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

1774/11

Nuclear Fuels and Fuel Cycle Activities in IAEA

C. Ganguly
IAEA Vienna

ICTP Workshop

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

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Nuclear Fuels and Fuel Cycle Activities in IAEA

Chaitanyamoy GANGULY
Head, Nuclear Fuel Cycle & Materials Section

IAEA
International Atomic Energy Agency

NUCLEAR POWER REACTORS

- **Light Water Reactor (LWR): 87%**

  - Pressurised Water Reactor (PWR) including Russian type known as VVER : ~ 65 %

  - Boiling Water Reactor (BWR) : 22 %

  USA, France, Germany, Sweden, Belgium, Russia & CIS (WER), Japan, South Korea, Brazil & China
- **Pressurised Heavy Water Reactor (PHWR):6%**

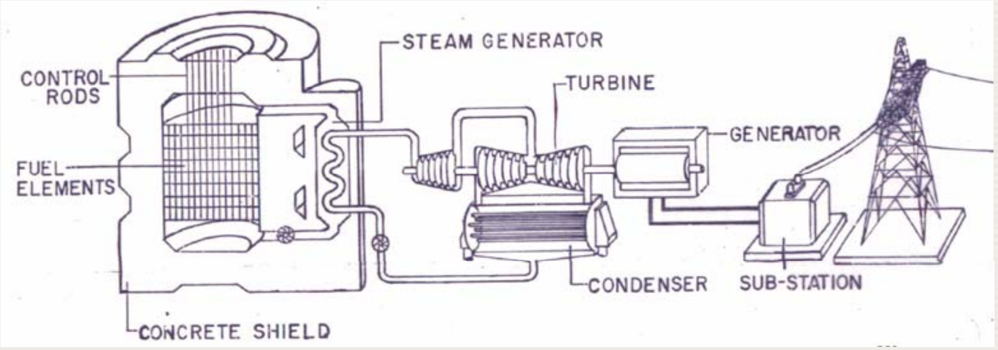
  (also known as CANDU) Canada, India, South Korea, Romania, Argentina, Pakistan & China
- **Light Water Graphite moderated Reactor (LWGR): 3%**

  Russia and CIS - known as RBMK type reactor.
- **Gas Cooled Graohite Moderated Reactors: AGR & Magnox: 3%**

  Popular only in UK.
- **Liquid Metal Fast Reactor (LMFR): < 1%**

  Presently, only one commercial LMFR is in operation: BN-600 in Russia .

Demonstration & Prototype LMFR in operations are: Phenix 250 MWe in France, Monju 250 MWe(to be restarted shortly) in Japan, BOR 60 in Russia , Joyo in Japan and FBTR in India.



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REACTORS IN OPERATION
443 Nos. 3 69 552 MWe

Typical Fuels for Operating Nuclear Power Reactors in the World

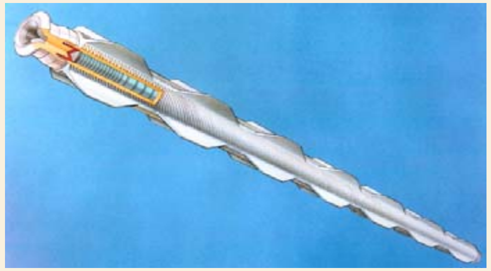
PHWR

UO_2 or $(U, Pu)O_2$ Fuel Pellets

LMFR

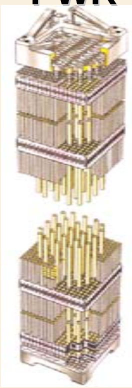
SS clad
$(U,Pu)O_2$

MAGNOX



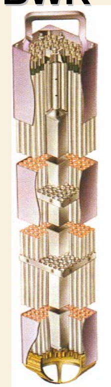
Magnesium Alloy Clad
Natural Uranium Metal Pin

PWR



17x17 Fuel Elements

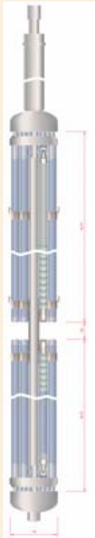
BWR



9x9 Fuel Elements

Zircaloy clad
Enriched UO_2
(<5%U -235)

RBMK



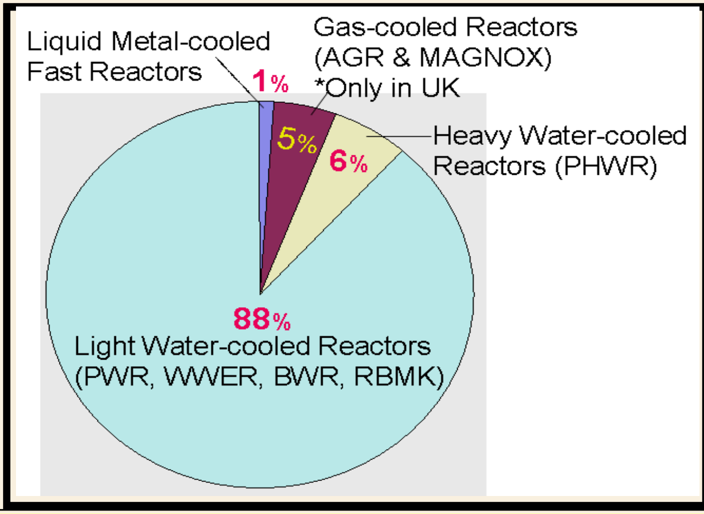
VVER

312 Fuel Elements

Zr-1%Nb clad
(<5%U -235)UO_2

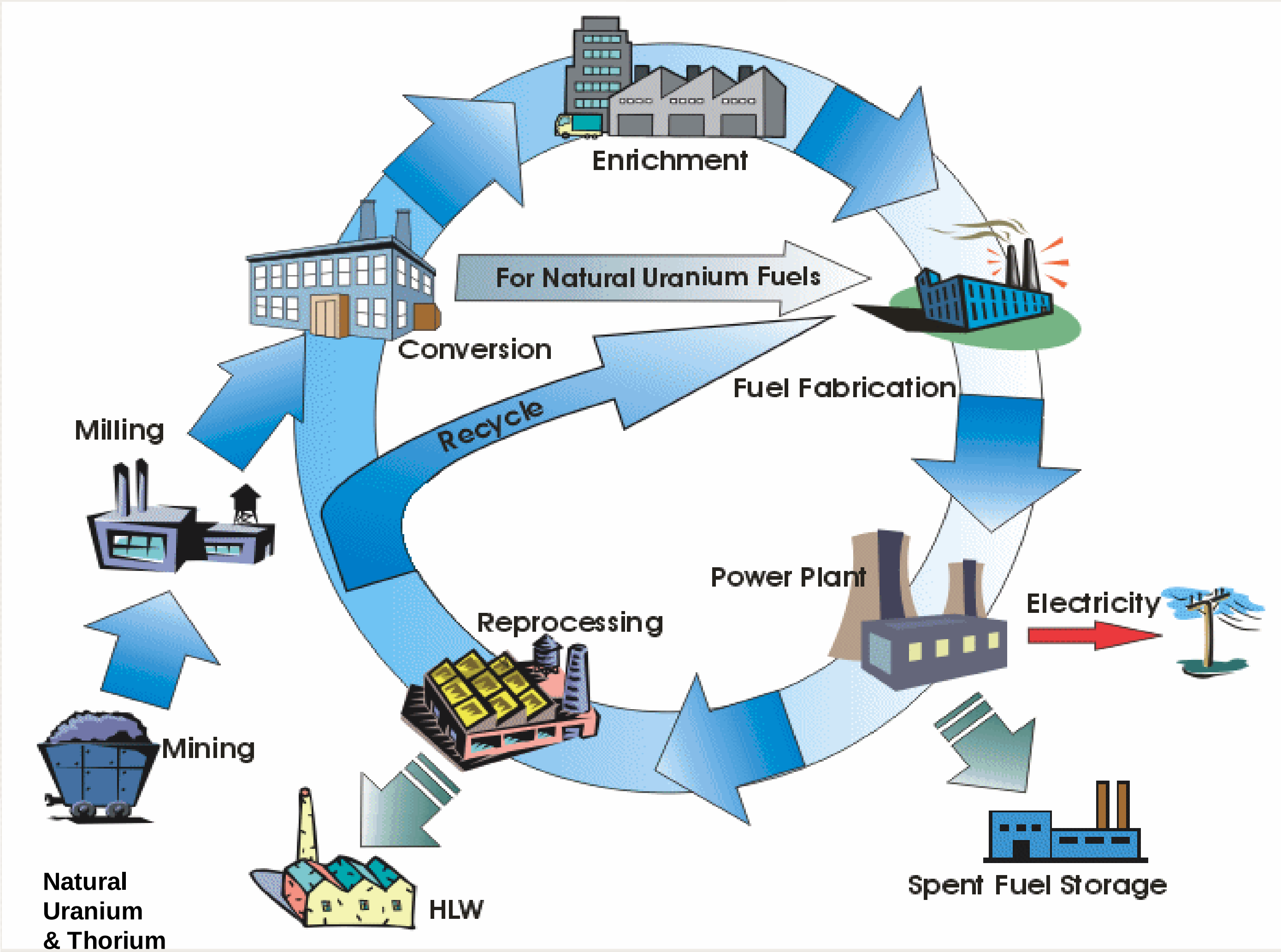
AGR

SS Clad
Enriched UO_2
(<5%U -235)



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.

