Nuclear Fuels and Nuclear Fuel Cycle

Chaitanyamoy Ganguly

Head

Nuclear Fuel Cycle and Materials Section

Seminar on Nuclear Science and Technology for Diplomats

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International Atomic Energy Agency

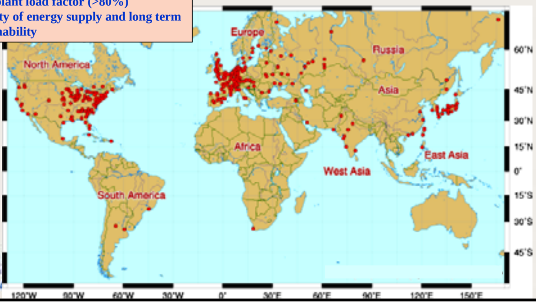
Nuclear Power Reactors Worldwide (January 2009)

Why 'rising expectation' for nuclear power?

- more economic(rising cost of gas and coal)
- no CO_2 emission (climate change/global warming)& environment-friendly
- Excellent safety records
- High plant load factor (>80%)
- Security of energy supply and long term sustainability

438 Nuclear Power Reactors in 30 countries ~372GWe, ~ 14.2% electricity; 44 under construct.

Projection of nuclear power in 2030
: low 473 GWe
: high 748 GWe



Nuclear Power Reactor & Nuclear Fuel Cycle Go Hand in Hand

Natural Uranium & Natural Thorium are the basic raw materials for nuclear fuels

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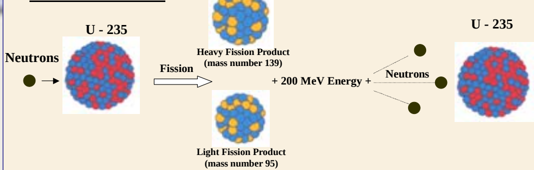
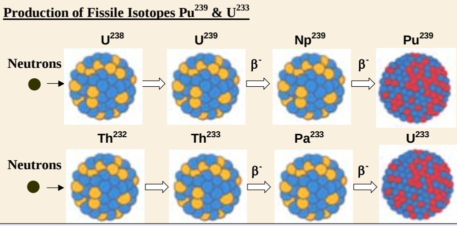
Nuclear Fission and Fission Heat Energy

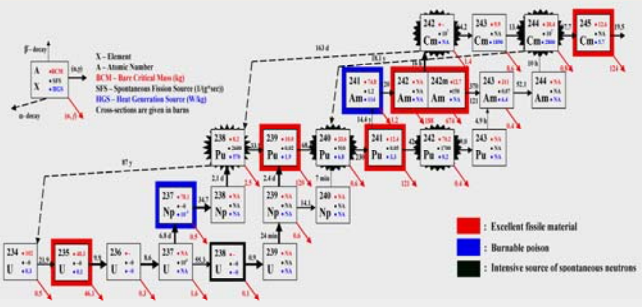
- Fission Chain Reaction



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



Formation of Plutonium (Pu) and Minor Actinides (Np, Am & Cm) isotopes in reactor



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Nuclear Reactors & Their Applications

(A Reactor is a Source of intense heat energy & neutrons)

- **Power Reactors:**

- Generation of Electricity
- Desalination of Sea Water
- Marine Propulsion
  - Ships
  - Submarines
- Production of Fissile Isotopes (Pu^{239} and U^{233}) & Co^{60}
- District Heating

- **Non-Power Reactors:** (Neutron Source)

- Production of Radioisotopes (Tc^{99}, I^{131}, P^{32}, Co^{60}, Ir^{192}, Cr^{51} etc.)
- Neutron Radiography
- Neutron Diffraction
- Neutron Activation Analysis
- Irradiation Testing of Materials
- Training, Education & Basic Research

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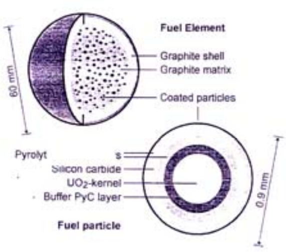
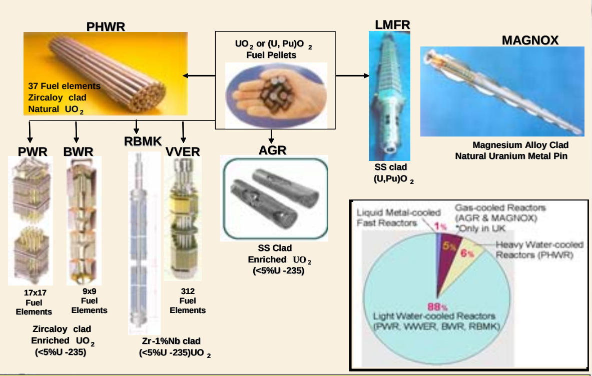
Forms of Nuclear Fuels – Pellets and Coated Particles

FUEL PELLETS



COATED FUEL PARTICLES

Typical Fuels for Operating Nuclear Power Reactors in the World



Water-cooled nuclear power reactors are most common in the world today. Except, Magnox all operating reactors use "Uranium Oxide Fuel Pellets" and to a limited extent "Mixed Uranium Plutonium Oxide (MOX)" pellets.

