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

1774/12

Opening Address

C. Ganguly
IAEA Vienna

ICTP Workshop

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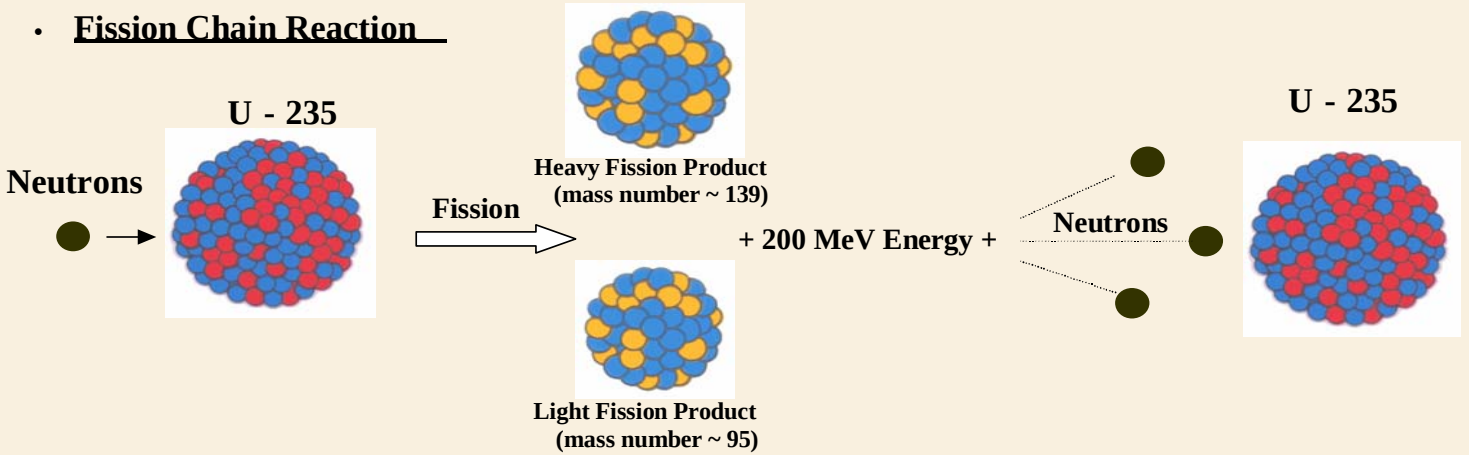
Chaitanyamoy GANGULY
Head, Nuclear Fuel Cycle & Materials Section

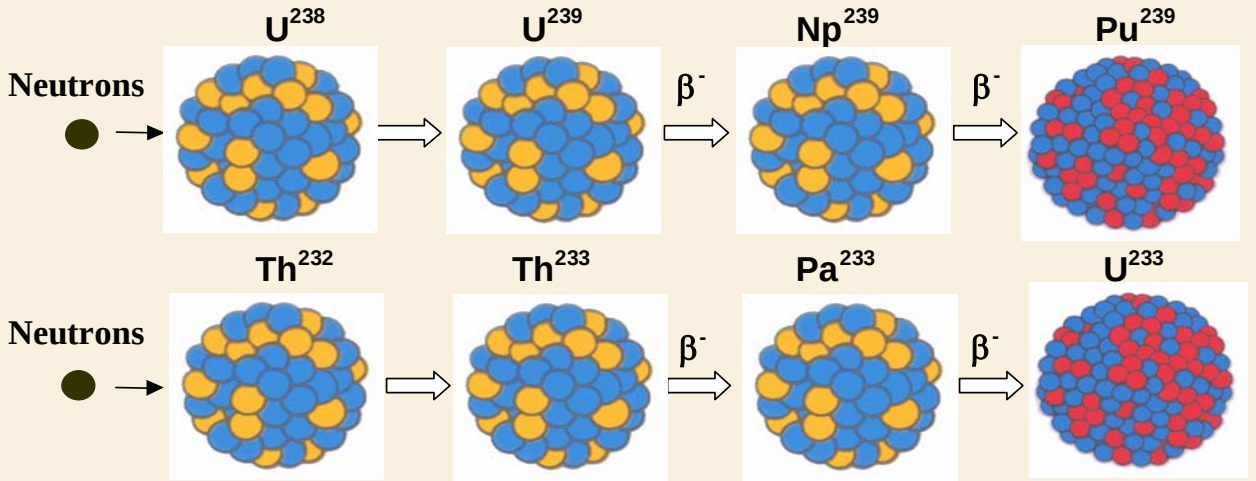
IAEA
International Atomic Energy Agency

NUCLEAR FISSION

- **Fission Chain Reaction**



- **Production of Fissile Isotopes Pu^{239} & U^{233}**



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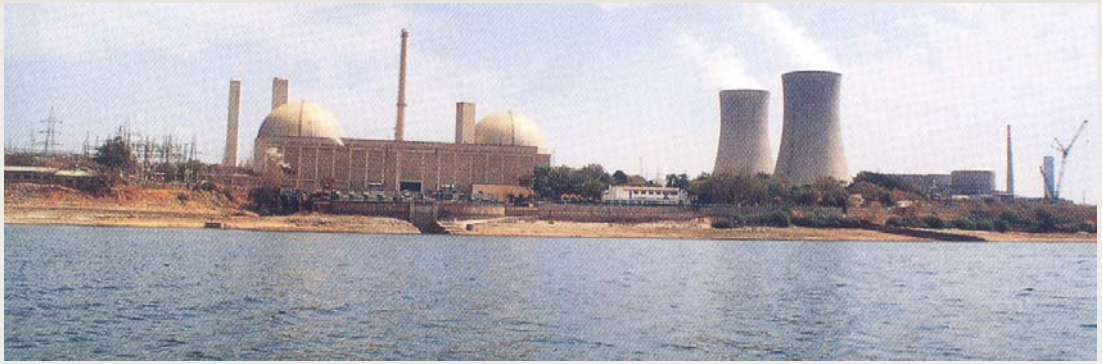
NUCLEAR REACTORS & THEIR APPLICATIONS

Source of intense heat energy & Source of neutrons

- **Power Reactors:**



- Generation of Electricity
- Desalination of Sea Water
- Marine Propulsion
- Production of Hydrogen
- District Heating

- **Non-Power Reactors:**

- Production of Radioisotopes
  - Nuclear Medicine, Radiopharmaceuticals Radioimmunotherapy - ^{99m}Tc, I^{131}, Sm^{153}, P^{32}, etc.
  - Cancer Diagnosis & Therapy
  - Sterilisation of Medical Kits, Hospital Wastes & Sewage
  - Food Irradiation & Preservation
  - γ-radiography - Co^{60}, Ir^{192} & Cs^{137}
- Production of Fissile Isotopes (Pu^{239} and U^{233})
- Neutron Radiography, Neutron Diffraction & Neutron Activation Analysis
- Irradiation-Testing of Materials
- Training, Education & Basic Research