NUCLEAR FUEL CYCLE



For nuclear energy to be sustainable as a global source of emission – free energy, the reactor fuel cycle must also remain sustainable (DG-IAEA Scientific Forum 2004)

Major Programme 1 B of IAEA : Nuclear Fuel Cycle & Materials Technologies

Mission Statement

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

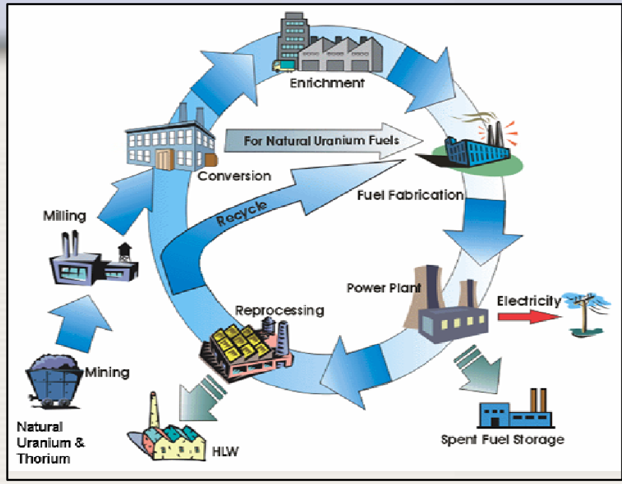
To promotes information exchange on:

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 fue, 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. **Maintaining & updating databases on nuclear fuels and fuel cycles**
4. **preparation of state -of -the art technical documents**

IAEA Prog. 1 B. Nuclear Fuel Cycle & Materials Technologies



International Working Groups

Subprogramme B1: **Information and Analysis of the Nuclear Fuel Cycle and Materials Management**

Working Group for B1: OECD/NEA – IAEA Uranium Group

(~34 Members including EU)

Subprogramme B2: **Nuclear Power Reactor Fuel Engineering**

Working Group for B2:

Technical Working Group on Nuclear Fuel Performance and Technology (TWGFPT) (28 Members including OECD-NEA & EC)

Subprogramme B3: **Management of Spent Fuel from Nuclear Power Reactors**

Subprogramme B4: **Topical Nuclear Fuel Cycle Issues**

Working Groups for B3&B4:
Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management (TWGNFCO) (~41 Members including ISTC,OECD-NEA & EC)

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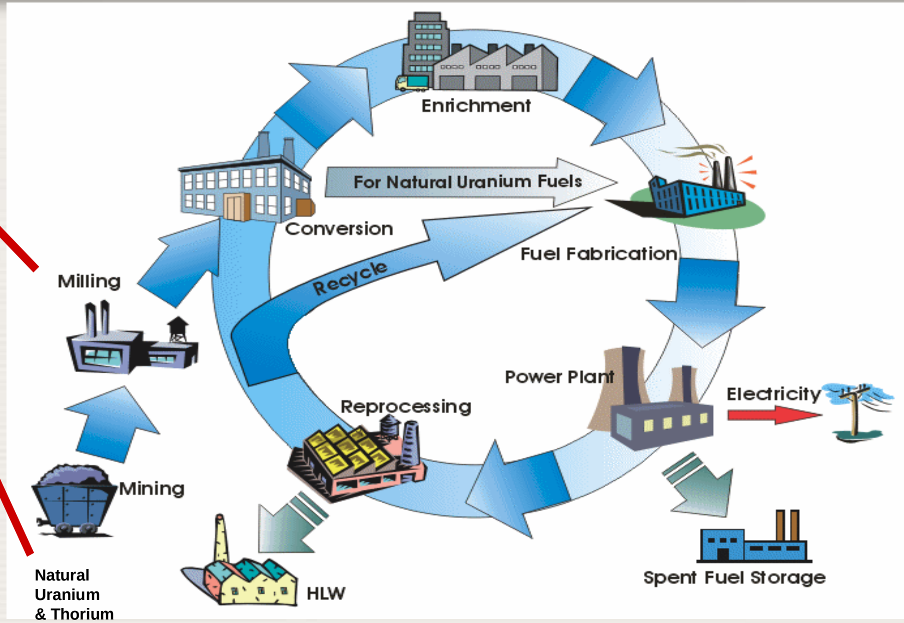
NUCLEAR FUEL CYCLE ACTIVITIES IN IAEA

Front-end: Subprogramme B1



- Uranium Exploration
  (helping developing countries: on-going/ forthcoming TC projects: Argentina, Brazil, China, Egypt, Pakistan, Romania)
- Promoting Best Practices in Uranium Mining & Production & Environmental Protection
  [helping developing countries through on –going & forthcoming TC projects.]
- Uranium Resources, production & Demand
  (popularly known as Red Book) with OECD-NEA
  Uranium 2005: Resources, production & Demand. Published:June, 2006
- integrated Nuclear Fuel cycle Information System (iNFCIS)-Database(UDEPO, NFCIS)

Major Events:

IAEA International Symposium on Uranium Exploration, Mining, Milling, Production, Supply, Demand & Market , Vienna, June 2005

Next International symposium on "Uranium" planned in June 2009

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Nuclear Fuel Cycle Activities and Commercial Facilities in Selected Countries

(as of 31 Dec. 2005)

References: NFCIS, PRIS, RedBook, NAC Reports

Country	Uranium Production (Mines & Mills)		UF6 Conversion	Enrichment	Uranium Fuel Fabrication	Reactors in Operation		Reprocessing	MOX Fabrication
	Identified Reserves (<$130/kgU) (t U)	2005 Production (t U)	Capacity (t HM/y)	Capacity (MTSWU/y)	Capacity (t HM/y)	#	Share in Electricity %	Capacity (t HM/y)	Capacity (t HM/y)
Australia	1 143 000	0 900	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Kazakhstan	813 039	4 175	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Argentina	15 640	Being revived	62	Has possibility	160	2	6.9	Nil	Nil
Brazil	273 700	340	Nil	5	240	2	2.5	Nil	Nil
China	59 723	730	1 500	1 500	450	10	2.0	Nil	Nil
India	64 840	230	Nil	Nil	618	16	2.8	380	20
France	11 740	Nil	14 350	10 800	820	59	78.5	2 000	145
Japan	6 600	Nil	50	2 272	1 705	55	29.3	90	55
RO Korea	Nil	Nil	Nil	Nil	800	20	44.7	Nil	Nil
UK	Nil	Nil	3 500	3 156	Nil	23	19.9	900	60
Canada	443 800	11 800	12 500	Nil	1 200	18	14.6	Nil	Nil
Russia	172 402	3 275	14 000	23 500	1 635	31	15.8	400	Likely to be set up
USA	342 000	835	14 000	11 300	3 850	103	19.3	Likely to be revived	Likely to be revived

- **Global 'Identified' Uranium reserves: ~ 4.74 Mt; 'U' Demand: ~ 67 000 t/y (443 reactors, 369.5 GWe); 'U' Production: ~ 41,000 t/y.**
- **Global UO2 fuel fabrication capacity (~17,000 t/y) is surplus compared to present requirement (~ 10,000 t/y).**
- Australia has the largest U reserves (24%), followed by Kazakhstan (17%). These 2 countries do not have nuclear power reactors.
- Canada: third largest U reserves (9.4%), highest grade uranium ores and largest producer of U (29%) followed by Australia (22%).
- France, UK, West Europe, Japan & RoK have large number of nuclear power reactors.They depend totally on overseas 'U' for nuclear fuel.
- India and China have the largest projected growth of nuclear power for future. Both countries have limited uranium reserves. China has access to international uranium market and overseas uranium mines. India has no such access. India has large thorium deposits (520 000 t).
- Brazil and Argentina have relatively small nuclear power programme. Brazil has significant uranium reserves and enrichment facility, Argentina is reviving their uranium exploration and mining activities.

