# E-DRIVEN SUBCRITICAL REACTORS FOR AdS STUDIES

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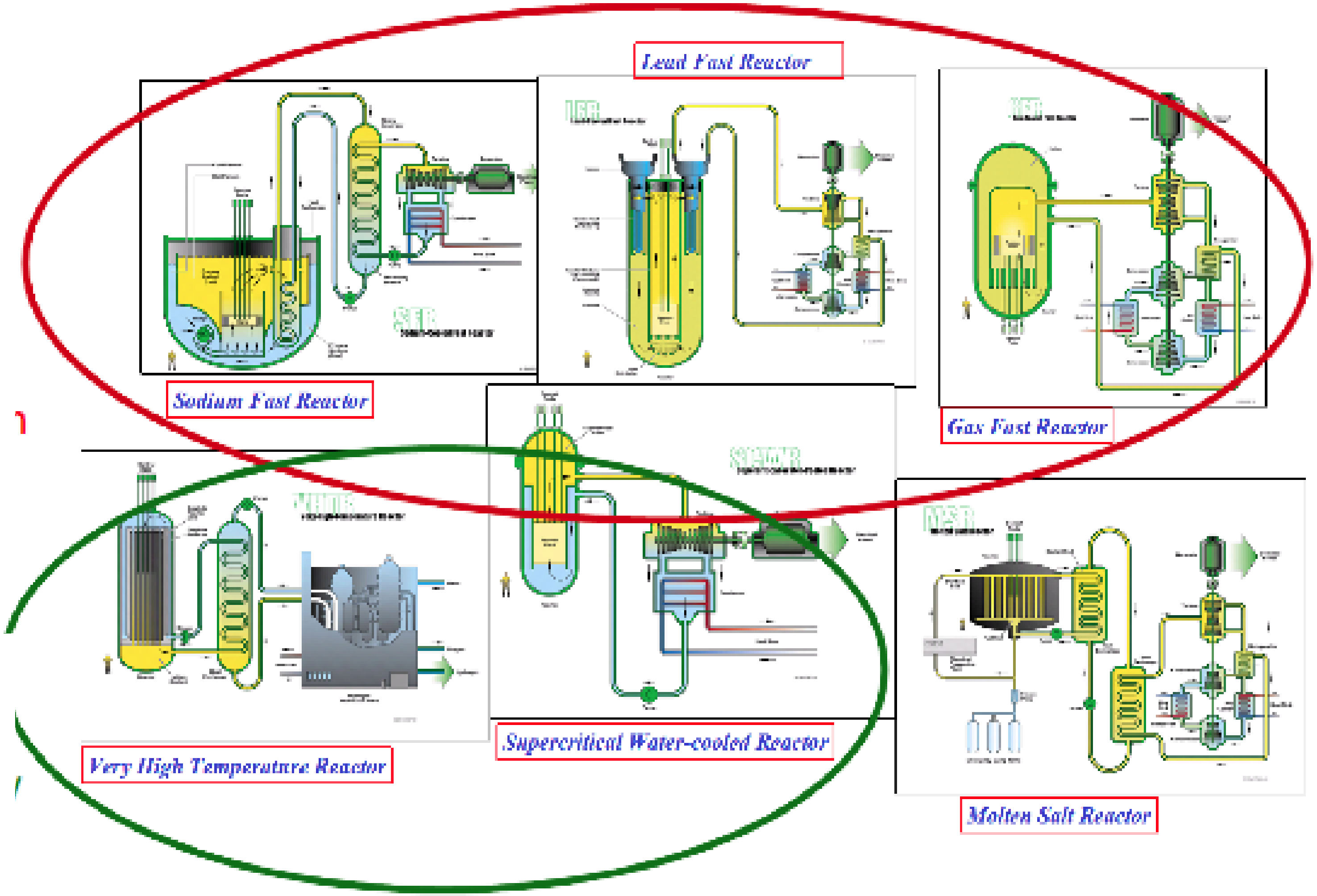
- **Nuclear Waste and IV Generation Forum**
- **Nuclear Waste treatment**
- **Subcritical vs. Critical Reactors**
- **Worlwide Activities on Accelerator-driven Systems (AdS)**
- **Issues on AdS-oriented research**
- **An electron Linac for AdS?**
- **e-Linac AdS: useful for research?**
- **Recent Activities**
- **Conclusions**


# Generation IV

Neutroni veloci
Abbattimento scorie
Uso ottimale del combustibile
Riduzione del rischio di proliferazione



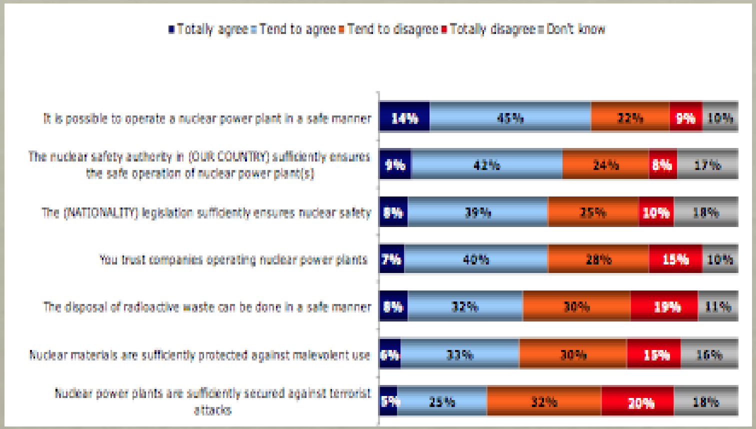

Neutroni termici
Maggiore efficienza energetica
Produzione di idrogeno

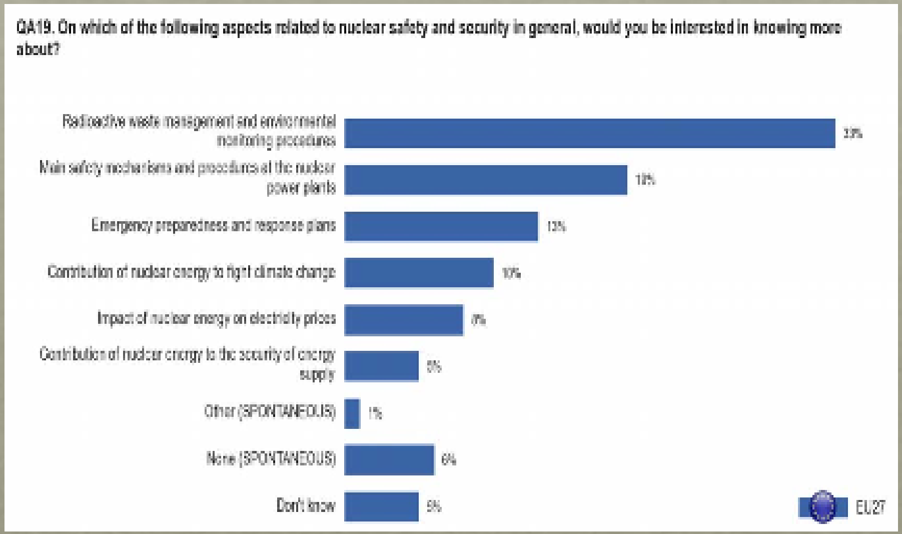
http://www.gen-4.org/GIF/

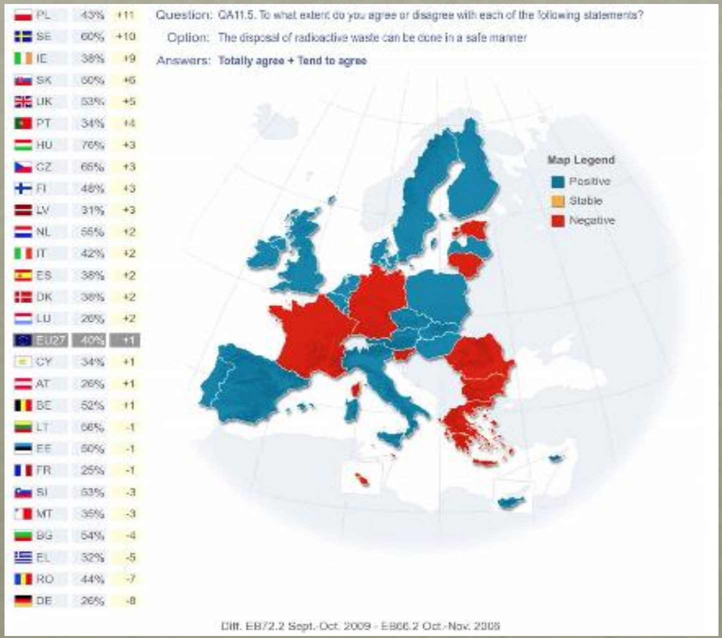
# L'opinione pubblica in Europa e il problema delle scorie nucleari e radioattive

Percepito come uno dei più gravi

Quello su cui si hanno più dubbi e si desidera più informazione




**Fonte: Special Eurobarometer 324, Marzo 2010**

# Cosa si fa ora e cosa si potrebbe fare in futuro

**Principi generali del trattamento attuale**

- Concentrare ed isolare i rifiuti in siti predisposti (non ancora pronti per gli HLW)
- Attesa fino a quando il livello di radioattività sia più gestibile (non per gli HLW)
- Diluizione e dispersione nell'ambiente (sotto la soglia regolamentata o naturale)
- Decontaminazione ambientale: metodi chimico-fisici, ancora sperimentali

