IAEA Programme on Advanced Fuels and Fuel Cycle Options

Chaitanyamoy Ganguly
Head
Nuclear Fuel Cycle and Materials Section
International Atomic Energy Agency (IAEA)

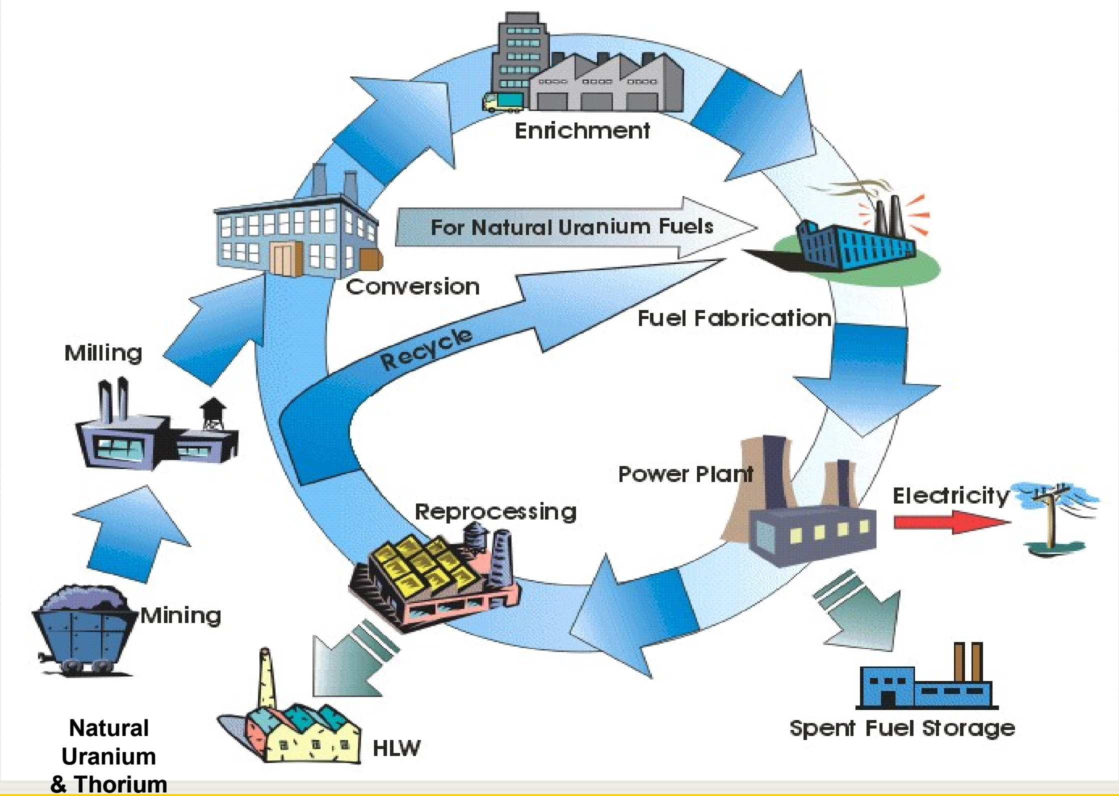
IAEA
International Atomic Energy Agency

ATALANTE 2008, 19-23 May 2008,
Montpellier, France

NUCLEAR FUEL CYCLE

Mission Statement

To facilitate development of 'fuel cycle options' in Member States, that are economically viable, safe, environment-friendly, and proliferation-resistant



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)

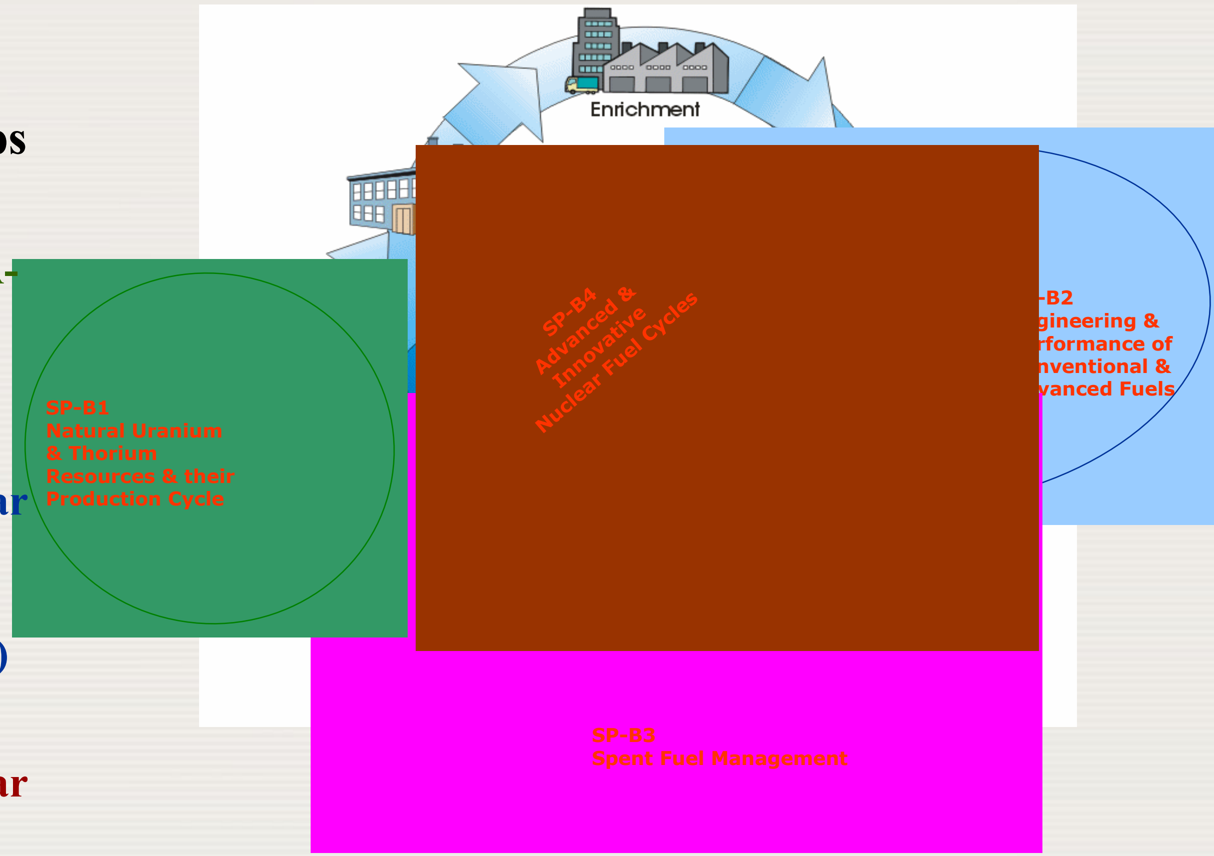
IAEA Programme B : Nuclear Fuel Cycle and Materials Technologies

International Working Groups

Subprogramme B1
Working Group for B1: OECD/NEA-IAEA Uranium Group
(~34 Members incl. EU)

Subprogramme B2
Technical Working Group on Nuclear Fuel Performance & Technology (TWGFPT)
(28 Members incl. OECD-NEA&EC)

