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Partitioning and Transmutation 1 & 2

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Partitioning and Transmutation (P&T): Radioactive Waste Management Option

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IAEA

International Atomic Energy Agency

Outline

- Background
- Basics and objectives of P&T
- Nuclear fuel cycle options
- Advanced fuel cycles with P&T
- Transmutation reactors
- Conclusions

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- **Background**
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Background

- Worldwide significant nuclear energy figures
  - 372 GWe capacity distributed roughly 1/3 in each region USA / Europe / rest of the world
  - ~11’000 t HM annual spent fuel discharge
  - ~4’000 t HM industrial reprocessing capacity
  - ~130’000 t HM cumulative stored spent fuel inventory
  - ~70’000 t HM reprocessed and transformed into HLW and spent LWR-MOX

Background (cont'd)

- Repository needs and characteristics
  - Present worldwide **spent fuel** and **HLW** arising would need **TWO** and **ONE** Yucca Mountain size repositories, respectively
  - **Spent fuel** repository: high Pu content ➔ non proliferation and criticality concerns
  - **Spent fuel** and **HLW** repository heat load determined by medium-lived fission products (^{137}Cs and ^{90}Sr)
  - **Spent fuel** and **HLW** repository radiotoxicity determined by minor actinides (Np, Am, Cm)

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Basics and Objectives of P&T

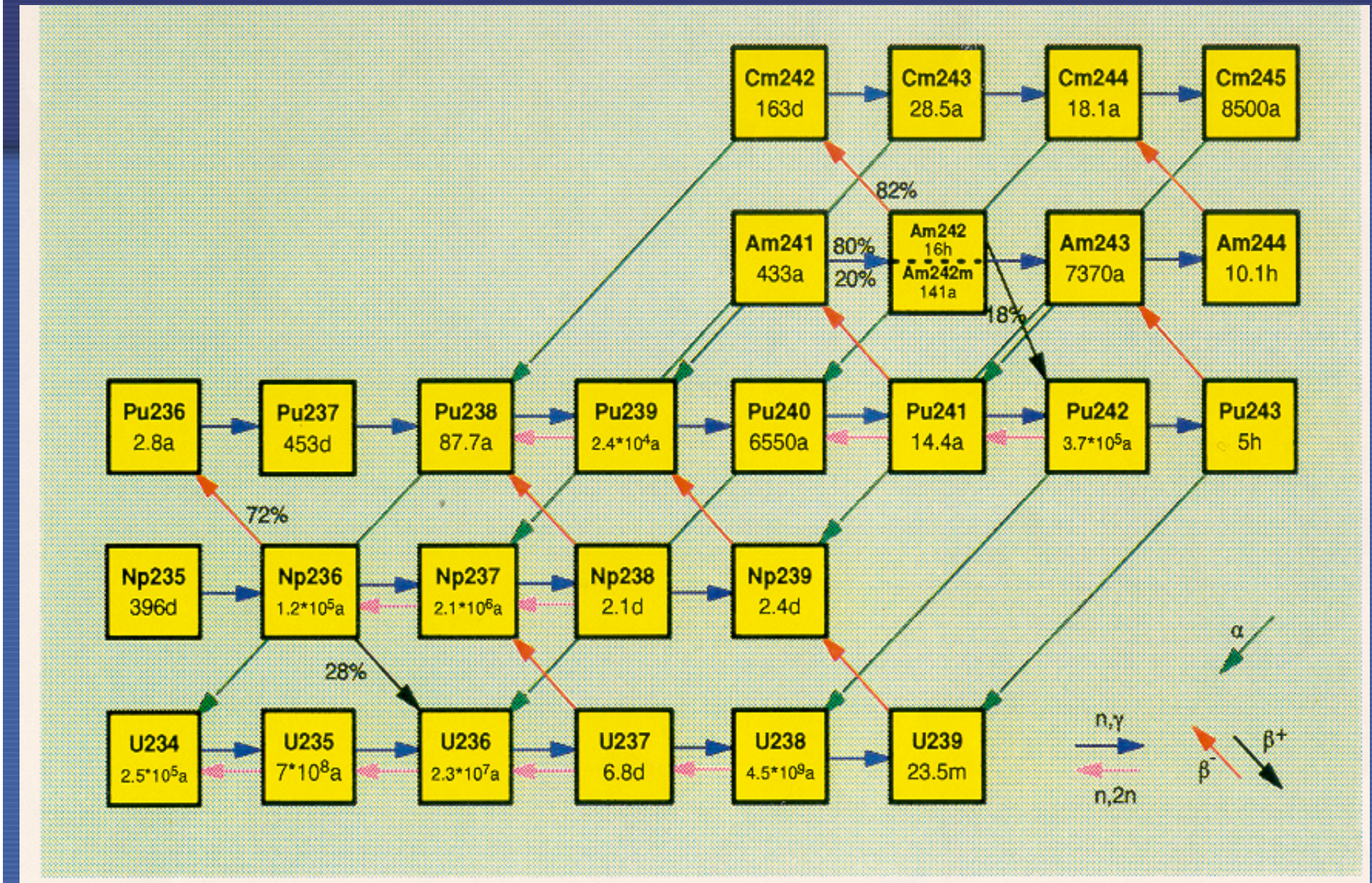
- Renewed interest in P&T $\Rightarrow$ numerous efforts worldwide to assess its potential as a radioactive waste management option
- P&T is a complex technology $\Rightarrow$ advanced reprocessing and transuranics fuel fabrication plants, innovative and/or dedicated transmutation reactors
- In addition to U, Pu and ^{129}I, “Partitioning” extracts from the liquid high level waste the minor actinides (MA) and the long-lived fission products (LLFP, ^{99}Tc, ^{93}Zr, ^{135}Cs, ^{107}Pd, and ^{79}Se)

Basics and Objectives of P&T (cont'd)

- "Transmutation" requires fully new fuel fabrication plants and reactor technologies to be developed and implemented on industrial scale
- Present LWRs are not suited for MA and LLFP transmutation (safety consideration, plant operation, poor incineration capability)
- Only specially licensed LWRs can cope with MOX-fuel; for increased Pu loadings (up to 100%), special reactor designs (e.g. EPR, ABB80+) are required; a combination of these reactor types could allow Pu inventory stabilization, albeit at the price of increased MA production

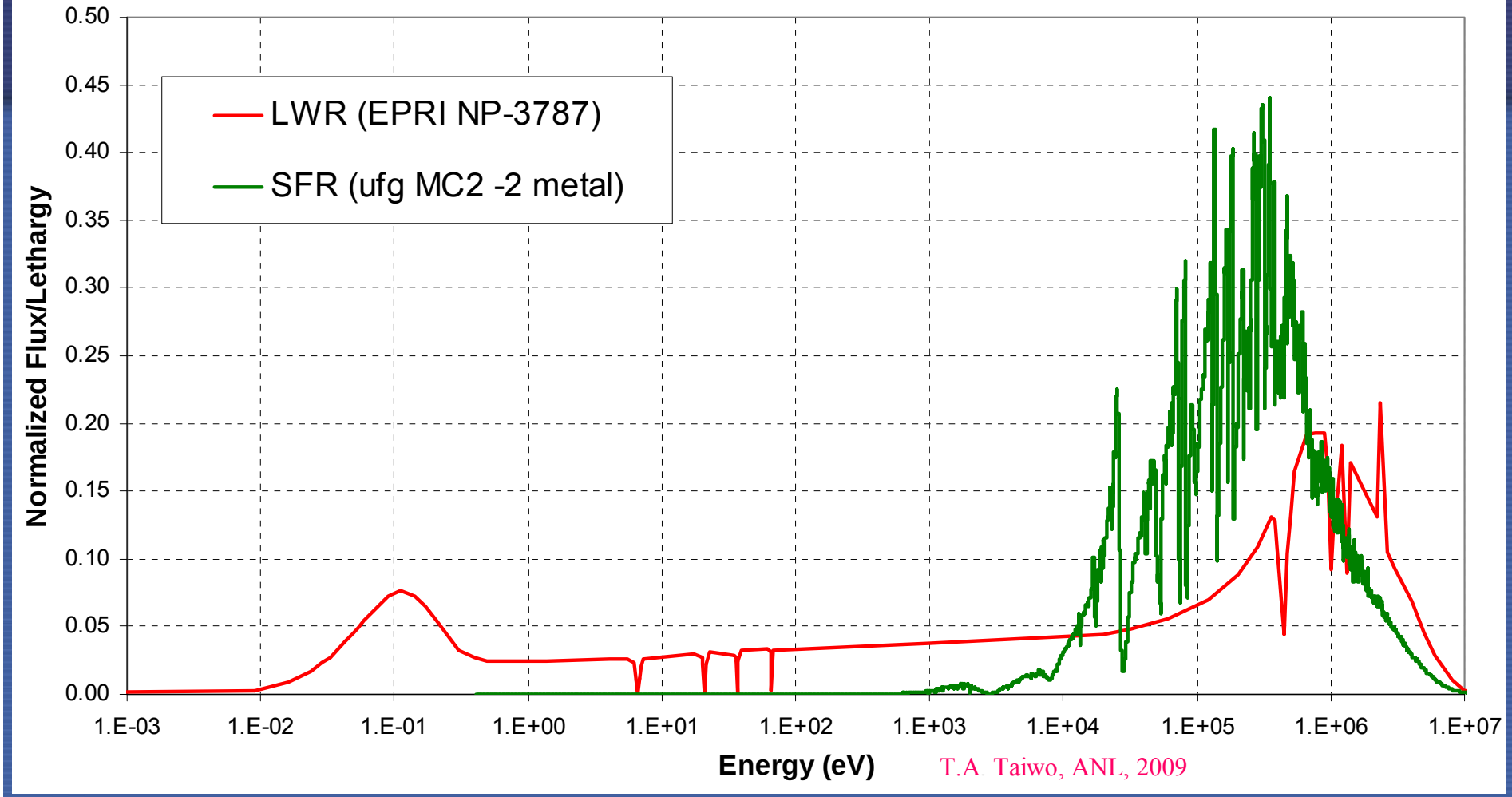
Basics and Objectives of P&T (cont'd)