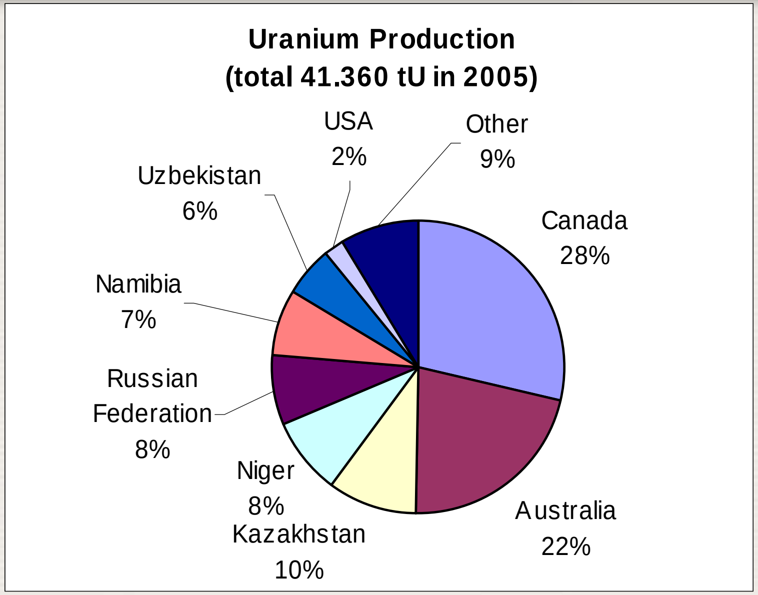
Global Uranium Resources & Production

Known Conventional & Identified Resources
(3.297-RAR + 1.446-Inferred) : **4.743 million tons U**
(<130 US$/kg U)

Undiscovered Conventional Resources
(prognosticated+speculative): **7.07 million tons U**
(<130 US$/kg U)

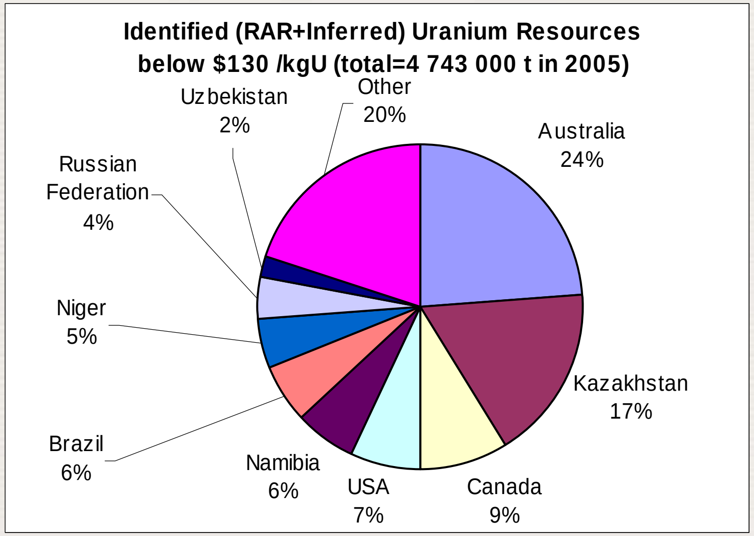
Undiscovered Conventional & Speculative Resources
(cost range unassigned): **2.98 million tons U**

Unconventional Resources in Rock Phosphates alone: **22 million tons U**
(<130 US$/kg U)



'U' Demand to fuel nuclear power till 2050

Nuclear Power Growth	Nuclear Power up to 2050 (GWe)	Demand of Uranium in 2050 (t U)	Cumulative Demand of Uranium up to 2050 (million tonnes U)
Low Case	295	52 000	3.18
Ref. Case	804	142 000	4.45
High Case	1 274	225 000	5.72



Conclusion from IAEA Intl. Uranium Symposium, June 2005

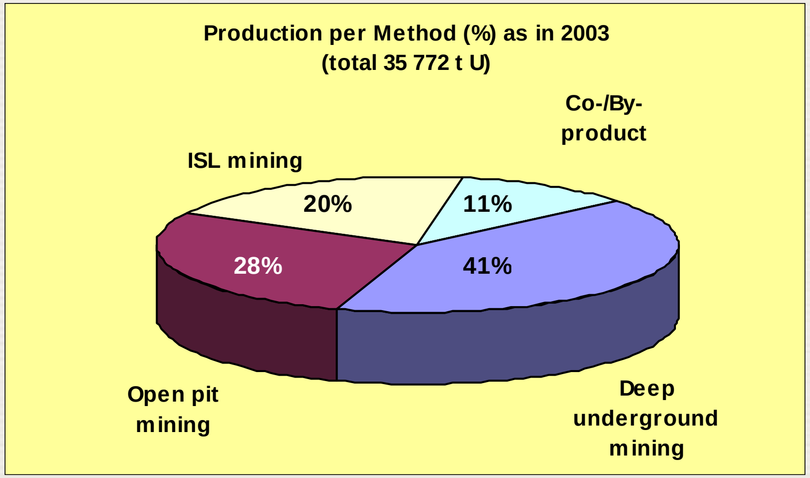
There is sufficient uranium resource in 'ground' to fuel the expanding nuclear power programme beyond 2050. However, the gap between uranium demand and uranium concentrate in market place has to be narrowed and bridged by expansion of uranium exploration, mining, milling and production .

URANIUM MINING TRENDS

Open Cast Mining

Underground Mining

In-Situ Leach(ISL) Mining



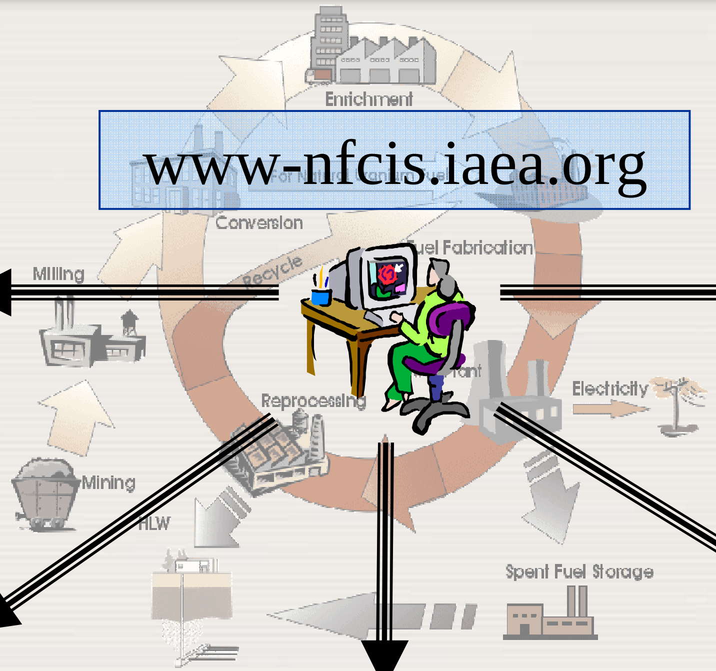
INTEGRATED NUCLEAR FUEL CYCLE INFORMATION SYSTEMS (iNFCIS)

NFCIS

(Nuclear Fuel Cycle Information System)

- Directory of Civilian Nuclear Fuel Cycle Facilities Worldwide
- Facilities from uranium milling to reprocessing, spent fuel storage and heavy water production
- Includes facilities at planning stage and decommissioned
- Available online since 2001

www-nfcis.iaea.org



PIE

(Post Irradiation Examination)