Coated Fuel Particles for High Temperature Gas-cooled Reactors

1. Coated fuel particles for HTGR

Prismatic block

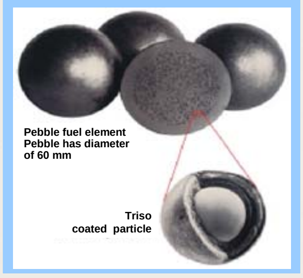
US, Japan, Russia and France

2. Fuel particles (dry or wet route) for vibratory compacted fuel pins

Pebble Bed

coated particle fuels embedded in spherical shape

Germany, South Africa, China



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UNIQUE FEATURES OF NUCLEAR FUEL AND NUCLEAR POWER REACTOR

High Energy Density :

1 atom of 'C' on combustion releases:	~ 4 eV
1 atom of U235 on fission release:	~200 MeV
1 kg of coal can generate:	3 kWh
1 kg of oil can generate:	4 kWh
1 kg of natural uranium (0.7% U-235):	50,000 kWh
1 kg of plutonium:	60,000,000 kWh

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 & NOx –does not contribute to global warming, climate change and acid rain

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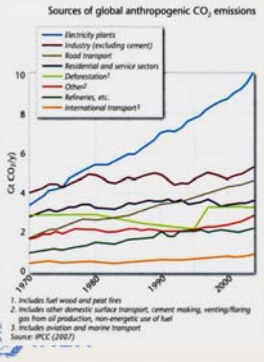
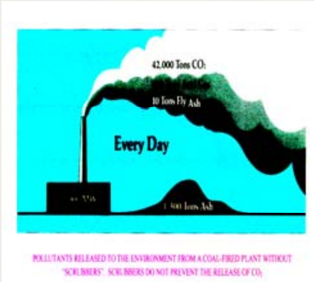
Thermal Power stations burn Carbon and Hydrocarbon Fossil Fuels (Coal , Oil or Natural Gas) to heat water and produce steam that run the turbine and generate electricity.

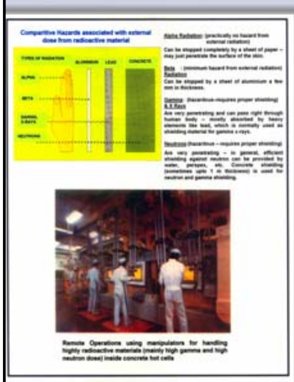
The released CO_2 greenhouse gas cause global warming and climate change .
Other released pollutants cause Global Environmental Degradation





Nuclear Power is one of the viable options for minimizing CO_2 emission and the associated climate changes

UNIQUE FEATURES OF NUCLEAR FUEL AND NUCLEAR POWER REACTOR (contd.)



Requires High Radiological and Criticality Safety

- Natural uranium (U-235 & U-238) and thorium (Th-232) are mildly radioactive and have very little hazard from external radiation. Pu-239 (with Pu-240, Pu-241, Pu-242 & Pu-238), U-233 (with U-232) and fission products are highly radiotoxic and health hazardous & require proper containment, beta, gamma and neutron shieldings and remote handling.
- 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 be handled at a time.
- The radioactive waste is health hazardous and has to be properly treated, fixed and stored or disposed.

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UNIQUE FEATURES OF NUCLEAR FUEL AND NUCLEAR POWER REACTOR (contd.)

Generates new 'fissile' isotopes from 'fertile' isotopes while producing high heat energy from 'fission'

Fresh Fuel
(5 % U235 + 95 % U238)

Spent Fuel
(1 % U235 + 94 % U238 + 1 % Pu239 (~0.1 % MA) + 4 % FPs)

Light Water cooled Reactor (LWR)

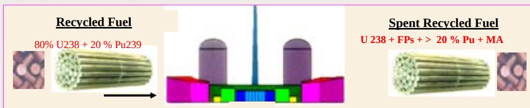
$U^{235} + {}_0n^1 \longrightarrow$ Fission Products (FPs) $+ 3\,{}_0n^1 + 200$ MeV

