



The Abdus Salam
International Centre for Theoretical Physics



Workshop on

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

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**Overview of Aqueous Methods for
Partitioning Minor Actinides
and
Fission Products**

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Overview of Aqueous Methods for Partitioning Minor Actinides and Fission Products

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- ❑ Nuclear Fuel Cycle
- ❑ PUREX Process
- ❑ Partitioning & Transmutation
- ❑ Chemistry of Lanthanides and Actinides
 - ❖ Occurrence
 - ❖ Valency
 - ❖ Hydrolysis
 - ❖ Complexation
 - ❖ Polymerization
 - ❖ Disproportionation
 - ❖ Interconversion of valencies
 - ❖ Criticality
 - ❖ Radiological safety

□ Extractants and Diluents for Reprocessing, Partitioning, An/Ln Separation

- ❖ TBP
- ❖ Dialkyl Monamides
- ❖ CMPO (O Φ CMPO, D Φ CMPO)
- ❖ Diamides (TODGA, TEHDGA, DMDOHEMA)
- ❖ TOPO, TRPO
- ❖ D2EHPA, DIDPA, DNPPA
 - Type of species
 - extraction characteristics
 - degradation (radiolysis, chemical and thermal)
 - solvent clean-up
 - third phase formation
 - synthesis
- ❖ Diluents
- ❖ Problems in Reprcesing and Partitioning
 - ❖ Solvent Degradation
 - ❖ Third Phase Formation

- LLFPs

- Chemistry

- Half Life, Decay scheme

- Fission Yield

- Fate in Reprocessing

□ Overview of R&D on Partitioning Research on MAs and LLFPs

❖ Japan

❖ India

❖ China

❖ Russia

❖ Germany

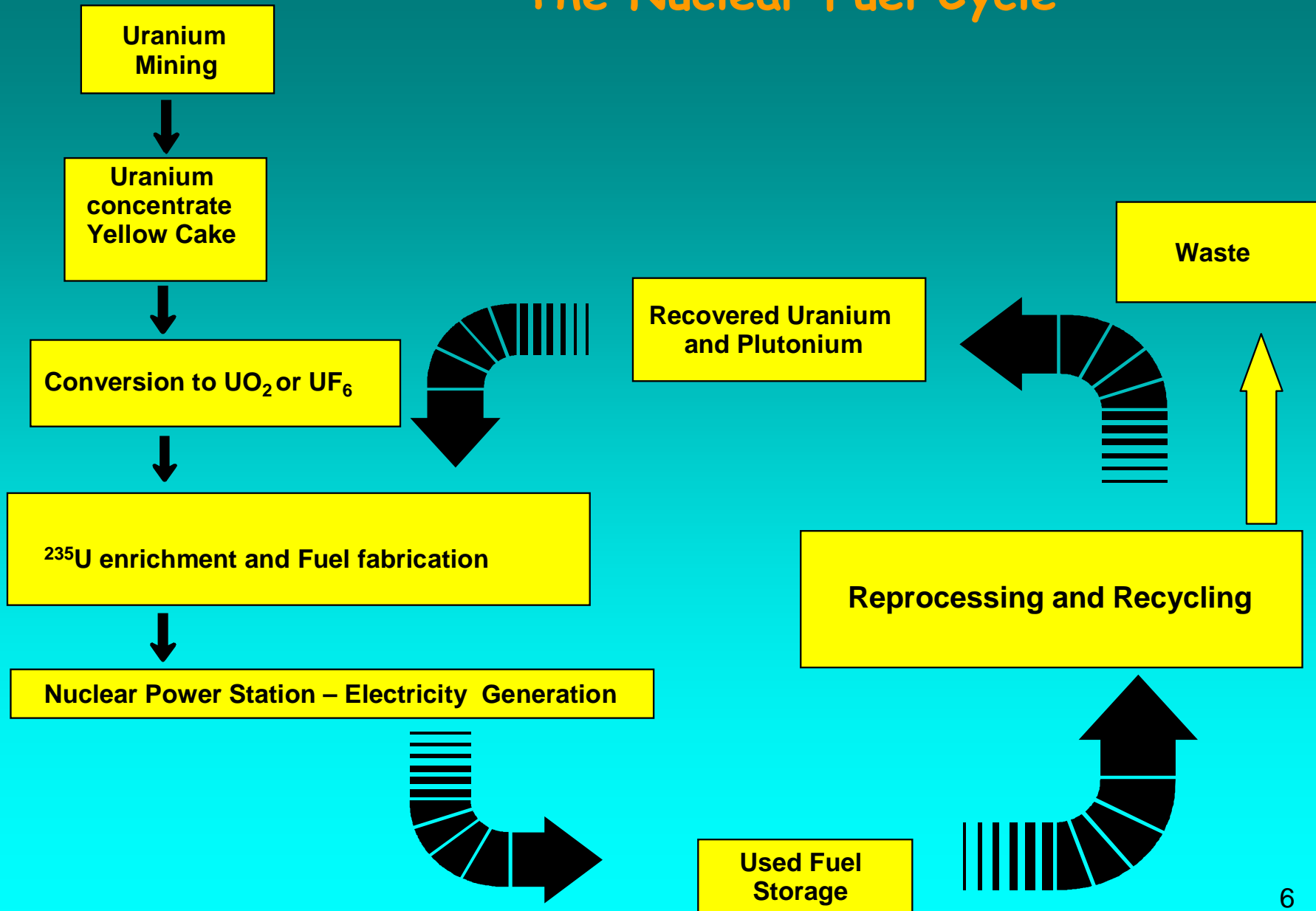
❖ France

❖ UK

❖ USA

❖ Korea (Essentially Pyro)

