The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

Workshop on

ROLE OF PARTITIONING AND TRANSMUTATION IN THE MITIGATION OF THE POTENTIAL ENVIRONMENTAL IMPACTS OF NUCLEAR FUEL CYCLE

20 - 24 November 2006

ICTP - Trieste, Italy

1774/9

Introduction to the Workshop

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Introduction to the Workshop on 'Role of Partitioning and Transmutation in the Mitigation of the Potential Environmental Impacts of Nuclear Fuel Cycle'

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IAEA
Atoms for Peace: The First Half Century
1957–2007

Outline

- Background
  - Objectives of the Workshop
  - Nuclear energy
  - Partitioning and Transmutation
  - Fuel cycles options
- Partitioning methods, Aqueous and non-aqueous
- Proliferation resistance
- Advanced fuels
- Transmutation concepts, Gen-IV
- Environmental impact, HLLW, Repository

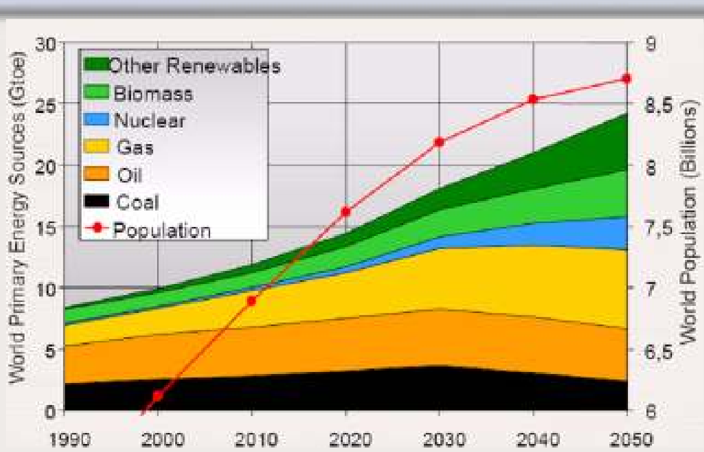
Objectives of the workshop on 'Role of Partitioning and Transmutation in the Mitigation of the Potential Environmental Impacts of Nuclear Fuel Cycle'

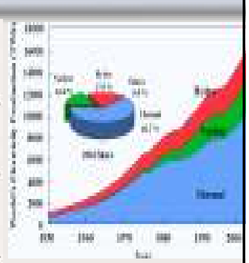
- Review of partitioning and recycling of TRUs fuels
- Overview of Transmutation schemes including Accelerators
- Important radio-nuclides and factors that determine environmental impact and the Separation criteria
- Relationship between environmental impact and parameters of P&T system
- Comparative evaluation of reduction of potential environmental impact in different fuel cycles with and without partitioning and transmutation scheme

Scope of the workshop

- Module 1: P&T
  - Introduction to fuel cycle
  - Review of partitioning methods
  - Appraisal of Advanced fuels
  - Overview of transmutation concepts
  - Overview of P&T concepts
- Module 2: Environmental impact
  - Assessment of radio-toxicity in fuel cycle
  - Waste forms / repositories
  - Definition of environmental impact
  - Important radionuclides and factors
  - Comparative evaluation of reduction of potential environmental impact

Future energy forecast

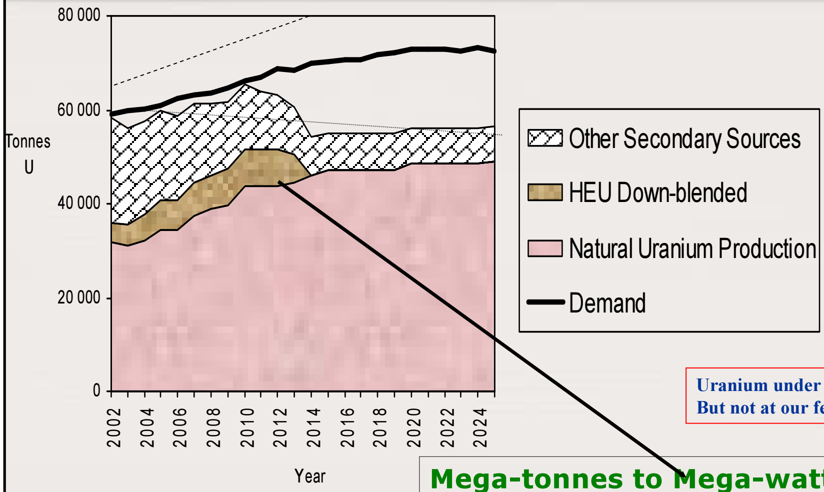




NUCLEAR CONTRIBUTION TO ELECTRICITY GENERATION

Sustainable development vision scenario, Gtoe stands for Giga (10^9) tonnes of oil equivalent ; Ref:- Energy to 2050 Scenarios for sustainable future, IEA, 2003

World uranium demand and supply projections

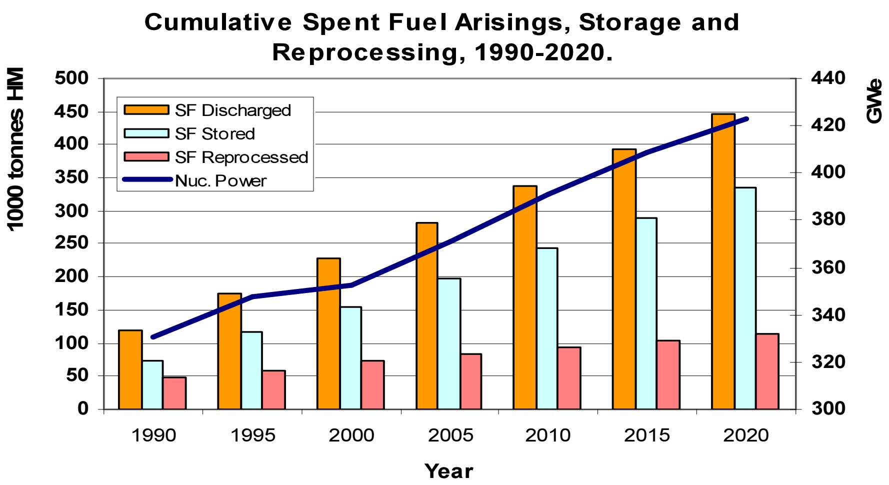


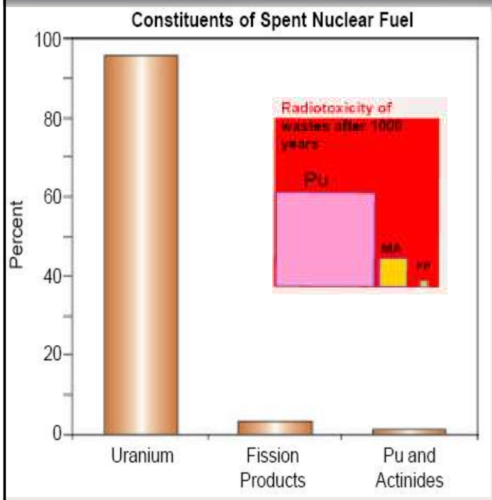
Uranium under our feet ….
But not at our feet

Mega-tonnes to Mega-watts

Ref: IAEA TECDOC on Management of High Enriched Uranium for Peaceful Purposes; *Status and Trends, TECDOC-1452, 2005*

Global Spent fuel accumulation





95.6% is uranium
3% is stable or short-lived fission products that do not pose major disposal challenges
0.3% is caesium and strontium that decays in a few centuries
0.1% is long-lived iodine and technetium
0.9% is plutonium
0.1% is long-lived actinides

- Several aspects of waste arisings:
  - Mass (tHM/TWhe)
  - Volume (m^3/TWhe)
  - Decay heat output
  - Radiotoxicity
- LWR once through and reprocessing cycles can be used to define baseline for advanced fuel cycle (AFC) systems