Subprogramme B3&B4
Technical Working Group on Nuclear Fuel Cycle Options & Spent Fuel Management (TWGNFCO) for B3&B4
(~41 Members incl. ISTC, OECD-NEA&EC)



IAEA

Subprogramme 1.B.1
Uranium Resources and Production

Topics

- *Uranium exploration, mining and milling*
- *Uranium 2007: Resources, production and demand - (Popularly known as Red Book) prepared jointly with OECD/NEA (publication by OECD in first half of 2008)*

Challenges

- *Uranium annual production meets 2/3 of consumption – 1/3 secondary supply*
- *Uranium prices($ /lb U_3O_8) dramatically rose from $7.10 on 25 Dec. 2000 to $71 in the beginning of 2007 to peak of $ 135 in June 2007 and $75 in 8 Oct, 2007*
  Uranium price on May 16, 2008 : 60 US$/lb U_3O_8
- *Exploration & Mining increasing in developed and developing countries with lot of junior companies*

Reaction

- *Increased activities on technical meetings , training and info sharing on exploration, mining and processing [India, China ,Kazakhstan, Argentina & Namibia in 2006-07] (2008: Jordon and Vienna).*
- *Increasing Technical Co-operation(TC) activities with focus on 'good practices in uranium production cycle'(Algeria ,Argentina, Brazil , China,DRC, Egypt, Jordon , Mongolia, Venezuela etc)*

IAEA

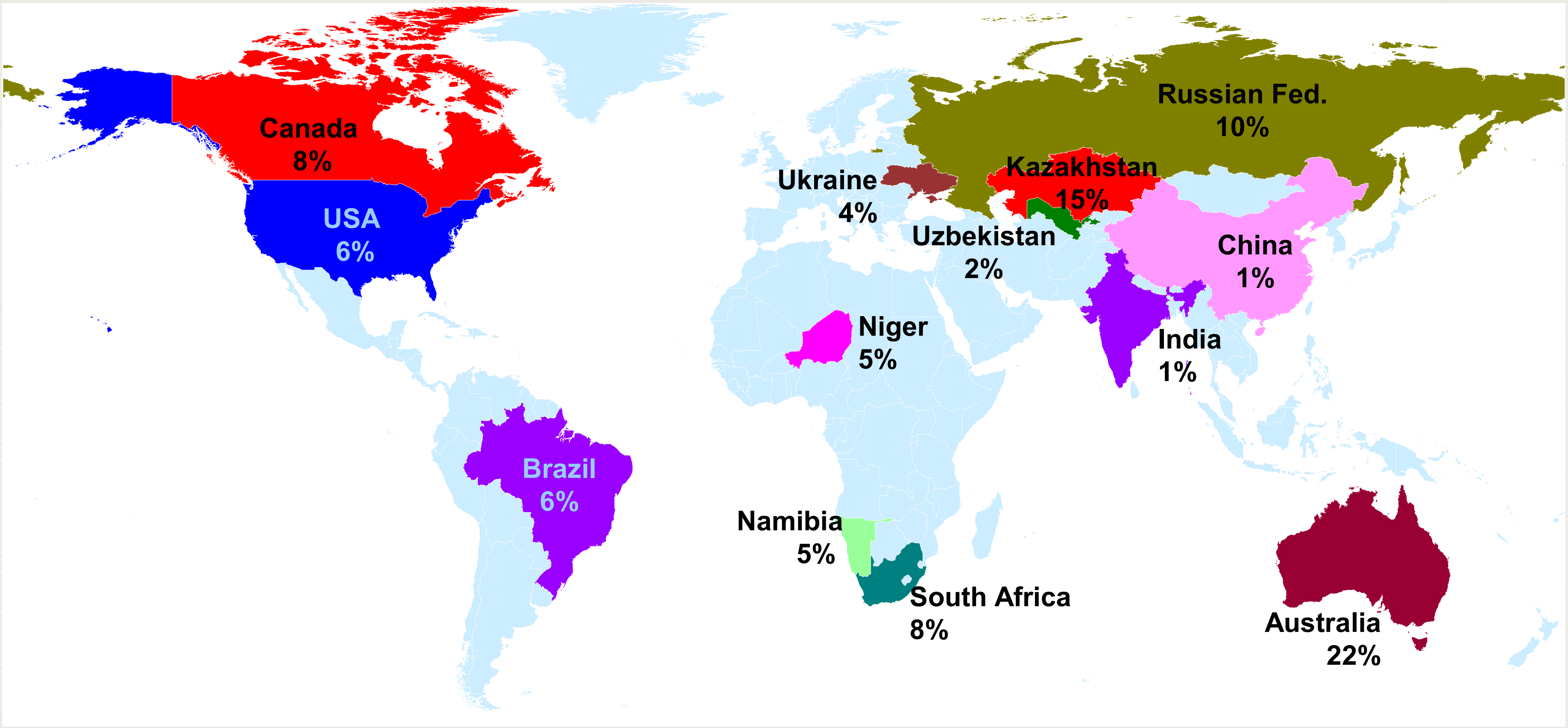
Is there enough Uranium ?

(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)



IAEA

Subprogramme 1.B.2
Nuclear Power Reactor Fuel Engineering
(focus on LWRs and PHWRs)

Topics

- ***Fuel performance and modelling, fuel manufacturing***
- ***Water chemistry for good fuel performance***
- ***Fuel Structural materials***

Challenges

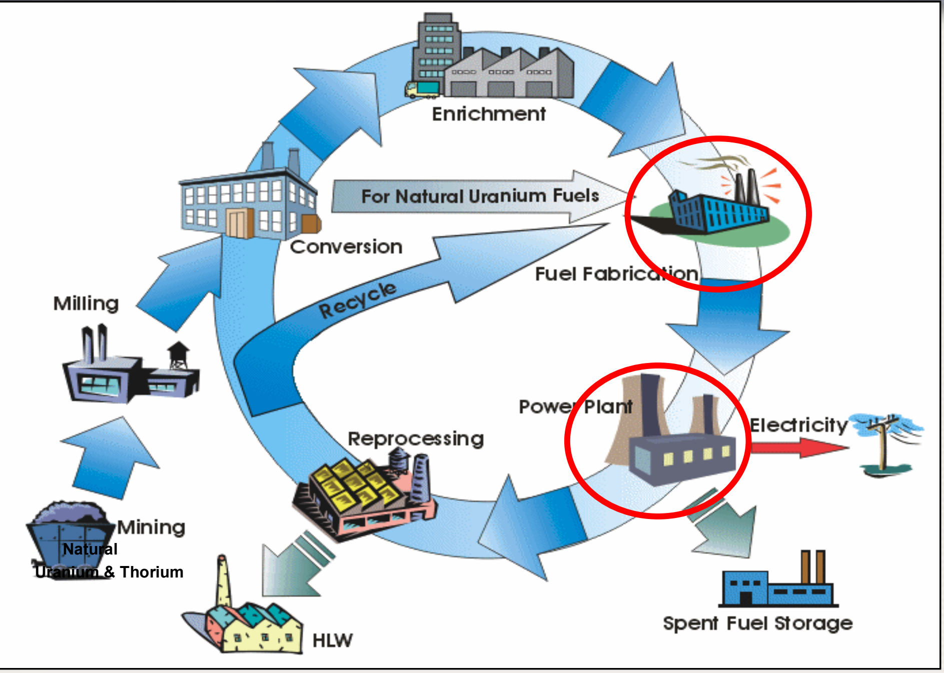
- ***Increasing burn - up***
- ***Ageing irradiated core materials***