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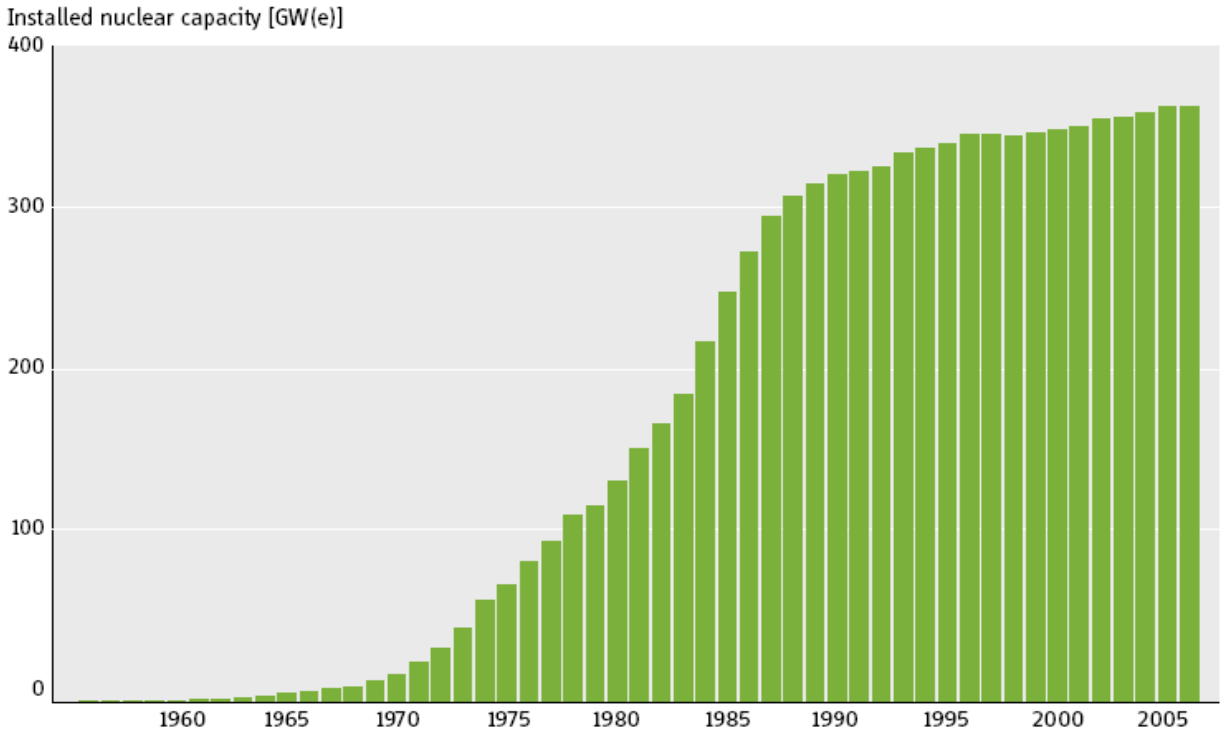

Figure 3.6 - Nuclear power capacity, historically. Global nuclear capacity grew rapidly during the 1970s and 1980s. Public opposition, high costs, unresolved waste issues, and the accidents at Three-Mile-Island and Chernobyl in 1979 and 1986 led to a sharp decline of new orders of nuclear power plants worldwide. In 2006, there were 440 power reactors with an installed capacity of about 370 GW(e). Due to the shutdown of aging reactors, this capacity will decline during the next few decades unless the rate of ordering new nuclear power plants rises above an average of about ten per year.

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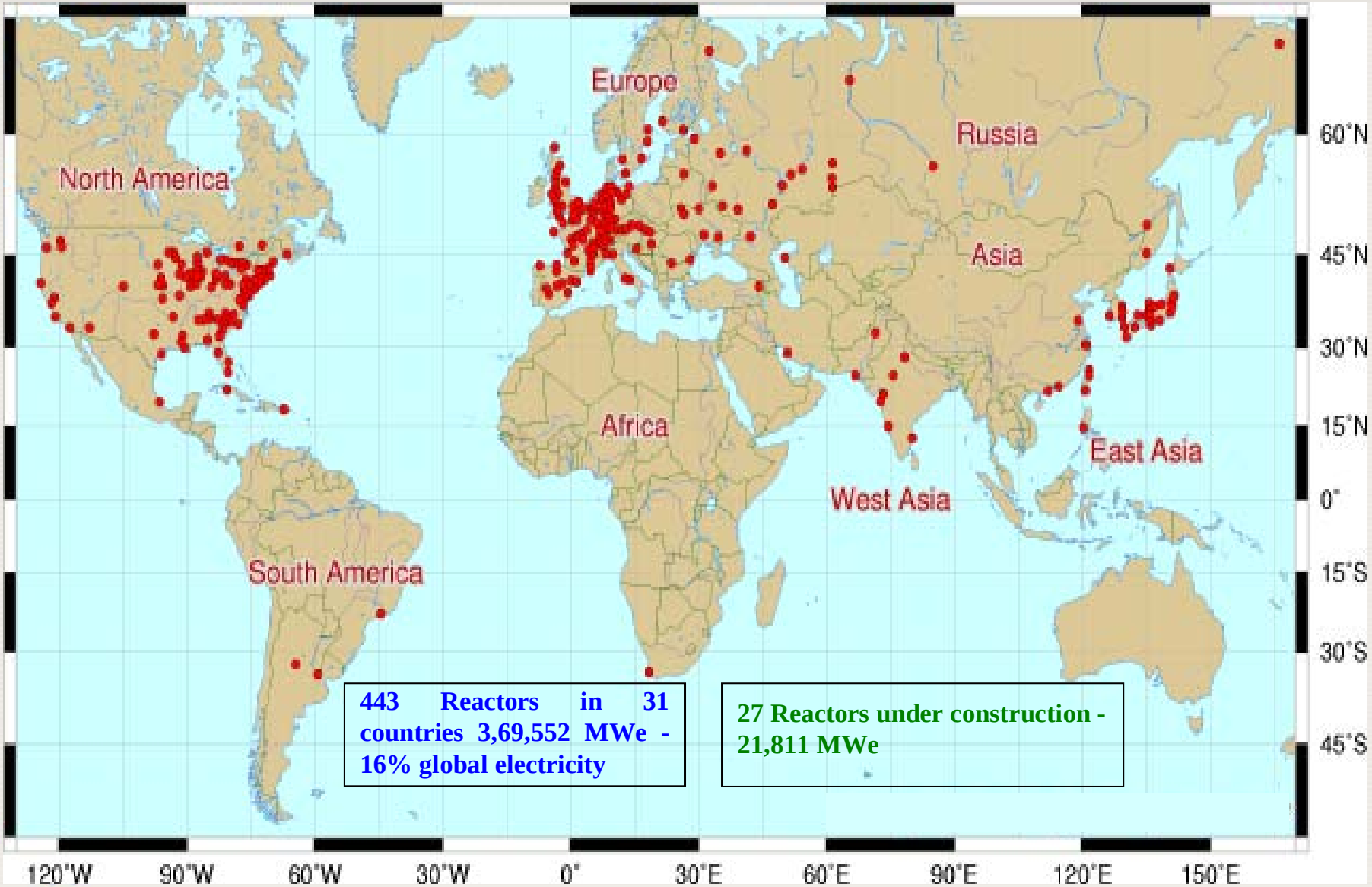
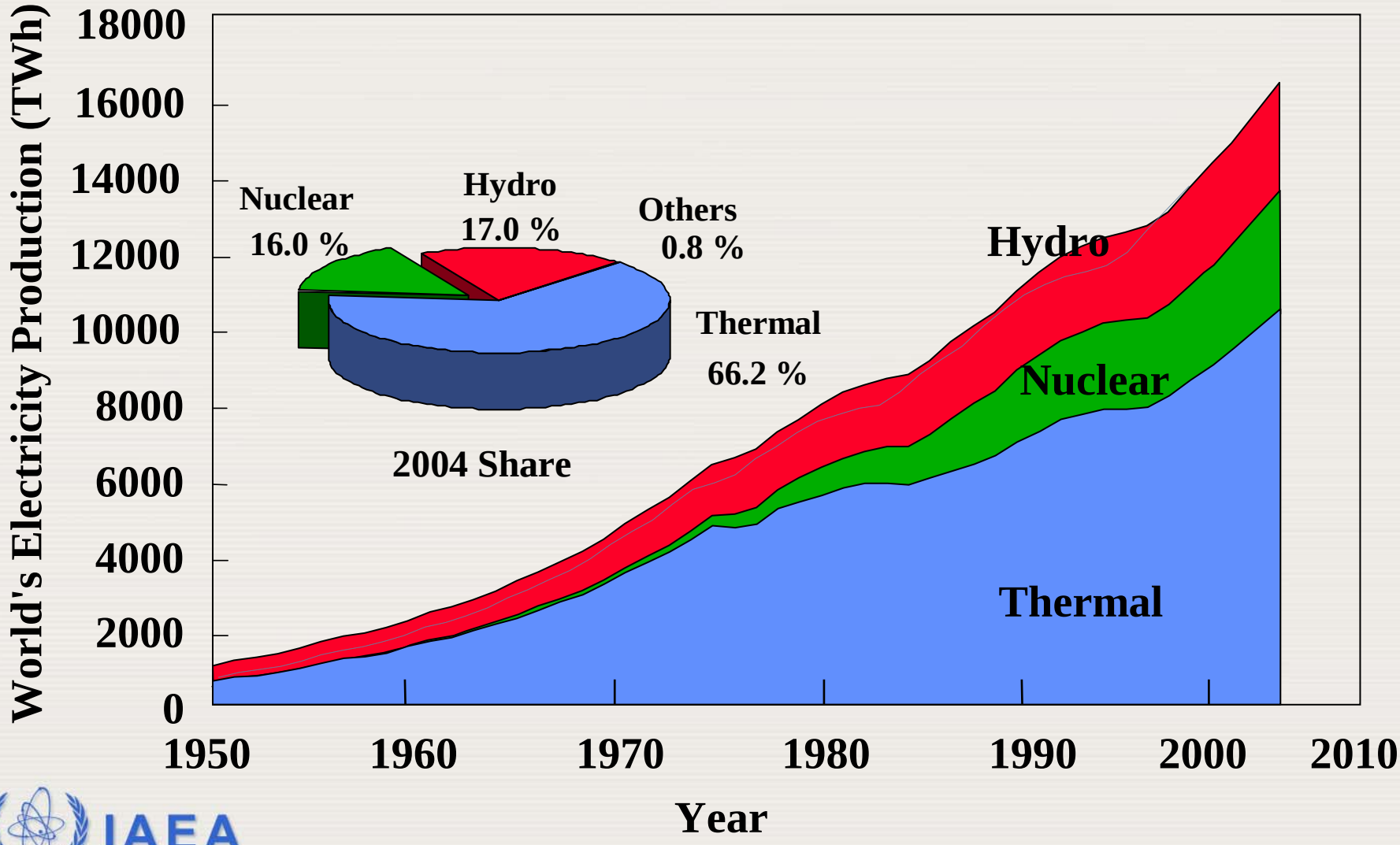
NUCLEAR POWER REACTORS