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

or

Recycled Fuel
80% U238 + 20 % Pu239

Spent Recycled Fuel
U 238 + FPs + > 20 % Pu + MA



Liquid Metal Cooled Fast Breeder/ Burner Reactor

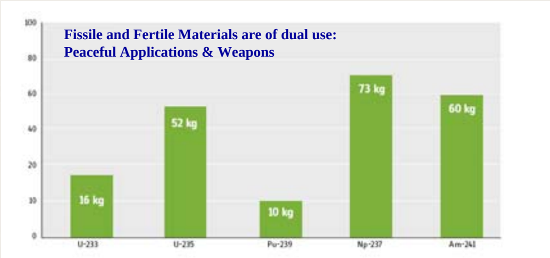
$Pu^{239} + {}_0n^1 \longrightarrow$ Fission Products $+ 3\,{}_0n^1 + 200$ MeV

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

In LMFBRs you can produce(breed) more Pu from U238 than you consume-
The Pu content in Spent Fuel is more than Pu content in Fresh Fuel

UNIQUE FEATURES OF NUCLEAR FUEL AND NUCLEAR POWER REACTOR (contd.)

Requires stringent safeguard procedures, physical protection and proliferation resistant features in order to avoid clandestine diversion of ‘fissile’ and ‘fertile’ isotopes for non-peaceful purpose



Bare critical masses for various fissile materials

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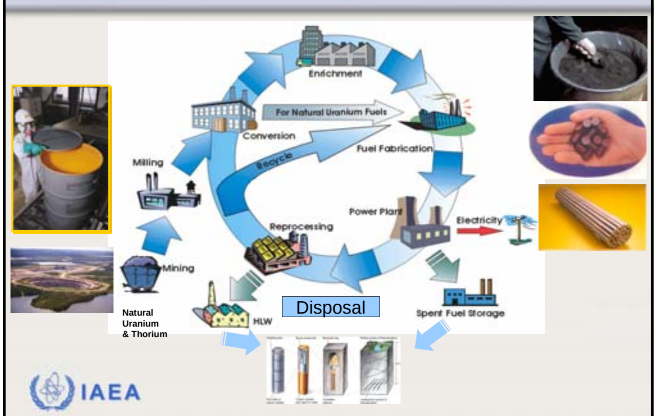
Civilian & Military Grade Uranium & Plutonium

CIVILIAN APPLICATION	MILITARY APPLICATION

URANIUM
• **Natural Uranium** (~0.7% U-235)
  • Fuel for PHWR: UO2 pellets
  • Fuel for Magnox U-alloy
  • Fuel for heavy water-cooled and moderated research reactor U-metal
• **Low Enriched Uranium** (**LEU:** <20% U-235)
  • Fuel for LWRs, AGRs, RBMK UO2 pellets containing <5% U-235
  • Fuel for compact research reactors [up to 19.75% U-235]
• **Reprocessed Uranium** [**RepU**: 0.8 – 1.1% U-235] from reprocessing spent fuel from thermal reactors
  • Re-enrichment & use as LEU fuel in LWRs
  • Use in CANDU reactor [DUPIC (**D**irect **U**tilization of **P**WR Spent Fuel **I**n **C**ANDU]
  • Blanket material for LMFR
• **Depleted Uranium** (< 0.7% U-235)
[tailings of enrichment plant: 0.1% - 0.3% U-235 or reprocessed spent fuel from PHWRs using natural uranium oxide fuel
  • Use as blanket material in LMFR for breeding Pu-239
  • Use for neutron-flux flattening of initial core of PHWR during start up.
	URANIUM
	• **High Enriched Uranium (HEU)** : (>20% U-235)
	Weapon grade HEU: >90% U-235

PLUTONIUM **Civilian ‘Pu’ from spent thermal power reactors** contain 55-70% Pu-239 (balance is Pu-240, Pu-241, Pu-242 & Pu-238) could be used as ‘Dirty Bomb’ • Use as mixed uranium plutonium oxide (MOX) fuel for LWR, PHWR & LMFR • Use as advanced LMFR fuel as mixed uranium plutonium carbide, nitride and U-Pu-Zr alloy containing 15-25% Pu	**PLUTONIUM** • **Weapon grade plutonium:** >95% Pu-239 • **Civilian plutonium** could be used as a ‘dirty’ bomb

Nuclear Fuel Cycle



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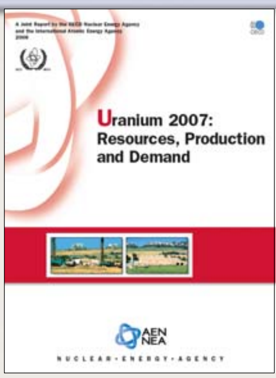
Uranium Resources: Red Book 2007

- Is there enough uranium worldwide?
- Are uranium supplies secure?
- Can the global uranium demand be met?