Reaction

- ***CRPs on fuel performance modelling (FUMEX-II, FUMEX-III), on water chemistry management (FUWAC), and on delayed hydride cracking of zirconium alloys (DHC)***
- ***TMs on high burn up experience, PIE inspection techniques, fuel rod instrumentation and in-pile measurement techniques, and fuel failures***

IAEA

Subprogramme 1.B.2
Nuclear Power Reactor Fuel Engineering
(focus on LWRs and PHWRs)



IAEA Technical Working Group on Fuel Performance & Technology (TWGFPT)

Coordinated Research Projects:

- Fuel element performance modelling (Fuel Modelling at Extended Burnup, FUMEX-II 2002-2007, FUMEX-III to start in 2008)
- Optimisation of water chemistry (Optimisation of coolant water chemistry to ensure reliable fuel performance at high burnup and in ageing plants FUWAC 2007-2010)
- Delayed hydride cracking of Zr alloys (DHC-II, fuel cladding materials, 2005-2009)
- Simulation & Modelling of Radiation Effects (SMoRE) to start in 2008

Data Bases:

- IAEA PIE Data Base
- Joint IAEA-OECD/NEA IFPE Data Base

Expert Reviews:

- Handbook on Zirconium & its Alloys for Nuclear Applications (final draft in 2008)
- Fuel Failures Review (final draft in 2008)

IAEA

Subprogramme 1.B.3
Spent Fuel Management (SFM) from Nuclear Power Plants

Topics

- ***Long-term interim storage of spent fuel***
- ***Fuel management strategies: treatment, reprocessing and recycling options***

Challenges

- ***Increasing amounts of fuel in storage and longer interim storage times***

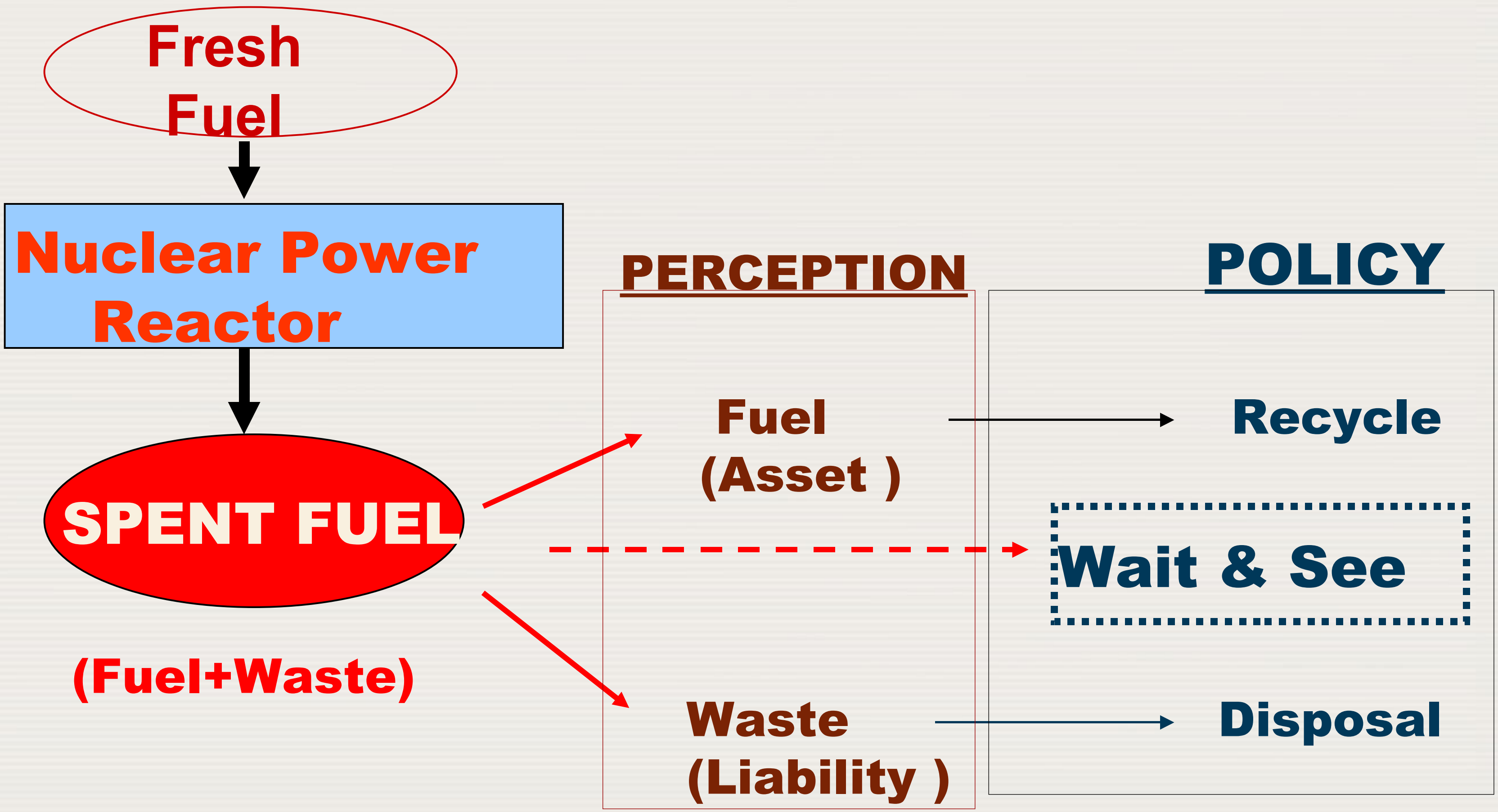
  (> 100 years)are becoming a reality More effective storage
- ***Increasing interest in recycling Pu & Reprocessed Uranium in thermal & fast reactors***

Reaction

- ***International conference on SFM in June 2006***
- ***CRP on spent fuel performance assessment & research (SPAR-II)***
- ***TMs on burnup credit applications, operation and maintenance of spent fuel storage and transport casks, influence of high burnup and MOX, and spent fuel treatment options***

