International Conference on Fast Reactors and Related Fuel Cycles (FR09)

7-11 December 2009, Kyoto, Japan

Advanced and innovative reactor concept designs, associated objectives and driving forces

Jean-Louis CARBONNIER

Commissariat à l'Energie Atomique (CEA)

Present status of nuclear energy

- World nuclear capacity : 370 GWe, 15% of the world's electricity generation.

- In the next decades, growing of nuclear energy will be based on LWRs, which are safe, reliable and efficient.

Resources :

- LWRs consume less than 1 % of natural Uranium
- Uranium resources may be an issue if LWR fleet grows bigger

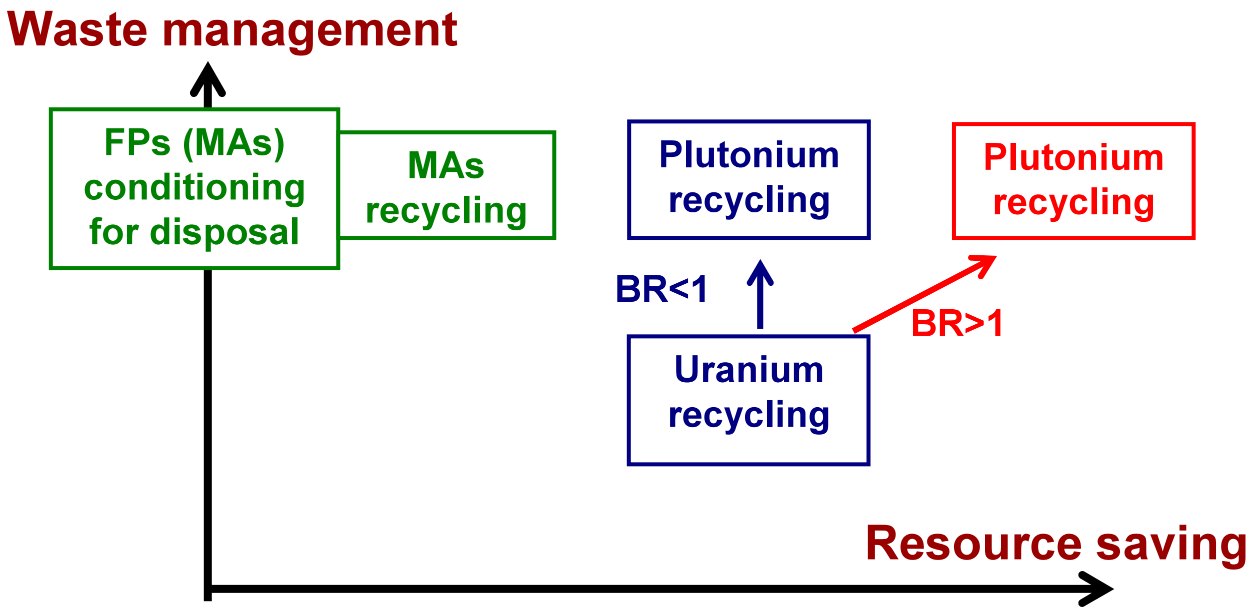
Nuclear spent fuel :

- Open Cycle : huge amount of NSF stored
- Closed cycle : allows some uranium savings and conditioning nuclear waste in safe and secure waste forms. Plutonium may be recycled once.

→ LWRs are able to answer growing needs in an environmentally responsible manner, but are not fully sustainable.

Fast Neutron Reactors for sustainability

FNRs enable the expansion of nuclear energy all while meeting sustainable development criteria: resource saving and more complete waste management.



→ **Sodium cooled FNRs (SFRs) : most mature technology**

→ **Heavy metal cooled FNRs (LBRs) : alternative to sodium**

→ **Gas cooled FNRs (GFRs) : electricity & high temperature applications**

Experience on SFRs Fuels

- Plutonium-Uranium Oxide, MOX : (U,Pu)O2, has the most experience in the world and showed a good behaviour. It has high fusion temperature but, due to poor conductivity has also a high operating temperature.

- Metal fuel has been developed under ternary form : (U,Pu,Zr), 10% Zr address fuel cladding chemical interaction(FCCI), extensive experience has also been gained, mainly at EBR II, [3]. It shows higher fissile density, low operating temperature and low fusion temperature.