- Catalogue of PIE facilities worldwide
- General information about the facilities
- Technical capabilities of the facilities
- Available online since 2004

VISTA

(Nuclear Fuel Cycle Simulation System)

- Scenario based simulation system
- Estimates nuclear fuel cycle material and service requirements
- Calculates spent fuel arisings and actinide contents
- The simple web version is expected to be online as of end of 2005

UDEPO

(World Distribution of Uranium Deposits)

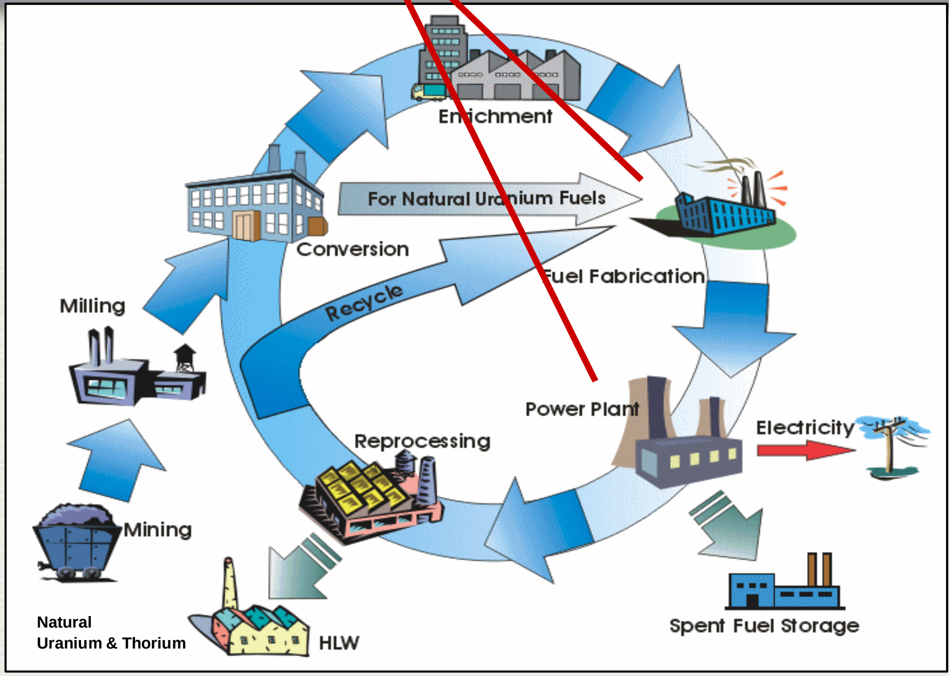
- Technical and geological information on uranium deposits
- Country level maps of the deposits will be displayed on the web site
- Deposits containing $\geq 0.03\% U_3O_8$ included
- More than 800 deposits stored in the database
- Available online since 2004

MADB

(Minor Actinide Property Database)

- Bibliographical database on physico-chemical properties of minor actinides bearing materials
- Carbides, Nitrides, Alloys, Oxides, Halides, Elements and other forms are covered
- More than 750 data records from 164 publications
- Under development

Subprogramme B.2. Nuclear Power Reactor Fuel Engineering



Technical Working Group on Fuel Performance & Technology (TWGFPT)

- manufacturing, characterization, QA & performance of water-cooled reactor fuels

Coordinated Research Projects:

- Fuel element performance modelling (D-COM 1982-1984, FUMEX-I 1993-1996, FUMEX-II 2002-2007)
- Optimisation of water chemistry (CCI 1981-1986, WACOLIN 1987-1991, WACOL 1995-2000, DAWAC 2001-2005, FUWAC 2007-2010)
- Delayed hydride cracking of Zr alloys (DHC-I 1998-2002, DHC-II 2005-2009)

Data Bases:

- IAEA Data Base on Post-Irradiation Examination Facilities / Techniques
- Joint IAEA-OECD/NEA International Fuel Performance Data Base

Handbook on Zirconium & its Alloys for Nuclear Applications

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Sub-programme B.3 Management of Spent Fuel from Power Reactors

Objective

To improve the capability of interested Member States to plan, develop and implement safe and efficient spent fuel management by the identification and mitigation of the associated problems, using information and guidance provided by the Agency.

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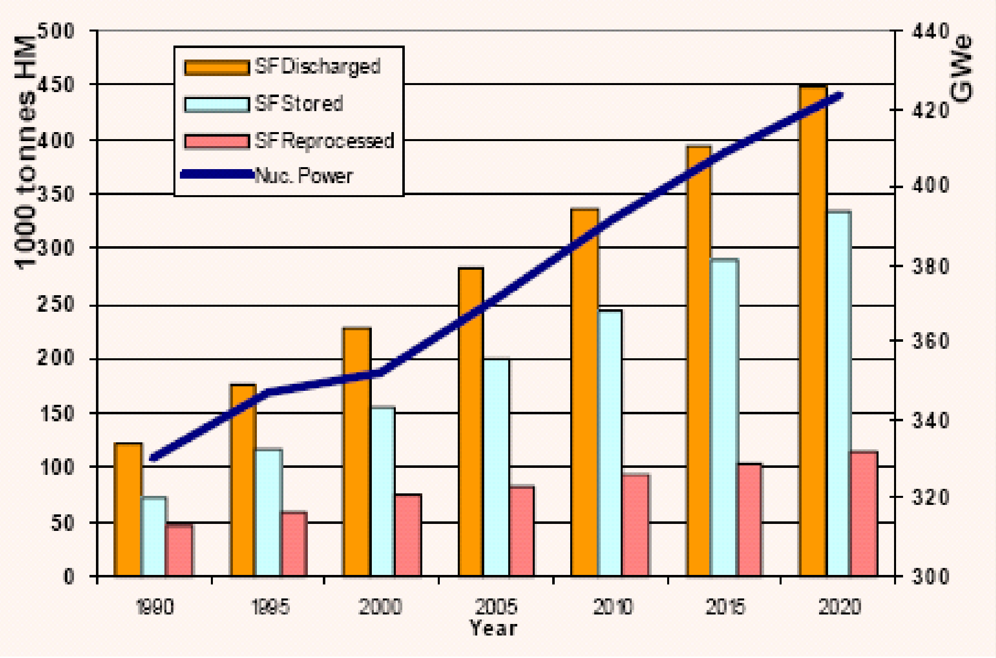
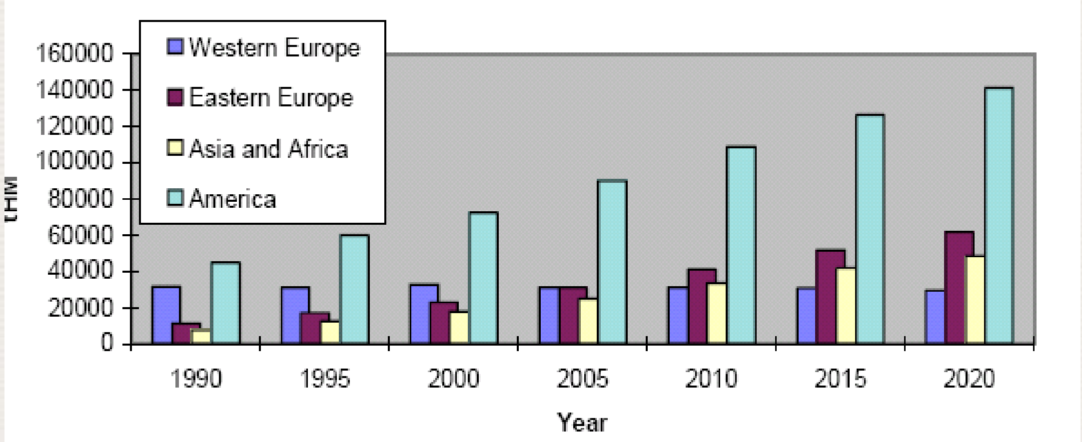


Cumulative spent fuel discharged, stored and reprocessed from 1990 to 2020.

Spent fuel stored by regions.