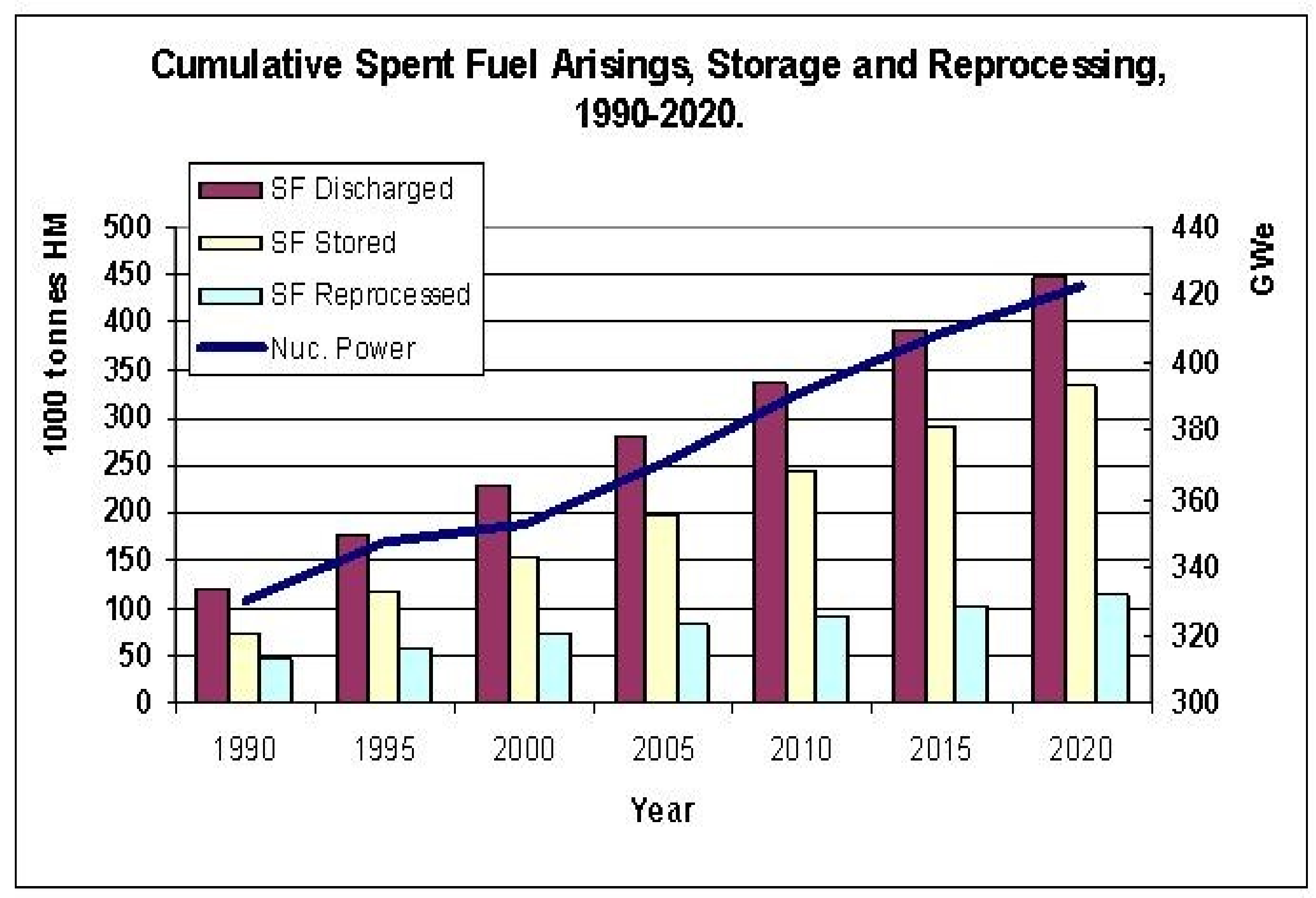
IAEA

Spent Fuel Management Strategies



IAEA

Global Statistics on Spent Fuel



IAEA

Input and output information flow in Nuclear Fuel Cycle Simulation System(NFCSS) code

Input

Strategy Parameters

- Nuclear power projections
- Reprocessing-recycling strategies
- Reactor mixtures
- Load factors

Fuel Parameters

- Avg. discharge burnup
- Avg. initial enrichment
- Avg. tails assay

Control Parameters

- Share of MOX fuel in core
- Lead and lag times for different processes
- # of reprocessing cycles

NFCSS

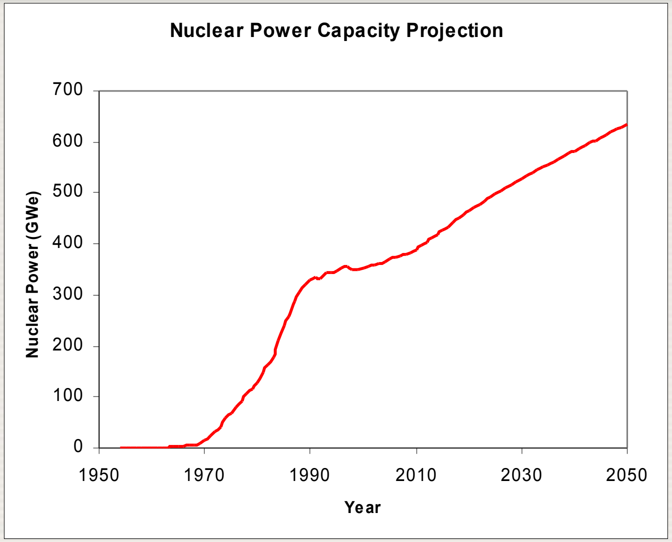
CAIN
Calculation of Actinide Inventory

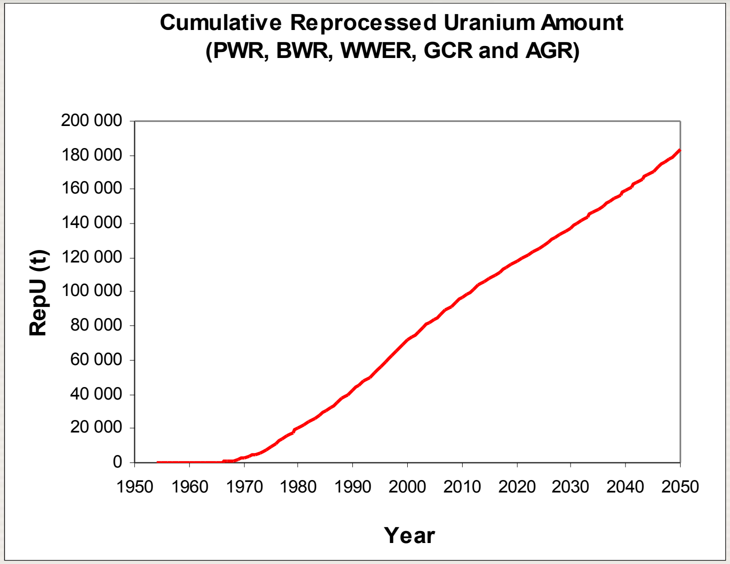
Output

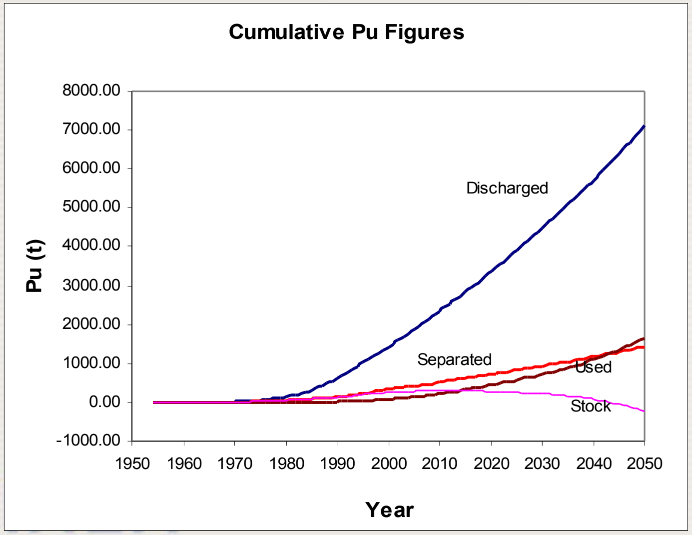
- Natural uranium requirements
- Conversion requirements
- Enrichment requirements
- Fresh fuel requirements
- Spent fuel arisings
- Plutonium accumulation
- Minor Actinide accumulation
- Reprocessing requirements
- MOX fuel fabrication requirements