More than 50% uranium reserves (and production) are in countries with no nuclear power reactors (Australia, Kazakhstan, Namibia, Niger, Uzbekistan, etc). Countries (France, nearly whole of Europe, Japan, ROK) that have large number of nuclear reactors do not have or produce uranium in their soil)



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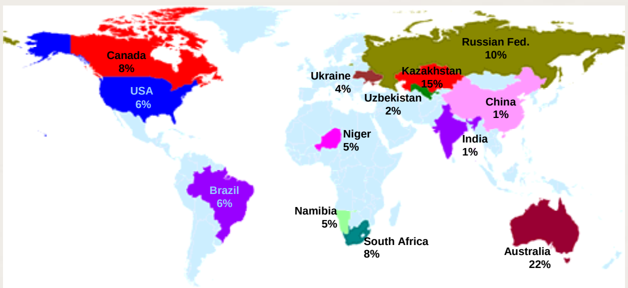
Is there enough Uranium ?

(Ref: Red Book 2007)

Identified Resources (<US$ 130/kgU)	**5.55 Mt**
Total Conventional Resources	**15.9 Mt**
Phosphates (unconventional)	**22 Mt (?)**

Reactor/Fuel cycle	Number of Years Uranium Resources will last assuming uranium consumption of ~ 66,500 tons / year (corresponding to the year 2006 when 2663 TWh nuclear electricity was generated)		
	Using only Identified Resources	Using Total Conventional Resources	Using Total Conventional and Unconventional Phosphate Resources
Current technology	100	300	> 675
Fast reactors with closed fuel cycle and recycling.	>2 500	>8 000	~20 000

Distribution of Identified Uranium resources Worldwide (Is the supply secure?) Total Identified Resources: 5.55 Mt (2007)



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World Thorium Reserves (economically extractable)

COUNTRY	RESERVES
Australia	300 000
India	290 000
Norway	170 000
USA	160 000
Canada	100 000
South Africa	35 000
Brazil	16 000
Other countries	95 000
World Total	1 200 000

Source : US Geological Survey, Mineral Commodity Summaries, January 2005

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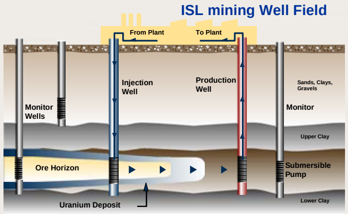
Uranium Mining Techniques

Open Pit Mining (24%)

In Situ Leach (ISL) Mining (~28%)

Other techniques (~2%)

ISL mining Well Field



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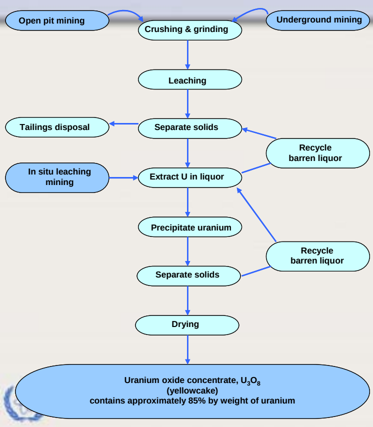
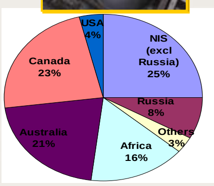
Underground Mining (~38%)

Process Flowsheet in Uranium Milling Plant & Statistics of Mining methods and World Uranium Production





World uranium production (41,279 Ut), 2007

IAEA URANIUM PRODUCTION SITE APPRAISAL TEAM (UPSAT) – REVIVED IN 2008

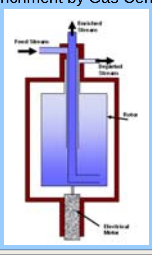
UPSAT Guidelines — IAEA-TECDOC-878(1996)

The objective of IAEA Uranium Production Site Appraisal Team (UPSAT) is to assist to improve the Operation & Safety of Uranium Production Sites , in Member States(on request) by peer review involving international experts.

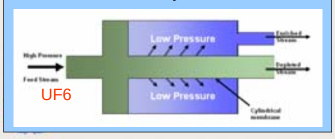
Schematics of Industrial Processes for Enrichment of Uranium-235 Isotope

[Feed Material : Uranium HexaFluoride (UF6) gas]

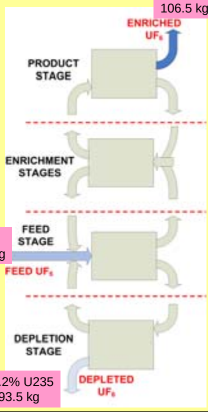
Enrichment by Gas Centrifuge



Enrichment by Gas Diffusion



Enrichment Cascades



Gas Centrifuge Types Worldwide for U-235 Enrichment

Russian centrifuge plant

Urenco centrifuges (Germany, Netherlands, UK)