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Radiotoxicity

The radiotoxicity of a nuclide is determined by its *effective dose coefficient* e(T), which accounts for radiation and tissue weighting factors, metabolic and biokinetic information. The quantity T is the integration time in years following intake. For *adult workers*, the integration time is 50 years, such that the radiotoxicity (in Sv) resulting from intake of a particular nuclide is the product of the effective dose coefficient (units Sv/Bq) and the activity (in Bq) of that nuclide i.e

$$\text{Radiotoxicity} = \text{Activity} \times e(50)$$

Annual Limits of Intake

A useful quantity in connection with radiation exposure is the Annual limit of Intake or ALI value. The ALI value is the Annual Limit of Intake for a particular radionuclide and can be obtained by dividing the reference annual average dose (0.02Sv for workers) by the dose coefficient i.e

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$$ALI(Bq) = 0.02Sv/e(50)$$

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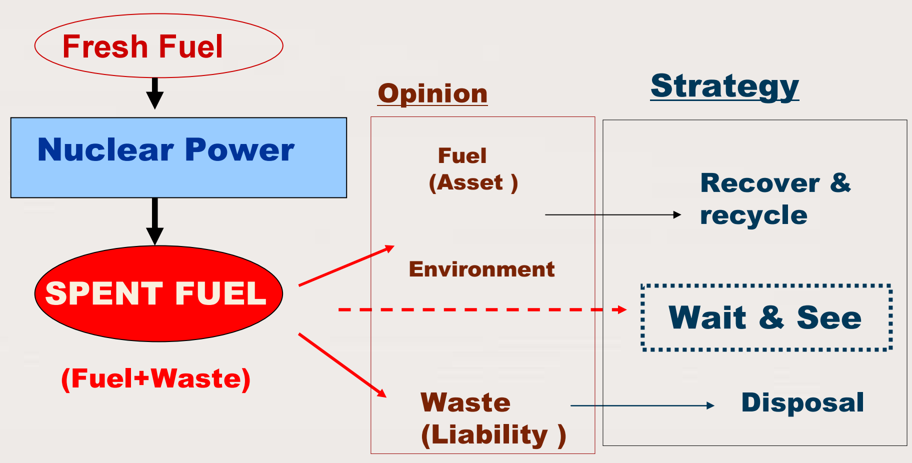
Radio-toxicity of average PWR spent fuel assemblies

Radionuclide	$T_{1/2}$ (y)	Sv	Radionuclide	$T_{1/2}$ (y)	Sv	Radionuclide	$T_{1/2}$ (y)	Sv
Hydrogen-3	12.3	7.99E+01	Antimony-125	2.77	1.06E+03	Uranium-236	2.34E+07	2.43E+02
Carbon-14	5.73E+03	1.42E+01	Tin-126	1.00E+05	7.83E+01	Uranium-238	4.47E+09	2.33E+02
Chlorine-36	3.01E+05	1.89E-01	Iodine-129	1.57E+07	7.33E+01	Neptunium-237	2.14E+06	9.77E+02
Iron-55	2.7	4.15E+01	Cesium-134	2.06	3.09E+04	Plutonium-238	87.7	1.62E+07
Cobalt-60	5.27	2.77E+04	Cesium-135	2.30E+06	2.00E+01	Plutonium-239	2.41E+04	1.67E+06
Nickel-59	7.50E+04	3.03E+00	Cesium-137	30	1.64E+07	Plutonium-240	6.54E+03	2.59E+06
Nickel-63	96	1.05E+03	Promethium-147	2.62	1.25E+03	Plutonium-241	14.4	4.26E+06
		-	Samarium-151	90	6.89E+02	Plutonium-242	3.76E+05	8.88E+03
Selenium-79	6.50E4	2.47E+01	Europium-154	8.8	7.10E+04	Americium-241	432	1.18E+07
Strontium-90	29.1	2.38E+07	Europium-155	4.96	1.30E+04	Americium-242m	152	7.73E+04
Zirconium-93	1.53E+06	4.88E+01	Actinium-227	21.8	2.97E-01	Americium-243	7.38E+03	1.04E+05
Niobium-93m	13.6	3.60E+00	Thorium-230	7.70E+04	1.09E+00	Curium-242	0.447	4.04E+03
Niobium-94	2.03E+04	3.77E+01	Protactinium-231	3.27E+04	4.20E-01	Curium-243	28.5	5.38E+04
Technetium-99	2.13E+05	1.73E+02	Uranium-232	72	2.56E+02	Curium-244	18.1	4.00E+06
Ruthenium-106	1.01	8.55E+00	Uranium-233	1.58E+05	5.85E-02	Curium-245	8.50E+03	1.63E+03
Palladium-107	6.50E+06	9.04E-02	Uranium-234	2.44E+05	1.18E+03	Curium-246	4.73E+03	3.65E+02
Cadmium-113m	13.6	9.36E+03	Uranium-235	7.04E+08	1.39E+01			

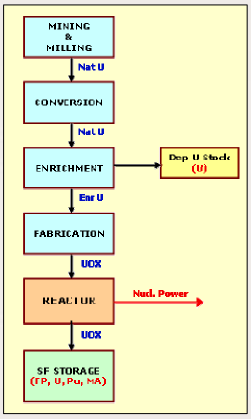
Inventory data: Inventory and Characteristics of Spent Nuclear Fuel, High-Level Radioactive Waste, and Other Materials (DOE/EIS-0250, February 2002): Burnup = 41,200 MWd/MTHM, enrichment = 3.75%, cooling = 23 years

Back-end fuel cycle strategies -

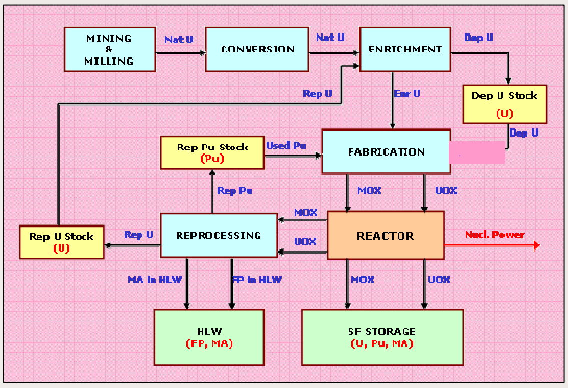


Fuel cycle options

Fuel Cycle in Once-Through Mode



Example for Closed Fuel Cycle viz., U + Pu Recycle Mode



Partitioning and Transmutation

- Partitioning is a series of physical and chemical separation processes which separate different radio-nuclides from a mixture, in order to permit their segregated treatment - e.g., Separation of TRUs and LLFPs - ^{99}Tc, ^{129}I
- Refabrication of TRU-rich fuel and targets
- Transmutation, on the other hand, is the process applied to the separated components. It is the destruction of radio-nuclides by converting them to different nuclides which are likely to have shorter half-lives and generally low toxicity. Transmutation is achieved by subjecting the "partitioned" (separated) radionuclides to intense neutron or proton radiation in either a nuclear reactor or a particle accelerator

Fuel Cycle that incorporate P&T to burn TRU elements is called Advanced Fuel Cycle

