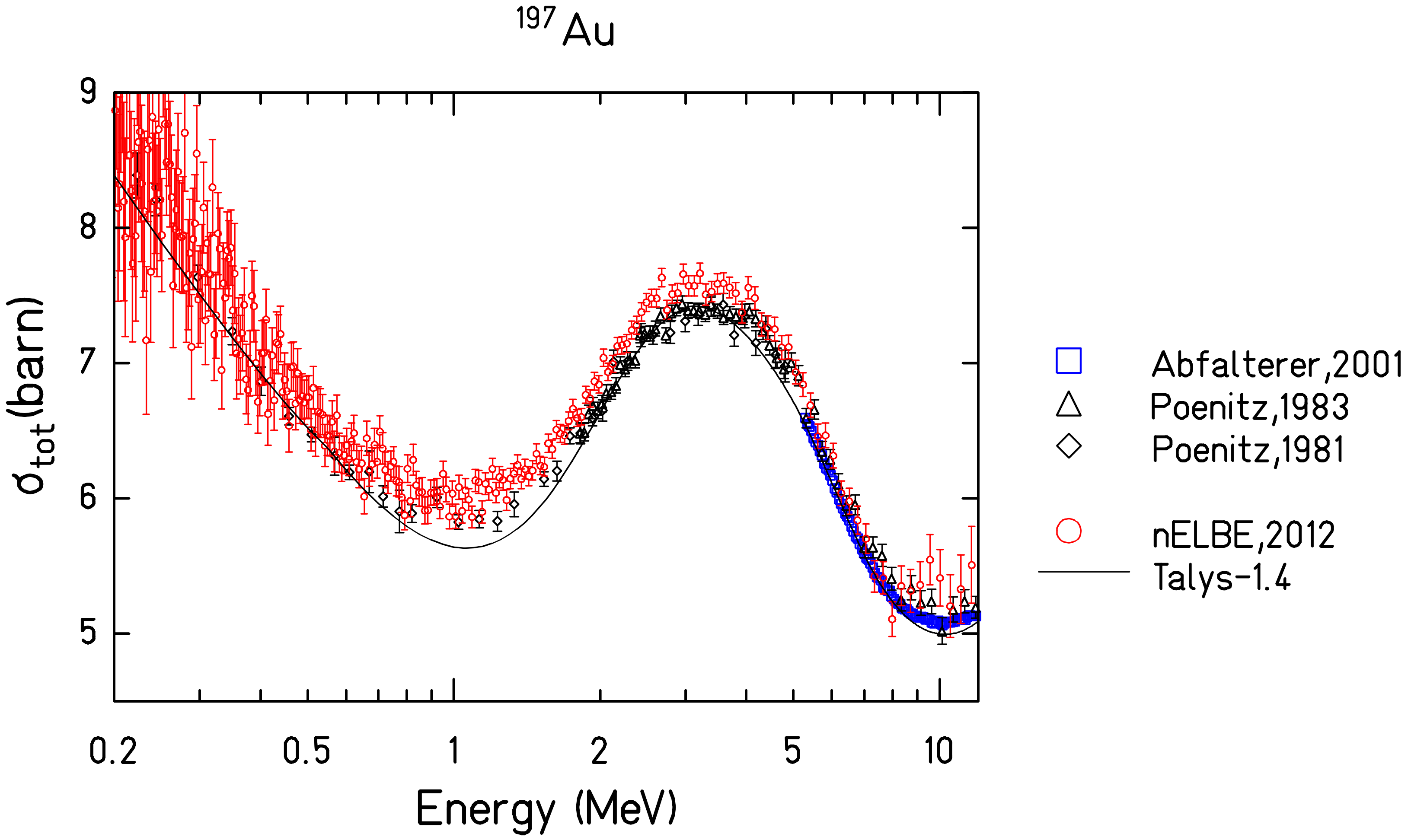
.

Broad resonances in ^{208}Pb

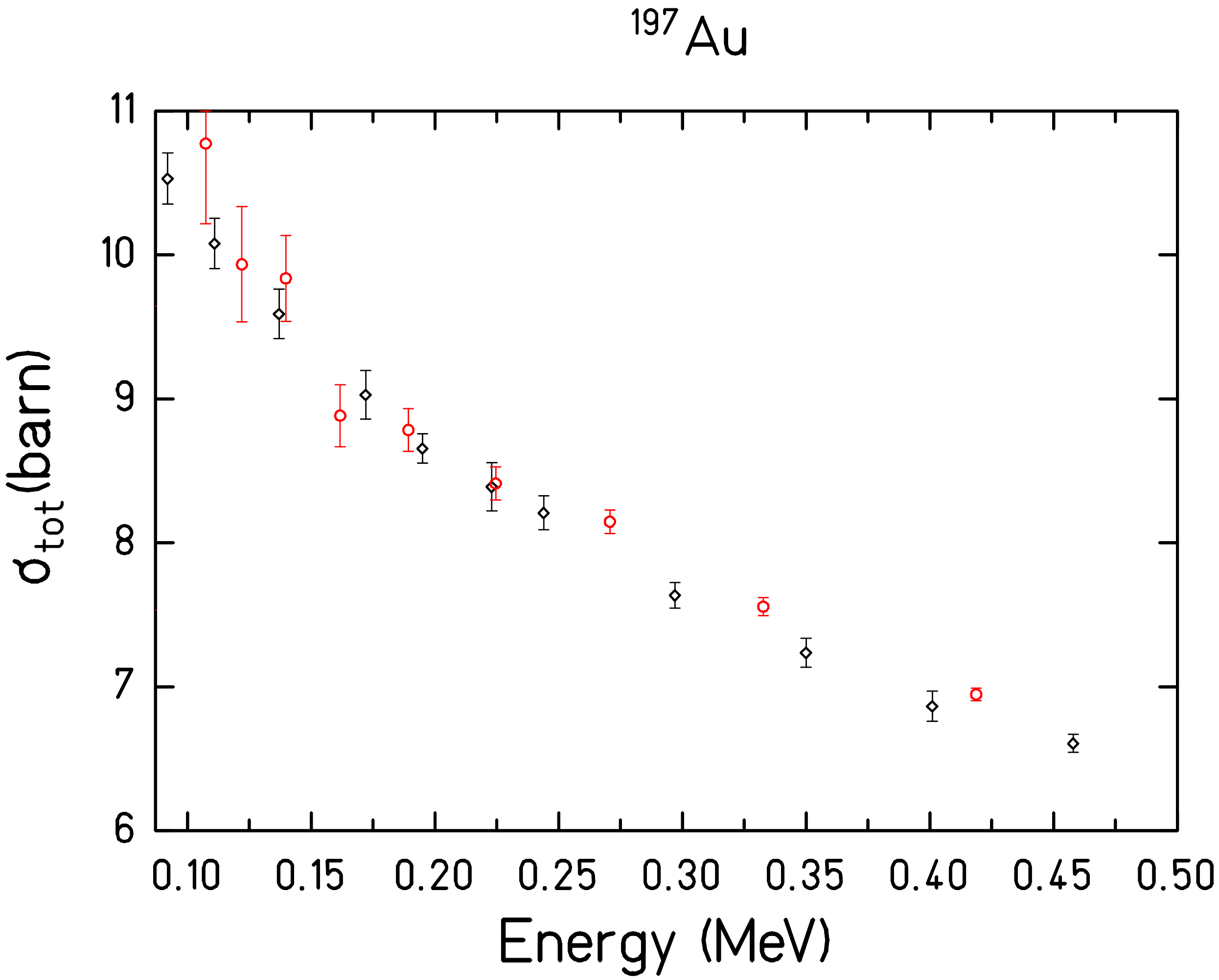


Energy-averaged transmission
gaussian energy resolution approx. $5 \cdot 10^{-3}$ (1σ).