The Nuclear Fuel Cycle



ACTINIDE IN SPENT FUEL

<table border="1" style="margin: auto;"> <tr> <td colspan="2" style="text-align: center;"> UOX 45 GWd/t (4 years cooled) </td> </tr> <tr> <td style="text-align: center;"> U Pu Np Am Cm </td> <td style="text-align: center;"> 941 kg/tMLI 11,3 kg/tMLI 611 g/tMLI 605 g/tMLI 90 g/tMLI </td> </tr> </table>																		UOX 45 GWd/t (4 years cooled)		U Pu Np Am Cm	941 kg/tMLI 11,3 kg/tMLI 611 g/tMLI 605 g/tMLI 90 g/tMLI
UOX 45 GWd/t (4 years cooled)																					
U Pu Np Am Cm	941 kg/tMLI 11,3 kg/tMLI 611 g/tMLI 605 g/tMLI 90 g/tMLI																				
1 H																	2 He				
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne				
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 A				
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr				
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn				
87 Fr	88 Ra	89 <i>An</i>	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun												

57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

 ACTINIDES MAJEURS	 ACTIVATION PRODUCTS
 FISSION PRODUCTS	 FISSION AND ACTIVATION PRODUCTS
 ACTINIDES MINEURS	

Courtesy : Bernard Boullis, CEA

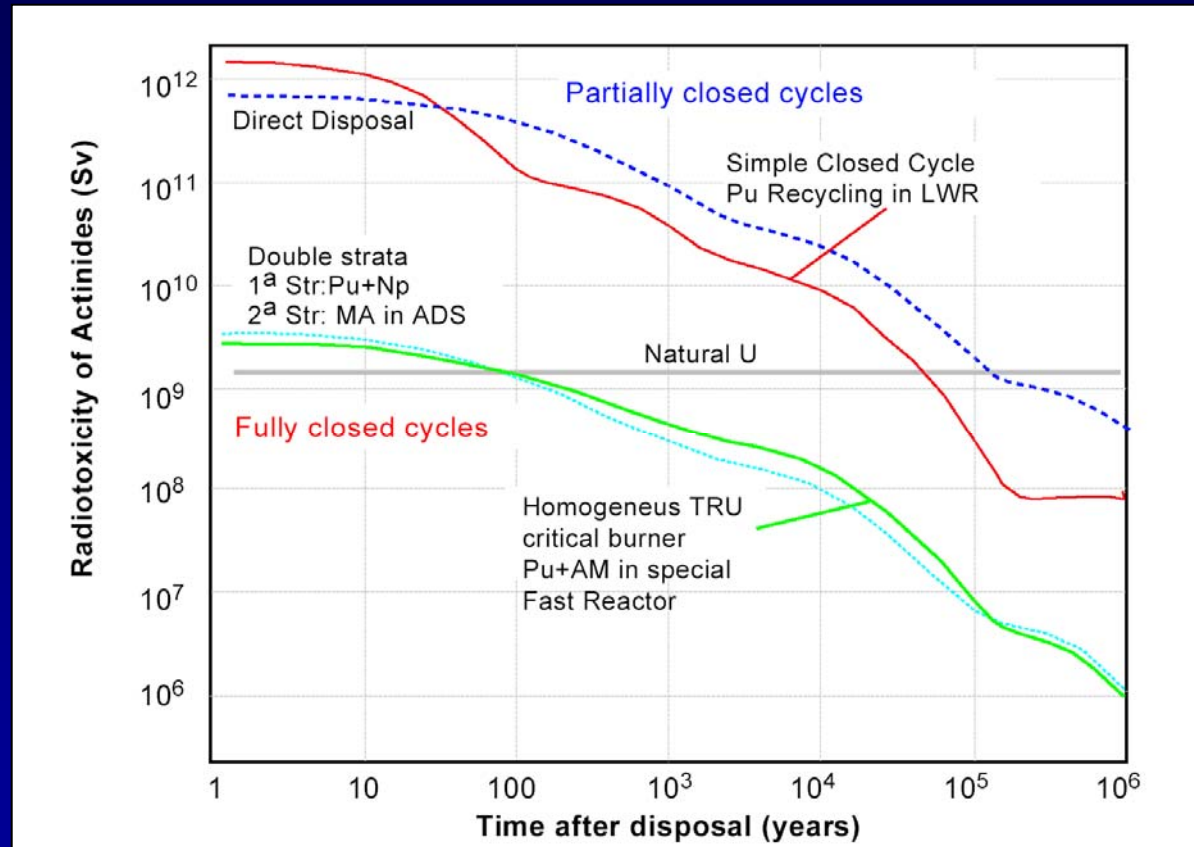
Element	Nuclide	Sv/Bq (ingestion)
Uranium	^{235}U	4.6×10^{-8}
	^{238}U	4.4×10^{-8}
Neptunium	^{237}Np	1.1×10^{-7}
Plutonium	^{238}Pu	2.3×10^{-7}
	$^{239}\text{Pu}, ^{240}\text{Pu}$	2.5×10^{-7}
Americium	$^{241}\text{Am}, ^{243}\text{Am}$	2.0×10^{-7}
Curium	^{243}Cm	1.5×10^{-7}
	^{244}Cm	1.2×10^{-7}
	$^{245}\text{Cm}, ^{246}\text{Cm}$	2.1×10^{-7}