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Developments and Challenges in Spent Fuel Storage

- Currently, annual spent fuel discharge from power reactors:10,500tHM/y. Likely to rise to 11,500tHM/y by 2010. Annual spent fuel reprocessing capacity: 5000tHM/y . Cumulative spent fuel discharge/reprocessing(Sept. 2006): ~280,000/100,000 tHM' Storage quantities and durations continue to grow…"**long term storage is becoming a progressive reality**."
- More incentives for efficiencies, license extensions, possible multi-national cooperation…"major current issue – **provide additional storage space**."
- As durations grow, "new challenges arise in the institutional as well as technical area…management of liabilities and knowledge…longevity of spent fuel packages and behavior of structural materials of storage facilities."

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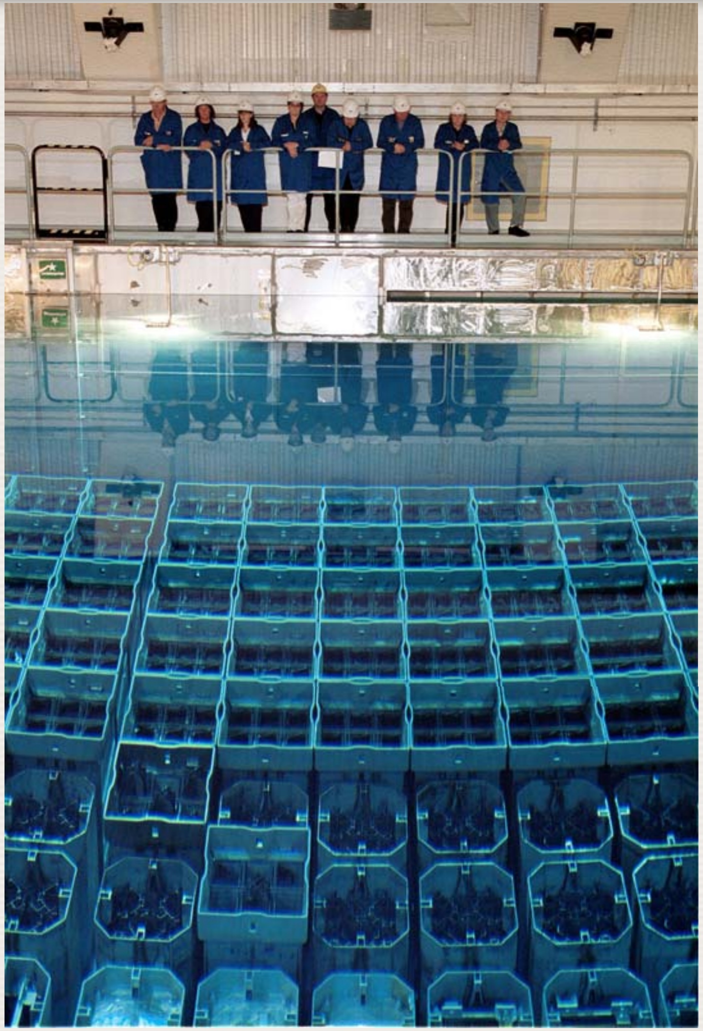
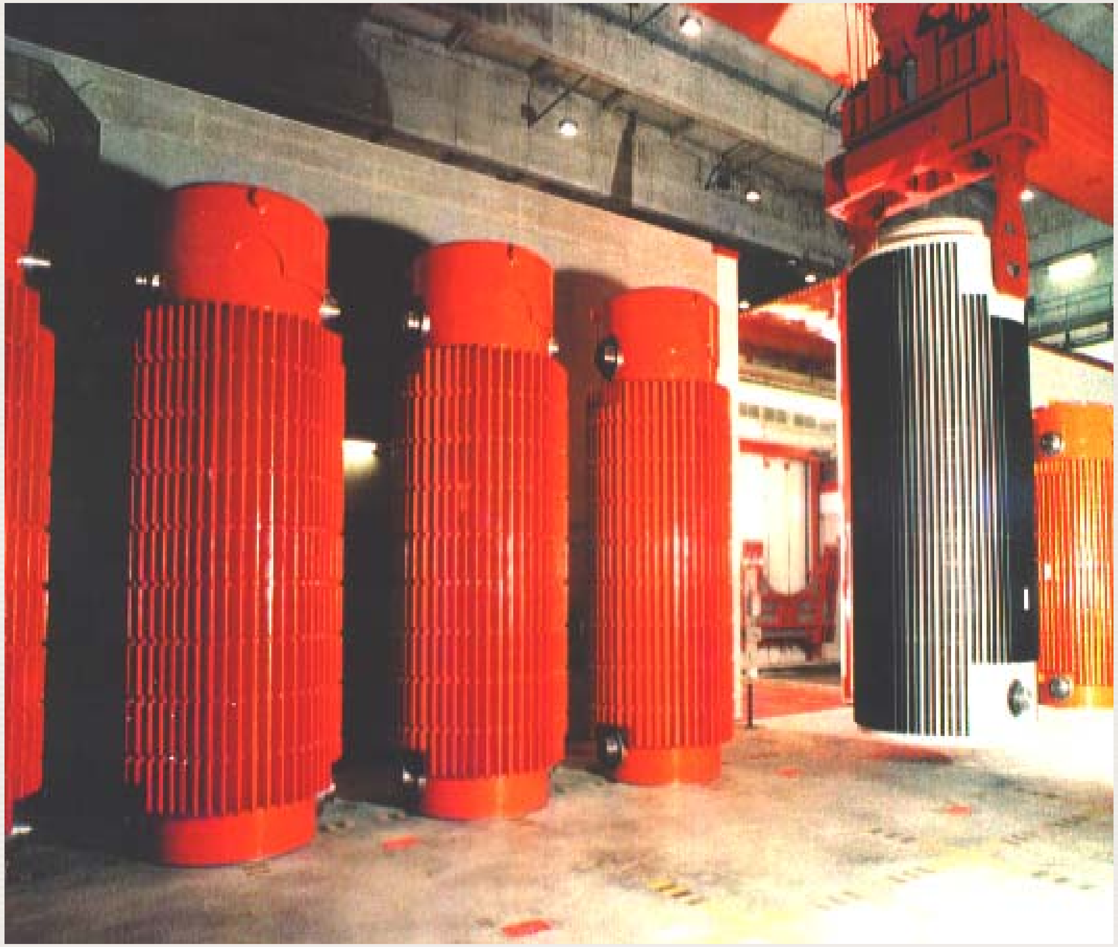
Storage of Spent Fuel





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Options for 'natural' and 'low enriched' (U235<5%) UO2 & MOX Spent Fuel Management

1. ***Once-through "open" cycle*** **– long term storage of spent fuel followed by disposal;**
2. ***Deferring a decision (wait & see): interim storage;***
3. ***Classical "closed" cycle*** **– spent fuel reprocessed, Pu + U recycled and waste [fission products & Minor Actinides(MA)] disposed;**
4. ***Advanced "closed" cycle*** **– spent fuel reprocessed, Pu+U+ MA recycled & fission products disposed**