- Long-term waste heat, radio-toxicity and peak dose
  - Dominated by the $^{241}Pu \rightarrow {}^{241}Am \rightarrow {}^{237}Np$ decay chain
  - Thus, can only be effectively reduced if transuranics are "incinerated" through fission $\Rightarrow$ very hard neutron spectra needed
- New reactor concepts [dedicated fast reactors, Accelerator Driven Systems (ADS), fusion/fission hybrid reactors] have been proposed as transmuters/incinerators


Cm242
163d
Cm243
28.5a
Cm244
18.1a
Cm245
8500a
82%
Am241
433a
80%
20%
Am242
16h
Am242m
141a
Am243
7370a
Am244
10.1h
18%
Pu236
2.8a
Pu237
453d
Pu238
87.7a
Pu239
2.4*10^4a
Pu240
6550a
Pu241
14.4a
Pu242
3.7*10^5a
Pu243
5h
72%
Np235
396d
Np236
1.2*10^5a
Np237
2.1*10^6a
Np238
2.1d
Np239
2.4d
28%
U234
2.5*10^5a
U235
7*10^8a
U236
2.3*10^7a
U237
6.8d
U238
4.5*10^9a
U239
23.5m
α
n,γ
n,2n
β+
β-

Basics and Objectives of P&T (cont'd)

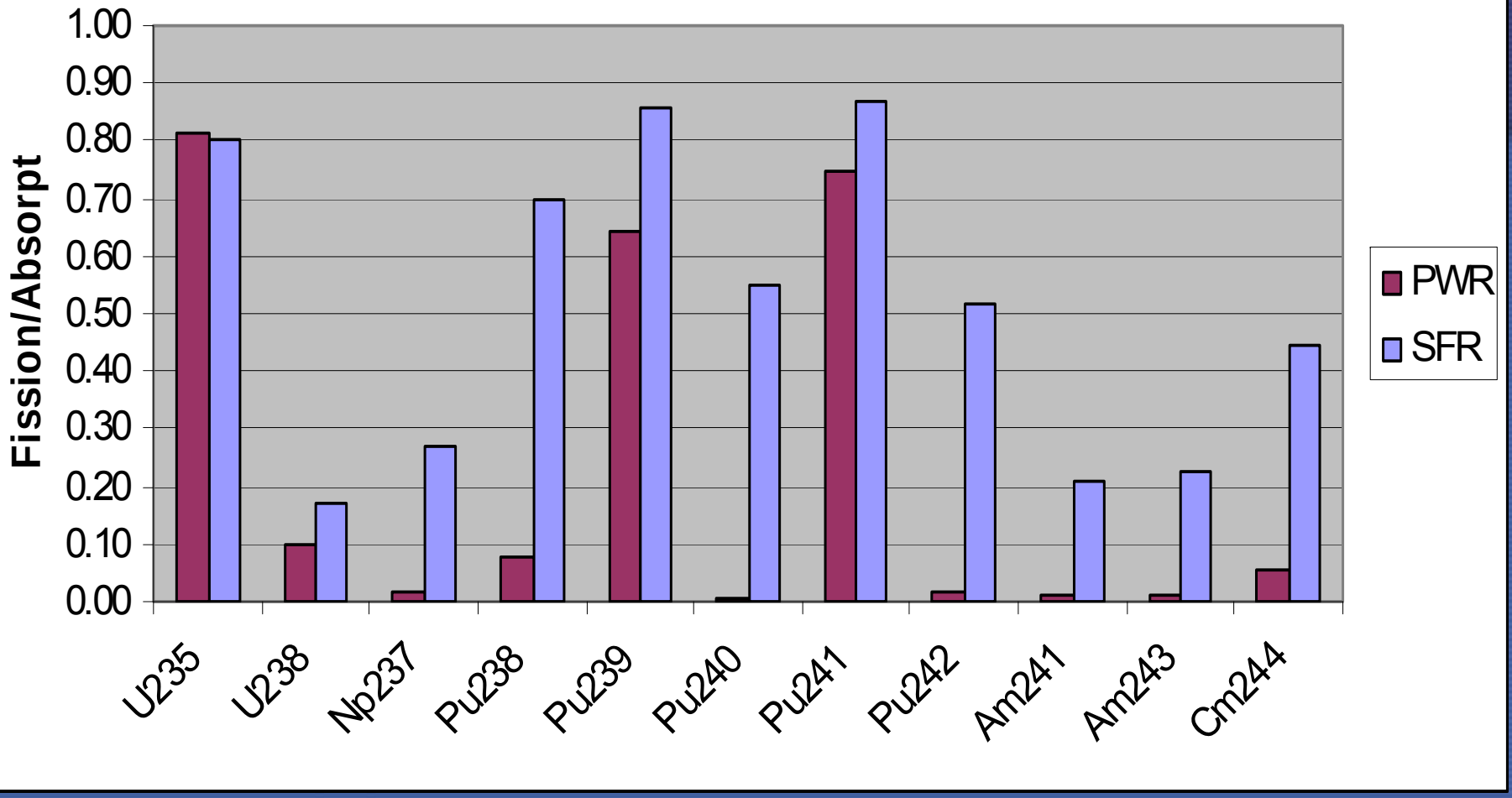
- Significant Pu+MAs incineration rates can be achieved in symbiotic scenarios: LWR-MOX & dedicated fast reactors
- Fast neutron spectrum ADS could be reserved for MA incineration
- Very high thermal flux ADS concepts could also provide a significant transuranics destruction



T.A. Taiwo, ANL, 2009

No moderation in SFR – only fast fissions

In LWR almost all fissions in thermal 0.1 eV thermal hump



- Fissile isotopes fission in both fast and thermal spectra, with fission fraction higher in fast spectra
- Fertile isotopes fission much better in fast spectra
- Fast spectra $\Rightarrow$ less actinide generation and more excess neutrons

Basics and Objectives of P&T (cont'd)

- LLFP transmutation problematic:
  - Occur in elemental mixtures (different isotopes of the same element) $\Rightarrow$ isotopic separation required
  - Transmutation yields small because of very low capture cross sections in thermal neutron fields $\Rightarrow$ dedicated reactors required with very high loadings and/or high thermal flux levels

Basics and Objectives of P&T (cont'd)

- **Spent fuel** and **HLW** repository *hazard* vs. *risk*
  - **P**artitioning and **T**ransmutation (P&T) objective → reduction of long-term hazard of **spent fuel** or **HLW** repository by **transforming** long-lived radionuclides into short-lived or inactive elements
  - "Conventional" waste management objective → reduction of long-term radiological risk (combination of potential hazard and confining properties)

Basics and Objectives of P&T (cont'd)

- Hazard reduction (P&T objective) requires very different and much more fundamental measures as compared to risk reduction:
  - **Long-term hazard** of spent fuel and HLW is associated with the radioactive source, i.e. the transuranics
  - **Short and long-term risks** are due to the **mobility** of fission products in the **geosphere** and the possibility to **enter** the **biosphere**

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Nuclear Fuel Cycle Options

- Conventional
  - **O**nce **t**hrough fuel **c**ycle with direct disposal of spent fuel (OTC)
  - Aqueous reprocessing fuel cycle with vitrification of high-level liquid waste (RFC)
- **A**dvanced **f**uel **c**ycle with partitioning of actinides (AFC)