Effective dose coefficients of actinides and lanthanides

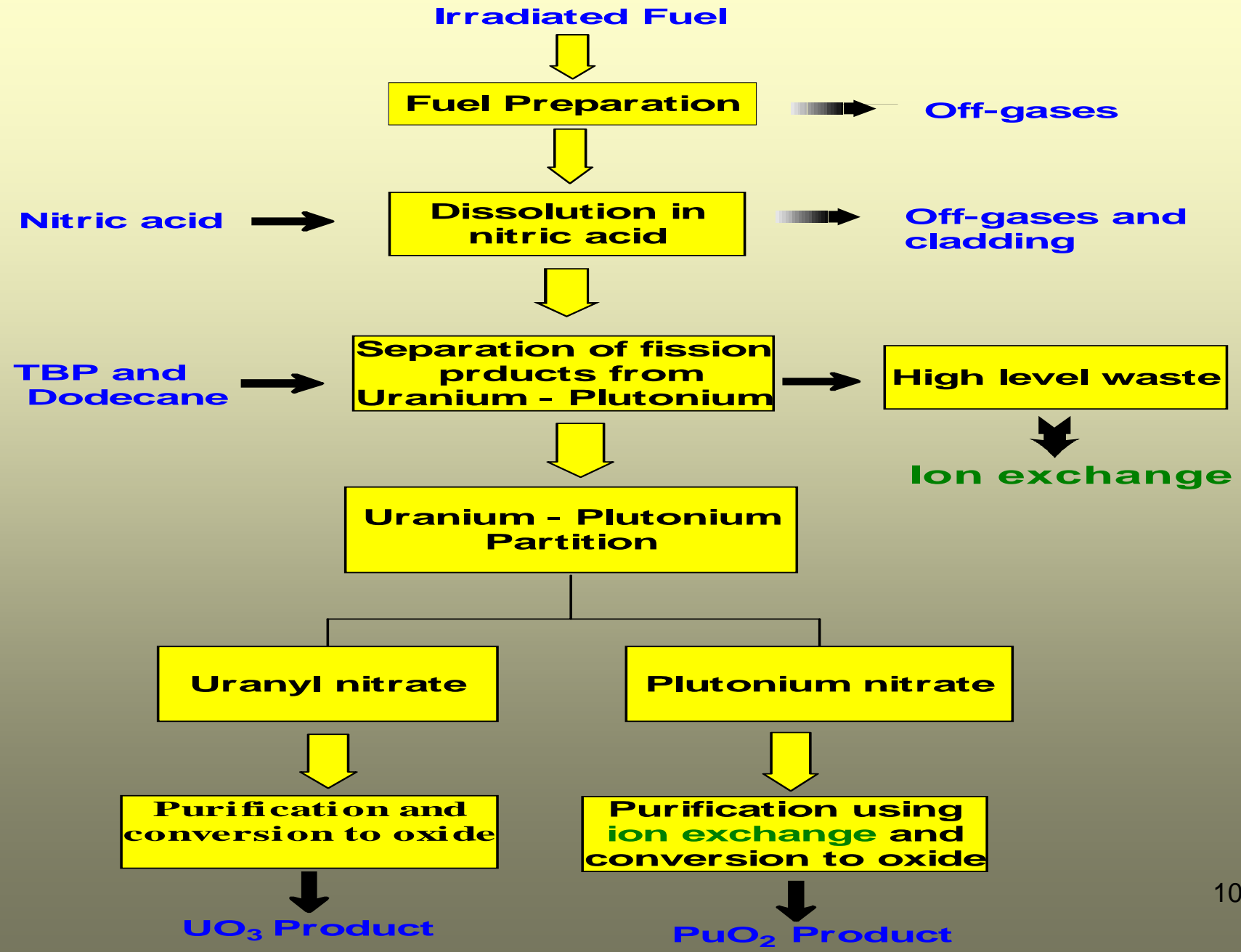
Element	Nuclide	Sv/Bq (ingestion)
Strontium	^{90}Sr	3.4×10^{-10}
Zirconium	^{93}Zr	8.6×10^{-10}
Technetium	^{99}Tc	6.4×10^{-10}
Iodine	^{129}I	1.1×10^{-7}
Caesium	^{135}Cs	2.0×10^{-9}
	^{137}Cs	1.3×10^{-8}

Effect of transmutation on partitioned actinides

Courtesy : Enrique M. Gonzalez, CIEMAT



PUREX Process



Actinide Chemistry

- The series of elements beginning with actinium (atomic number 89) and including Th, Pa, U and the transuranium elements through the element lawrencium (atomic number 103). These elements have strong chemical resemblance to the lanthanides (atomic numbers 57 to 71).
- Except for Th and U, actinides are not present in nature in appreciable quantities. The transuranium elements were discovered and investigated as a result of their synthesis in nuclear reactions. All are radioactive.
- Most actinide elements have following in common:
 - Trivalent cations which form complex ions and organic chelates
 - Soluble sulfates, nitrates, halides, perchlorates, and sulfides
 - Acid-insoluble fluorides and oxalates.

- All members of the series can resemble actinium in their chemical and electronic properties; they form separate group within periodic table.
- The actinides display less similarity in their chemical Properties than the lanthanide series, for instance exhibiting a wider range of oxidation states.
- Actinides are metals and all are radioactive. As a result, they dominate the study of nuclear chemistry. The elements emit energy in the form of alpha particles, beta particles, or gamma rays.
- Actinides undergo radioactive decay at different rates; i.e. they have different half-lives. Elements with higher atomic numbers have short half-lives. Some actinides with lower atomic numbers, however, have half-lives ranging between thousands and millions of years.