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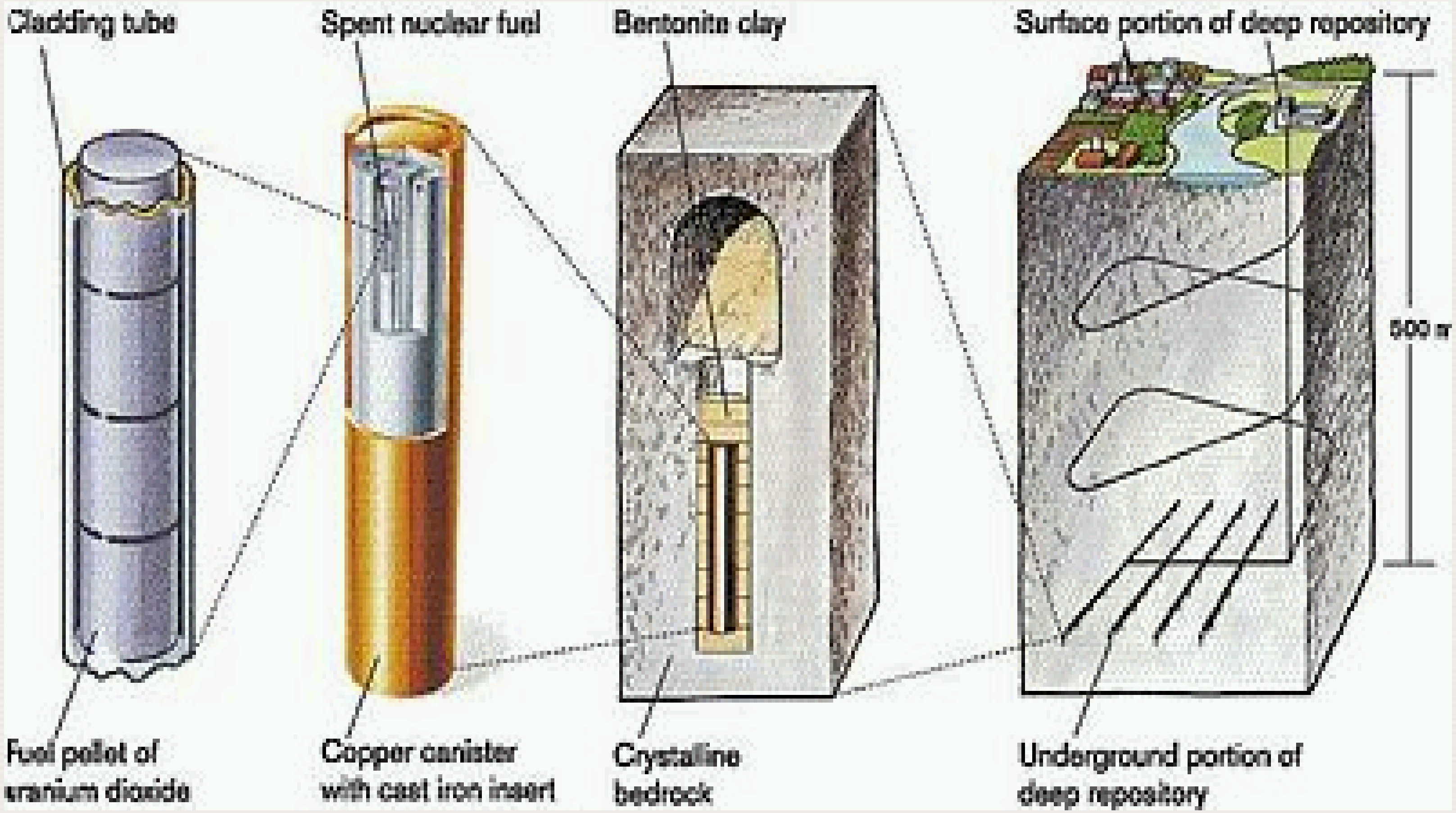
Barriers for Geological Disposal



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Commercial Spent Fuel Reprocessing Plants

COMMERCIAL SIZE REPROCESSING PLANTS

Name	Country	Capacity (tHM/year)	Type of fuel
BNFL Magnox	UK	1500	Magnox
BNFL Thorp	UK	900	LWR, AGR
JNC Tokai	Japan	210	LWR
La Hague – UP2-800	France	1000	LWR
La Hague – UP-3	France	1000	LWR
RT-1 Mayak	Russia	400	LWR
Rokkasho *	Japan	800	LWR

* The Rokkasho plant is commissioning with a planned start of commercial operation in 2007.

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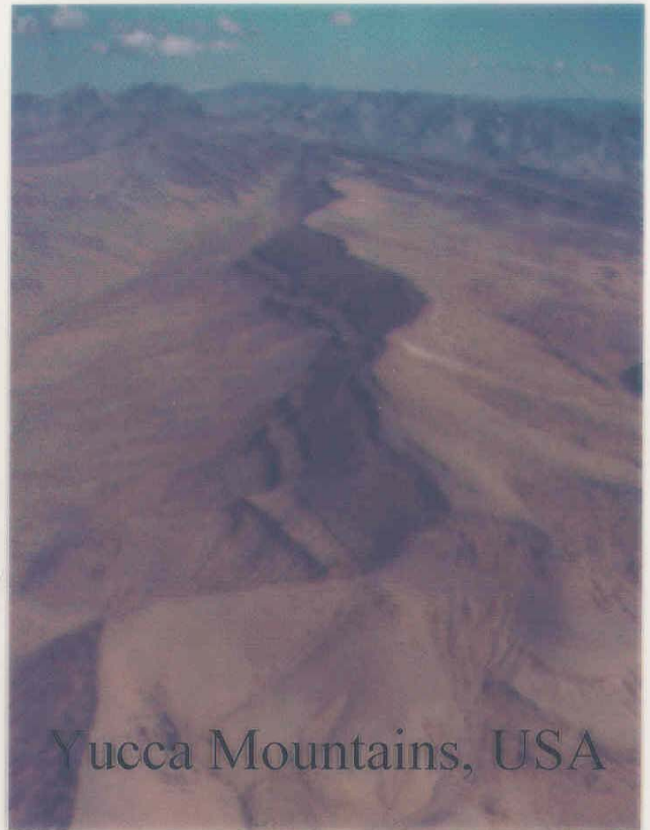
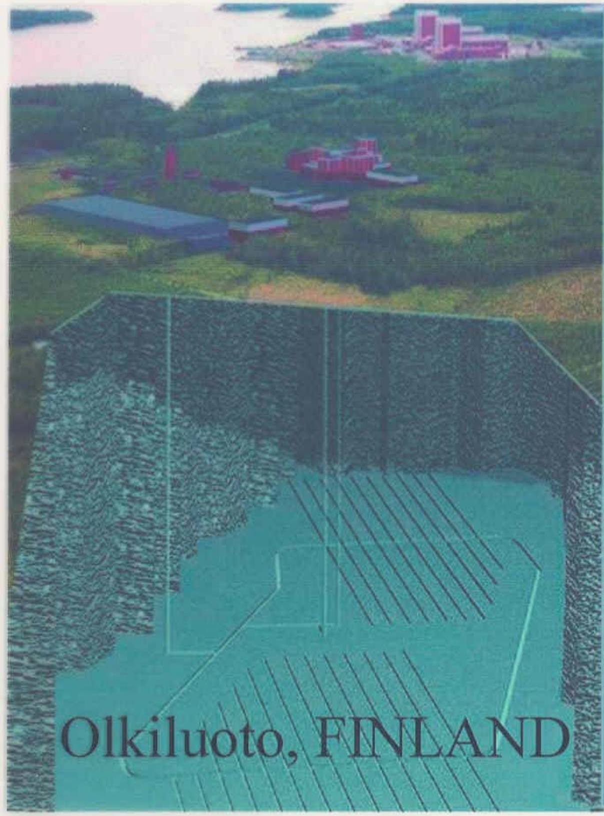
Permanent Repositories for Safe Disposal of Nuclear Wastes

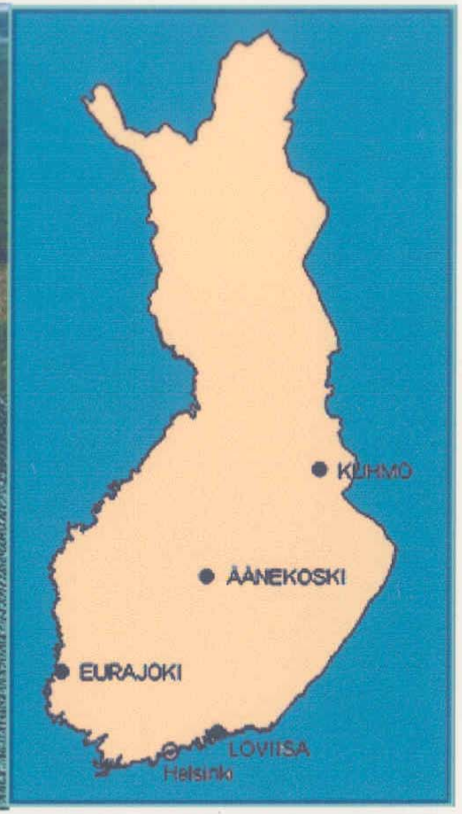


<u>Monitored Geological Repository for High Level Radioactive Waste at Yucca Mountains, Nevada</u>