Advanced Fuel Cycle consists

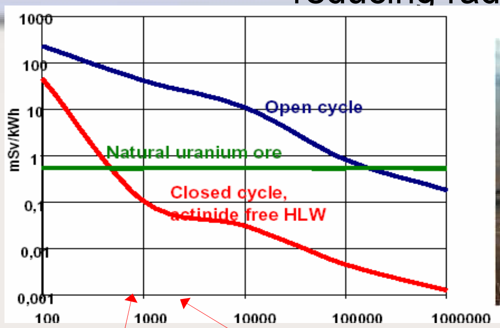
a) Reprocessing of LWR-UO_2 fuel
b) Separation of minor actinides from HLLW resulting from LWR-UO_2 reprocessing
c) Fabrication of MA targets for heterogeneous irradiation in LWRs
d) Quantitative recycling of U and Pu into LWR-Mixed Oxide (MOX) fuel
e) Reprocessing of spent LWR-MOX fuel in adequate facilities (higher Pu inventory)
f) Separation of MAs from HLLW & conditioning of individual elements MAs
g) Fabrication of FR -fuel (MOX, -metal or -nitride) with limited MA content
h) Irradiation in FRs or dedicated hybrid facilities to very high burnup
i) Reprocessing of spent FR-fuel in specially (aqueous and non-aqueous)
j) Quantitative separation of all TRUs from the spent FR fuel processing during multiple recycling
k) Multiple recycling of FR-MOX fuel (and /or ADS) with major TRU content until significant depletion
l) Separation of certain fission products with long half-lives if required for the disposal step

Source: P&T as a Waste Management Option in a Future Nuclear Era, L.H. Baestslé, in Proc. Workshop on Hybrid Nuclear Systems for Energy Production, Utilisation of Actinides & Transmutation of Long-lived Radioactive Waste, IAEA, Sep 3-7, 2001, ICTP, Trieste, Italy and IAEA, Vienna, Austria, 2001, IAEA/SMR/1326-3

Effects of Partitioning & Transmutation

- Toxicity reduction: A reduction of the hazard associated with spent fuel over the medium and long-term (> 300-400 years) by a significant reduction of the inventory of Pu and Minor actinides.
- Better use of repository capacity: Decrease of the spent fuel volume by separation of all actinides would result effective usage of repository. However, this approach might require special handling of Sr and Cs after partitioning.
- Effective resource utilization: Reuse of fissile and fertile materials from the spent fuel would drastically reduce fresh fissile materials requirements.
- Additional effects:
  - *Elimination of recriticality concern*: There may be a low probability of forming a recriticality condition by certain reconfiguration of wastes in a repository after a very long period of time.
  - *Long-term proliferation resistance*: Permanent safeguard monitoring may be required for those waste materials, which originated from safeguarded civilian facilities, unless they are converted into irrecoverable forms.

Role of partitioning and transmutation in reducing radio-toxicity

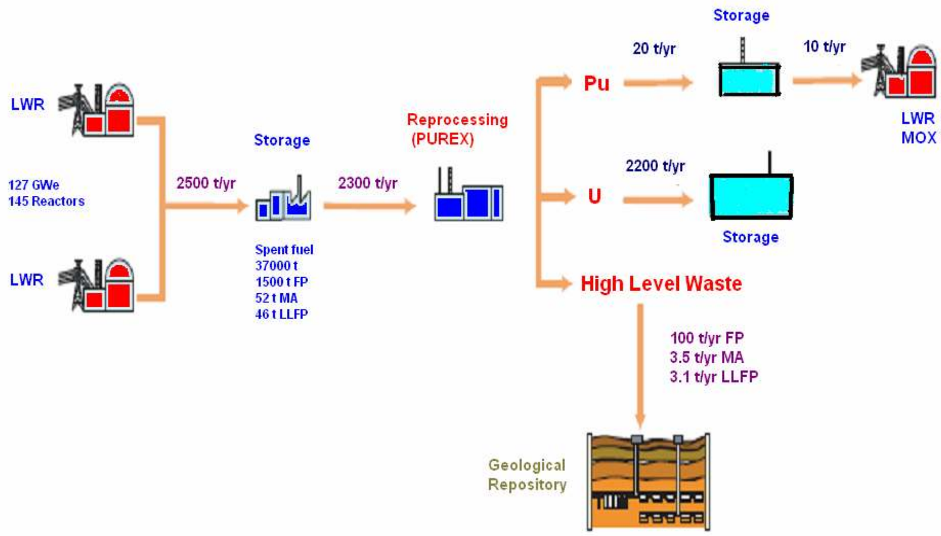


Notre Dame

Pyramids at Giza

Plutonium and minor actinides are responsible for most of the long term hazards

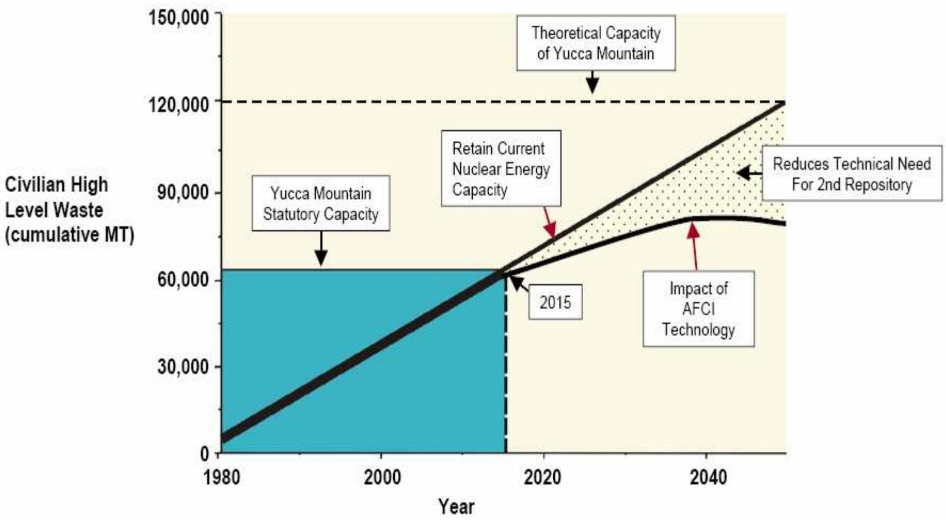
Public Confidence



Spent and processed fuel flow sheet in the European reactor park (127 GWe), cumulative amount and annual change as of 2001. Fuel burnup is 50 GWd/tHM. Figure is adopted from an EU roadmap report*1.

*1 A EU roadmap for developing accelerator driven systems (ADS) for nuclear waste incineration, Technical report, The European Technical Working Group on ADS, ENEA, 2001.

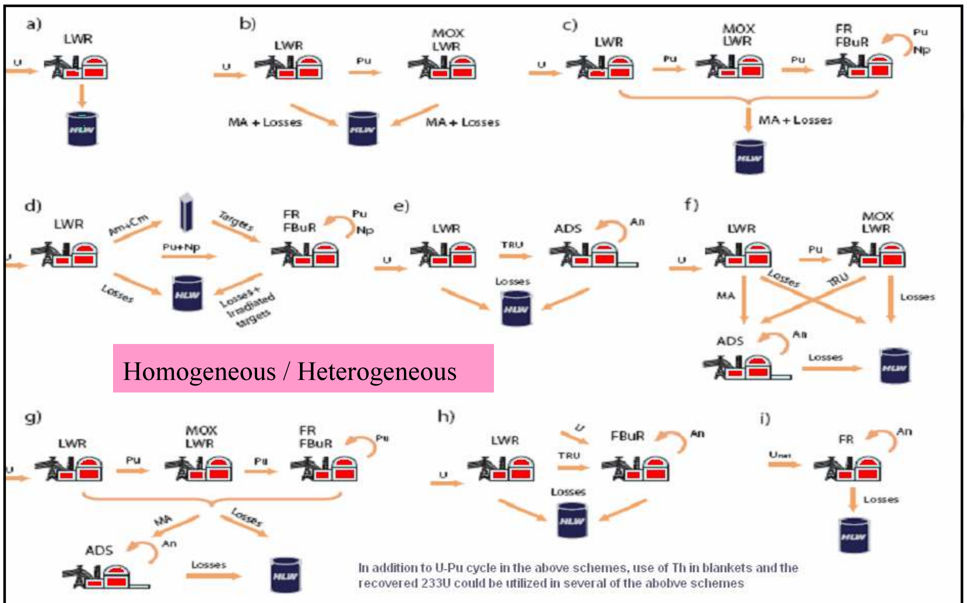
Spent fuel accumulation – Repository limitations