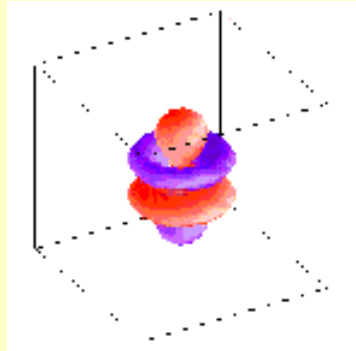
- Actinides are quite electropositive
- Pa - Pu show significant redox chemistry
e.g. all 4 oxidation states of Pu can co-exist in appropriate conditions in (aq)
- stability of high oxidation states peaks at U (Np)
- An^{3+} is the maximum oxidation state for (Cf) Es -Lr
- $No^{2+}(aq)$ is especially stable ~ most stable state for No in (aq)
- Redox potentials show strong dependence on pH (data for Ac - Cm)

Lanthanide - Actinide contraction

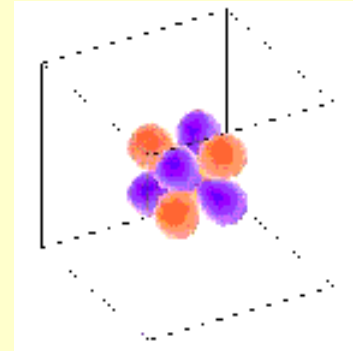
- There is a steady decrease in metallic and ionic radii of lanthanides as the series is traversed from La to Lu. **Similar contraction is found for the actinide series**
- In multi-electron atoms, decrease in radius brought about by increase in nuclear charge is partially offset by electrostatic repulsion among electrons. Particularly, a shielding effect operates. i.e., as electrons are added in outer shells, electrons already present shield the outer electrons from nuclear charge making them see an lower effective charge on the nucleus
- The shielding effect exerted by inner electrons decreases in order $s > p > d > f$. Usually in a period as a particular sub-shell is filled up, atomic radii go on decreasing. This effect is particularly pronounced in case of lanthanides as their 4f sub-shells are being filled across the period and they are least able to shield outer(5th and 6th) shell electrons. Thus shielding effect is least able to counter decrease in radii due to increasing nuclear charge

This leads to "Lanthanide contraction". Ionic Radius drops from 1.020 Å in case of Ce(III) to 0.861 Å in case of Lu(III)

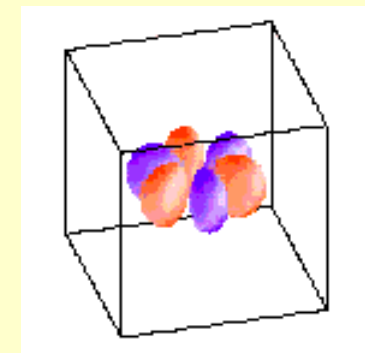
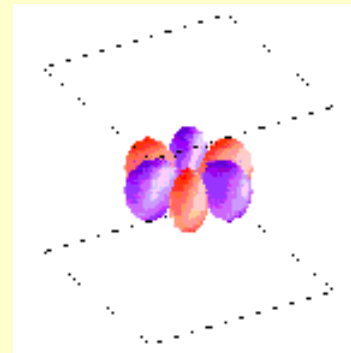
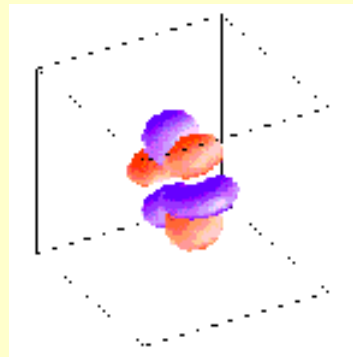
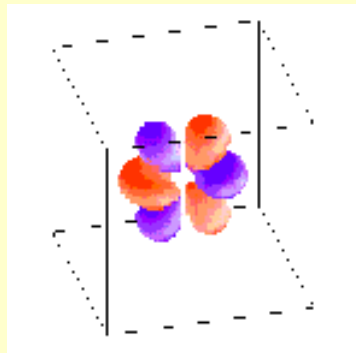
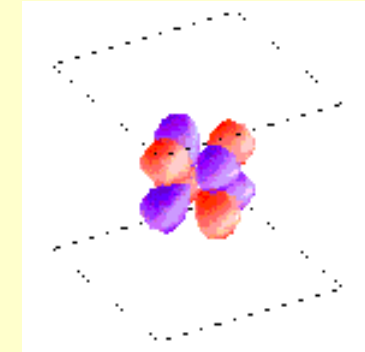
Shapes of 4f Orbitals