Once-through Fuel Cycle

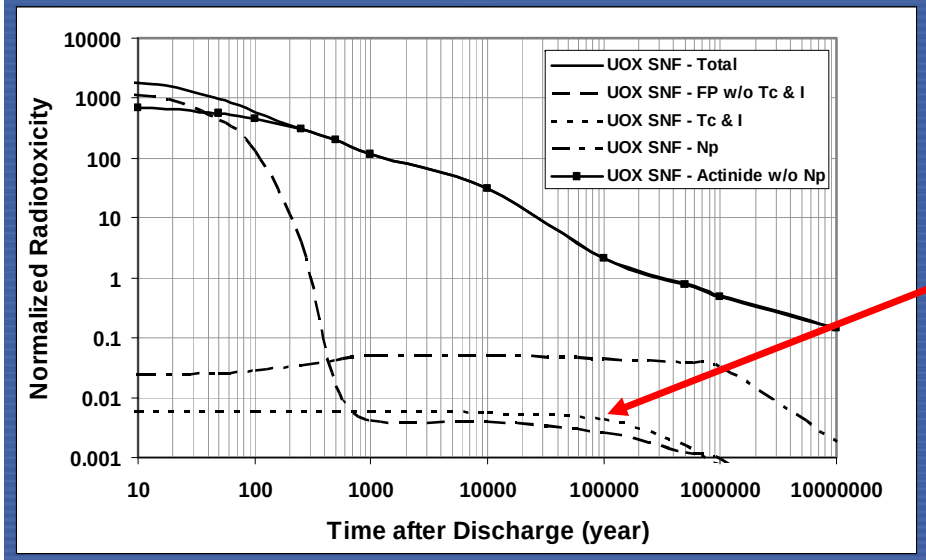
- Option considered in Canada, Spain, Sweden, USA, and some other countries
- Cheapest option at present low uranium prices
- Residual fissile material (1% Pu and 0.8% ^{235}U) and remaining fertile material (^{238}U) in spent fuel is not recovered and considered waste material
- Spent fuel long-term radiotoxicity (hazard!) from Pu, Np, Am, Cm, ... $\Rightarrow$ significant radiological source term in repository over hundred thousand years
- Effective isolation of transuranics in repository due to intrinsic insolubility of actinides in deep geological formations

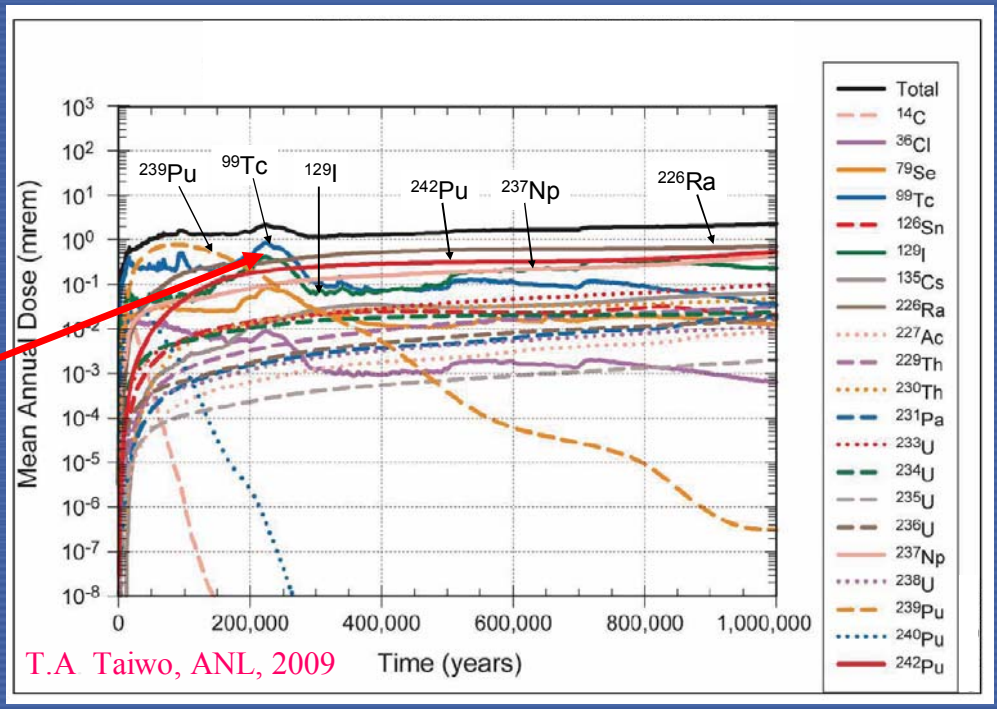
Once-through Fuel Cycle (cont'd)

- Fission products γ-radiation and decay heat are most limiting short-term repository design factors
- Most fission products have decayed after 300 - 500 years, except for a few long-lived nuclides (^{135}Cs, ^{99}Tc, ^{129}I, ^{93}Zr, ...)
- Some long-lived fission products are relatively mobile in the geosphere

Once-through Fuel Cycle (cont'd)

- After a few hundred years, fission products do not contribute significantly to radio-toxicity (exceptions: ^{135}Cs, ^{99}Tc, ^{129}I)
- Transuranics determine radio-toxicity after ~100 yrs





Once-through Fuel Cycle (cont'd)

- Long-term OTC radiological impact can be controlled by engineering design and natural barriers which should provide protection for the time period defined by the life-time of the confined source term $\Rightarrow$ long time periods involved require a careful analysis of the confinement technology and of the long-term consequences of accident scenarios
- There is no worldwide agreement on the time periods for confinement of HLW in a geologic repository; periods of 10^3 – 10^5 years, or even longer, have been put forward, but no internationally accepted confinement period has been established

Once-through Fuel Cycle (cont'd)

- Safety and regulatory aspects of OTC
  - Substantial quantities of fissile material are deposited, in addition there is decay ^{239}Pu to $^{235}U \Rightarrow$ criticality potential must be addressed in the licensing process
  - ^{129}I is the limiting nuclide in risk repository analyses: if no specific actions are taken to limit ^{129}I solubility in the deep aquifers, the entire ^{129}I inventory will be fully dispersed in the geosphere after a few 10^4 yrs
  - Beyond 500 years, spent fuel heat emission due to total actinide content is significantly higher than that of the fission products; long-term heat absolute value is, however, significantly lower than that of the initially loaded fission products

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW

- Natural uranium contains only 0.72% of fissile ^{235}U $\Rightarrow$ recycling of the "major actinides", i.e. U and Pu, from spent fuel in the aqueous reprocessing fuel cycle (RFC) with vitrification of HLLW is standard scenario of nuclear energy production
- Reduced support for this option in many countries due to costs and proliferation concerns

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- ~99.9% of the U and Pu streams are extracted, thus only a very minor fraction of the "major actinides" goes to HLLW, and thus to HLW, and to geologic repository
- Removal of minor actinides (that become more important with increasing burnup) from HLLW would reduce the residual HLW radiotoxicity
- Adding a minor actinides partitioning module to the standard reprocessing plant would be the most obvious change to the current RFC $\Rightarrow$ countries with reprocessing infrastructure (France, UK, Japan, India, Russia, and China) could implement, in a medium-term, a partial partitioning scenario by which the HLW would be practically free from long-lived transuranics

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- Use of LWR-MOX RFC is industrially significant in Europe (specially licensed reactors in France, Germany, Switzerland and Belgium are fuelled with MOX)
- Within the broader context of resources utilization and waste management, the reuse of Pu is the first step in a global P&T scenario
- Recycling spent LWR fuel as MOX provides ~5 overall mass reduction factor, but radiotoxicity is not significantly reduced, since only ~25% of the recycled Pu is consumed and about 10% is transformed into long-term radiotoxic minor actinides source

Little Exercise: Improving Economics And Energy Resource Utilization when Recycling MOX…

How much transuranics (mostly Pu) inventory is fissioned (converted into energy) when recycling LWR spent fuel as MOX?

✓From a typical 1 GWe LWR fuelled with 3-5% ^{235}U enriched UOX used to 50 GW×d/t_{HM} burnup, approximately 250 kg of transuranics are discharged per year (~1.3% transuranics content at discharge)

✓Every time 1 g of actinides fissions, approximately 1 MW×d of thermal energy is produced ⇨ hence, at an average discharge burnup of 50 GW×d/t_{HM} 5% of the actinides are fissioned

✓Having at discharge ~1.3% transuranics to be recycled as MOX, if follows that about 1.3%/5% = 25% of the LWR energy produced during the UOX burnup (up to 50 GW×d/tHM) will be gained through MOX recycle – albeit at the price of more transuranics production (about 10%), a long-term radiotoxic source

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- Further radiotoxicity reduction requires loading of the spent LWR-MOX transuranics into a fast reactor ⇒ part of the advanced fuel cycle (AFC)

So Let's Do Another Little Exercise...