The table shows the number of Yucca Mountain equivalent repositories needed in the U.S. for various growth scenarios

Nuclear Futures	Legislative Limit	Existing License Completion	Extended License Completion	Continuing Level Energy Generation	Continuing Market Share Generation	Growing Market Share Generation
Cumulative Spent Fuel in 2100 (MTHM)	63,000	86,000	118,000	240,000	600,000	1,300,000
	Number of Repositories Needed					
Current Management Approach		2	2	4	10	20
1 % Net Efficiency improvement		2	2	4	9	18
Expand Repository Capacity		1	2	3	6	13
Efficiency Improvements + Capacity improvements		1	~1	~2	~5	11
Separation of Pu, minor actinides. Longer cooling		1	1	1	2	~4
Separation of Pu, minor actinides, Cs, and Sr		1	1	1	1	1

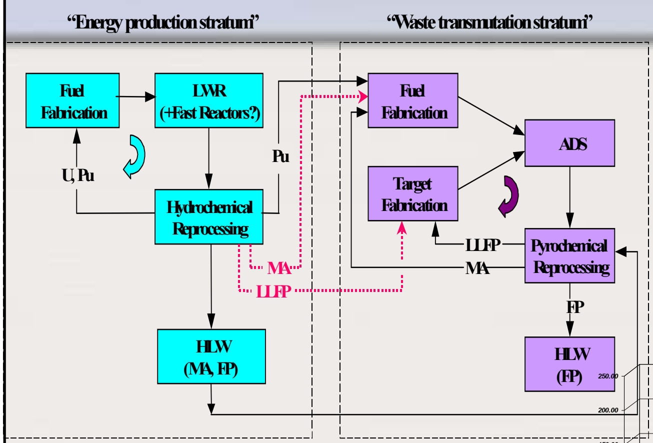
O. Kemal Pasamehmetoglu, The Fuels Development Program for the Advanced Fuel Cycle Initiative, ARWIF-2005, ORNL, USA

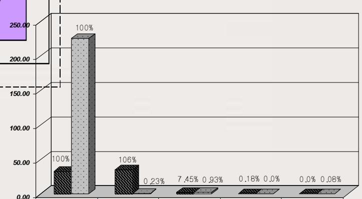


Fuel cycle/P&T scenarios: a) open "once-through" cycle; b) Pu MOX burning in LWRs; c) Pu MOX burning in LWRs & fast reactors (~70% LWR-UOX − ~10% LWR-MOX − ~20% FR); d) Pu burning & heterogeneous MA recycling in fast reactors; e) two-component strategy, TRU burning in ADS, ADS support ratio ~21%; f) two-component strategy, Pu MOX recycling in LWR prior to TRU burning in ADS, fraction of ADS ~15%; g) double-strata (multi-component, two-tier) scheme, fraction of ADS ~ 5-10%; h) TRU burning in FBuR, the reactor park consists of 63% LWRs and 37% FBuRs; i) one-component fast reactor cycle.

Based on the Ref: Neutronic and Burnup Studies of Accelerator-driven Systems Dedicated to Nuclear Waste Transmutation, Kamil Tuˇcek, Doctoral Thesis, (2004) Royal Institute of Technology, Sweden, http://www.neutron.kth.se/publications/library/KamilPhD.pdf

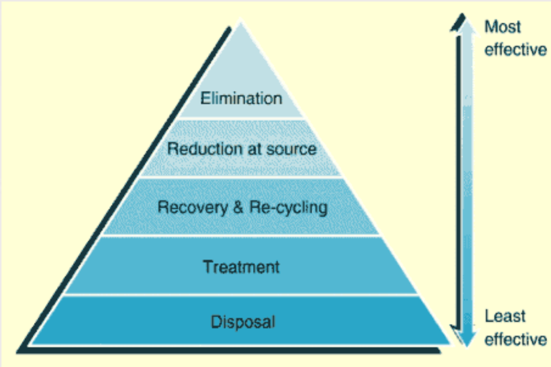
Double Strata approach



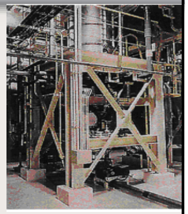


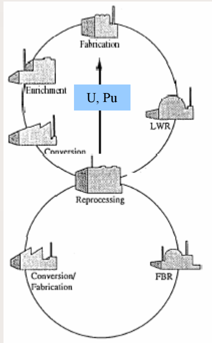
	Once through	LWR + FR (Homo)	LWR + FR (Hetero)	100% FR	double strata
MA (kg/Gwe-year)	32.94	35.04	2.45	0.06	0.00
Pu (kg/Gwe-year)	225.57	0.53	2.10	0.00	0.18

Relation between Recycling, Waste Minimization and Environmental impact



Any Industry

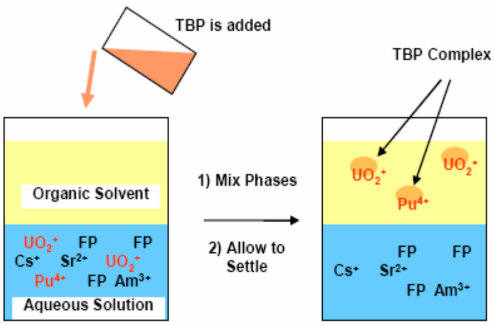




Classification of partitioning processes

- **Aqueous based processes**
  - **Liquid-liquid extraction**
  - Precipitation
  - Ion exchange
  - Membranes
  - Crystallization
  - Supercritical fluid extraction

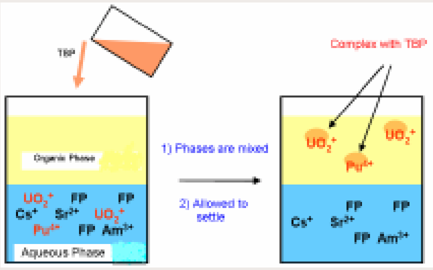
- **Dry processes**
  - Pyroprocessing
  - *Electrorefining*
  - *Oxide reduction*
  - Volatilization
- **Others**



Solvent Extraction Principle

- **Based on the relative stability of a metal species in two immiscible liquids**
  The metal species to be separated is contacted with both liquids and is distributed into each at a constant ratio.

- **Multiple extractions**
  - Not always possible to remove 100% metal with one contact.
  - Options are to greatly increase amount of solvent volume or to use multiple contacts

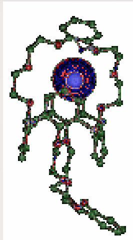


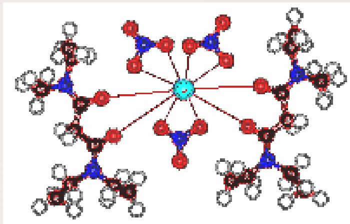
GLOBAL STATUS OF FUEL REPROCESSING BY PUREX

COUNTRY	FACILITY	OPERATION (Year)	CAPACITY (Fuel Type)
France	Marcoule (UP1) La Hague (UP2/3)	1958 -1985 1967/1990~	400 (GCR):decom 1600 (LWR)
Germany	WAK	1971 -1990	30 (LWR);decom
Japan	Tokai-Mura Rokkasho-Mura	1977 ~ 2006 ~	90 (LWR) 800 (LWR)
Russia	Chelyabinsk Krasnoyarsk	1971 ~ 2020 ~	400 (VVER-440) 1500 (VVER-1000)
UK	B205 THORP	1967~ 1994 ~	1500 (GCR) 900 (LWR)
USA	NFS West Valley	1966 -1972	194(LWR):decom
EURATOM	Mol	1966 -1975	105 (GCR+LWR):decom
India	Tarapur / Kalpakkam	1977~	~200 (PHWR)

Design of new extractants : main criteria

- Ability to separate
  - Selectivity
  - Reversibility
- Medium effects
  - Solubility
  - Stability / hydrolysis,
  - radiolysis
- Industrialization
  - Kinetics
  - Ability to regeneration
- Secondary waste minimization
  - Incinerability (C, H, O, N)





Actinide extraction by diamide

Recent progresses in actinide partitioning at ITU, Glatz J.P., et. al., in 8th Information exchange meeting on partitioning and transmutation, Las Vegas, NV , United States, 9-11 Nov 2004, OECD/NEA

Review of other aqueous partitioning methods for actinide–lanthanide group separation:

- DIAMEX (Diamide Extraction process) process to extract Am+Cm
- SESAME process for Am/Cm separation
- NEXT (New Extraction System for TRU Recovery) process for co-recovery of actinides which includes uranium crystallization step
- GANEX Process (Actinide Group Separation method)
- UREX process (Uranium Extraction)

What is the proliferation resistance?