- Nitride (U,Pu)N and carbide (U,Pu)C fuels show high density , high conductivity and high fusion temperature but have less experience. Carbide with high Pu content has been experienced at FBTR, with good behaviour and high burn up, [6]. Theses fuels have higher swelling with irradiation.

Transmutation fuels for SFRs

Minor actinide bearing fuels require addressing several issues :

- Remote handling fabrication
- High volatility of Americium during fabrication process
- Influence of minor actinides in safety parameters
- Increased gas production (helium)

Homogeneous and heterogeneous recycling

- Homogeneous fuel has low MA content (1-2%) and seems to have quite similar behaviour to U-Pu Fuel, for both metal and oxide fuels.

- Heterogeneous fuels are located in periphery of core, and have higher MA content (10-20%). Low power and high helium release have to be addressed.

Some challenges for innovative SFRs Fuels

Oxide fuels :

- Remote handling fabrication process, for instance vibrocompacting.

- Developing Minor Actinides Bearing Blankets, remote handled with specific microstructure.

Metal fuels :

- Low Zr fuel, including lined cladding, to improve fissile density and simplify Zr management in cycle.

- He bond particulate metal fuel to simplify fabrication and avoid casting moulds.

Carbide or Nitride fuels :

- Improved microstructure to address gas retention and swelling

- Choice of sodium or gas bond : sodium bond allows for better behaviour thanks to high conductivity but needs specific treatment before aqueous dissolution.

Cladding material :

- Improved cladding material is needed for higher burn ups, oxide dispersion strengthened (ODS) steels are considered.

SFR's core design and safety (1/2)

→ Decreasing sodium void worth and increasing breeding ratio has been obtained in several countries, by using large pins and low amount of sodium with reduced volumic power (~200 MW/m3), [9].

→ Low reactivity loss improves behaviour during reactivity accidents.

→ Sodium plenum allows for additional reduction of sodium void worth [8].

Severe accidents

Japanese teams worked on severe accident evaluation technology in view of level 2 PSA, [10].

Tools exists or are in development to address relocation phase, including long term analysis and Decay Heat Removal phase , and ex vessel accident sequences.

To enhance molten-fuel discharge and prevent re criticality risk, devices such as subassemblies with inner duct structure (FAIDUS), have been developed for JSFR project.

SFR's core design and safety (2/2)

Thanks to high fissile density and better conductivity, carbide cores show higher performances than oxide (volumic power and fissile inventory) and better safety behaviour.

To enhance economical performance, large metal fuelled cores up to 1200 MWe have been studied [11]. They allow for low plutonium inventory and conversion ratio close to 1, but sodium void worth is quite high.

US ANL has done parametric studies [12] on a 1000 MWth core using both oxide and metal fuel. Large range of TRU conversion ratio from 0,2 to break even can be achieved. Metal cores appear to have better inherent safety features.

India plans to implement beyond 2020 advanced metal fuel with the goal to reach 1.45 conversion ratio and 9 years doubling time.

The superiority of metal or oxide fuel for safety issues remains an open question.

Reprocessing

2 main tracks : Aqueous and Pyro

Aqueous reprocessing has proven, at commercial plant scale, its performance, reliability and mastering of technological wastes.

French think that R&D is able to allow for adapting solvent extraction to new needs, for instance Minor Actinides separation and no pure plutonium separation [13].

JAEA proposes advanced aqueous reprocessing with innovations like uranium crystallisation and extraction chromatography for MA recovery [14].

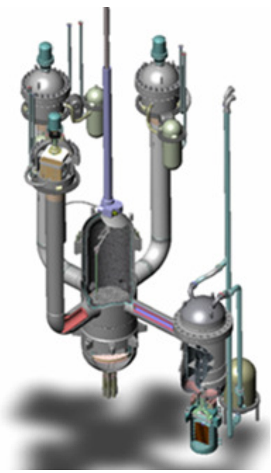
The US are now focusing on long term, science based, R&D. They investigate some important issues like off gas capture and immobilisation, and have always a high priority in advanced electrochemical processes [16].

India will use aqueous reprocessing for MOX fuels but intend to rely, beyond 2020, on pyroprocessing of short cooled metal fuels, to contribute to reach doubling time lower than 10 years.

Gas cooled Fast Reactor (GFR)

Combines the benefits of fast spectrum and high temperature using Helium as coolant [17].