- In UOX and MOX fuelled reactors, CR (the conversion ratio) quantifies the transuranics production:

$$Conversion\,Ratio = \frac{transuranics\ production\ rate}{transuranics\ destruction\ rate}$$

The transuranics produced in the LWR recycling spent UOX can be "destroyed" (i.e. transformed into energy) in a fast reactor (FR).
This little exercise will show, in function of the CR, the relation between LWRs and FRs assuming that the transuranics production in the former is balanced by the "destruction" in the latter:

We want to completely “destroy” in the FR the transuranics produced in the LWR (50 GWd/t burnup, 1.3% transuranics content at discharge). Thus, depending on the CR of the FR, the relation between LWRs and FRs will be

$$\frac{LWR}{FR} = \frac{\frac{50\ GWd/t}{0.013}}{\frac{1000\ GWd/t}{1-CR}} = \frac{50}{0.013} \times \frac{1-CR}{1000} = \frac{1-CR}{0.26}$$

- FR is pure transuranics “destroyer” (CR=0) ⇨ 1 FR for every 4 LWRs
- FR produces 4 times less transuranics than destroying (CR=0.25) ⇨ 1 FR for every 3 LWRs
- FR produces as many transuranics as it “destroys” (CR=1) ⇨ only LWRs recycle reactors

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- In theory, reprocessing the spent LWR-MOX fuel in view of recycling the transuranics in FRs is possible in present reprocessing plants
- Additional transuranics separation module is required to reduce significantly the radiotoxicity of the HLLW produced during reprocessing of LWR-MOX (up to levels comparable to those of non-reprocessed spent LWR-MOX), and this could be done with the same technology for HLLW from LWR-UO_2

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- Recovery of U from spent fuel by TBP extraction in the PUREX process
  - Very little of recovered U stockpile has been reused in subsequent reactor loadings
  - Reprocessed U contains some troublesome radioisotopes [^{232}U, a parent of natural decay chains with radiotoxic daughter nuclides (strong γ emitters), and ^{236}U forming ^{237}Np in a neutron field via (n,γ) reaction to ^{237}U and its decay (β^-, $T_{½}$=6.8 d)]
  - Recycling of reprocessed U in LWR fuel is done industrially $\Rightarrow$ fresh fuel fissile enrichment increase

Aqueous Reprocessing Fuel Cycle with Vitrification of HLLW (cont'd)

- The radiotoxic impact from stockpiling depleted and reprocessed U is greater than, e.g. Np $\Rightarrow$ large amounts of depleted U (8 to 9 tonnes per tonne LWR fuel produced), stored as UF_6, constitute an important long term radiotoxic and chemical hazard to be addressed

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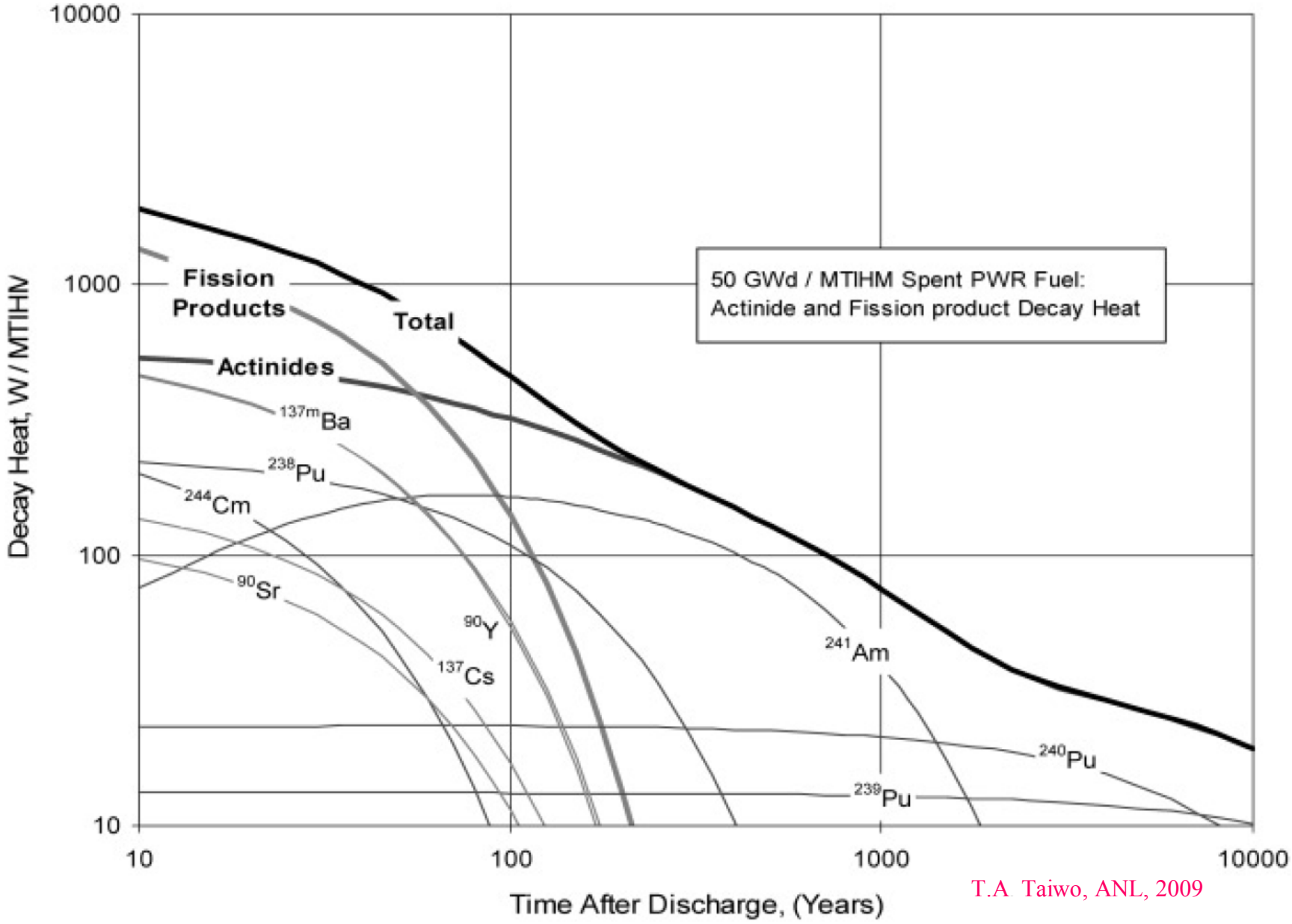
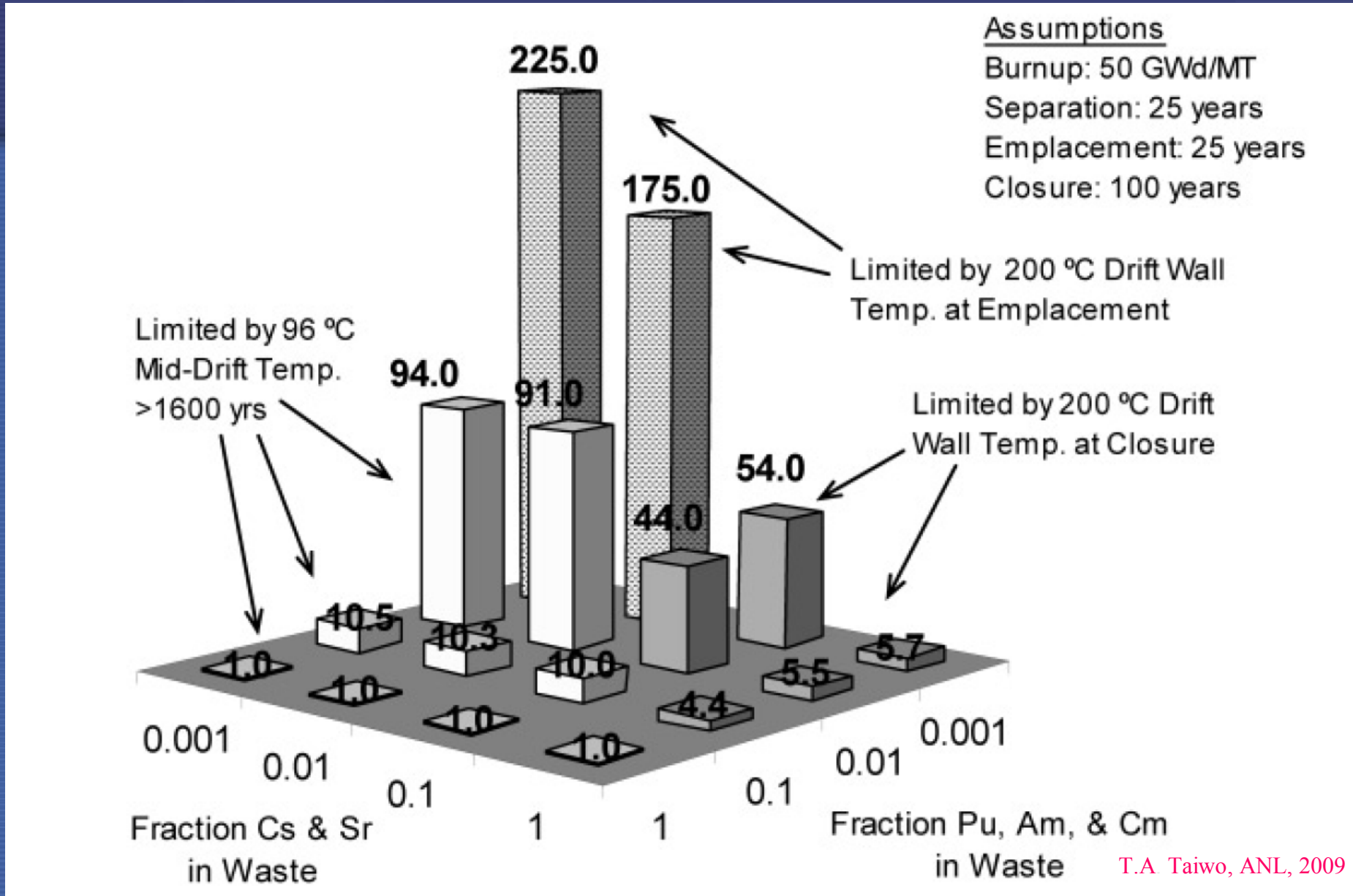
Advanced Nuclear Fuel Cycles