(July 2006)



NUCLEAR CONTRIBUTION TO ELECTRICITY GENERATION



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Civilian Nuclear Power Programme in the 21st Century:

On-going International Programmes:

- **IAEA-initiated INNOVATIVE NUCLEAR REACTORS & FUEL CYCLE PROGRAMME (INPRO)**
- **US-initiated Generation IV International Forum (GIF)**

In both INPRO and GIF, nuclear power reactors have been perceived to be utilised for the following purpose:

- **Generation of Electricity.**
- **Production of Hydrogen Fuel**
- **Desalination of Sea Water**
- **District Heating**

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UNIQUE FEATURES OF NUCLEAR ENERGY & POWER

- **Relatively New**

"Nuclear Fission Energy" is very recent (< 60 years) in the time scale of human civilisation.
First Nuclear Power Reactor in the world : 1955

- **High Energy Density** :

1 atom of 'C' on combustion releases ~ 4 eV
1 atom of U^{235} on fission release ~200 MeV

Annual Fuel Requirement of a 1000 MWe Power Station:
Nuclear : 30 tons; Coal : 2.6 million tons; Oil : 2.0 million tons

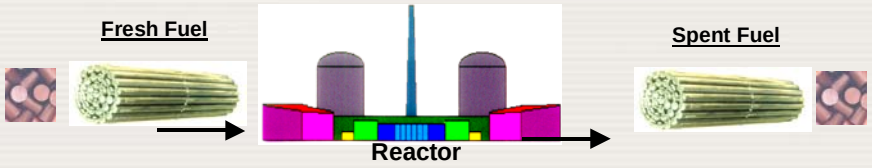
- **Environment Friendly**:

Zero emission of CO_2, SO_2 & NO_x – no global warming and acid rain
Annual Discharge from 1000 MWe Power Station:
Nuclear : 3.5 tons spent fuel; Coal Fired : 6.5 million tons CO_2

CO_2 emission per kWh: 0.967 kg Denmark (82% Coal, 0% Nuclear)
0.63 kg UK (49.5% Coal, 28% Nuclear)
0.064 kg France (77.36% Nuclear)

- **Generates man-made 'fissile' isotopes or fuels** :

Nuclear fuel is made up of 'fissile' (U^{235}, Pu^{239} & U^{233}) and 'fertile' (U^{238} & Th^{232}) isotopes. U^{235} is the only 'fissile' isotope occurring in nature. The 'fission' process splits up 'fissile' nuclei, releases very high heat energy and generates extra neutrons which could convert naturally occurring 'fertile' isotopes, U^{238} & Th^{232} to man-made 'fissile' isotopes Pu^{239} & U^{233} respectively.



U^{235}, Pu^{239} or U^{233} $+ {}_0n^1 \rightarrow$ Fission Products $+ 3\ {}_0n^1 + 200$ MeV

$+ U^{238}$ $+ {}_0n^1 \rightarrow U^{239} \xrightarrow{\beta^-} Np^{239} \xrightarrow{\beta^-} Pu^{239}$

or

$+ Th^{232}$ $+ {}_0n^1 \rightarrow Th^{233} \xrightarrow{\beta^-} Pa^{233} \xrightarrow{\beta^-} U^{233}$

- **High Safety & Security**

From radiation safety point of view, natural uranium (U^{235} & U^{238}) and thorium (Th^{232}) are mildly radioactive and have very little hazard from external radiation. However, Pu^{239} (always associated with Pu^{240}, Pu^{241}, Pu^{242} & Pu^{238}), U^{233} (always associated with U^{232}) and fission products are highly radioactive and health hazardous & require proper containment, beta, gamma neutron shieldings and remote handling. In order to ensure safety from any 'criticality accident' (uncontrolled nuclear fission chain reaction), only limited and controlled quantity of 'fissile ' (U^{235}, Pu^{239} or U^{233}) materials are permitted to handle at a time. The radioactive waste has to be properly treated, fixed and stored or disposed. From security point of view, physical protection of 'fissile' material is essential to avoid proliferation risk for non-peaceful purpose.