USEC American Centrifuge

Japan, Rokassho plant

Commercial Operating Enrichment Facilities

Country	Facility	Capacity	Status
Brazil	Resende Enrichment	120	Commissioning
China	Lanzhou 2	500	In operation
China	Shaanxi Uranium Enrichment Plant	500	In operation
France	Eurodif (Georges Besse)	10 800	In operation
Germany	Urenco Germany GmbH	1 800	In operation
Japan	Rokkasho Uranium Enrichment Plant	1 050	In operation
Netherlands	Urenco Nederland	3 500	In operation
Pakistan	Kahuta	5	In operation
Russian Federation	Angarsk	1 000	In operation
Russian Federation	Siberian Chemical Combine (Seversk)	4 000	In operation
Russian Federation	Ekaterinburg (Sverdlovsk-44)	7 000	In operation
Russian Federation	Krasnoyarsk	3 000	In operation
United Kingdom	Urenco Capenhurst	4 000	In operation
United States of America	Paducah Gaseous Diffusion	11 300	In operation
	Total Capacity	**48 575**	**MTSWU/year**

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Commercially Operating Conversion Plants (Refined Uranium Oxide to UF6)

Country	Facility	Capacity	Status
Argentina	Pilcaniyeu - 1	62	In operation
Canada	Cameco - Port Hope (UF6)	12 500	In operation
China	Lanzhou	400	In operation
France	Comurhex Pierrelatte (UF6)	14 000	In operation
Russian Federation	Angarsk	20 000	In operation
Russian Federation	Ekaterinburg (Sverdlovsk-44)	4 000	In operation
United Kingdom	BNFL Springfields Line 4 Hex Plant	6 000	In operation
United States of America	Metropolis / Converdyn	17 600	In operation
	Total Capacity	**74 562**	**tHM/year**

Commercially Operating Conversion Plants (UF6/Refined Uranium Oxide to UO2 Powder ready for Pettetizing)

Country	Facility	Capacity	Status
Argentina	Complejo Fabril Cordoba	150	In operation
Brazil	Fabrica de Combustivel Nuclear	120	In operation
Canada	Cameco - Port Hope (UO2)	2 800	In operation
France	TU2 Cogema	350	In operation
India	NFC - Hyderabad (UOP)	450	In operation
Pakistan	Islamabad	0	In operation
United Kingdom	BNFL Springfields OFC IDR UO2 Line	550	In operation
United Kingdom	BNFL Springfields Enr. U Residue Recovery Plant	65	In operation
	Total Capacity	**4 485**	**tHM/year**

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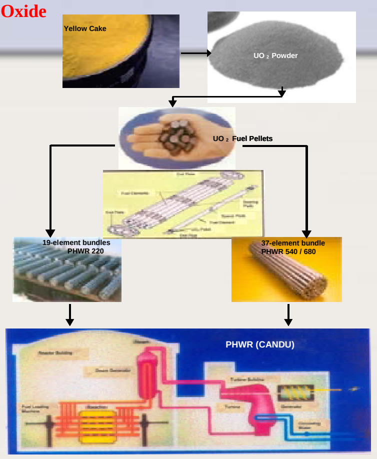
Production of Natural Uranium Oxide Fuel Bundles for PHWR



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Commercial Operating PHWR FA Fabrication Facilities

Country	Facility	Capacity	Status
Argentina	Ezeiza - Nuclear Fuel Manufacture Plant	160	In operation
Canada	Peterborough Facility	1 200	In operation
Canada	Zircatec Precision Ind. - Port Hope	1 200	In operation
China	Candu Fuel Plant	200	In operation
India	NFC - Hyderabad (PHWR)	270	In operation
India	NFC - Hyderabad (PHWR)-2	300	In operation
Korea, Republic of	CANDU Fuel Fabrication Plant (2)	400	In operation
Pakistan	Chashma	20	In operation
Romania	Pitesti Fuel Fabrication Plant (FCN)	200	In operation
		3 950	tHM/year

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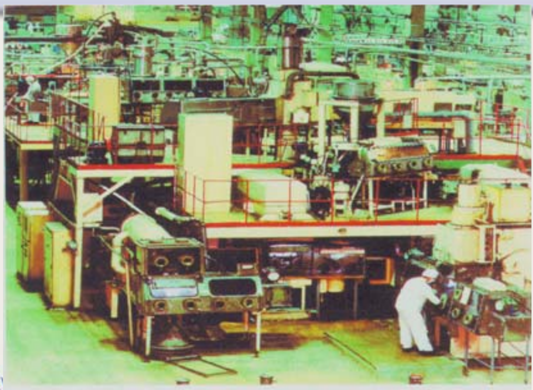
Low enriched Uranium Dioxide Powder Handling & Granulation Facility (operations inside glove box)



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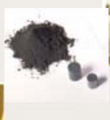
Cold-Pelletization, High Temperature Sintering and Centerless Grinding of Uranium Oxide Fuel Pellets