$$f_z^3 = f_{z(2z^2 - 3x^2 - 3y^2)} [m_l = 0]$$



$$f_{xyz} \text{ \& } f_{z(x^2 - y^2)} [m_l = \pm 2]$$

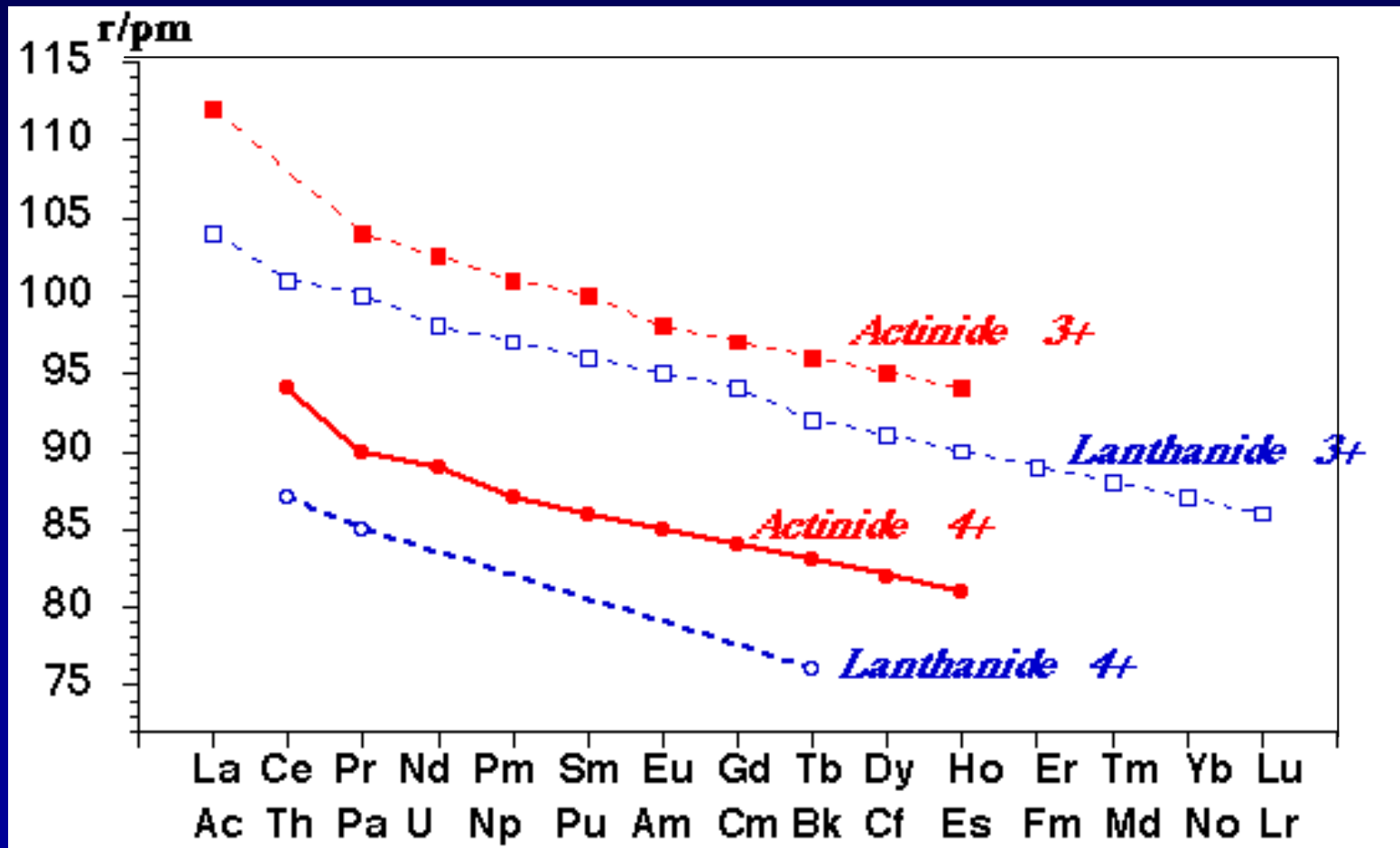


$$f_{xz^2} = f_{x(4z^2 - x^2 - y^2)} \text{ \& } f_{yz^2} = f_{y(4z^2 - x^2 - y^2)} [m_l = \pm 1]$$

$$f_{x(x^2 - 3y^2)} \text{ \& } f_{y(3x^2 - y^2)} [m_l = \pm 3]$$

Actinide Contraction

Actinide 3+ or 4+ ions with radii similar to their Lanthanide counterparts show similarities in properties that depend upon ionic radius



Actinides: Electronic subshells are filled in a manner analogous to the lanthanide series

	Ac	Th	Pa	U	Np	Pu	Am	Cm
Z	89	90	91	92	93	94	95	96
M(g)	6d7s ²	6d ² 7s ²	5f ² 6d7s ²	5f ³ 6d7s ²	5f ⁴ 6d7s ²	5f ⁶ 7s ²	5f ⁷ 7s ²	5f ⁷ 6d7s ²
M ⁺ (g)	7s ²	6d7s ²	5f ² 7s ²	5f ³ 7s ²	5f ⁵ 7s ²	5f ⁶ 7s	5f ⁷ 7s	5f ⁷ 7s ²
M ²⁺ (g)	7s	5f6d	5f ² 6d	5f ³ 6d?	5f ⁵ ?	5f ⁶	5f ⁷	5f ⁸
M ³⁺ (g)		5f	5f ²	5f ³	5f ⁴	5f ⁵	5f ⁶	5f ⁷
M ⁴⁺ (g)			5f	5f ²	5f ³	5f ⁴	5f ⁵	5f ⁶

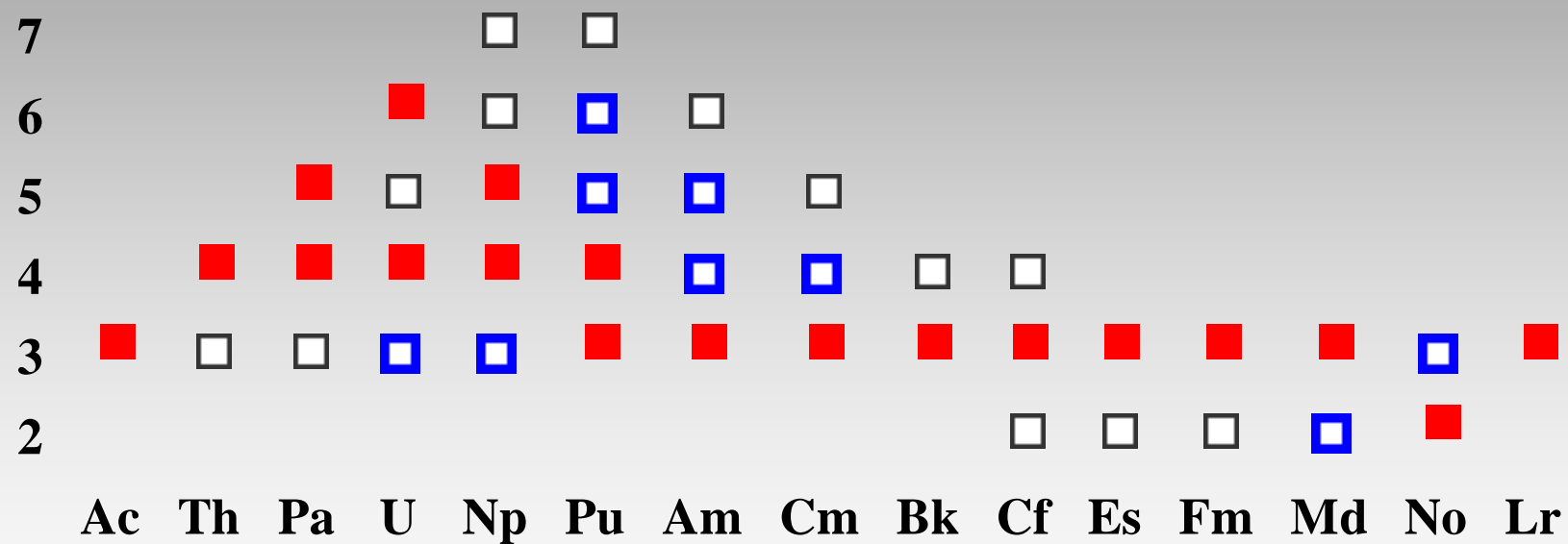
Actinides: Electronic subshells are filled in a manner analogous to the lanthanide series