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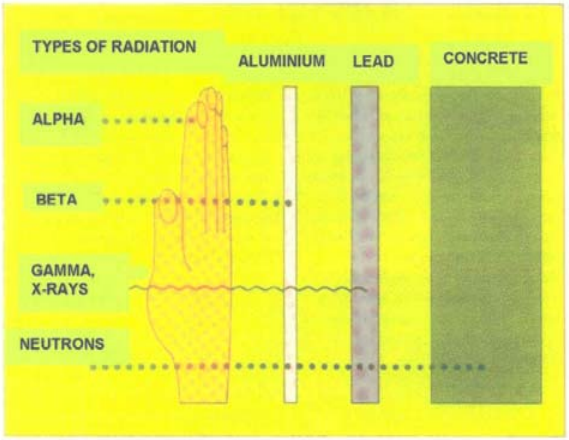
Comparitive Hazards associated with external dose from radioactive material



Alpha Radiation: (practically no hazard from external radiation)

Can be stopped completely by a sheet of paper – may just penetrate the surface of the skin.

Beta : (minimum hazard from external radiation) Radiation

Can be stopped by a sheet of aluminium a few mm in thickness.

Gamma: (hazardous–requires proper shielding) & X Rays

Are very penetrating and can pass right through human body – mostly absorbed by heavy elements like lead, which is normally used as shielding material for gamma x-rays.

Neutrons:(hazardous – requires proper shielding)

Are very penetrating – in general, efficient shielding against neutron can be provided by water, perspex, etc. Concrete shielding (sometimes upto 1 m thickness) is used for neutron and gamma shielding.

Remote Operations using manipulators for handling highly radioactive materials (mainly high gamma and high neutron dose) inside concrete hot cells

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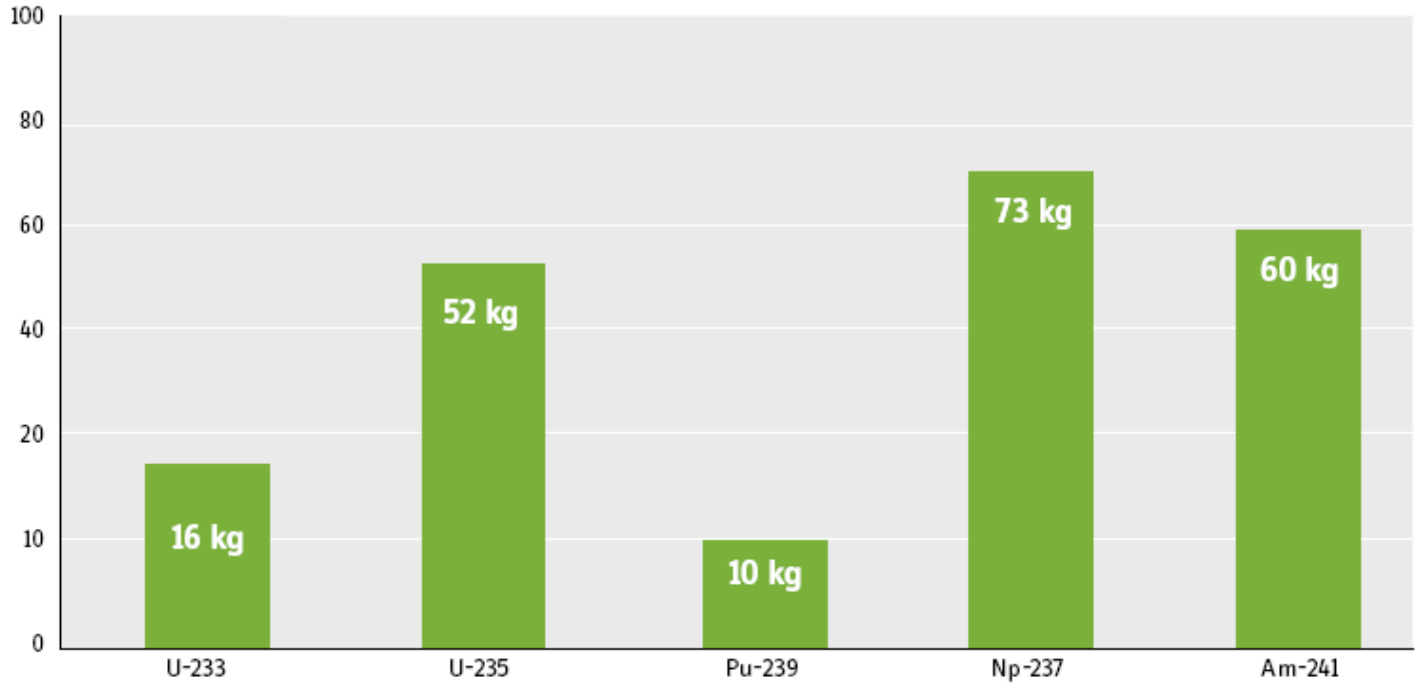

Figure 1.5 – Bare critical masses for various fissile materials.[16]

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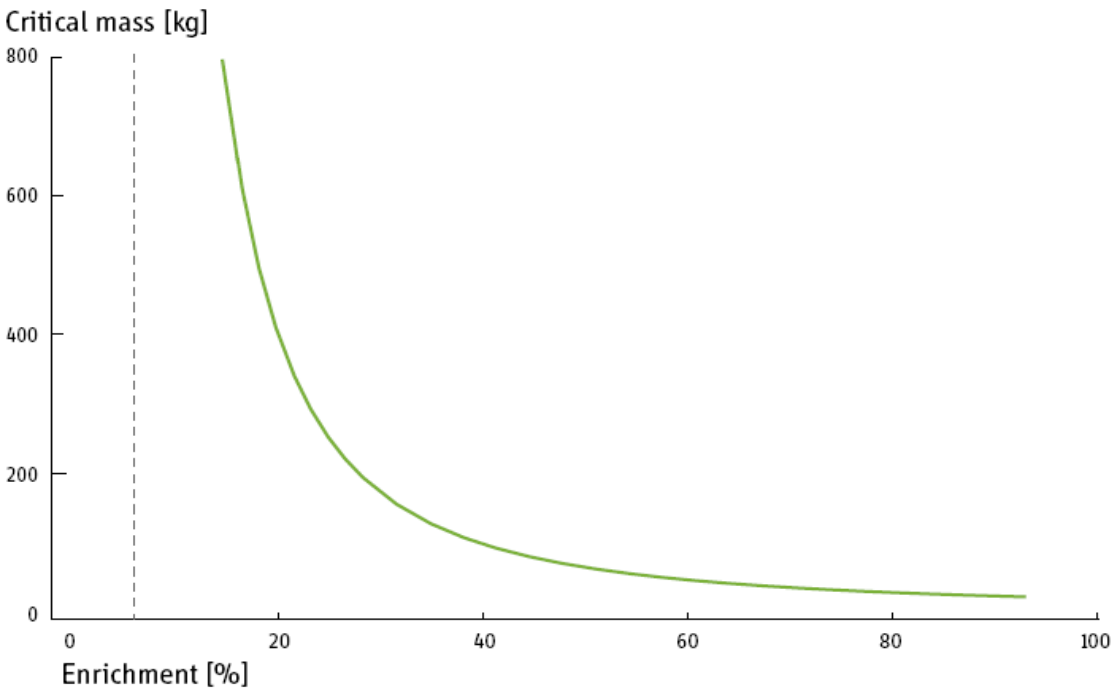