Pre-feasibility studies of a 2400 MWth (~1100 MWe) GFR has been achieved in 2007



- Carbide fuel with ceramic cladding,
- Break even core without blankets able to recycle uranium plutonium and minor actinides
- Low coolant void worth < 1$
- DHR by both active and passive devices.
- Indirect conversion energy system using a binary He-N2 or He-Ar mixture with a compact plate stamped heat exchanger.

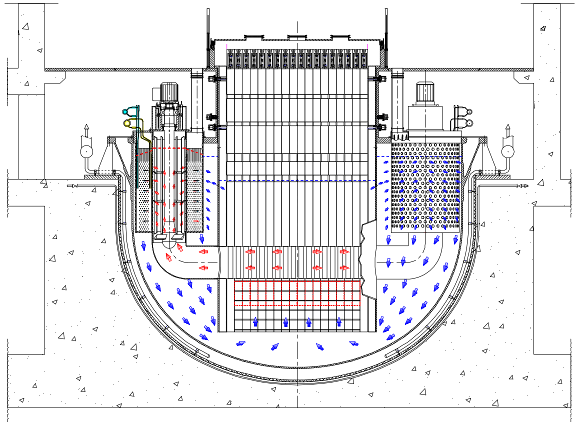
→ Optimization in progress : operating temperature, severe accident analysis, use of pre-stressed concrete pressure vessel.

→ ALLEGRO, an experimental reactor in the range 50-100 MWth is proposed as a first realisation of GFR.

Heavy metal cooled Fast Reactor

Lead Fast Reactor (LFR) :

ELSY is a 600 MWe European project [18] :



- Pure lead coolant and oxide fuel (U, Pu, MAs)
- Open fuel assemblies with square pitch
- Handling machine operates under full visibility
- Spiral tube steam generators located inside the main vessel
- DHR dip bayonet exchangers
- temperature limited to 480 °C

Lead Bismuth Reactor :

SVBR-100 is a 100 MWe reactor, with original fuel cycle [19] :

At the beginning, it uses enriched uranium oxide fuel, and moves towards closed fuel by reusing plutonium and minor actinides, remaining U235, and a decreasing additional amount of enriched uranium. Pyro-electro-chemical methods of SNF reprocessing and vibro-technology for re-fabrication of fresh fuel are envisioned.

Proliferation Resistance

- Short term expansion of nuclear energy will be provided by Gen 3 LWRs.

- When Gen 4 FNR, with improved features in economics, safety and sustainability become available, countries will be interested in pursuing their nuclear equipment with such FNR.

- Fast reactors have some specific features in the field of proliferation resistance :

  - No need for uranium enrichment,
  - Inherent associated fuel cycle with plutonium and possibly MAs recycling
  - Breeding blankets.

→ International community has to address these features with appropriate extrinsic and intrinsic safeguards, physical protection and guarantees of fuel services; GNEP statement of principles provides some relevant orientations for this.

Main trends

→ **Sodium Fast Reactor** is the main stream for development and mid term deployment of Fast Reactors, it has 2 tracks :

- Oxide fuel associated with aqueous reprocessing is the most mature track due to previous industrial experience. Carbide or nitride are long term alternative to oxide with improved capabilities.

- Metal fuel with pyroprocessing is also widely considered. It has high fissile density, good inherent behaviour during transients, and ability to process short cooled fuels, but needs more industrial experience.

Loop versus pool issue seems less fundamental than fuel and associated reprocessing.

→ **Alternative coolants are much long term** and they need development phase with experimental reactors.

- Heavy metal (pure lead or lead bismuth) has similarities with sodium but lower reactivity with air and water.

- Helium has opposed features when compared to sodium, it allows for electricity generation and high temperature applications.

Driving Forces

Driving forces for FNR and associated cycle may be :

- Saving resources and autonomy from uranium procurement
- Waste management
- Economics, including investment, operating costs and reliability

Safety, security and proliferation resistance have to be fulfilled for any reactors.

Two opposite country-user profiles may be shaped :

Large existing LWR fleet Confidence about uranium availability Uncertainty about FNR economics	→	Burner FNR devoted to waste management of lasting LWR fleet
No large LWR fleet Uncertainty about uranium availability Need for strong nuclear expansion	→	Breeder FNR with short doubling time for self sustained expansion

FNR development in progress

→ **Today, FNR are not only a matter of R&D but also a matter of concrete realisations :**

- China has just built CEFR, 65 MWth experimental reactor
- PFBR, 500 MWe prototype is under construction in India and should become critical by 2010
- Russia is constructing BN 800

→ **Other countries have plans for prototypes in the next future :** France Japan and Republic of Korea have plans for the 2020-2030 decade.