Basis of Selection:

i) its remote location and long distance from a large population center—100 miles from Las Vegas, Nevada;
ii) its very dry climate—less than 6 inches of rainfall a year
iii) its extremely deep water table—800 to 1,000 feet below the level of the potential repository





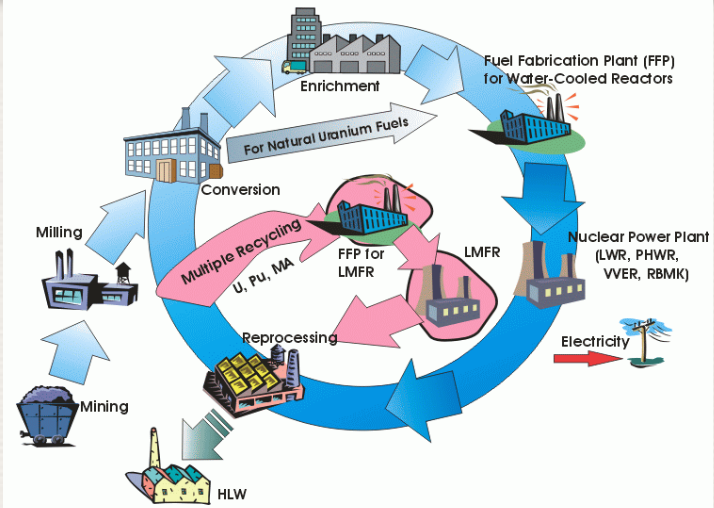
<u>Four Permanent Deep Repositories in Finland for Safe Disposal of Highly Radioactive Spent Fuels: 2 at Nuclear Power Plant sites, namely Olkiluoto at Eurojoki & Lovisa and other 2 at Kuhmo at Aanekoski.</u>

The ONKALO facility at Olkiluoto is under construction at depths of 300, 400 and 500 meters with an access tunnel and an associated ventilation tunnel. The bed-rock at Olkiluoto is suitable for safe disposal. The radioactive waste would be packed in copper based canisters, which will be surrounded by compacted bentonite in the repositories. The Permanent Repository at Olkiluoto would be operational in 2010.

Subprogramme B4.01

Liquid Metal-cooled Fast Reactor (LMFR) Fuel & Fuel Cycle

(Fuel: Mixed uranium plutonium oxide, monocarbide, mononitride, U-Pu-Zr alloy & inert matrix fuels)



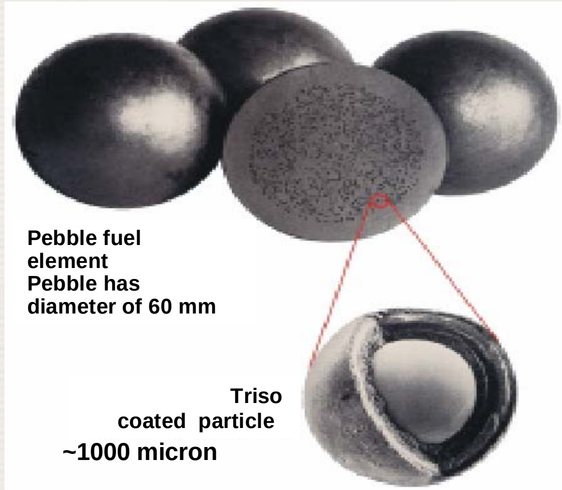
- Preparation of Technical Document on LMFR Fuels Technology
- Preparation of Technical Document on LMFR Fuel Cycle Technology
- Minor Actinide Database
- Technical Meetings.

High Temperature Gas-cooled Reactor (HTGR) Fuel & Fuel Cycle

(Fuel: pebbles or prismatic blocks; Multi-layer coated fuel particles of U&Th based oxide & carbide embedded in graphite in the form of pebbles or prismatic blocks)

- CRP on advances in HTGR fuel technology development
- CRP on evaluation of HTGR performance
- Training/workshop on HTGR technology
- Technical Meetings & Technical Documents

Prismatic block



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Subprogramme B 4 : Advanced Fuels and Fuel Cycle options

Common Objectives of International & National Fuel Cycle Initiatives:
(INPRO-IAEA, GIF, GNEP- USA, GNI-IFCC of Russia, France & Japan)

- **Reduce decay heat, volume & radiotoxicity of high level waste by Partitioning & Transmutation to minimize space requirement in repository.**
- **Multilateral/ Regional Fuel Cycle Facilities : working on the principle of "assurance of fuel supply" and "assurance of proliferation – resistance".**
- **Efficient utilization of Uranium & Thorium natural resources by multiple recycling of fissile & fertile materials and Minor Actinides in "closed" nuclear fuel cycle.**
- **Ensuring "Safety &Security" and "proliferation – resistance" (intrinsic and extrinsic) in nuclear fuel cycle activities.**
- **Advanced fuels and advanced fuel cycles, utilizing Pu and Minor Actinide(MA: Np, Am & Cm) based fuels & fuel cycle options.**

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Protected Plutonium Production (P3) Project

- Protected Plutonium Production (PPP) and utilization is a collaboration between Tokyo Institute of Technology and IAEA

  on "intrinsic proliferation resistance" of growing Plutonium inventories (~1900 tons) through utilisation of Minor Actinides (MA) inventories (~200tons)[MA: Np, Am & Cm].

- PPP addresses the challenges of introducing enriched uranium (<5%) oxide and MOX fuels containing < 1% MA in operating water –cooled power reactors and MA bearing fuel and blanket (U-238/Th-232) for LMFR , with respect to manufacturing, reprocessing, safety and economics

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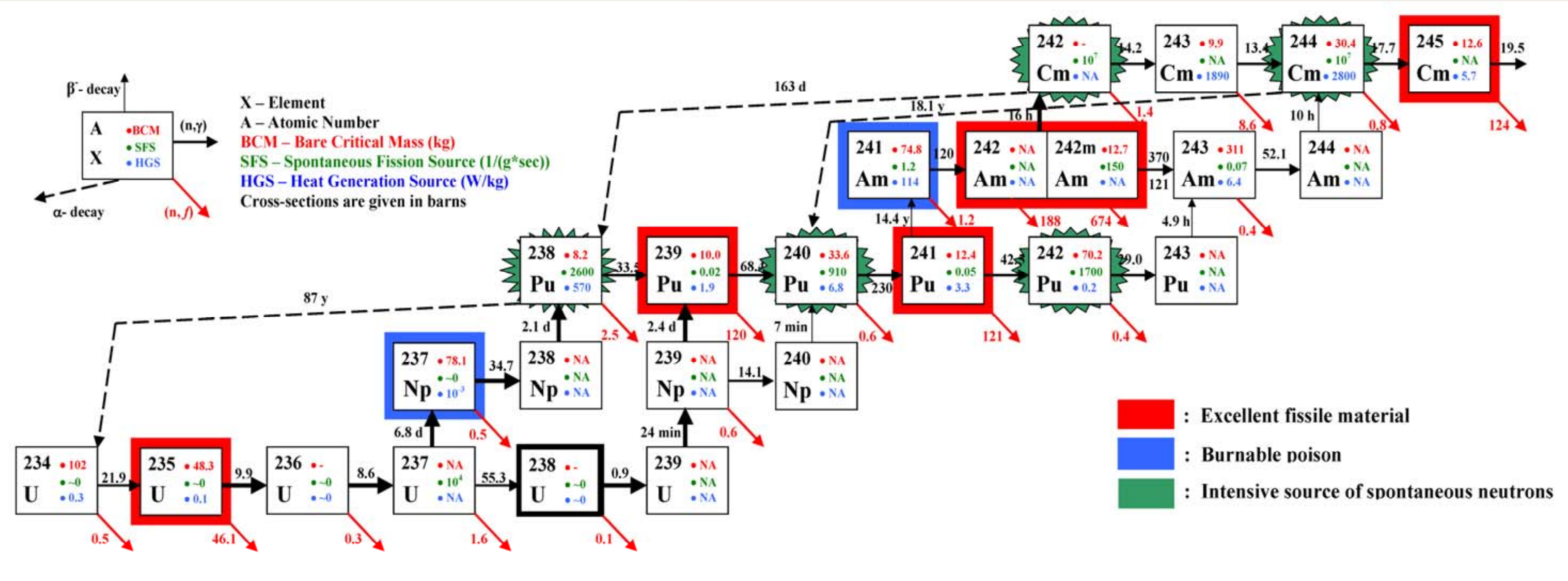
Summary of “Protected Plutonium Production (P3)” concept:

The P3 concept enhances “proliferation resistance” (PR) of plutonium by the transmutation of Minor Actinides (MAs). Addition of small amount of MAs (Np-237 or Am-241) with large neutron capture cross-section to fresh uranium fuel enhances the production of Pu-238, which is effective for improving the isotopic barrier of Pu in the spent fuel from thermal reactors.