Rotary Press for Powder Compaction



Sintering Furnace in Hydrogen Atmosphere

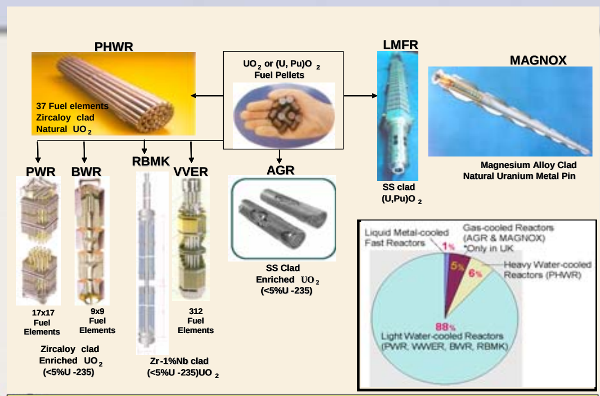
Centreless Grinding of Sintered Pellets

Shrinkage of Pellets after Sintering

From Zircon Sand to Zirconium Alloy Ingots at NFC, Hyderabad

Major Activities of Zirconium Alloy Fabrication Plant at NFC

Typical Fuels for Operating Nuclear Power Reactors in the World



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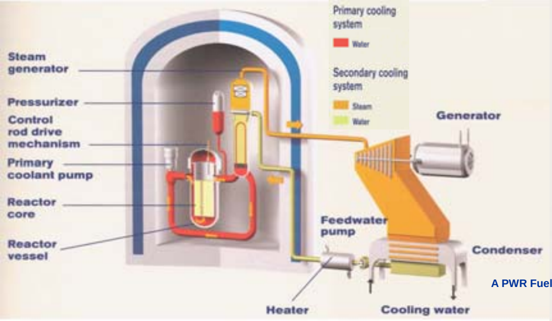
Pressurized Water Reactor (PWR) Concept

A typical 1,000 MWe PWR core has 157 Fuel Assemblies (FA) containing ~ 85 tonnes UO_2 pellets (~ 5% enriched U-235); Each FA has 268 zirconium alloy clad fuel rods in 17x17 square array. Each fuel rod (~ 4 m length, and 9-10 mm dia) contains ~ 500g UO_2 pellets. Annually, 60 FAs (1/3 core) are replaced.

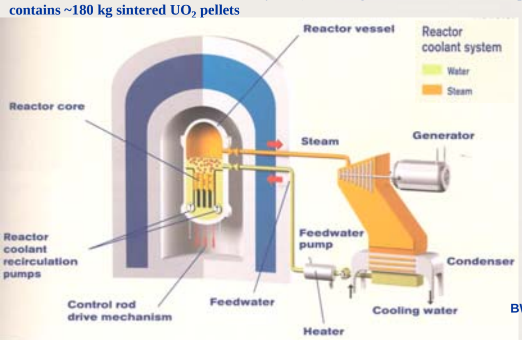


A PWR Fuel Assembly (FA)

Boiling Water Reactor (BWR) Concept

A typical 1,000 MWe BWR core has 764 Fuel Assemblies(FA) containing ~130 t U (~ 4% U-235 enrichment) in the form of UO_2 pellets.

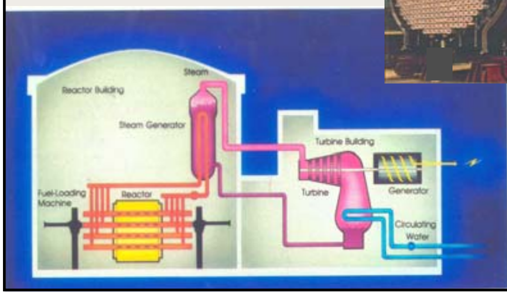
Each FA has 60 fuel rods (zirconium alloy clad), 4 m height, ~12 mm dia, in 8x8 square array and contains ~180 kg sintered UO_2 pellets



BWR Fuel Assembly

Illustration of Pressurized Heavy Water Reactor (PHWR) and Fuel Assembly

PWHRs are pressure tube type reactors, where the fuel assemblies are loaded in horizontal zirconium alloy pressure tubes. A typical PHWR 1,000 MWe, has 6,240 fuel assemblies containing ~120tU. Each fuel assembly has 37 zirconium alloy clad fuel pins of ~ 0.5 m length containing ~22kg natural uranium oxide pellets. PHWRs can be fuelled on-line.