Figure 1.4 - The fast critical mass of uranium increases to infinity at 6-percent enrichment. According to weapon-designers, the construction of a nuclear device becomes impractical for enrichment levels below 20 percent. The critical mass data in the figure is for a uranium sphere enclosed in a 5-cm beryllium reflector.[10]

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Elements in Fresh & Spent Uranium Fuels

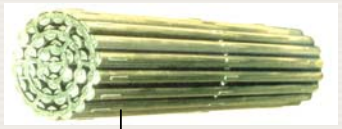
FRESH FUEL

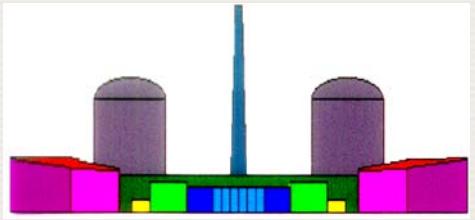
Fuel Pellets
(U & O) atoms
U^{235},U^{238},O

Natural 'U' { Nu: 0.7% U^{235} ; Rest U^{238} }

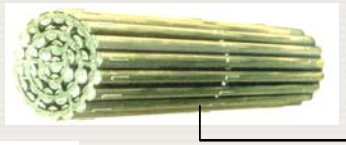
SEU: { 1 to 5% U^{235} ; Rest U^{238} }

Cladding





SPENT FUEL



Spent Fuel Pellets
U^{238},Pu^{239} & other
Pu isotopes,
fission products &
unused U^{235}

{ U^{235}: <0.2% for NU: Dep.U ; 0.8-1.2% for SEU: REU }

Cladding

Water-cooled Nuclear Power Reactor

$$U^{235} + {}_0n^1 \longrightarrow U^{236} \longrightarrow \text{Fission Products} + \text{(2 or 3) neutrons} + 200\ \text{MeV}$$

$$U^{238} + {}_0n^1 \longrightarrow U^{239} \xrightarrow{\beta^-} Np^{239} \xrightarrow{\beta^-} Pu^{239}$$

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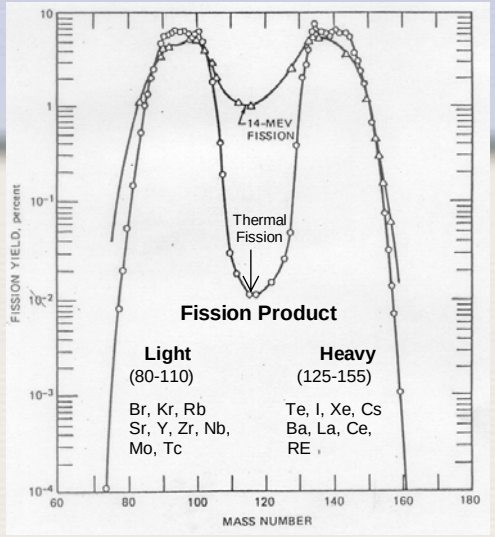
FISSILE & FERTILE ISOTOPES



URANIUM

- 4 ppm in earth's crust, Klaproth, 1789
- Natural Uranium:

U^{238}(fertile): 99.3%; 4.5×10^9 y
U^{235}(fertile): 0.7%; 8.0×10^8 y

U^{235}_{92}(fissile) + n^1_0 → U^{236}_{92} → $M_1(95)+M_2(139)+(2\text{-}3)n^1+200$ MeV

U^{238}_{92}(fertile) + n^1_0 → U^{239}_{92} —(β^-, 23.5 m)→ Np^{239}_{93} —(β^-, 2.35 days)→ Pu^{239}_{94} (fissile)

THORIUM

- 12 ppm in earth's crust, Berzellius, 1828

Natural Thorium: No fissile isotope,

Fertile Th^{232}_{90}(fertile); 1.4×10^{10} y

Th^{232}_{90} (fertile) + n^1_0 → Th^{233}_{90} —(23.5 min)→ Pa^{233} —(27 days)→ U^{233} (fissile)

PLUTONIUM

- Does not occur in nature; man-made, Seaborg, Wahl and Kennedy, 1941
  - ➢ Pu^{239} : ∝ ; 2.4×10^4 y
  - ➢ Pu^{240} : ∝, n ; 6.58×10^3 y
  - ➢ Pu^{241} : β^- ; 13y, Am241 strong γ emitter
  - ➢ Pu^{242} : ∝, n ; 3.79×10^5 y
  - ➢ Pu^{238} : ∝, n ; 86.4 y
- Maximum limits

body burden	:	0.18 – 0.65 μ g
concentration in air	:	2×10^{-12} μ curie per cc
concentration in water	:	10^{-4} μ curie per cc

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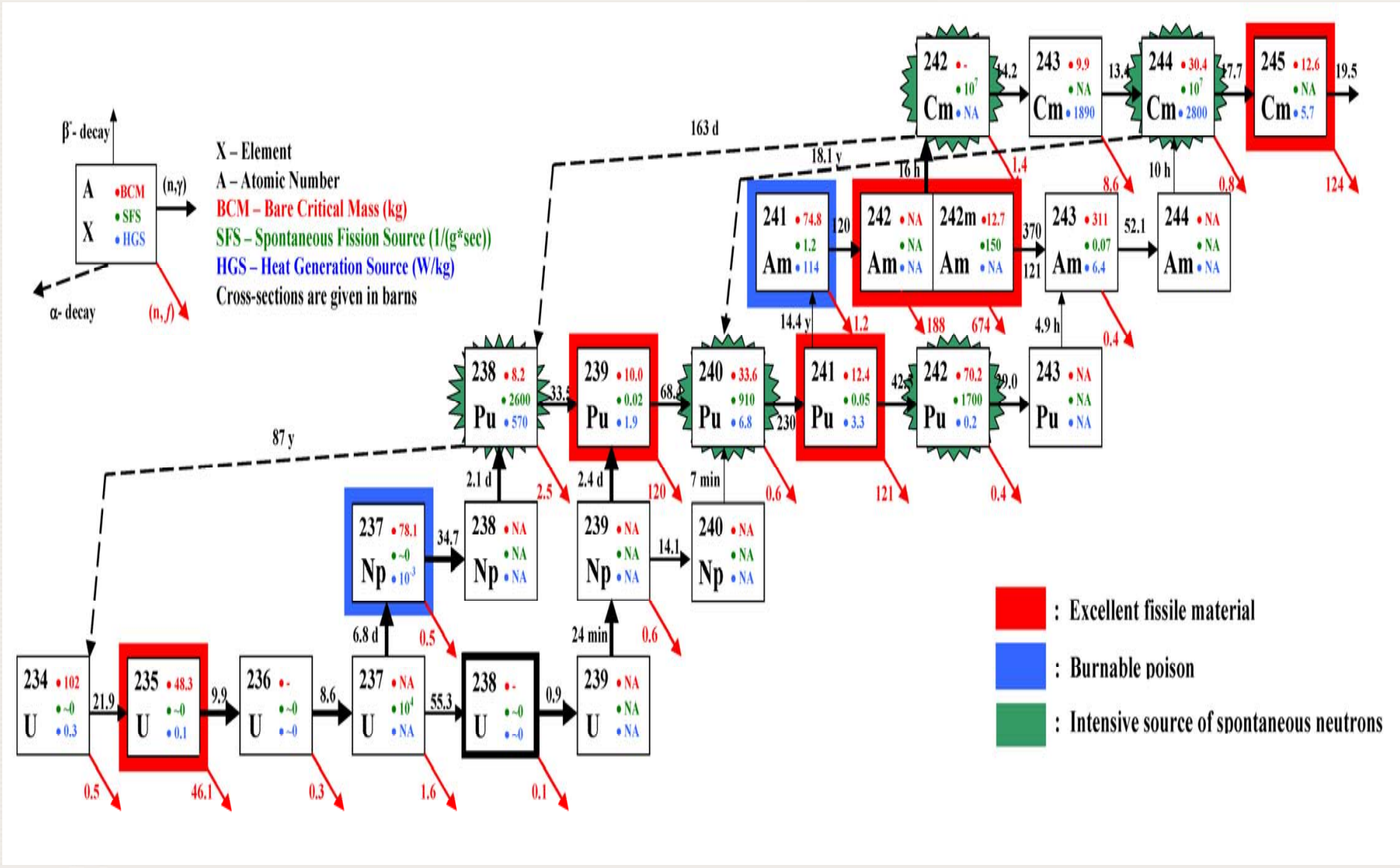
Formation of Minor Actinides (Np, Am & Cm) in reactor-