Total neutron cross section data on Au

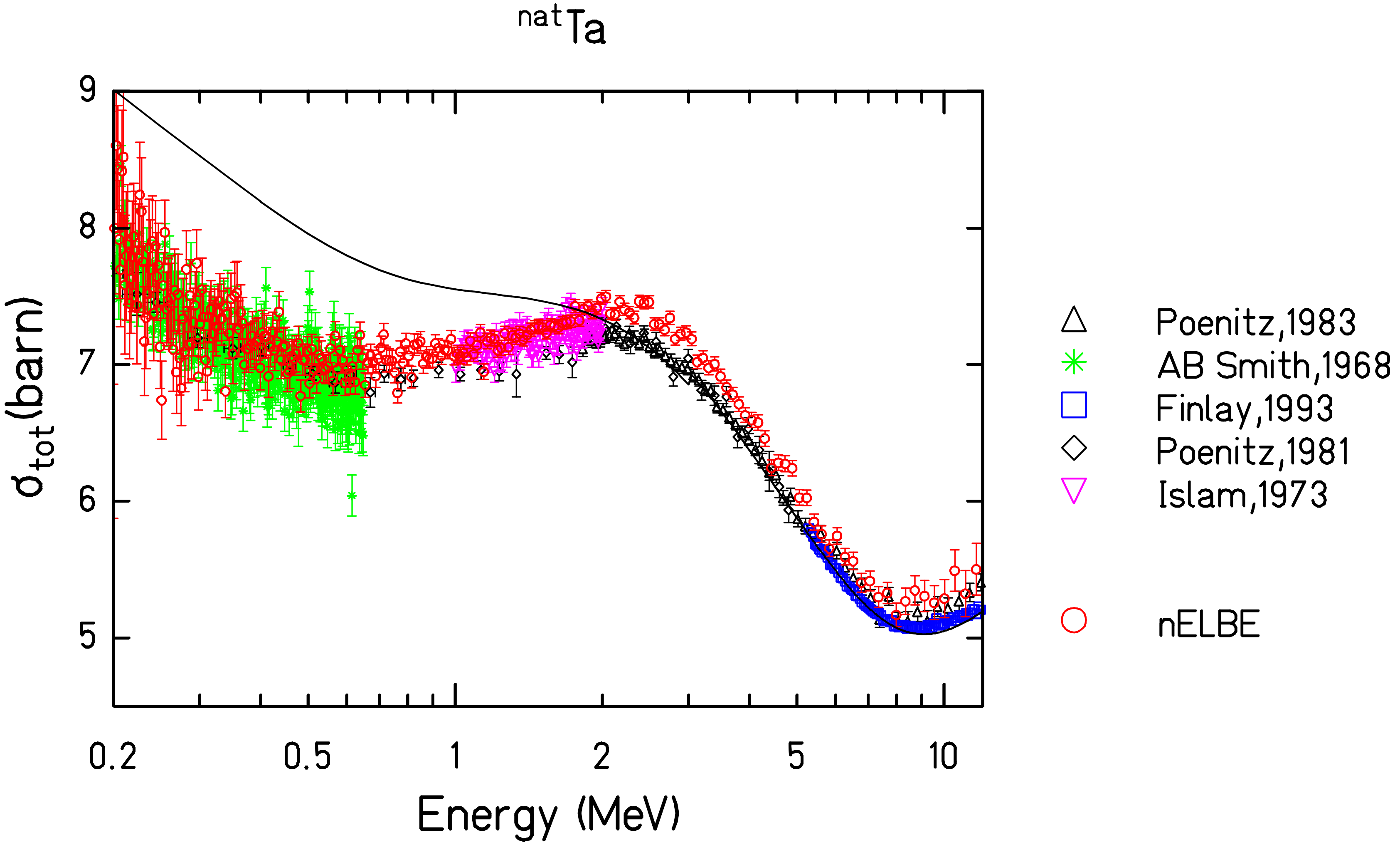


Total neutron cross section below 0.5 MeV



nELBE data about 2% higher than Poenitz et al. (ANL)

Total neutron cross section of Ta



Sustainable Nuclear Energy Technology Platform

More and better quality data

Availability of accurate nuclear data (cross sections, decay constants, branching ratios, etc.) is the basis for precise reactor calculations both for current (applications to higher burn-up, plant life extension) and new generation reactors. *Additional experimental measurements and their detailed analysis and interpretation are required in a broad range of neutron energies and materials. This is particularly true for fuels containing minor actinides for their transmutation in fast spectra*