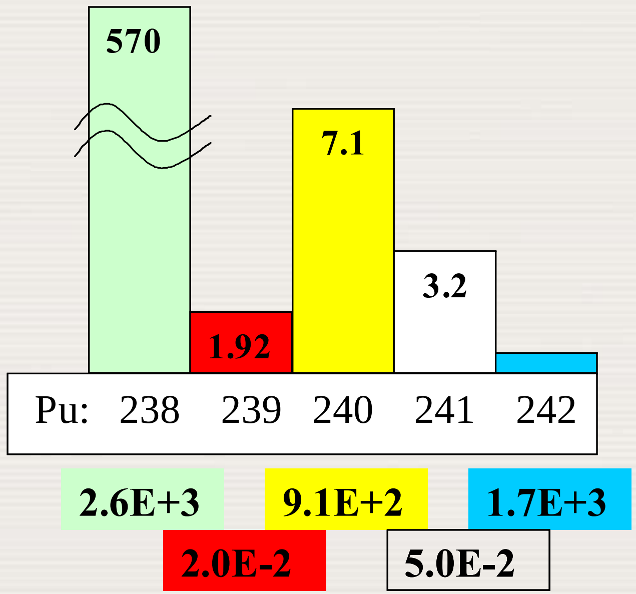


Spontaneous Fission Neutrons and Decay Heat of Plutonium Isotopes

- Pu-238 emits high spontaneous fission neutrons which deteriorate the quality of nuclear explosive
- Pu-238 has high decay heat (570 W/kg) which makes the process of the nuclear weapon manufacture and maintenance difficult

	Half-life (years)	Spontaneous fission neutrons (n/kg/sec)	Decay heat (Watt/kg)	Bare critical mass (kg)
Pu-238	87.7	2,600,000	560	10
Pu-239	24,100	22	1.9	10
Pu-240	6,560	910,000	6.8	40
Pu-241	14.4	49	4.2	10
Pu-242	376,000	1,700,000	0.1	100

Decay Heat (W/kg)



Neutron Source due to Spontaneous Fission (n/g·s)

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Innovative Back-end Technology of Fuel Cycle – Developments in Japan

Reprocessing	Simplified PUREX Process	Alternative Aqueous Process	Oxide–Electrowinning Process	Metal – Electrorefining Process
	Dissolution	Direct Extraction	Uranium Electrowinning	Oxide Reduction
U Recovery	Crystallization			U Electrorefining (solid cathode)
U, Pu,MA Recovery	Single Cycle Extraction	Supercritical Fluid Extraction TBP–CO_2–HNO_3	MOX Electro-codeposition	U, Pu, MA Electrorefining (Liq. Cd cathode)
MA Recovery	SETFICS Process /TRUEX Process	Ion Exchange / Amine Extraction	MAElectrowinning	Cd Extraction (pyro contactor)

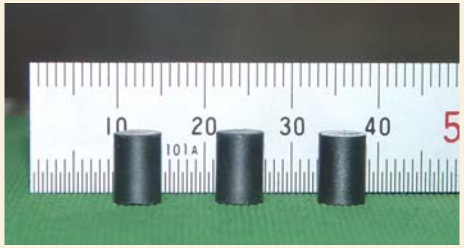
Oxidation

Fuel Refabrication	Pellet short Process	Sphere Packing Process	Vibro –Packing Process	Casting Process
	Simplified Pelletizing	Gelation (MOX– MA)	Granulation (MOX,MA)	Casting (U,Pu–Zr–MA)
	Stacking	Vibration Packing	Vibration Packing	Stacking
	MOX Fuel		MOX Fuel	Metal Fuel

:MOX Aqueous Recycle :M n –Aqueous Recycle :Metal No Aqueous Recycle

CANDIDATES OF FUEL CYCLE SYSTEMS

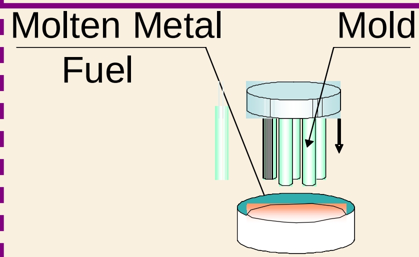
Fuel Fabrication



Simplified Pelletizing

[Special Features]

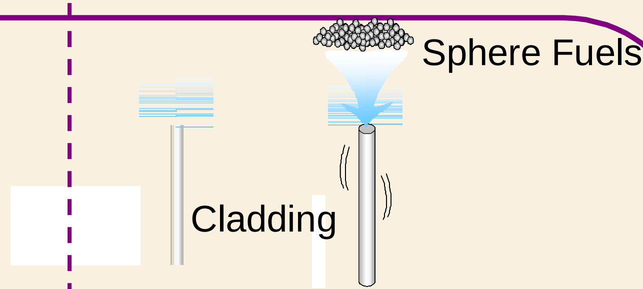
- **Abundant Experiences**
- **Rationalize to 1/3 Processes**



Injection Casting

[Special Features]

- **Simple Process**
- **Small Fabrication Equipment**

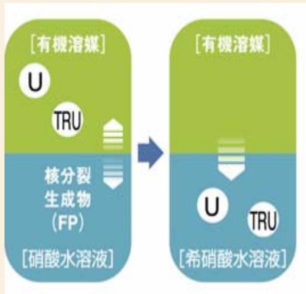


Sphere and Vibro-Packing

[Special Features]

- **Simple Process**
- **Possibility of High Economics**

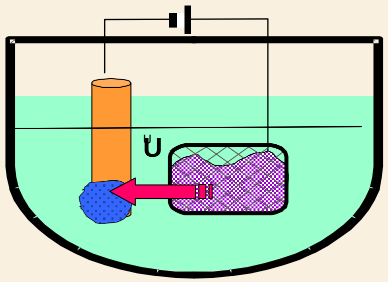
Reprocessing



Advanced Aqueous

[Special Features]

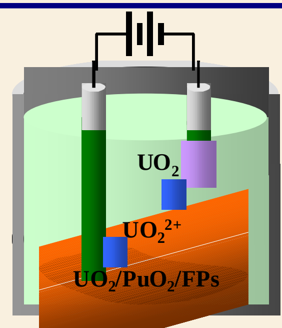
- **Abundant Experiences**
- **Higher Technical Realization**



Metal Electro-refining

[Special Features]

- **Possibility of Higher Economics**
- **Accomplishments in the U.S.**



Oxide Electro-winning

[Special Features]

- **Many Fundamental Subjects**
- **Accomplishments in Russia**

Conventional and Advanced Methods of Spent Fuel Reprocessing

AQUEOUS PROCESS :

Dissolution of spent fuel in Nitric acid followed by purification by solvent extraction by adapting the PUREX process, using TriButyl Phosphate (TBP) as solvent, is being used on an industrial scale for reprocessing of spent UO2 and MOX fuels. The PUREX process is not suitable for mixed carbide fuel but could be utilized for reprocessing mixed nitride and metallic fuels.

Modifications are being incorporated in PUREX process to make it proliferation resistant and economic.

PYROPROCESSING :

– **Pyroprocessing involving electrolytic reduction**
This route has been initially developed on a pilot plant scale for reprocessing of spent metallic fuels (U-Zr & U-Pu-Zr) in USA and was successfully extended on a laboratory scale for reprocessing of carbide and nitride fuels. The pyroprocessing route is yet to be adapted on an industrial scale.
In recent years, the Russian Federation has successfully demonstrated the pyroprocessing route for reprocessing of spent oxide fuels on a pilot plant scale.

– **Pryoprocessing involving fluoride volatilization**
The process includes fluorination followed by distillation. The method has so far been demonstrated on a laboratory scale only.