Nuclear Fuel Cycle Issues and Challenges
21 - 22 September 2004
Scientific Forum
during the 48th Regular Session of the IAEA
General Conference
Conference Room C, 2nd Floor, Austria Center
Vienna, Austria

Organized by the
International Atomic Energy Agency

Session Summaries and Reports

IAEA-CN-137
Scientific Forum location: Conference Room C
2nd Floor
Austria Center Vienna

Chair: B. Bigot
High Commissioner
CEA – Commissariat à l’énergie atomique, France

Scientific Secretaries:

Session 1: Advanced Fuel Cycles and Reactor Concepts
J. Kupitz, Department of Nuclear Energy

Session 2: Waste and Spent Fuel Management Issues
W. Danker, Department of Nuclear Energy

Session 3: Research Reactor Fuel Cycle and Related Issues
I. Ritchie, Department of Nuclear Energy

Forum Office: 02 A 348, Austria Center Vienna, tel.ext.: 2033
Tuesday, 21 September 2004

10.00-13.00 hours

Opening Address: M. ElBaradei, Director General, IAEA

Session 1: Advanced Fuel Cycles and Reactor Concepts

The keynote presentations will be followed by a panel discussion including the keynote speakers and the following panellists:

R. Bennett; I.S. Chang

Moderator: A. Kakodkar

Keynote Speakers: R.T.H. Mayson, “Key Issues in Fuel Cycle Options”


A. Kakodkar, “Challenges and Directions of Research & Development in Fuel Cycle”

13.00-15.00 hours Break
Tuesday, 21 September 2004

15.00-18.00 hours

Session 2: Waste and Spent Fuel Management Issues

The keynote presentations will be followed by a panel discussion including the keynote speakers and the following panellists:

E. Dowdeswell, V. Ryhanen, C. Zhu, J. Maiorino

Moderator: L. Shephard

Keynote Speakers:

P. Bernard, “Advances in Treatment of Wastes from Reprocessing of Spent Fuel: Transmutation, Solidification”

A. Mayorshin, “Advances in Reprocessing of Spent Fuel: Partitioning”

L. Shephard, “Spent Nuclear Fuel Management”
Wednesday, 22 September 2004

10.00-13.00 hours

Session 3: Research Reactor Fuel Cycle and Related Issues

The keynote presentations will be followed by a panel discussion including the keynote speakers and the following panellists:

N. Arkhangelski, H. Boeck, I. Smith

Moderator: S.K. Sharma

Keynote Speakers:


S. Tőzsér, “Spent Fuel Management: Semi-dry Storage”

R. Lockwood, “Research Reactor Decommissioning”
Mr. President,

As a Chairman, it is my privilege and duty to report to you and the Plenary the main points from the presentations and debates of the 7th Scientific Forum organized during the 48th regular session of the IAEA General Conference. This meeting took place on 21-22 September 2004 in Vienna, in an excellent and constructive spirit under the general title of “Nuclear Fuel Cycle Issues and Challenges”. It gathered about 180 participants. The three sessions focused on: Advanced Fuel Cycles and Reactor Concepts; Waste and Spent Fuel Management Issues; and Research Reactor Fuel Cycle and Related Issues. All together, 12 detailed presentations were made by leading experts, followed by panellists’ comments and discussion with participants.

Before presenting a short report on the points related to the three sessions, let me share with you some general comments:

After years of large R & D efforts in several countries, we presently have a wealth of important scientific results offering answers to a range of issues related to reactors, fuels and nuclear material cycles. New important results are expected to come in the next five/ten years in the considered fields.

We are now moving towards large-scale demonstrations of technologies which could give us an incentive to consider new R & D programs for fully satisfying economical, safety, reliability and non-proliferation expectations.

Due to the present world-wide energy and security context, the next years and decades will see the need for important decisions regarding the building of new power plants, the life extension of the present ones, the decommissioning of reactors as well as the
commencement of long term waste disposal projects. All these topics require firm scientific basis, which have to be shared by the public opinion as well as by the political decision makers. There is a great need to communicate on the scientific and technological achievements if we want to gain the agreement of the public.

Our discussions in the Forum revealed that there is no unique way to deal with these issues; diversity has to be fully accepted as far as we agree on the fundamental principles of safety, and environmental and health requirements. We have to set some R & D programs accordingly and work towards international cooperation and discussions to further facilitate the decision process.

Let me now turn to the discussions that took place in the Forum.