Proliferation resistance is to be a characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology by States, in order to acquire nuclear weapons or other nuclear explosive devices.

- Material Barriers
  - Isotopic
  - Chemical
  - Radiological
  - Mass and Bulk
  - Detectability
- Technical barriers
  - Facility Unattractiveness
  - Facility Accessibility
  - Available Mass
  - Diversion Detectability
  - Skills and Knowledge
  - Time
- Institutional Barriers
  - Safeguards
  - Access and Security
  - Location

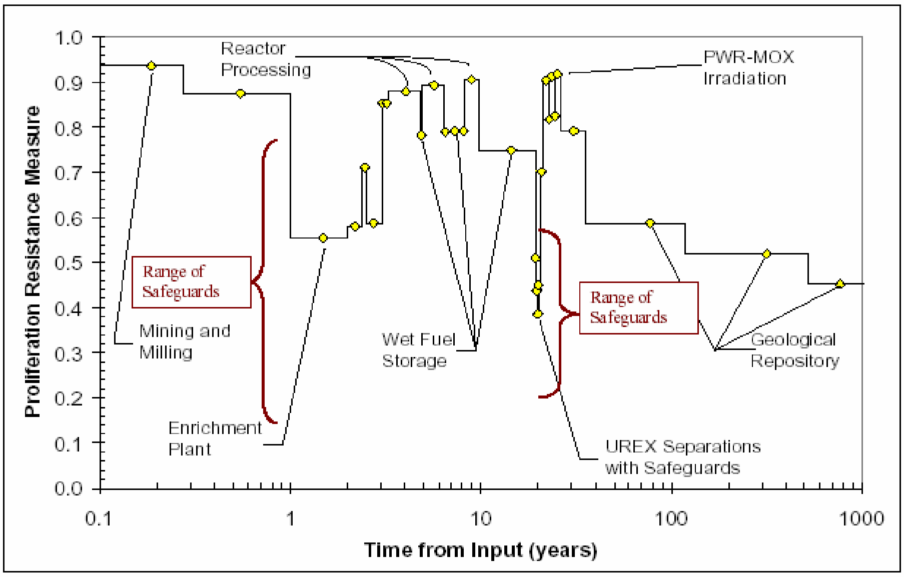


Figure . Proliferation Resistance Measure of a Single Fuel Assembly for All Steps in the Fuel Cycle with UREX and Neptunium Doping

Blue ribbon report: Total Nuclear Security Measures Integrated Over One Hundred Years

Cycle	Total Nuclear Security Measure
Once-Through PWR Cycle	0.657
LWR MOX w/ PUREX	0.641
LWR MOX w/ UREX	0.644
Inert Matrix Fuel w/ UREX	0.746
UREX with Np Doping	0.664
UREX with Np and Am Doping	0.665

Congruency in different partitioning methods

Aqueous method	Pyro-chemical method
Very high throughputs	Short-cooled fuels with with large MAs-content
Industrial maturity	Compact and integrated processing facility with reactor
	Less criticality concerns
	Intrinisic proliferation-resistant attributes
	Very small volumes of the wastes
	Minimum TRU-losses.
Required for large volumes of spent fuel from LWRs	Meets the needs of TRU-Burner & ADS

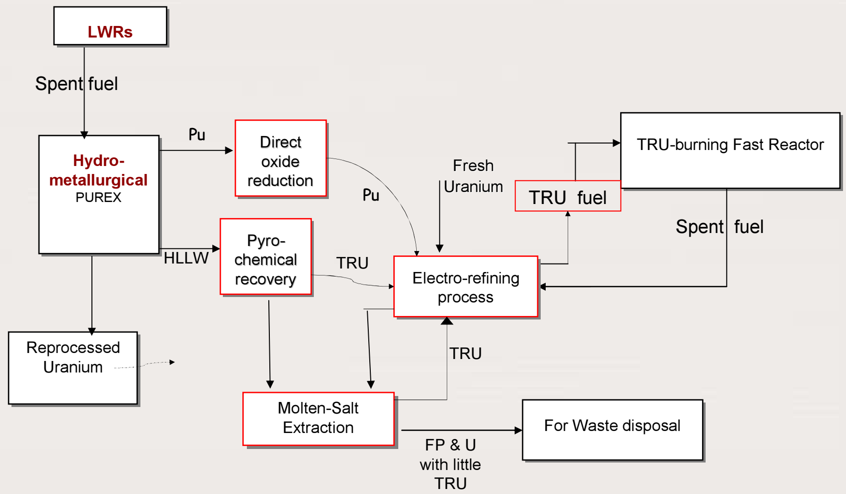
List of Pyroprocesses

- Halide Volatility Process
- Liquid-liquid extraction: Salt Transport Process
- Melt Refining Process
- Electro-refining / Electro-winning
- Others – AIROX, Voloxidation, DUPIC, Plasma process

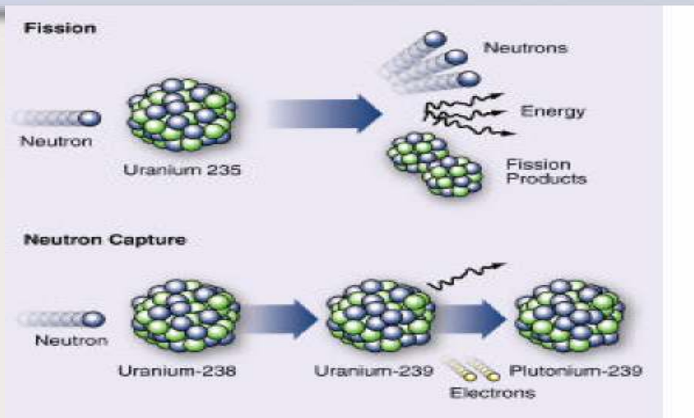
Review of pyro-chemical methods

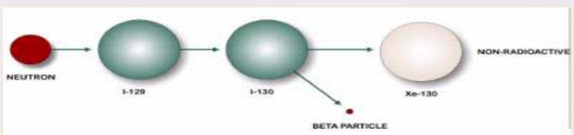
	Metal Electro-refining	Oxide Electro-winning	Chloride / fluoride volatility	Nitride electro-refining	Pyro for HLLW	Novel and auxiliary methods
1. Fuel form	Zr-based actinide alloys	Mixed actinide oxides	ADS targets & TRISO fuel	Actinide nitride	Link from aqueous methods	Plasma process Li reduction
2. MA loading	Single step Fuel fabrication	Different steps		High MA loading		
3. Scale	Semi-plant	Semi plant	Laboratory	Laboratory	Laboratory	Laboratory
4. Some of the interested Member States	USA, Japan, EU, Korea, India	Russia, Japan, EU	USA, EU	Japan	USA, Russia, Japan, EU	USA, Russia, Japan, EU