- Sustainability (resources, waste management)
- Public acceptance
- AFC
  - Recycle fissile resources
  - Minor actinides and long-lived fission products utilization/transmutation
  - Waste amount and radio-toxicity reduction

Advanced Nuclear Fuel Cycles (cont'd)

- 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


10000
1000
100
10
Decay Heat, W / MTIHM
Fission Products
Total
Actinides
137m Ba
238 Pu
244 Cm
90 Sr
90 Y
137 Cs
241 Am
240 Pu
239 Pu
50 GWd / MTIHM Spent PWR Fuel:
Actinide and Fission product Decay Heat
10
100
1000
10000
Time After Discharge, (Years)
T.A Taiwo, ANL, 2009


Assumptions
Burnup: 50 GWd/MT
Separation: 25 years
Emplacement: 25 years
Closure: 100 years
225.0
175.0
Limited by 200 ºC Drift Wall Temp. at Emplacement
Limited by 96 ºC Mid-Drift Temp. >1600 yrs
94.0
91.0
Limited by 200 ºC Drift Wall Temp. at Closure
54.0
44.0
10.5
10.3
10.0
5.7
5.5
4.4
1.0
1.0
1.0
1.0
0.001
0.01
0.1
1
1
0.1
0.01
0.001
Fraction Cs & Sr in Waste
Fraction Pu, Am, & Cm in Waste
T.A Taiwo, ANL, 2009

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

Advanced Nuclear Fuel Cycles (cont'd)

- 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)

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Core Physics Characteristics

Thermal reactors

- Fuelled with low enriched uranium
- Core physics characteristics naturally lead to designs for once-through cycles
- Can operate on low enriched uranium
- Neutron balance does not allow for breeding
- Limited plutonium recycle possible, but to allow recycle
  - ✓ Higher actinides must be separated from spent fuel (and disposed off)
  - ✓ Fissile feed needed

Core Physics Characteristics (cont'd)

Fast reactors

- Core physics characteristics naturally lead to designs for closed fuel cycles
- Neutron balance allows flexibility for
  - ✓ Breeding, hence enhanced resources utilization
  - ✓ Transuranics recycle (with no need for fissile feed), hence utilization of minor actinides
  - ✓ Higher actinide generation is suppressed

Transuranics Recycle in Fast Reactors

- 0.5<CR<1.0 FR designs can be achieved with today's technology allowing improved transuranics recycling
  - CR=0.75 ⇨ FR fraction at equilibrium ~½, transuranics enrichment ~20%

Transuranics Recycle in Fast Reactors (cont'd)

- 0≤CR≤0.5 FR designs are needed for dedicated transmutation applications and would require innovative solutions
  - CR=0.50 ⇨ FR fraction at equilibrium ~ 1/3, transuranics enrichment ~30%
  - CR=0.25 ⇨ FR fraction at equilibrium ~¼, transuranics enrichment ~50%
  - CR=0 ⇨ FR fraction at equilibrium ~1/5, transuranics enrichement 100% (uranium-free fuel)

Transuranics Recycle in Reactors: Some Conclusions

- The ultimate goal of transmutation is to alleviate burden on final repository
- Goal to be achieved gradually
  - Advanced fuel cycles with recycling must be introduced
  - Development of reprocessing technologies (non-aqueous) and of advanced fuels (MOX, inert-matrix fuels)
  - Since LWR will dominate nuclear energy production in the short-term, transmutation strategies involving thermal systems could be gradually implemented and would provide some benefits

Transuranics Recycle in Reactors: Some Conclusions

- Fast reactor core physics offers the flexibility to design from very high (breeders) to very low CRs (enhanced transuranics utilization)
- Research and technology development is needed to produce innovative fast reactor designs aimed at enhanced transuranics utilization (e.g. to cope with a significant increase in the burnup reactivity loss)

ADS Technology

- ADS couples spallation source with sub-critical core
- The basic idea is to make use of the additional flexibility offered by the excess neutrons produced by the spallation source to
  - Produce energy
  - Transmute radio-toxic isotopes
  - Breed fissile material
- Spallation source
  - High energy proton beam on heavy nuclide target producing hard neutrons
  - Less effective than fission neutron source

ADS Technology (cont'd)

Spallation neutrons more "expensive", e.g. for Pb target:

200 MeV ➔ spallation target ➔ $200\times\eta_{th}\times\eta_e\times\varepsilon$ = $200\times0.4\times0.5\times0.5$ = 20 MeV plus $200\times\eta_{th}\times\eta_e\times Z/E_p$ = $200\times0.4\times0.5\times25/10^3$ = 1 hard neutron (φ^* ➔ 1.5 hard neutrons) ➔ compared to fission (producing 200 MeV plus 3 hard neutrons), spallation source needs 180 MeV to produce ½ the number of hard neutrons

η_{th} efficiency of thermal to electrical energy transformation

η_e efficiency of electric energy to proton current transformation

ε fraction of incident protons having kinetic energy ≥ spallation nucleus dissociation energy

Z neutrons produced in Pb by each proton of energy E_p

ADS Technology (cont'd)

- Power control is possible up to a certain extent via the proton beam current
- Should the accelerator have enough reserve, even burnup compensation could be done via the accelerator
- Level of sub-criticality can be chosen, within the technological limits set by the accelerator, larger than β_{eff} → beneficial to power control and safety
- Potential advantages → enhanced safety and flexibility
- Potential advantages need substantiation

ADS Technology (cont'd)

- Justification for using "expensive neutron source"
  - Improvement of the dynamics behavior
  - Enhanced flexibility
- R&D efforts aiming at substantiating the potential of ADS and studying their role in innovative reactor and fuel cycle strategies that include systems for large-scale utilization and transmutation of minor actinides and long-lived fission products

Status of ADS R&D: European Union

- EURATOM 6th (2002 – 2006) and 7th (2007 – 2011) Framework Programmes (FPs)
- EUROTRANS project → funded with a total of EUR 45 million, EC contributed 23 million
- Objectives
  - Preliminary design → MYRRHA / XT-ADS (experimental ADS, 50 – 100 MWth)
  - Conceptual design → European Transmutation Demonstrator (ETD, several hundred MWth, modular)
- Major activities
  - MEGAPIE
  - MYRRHA / XT-ADS project
  - GUINEVERE experimental facility
  - FASTEF and CDT (Central Design Team)

Status of ADS R&D: European Union (cont'd)