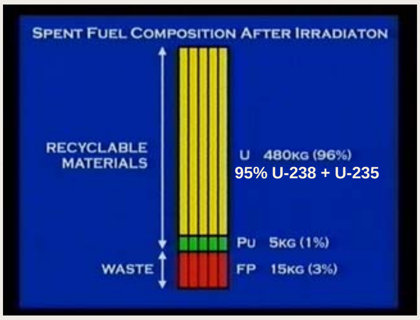


PHWR fuel assembly

Current Capacity of Fabrication of Zirconium Alloy Clad, Low Enriched Uranium Oxide Fuel for Light Water Reactors Worldwide (MTU/year) (Powder, Pellet and Assembly)

Country	Operator	Facility	Powder	Pellet	Assembly
Belgium	AREVA NP EU	Dessel	0	700	700
Brazil	INB-Resende	FCN Resende	165	120	240
China	Jianzhong	Jianzhong	400	400	450
France	AREVA NP EU	Romans	1200	820	820
Germany	AREVA NP EU	Lingen Fab	650	650	650
India	NFC-Hyderabd	Hyderabad	48	48	48
Japan	NFI-Kum/Tok	Kumatori	0	360	284
	MNF-TokaiMur	Tokai MNF	475	440	440
	NFI-Kum/Tok	Tokai NFI	0	250	250
	JNF-Yokosuka	Yokosuka	0	620	750
Kazakhstan	Kazatomprom	Ulba	3000	1000	0
Russia	TVEL-Ele/Nov	Elemash	1000	850	785
	TVEL-Ele/Nov	Novosibirsk	150	150	1000
South Korea	KNFC-Daejeon	Daejeon	600	600	600
Spain	ENUSA-Juzbad	Juzbado	0	400	400
Sweden	WestSE-Vas	Vasteras	530	530	400
U.S.A.	WestUS-Colum	Columbia Fab	1350	1500	1500
	AREVA NP US	Lynchburg	0	0	700
	AREVA NP US	Richland	1800	700	700
	GNF-Wilmingt	Wilmington	1000	1100	1100
United Kingdom	WestUK-Sprin	Springfields	440	440	0
Total		**MTU/Year**	**12808**	**11678**	**11817**

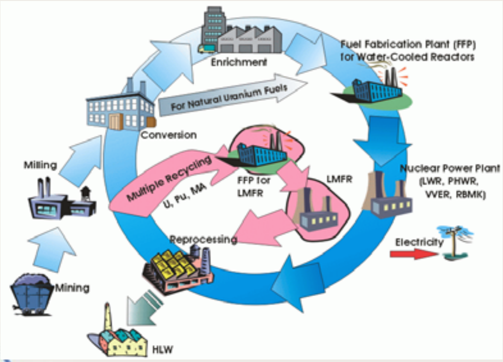
Light Water Reactor Spent Fuel Composition after Irradiation



Commercial Operating Reprocessing Facilities

Country	Facility	Capacity	Status
France	La Hague - UP2-800	1000	In operation
France	La Hague - UP3	1000	In operation
India	Plutonium Plant, Trombay		In operation
India	Prefre-2, Kalpakkam		In operation
India	Prefre-1, Tarapur		In operation
Russian Federation	RT-1, Combined Mayak	400	In operation
United Kingdom	BNFL B205 Magnox Reprocessing	1500	In operation
United Kingdom	BNFL Thorp	900	In operation
	Total Capacity	**4 800**	**tHM/year**

Multiple recycling of Pu with Minor Actinides (MA) in Liquid Metal-cooled Fast Reactor (LMFR) with 'Closed Fuel Cycle'



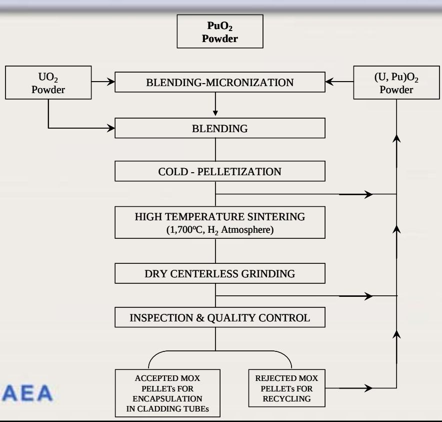
Mixed Uranium Plutonium Oxide (MOX) Fuel Fabrication Facility inside Alpha Tight Glove Boxes (Beta Gamma & Neutron Shielding for Pilot and Industrial Plants


MOX Laboratory facility in India


MOX Pilot Plant in Japan

Country	Industrial Facility	Capacity	Status
United Kingdom	Sellafield MOX Plant (SMP)	120	Commissioning
France	Melox	195	In operation
Belgium	FBFC International - MOX	100	In operation
		415	**tHM/year**

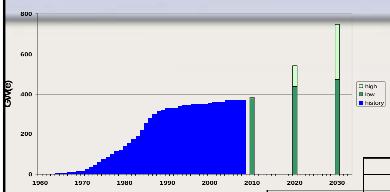
Flowsheet for Fabrication of Mixed Uranium Plutonium Oxide (MOX) Fuel Pellets by MIMAS Process [MIMAS: MIcronized MAster Blend]