TRU- FR burner, multiple recycling fuel cycle scenario



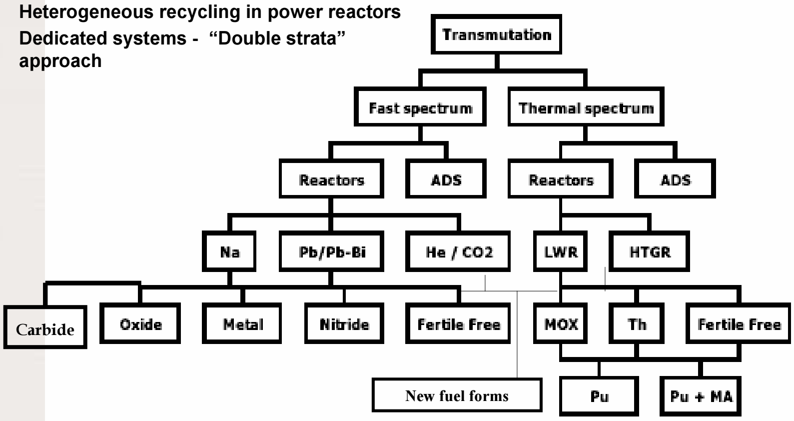
What is transmutation





Types of transmutation schemes

- Homogeneous recycling in power reactors
- Heterogeneous recycling in power reactors
- Dedicated systems - “Double strata” approach

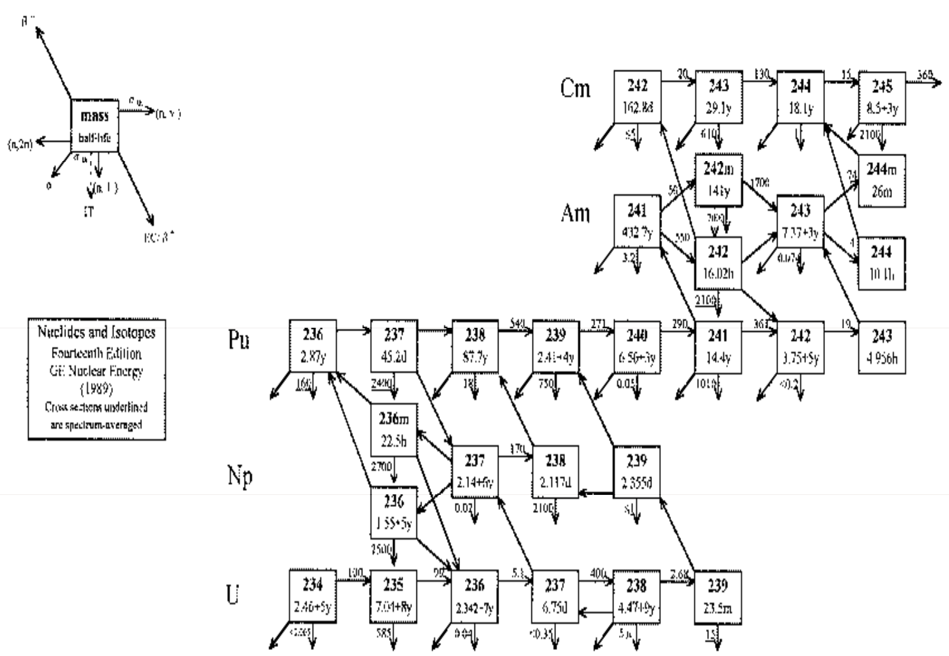


The physics of the transmutation : the neutron cross-sections

Isotope	Thermal neutron spectrum (PWR)			Epithermal neutron spectrum (PWR - MOX)			Fast neutron spectrum (FNR)		
	σ_f	σ_c	$\alpha = \sigma_c / \sigma_f$	σ_f	σ_c	$\alpha = \sigma_c / \sigma_f$	σ_f	σ_c	$\alpha = \sigma_c / \sigma_f$
^{235}U	38.8	8.7	0.22	12.6	4.2	0.3	1.98	0.57	0.29
^{238}U	0.103	0.86	8.3	0.124	0.8	6.5	0.04	0.30	7.5
^{237}Np	0.52	33	63	0.6	18	30	0.32	1.7	5.3
^{241}Am	1.1	110	100	0.8	35.6	44.5	0.27	2.0	7.4
^{243}Am	0.44	49	111	0.5	31.7	63.4	0.21	1.8	8.6
^{243}Cm	88	14	0.16	43.1	7.32	0.2	7.2	1.0	0.14
^{244}Cm	1.0	16	16	1	13.1	13.1	0.42	0.6	1.4
^{245}Cm	116	17	0.15	33.9	5.4	0.2	5.1	0.9	0.18

Neutron cross sections of the actinides and σ_c / σ_f ratio

M. Delpech, et. al., Technical Meeting on “Fissile Material Management Strategies for Sustainable Nuclear Energy” – Sept. 12-15, 2005 , IAEA, Vienna

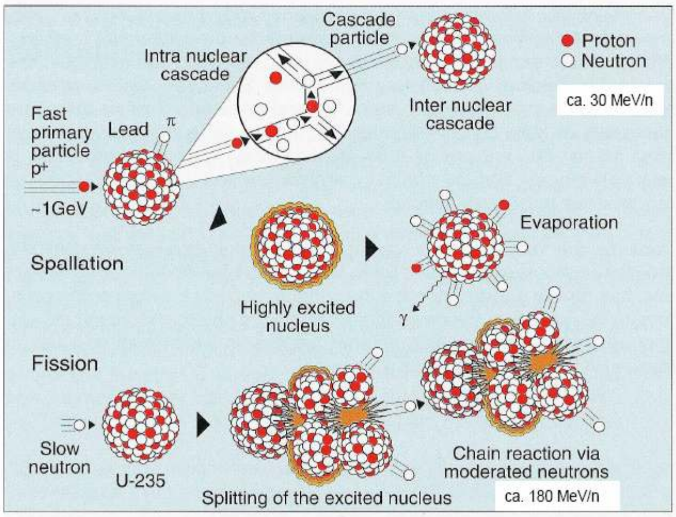


Accelerator-driven system

- Powerful accelerators can produce neutrons by spallation.
- This process may be linked to conventional nuclear reactor technology in Accelerator-Driven Systems (ADS) to transmute heavy isotopes in spent nuclear fuel into shorter-lived fission products.
- There is also increasing interest in the application of ADS to running sub-critical nuclear reactors, powered by thorium.

IAEA Technology Advances in Fast Reactors and Accelerator Driven Systems
(http://www.iaea.org/inis/aws/fnss/)

Visualisation of the Spallation and Fission Processes



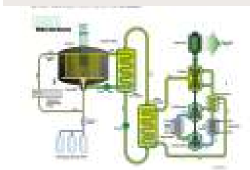
Cascade particles have energies up to the incident proton energy and can cause evaporation reactions in other nuclei

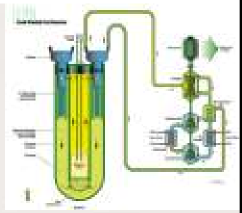
In contrast to fission, spallation cannot be self sustaining!