**Advanced Fuel Cycle (AFC): trattamento delle scorie HLW con il metodo P&T (Partitioning & Transmutation) vs. Once-through Cycle (OTC)**

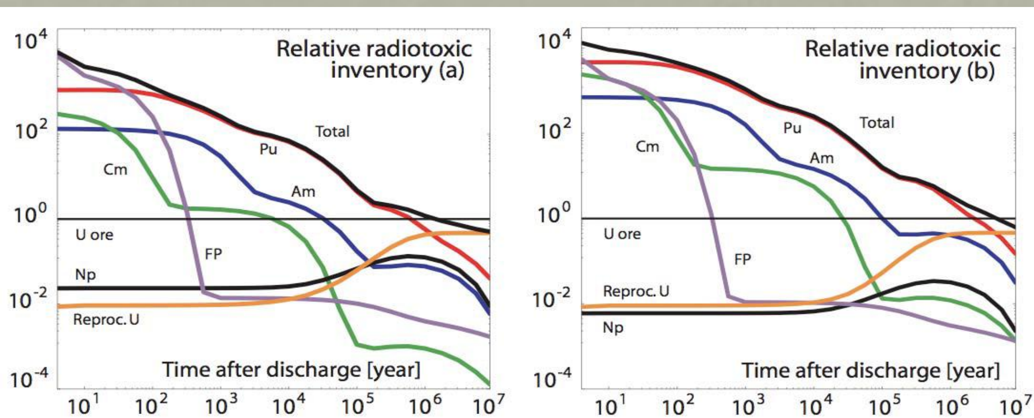
- Separare il materiale fissile (U +Pu), gli attinidi minori (MA), i prodotti di fissione (FP) con riduzione del calore di decadimento
- Avviare U +Pu al riprocessamento, oppure trasmutarli, insieme agli MA e FP, in reattori ibridi, critici o subcritici pilotati da un acceleratore di protoni (sistemi AdS, Accelerator Driven Systems)
- Ricerca da fare: riprocessamento non acquoso, combustibili avanzati, sistemi di trasmutazione

**Decontaminazione ambientale con l'uso di microorganismi e piante (Bioremediation)**

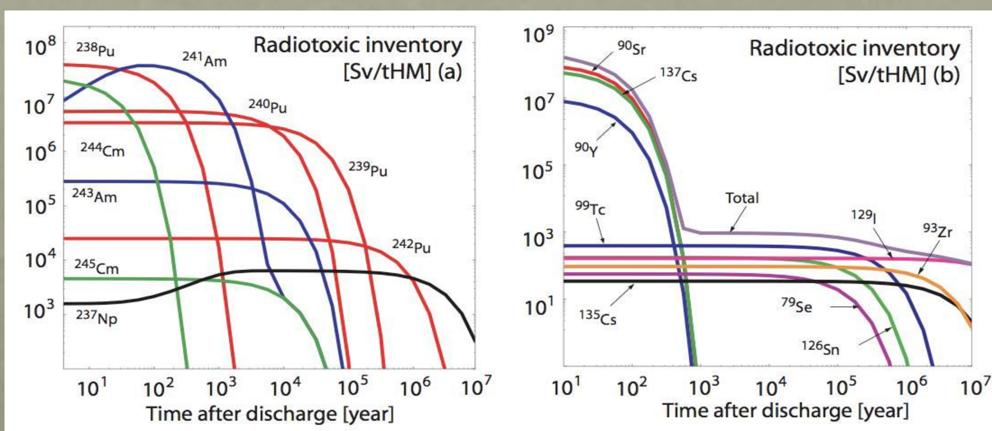
# L'INVENTARIO RADIOTOSSICOLOGICO

Dose efficace impegnata: su un'esposizione di 50 anni

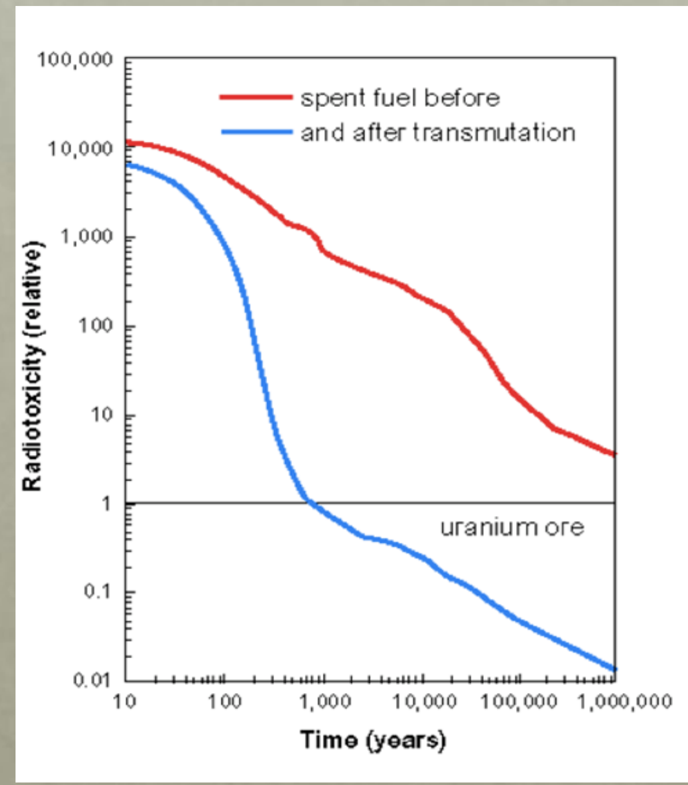
$E_{50} = \Sigma_T \, \omega_T \, H_T^{50}$




UOX: dominato dagli FP MOX: dominato dal Pu




LWR (UOX): MA +Pu FP




Radiotossicità derivante da 1 tonnellata di combustibile nucleare esausto.

Con un'efficienza di partizione del 99.9% dei prodotti a lunga vita dai rifiuti seguita da trasmutazione, il livello di radiotossicità di riferimento può essere raggiunto entro 700 anni!

(NEA Rep. 2002)

# La trasmutazione delle scorie

| Combustibile | TRU burner termico (ADS) | | TRU burner veloce (ADS) | | MA burner (ADS) | | Reattore veloce critico | |
|---|---|---|---|---|---|---|---|---|
| | ***D*** | **$\eta_{ec}$** | ***D*** | **$\eta_{ec}$** | ***D*** | **$\eta_{ec}$** | ***D*** | **$\eta_{ec}$** |
| $^{238}$U | +0.24 | 0.92 | -0.64 | 1.28 | -0.64 | 1.28 | -0.85 | 1.41 |
| Pu | -0.40 | 1.15 | -1.34 | 1.80 | -1.28 | 1.74 | -1.53 | 2.03 |
| MA | +0.37 | 0.89 | -0.86 | 1.37 | -0.79 | 1.33 | -1.10 | 1.52 |
| TRU | -0.30 | 1.11 | -1.29 | 1.75 | -1.23 | 1.69 | -1.48 | 1.96 |

Confronto fra varii AdS e reattore critico
Consumo neutronico D (<0 eccesso)
Bilancio neutronico $\eta_{ec}$ (<1 insuff.)

Reattori termici critici
LWR, PWR, BWR
HWR, CANDU
Adatti per OTC
Riduzione del Pu; però:
Pochi neutroni ritardati⇒
Reattori piú instabili
Piú MA prodotti
Alti flussi $10^{16}$ n/cm$^2$/sec necessari
Aumento dell'inventario radiotossicologico!
Costi elevati!

Reattori veloci critici
BN-600, Phénix
Superphénix
Adatti per AFC
Efficienti per Pu e Am ma non per Cm e Cf difficili da trattare
Minore produzione di MA
Costosi (Pu) e problematici (Na raffr.)
Pb-cooling
Grandi volumi di combustibile necessari

Reattori ADS subcritici
Acceleratori-driven Systems
Utilizzano qualsiasi tipo di combustibile nucleare
Elevata efficienza e flessibilità e soprattutto Sicurezza!
CW proton Accelerator: 0.6 – 1 GeV, 4-25 mA, beamtrip max 1/250 hrs$^{-1}$
Spallation Source: LBE or ML target con/senza finestra
Subcritical systems: $k_{eff}$ = 0.95 - 0.98
ML or LBE cooling, MA fuel design,
Potenza 100 – 3000 $MW_{th}$
Flusso totale 1- 5 × $10^{15}$ n/sec/cm$^2$