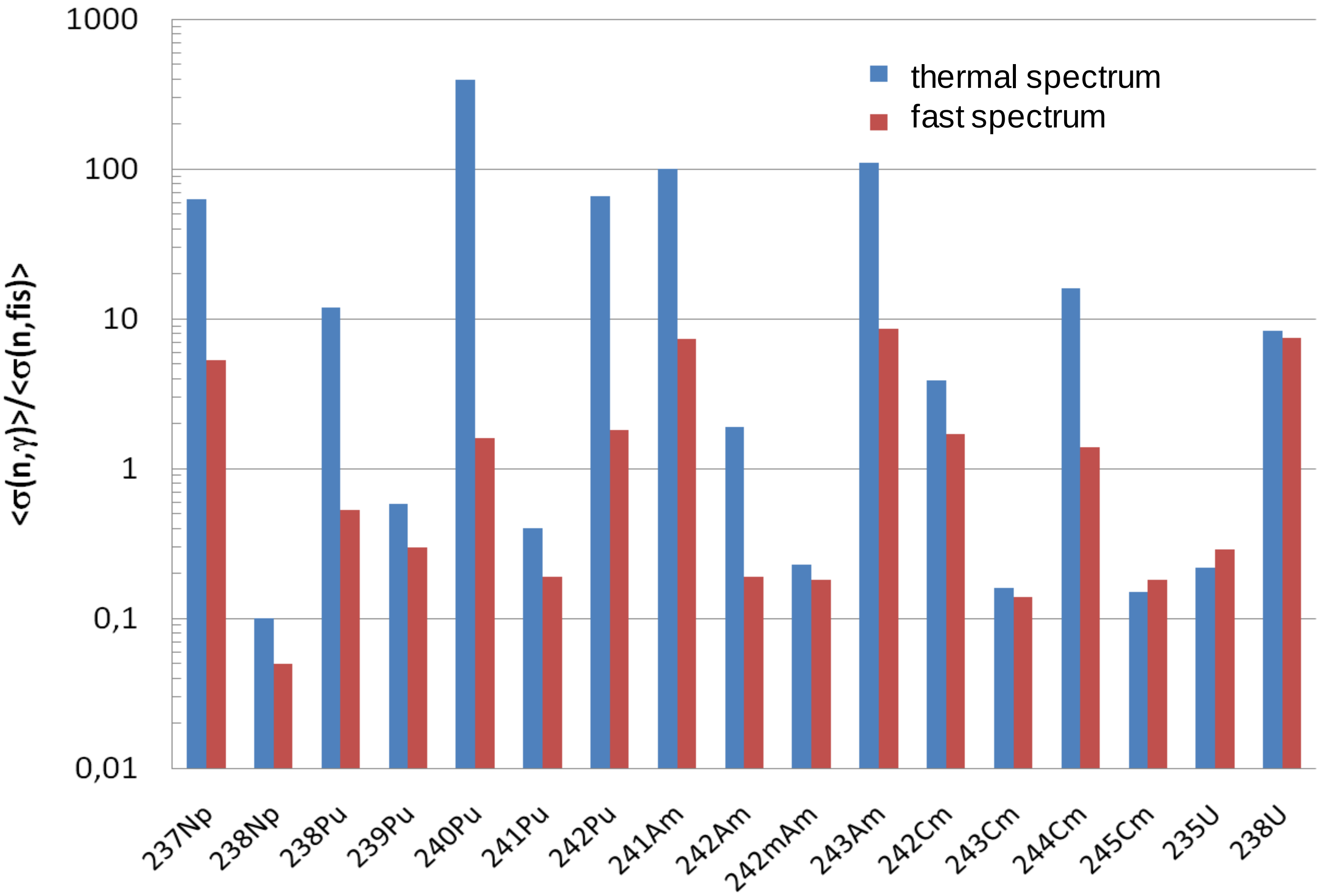
SNETP

Sustainable Nuclear Energy Technology Platform

Strategic Research Agenda

May 2009

Ratio of neutron capture to fission



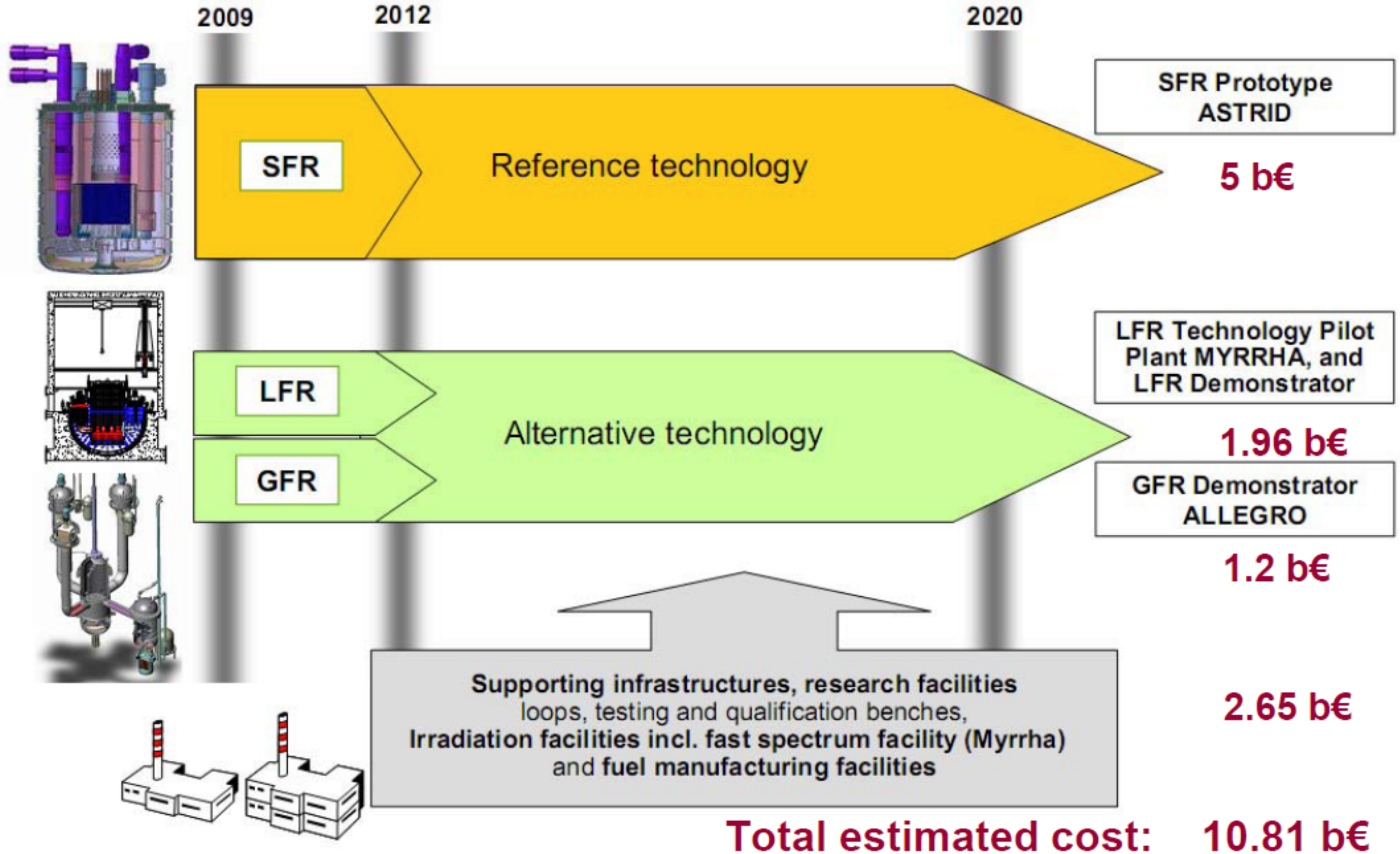
Data from Salvatores, NEA report No. 6090, 2006

List of invited lecturers

Hamid Aït Abderrahim	SCK-CEN	Belgium
Roberto Capote-Noy	IAEA	Austria
Klaus Eberhardt	Univ. Mainz	Germany
Jutta Escher	LLNL	United States of America
Thomas Faestermann	TU München	Germany
Jean-Paul Grouiller	CEA	France
Frank Gunsing	CEA	France
Robert Jaqmin	CEA	France
Arnd Junghans	HZDR	Germany
Beatriz Jurado	CEN Bordeaux-Gradignan	France
Bruno Merk	HZDR	Germany
Ralf Nolte	PTB	Germany
Arjan Plompen	IRMM	Belgium
Syed Qaim	FZJ	Germany
Ulrich Ratzinger	Univ. Frankfurt	Germany
Peter Reiter	Univ. Köln	Germany
Andrei Rineiski	KIT	Germany
Karl-Heinz Schmidt	CEN Bordeaux-Gradignan	France
Laurent Tassan-Got	IPN Orsay	France

The European Sustainable Nuclear Industrial Initiative

2040: Target for the deployment of Gen-IV Fast Neutron Reactors with Closed Fuel Cycle



SFR Prototype ASTRID

5 b€

LFR Technology Pilot Plant MYRRHA, and LFR Demonstrator

1.96 b€

GFR Demonstrator ALLEGRO

1.2 b€

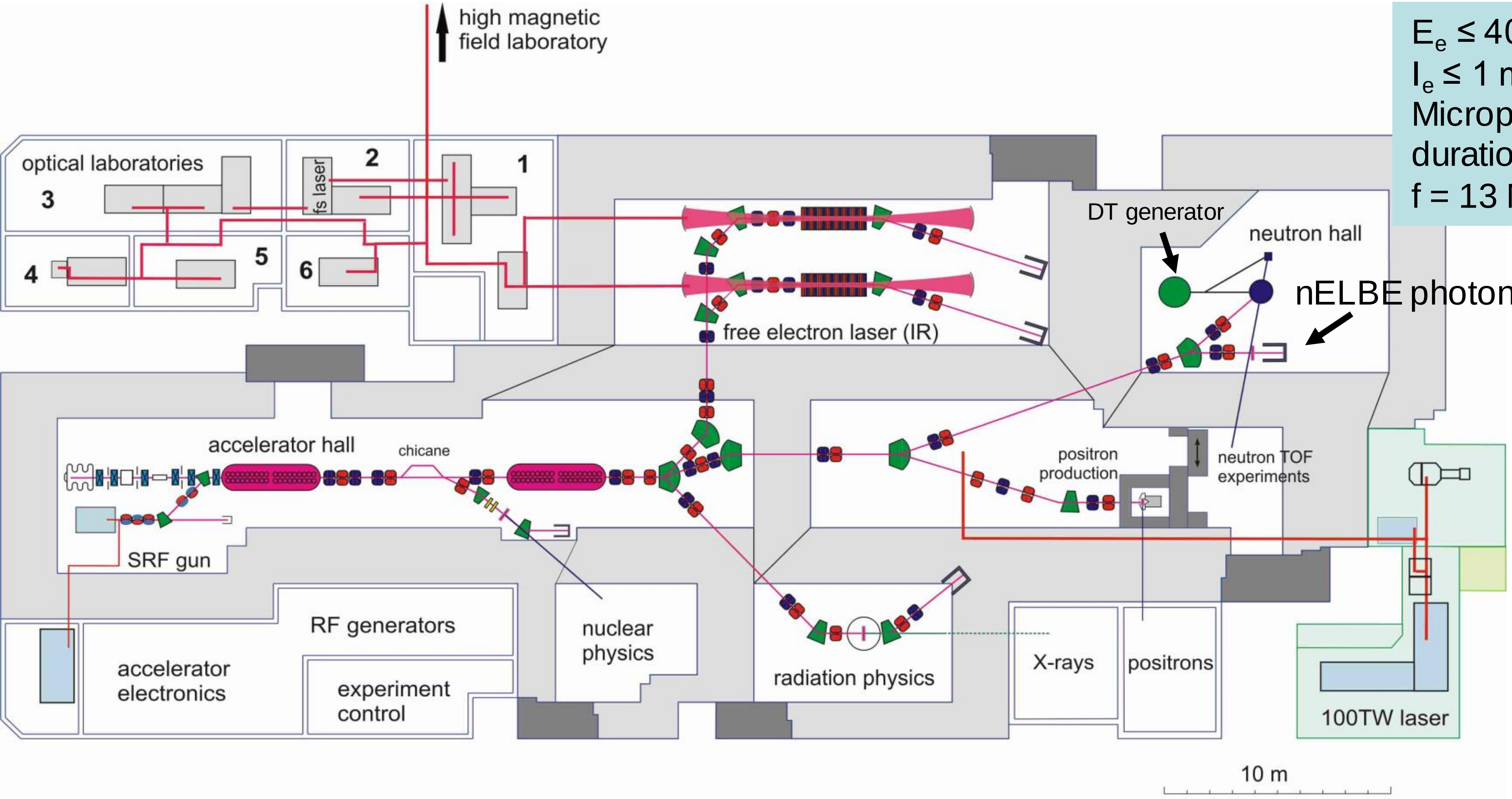
Supporting infrastructures, research facilities
loops, testing and qualification benches,
Irradiation facilities incl. fast spectrum facility (Myrrha)
and **fuel manufacturing facilities**

2.65 b€

Total estimated cost: 10.81 b€

Courtesy: Roger Garbil, EC DG RTD K4, presentation at ERINDA Kick-off meeting, Jan. 2011

ELBE: Electron Linear accelerator with high Brilliance and low Emittance



$E_e \leq 40$ MeV
$I_e \leq 1$ mA
Micropulse duration $\Delta t < 10$ ps
$f = 13$ MHz / 2^n

nELBE photoneutron source

1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
3: Time-resolved semiconductor spectroscopy, THz-spectroscopy
4: FTIR, biological IR experiment
5: Near-field and pump-probe IR experiment
6: Radiochemistry and sum frequency generation experiment, photothermal deflection spectroscopy