Important isotopes of minor actinides.



Elemental Constituents in Uranium Fuel Discharged from a Typical PWR (30,000 MWd/t) 150 days after discharge

	g/Mg	Ci/Mg	W/Mg
Actinides			
Uranium	9.54×10^{5}	4.05	4.18×10^{-2}
Neptunium	7.49×10^{2}	1.81×10^{1}	5.20×10^{-2}
Plutonium	9.03×10^{3}	1.08×10^{5}	1.52×10^{2}
Americium	1.40×10^{2}	1.88×10^{2}	6.11
Curium	4.70×10^{1}	1.89×10^{4}	6.90×10^{2}
Subtotal	9.64×10^{5}	1.27×10^{5}	8.48×10^{2}
Fission products			
Tritium	7.17×10^{-2}	6.90×10^{2}	2.45×10^{-2}
Selenium	4.87×10^{1}	3.96×10^{-1}	1.50×10^{-4}
Bromine	1.38×10^{1}	0	0
Krypton	3.60×10^{2}	1.10×10^{4}	6.85×10^{1}
Rubidium	3.23×10^{2}	1.90×10^{2}	0
Strontium	8.68×10^{2}	1.74×10^{5}	4.50×10^{2}
Yttrium	4.53×10^{2}	2.38×10^{5}	1.05×10^{3}
Zirconium	3.42×10^{3}	2.77×10^{5}	1.45×10^{3}
Niobium	1.16×10^{1}	5.21×10^{5}	2.50×10^{3}
Molybdenum	3.09×10^{3}	0	0
Technetium	7.52×10^{2}	1.43×10^{1}	9.67×10^{-3}
Ruthenium	1.90×10^{3}	4.99×10^{5}	3.13×10^{2}
Rhodium	3.19×10^{2}	4.99×10^{5}	3.99×10^{3}
Palladium	8.49×10^{2}	0	0
Silver	4.21×10^{1}	2.75×10^{3}	4.16×10^{1}
Cadmium	4.75×10^{1}	5.95×10^{1}	2.13×10^{-1}
Indium	1.09	3.57×10^{-1}	1.04×10^{-3}
Tin	3.28×10^{1}	3.85×10^{4}	1.56×10^{2}
Antimony	1.36×10^{1}	7.96×10^{3}	2.74×10^{1}
Tellurium	4.85×10^{2}	1.34×10^{4}	1.66×10^{1}
Iodine	2.12×10^{2}	2.22	8.98×10^{-3}
Xenon	4.87×10^{3}	3.12	3.04×10^{-3}
Cesium	2.40×10^{3}	3.21×10^{5}	2.42×10^{3}
Barium	1.20×10^{3}	1.00×10^{5}	3.93×10^{2}
Lanthanum	1.14×10^{3}	4.92×10^{2}	8.16
Cerium	2.47×10^{3}	8.27×10^{5}	7.87×10^{2}
Praseodymium	1.09×10^{3}	7.71×10^{5}	5.73×10^{3}
Neodymium	3.51×10^{3}	9.47×10^{1}	2.65×10^{-1}
Promethium	1.10×10^{2}	1.00×10^{5}	9.17×10^{1}
Samarium	6.96×10^{2}	1.25×10^{3}	2.18
Europium	1.26×10^{2}	1.35×10^{4}	7.19×10^{1}
Gadolinium	6.29×10^{1}	2.32×10^{1}	3.34×10^{-2}
Terbium	1.25	3.02×10^{2}	2.54
Dysprosium	6.28×10^{-1}	0	0
Subtotal	3.09×10^{4}	4.18×10^{6}	1.96×10^{4}
Total	9.95×10^{5}	4.31×10^{6}	2.04×10^{4}

Ref: Nuclear Chemical Engineering

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Actinides in Discharge Uranium Fuel

Radionuclide	Half-life	kg/yr	Ci/yr	Elemental boiling temperature, °C‡
^{234}U	2.47×10^{5} yr	3.14	1.94×10^{1}	
^{235}U	7.1×10^{8} yr	2.15×10^{2}	4.61×10^{-1}	
^{236}U	2.39×10^{7} yr	1.14×10^{2}	7.22	
^{237}U	6.75 days	9.15×10^{-7}	7.47×10^{1}	
^{238}U	4.51×10^{9} yr	2.57×10^{4}	8.56	
Total		2.60×10^{4}	α 3.56×10^{1}	4135
			β 7.47×10^{1}	
^{237}Np	2.14×10^{6} yr	2.04×10^{1}	1.44×10^{1}	
^{239}Np	2.35 days	2.05×10^{-6}	4.78×10^{2}	
Total		2.04×10^{1}	α 1.44×10^{1}	–
			β 4.78×10^{2}	
^{236}Pu	2.85 yr	2.51×10^{-4}	1.34×10^{2}	
^{238}Pu	86 yr	5.99	1.01×10^{5}	
^{239}Pu	24,400 yr	1.44×10^{2}	8.82×10^{3}	
^{240}Pu	6,580 yr	5.91×10^{1}	1.30×10^{4}	
^{241}Pu	13.2 yr	2.77×10^{1}	2.81×10^{6}	
^{242}Pu	3.79×10^{5} yr	9.65	3.76×10^{1}	
Total		2.46×10^{2}	α 1.23×10^{5}	3508
			β 2.81×10^{6}	
^{241}Am	458 yr	1.32	4.53×10^{3}	
^{242m}Am	152 yr	1.19×10^{-2}	1.16×10^{2}	
^{243}Am	7,950 yr	2.48	4.77×10^{2}	
Total		3.81	α 5.01×10^{3}	2880
			β 1.16×10^{2}	
^{242}Cm	163 days	1.33×10^{-1}	4.40×10^{5}	
^{243}Cm	32 yr	1.96×10^{-3}	9.03×10^{1}	
^{244}Cm	17.6 yr	9.11×10^{-1}	7.38×10^{4}	
^{245}Cm	9,300 yr	5.54×10^{-2}	9.79	
^{246}Cm	5,500 yr	6.23×10^{-3}	1.92	
Total		1.11	α 5.14×10^{5}	–
Total		2.63×10^{4}	α 6.42×10^{5}	
			β 2.81×10^{6}	