# Efficienza dei reattori veloci

**Thermal** vs. **Fast**

Thermal:
- ↑ fission in fissile
- ↓ capture in fertile

Fast:
- ↑ fission in fissile ↓ fissile to fertile concentratior
- ↑ fission/capture and neutron multiplicity

| Isotope | $^{235}U$ | | $^{239}Pu$ | | $^{233}U$ | |
|---|---|---|---|---|---|---|
| Spectrum | Thermal | Fast | Thermal | Fast | Thermal | Fast |
| $\sigma_f$ (barn) | 582 | 1.81 | 743 | 1.76 | 531 | 2.79 |
| $\sigma_c$ (barn) | 101 | 0.52 | 270 | 0.46 | 46 | 0.33 |
| $\alpha=\sigma_c/\sigma_f$ | 0.17 | 0.29 | 0.36 | 0.26 | 0.09 | 0.12 |
| ν | 2.42 | 2.43 | 2.87 | 2.94 | 2.49 | 2.53 |
| $\eta=\nu\sigma_f/\sigma_a$ Neutron Multiplicity | 2.07 | 1.88 | 2.11 | 2.33 | 2.29 | 2.27 |
| $\beta_{eff}$ (pcm) | 650 | | 210 | | 280 | |

| | Thermal | Fast |
|---|---|---|
| Isotope | $\alpha = \sigma_c / \sigma_f$ | |
| $^{235}U$ | 0.22 | 0.29 |
| $^{238}U$ | 8.3 | 7.5 |
| $^{239}Pu$ | 0.58 | 0.3 |
| $^{240}Pu$ | 396.6 | 1.6 |
| $^{241}Pu$ | 0.40 | 0.19 |
| $^{242}Pu$ | 65.5 | 1.8 |
| $^{237}Np$ | 63 | 5.3 |
| $^{241}Am$ | 100 | 7.4 |
| $^{243}Am$ | 111 | 8.6 |
| $^{244}Cm$ | 16 | 1.4 |
| $^{245}Cm$ | 0.15 | 0.18 |

# WORLDWIDE ACTIVITIES ON ACCELERATOR-DRIVEN SYSTEMS

**CHINA:** high current injector, RFQ acc. Structure, zero–power subcritical assembly VENUS1

**INDIA:** maximize fissile resources through the use of Thorium. Design studies for a 1 GeV, 30 mA p-Linac, LBE expt. loop for target design, development of SC technology and computational tools for neutronics simulation of coupled systems

**JAPAN:** J-PARC linac up to 400 MeV and 50 mA p-beams. Two facilities:
TEF-P, a zero-power subcritical assembly driven by a 10 W p-beam
TEF-T, irradiation test cupled to a 200 kW LBE spallation target
Design study of a 30 MW SC proton Linac for 800 MWth AdS

**EUROPE:** MYRRHA
(Multipurpose hYbrid Research Reactor for Hitech Applications c/o SCK-CEN (B)
Large infrastructure to be used for next 40 years
But slowly progressing, lack of funding

| Application | Requirements |
|---|---|
| ADS demonstration | 50 to 100 $MW_{th}$ |
| Efficient transmutation studies | $\Phi_{Fast}$ = ~$10^{15}$ n/cm²s, ($E_n$>0.75 MeV) |
| Material research | $\Phi_{Fast}$ = 1.0 to $5.0\times10^{14}$ n/cm²s, ($E_n$>1 MeV) in large volumes |
| Material research for fusion | $\Phi$ = 1.0 to $5.0\times10^{14}$ n/cm²s, (ppm He/dpa ~ 10) in medium-large volumes |
| Fuel research | $\Phi_{tot}$ = 0.5 to $1.0\times10^{15}$ n/cm²s |
| Productionof radioisotopes | $\Phi_{th}$ = 0.5 to $2.0\times10^{15}$ n/cm²s, ($E_n$<0.4 eV) |
| Si Doping | $\Phi_{th}$ = 0.1 to $1.0\times10^{14}$ n/cm²s, ($E_n$<0.4 eV) |

# A low power ADS based on enriched U fuel and solid Lead

Courtesy of M. Ripani, INFN

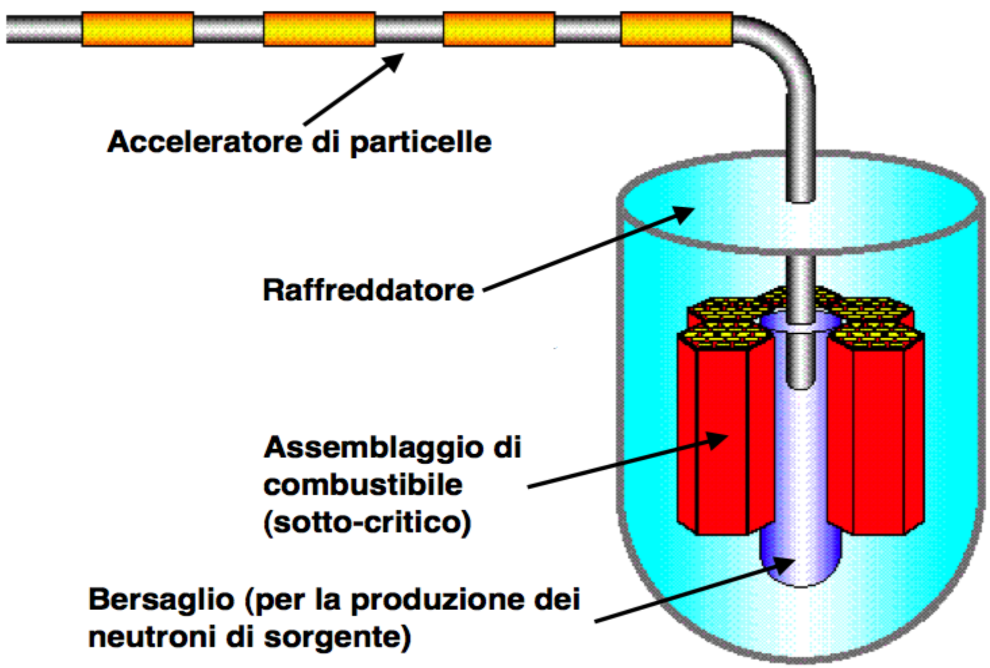
Motivation

- Availability of 70 MeV, 0.5 mA proton cyclotron purchased by INFN as driver for SPES project on radioactive ion beams
- Collaboration with Ansaldo Nucleare, leader in technology for fast reactors based on Lead coolant (also, one of the proposed technologies in the EU)
- Choice of Pu-free fuel to minimize security issues → $UO_2$ w/ 20 % $^{235}U$
- Low thermal power 150-200 kW to limit safety issues but sufficient to study some aspects of dynamics
- Temperature < 300 $C^o$ → solid Lead matrix
- $k_{eff} \sim 0.95$ (limit for storage facil's)
- Relatively low beam energy → Target: Beryllium (weakly bound n)

**Broad collaboration between INFN, Ansaldo Nucleare, ENEA, Politecnico di Milano, Politecnico di Torino, LENA-Pavia**

Project initiatied by G. Ricco, INFN and University of Genova

Core design by C.M. Viberti, fellowship INFN Genova



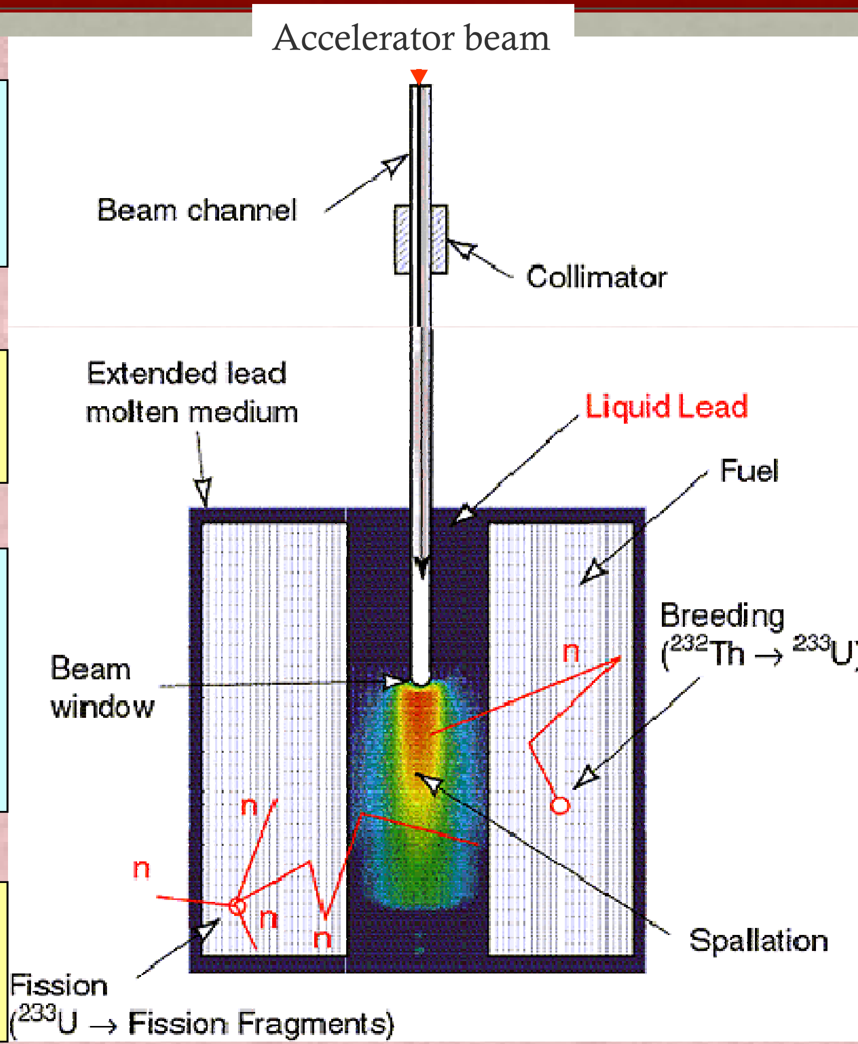
# ISSUES ON AdS-ORIENTED RESEARCH

**ACCELERATOR**
- High Intensity
- Reliability
- Stability
- Efficiency
- Activation

**HEAT REMOVAL**
- Heat Transfer
- Thermal cycling
- Coolant

**TARGET MODULE**
- Thermal hydraulics
- Materials compatibility
- Window thermal stresses
- Radiation effects
- Maintainability