HZDR invites external groups for experiments at ELBE

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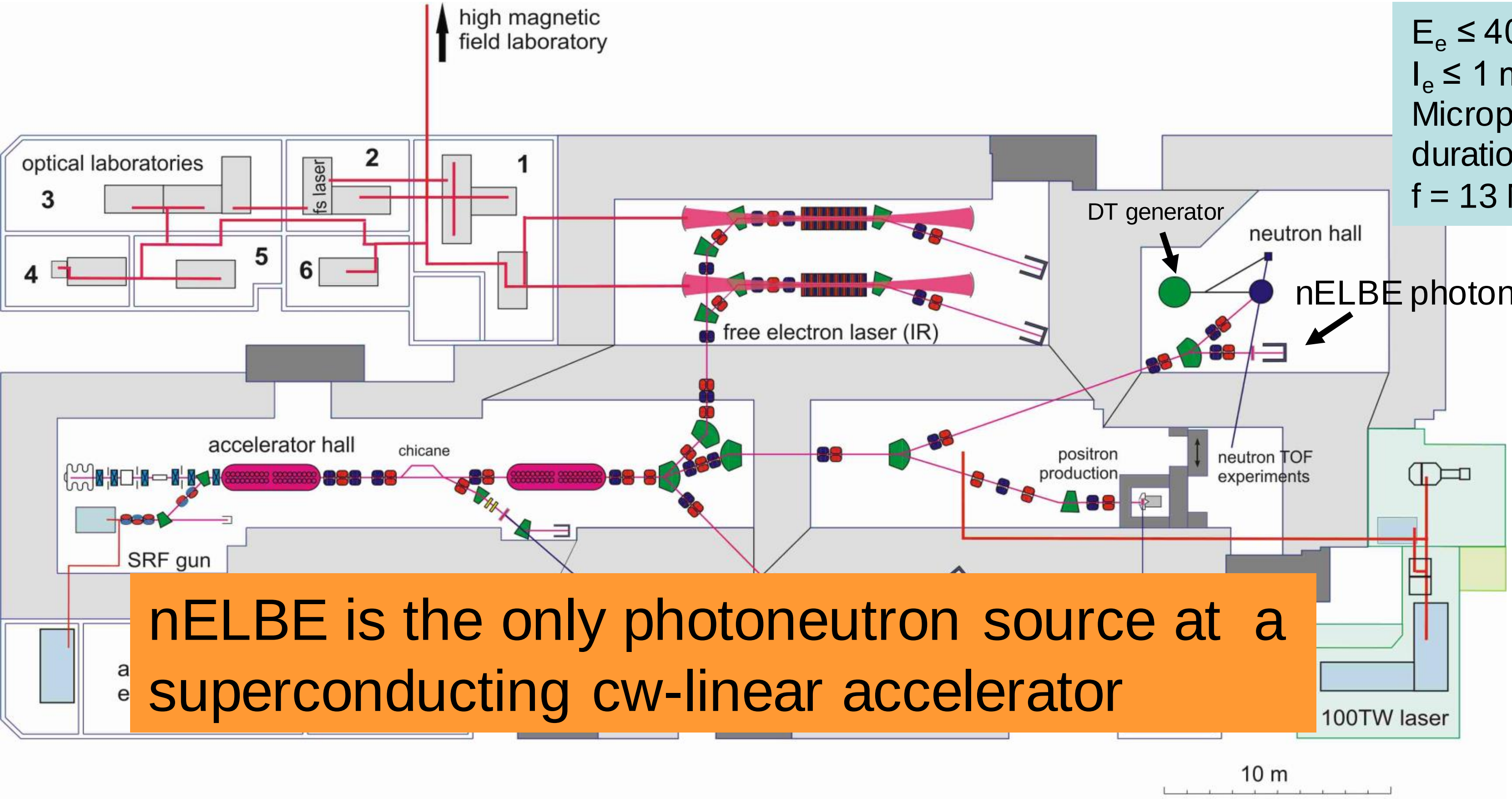

nELBE photoneutron source

nELBE is the only photoneutron source at a superconducting cw-linear accelerator

1: Diagnostic station, IR-imaging and biological IR experiment
2: Femtosecond laser, THz-spectroscopy, IR pump-probe experiment
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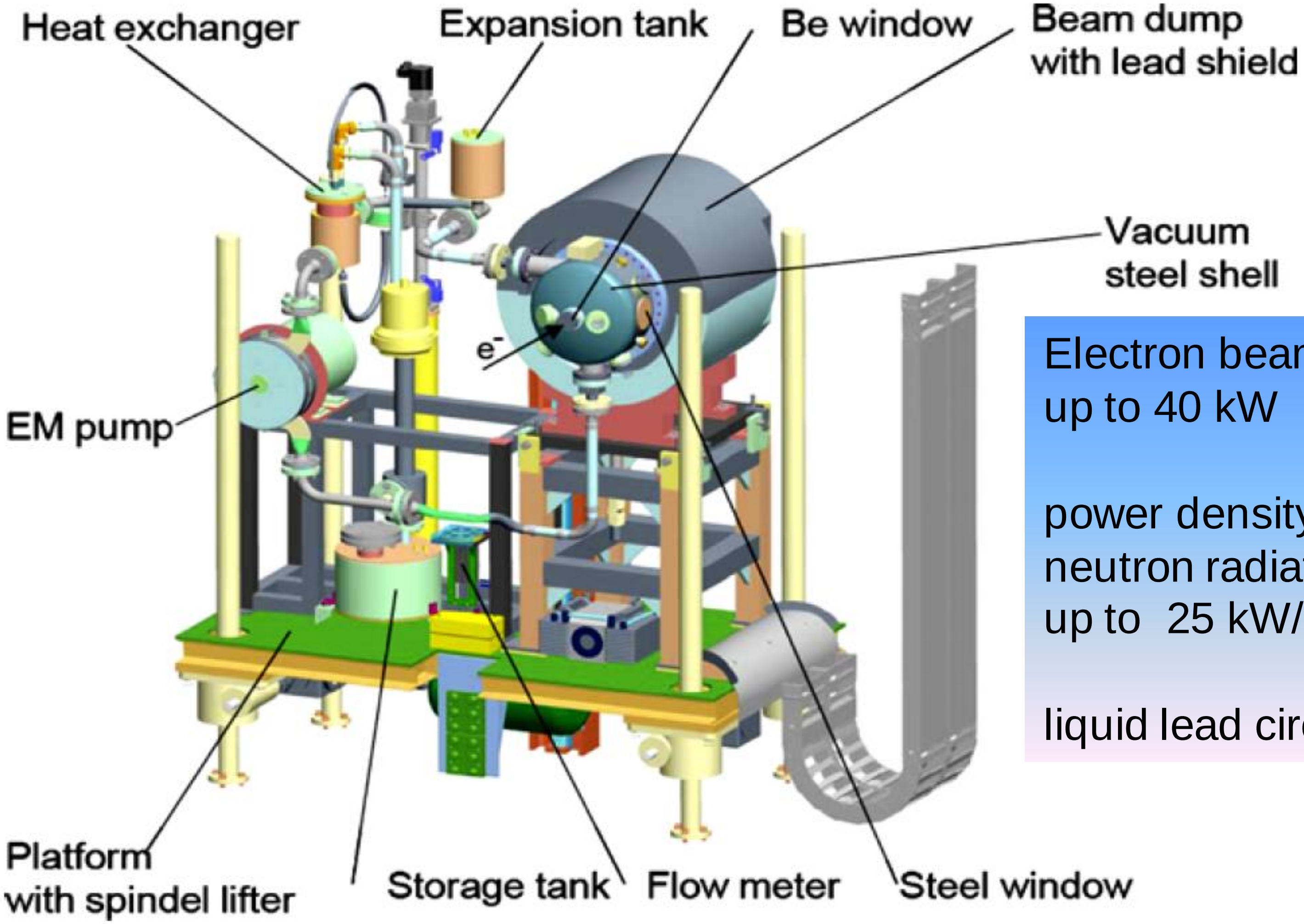
nELBE – photoneutron source

nELBE photoneutron target



Electron beam power
up to 40 kW

power density in the
neutron radiator
up to 25 kW/cm^3

liquid lead circuit for heat transport

nELBE at ELBE : something special

- superconducting electron accelerator cw operation with variable micropulse repetition rate
  - micropulse charge 80 pC (thermionic Injector)
  - micropulse length $\Delta t < 10$ ps ➔ precise definition of time of flight