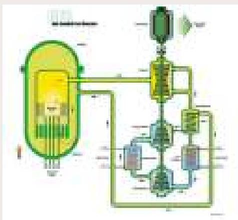
Fission neutrons must be moderated (slowed down to thermal energies) to cause fission in other nuclei

Generation IV Nuclear Energy Systems

Generation IV System	Acronym
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical-Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR







Conventional & Advanced Nuclear Fuels for Power Reactors

Reactors	Conventional Fuels	Advanced/Alternative Fuels
Light Water Reactor (LWR): BWR, PWR & VVER		
Fuel	LEU ($U^{235} \leq 5\%$) as UO_2	LEU (U^{235} 5-10%) Mixed Uranium Plutonium Oxide ($\leq 10\%$ PuO_2)
Cladding	Zircaloy 2 (BWR) Zircaloy 4 (PWR) Zr-1% Nb (VVER)	Zr-Sn-Nb-Fe & Zr-Nb-O alloys
Burn up	20,000-30,000 MWD/t	High : upto 60,000 MWD/t Ultra High: upto 90,000 MWD/t
Pressurised Heavy Water Reactor (PHWR)		
Fuel	Natural UO_2	REU, SEU in the form of UO_2, $(Th,Pu)O_2$ & $(Th,U^{233})O_2$, containing upto 2% fissile material
Cladding	Zircaloy 4	Zircaloy 4
Burn up	6,700 MWD/t	15,000-20,000 MWD/t
Liquid Metal-cooled Fast Breeder Reactor (LMFBR)		
Fuel	HEU in the form of UO_2 & $(U,Pu)O_2$ ($\leq 25\%$ Pu)	(U,Pu)C, (U,Pu)N & U-Pu-Zr, ($\leq 25\%$ Pu) with/without minor actinides
Cladding	Stainless Steel D-9	S.S. (HT-9 or Oxide dispersed)
Burn up	100,000 MWD/t	Upto 200,000 MWD/t
Breeding Ratio	≤ 1.2	Upto 1.5
High Temperature Gas Cooled Reactors (HTR)	Multi-layer (pyrolytical carbon & SiC-coated) Uranium Oxide fuel particles (BIS or TRISO) embedded in graphite	Multi-layer (pyrolytical carbon & ZrC coated) Uranium Oxide, Mixed Uranium Plutonium Oxide, Mixed Uranium Thorium Dicarbide, etc., embedded in graphite

Issues in MA-based fuel development

- MA-based fuel must be fabricable using remote processes
- The fuel must be compatible with the fuel recycle process
- The fuel form must provide robust containment for fission products

- The technologies of minor actinide-bearing-fuel materials are not well established (although, for dilute minor actinide contents, the properties should not differ substantially from the base U-Pu-bearing materials).

Fuel type	PWR		FR			ADS
Fuel cycle management	*MOX as reference*	*Pu+MA recycling*	*Pu-only recycling*	*Pu+MA recycling*	*MA target subass.*	*MA recyling*
At fabrication step						
Decay heat (W g^{-1} H.M.)	1	x 3	0,5	x 2,5	x 80	x 90
Neutron sources (n s^{-1} g^{-1} H.M.)	1	x 8 000	1	x 150	x 5 000 / x 10 000	x 20 000

iHM: initial Heavy Metal

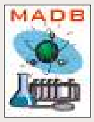
M. Delpech, et. al., Technical Meeting on "Fissile Material Management Strategies for Sustainable Nuclear Energy" – Sept. 12-15, 2005 , IAEA, Vienna

PROGRAMME ON TRANSMUTATION AND INCINERATION SHOWING FUELS AND TARGETS FABRICATED AT ITU (Ref: IAEA-TRS-435)

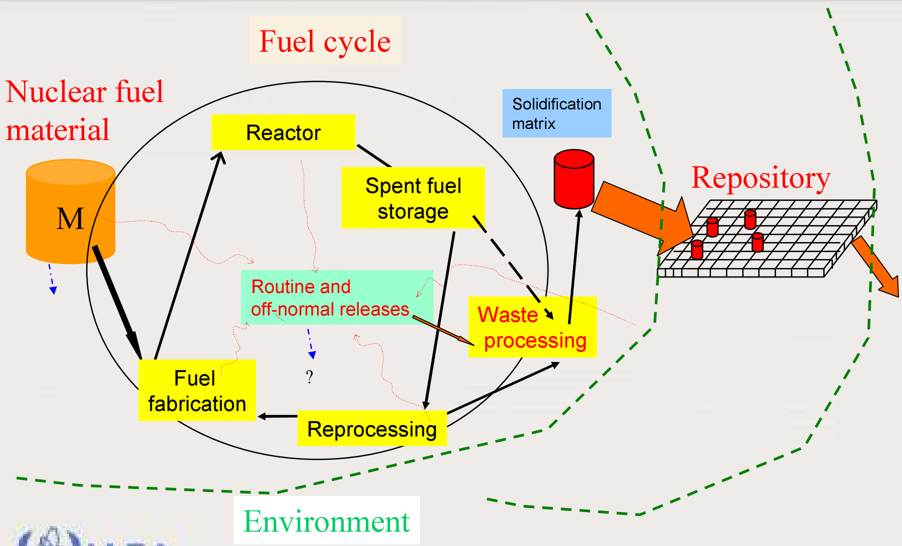
Programme	Reactor	Fuel/Target	Method	Status
FACT	FR2(1981)	$(U_{0.5}Am_{0.5})O_2$	sol-gel	PIE complete
MTE2	KNK II (1984-85)	NpO_2; $(U_{0.5}Am_{0.5})O_2$	sol-gel	PIE complete
		$(U_{0.73}Pu_{0.25}Np_{0.02})\ O_2$	sol-gel	PIE complete
		$(U_{0.73}Pu_{0.25}Am_{0.02})\ O_2$	sol-gel	PIE complete
SUPERFACT1	Phenix (1986-88)	$(U_{0.74}Pu_{0.24}Np_{0.02})O_2$	sol-gel	PIE complete
		$(U_{0.74}Pu_{0.24}Am_{0.02})O_2$	sol-gel	PIE complete
		$(U_{0.55}Np_{0.45})O_2$	sol-gel	PIE complete
		$(U_{0.6}Am_{0.2}Np_{0.2})O_2$	sol-gel	PIE complete
POMPEI	HFR (1993-94)	Tc metal	casting	PIE in progress
		Tc-50% Ru metal	casting	PIE in progress
		Tc-80% Ru metal	casting	PIE in progress
TRABANT1	HFR (1995-96)	$(U_{0.55}Pu_{0.40}Np_{0.05})O_2$	sol-gel	PIE in progress
		$(Pu_{0.47}Ce_{0.53})O_{2-x}$ [two O/M]	sol-gel	PIE in progress
EFTTRA-T1	HFR (94-95)	Tc metal [three pins]	casting	PIE complete
EFTTRA-T4	HFR (96-97)	$MgAl_2O_4$-12% Am	INRAM (pellets)	PIE complete
EFTTRA-T4bis	HFR (97-99)	$MgAl_2O_4$-12% Am	INRAM (pellets)	PIE in progress
TRABANT2	HFR	$(U_{0.55}Pu_{0.45})O_2$	sol-gel	Irrad. to be started
		$(U_{0.6}Pu_{0.4})O_2$ [two pins]	mech.mix.	Irrad. to be started
ANTICORP	Phenix	Tc metal	casting	Irrad. to be started
METAPHIX	Phenix	U,Pu,Zr	casting	Irrad. to be started
		UPuZrMA2%RE2%	casting	Irrad. to be started
		UpuZrMA5%RE5%	casting	Irrad. to be started
		UpuZrMA5%	casting	Irrad. to be started

IAEA Minor Actinide Property Database (MADB)

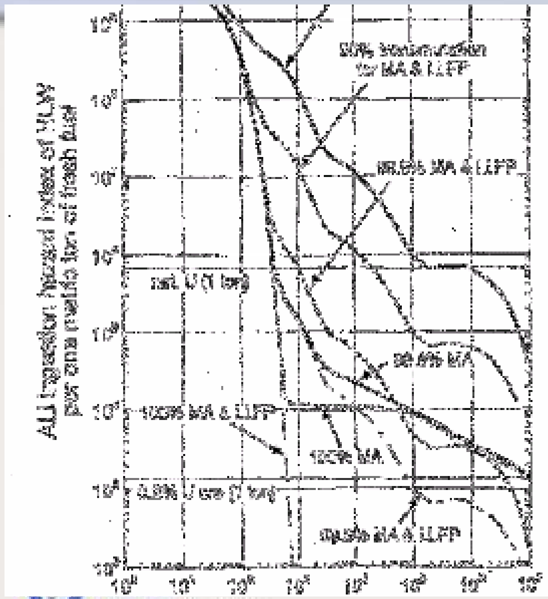
- Bibliographic database on thermodynamic and thermophysical properties of minor actinide (Np, Am, Cm) metals, alloys and compounds
- Access on the internet with some search and filter capabilities (www-nfcis.iaea.org)