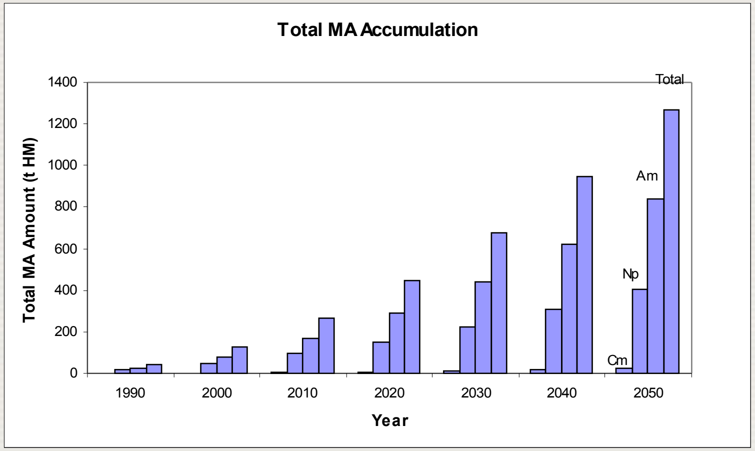
IAEA

Projected power profile, cumulative Pu, RepU and MAs inventories up to 2050









Half life, neutron yield, decay heat and critical mass of actinide isotopes

Isotope	Half-life (y)	Neutrons/sec-kg	Watts/kg	Critical Mass (kg)
^{231}Pa	32.8×10^3	nil	1.3	162
^{232}Th	14.1×10^9	nil	nil	infinite
^{233}U	159×10^3	1.23	0.281	16.4
^{235}U	700×10^6	0.364	6×10^{-5}	47.9
^{238}U	4.5×10^9	0.11	8×10^{-6}	infinite
^{237}Np	2.1×10^6	0.139	0.021	59
^{238}Pu	88	2.67×10^6	570	10
^{239}Pu	24×10^3	21.8	2.0	10.2
^{240}Pu	6.54×10^3	1.03×10^6	7.0	36.8
^{241}Pu	14.7	49.3	6.4	12.9
^{242}Pu	376×10^3	1.73×10^6	0.12	89
^{241}Am	433	1540	115	57
^{243}Am	7.38×10^3	900	6.4	155
^{244}Cm	18.1	11×10^9	2.8×10^3	28
^{245}Cm	8.5×10^3	147×10^3	5.7	13
^{246}Cm	4.7×10^3	9×10^9	10	84
^{247}Bk	1.4×10^3	nil	36	10
^{251}Cf	898	nil	56	9

Subprogramme 1.B.4
Topical Nuclear Fuel Cycle Issues

Topics

- *LMFR and HTGR fuel and fuel cycle, and other concepts*
- *Proliferation - resistant fuel cycles*
- *Thorium Fuels and Fuel Cycle options*
- *Partitioning & Transmutation,Recycling options of Plutonium & Minor Actinides(MA) and reuse options of Reprocessed Uranium(Rep. U)*

Challenges

- *Increasing interest in advanced "closed fuel cycles" and the corresponding proliferation issues*
- *Balance in Agency's involvement in sensitive technology*

Reaction

- *Selected non-sensitive topics for TMs and CRPs*
- *Close co-operation with INPRO*
- *Fuel cycles to increase proliferation resistance*

IAEA

Advanced and Innovative Fuel Cycle

Major Topics

2. Liquid Metal-cooled Fast Reactor Fuels (oxide, carbide, nitride, metallic and inert matrix fuels) & Fuel Cycle Options (aqueous and pyro - electrolytic)
3. High Temperature Gas-cooled Reactor (HTGR) Fuels & Fuel Cycle Options
4. Small & Medium Size Reactor (SMR) Fuel with long core life
5. P & T options including minor actinide bearing fuels and targets
6. Reuse options of Reprocessed Uranium
7. Proliferation-Resistant Fuels

Major Activities

- Technical Documents on LMFR Fuels Technology , Fuel Cycle Technology & SS structurals for fuel assembly
- Technical Documents on Proliferation Resistance Fuel Cycle & Protected Plutonium Production (PPP)
- Technical Documents on P&T options and Minor Actinide based targets and fuels
- IAEA Coordinated Research Project(CRP) on Simulation and Modelling of Radiation Effects(SMoRE)

IAEA

Technical Documents under preparation and Major Events planned on LMFR fuel technology and fuel cycle technology

Technical Documents under preparation

1. **LMFR Fuels Technology (UOX, MOX, MC, MN, Metallic) -**
   - Industrial, Pilot & Lab scale manufacturing experience
   - Thermo-physical and thermo-mechanical properties
   - Irradiation behaviour
2. **LMFR Fuel Cycle Technology**
   - Conventional PUREX
   - Partitioning (Aqueous & Pyroelectrolytic)
   - Minor actinide bearing fuels and targets
3. **Stainless Steel Components for LMFR Fuel Rod & Assembly (SS-316, D-9, HT-9 & ODS)**
   - Manufacturing technology
   - Out-of-pile mechanical & thermophysical properties
   - Irradiation behaviour
   - Radiation damage studies using accelerators (Ion beam) & high flux fast reactors

Major events planned:

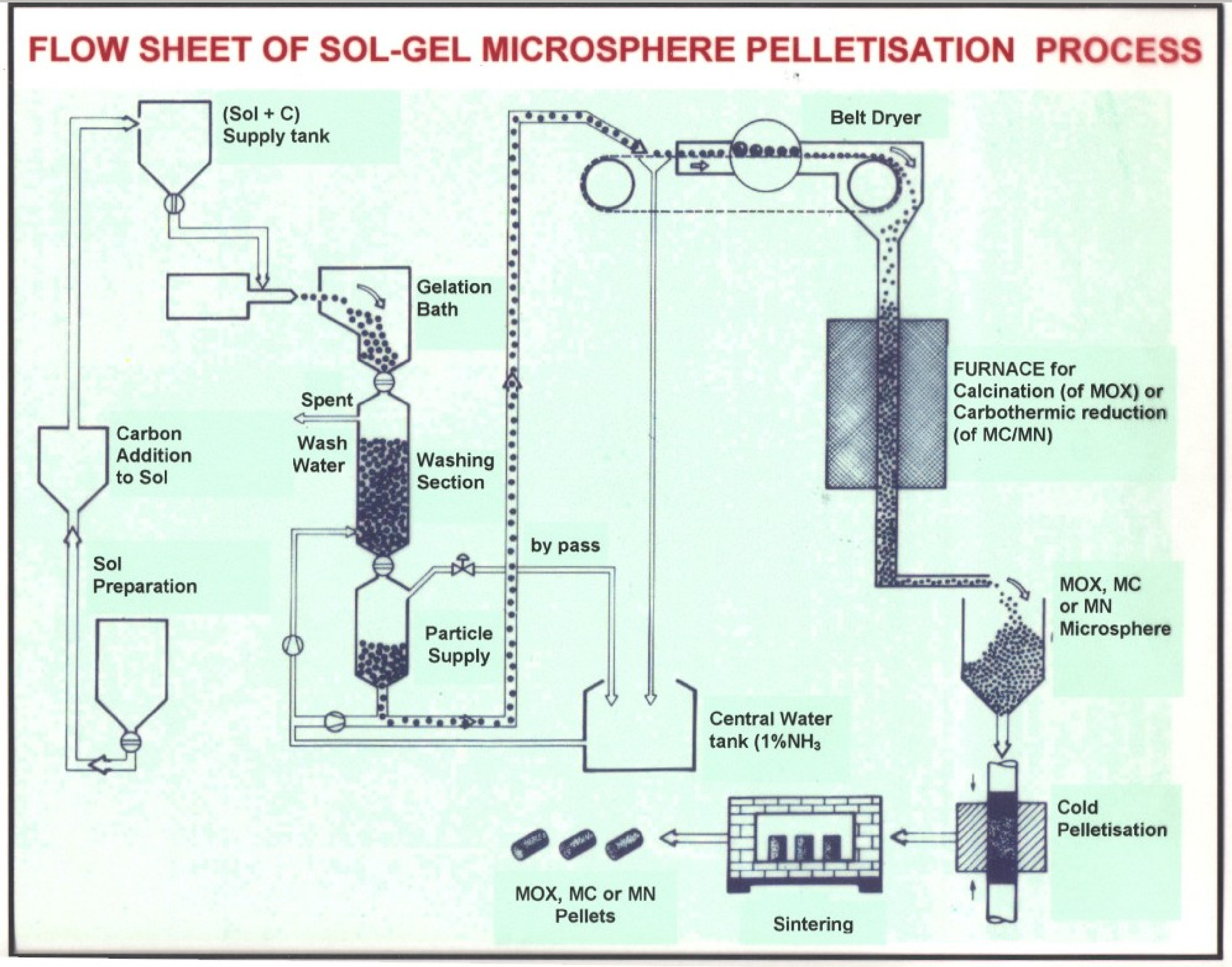
IAEA-TM on Stainless Steel Components for LMFR Fuel Rod & Assembly, Hyderabad, India, 2-4 July 2008

IAEA International Conference on Fast Reactors and Closed Fuel Cycle - Challenges and Opportunities, Kyoto , Japan, 7-11 December 2009

Objectives of Advanced Methods of Fabrication of Ceramic Nuclear Fuel Pellets

Safety	Economics	Performance
• Avoid generation and handling of fine powder of fuels for minimising : – radiotoxic dust hazard – fire hazard (for carbide & nitride fuels) • Fabrication flow sheet should be amenable to automation & remotisation – for minimising personnel exposure to radiation	• Minimise process steps • Reduce fuel synthesis and sintering temperatures • Reduce gas cost during synthesis and sintering – use recirculation and purification – use less expensive gas • Reduce process losses and rejects	• Tailor make microstructure of fuel pellets for higher burn up – High density (>= 96% T.D.) closed "porosity" and large (>25μ) grain size for LWR & PHWR – Low density (<85% T.D.) "open" porosity and small (<5μ) grain size for LMFBR – Excellent micro homogenity of fissile material in fuel – avoid fine pores (<1μ) for minimising in-pile densification

Sol-gel Microsphere Pelletization (SGMP) Process for Manufacturing of $(U,Pu)O_2$, (U,Pu)C or (U,Pu)N fuel pellets, using mixed uranium plutonium nitrate solution as feed material



Management and Re-use options of Reprocessed Uranium(Rep. U)

1. IAEA-TECDOC-1529 (May 2007) on Management of Reprocessed Uranium

- Technical Meeting " Reuse options for Rep. U",Vienna,29-31 Aug , 2007 (55 participants, 24 technical presentations from 14 M. S. and OECD /NEA)
  Hand-book for use of reprocessed uranium in energy generation:
  (to be finalized in 2008 and published in 2009)

Topics:

- Management of RepU: recent analyses of IAEA and OECD;
- Storage, packaging, and transport of RepU;
- RepU fuel assembly manufacturing;
- Processing of RepU;
- Utility experience and potential use; and
- Economics, market aspects, and Long-term perspectives of RepU utilization

IAEA

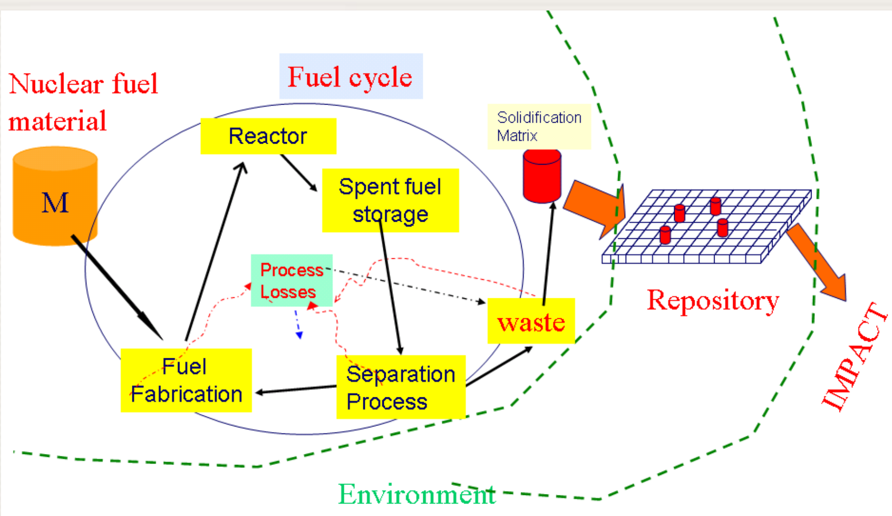
Coordinated Research Project (CRP) on Study of process-losses in separation processes in partitioning and transmutation systems in view of minimizing long term environmental impacts

CRP Objectives

- Basic studies to compare dry partitioning process with aqueous partitioning processes
- Defining proliferation resistance attributes
- Advanced characterization methods for actinides
- Minimization of losses
- Separation criteria to minimize environmental impact
- Defining environmental impact associated with partitioning processes

Participating MS

- China
- Czech Republic
- Germany
- India
- Japan
- Korea
- Russian Federation
- USA



- ✓ Initiated in 2002 and to be finalized in 2008
- ✓ 1st Research Coordination Research Meeting (RCM) -Dec 2003, Vienna
- ✓ 2nd RCM - Dec 2004, Czech Republic
- ✓ 3rd RCM - May 2006, Beijing, China
- ✓ 4th RCM – Nov 2007, Kalpakkam, India