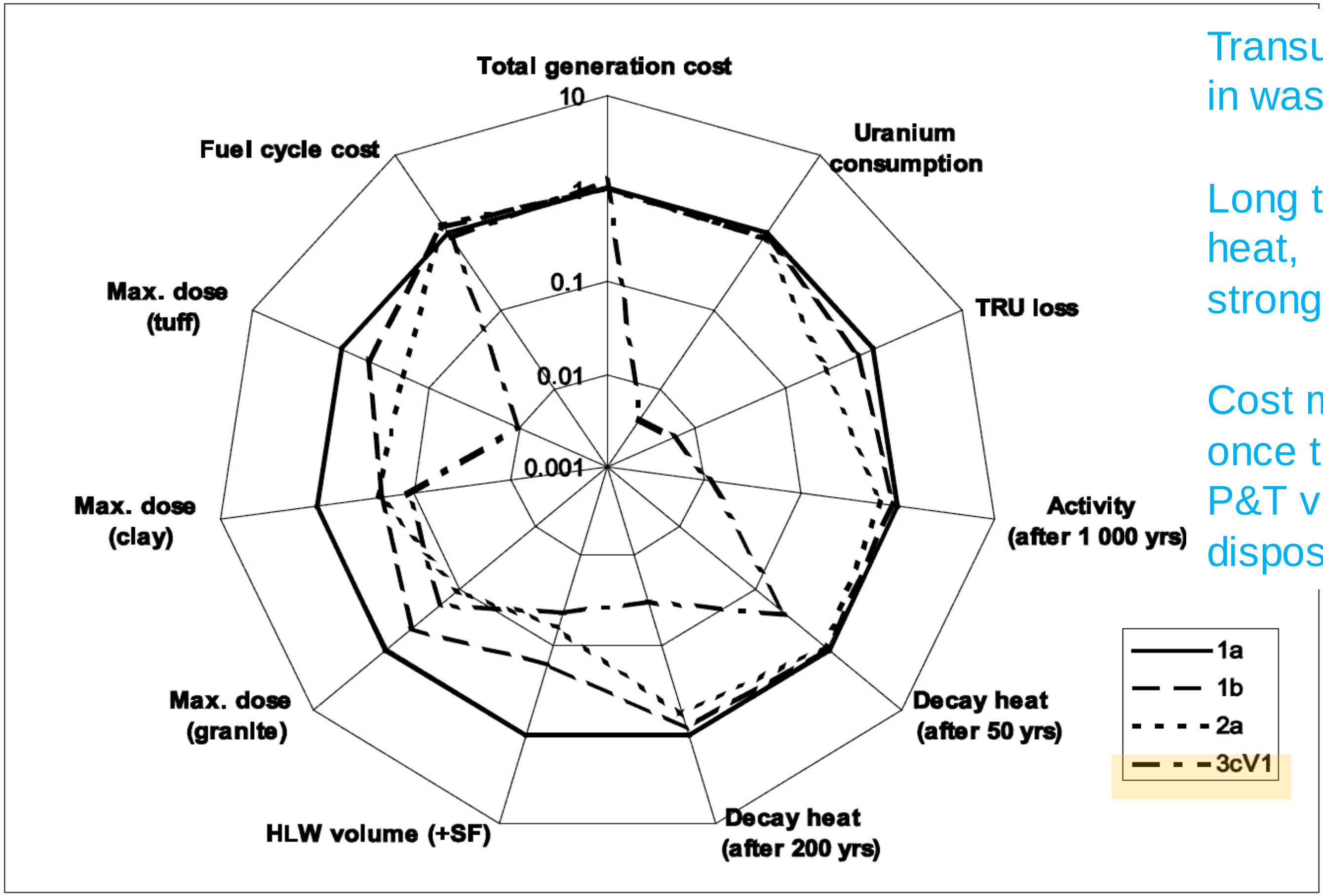
- For time of flight measurements the repetition rate is adjustable
  13 MHz / 2^n , n = 0,…,10
- Very high repetition rate (200 kHz), low instantaneous neutron-flux
  ➔ background of photon flash from bremsstrahlung is reduced

- since Januar 2010 : SRF Laser-Injector development
  bunch charge up to 1 nC (not yet reached)

• fligh path	4.0 - 8.0 m
• neutron flux on target sample	$0.8 \cdot 10^7$ cm^{-2} s^{-1}
• neutron energy range (Liquid lead target, without moderator)	100 keV < E_n < 10 MeV
• energy resolution with 6.0 m flight path	$\Delta E/E < 1$ %

Impact of Partitioning and Transmutation

Figure 3.2. Comparison of 11 representative indicators for various fuel cycle schemes



Transuranium elements in waste strongly reduced.

Long term activity, decay heat, peak dose rate strongly reduced

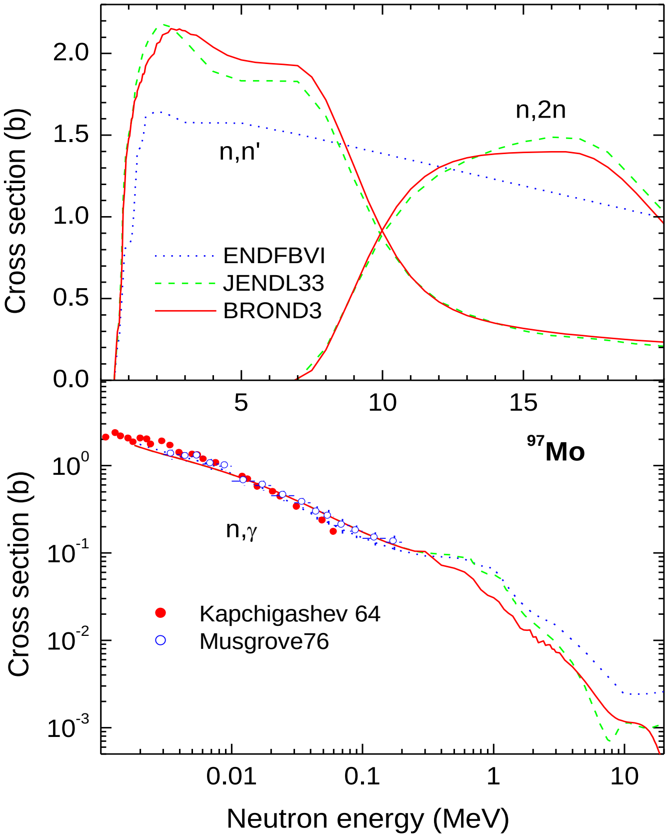
Cost might be similar to once through fuel cycle. P&T versus reduction in final disposal ?

1a: once-through PWR scheme (reference); 1b: 100% PWR, spent fuel reprocessed and Pu reused once; 2a: 100% PWR, spent fuel reprocessed and multiple reuse of Pu; 3cV1: 100% fast reactors and fully closed fuel cycle.

Source: OECD/NEA, 2006 [19], Figure 1.

http://www.oecd-nea.org/science/reports/2011/6894-benefits-impacts-advanced-fuel.pdf

nELBE research program:



A. V. Ignatyuk, priv.com. 2008

- Investigation of fast neutron induced reactions of relevance for nuclear transmutation and the development of Gen IV reactor systems

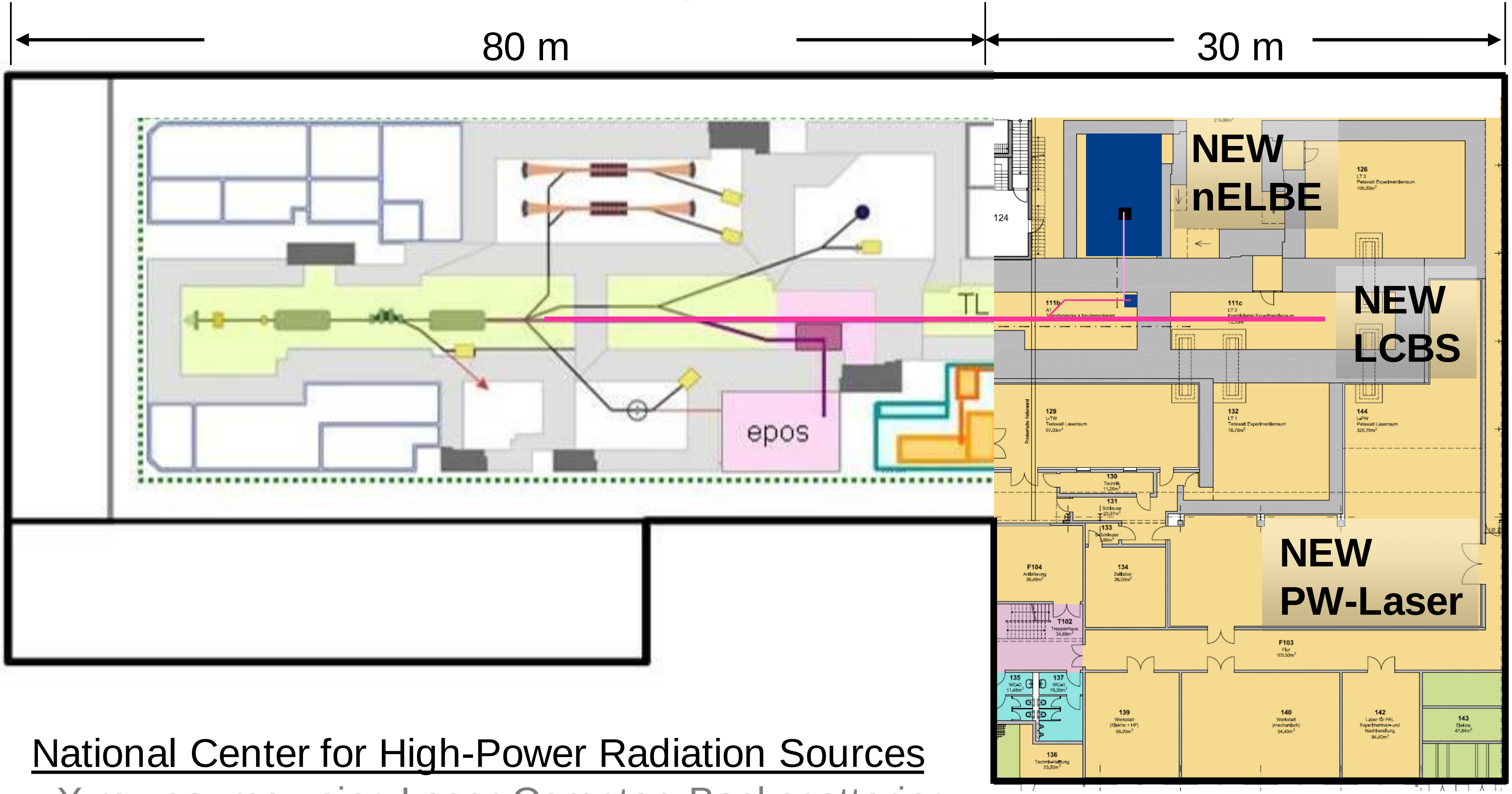
1. **Inelastic neutron scattering (n,n'γ)**
   ^{56}Fe, Mo, Pb, ^{23}Na and total neutron cross sections σ_{tot} (Ta, Au, Al, C, H)
2. **Investigation of actinides (radioactive targets)**
   Collaboration with n-TOF at CERN
   Joint research project „Nuclear physics data of relevance for transmutation“ (German Federal Ministry for Science and Technology funded , 02NUK13)