In an introductory stimulating presentation, the interest for sub-critical reactors with accelerator driven systems, from the safety point of view, was emphasized. The thorium cycle for minimizing the minor actinide problems associated with the uranium cycle was also advocated. The presentation also highlighted the need to work on highly innovative ideas to generate electricity without any radioactivity by using inertial nuclear fusion involving protons, and boron or lithium.

In Session 1, the importance of optimising in a coherent and global way the nuclear fuel cycle with respect to economics, proliferation resistance, safety and environmental aspects was emphasized. In this connection, the advanced aqueous processing of spent fuel and the emerging dry pyrochemical processes involving molten salt and electro refining were highlighted. The importance of the efficient use of uranium in fast breeder reactors was also stressed.

A survey of evolutionary and innovative reactors and fuel cycles was presented. A comprehensive review of advanced water-cooled, gas cooled, and liquid metal cooled reactors, was provided highlighting their design and operational features. The importance of international initiatives such as INPRO and GIF was emphasized in this context to optimise the large R & D efforts required.
There was emphasis on multi-recycling of plutonium and minor actinides in fast reactors, to produce additional energy from fissioning all the actinides. It was mentioned that there is a need for progressive changes in the fuel cycles from plutonium recycling in LWRs to multiple plutonium recycling in fast reactors in a phased manner over the next hundred years, for optimal utilization of uranium resources and burning of all the actinides.

The R&D needs for innovative reactor and fuel cycle technologies were discussed highlighting the Indian experience of its three-stage nuclear power programme combining pressurized heavy water reactors, fast reactors and thorium-232/uranium 233 breeders.

The Advanced Fuel Cycle Initiative (AFCI), which is designed to pave the way for an expanded role of nuclear energy in the USA was presented. AFCI is considering the technical and economic viability of four fuel cycle options, including the open cycle option, recycling in thermal reactors, recycling in thermal and fast reactors, and multiple recycling in fast reactors.

The panel discussion centered on the real need for accelerator driven systems (ADS) and FBR for waste minimization, and utilization of research reactors for development of advanced fuels and materials for innovative reactors. The panel explained the technical reasons for ADS introduction and confirmed its potential, but not yet demonstrated, role for transmutation and energy production.

Regarding the question on the introduction of innovative nuclear energy systems in developing countries, the panel pointed out that developing countries have the highest energy demand in the foreseeable future. Nuclear energy could cater to this demand. In particular, innovative reactor systems in the small and medium size category with inherent safety features and enhanced proliferation resistance are seen as a future potential source of energy in these countries.

At the end of the session there was a broadly shared view among the participants that nuclear energy as an emission free energy source is indispensable for sustainable
development. The continuous research and development in support of innovative reactors and fuel cycles is crucial. The panel also confirmed the need for research reactors as an important tool for development of innovative reactor systems. In this respect, the closure of the fuel cycle with fast reactors was highlighted.

Session 2 on waste and spent fuel management noted that the growth of nuclear power, while providing many benefits, has also resulted in an increasing global challenge over safe waste and spent fuel management. Over the past fifty years, the world has come to better understand the strong interplay between all elements of the nuclear fuel cycle, global economics and security. The nuclear fuel cycle is no longer managed as a simple sequence of technological, economic and political challenges. Rather it must be managed as a system of strongly related issues. Waste and spent fuel management cannot be relegated to the back-end of the fuel cycle as only a storage or disposal issue. There exists a wealth of success and experience with waste and spent fuel management that can be forged together to mitigate these global challenges in the future.

The participants of this session reviewed the R & D results and the experience to date, in some specific countries like Russian Federation, USA and France for instance, including approaches from direct disposal to the closed cycle. Regarding the latter, reprocessing of irradiated power reactor fuel was noted to be a mature industrial technology. Experience to date has demonstrated that reprocessing can be compatible with security and non-proliferation requirements. There has also been a continuing reduction in the volume of waste arising from reprocessing. This trend will continue with the implementation of improved technology and operating practices. R&D programmes to study the partitioning and transmutation of environmentally significant radionuclides are being pursued to further assess potential paths to enhancing the effectiveness of waste minimization programmes.

The session also noted that safe and robust interim storage technologies are available to provide system flexibility while addressing longer term waste and spent fuel management options and issues. Regarding direct disposal, session 2 participants described significant progress to date. The majority of technological issues were noted to have been
satisfactorily addressed, but ethical and social issues, remain to be addressed appropriately in some countries.

The discussions centered on the issues regarding reprocessing to preclude the need for repositories and the question of relative economics associated with the fuel cycles. The consensus among the participants was that geological disposal remains an ultimate requirement for the open as well as the closed cycle. In the discussion regarding national and multinational repositories, it was noted that it would be desirable to have operating national repositories and to further public acceptance and facilitate progress on multinational geological repositories.