Partitioning processes

Aqueous based partitioning methods:

►**PUREX: P**lutonium **U**ranium **R**efining by Solvent **Ex**traction: Pure U & Pu streams + (Fission products & Minor Actinidess in Raffinate)
►**TRUEX:- TRU** (Transuranic) **Ex**traction: Pu and minor actinide recovery from Raffinate
►Supercritical fluid extraction

Processes primarily adaptations of TRUEX with co-recovery of actinides

- **DIAMEX (Diamide Extraction process) to extract Am+Cm from raffinate**
- **SANEX: Selective Actinide Extraction (removal of actinides from Raffinate viz., separating actinides from lanthanides)**
- **SESAME process for Am/Cm separation**
- **NEXT (New Extraction System for TRU Recovery) for co-recovery of actinides which includes uranium crystallization and micro-wave de-nitration (Japan)**
- **GANEX (Group Actinide Extraction) (France)**
- **UREX (Uranium Extraction) (USA)**
- **CCD-PEG for Cs and Sr extraction from raffinate with (Chlorinated Cobalt Dicarbollide/Poly Ethylene Glycol)**

Dry partitioning methods

- **Voloxidation, AIROX {USA}**
- **DUPIC (Direct Use of spent PWR fuel In CANDU) [ROK]**
- **Volatilization (Fluoride volatility process)**
- **Melt-refining, skull reclamation methods**
- **Halide-slagging {EBR-II,USA}**
- ***Electro-refining process (metal, oxide & nitride) [USA & Japan]***
- ***Electro-winning process* - DOVITA (Dry reprocessing, Oxide fuel, Vibropac, Integral, Transmutation of Actinides) [RF]**

Synergistic combinations of aqueous and pyro-methods

☼ *UREX+PYRO-A [USA]*

The HTR Fuel and Materials Fact-book 2007- 2009

Develop manuals/handbooks and best practice documents for use in training and education in coated particle fuel technology

Outline of the document as following:

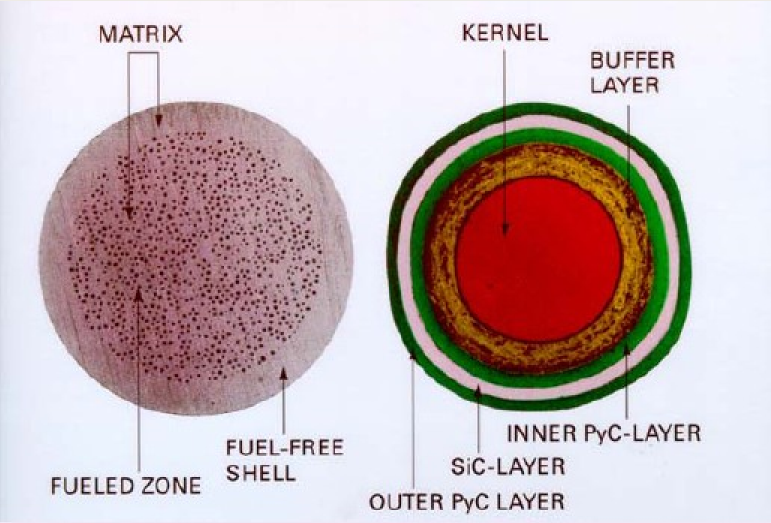
1. Introduction;
2. Energy and Electricity;
3. Nuclear Hydrogen Generation;
4. Nuclear Fuel;
5. Structural Materials;
6. Fuel Structural Materials;
7. Particle Fuel Manufacturing and QA/QC Activities;
8. Sphere Making;
9. Fabrication of Fuel Compacts;
10. Block Making;
11. Fuel Chemistry;
12. Fuel Failure Mechanisms;
13. Fission Product Retention;
14. Accident Testing;
15. Particle Modeling;
16. Quality Control and Quality Assurance;
17. Spent Fuel Management; and
18. The Way Forward.

RAPHAEL & PUMA in cooperation with IAEA EUROCOUSE on

Coated particle fuel,4-7Dec 2007

NRG, Petten, The Netherlands

✌ **Large number of experts are helping IAEA in making fact-book**



ance

Activities on Thorium Fuel Cycle up to 2011

TECDOC-1450 (2005)
Thorium Fuel Cycle – Potential Benefits and Challenges

- Current information base
- Front end issues
- Back end issues
- Proliferation resistance issues
- Economic aspects

2008 – 11

- Database (Thorium Deposits Worldwide)
- Comparative assessments of thorium-based fuel cycle concepts

Meetings

- TM on Thorium-based Fuels and Fuel Cycle Options for PHWR, LWR and HTGR, 22 to 25 October 2007, Istanbul
- Worldwide thorium deposits; start IAEA Database TDEPO)
- Processing of thorium ores
- Manufacturing experience of thorium based fuels
- Proliferation resistant thorium fuel in LWRs (Thorium Power, USA)

- Consultancy: INPRO Collaborative Project on "Further investigations of the ^{233}U/Th fuel cycle, 3 Dec 2007, Beijing,

IAEA

Protected Plutonium Production (P3) Project
(Extrabudgetary)

- **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].

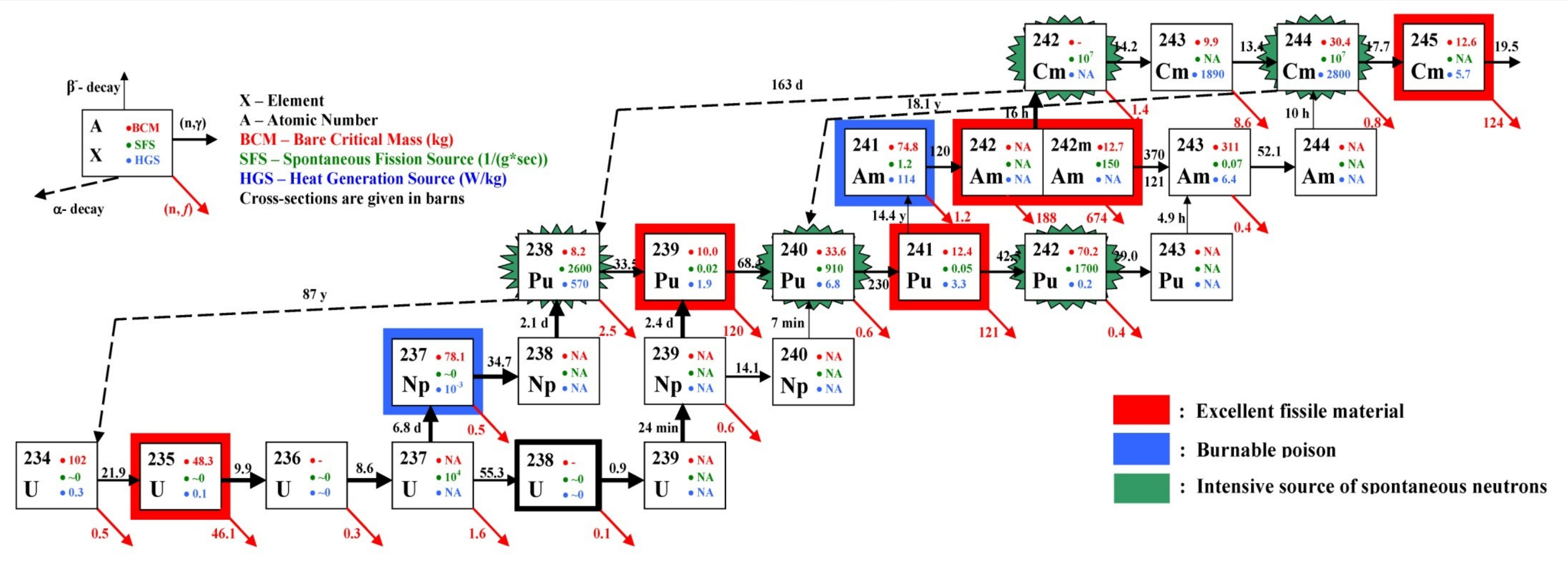
- **PPP addresses the challenges of introducing low enriched uranium (<5% U235) oxide and MOX fuels containing < 1% MA in operating water –cooled power reactors and MA- bearing fuel and blanket (U-238/Th-232) for LMFR , with respect to manufacturing, reprocessing, safety and economics**