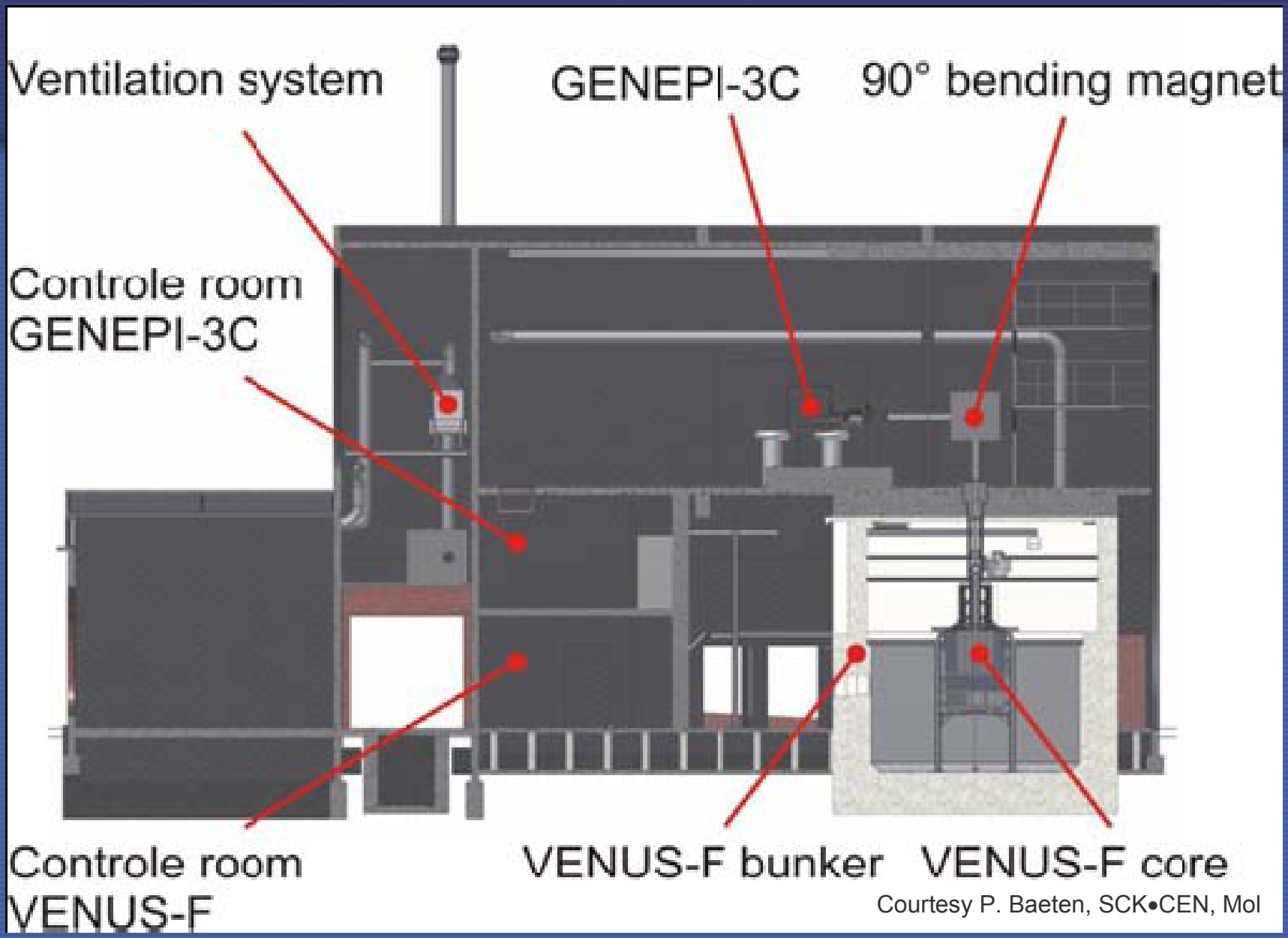
- MEGAPIE **MEGA**watt **PI**lot **E**xperiment
- Joint effort by 6 European Institutes (PSI, FZK, CEA, SCK•CEN, ENEA, CNRS) plus JAEA (Japan), DOE (USA) and KAERI (Rep. of Korea) to demonstrate
  - Design, manufacturing, safe operation, and dismantling of a liquid Pb-Bi eutectic target for high power spallation and ADS applications
  - Assess the target's neutronics performance
  - Collect material data in view of establishing a data base for liquid Pb-Bi eutectic targets
- MEGAPIE was the first liquid Pb-Bi eutectic target operated in the Megawatt regime (0.8 MW provided by the PSI proton accelerator)
  - Successfully irradiated from August until December 2006 at the Swiss Spallation Neutron Source (SINQ) at PSI
  - MEGAPIE received a beam charge of 2.8 Ah of 575 MeV protons
- Dismantling and PIE planned from summer 2009 on

Status of ADS R&D: European Union (cont'd)

- MYRRHA / XT-ADS demonstrates the feasibility of transmutation with ADS
  - 600 MeV / 2.5 mA or 350 MeV / 5 mA LINAC
  - Pb-Bi eutectic spallation target and coolant
  - Mixed U-Pu oxide fuelled sub-critical core
  - SCK•CEN aligned MYRRHA (full scale ADS demonstrator) R&D activities with XT-ADS efforts:
    - ✓Investigation of design cliff edges
    - ✓Demonstration of accelerator components
    - ✓Thermal hydraulics design of spallation target
    - ✓Experimental coupling of a fast sub-critical core with a neutron source in GUINEVERE

Status of ADS R&D: European Union (cont'd)

- GUINEVERE (**G**enerator of **U**ninterrupted **I**ntense **NE**utrons at the lead **VE**nus **RE**actor)
  - Experimental facility allowing physics experiments and technological research under conditions representative for XT-ADS
  - Deuteron GENEPI-3C accelerator operating in pulsed and continuous mode
  - $Ti^{3}H$ target producing 14.1 MeV neutrons
  - Zero-power fast sub-critical 30% ^{235}U enriched metallic U fuelled core in Pb matrix



Courtesy P. Baeten, SCK•CEN, Mol

Status of ADS R&D: European Union (cont'd)

- GUINEVERE studies of on-line reactivity monitoring techniques at various sub-criticality levels
  - Current-to-flux reactivity monitoring (GENEPI-3C in continuous mode, representative for power ADS)
  - Time dependent neutron spectra measurements (after beam interruptions) ➔ prompt decay method, source jerk, etc

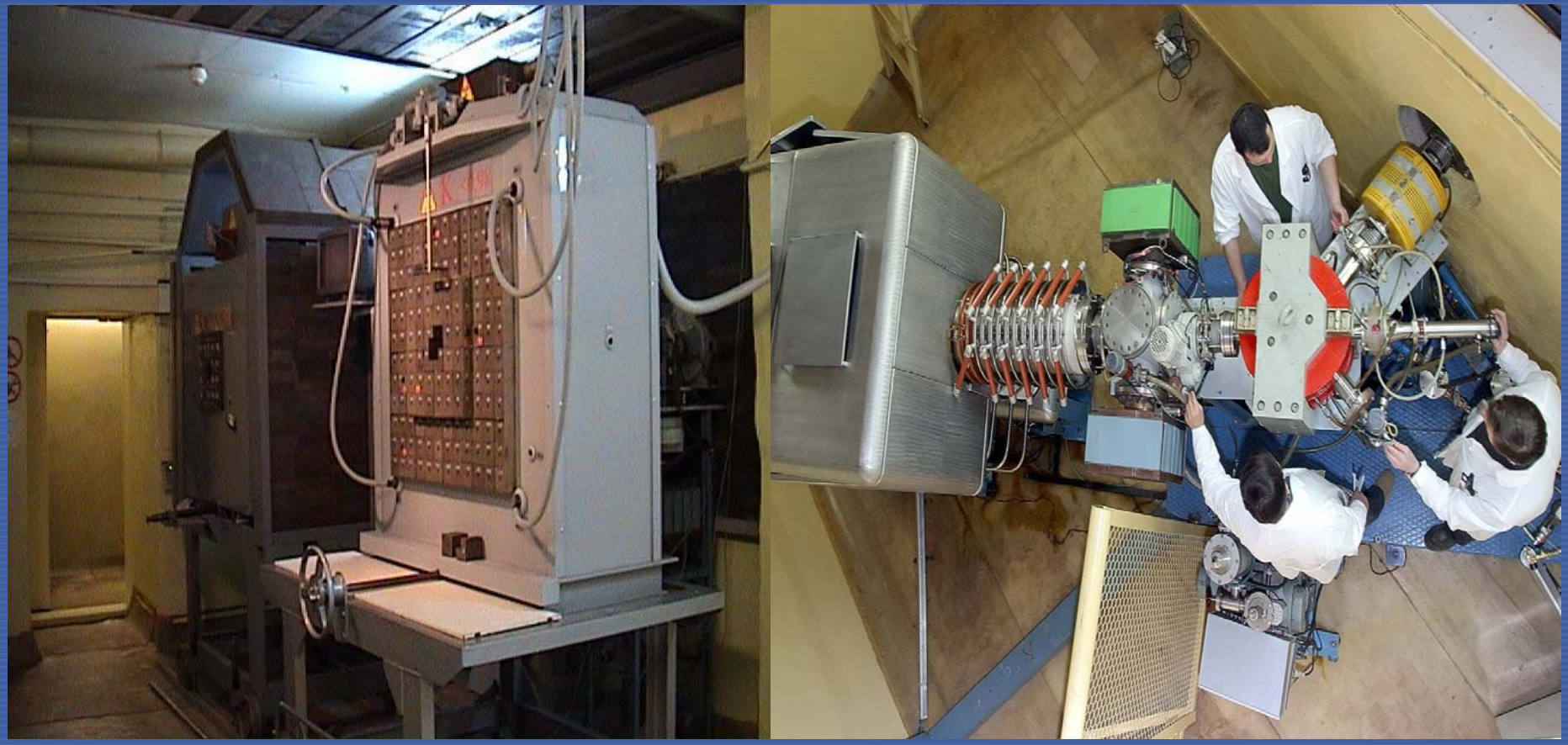
Status of ADS R&D: Belarus

- Joint Institute for Power and Nuclear Research – SOSNY (JIPNR-SOSNY) ➔ YALINA experimental program
- Contributes to EUROTRANS and to an ISTC project (HEU to LEU conversion)
- Objectives
  - Minor actinides and long-lived fission product transmutation in fast spectrum sub-critical facilities
  - ADS physics