Session 3 dealt with several aspects of the research reactor fuel cycle from the development and qualification of high density low enriched uranium (LEU) fuels as replacements for highly enriched uranium (HEU) fuels, through utilization, interim spent fuel management, reactor refurbishment and ultimate decommissioning.

The extensive development work to increase the uranium loading in LEU fuels and the substantial success achieved so far were reported. Also, work is in progress for development of LEU targets for fission Mo99 production. It is not expected that qualified U-Mo fuels will become available before the year 2010. In this context, the extension of the United States foreign research reactor spent fuel return program would be welcome.

While research reactors will continue to play a crucial role in nuclear science and technology it is important to ensure operational ability in terms of technical and financial resources, meeting the current standards of nuclear and conventional safety, and other aspects related to physical security, public acceptance and environmental responsibility. The technical aspects that need to be addressed include the capability for safe spent fuel management and storage, reactor refurbishment when required and the eventual decontamination and decommissioning of the facility.

For extended interim storage of aluminium-clad spent fuel, a semi-dry storage technique developed and implemented at the Budapest research reactor institute was discussed.
Irradiated fuel was encapsulated in sealed tubes filled with dry nitrogen and turned to the water storage pool. This is expected to prevent further corrosion of the irradiated fuel and hence can be used for storing spent fuel over extended periods.

Various aspects of decommissioning of research reactors were presented wherein it was highlighted that early development of a decommissioning strategy is highly beneficial. It was also underlined that a cooling-off period after the final shutdown of the reactor can be highly beneficial, not only because of the decay in radioactivity, but in the progressive availability of newly developed technologies for decommissioning. Problems of dealing with stakeholders, funding issues and waste management associated with the decommissioning of a low power research reactor were also presented and discussed.

It was stated that new research reactors would be required to investigate and develop the advanced fuel and core materials for many of the proposed innovative power reactor concepts. It was stressed that this reactor may have to be powered with HEU or plutonium fuels to investigate the conditions that will prevail in fast reactors.

Let me now conclude. The scientific and industrial communities greatly appreciate the IAEA initiative to organize this Scientific Forum on Nuclear Fuel Cycle Issues and Challenges. It allowed very fruitful discussions and provided opportunities for enhancing further cooperation involving the national programs. The meeting showed that large progresses have been made, but difficult issues still remain open. Therefore, it is important for all interested countries to carry on with ambitious R & D programs in due time in order to prepare for the future.
Remarks by Dr. R. G. Bennett

Session 1: Advanced Fuel Cycles and Reactor Concepts

The main program responsible for research and development of advanced fuel cycle systems in the United States is our Advanced Fuel Cycle Initiative, or AFCI. The AFCI program addresses three needs associated with past and future use of nuclear energy in the U.S.: First, the AFCI provides alternatives to building multiple repositories for geological disposal of existing commercial spent nuclear fuel while supporting an expanding role for nuclear energy in the future. Second, the AFCI explores fuel cycles in conjunction with the complementary Generation IV program. Third, the AFCI seeks nuclear fuel cycles that improve proliferation resistance by using advanced separations and fuels technologies, and by reducing the inventory of weapons-usable material. While accomplishing these goals, both programs also work towards the goal of ensuring competitive economics and exceptional safety for the entire nuclear fuel cycle.

The range of our options in the U.S. follows the potential for growth: We examine the combinations of market factors that drive the amount of spent fuel produced, along with the options for managing that material. In short, alternative levels of nuclear energy generation result in different amounts of SNF. Alternative management approaches for the SNF result in different amounts of material that go to geologic disposal. Currently, the AFCI program follows four alternative strategies: (1) the once-through fuel cycle, (2) a closed fuel cycle with thermal recycle, (3) a combination of thermal and fast recycle, or (4) exclusively fast recycle. While the U.S. has adopted the once-through cycle, the other alternatives are being explored to address future needs arising from a continuing and expanding role for nuclear energy in the U.S. We are also considering the case where an international provider-user arrangement may be developed in which the U.S. and other existing nuclear weapons states lease fuel to non-weapons states.