**LIQUID METAL**
- Corrosion and erosion
- Online instrumentation




**BEAM TRANSPORT**
- Losses
- Monitoring
- Expansion

**SHIELDING**

High energy particles

**FUEL TYPE & FORM**
- Composition
- Fabrication
- Reprocessing

**SUB-CRITICAL CORE**
- Neutronic Kinetics
- Performance
- Subcriticality Monitoring
- Fuel integrity

from P.K. Nema et al., ADS/INT-03, IAEA, Vienna (2009)

# E-Linac Assets for AdS

RF Electron Linacs :

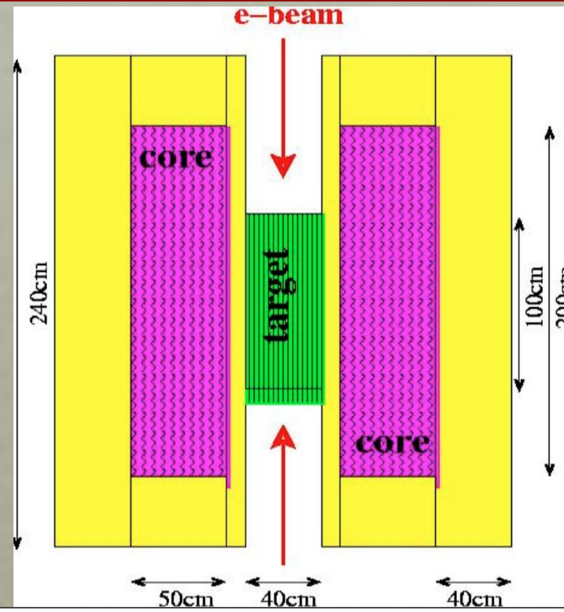
- Photonuclear and photofission neutrons
- Yield/beam power second only to proton spallation
- Robust technology
- Flexible output characteristics
- Inexpensive and “small,” transportable
- Evaporation neutron spectrum, similar to spallation source, but less high energy tail

# Subcritical, e-driven reactors

D. Ridikas et al., CEA, 2002

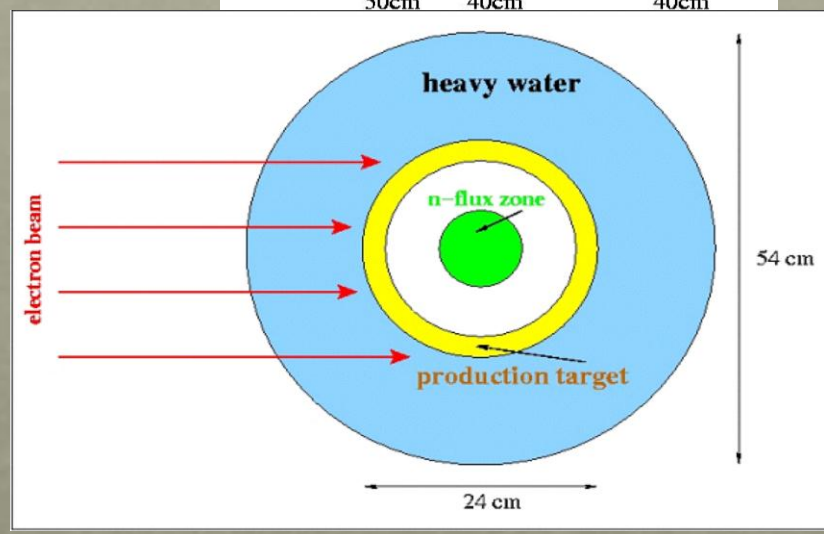
Low # of delayed neutrons => Beta compensated Reactor (BCR) based on GT-MHR He-cooled

Reactor power (density), MWth (W/cm3) 50 (14.5)
Multiplication coefficient **$k_{eff}$ 0.995 ÷ 0.997**
Neutron multiplication 200
Electron energy, MeV 250
Beam current (power), mA (MW) 2 x 10 (2 x 2.5)
Neutron yield, n/e- 0.15
External neutrons, n/s $1.88 \cdot 10^{16}$
Total neutrons, n/s $3.76 \cdot 10^{18}$
Total fissions, fiss/s $1.56 \cdot 10^{18}$
Neutron flux in the core, n/s cm2 $2.2 \cdot 10^{14}$




Very difficult: subcriticality level, flux measurement, accelerator cost, feedback with control rods… A lot of R&D required!

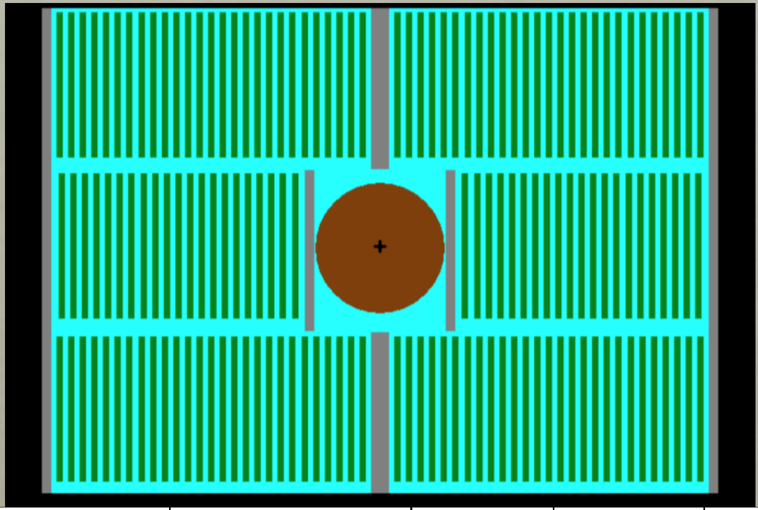
Spherical geometry, n-flux zone 5 cm radius
Heavy-water thermalization
Multiplication coefficient **$k_{eff}$ 0.80**
No need for U-target enrichment (< 20%) to get neutron flux in the core, n/s/cm² $\approx 10^{14}$
Electron energy, MeV 100÷200
Beam current (power), mA (MW) 80 (8)
External neutrons, n/s $2.8 \cdot 10^{16}$
Total neutrons, n/s $3.0 \cdot 10^{16}$
Power density in target, kW/cm³ $0.5 \pm 1.5$




Small geometry
Cooling difficult
Big accelerator
Not cost-Effective!

# E-Linac Based Research Reactor

- Standard design
- Classical lattice structure
- Low enrichment < 20% U-Al fuel
- $k_{eff}$ <0.98
- Water-cooled with graphite reflector
- Electron beam power ≈100kW
- Total $P_{th}$ ≈ 300 kW with U-target



Parameters for RACE subcritical assembly with $E_b$ =25 MeV, $\langle I_b \rangle$ = 1 mA

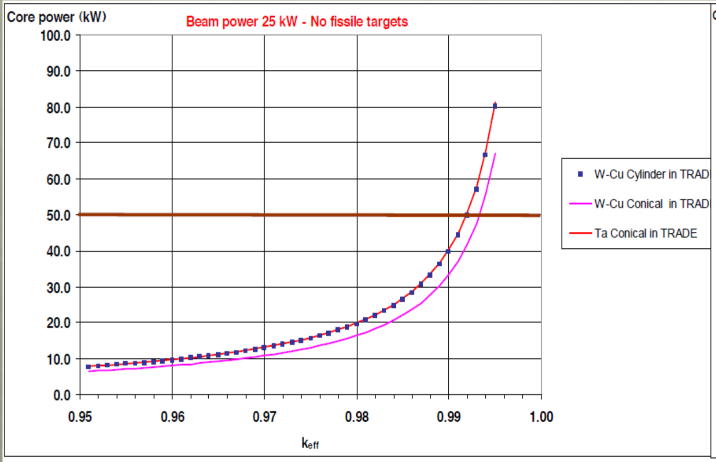
| Target type | Tantalum Conical | Uranium cylinder | Uranium Conical | Uranium Hollow Cylinder |
|---|---|---|---|---|
| Target neutron yield $\gamma_t$ (n/e) | 4.69E-03 | 1.09E-02 | 1.10E-02 | 1.09E-02 |
| Core (γ,n) contribution $\varepsilon_c$ | 0.16[a] | 0.07[a] | 0.07[a] | 0.07[a] |
| Total neutron yield $\gamma_t \cdot (1+\varepsilon_c)$ (n/e) | 5.44E-03 | 1.16E-02 | 1.17E-02 | 1.17E-02 |
| $k_{eff}$ | 0.97875 | 0.97875 | 0.97875 | 0.97875 |
| $\rho_{eff}$ (pcm) | -2171 | -2171 | -2171 | -2171 |
| Φ* | 0.94 | 1.05 | 1.05 | 1.05 |
| $\rho_s$ (pcm) | -2310 | -2068 | -2068 | -2068 |
| <S> (n/s) | 3.40E+13 | 7.26E+13 | 7.34E+13 | 7.29E+13 |
| $g=\gamma_t \cdot (1+\varepsilon_c) \cdot \varphi^*$ | 5.11E-03 | 1.22E-02 | 1.23E-02 | 1.23E-02 |
| P reactor power (kW) | 18.81 | 44.91 | 45.39 | 45.09 |
| G | 0.75 | 1.80 | 1.82 | 1.80 |