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

ERINDA
European Research Infrastructures for Nuclear Data Applications

FP7 support action, transnational access, www.erinda.org

National Center for High-Power Radiation sources



ground breaking started April 2010

National Center for High-Power Radiation Sources

- X-ray source using Laser-Compton-Backscattering
- High-Power Laser (PW) for Ion Acceleration
- New Neutron Time-of-Flight Facility for Transmutation Studies

Deutsche Akademie der Naturforscher Leopoldina/
Nationale Akademie der Wissenschaften

acatech – Deutsche Akademie der Technikwissenschaften

Berlin-Brandenburgische Akademie der Wissenschaften
(für die Union der deutschen Akademien der Wissenschaften)

Konzept für ein integriertes Energieforschungsprogramm für Deutschland

http://www.acatech.de/

Research potential

Module 1: Renewable

Modul 1: Erneuerbare Energien

Module 2: Fossile

Modul 2: Fossile Energien

Module 3: Nuclear

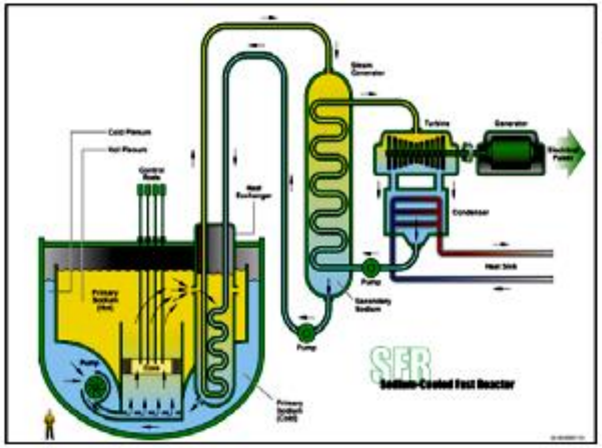
Modul 3: Kernenergie

Module 3: Nuclear power

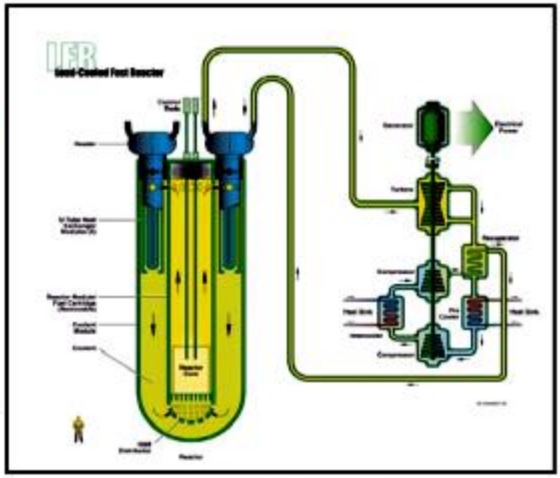
Germany has – in contrast to most other european countries – decided to abandon nuclear power. In the course of this legislation the remaining federal research funds for nuclear safety and final storage were reduced to a minimum. Even if Germany will stick to this decision and will shut down all nuclear power stations in the next ca. 15 years, a further need for research is indispensable in the fields of nuclear safety, final storage and radiation research.It is both in the common interest as well as in the national self-interest to further develop the very high german safety standards to contribute to the design, the operation and the building of future nuclear power plants elsewhere in the world.

Quelle: acatech
Konzept
für ein integriertes
Energieforschungsprogramm
für Deutschland