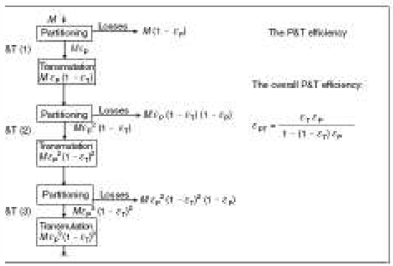


Nuclear Fuel Cycle and Environmental Impact



Relation between efficiency of P&T and toxicity reduction





Cradle-to-grave approach

Environmental impact categories / classification factors

- Global warming potential (CO_2-eq)
- Acidification potential (SO_2-eq)
- Ozone depletion potential
- Radiological impact potential
- Nitrification potential
- Abiotic resource depletion potential
- Human toxicity air/water
- Eco-toxicity aquatic

Waste categories

Category	HLW (deep geological disposal)	LILW-LL (geological disposal)	LILW-SL (surface or geological disposal)
Main characteristic	Highly radioactive waste, containing mainly fission products, as well as some actinides, separated during reprocessing of irradiated fuel. Spent fuel, if it is declared a waste.	Waste which, because of its radionuclide content requires shielding but needs little or no provision for heat dissipation during its handling and transportation.	Waste, which, because of its low radionuclide content, does not require shielding during normal handling and transportation.
Heat generation	Any other waste with radio-activity levels intense enough to generate heat more than 2 kW/m^3 by the radioactive decay process.	< 2 kW/m^3	< 2 kW/m^3
Half-life		> 30 y	< 30 y
Other characteristic			Activity content < 400 Bq/g of long lived alpha emitters.

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Advanced Fuel Cycles and Radioactive Waste Management, OECD / NEA, (2006)

WASTE FORMS

- **High level Waste (HLW):**
  - **- nuclear power plants**
  - **- research reactors**
  - **- production of radio-istopes**
- **Low/Intermediate Level waste (L/ILW):**
  - **- nuclear power plants**
  - **- research reactors**
  - **- nuclear medicine**
  - **-research / industry**

-Storage
-Performance

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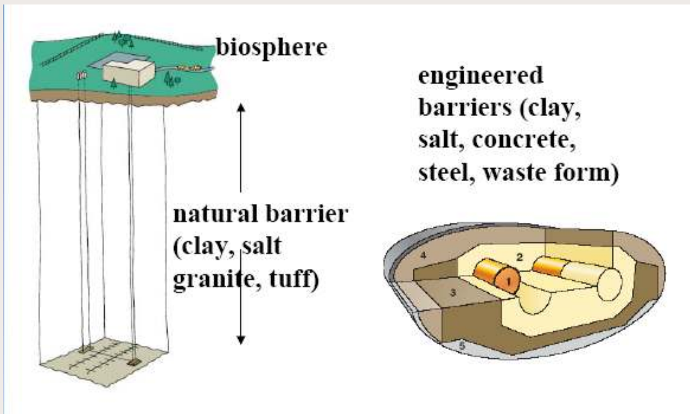
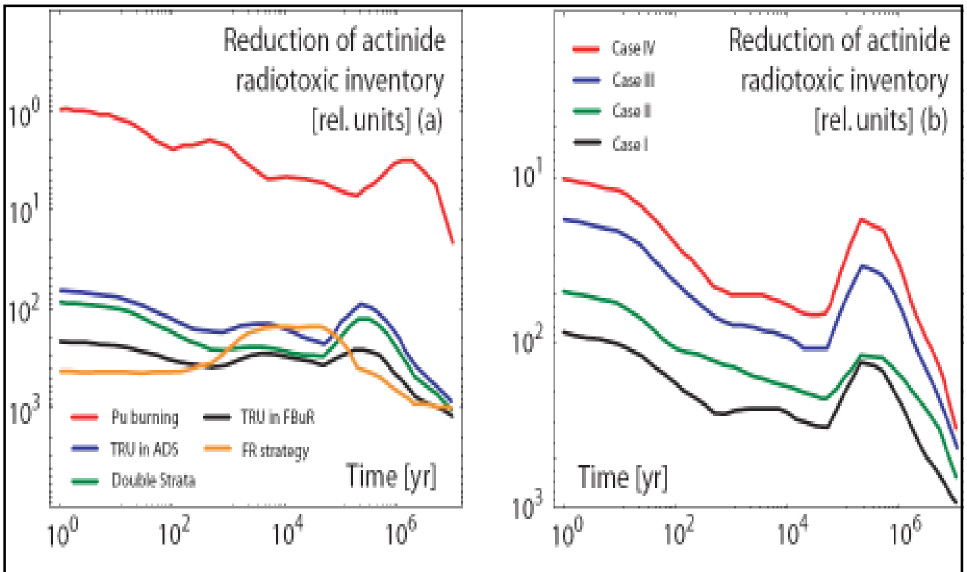
Deep disposal of HLW



Environmental impact measure

Measure for repository performance	Significance of geosphere	Effect of reducing toxicity by transmutation
Exposure dose rate of a human living in a certain location from the repository	Natural barrier to the radionuclides migration	Little sensitive
Environmental impact as the sum of toxicity indices existing in the far field	Part of the environment	Sensitive

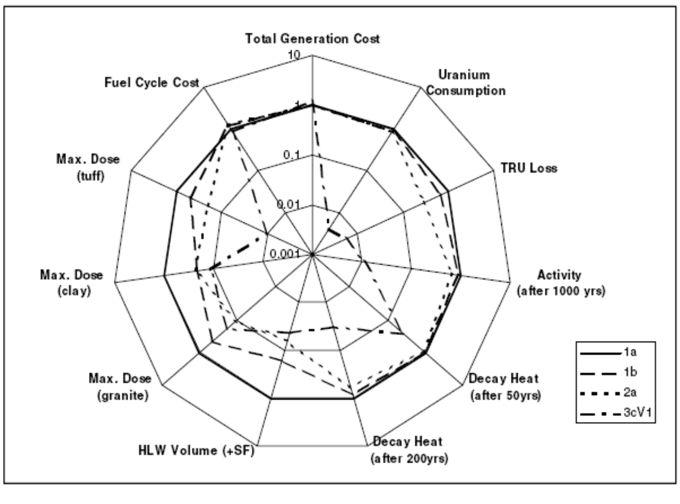
Schematic view of repository and environment.



Reduction of radiotoxic inventory for different P&T schemes (a) and an impact of fuel losses in separation technologies on a performance of double-strata scenario (b). Reprocessing losses in advanced PUREX of the first stratum were assumed to be either 0.1% for all actinides in Case I, or 0.1% for U&Pu and 1% for MA in Cases II-IV. Losses in pyro-reprocessing are 0.1% (Case I&II), 0.5% (Case III) and 1.0% (Case IV), respectively.

Figure from Ref. *Accelerator-driven Systems (ADS) and Fast Reactors (FR) in Advanced Nuclear Fuel Cycles, A Comparative Study*, OECD/NEA, 2002.

Comparison of 11 representative indicators for various fuel cycle schemes



Note: 1a: once-through PWR scheme (reference); 1b: 100% PWRs, 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.

Advanced Fuel Cycles and Radioactive Waste Management, OECD / NEA, (2006)

Cross-cutting issues

- Regional centres for implementation of P&T
- Holistic Environmental impact assessment

Future directions

- Regional centres for implementation of P&T
- Transmutation of LLFP
- Reuse options for waste
- Scientific breakthroughs – such as LASER transmutation, - group separation of actinides

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