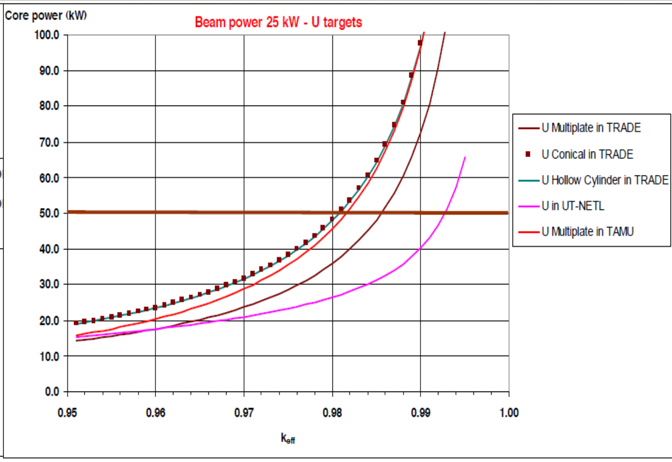
# Reactor-Accelerator Coupling Experiments (RACE)

As a part of US DoE AFCI (Advanced Fuel Cycle Initiative)
Series of ADSS experiments meant as a bridge between european MUSE (Cadarache) and TRADE (Casaccia) programs
Started in 2004

| Project | Source | Source Strength (n/s) | Energy (MeV) | Source Characteristics | Reactor Type | Reactor Power | Cost ($M) |
|---|---|---|---|---|---|---|---|
| MUSE | DD and DT Accelerator | $10^8$ | 2.45 and/or 14.1 | Mono-energetic, anistotropic, point, pulsed | Fast | Zero | ~60 |
| TRADE | DT Accelerator and Proton Cyclotron | $10^{15}$ | Up to 140 | Mono-energetic, anistotropic, point, pulsed | TRIGA | 200 kWth | ~90 |
| RACE | Electron Linac (photo-neutron) | $10^{12}$ | Up to 40 | Fission spectrum with small tail, anistotropic, asymetric, volumetric, pulsed | ISU ADS & two Texas TRIGAs | 1 MWth (pulse to 1 GWth) | 2.6 |

Comparison between TRIGA e-coupled (RACE) and TRIGA p-coupled (TRADE)
Dynamic response,
Energetic gain
Thermal reactivity feedback for various targets

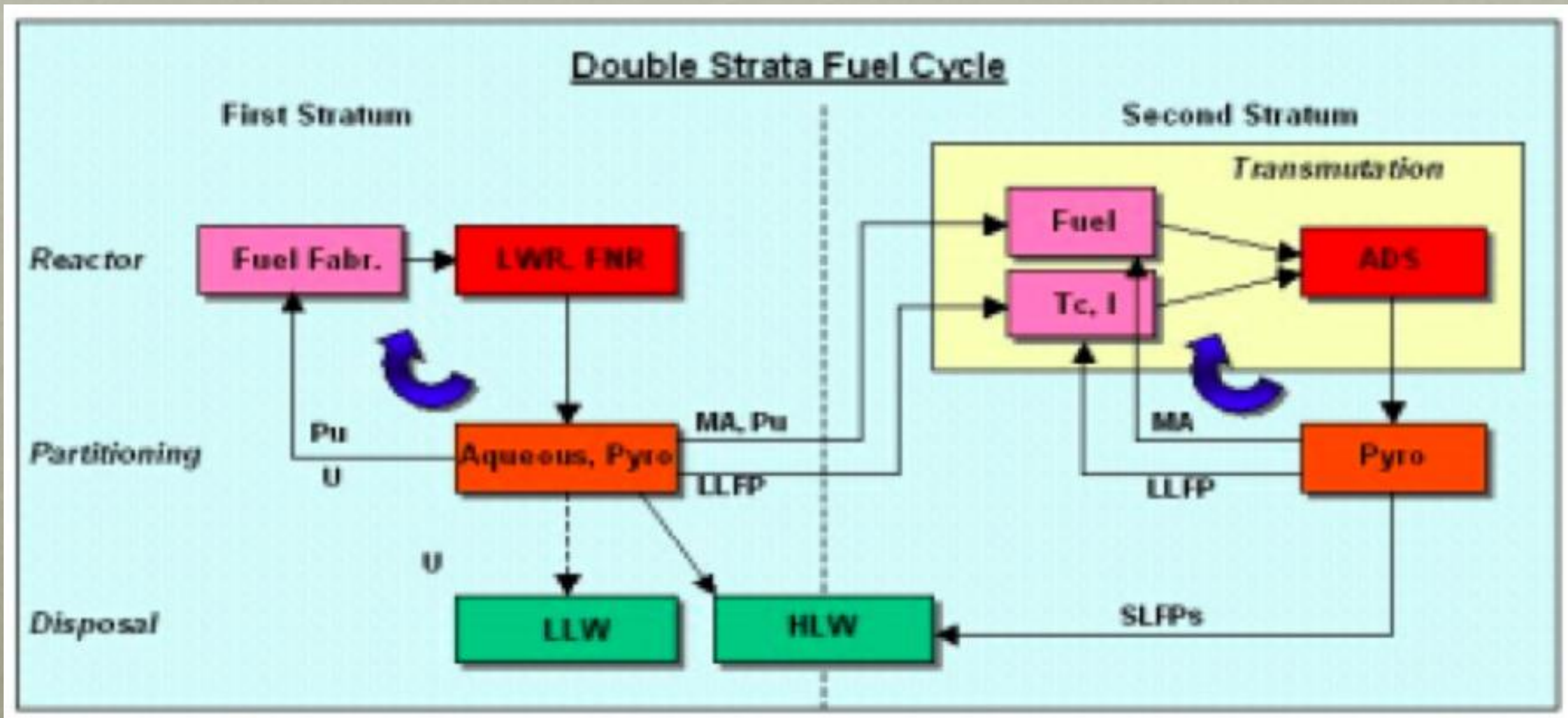


# Conclusions

- An operating electron-driven AdS doesn't appear a viable option for P&T strategies
- An e-driven 'classical' research reactor for AdS studies is however quite feasible, also because of its broad potentiality in other research fields (ultracold neutrons ?)
- Measurements of coupling efficiency, reactivity, multiplication, source-driven transients, importance of driving neutron sources for subcritical assemblies, development of benchmarks, testing of computer codes etc are typical research goals for AdS.
- Neutron producing target might be the only 'critical' point for such a reactor
- IRIDE medium power CW Linac seems a good candidate for the e-driver also in view of non-parasitic simultaneous operation with FEL physics
- Infrastructure, shielding and licensing (not to mention funding) are clearly the most severe challenges (….we're in Italy!)

Thanks for your attention!