→ **United states are focusing on long term, science based, R&D.**

→ Large amount of R&D all around the world

→ Variety of orientations and schedules

→ Confidence that FNR are needed to address growing energy needs in sustainable, safe and secure manner.

References (1/2)

[1] B. Valentin & al, “Heterogeneous minor actinide transmutation on a UO2 blanket and on (U,Pu)O2 fuel in a Sodium Fast Reactor – Preliminary design of pin & subassembly”. Proceedings of Global 2009, Paris, France, Paper 9355

[2] L. Buiron & al, “Heterogeneous Minor Actinide Transmutation on a UO2 blanket and on (U,Pu)O2 fuel in a Sodium-cooled Fast Reactor – Assessment of core performances”. Proceedings of Global 2009, Paris, France, Paper 9109

[3] J. Sackett, “Operating and Test Experience for the Experimental Breeder Reactor II (EBR-II)” Proceedings of Global 2009, Paris, France, Paper 9515

[4] S. Hayes & al, “Status of Transuranic Bearing Metallic Fuel Development”, Proceedings of Global 2009, Paris, France, Paper 9475

[5] T. Ogata, T. Mizuno, “Directions of Metal Fuel Development for Fast Reactors”, Proceedings of Global 2009, Paris, France, Paper 9135

[6] K.V. Suresh Kumar & al, “Operating experience of Fast Breeder Test Reactor”, Proceedings of the 17th International Conference on Nuclear Engineering, July 12-16, 2009, Brussels, Belgium, ICONE17-75592

[7] G. Rimpault & al, “A Search for Improved SFR Cores Using Carbide Fuel”, Proceedings of GLOBAL 2009, Paris, France, Paper 9255

[8] Yu. S. Khomyakov & al; "Optimization of Parameters of MOX Fuel Core of Sodium Cooled Large Size Fast Reactor" Proceedings of Global 2009, Paris, France, Paper 9235

[9] P. Sciora & al, “A break even oxide fuel core for an innovative French sodium-cooled fast reactor: neutronic studies results”, Proceedings of GLOBAL 2009, Paris, France, Paper 9528

[10] R. Nakai & al, “Development of Severe Accident Evaluation Technology (Level 2 PSA) for Sodium-cooled Fast Reactors”, Overview of Evaluation Methodology Development, Proceedings of ICAPP ’09 Tokyo, Japan, Paper 9117

References (2/2)

[11] Ki-Bog Lee & al, “Sensitivity study of dimensional variables for a 1,200 MWe sodium cooled fast reactor core design”, International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14-19, 2008, FP 180.

[12] T.K. Kim & al, “Core Design Studies for a 1000 MWth Advanced Burner Reactor”, International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14-19, 2008, FP 257

[13] B. Boullis, MF. Debreuille, “New Perspectives and Advanced Technologies for Fuel Recycling through French Operational Experience”, Proceedings of Global 2009, Paris, France, Paper 9555

[14] T. Washiya & al, “Current Status on Advanced Aqueous Reprocessing Process (NEXT) in FaCT Project”, Proceedings of ICAPP ’09, Tokyo, Japan, May 10-14, 2009, Paper 9465

[15] K.V. Govindan Kutty, “Current Status of the Development of the Fast Reactor Fuel Cycle in India”, Proceedings of Global 2009, Paris, France, Paper 9547

[16] T A Todd &al, “The Advanced Fuel Cycle Initiative Separations and Waste Campaign: Accomplishments and Strategy”, Proceedings of Global 2009, Paris, France, Paper 9111

[17] JY. Malo & al, "Gas Cooled Fast Reactor 2400 MWTh, status on the conceptual design studies and preliminary safety analysis”, Proceedings of ICAPP ’09, Tokyo, Japan, May 10-14, 2009, Paper 9109

[18] L. Cinotti & al, “The ELSY Project”, International Conference on the Physics of Reactors, Interlaken, Switzerland, September 14-19, 2008, FP 377

[19] Z.A. Zrodnikov & al, “Fuel Cycle of Reactor SVBR-100”, Proceedings of Global 2009, Paris, France, Paper 9236

[20] Yeong-il Kim and Dohee Hahn, “Status of Advanced SFR Concept Design Studies at KAERI”, Proceedings of ICAPP ’09, Tokyo, Japan, May 10-14, 2009, Paper 9455