Ref: Nuclear Chemical Engineering

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Inventory of Actinides and Fission Products of Natural Uranium Fuelled Spent PHWR Fuel (burnup: ~7000 MWd/t HM) after 10 years of cooling

Ref: Final Safety Report of Darlington Waste Management Facility

Radionuclide	Activity TBq/bundle	Radionuclide	Activity TBq/bundle	Radionuclide	Activity TBq/bundle
H-3	6.508E-02	Ag-108	1.409E-09	Ba-137m	1.832E+01
Be10	6.431E-10	Ag-108m	1.619E-08	La-138	4.769E-14
C-14	2.591E-08	Ag-109m	5.894E-11	Ce-139	3.427E-13
Se-79	1.506E-04	Ag-110	3.275E-07	Ce-142	5.909E-09
Kr-81	1.406E-11	Ag-110m	2.408E-05	Ce-144	5.646E-02
Kr-85	1.011E+00	Cd-109	5.894E-11	Pr-144	5.646E-02
Rb-87	4.148E-09	Cd-113	7.829E-18	Pr-144m	7.907E-04
Sr-89	6.331E-20	Cd-113m	3.970E-03	Nd-144	3.371E-13
Sr-90	1.221E+01	In-115	4.473E-15	Pm-145	1.323E-06
Y-89m	5.890E-24	Sn-119m	2.041E-06	Pm-146	4.603E-05
Y -90	1.221E+01	Sn-121	4.507E-04	Pm-147	4.277E+00
Y-91	7.781E-17	Sn-121m	5.805E-04	Sm-145	1.483E-08
Zr-93	2.508E-04	Sn-123	9.243E-10	Sm-146	4.895E-12
Zr-95	4.829E-15	Sn-126	1.516E-04	Sm-147	1.609E-09
Nb-91	1.753E-12	Sb-124	4.710E-20	Sm-148	3.752E-15
Nb-92	4.111E-15	Sb-125	1.954E-01	Sm-149	2.253E-16
Nb-93m	9.206E-05	Sb-126	2.122E-05	Sm-151	5.095E-02
Nb-94	2.564E-08	Sb-126m	1.516E-04	Eu-149	4.085E-22
Nb-95	1.064E-14	Te-123	1.859E-17	Eu-150	1.066E-10
Nb-95m	5.680E-17	Te-123m	1.254E-13	Eu-152	4.814E-05
Tc-98	7.060E-11	Te-125m	4.773E-02	Eu-154	3.232E-01
Tc-99	3.236E-03	Te-127	6.168E-10	Eu-155	1.454E-01
Ru-103	7.888E-26	Te-127m	6.297E-10	Gd-152	6.068E-17
Ru-106	2.225E-01	I-129	7.733E-06	Gd-153	3.619E-08
Rh-102	6.105E-07	Cs-134	5.561E-01	Tb-160	7.940E-17
Rh-103m	7.874E-26	Cs-135	3.393E-05	Ho-166m	5.247E-08
Rh-106	2.225E-01	Cs-137	1.940E+01	Tm-170	4.836E-17
Pd-107	3.163E-05	Ba-133	4.551E-09	Tm-171	3.471E-08
Total					6.938E+01

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Typical PHWR Fuel Bundle

Properties	Standard Bundle	Long Bundle
Number of fuel Elements	37	37
Total Length	49.53 cm	50.8 cm
Total mass of UO_2	21.78 kg	22.3 kg
Total mass of Zircaloy	2.22 kg	2.24 kg
Total mass of U	19.2 kg	19.7 kg
Total mass of the bundle	24.0 kg	24.6 kg
Total volume of UO_2	2040 cm^3	2090 cm^3
Total volume of Zircaloy	340 cm^3	340 cm^3
Reference bundle power	445 kW	456 kW
Exit reference burnup	240 MWh/kgU	240 MWh/kgU
Time after discharge	10 years	10 years

Ref: Final Safety Report of Darlington Waste Management Facility

Actinides and Heavy Metals Inventory in PHWR Fuel after days of cooling

Radionuclide	Activity TBq[7]/bundle	Radionuclide	Activity TBq/bundle	Radionuclide	Activity TBq/bundle
Tl-206	6.386E-18	**Ra-226**	4.555E-11	**Pu-236**	3.815E-07
Tl-207	3.068E-10	**Ra-228**	9.383E-15	**Pu-238**	9.568E-02
Tl-208	8.647E-08	**Ac-225**	1.149E-12	**Pu-239**	1.231E-01
Tl-209	2.414E-14	**Ac-227**	3.076E-10	**Pu-240**	2.335E-01
Pb-209	1.149E-12	**Ac-228**	9.383E-15	**Pu-241**	1.463E+01
Pb-210	4.836E-12	**Th-227**	3.034E-10	**Pu-242**	3.656E-04
Pb-211	3.077E-10	**Th-228**	2.406E-07	**Pu-243**	2.737E-13
Pb-212	2.406E-07	**Th-229**	1.149E-12	**Pu-244**	3.610E-20
Pb-214	4.555E-11	**Th-230**	1.893E-08	**Pu-246**	1.433E-20
Bi-210	4.836E-12	**Th-231**	2.296E-06	**Am-241**	3.100E-01
Bi-211	3.077E-10	**Th-232**	2.136E-14	**Am-242m**	4.566E-04
Bi-212	2.406E-07	**Th-234**	2.413E-04	**Am-242**	4.547E-04
Bi-213	1.149E-12	**Pa-231**	1.324E-09	**Am-243**	1.143E-03
Bi-214	4.555E-11	**Pa-233**	1.988E-05	**Am-245**	4.026E-18
Po-210	4.836E-12	**Pa-234m**	2.413E-04	**Am-246**	1.433E-20
Po-211	8.462E-13	**Pa-234**	3.136E-07	**Cm-242**	3.763E-04
Po-212	1.541E-07	**U-232**	2.587E-07	**Cm-243**	5.232E-04
Po-213	1.125E-12	**U-233**	1.365E-09	**Cm-244**	3.142E-02
Po-214	4.555E-11	**U-234**	1.864E-04	**Cm-245**	7.019E-07
Po-215	3.077E-10	**U-235**	2.296E-06	**Cm-246**	1.903E-07
Po-216	2.406E-07	**U-236**	4.037E-05	**Cm-247**	2.737E-13
Po-218	4.555E-11	**U-237**	3.500E-04	**Cm-248**	4.488E-13
At-217	1.149E-12	**U-238**	2.413E-04	**Cm-250**	5.735E-20
Rn-219	3.077E-10	**U-240**	3.606E-20	**Bk-249**	2.775E-13
Rn-220	2.406E-07	**Np-235**	5.643E-10	**Bk-250**	2.301E-19
Rn-222	4.555E-11	**Np-236**	9.331E-11	**Cf-249**	1.965E-12
Fr-221	1.149E-12	**Np-237**	1.988E-05	**Cf-250**	6.497E-12
Fr-223	4.244E-12	**Np-238**	2.055E-06	**Cf-251**	4.547E-14
Ra-223	3.077E-10	**Np-239**	1.143E-03	**Cf-252**	6.952E-13
Ra-224	2.406E-07	**Np-240m**	3.606E-20	**Es-254**	2.220E-19
Ra-225	1.149E-12	**Np-240**	4.329E-23	**Total**	**1.543E+01**