Double Strata Fuel Cycle
First Stratum
Second Stratum
Transmutation
Reactor
Fuel Fabr.
LWR, FNR
Fuel
Tc, I
ADS
Pu
MA, Pu
MA
Partitioning
Aqueous, Pyro
Pyro
U
LLFP
LLFP
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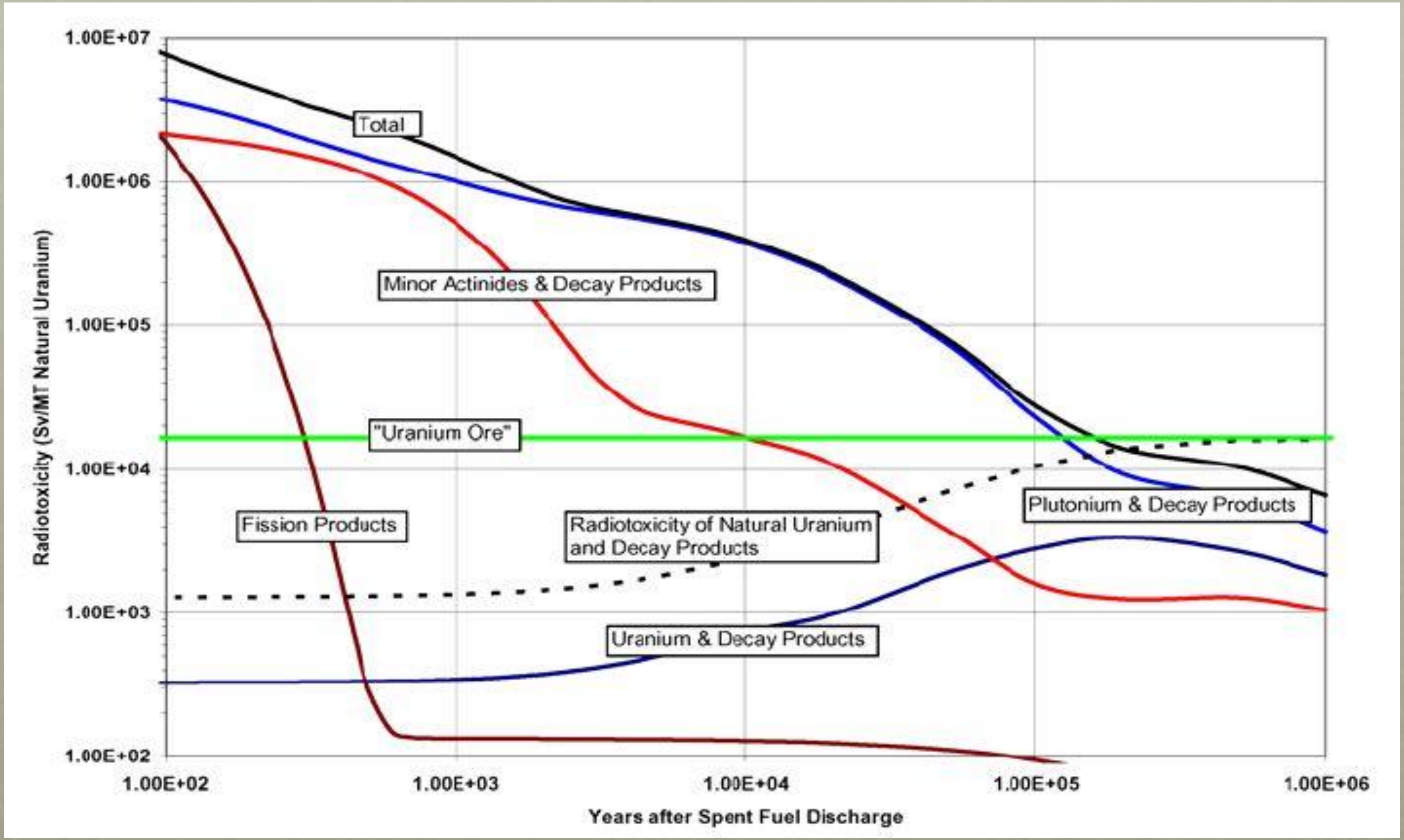
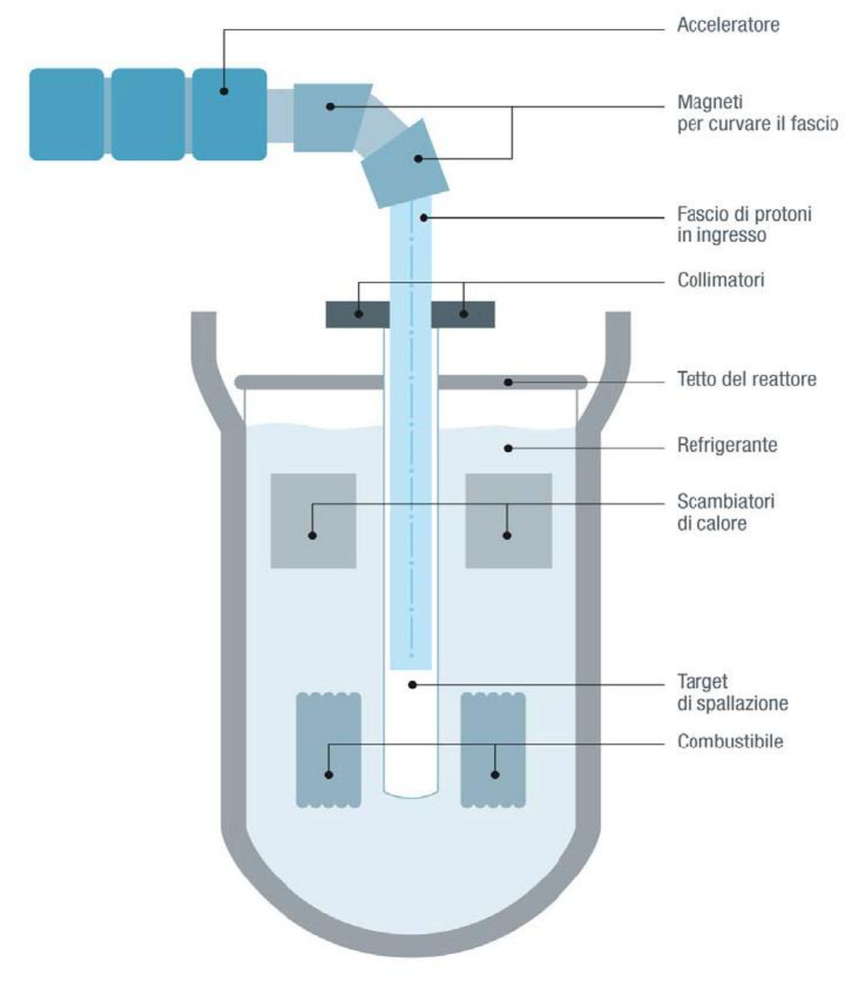
Disposal
LLW
HLW
SLFPs




**Radiotoxicity of spent nuclear fuel as a function of time**

*Source: Physics & Safety of Transmutation Systems , NEA 6090*

# La trasmutazione delle scorie HLW: i sistemi ADS




Schema di principio di un ADS

Reattori ADS subcritici

Utilizzano qualsiasi tipo di combustibile nucleare

Elevata efficienza, estrema sicurezza

Amplificatore di energia (Rubbia)

Però ancora molta ricerca da fare:

- Acceleratore
- Bersaglio neutronico
- Combustibile e suo ciclo
- Reattore subcritico

**Unico progetto europeo: MYRRHA in sviluppo presso SCK-CEN a Mol (Belgio). Partito nel 1997 ==> 2018-2023**

**Costo previsto ≈ 1 G€ di cui contributo UE < 10%**

| | FPVI 2001-2006 | FPVII 2007-2012 |
|---|---|---|
| Fusione Nucleare | 824 | 1947 |
| Fissione Nucleare | 209 | 287 |
| centri (JRC) | 319 | 517 |
| Totale M€ | 1352 | 2751 |

# PERCHÈ ANCORA IL NUCLEARE ?

- Necessità di abbattere le emissioni di $CO_2$, di diversificare le fonti energetiche e la dipendenza dall'estero

- I paesi in possesso della tecnologia nucleare sono caratterizzati da un forte senso dell'identità nazionale.

- Il ritorno al nucleare impone anche una ripresa dell'attività di ricerca e di produzione di dati nucleari su base nazionale, non limitata alle collaborazioni internazionali, in modo da recuperare quel know-how che è andato perduto negli anni.

- L'uso militare della tecnologia nucleare appare una prospettiva allettante per molti ex-paesi del terzo mondo, evidentemente desiderosi di assicurarsi l'intangibilità da parte di superpotenze (*le pouvoir rationalisant du nucleaire…C. De Gaulle)*

- Insomma, il nucleare è un po' come… il profumo per le signore:

**it is a pity that it is needed and a good that we have it! (H. Blix, ex-ispettore capo IAEA)**

Economicità (costi inferiori alle altre fonti energetiche e basso rischio finanziario)
Sicurezza aumentata (generazione III+) e affidabilità
Sostenibilità (efficienza d'utilizzo del combustibile e minimizzazione delle scorie) Resistenza alla proliferazione e protezione fisica
Sono concepite per rispondere alle necessità di un ampio spettro di nazioni e di utenti.
Criteri regionali per chiusura del ciclo del combustibile nucleare

| System | Neutron Spectrum | Fuel Cycle | Size (MWe) | Applications | R&D Needed |
|---|---|---|---|---|---|
| Very-High-Temperature Reactor (VHTR) | Thermal | Open | 250 | Electricity, Hydrogen, Process Heat | Fuels, Materials, $H_2$ production |
| Supercritical-Water Reactor (SCWR) | Thermal, Fast | Open, Closed | 1500 | Electricity | Materials, Thermal-hydraulics |
| Gas-Cooled Fast Reactor (GFR) | Fast | Closed | 200-1200 | Electricity, Hydrogen, Actinide Management | Fuels, Materials, Thermal-hydraulics |
| Lead-Cooled Fast Reactor (LFR) | Fast | Closed | 50-150 300-600 1200 | Electricity, Hydrogen Production | Fuels, Materials |
| Sodium Cooled Fast Reactor (SFR) | Fast | Closed | 300-1500 | Electricity, Actinide Management | Advanced recycle options, Fuels |
| Molten Salt Reactor (MSR) | Epithermal | Closed | 1000 | Electricity, Hydrogen Production, Actinide Management | Fuel treatment, Materials, Reliability |

# Il nucleare nei paesi emergenti

Oltre 45 paesi stanno considerando d'impegnarsi attivamente in programmi di sviluppo dell'energia nucleare

Questi vanno dalle economie avanzate ai paesi in via di sviluppo

I capifila dopo l'Iran sono gli UAE, la Turchia, il Vietnam, la Bielorussia e la Giordania

L'energia nucleare è seriamente considerata in oltre 45 paesi che attualmente ne sono privi (in alcuni ciò non avviene necessariamente a livello governativo).

In Europa: Albania, Serbia, Croazia, Portogallo, Norvegia, Polonia, Estonia, Lettonia, Irlanda.

Medio Oriente e Nordafrica: paesi del Golfo UAE inclusi, Arabia Saudita, Qatar & Kuwait, Yemen, Israel, Siria, Egitto, Tunisia, Algeria, Marocco, Sudan.

In Africa: Nigeria, Ghana, Senegal, Kenya, Uganda, Namibia.

In SudAmerica: Cile, Ecuador, Venezuela.

In Asia centrale e meridionale: Azerbaijan, Georgia, Kazakhstan, Mongolia, Bangladesh, Sri Lanka

In Asia nsudorientale: Indonesia, Filippine, Thailandia, Malaysia, Singapore, Australia, Nuova Zelanda.

In Asia orientale: North Korea

# REGIONAL SNAPSHOT OF NUCLEAR POWER DEVELOPMENTS

## THAILAND

Thailand had planned to start commercial operations of the first nuclear-power plant in 2020 but will now delay the commercial startup of five planned nuclear-power plants by three years. Thai authorities have long pinned hopes on nuclear power as an alternative to natural gas, as the country's reserves of the fuel are being depleted. Natural gas accounts for about 70% of Thailand's total electricity generation. The idea to build a nuclear-power plant was first proposed by the state-owned Electricity Generating Authority of Thailand in 1966. Under the government's Power Development Plan for 2010-2030, EGAT would develop five nuclear-power plants with a combined capacity of 5,000 megawatts within the five years beginning 2020.