	Bk	Cf	Es	Fm	Md	No	Lr
Z	97	98	99	100	101	102	103
M(g)	$5f^9 7s^2$	$5f^{10} 7s^2$	$5f^{11} 7s^2$	$5f^{12} 7s^2$	$(5f^{13} 7s^2)$	$(5f^{14} 7s^2)$	$(5f^{14} 6d 7s^2)$
M ⁺ (g)	$5f^9 7s$	$5f^{10} 7s$	$5f^{11} 7s$	$(5f^{12} 7s)$	$(5f^{13} 7s)$	$(5f^{14} 7s)$	$(5f^{14} 7s^2)$
M ²⁺ (g)	$5f^9$	$5f^{10}$	$5f^{11}$	$(5f^{12})$	$(5f^{13})$	$(5f^{14})$	$(5f^{14} 7s)$
M ³⁺ (g)	$5f^8$	$5f^9$	$5f^{10}$	$(5f^{11})$	$(5f^{12})$	$(5f^{13})$	$(5f^{14})$
M ⁴⁺ (g)	$5f^7$	$5f^8$	$(5f^9)$	$(5f^{10})$	$(5f^{11})$	$(5f^{12})$	$(5f^{13})$

Actinide Oxidation States

known oxidation states of the actinides

[importance: ■ > □ >]



+2 oxidation state

- Unusual oxidation state
- Common only for the heaviest elements
- No^{2+} & Md^{2+} are more stable than Eu^{2+}

+3 oxidation state

- ❖ The most stable oxidation state for all trans-Americium elements (except No?)
- ❖ General properties resemble Ln^{3+} and are size-dependent
- ❖ Stability constants of complex formation are similar for same size

An^{3+} & Ln^{3+}

- Isomorphism is common
- later An^{3+} & Ln^{3+} must be separated by ion-exchange/SX

+4 oxidation state

- ❑ Very important, stable state for Pa, U, Pu
- ❑ Am, Cm, Bk & Cf are increasingly easily reduced - only stable in certain complexes *e.g.* Bk⁴⁺ is more oxidizing than Ce⁴⁺
- ❑ Hydrolysis / Complexation / Disproportionation are all important in (aq)

+5 oxidation state

- ❑ Principal state for Pa
- ❑ Pa⁵⁺ chemistry resembles that of Nb⁵⁺ / Ta⁵⁺
- ❑ For U, Np, Pu and Am the AnO₂⁺ ion is known (i.e. quite unlike Nb/Ta)

+6 Oxidation state

- AnO_2^{2+} ions are important for U, Np, Pu, Am
 UO_2^{2+} is the most stable
- Few other compounds *e.g.* AnF_6 ($An = U, Np, Pu$), UCl_6 ,
 UOF_4 etc..., $U(OR)_6$

+7 Oxidation state

- Only the marginally stable oxo-anions of Np and Pu,
e.g. AnO_5^{3-}

- High oxidation states are more stable in basic conditions
- Even at low pH hydrolysis occurs: e.g. Pa^{5+} hydrolyses easily; potentials that indicate it to be most stable oxidation state are recorded in presence of F^- or $\text{C}_2\text{O}_4^{2-}$
- Tendency to disproportionation is particularly dependent on pH
e.g. at high pH, $3\text{Pu}^{4+} + 2\text{H}_2\text{O} = \text{PuO}_2^{2+} + 2\text{Pu}^{3+} + 4\text{H}^+$
- Early actinides have a tendency to form complexes
- Complex formation influences reduction potentials e.g. $\text{Am}^{4+}(\text{aq})$ only exists when complexed by fluoride (15 M $\text{NH}_4\text{F}(\text{aq})$)

Ion	Colour	Stability
Md ²⁺		easy to oxidize, but stable to water
No ²⁺		stable
Ac ³⁺	colorless	stable
U ³⁺	claret	evolves H ₂ on standing; easily oxidized by air
Np ³⁺	blue-purple	stable to water; easily oxidized by air
Pu ³⁺	blue-violet	stable to water & air; readily oxidized
Am ³⁺	pink	stable; difficult to oxidize
Cm ³⁺	pale yellow	stable; chemical oxidation not possible

Ion	Colour	Stability
Bk^{3+}	green	stable; can be oxidized to Bk^{4+}
Cf^{3+}	green	stable
Es^{3+}		stable
Fm^{3+}		stable
Md^{3+}		stable, but easily reduced to Md^{2+}
No^{3+}		easily reduced to No^{2+}
Lr^{3+}		stable