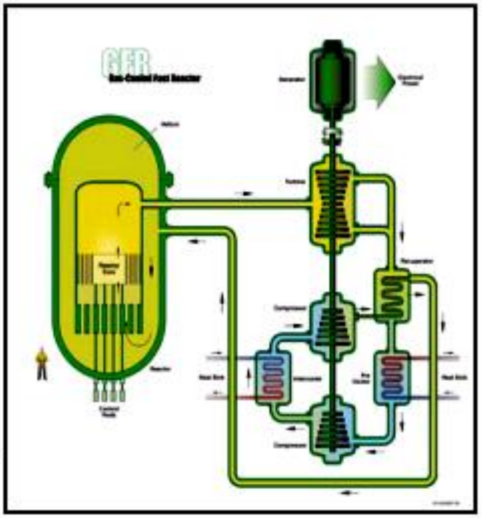
Generation IV nuclear power reactors



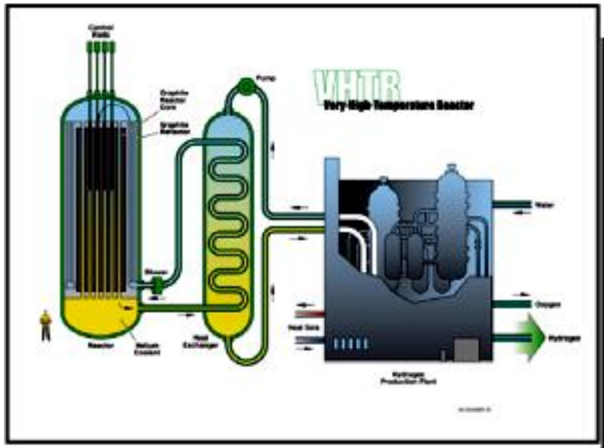
Sodium Fast Reactor



Lead Fast Reactor

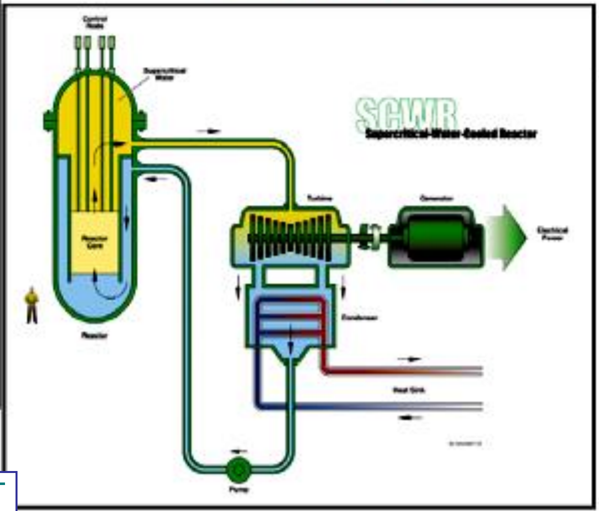


Gas Fast Reactor

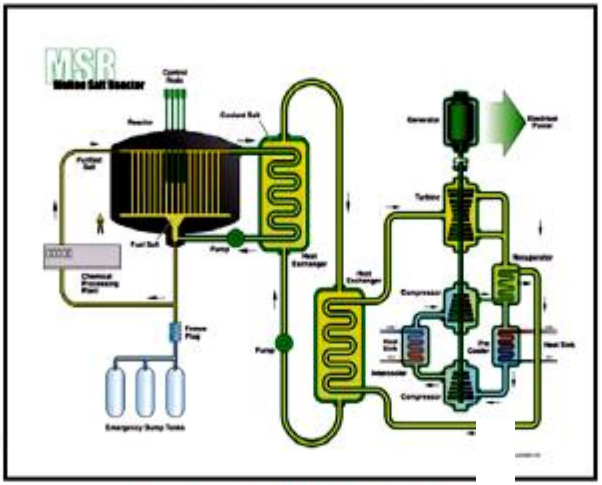


Very High Temperature Reactor

GEN IV Nuclear Energy Systems



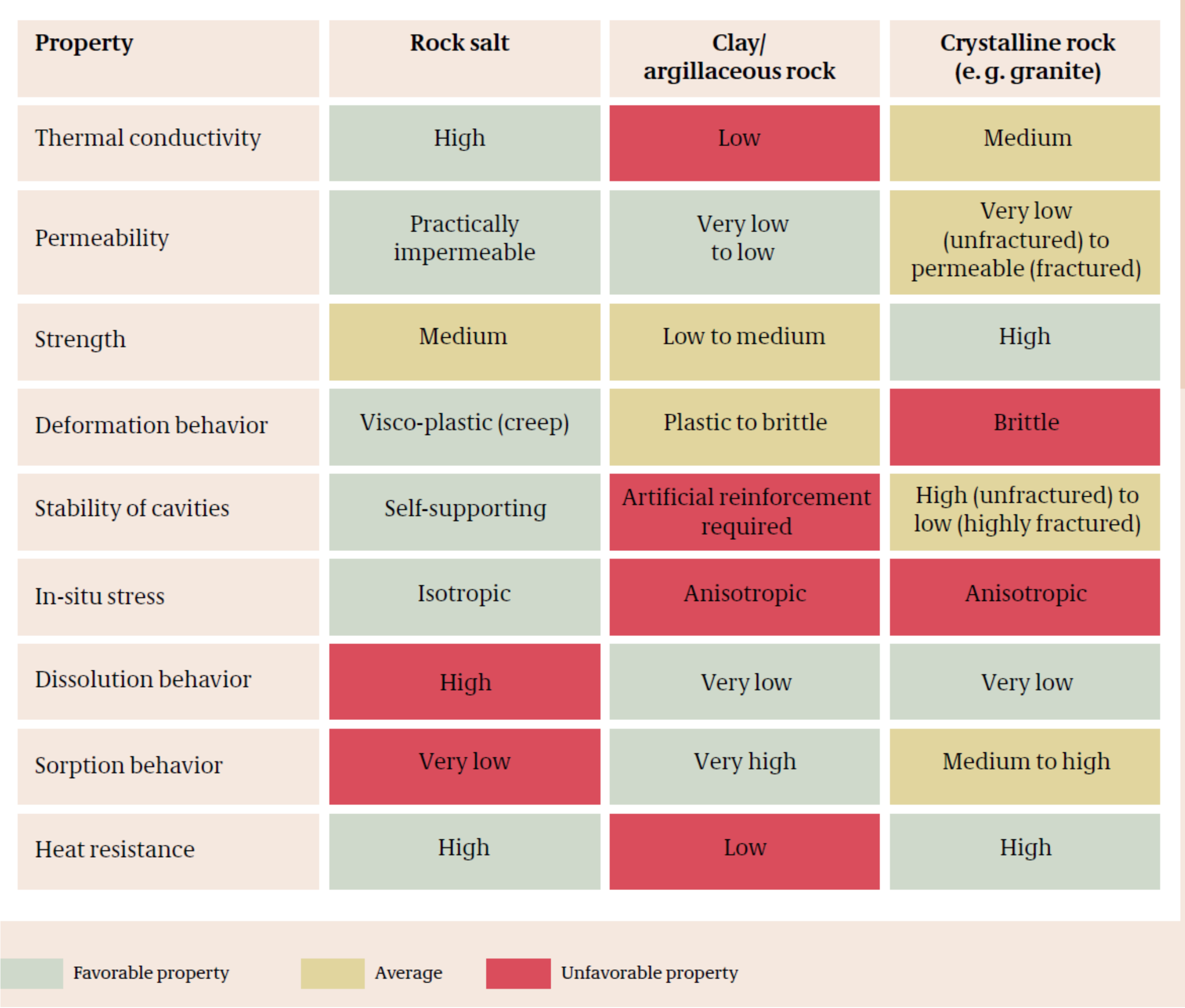
Superciritical Water Reactor



Molten Salt Reactor

concept

Comparison of host rock properties

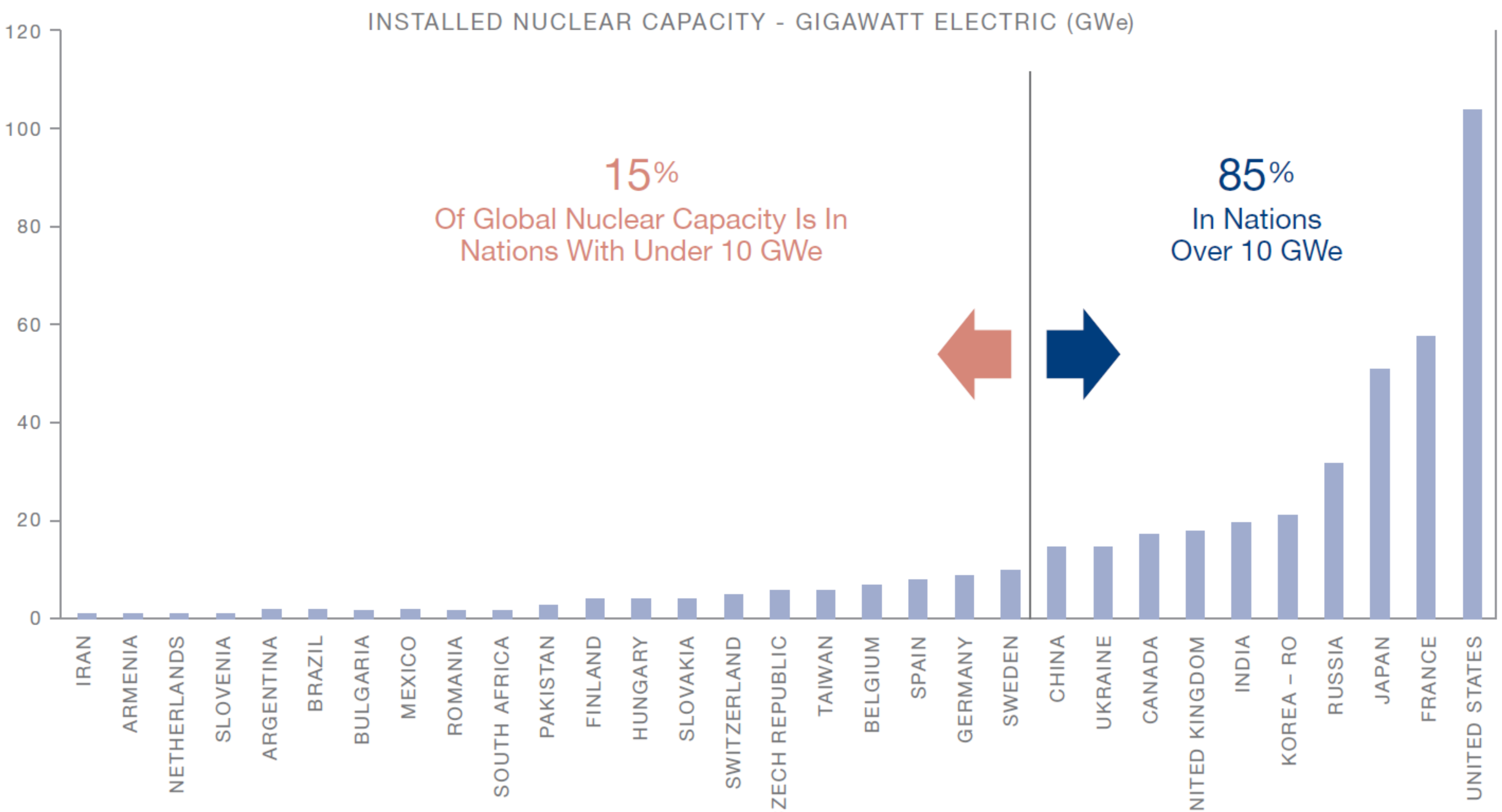


Property	**Rock salt**	**Clay/ argillaceous rock**	**Crystalline rock (e.g. granite)**
Thermal conductivity	High	Low	Medium
Permeability	Practically impermeable	Very low to low	Very low (unfractured) to permeable (fractured)
Strength	Medium	Low to medium	High
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle
Stability of cavities	Self-supporting	Artificial reinforcement required	High (unfractured) to low (highly fractured)
In-situ stress	Isotropic	Anisotropic	Anisotropic
Dissolution behavior	High	Very low	Very low
Sorption behavior	Very low	Very high	Medium to high
Heat resistance	High	Low	High

🟩 Favorable property 🟨 Average 🟥 Unfavorable property

http://www.bmwi.de/English/Redaktion/Pdf/final-disposal-of-high-level-radioactive-waste,property=pdf,bereich=bmwi,sprache=en,rwb=true.pdf

FIGURE 20. WORLDWIDE DISTRIBUTION OF CIVIL NUCLEAR ENERGY GENERATION CAPACITY IN 2010[298]



Blue Ribbon Commission on America's Nuclear Future Jan. 2012

Longer term, the United States should support the use of multi-national fuel-cycle facilities, under comprehensive IAEA safeguards, as a way to give more countries reliable access to the benefits of nuclear power while simultaneously reducing proliferation risks.