## VIETNAM

By 2030, power demand is forecast to be 101,955 MW. Announced plans to build 8 plants by 2030, producing 15000 to 16000 MW of electricity.

The National Assembly approved the construction of two nuclear power plants in Ninh Thuan province, totaling 4,000 MW in capacity. First plant, in Ninh Thuan province, will be operational by 2020. Construction expected to start by end of 2013. The total investment for this project is around $10.5 billion. In October 2010, the Vietnamese government announced that Russia will build the 1st NPP and Japan the 2nd NPP. May 2011 saw the establishment of the project management unit for the Ninh Thuan NPP project. Intergovernmental Agreement between Russia and Vietnam was signed by October 2010 as basic foundation for cooperation on Ninh Thuan 1 NPP project. Preparation work for the Ninh Thuan 1 NPP Project in Phuoc Dinh site include land clearance and resettlement, infrastructure preparation, PR centre In Phan Rang City and manpower development.

## MALAYSIA

Deploying Nuclear Energy for Power Generation is one of Entry Point Projects (EPP11) under Economic Transformation Program (ETP). Fossil fuels currently dominate 95% of total energy mix. By 2030, electricity demand is forecast to be 25,817 MW. Malaysia Nuclear Power Corporation (MNPC) was incorporated as NEPIO in Jan 2011. MNPC will lead the planning based on ETP's nuclear development timeline of 11 to 12 years from preparatory phase to commissioning, (targeting 1st NPP COD in the year 2021). Plans to have a twin-unit nuclear power plant with a total capacity of 2 GW. Building the twin-unit power plant is expected to require RM21.3b investment up to 2020. Construction of the nuclear power plants will have a temporary GNI impact in the construction sector, with GNI contribution of RM0.2b from the creation of 2600 jobs. 4 critical path items have been identified, public acceptance, ratify relevant international treaties, correct regulatory framework and approval for plan sites from local populace.

## PHILIPPINES

In 2007 the Philippines Department of Energy (DOE) set up a project to study the development of nuclear energy, in the context of an overall energy plan for the country. In its 2008 update of the national energy plan, 600 MWe was projected on line in 2025, with further 600 MWe increments in 2027, 2030 and 2034 to give 2400 MWe. Reviving the Bataan Nuclear Power Plant could not be considered because it would be very costly. The government is considering two 1000 MWe Korean Standard Nuclear Plant units.

## SINGAPORE

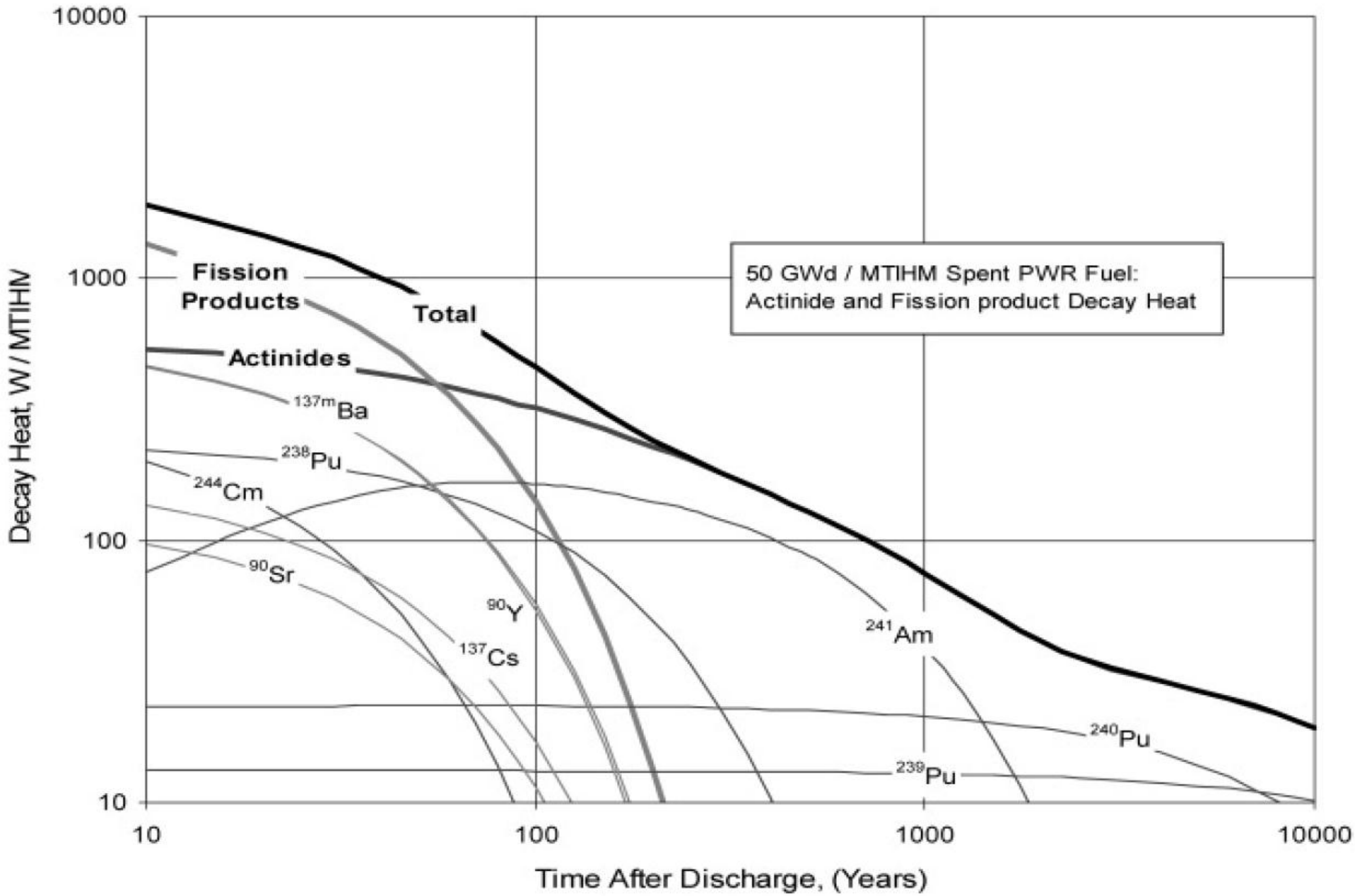
The nation is 80% dependent on gas-fired generation. The Economic Strategies Committee in early 2010 recommended that nuclear energy be considered in the long term as a way of meeting its energy needs. A feasibility study is currently underway.

## INDONESIA

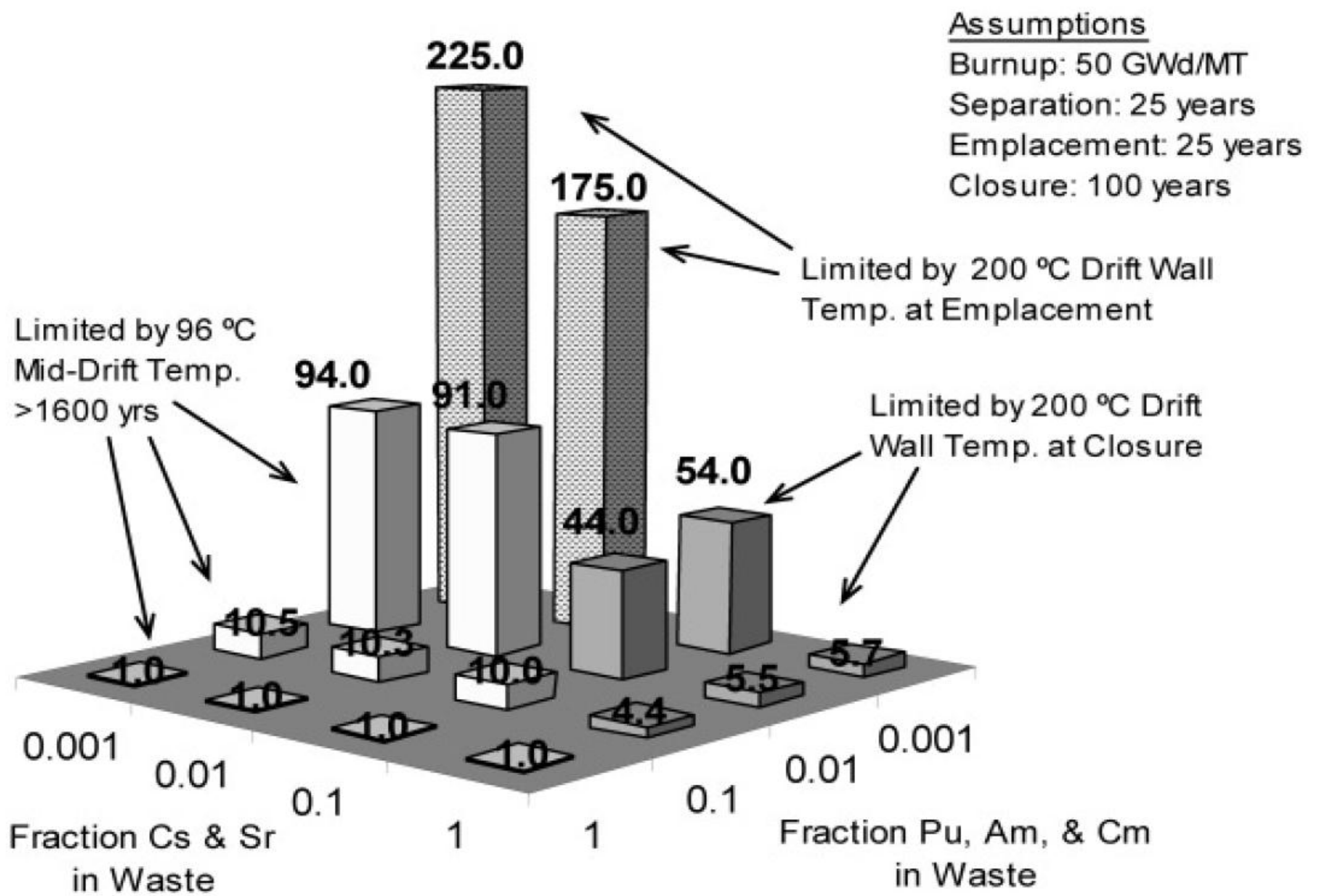
Plans to have 4 nuclear plants producing 6000 MW by 2025.The nuclear power plants will supply 40 percent of electricity needs in Sumatra, Java and Bali. The proposal is to build two plants with a combined capacity of 18,000 megawatts by 2022 in the provincial government of Bangka-Belitung, between the islands of Sumatra and Borneo. Currently has power generation capacity of only 30 GWe. With an industrial production growth rate of 10.5%, electricity demand is estimated to reach 450 billion kWh in 2026. In order to accelerate national development, President of Republic Indonesia issued Presidential Instruction No.1/2010 regarding Accelerating National Development Including Nuclear and Gov Reg No. 5/2010 on National Medium Term Development that Include Nuclear Power Plant as part of alternative energy. In line with Indonesia nuclear Infrastructure development progress in phase 1 and up coming phase 2, four main activities are now in progress i.e. Pre-Feasibility Study, technology assessment, feasibility study, assessment of Indonesia nuclear energy system.