Ion	Colour	Stability
Pa⁴⁺	Colourless	stable to water; easily oxidized
U⁴⁺	green	stable to water; easily oxidized by air to UO_2^{2+}
Np⁴⁺	yellow-green	stable to water; slowly oxidized by air to NpO_2^+
Pu⁴⁺	tan-brown	stable in 6M acid, disproportionates at higher pH
Am⁴⁺	pink?	only stable as fluoride complex; easily reduced
Cm⁴⁺	pale yellow	only as fluoride complex; stable only 1 hr at 25°C
Bk⁴⁺	yellow	marginally stable; easily reduced
Pa⁵⁺	Colorless	stable; readily hydrolyzed

Ion	Colour	Stability
UO_2^+		unstable to disproportionation (least at pH 2-4)
NpO_2^+	green	stable; disproportionates at high acidity
PuO_2^+	pink-purple	tends to disproportionate (least at low pH)
AmO_2^+	yellow	disproportionates in acid; reduced by its α -decay
UO_2^{2+}	yellow	stable; difficult to reduce
NpO_2^{2+}	pink-red	stable; easy to reduce
PuO_2^{2+}	orange-pink	stable; easy to reduce; reduced by its α -decay

Ion	Colour	Stability
AmO_2^{2+}	rum-brown	easy to reduce; rapidly reduced by its α -decay
NpO_5^{3-}	deep green	only in alkaline solution
PuO_5^{3-}	deep green	only in alkaline solution; oxidizes water

Hydrolysis

- ❑ Hydrolysis of actinides is an important phenomenon in solution chemistry, reprocessing, and waste management
- ❑ Hydrolysed actinides are insoluble and migrate less unlike complexed actinides (Cl^- , CO_3^{--} , NO_3^-)
- ❑ Like complexation hydrolysis is also valence dependent
(IV) > (III) > (VI) > (V)

Complexation

- ❖ Complexation of actinides is extremely important like hydrolysis
- ❖ The complexation depends upon the ionic potential of the cation and the anion
- ❖ Complexation markedly affects the formal redox potentials of ions and hence allows to manipulate redox reactions
(e.g. Davies & Gray method for U(VI),
Reduction of Pu in SO_4^{2-} medium)
- ❖ Among the actinide ions the complexation varies in the order,
(IV) > (III) > (VI) > (II) > (V)
- ❖ For the same actinide cation the complexation decreases in the order,



and



Problems in solvent extraction

- Radiation, Chemical and Thermal degradation of solvent
 - Lower DFs from FPs
 - Phase Separation
 - Emulsion and precipitation
 - Flooding
- Third Phase formation
 - Criticality
 - Flooding
 - Red oil formation leading to explosion

Actinide Third Phases



Light Phase

Heavy Phase

Aqueous
Phase



Pu(IV)



Pu(VI)



Np(IV)



Np(VI)

Courtesy : University of Nevada

Criticality Parameters for some actinides

Parameter	Form	U-235	U-233	Pu-239
Mass (kg)	Solution	0.82	0.59	0.51
	Metal	22.8	7.5	5.6 (α) 7.6 (δ)
Diameter of Infinite Cylinder (Inches)	Solution	5.4	4.4	4.9
	Metal	3.1	1.9	1.7
Solution Volume (lit)	Solution	6.3	3.3	4.5
Conc. (g/l)	Solution	12.1	11.2	7.8

Radiological Safety Parameters

S.No	Nuclide	ALI (Bq)	DAC (Bq/m ³)
1	²³⁹ Pu	625	0.26
2	²³⁷ Np	1333	0.555
3	²⁴¹ Am	740	0.308
4	²³⁸ Pu	666	0.277

Isotopes of high risk nature in repositories

Fission Products :

$^{129}\text{I} > ^{99}\text{Tc} > ^{135}\text{Cs} > ^{93}\text{Zr} > ^{126}\text{Sn}$ (in the order of toxicity)

Activation products ^{14}C and ^{36}Cl

^{137}Cs and ^{90}Sr with low half lives (~30 years) do not require transmutation

^{129}I

Half Life : 1.6×10^7 a

Fission yield %: (0.913 / 1.596)

ALI by Ingestion : 2×10^5 Bq/year

Emission : β^- 3.151 keV, γ 37.6 keV

- ❖ Has the highest toxicity among FPs equivalent to those of actinides
- ❖ High mobility element, enters the biosphere easily
- ❖ During aqueous reprocessing, iodine is removed from the dissolver solution with a yield of 95-98%
- ❖ To improve the separation yield, more complex chemical treatments are necessary
- ❖ Better separation yields achievable with pyrochemical processes
- ❖ Conditioning in the form of AgI , PbIO_4 , developed yet not effective to exclude migration into environment due to extremely long half-life

^{99}Tc

Half life : 2.1×10^5 a

Fission yield % : 5.774 / 5.998

ALI by Ingestion : 3×10^7 Bq/year

Emission : β^- 1.42 keV, γ 140.51 keV

- ❖ The radiologic significance of ^{99}Tc is important if the repository surroundings are slightly oxidic
- ❖ In reducing conditions ^{99}Tc is remarkably stable and insoluble as technetium metal or TcO_2 suboxide
- ❖ Partitioning of ^{99}Tc is not an easy task because it occurs as insoluble metal in the alloy form with other elements and as soluble TcO_4^- ion in solution
- ❖ Separation from aqueous effluents is possible in an advanced PUREX scheme, but recovery from insoluble residues is difficult, with the present recovery yield at best reaching 80%
- ❖ Improving this yield significantly implies the development of new separation technologies such as the not yet proven conversion of the technetium into a single chemical species
- ❖ Alternatively, a group separation together with the platinum metals may be carried out using pyrometallurgical processes
- ❖ If separated in metallic form, transmutation appears to be feasible because of its stability and relatively large neutron capture cross-section