Advanced Fuels for Liquid Metal-cooled Fast Reactors (LMFR)

Properties	$(U_{0.8}Pu_{0.2})O_2$	$(U_{0.8}\ Pu_{0.2})C$	$(U_{0.8}Pu_{0.2})N$	U-19Pu-10Zr
Theoretical Density g/cc	11.04	13.58	14.32	15.73
Melting point °K	3083	2750	3070	1400
Thermal conductivity (W/m °K) 1000 K 2000 K	2.6 2.4	18.8 21.2	15.8 20.1	40
Crystal structure	Fluorite	NaCl	NaCl	γ
Breeding ratio	1.1 - 1.15	1.2 – 1.25	1.2 - 1.25	1.35 - 1.4
Swelling	Moderate	High	High (?)	High
Handling	Easy	pyrophoric	Inert atmos	Inert atmos
Compatibility - clad coolant	average average	Carburisation good	good good	eutectics good
Dissolution & reprocessing amenability	Good	Demonstrated	risk of C^{14}	Pyro-reprocessing
Fabrication/Irradiation experience	Large Good	limited	very little	limited

IAEA's Nuclear Power Projection and Fuel Requirement until 2030



	2008	2030	
		Low	High
Nuclear power (GWe)	373	473	748
Natural U (ktonnes)	67	65-80	100-125
Conversion UF6 (ktonnes U)	64	60-75	95-120
Enrichment (MSWU)	46	55-70	85-110
Fuel fabrication (ktonnes U)	12	11-13	17-20
MOX fabrication (ktonnes HM)	0.2	0.2	0.5
SF discharge (ktonnes HM	12	11-13	18-21
SF reprocessing (ktonnes HM)	1.5	1-2	4-6

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Summary

- Natural uranium and natural thorium are the basic raw materials for nuclear fuels .
- Light water reactors (LWR) account for more than 80% of the operating nuclear power reactors, followed by pressurized heavy water reactor (PHWR) which contribute to ~ 6% of power reactors. LWRs will dominate the nuclear power worldwide up to 2050 and beyond.
- The present generation of nuclear power reactors use Uranium-235 as fuel. U-235 is the only fissile material in nature. The LWRs use LEU containing < 5% U-235 and the PHWRs use natural uranium as fuel. The plutonium 239 formed in the reactor by neutron capture reaction of fertile 238 is a man- made fissile material. In operating water cooled reactors , in-situ fission of Pu239 contribute ~ 30% of fission heat energy.
- Uranium resources are more or less uniformly distributed in the world and are adequate to meet any foreseeable growth scenario of nuclear power
- Uranium Mining & Milling, Conversion, Enrichment, and Fabrication of Uranium Oxide Powder, Pellets and Zirconium alloy clad Uranium Oxide Fuel Assemblies are being carried out on an industrial scale in several countries

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Summary – cont'd

- The operating nuclear power reactors utilize only 1% of the mined uranium – the rest is stored in the form of depleted and reprocessed uranium mostly as U-238. The U-238 could be utilized for breeding plutonium in a fast reactor. Plutonium is the best fissile material for fast reactor.
- Natural thorium has no fissile isotopes. Neutron capture reaction with thorium lead to the formation of man –made fissile isotope U-233. Thorium – based fuel must contain a fissile isotope (U-235, Pu-239 or U-233). Though thorium is three times more abundant in nature compared to uranium, thorium – based fuels are not likely to be commercialized till the uranium resources are utilized. Thorium 232- uranium 233 fuel cycle is best for thermal neutron reactors.
- The fissile isotopes (e.g. U-235 , Pu-239 , U-233 etc) are dual use materials – having both civil and military applications. Proliferation –resistance in nuclear fuel cycle is essential to avoid clandestine diversion of fissile materials for non peaceful purpose
- Nuclear Fuel Cycle activities are matured industries in several countries in the world

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IAEA's Mission on Nuclear Fuel Cycle & Materials Technologies

To promote development of nuclear fuel cycle options that are economically viable, safe, environment-friendly, proliferation-resistant and sustainable.

To promote information exchange on:

1. **exploration, mining and processing of uranium and thorium**
2. **design, manufacturing, and performance of nuclear fuels**
3. **management of spent fuel, including storage & treatment of spent fuel & recycling of plutonium & uranium fuel, and**
4. **development of advanced and innovative nuclear fuels and fuel cycles.**

Through:

1. **technical co-operation**
2. **organizing technical meetings, symposia and coordinated research projects**
3. **preparation of state -of -the art technical documents**
4. **maintaining & updating databases on nuclear fuels and fuel cycles**

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...Thank you for your attention

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