# *Advanced Nuclear Fuel Cycles (AFC)*

- Sustainability (resources, waste management)
- Public acceptance
- AFC
  - Recycle fissile resources
  - Minor actinides (MA) and long-lived fission products (LLFP) utilization/transmutation
  - Waste amount and radio-toxicity reduction
- P&T offers the possibility to reduce decay heat of the material going to final repository $\Rightarrow$ enhance utilization of repository
  - **Early decay** heat producers are the fission products (**Cs and Sr** and their decay products), **Pu and Cm**
  - **Late decay** heat producer is **Am**




T.A. Taiwo, ANL, 2009

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# Advanced Nuclear Fuel Cycles (cont'd)

- Present LWRs are not suited for minor actinides and long-lived fission products utilization/transmutation
  - Safety consideration
  - Plant operation
  - Poor utilization/transmutation capability
- Only specially licensed LWRs can cope with MOX-fuel
  - Special reactor designs (e.g. ABB80+, EPR) required for increased Pu loadings (up to 100%)
  - A combination of these reactor types allows Pu inventory stabilization, albeit with increased minor actinides production

# Advanced Nuclear Fuel Cycles (cont'd)

- Long-term waste radio-toxicity can be effectively reduced only if transuranics are fissioned (utilized) ➔ very hard neutron spectra needed
- New transmuter reactor concepts
  - Dedicated fast reactors
  - Accelerator Driven Systems (ADS)
  - Fusion/fission hybrid reactors
- Significant Pu and minor actinides utilization rates can be achieved in symbiotic scenarios
  - LWR-MOX and dedicated fast reactors
  - Fast neutron spectrum ADS for minor actinides utilization
  - Very high thermal flux ADS could also provide significant transuranics transmutation yields

# Advanced Nuclear Fuel Cycles (cont'd)

- Long-lived fission product transmutation difficult:
  - Occur in elemental mixtures (different isotopes of the same element) ➔ isotopic separation required
  - Transmutation yields small because of very low capture cross sections in thermal neutron fields ➔ dedicated reactors required with very high loadings and/or high thermal flux levels

# Advanced Nuclear Fuel Cycles (cont'd)

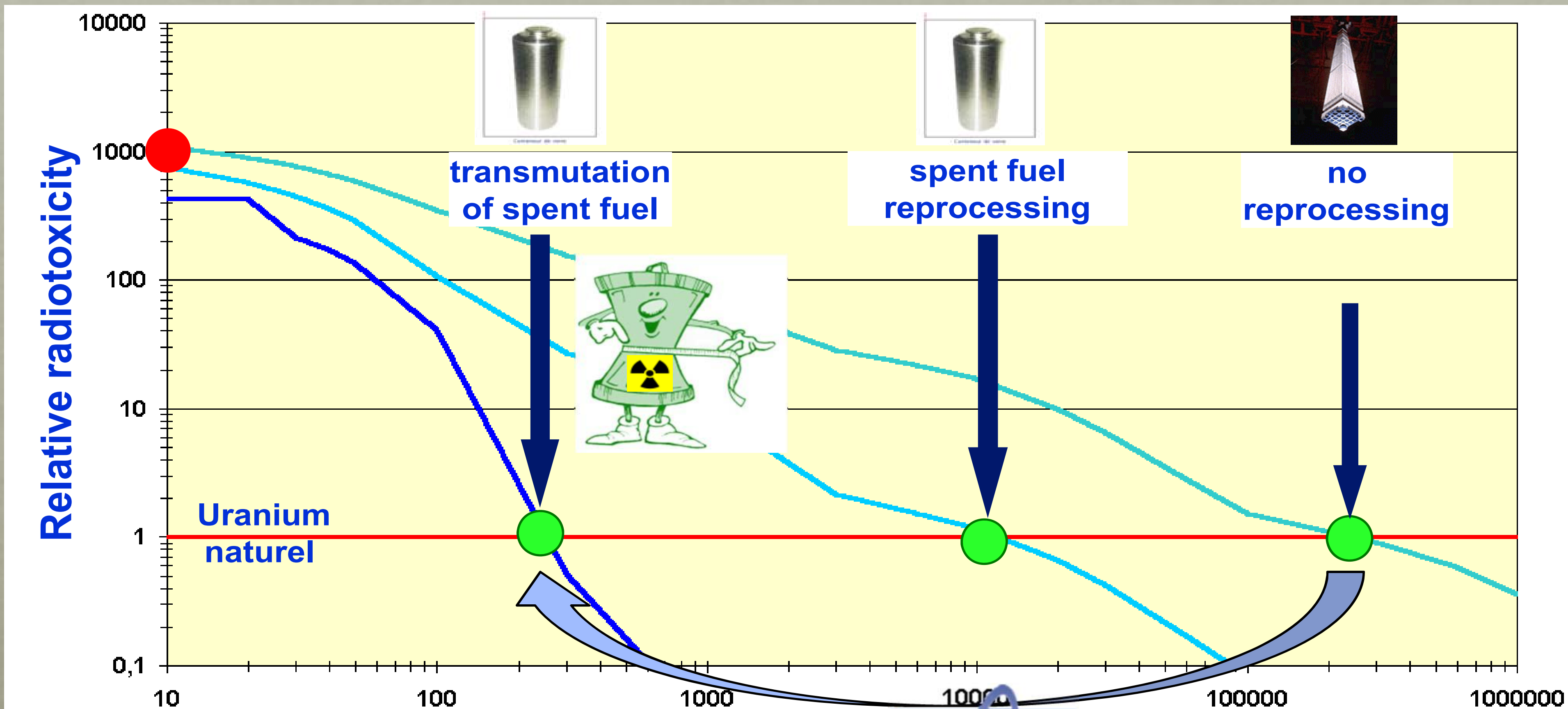
- Advanced Fuel Cycles (AFC) scenario with actinides P&T of comprises the following steps
  - Improved reprocessing of LWR $UO_2$ fuel with additional Np removal
  - Separation of MAs from HLLW resulting from LWR $UO_2$ reprocessing
  - Fabrication of MA targets for heterogeneous irradiation in LWRs
  - Recycling of U and Pu into LWR MOX fuel (single or multiple recycling)
  - Reprocessing of spent LWR MOX fuel in adequate facilities (higher Pu inventory)

# Advanced Nuclear Fuel Cycles (cont'd)

- Separation of MAs from HLLW and conditioning of individual elements (Np, Am, Cm)
- Long-term storage and eventual disposal of specially conditioned MA
- Fabrication of FR (MOX, metal, or nitride) fuel with a limited MA content
- Irradiation of FR-fuel in Fast Burner Reactors or dedicated hybrid facilities (very high burnup)
- Reprocessing of spent FR fuel in specially designed (aqueous and/or pyrochemical) and licensed facilities
- Separation of all transuranics from the spent FR fuel processing during multiple recycling

# Advanced Nuclear Fuel Cycles (cont'd)

- Multiple recycling of FR MOX fuel with major transuranics content until significant depletion
- Separation of certain long-lived fission products (if required for the disposal step)
- Revision of the fission product management $\Rightarrow$ $^{99}Tc$ separation (head-end, HLLW)
- If wanted, platinum metals separation and recovery (economics)



Relative radiotoxicity
10000
1000
100
10
1
0,1
10
100
1000
100000
1000000
transmutation of spent fuel
spent fuel reprocessing
no reprocessing
Uranium naturel