^{135}Cs ($T_{1/2} = 2.3 \cdot 10^6 \text{ a}$)
ALI by Ingestion : $3 \cdot 10^7 \text{ Bq/year}$
Fission yield % : 6.35 / 7.495
Emission : $\beta^- 1.081\text{keV}$, $\gamma 787.2, 846.1\text{keV}$

- ❖ Cesium occurs in the form of the isotopes 133 (stable), 135 and 137
- ❖ In terms of radiologic significance, ^{137}Cs is the major constituent of HLW
- ❖ The activity of the long-lived ^{135}Cs in HLW is a million times lower
However, once released from a matrix as glass, cesium is very mobile
- ❖ Transformation of ^{135}Cs to stable ^{136}Ba is possible from a neutronics point of view, but impracticable due to the requirement of close to 100% isotopic separation efficiency (traces of ^{133}Cs in the target would generate new ^{135}Cs during the irradiation)

^{93}Zr ($T_{1/2} = 1.5 \cdot 10^6 \text{ a}$),

FY% : 6.14 / 3.734

Emission : β^- 1.583 keV, γ 30.77keV

- ❖ ^{93}Zr is somewhat similar to ^{135}Cs , it has also a very long half-life and a small isotopic abundance (about 14% of the total Zr)
- ❖ An isotopic separation would be necessary, and its transformation to stable ^{94}Zr would be very slow because the thermal capture cross-section is about five times smaller than that of ^{135}Cs

^{126}Sn ($T_{1/2} = 1.0 \cdot 10^5 \text{ a}$)

ALI by Ingestion : $3 \cdot 10^6 \text{ Bq/year}$

FY% : 0.138 / 0.287

Emission : β^- 30.0 keV, γ 87.57 keV

- ❖ ^{126}Sn is partly soluble in HLW from aqueous reprocessing but occurs also as an insoluble residue, similar to technetium
- ❖ Isolation involves a special treatment of the HLW, and the use of isotopic separation techniques
- ❖ Transmutation of ^{126}Sn is questionable due to the very low neutron capture cross-section

TBP

- The workhorse of aqueous reprocessing industry for 50 years !
- economical
- easy commercial availability
- good stability

Drawbacks

- aqueous solubility
- third phase formation
- deleterious degradation products

N,N Dialkyl Monamides (DOHA,DHOA etc.,.)

- ❑ Easily incinerable to atmospheric elements (CHON Principle)
- ❑ Non-deleterious degradation products
 - ❑ amines and carboxylic acids

Drawbacks

- ❑ Viscosity of metal solvate
- ❑ phase separation behaviour
- ❑ third phase formation

Diamides

(DBDMTDMA, TODGA, TEHDGA, DMDOHEMA)

- ❑ Easily incinerable to atmospheric elements (CHON Principle)
- ❑ Non-deleterious degradation products
 - ❑ amines and carboxylic acids

Drawbacks

- ❑ Viscosity of metal solvate
- ❑ phase separation behaviour
- ❑ third phase formation

CMPOs

- ❖ Excellent extraction characteristics at high acidity
- ❖ Stripping at low acidity
- ❖ Widely studied
- ❖ A boon for complete polishing of aq. Solutions wrt actinides of almost all valencies

Drawbacks

- ❑ Leaves phosphate on final disposal
- ❑ Third phase formation (severe in Diphenyl version)
- ❑ Complicated synthesis
- ❑ Difficult purification
- ❑ Degradation products deleterious
- ❑ Requires large concentration of modifier

TRPO, TOPO

- ❑ TOPO is a solid
- ❑ synthesis is not as easy as TBP yet simple

Drawbacks

- ❑ third phase / precipitate formation
- ❑ Deleterious degradation products
- ❑ not very economical

D2EHPA (HDEHP), DIDPA, DNPPA

- ❑ Acidic compounds
- ❑ Hence extraction requires low acidity
- ❑ purification difficult
- ❑ Deleterious degradation products

Drawbacks

- ❑ leaves phosphate on final disposal
- ❑ phase separation behaviour
- ❑ third phase formation
- ❑ no selectivity

SOLVENT EXTRACTION VS EXTRACTION CHROMATOGRAPHY

- ❑ Continuous counter current extraction
 - ❑ Large throughput
 - ❑ Fast process
-
- ❑ Large theoretical plates, hence better separations
 - ❑ Batch process, hence less throughput
 - ❑ Large solid substrate waste
 - ❑ Slow process

Diluents in reprocessing and partitioning

- ❖ Kerosene
- ❖ N-paraffin mixtures (NORPAR, HNP, NPH etc.,)
- ❖ Isoparaffin mixtures (ISOPAR-L,M, SHELL SOL-T, HPT (TPH) etc.,)
- ❖ Aromatics (DEB, DBB)
- ❖ Fluorinated compounds (TCE, CCl_4 , Fluoropol-732)
 - ❖ safety (FP, BP)
 - ❖ economics (cost easy availability)
 - ❖ engineering (hydrodynamics, viscosity, density)
 - ❖ Are they really inert ?

SI Units

Physical Quantity	SI Unit	Non SI Unit	Relationship
Activity	Bq	Ci	$1 \text{ Bq} = 2.7 \cdot 10^{-11} \text{ Ci}$
Absorbed Dose	Gray (Gy) $1 \text{ Gray} = 1 \text{ J/kg}$	rad	$1 \text{ Gy} = 100 \text{ rads}$ $1 \text{ rad} = 0.01 \text{ Gy}$
Dose Equivalent	Sievert (Sv) $1 \text{ Sv} = 1 \text{ J/kg}$	Rem	$1 \text{ Sv} = 100 \text{ rems}$ $1 \text{ rem} = 10 \text{ mSv}$
Exposure	Coulomb/kg	Roentgen(R)	$1 \text{ C/kg} = 3876 \text{ R}$



Thank You