Spent Fuel Repository in Crystalline Rock

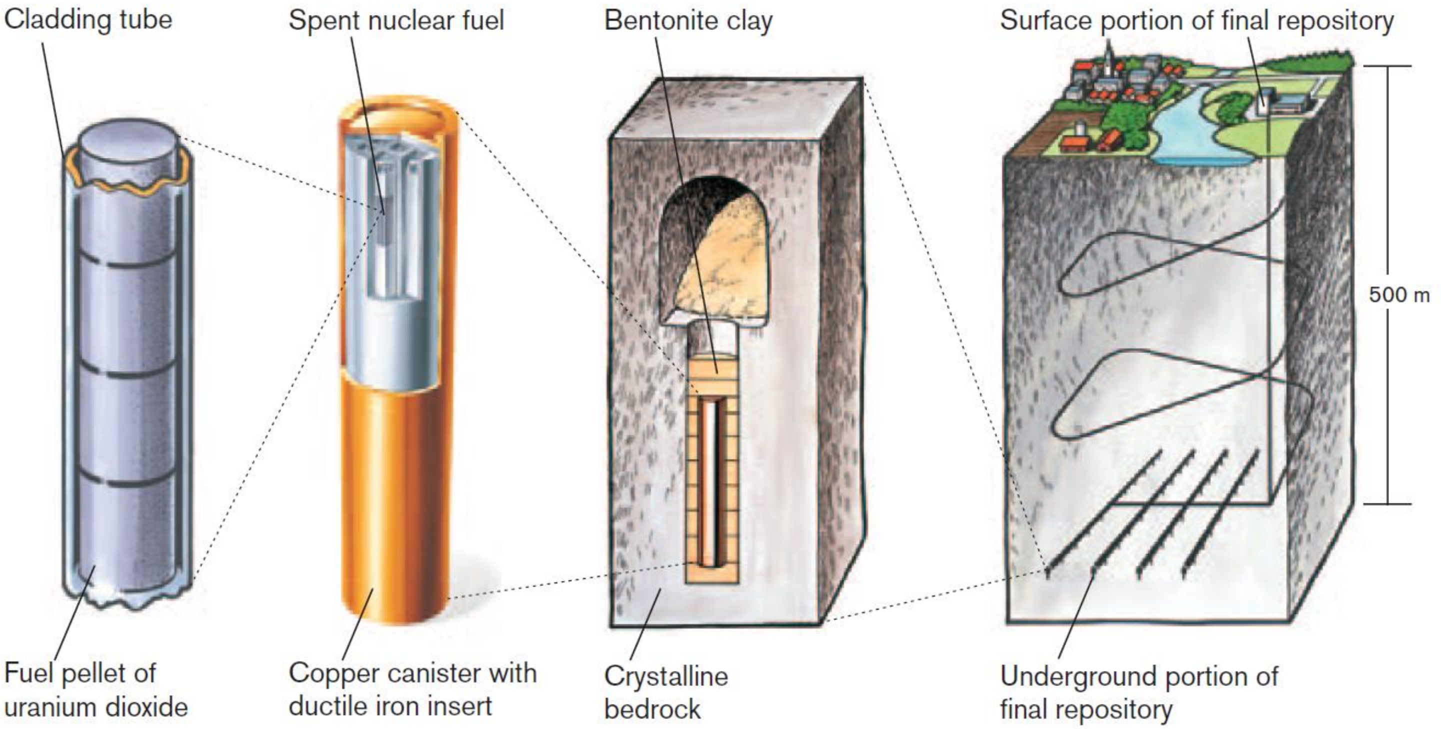


Figure S-1. *The KBS-3 concept for disposal of spent nuclear fuel.*

Final repository in Crystalline Rock (Granite)
Engineered barrier: corrosion resistant copper canister

Source:
http://www.stralsakerhetsmyndigheten.se/Global/Slutf%C3%B6rvar/KTL/KTL%203/01_vol1.pdf

Spent Fuel Repositories at Olkiluoto, Finland and Forsmark, Sweden

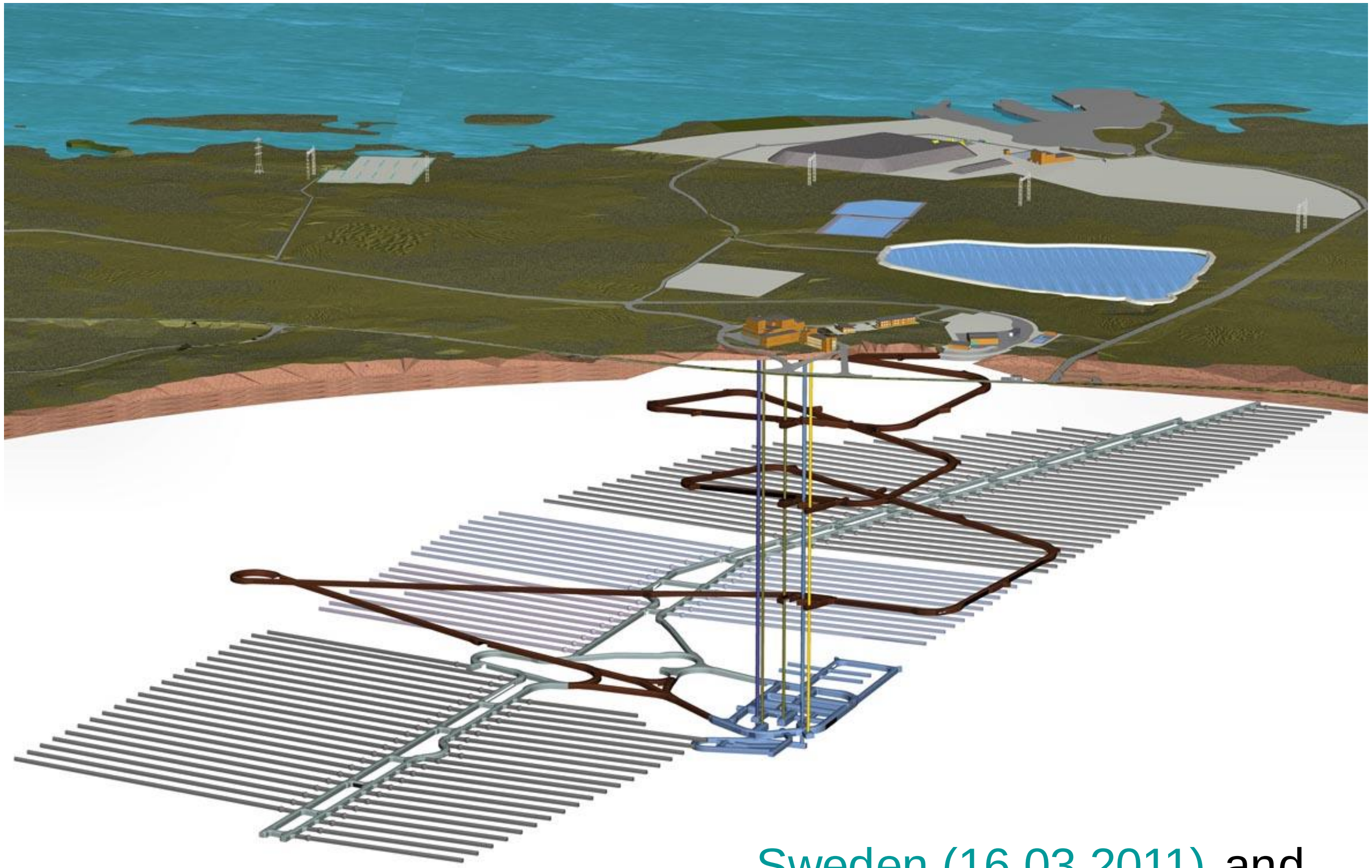


Figure: POSIVA

Sweden (16.03.2011) and
Finland (28.12.2012) submit
applications for constructions of
final repositories to the government