Status of ADS R&D: Belarus (cont'd)

- Research activities (YALINA-BOOSTER configuration)
  - Development and testing reactivity monitoring techniques used in power ADS
  - Investigation of spatial kinetics of sub-critical systems driven by external neutron sources
  - Measurement of transmutation reaction rates
  - Maintenance and operation characteristics of sub-critical systems driven by external neutron sources

YALINA Facility, JIPNR-SOSNY, Belarus

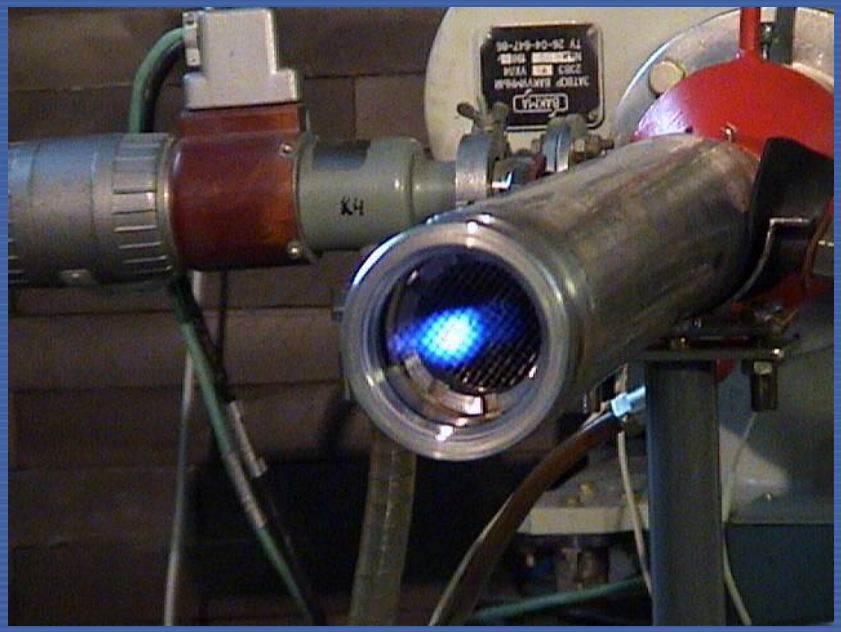


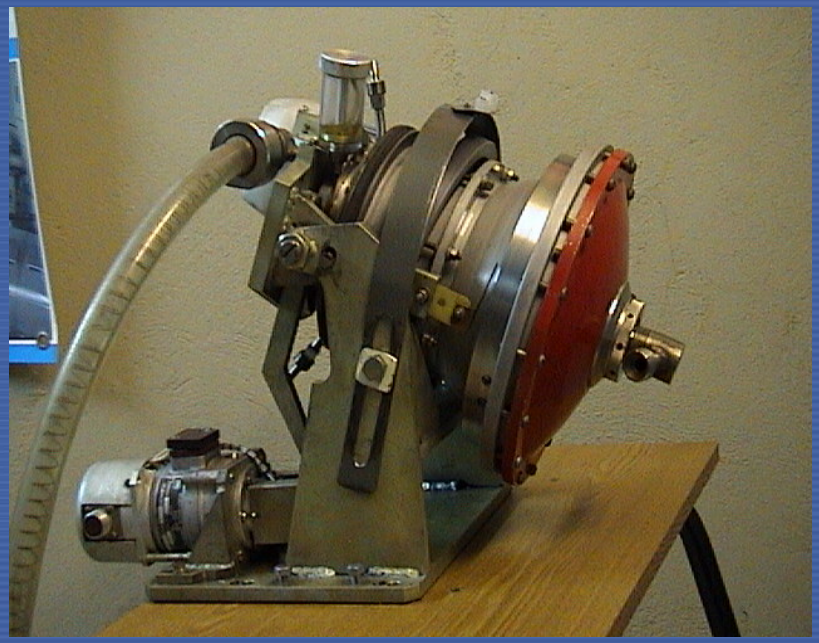
Courtesy of A. Kiyavitskaya, JIPNR-SOSNY

YALINA Targets

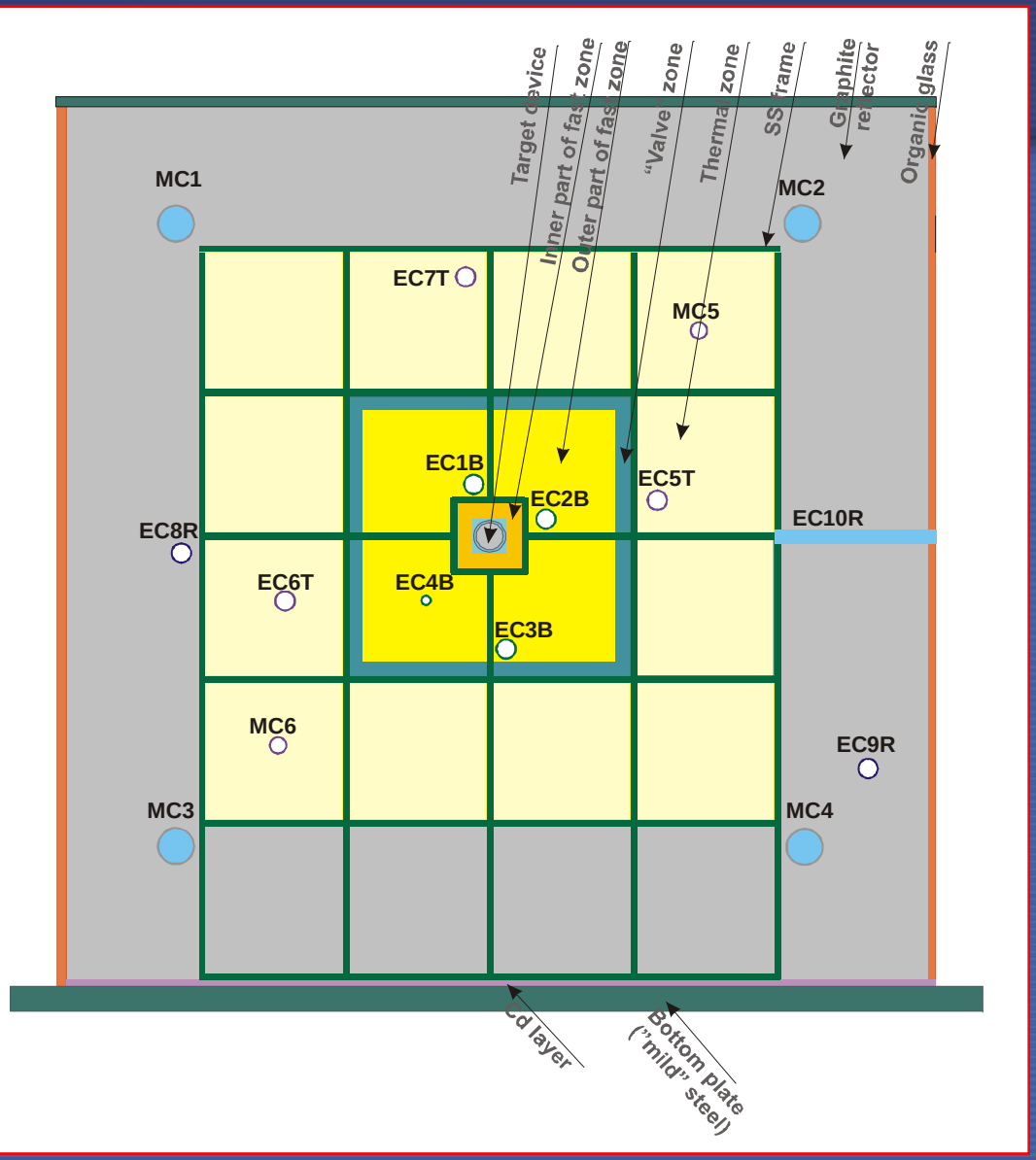
Target diameter [mm]	45	230
Rotation speed [rpm]	560	560
Beam current [mA]	1 – 2	1 - 12
Neutron energy [MeV] (D-D / D-T target)	2.5 / 14	2.5 / 14

Courtesy of A. Kiyavitskaya, JIPNR-SOSNY





YALINA Booster



EC1B-EC4B: experimental channels in fast zone [metallic U (90%) and UO_2 (36%) in Pb matrix)
EC5T-EC7T: experimental channels in thermal zone [UO2 (10%) in polyethylene matrix
EC8R-EC10R: experimental channels in reflector

Courtesy of A. Kiyavitskaya, JIPNR-SOSNY

Status of ADS R&D: India

- Objectives of ADS R&D programme
  - P&T as part of advanced fuel cycles
  - Fissile material breeding ➔ thorium utilization
- Nuclear data
- Code development for high energy particle transport
- High power proton accelerator technology
- 14-MeV D-T neutron source coupling with sub-critical reactor (water cooled, natural uranium fuelled)