IAEA

Protected Plutonium Production (P3) Project

(Extrabudgetary)

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.



Integrated Nuclear Fuel Cycle Information Systems (iNFCIS)

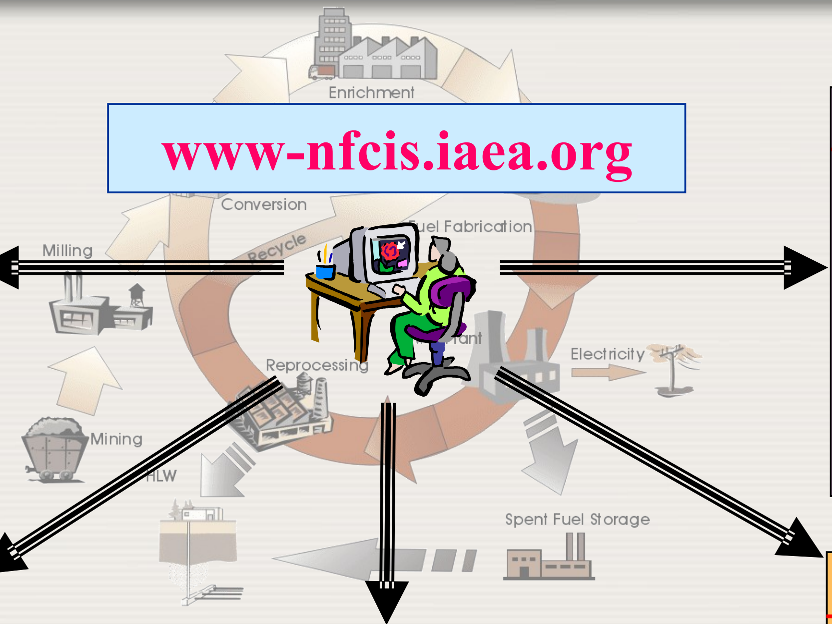
NFCIS

- Nuclear Fuel Cycle Information System
- Directory of Civilian Nuclear Fuel Cycle Facilities Worldwide
- Facilities from under planning stage to the decommissioned stage
- Facilities from uranium milling to reprocessing, spent fuel storage and heavy water production
- Available online since 2001
- 675 facilities in 54 countries (Oct 2007)
- TECDOC in preparation

www-nfcis.iaea.org

PIE

- Post Irradiation Examination Facilities Database
- Catalogue of PIE facilities worldwide
- General information about the facilities
- Technical capabilities of the facilities
- Available online since 2004
- 41 facilities in 18 countries (Oct 2007)



NFCSS (formerly 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
- TECDOC Published in 2007 (TECDOC-1535)
- The simple web version is online since 2005
- Full web version will be online before the end of 2007

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
- Available online since 2004
- Currently 874 deposits in 55 countries (Oct 2007)
- TECDOC in preparation

MADB

- Minor Actinide Property Database
- Bibliographical database on physico-chemical properties of materials containing minor actinides
- Carbides, Nitrides, Alloys, Oxides, Halides, Elements and other forms are covered
- More than 1000 data records from 162 publications (Oct 2007)
- Under development

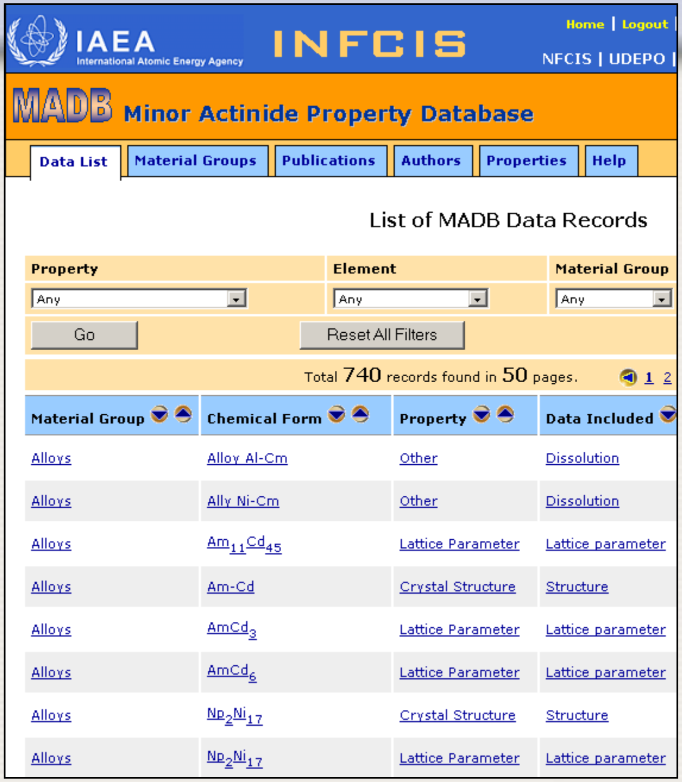
ThDEPO database to start soon

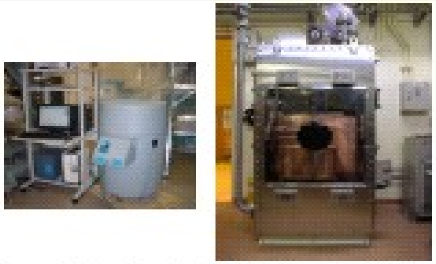
Database on LMFR fuel and fuel assembly structurals to start soon

IAEA

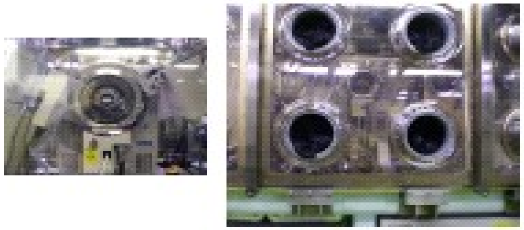
IAEA Minor Actinide Property Database (MADB)

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





Drop Calorimeter for Minor Actinides



High Temperature X-ray diffractometer for Minor Actinides

Minor actinide measrement facilities at JAERI

…Thank you for your attention

IAEA