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Main long-lived or parent Radionuclides present in Irradiated Fuel

Radionuclide	Half-life (Year)
Uranium	
U-234	2.46×10^{5}
U-235	7.04×10^{8}
U-236	2.34×10^{7}
U-238	4.47×10^{9}
Actinides (α emitters)	
Pu-238	87.7
Pu-239	24,100
Pu-240	6,560
Pu-241	14.35
Pu-242	3.74×10^{5}
Np-237	2.14×10^{6}
Am-241	432.7
Am-243	7,368
Cm-245	8.5×10^{3}
Cm-246	4.73×10^{3}
Fission Products (β/γ emitters)	
Se-79	6.5×10^{5}
Zr-93	1.5×10^{6}
Tc-99	2.13×10^{5}
Pd-107	6.5×10^{6}
Sn-126	1×10^{5}
I-129	1.57×10^{7}
Cs-135	2.3×10^{6}
Activation Products (β/γ emitters)	
C-14	5,715
Ni-59	7.6×10^{4}
Ni-63	100
Zr-93	1.53×10^{6}
Nb-94	2.03×10^{4}

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What is Partitioning and Transmutation (P&T) ?

Partitioning is a series of physical and chemical separation processes of different radionuclides (radioactive isotopes of different chemical elements) from a mixture in the spent nuclear fuel. Some of these (uranium, plutonium, thorium) can be recycled and used for fabricating new fuels.

Partitioning is practiced in currently operating "reprocessing" plants which follows and aqueous route and PUREX process. The spent fuel is dissolved in acid, then uranium and plutonium are separated out sequentially as individual chemical precipitates. The fission products and Minor Actinides (MA: Np, Am, Cm) remain in the raffinate and treated as high level waste.

Advanced Partitioning process aims at "proliferation resistance". For this, separation of pure plutonium is avoided and **MA** are recovered and co-precipitated with uranium and/or plutonium.

Transmutation involves the conversion of one chemical element into another by means of particle bombardment in a nuclear reactor or accelerator. Transmutation is the destruction of radionuclides by converting them to isotopes of lighter elements which are likely to have shorter half-lives and generally lower 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.

Benefits of P&T

- Resource conservation by making maximum use of the energy available from the primary fuel materials, uranium. This has been pursued through the separation of re-useable uranium and plutonium from spent nuclear fuel by means of reprocessing. The current trend of increase in price of uranium makes this unattractive and alternative.
- Reduction of the heat generation capacity of wastes. Repository designs can incorporate temperature limits designed to guard against thermal degradation of the surrounding rock and prevention of boiling that impedes natural groundwater movement. The benefit derives from enlarging the capacity of repository and reducing the number of sites required.
- Reduction of radiotoxicity of waste. By transmuting elements such as plutonium and americium, it is theoretically possible to transform the spent fuel so that it will decay to the activity of the original uranium in a few hundred (rather than tens of thousands) years, reducing the period over which it is a hazard.

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Closing the fuel cycle facilitates: a) Waste minimization [in terms of Pu & Minor Actinides (MA)]
b) Resource (natural uranium) utilization

Fresh unraium fuel (as oxide)

Reactor

SPENT FUEL

valuable materials 96%

Wastes 4%

- U: 94-96%
- Pu: ~1%

+

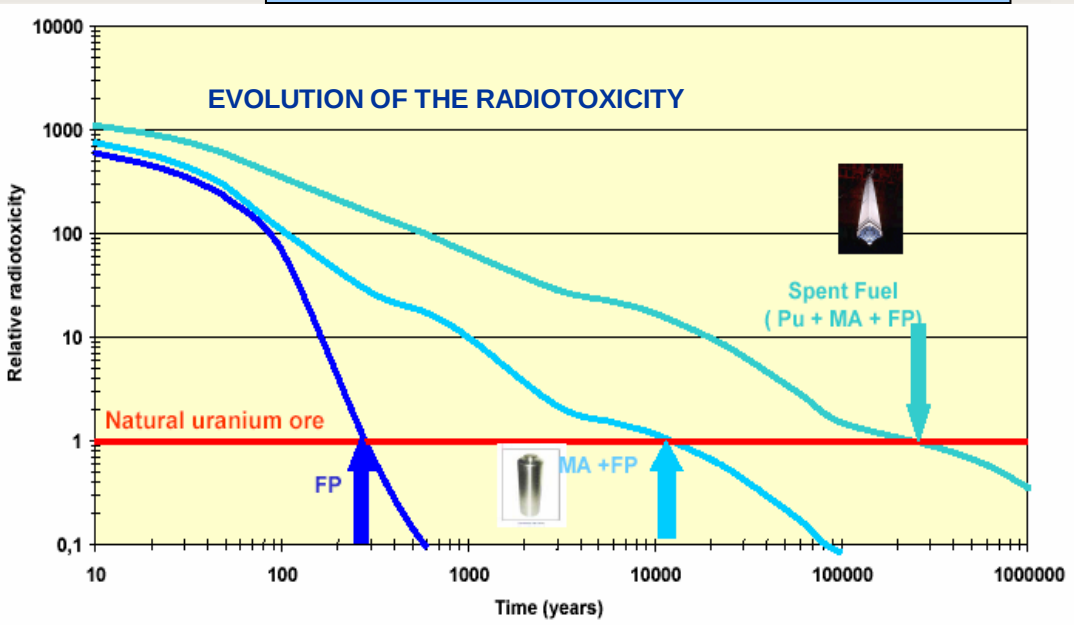
- FP: 3-4%
- MA: ~0.1%

Radiotoxicity of wastes after 1000 years

Pu

MA

FP



valuable materials 96%

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Goals of Partitioning

Several factors give rise to a more sophisticated view of reprocessing today, and use of the term partitioning reflects this. First, new management methods for high and intermediate-level nuclear wastes are under consideration, notably partitioning-transmutation (P&T) and partitioning-conditioning (P&C), where long-lived radionuclides are the prime objectives to separate out. Secondly, new fuel cycles such as those for fast neutron reactors (including a lead-cooled one) and fused salt reactors, and the possible advent of accelerator-driven systems, require a new approach to reprocessing. Here the focus is on pyrometallurgical processes ('pyroprocessing') in a molten salt bath, with electrochemical separation.

The main radionuclides targeted for separation for P&T or P&C are the actinides neptunium, americium and curium (along with U & Pu), and the fission products iodine (I-129), technetium (Tc-99), caesium (Cs-135) and strontium (Sr-90). Removal of the latter two significantly reduces the heat load of residual conditioned wastes. In Japan, platinum group metals are also targeted, for commercial recovery. Of course any chemical process will not discriminate different isotopes of any element.

Efficient separation methods are needed to achieve low residuals of long-lived radionuclides in conditioned wastes and high purities of individual separated ones in transmutation targets . Otherwise any transmutation effort is a random process with uncertain results. In particular one does not want fertile U isotopes in a transmutation target with slow neutrons, or neutron capture will bne the main action and hence it will generate further radiotoxic transuranic isotopes.

Achieving effective full separation for any transmutation program is likely to mean pyroprocessing of residuals from the PUREX or similar aqueous processes.