Status of ADS R&D: India (cont'd)

- Spallation target systems and heavy liquid metal thermal hydraulics
  - Pb-Bi eutectic loop with simulated proton beam window heating (plasma torch and electron beam)
  - Corrosion testing
  - Validation and qualification of Computational Fluid Dynamics codes
- Sub-critical core design
  - Thorium fuel utilization in sub-critical systems
  - Experimental reactor offering the flexibility of being transformed into a sub-critical system driven by a spallation source

Status of ADS R&D: Japan

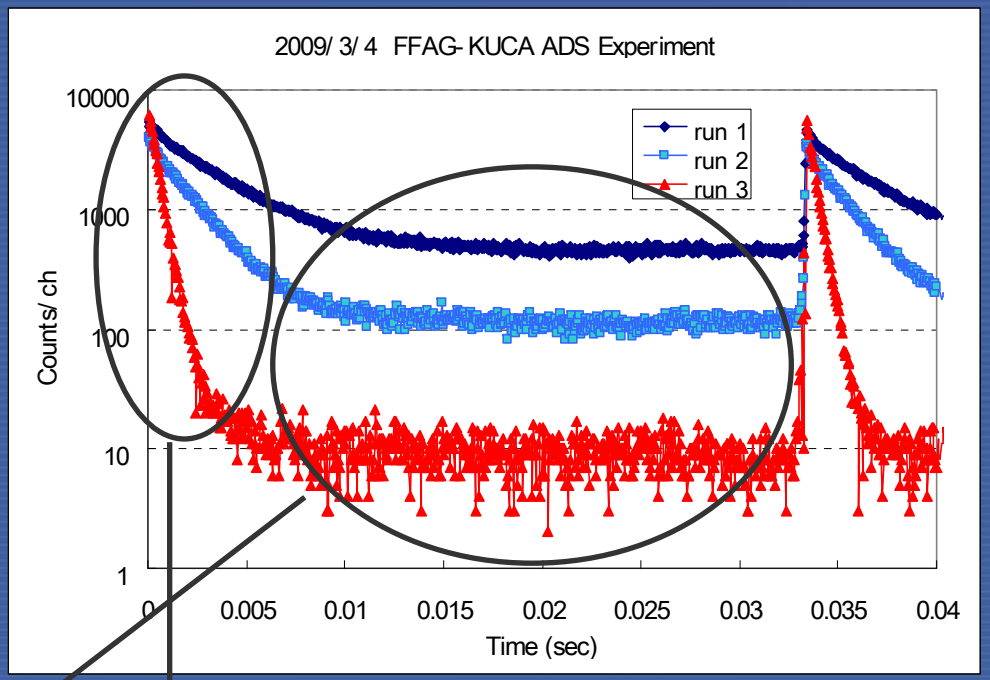
- Japan Atomic Energy Agency (JAEA) objective of R&D on ADS → transmutation of long-lived radioactive nuclides
- Sub-critical core design studies: 800 MWth Pb-Bi eutectic cooled ADS
  - Four-zone core concept (limit operating temperatures below 500°C and thus improve the compatibility with Pb-Bi eutectic)
- Corrosion tests for various structural material candidates in low oxygen concentration condition at 450°C and at 550°C

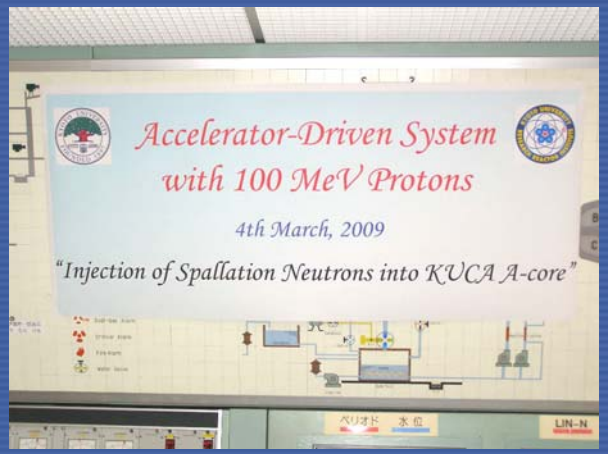
Status of ADS R&D: Japan (cont'd)

- TEF (Transmutation Experimental Facility) design studies ➔ within the framework of J-PARC (Japan Proton Accelerator Research Complex)
  - Handling of minor actinides bearing fuel
  - Remote handling system design

Subcritical Experiments at Kyoto University Critical Assembly (KUCA)

Courtesy of C.H. Pyeon, Kyoto University Research Reactor Institute





Spallation neutrons from target

Delayed neutrons in core

Spallation neutrons generated by protons multiplied in KUCA

IAEA

IAEA Activities

- Framework ➔ Technical Working Group on Fast Reactors (TWG-FR)
  - Information exchange on fast reactor and transmutation system (e.g. ADS) scientific and technical topics
  - Collaborative R&D (Coordinated Research Projects, CRPs)
  - Membership: Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, Russia, Switzerland, UK, and USA; EU (EC), ISTC, and OECD/NEA; observers: Belgium, Sweden

IAEA Activities, cont'd

- Advanced Workshop on "Model Codes for Spallation Reactions", collaboration with ICTP, 4 – 8 Feb 2008, Trieste, Italy
  - Intern. Nucl. Data Committee Report 0530
- Workshop on "Nuclear Reaction Data for Advanced Reactor Technologies", collaboration with ICTP, 19 – 30 May 2008, Trieste, Italy
  - Lecture notes on http://cdsagenda5.ictp.trieste.it/full_display.php?smr=0&ida=a07153

IAEA Activities, cont'd

- School on "Physics, Technology and Applications of Innovative Fast Neutron Systems"
  - IAEA's Department of Nuclear Energy and Department of Nuclear Sciences and Applications, in collaboration with ICTP, 9 – 20 November 2009, Trieste, Italy

IAEA Activities, cont'd

- International Topical Meeting on "Nuclear Research Applications and Utilization of Accelerators", Vienna, 4 – 8 May 2009
  - Organized by IAEA's Department of Nuclear Energy and Department of Nuclear Sciences and Applications, collaboration with ANS
  - Preliminary proceedings (not for citation yet, username and password: ***accapp09***) on

    www-naweb.iaea.org/napc/physics/accapp09/login2.html

IAEA Activities, cont'd

- International Conference on **"Fast Reactors and Associated Fuel Cycle – Challenges and Opportunities FR09", 7 – 11 Dec 2009, Kyoto**
  - **Organized by IAEA's Department of Nuclear Energy**
  - **Hosted by the Japan Atomic Energy Agency**

IAEA Activities, cont'd

- Coordinated Research Project on "Studies of Innovative Reactor Technology Options for Effective Incineration of Radioactive Waste" (2003 – 2008)
  - 17 institutions in 13 Member States & EC (JRC)
  - Transient behaviour of advanced transmutation systems, both critical and sub-critical
  - Papers at PHYSOR 2006, ICENES 2007, and GLOBAL 2007
  - Final CRP report to be published in 2009

IAEA Activities, cont'd

- Coordinated Research Project on "Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems" (2005 – 2010)
  - 27 institutions in 18 IAEA Member States
  - Computational and experimental benchmarking ➔ work domains: YALINA Booster, Kyoto University Critical Assembly (KUCA), TRADE, FEAT, TARC, ADS kinetics analytical benchmarks, actinides cross sections, spallation targets, ADS performance
  - Papers at AccApp2007, and PHYSOR2008

Outline

- Background
- Basics and objectives of P&T
- Nuclear fuel cycle options
- Advanced fuel cycles with P&T
- Transmutation reactors
- **Conclusions**

Conclusions for ADS

- Renewed interest in nuclear energy
- Sustainability ➔ spent fuel utilization and breeding returning to centre stage ➔ fast reactor necessary linchpin
- Significant reduction of the total Pu and minor actinides inventory ➔ closed fuel cycle strategy ➔ removal of minor actinides from liquid high-level waste before vitrification ➔ achieved by combining advanced MOX fuelled LWRs and dedicated fast reactors
- Significant radio-toxicity reduction levels ➔ innovative fuel cycles ➔ fast neutron ADS ➔ vastly enhanced core loadings flexibility, and ability to accommodate very high transuranics and minor actinides inventories) ➔ drastic minor actinides depletion

ADS an option considered for P&T

Conclusions for ADS (cont'd)

- Achieving the full potential of fast neutron system and closed fuel cycle technologies with regard to both efficient utilization of the fissile resources and waste management requires continued advances in research and technology development to ensure improved economics, and maintain high safety levels with increased design simplification
- IAEA assists Member States considering innovative fast neutron system technology options by providing an umbrella for information exchange and collaborative R&D to pool resources and expertise

For more information, please visit

http://www.iaea.org/inisnkm/nkm/aws/fnss/index.html

Thank You !