With regard to ultimate disposal, the AFCI program anticipates the licensing and operation of the Yucca Mountain repository. The program looks broadly at technologies that may be able to optimize the capacity of the first repository, as well as to greatly reduce the technical need for the development of future repositories. Our work in separations technology is exploring a number of avenues. First, separation of the SNF to remove the uranium provides some benefits to repository operation, but no improvement in capacity, from the standpoint of long-term decay heat from americium and plutonium. To increase the capacity, these elements must be partitioned and recycled. In addition, the short-term heat load may need to be mitigated or reduced. Partitioning cesium and strontium from the fuel could accomplish this if they are stored separately until they decay and then disposed as low level waste. Other advanced technology needs arise, such as specialized waste forms for nuclides that pose challenges to their storage.
Some notable accomplishments in the AFCI program are already evident: In the area of separations, laboratory scale separation of very pure uranium (to nearly five 9’s purity) from irradiated fuel was demonstrated with all associated partitioning steps, including U, Cs/Sr, Pu/Np, and Am/Cm separation. In the area of fuels, first irradiation of small samples of advanced metal, nitride and mixed oxide fuels has been completed. In the area of transmutation engineering, 1000-hour corrosion experiments on a wide variety of materials in Pb-Bi coolant have been completed. And finally, in the area of systems analysis, dynamic simulations have begun of fuel cycles, as well as a systematic study of thermal and fast transmutation concepts.

The AFCI is now focused on research and development supporting the advanced fuels and fuel cycles for Generation IV, and also on informing the Secretary of Energy’s recommendation in the 2007-2010 timeframe on the technical need for a second repository in the U.S. The highest priority AFCI program objectives over the next ten years include:

- **2008** – Providing engineering data and analysis to support the Secretarial recommendation;
- **2010** – Quantitatively defining feasible nuclear fuel cycle options and technologies for implementation, and developing fuel cycle technologies that enable our transition to an advanced fuel cycle; and
- **2015** – Providing engineering data and analysis for a recommendation of the best option for an advanced nuclear fuel cycle incorporating Generation IV technology.

The complementary Generation IV program is exploring a range of nuclear energy system options for future production of electricity, hydrogen for transportation, and potable water. The program also includes research and development to support the relatively near-term option for a very-high-temperature reactor. As it is becoming known in the U.S., the Next Generation Nuclear Plant seeks to demonstrate the potential for higher thermal efficiency and hydrogen production. More broadly, AFCI supports Generation IV with R&D into fuel technology and waste form development under the once-through strategy, as well as technology that can bridge this new generation into an advanced fuel cycle for the U.S.
Key Issues in Fuel Cycle Options

Richard Mayson

IAEA Scientific Forum
UK has Experience of Commercial Scale Reprocessing

Mixer Settlers

Pulsed Columns
BNFL are Investing in Advanced Fuel Cycle Studies

- **Aqueous**

  - Extract Scrub
  - Tc Rejection
  - U/Pu Split
  - Np Rejection
  - Backwash

- **Molten Salts**

  - Oxide Fuel
  - Metal to anode
  - Electrolyte
  - U
  - U$^{3+}$
  - TRU$^{3+}$

  Solid cathode

  Cadmium Pool Cathode

  Fission Products to Vitrification

  - HA Feed
  - Nitric acid
  - Concentrated nitric acid
  - Reducing agent
  - Complexing agent
  - Dilute nitric acid

  Pu Product
  Np Product
  U Product
Equipment for Aqueous Fuel Cycle Studies
Equipment for Pyrochemical Fuel Cycle Studies
BNFL Technology Centre will have a wide range of facilities
Objectives of an Optimised Fuel Cycle

- Increased proliferation resistance
- Reduction in costs
- Reduction in effluent volumes
- Minimise waste production
- Reduce radiotoxicity of High Level Waste
- Utilisation of full energy potential of spent fuel
Areas to Consider in a Fuel Cycle

- Proliferation
- Safety
- Economics
- Environment

Public Acceptance
The Ideal Solution Overlaps these Issues

- Proliferation
- Economics
- Public Acceptance
- Safety
- Environment
Increase proliferation resistance

- This is a major issue for public acceptance
- Producing Pu with other actinides will increase the proliferation resistance of the technology
- This is a focus for the work on aqueous flowsheets
- Pyrochemical processing can be inherently designed to be proliferation resistant
- Improvements are needed in both areas in parallel
Cost reduction can be achieved by a reduction in building size.

Minimise technology risks through use of stagegates.

A simplified process with low environmental impact will lead to a reduction in costs.
Reduction in Effluent Volumes

- Pyrochemical processing
  - Essentially a dry process hence will avoid liquid or aerial discharges

- Aqueous
  - Reduction in effluent volumes can be achieved by a reduction in solvent use
The choice of fuel cycle is important in minimising the waste produced.

Reprocessing has a major role to play in minimising waste volumes.

Waste volumes can be minimised by increasing the efficiency of waste treatment processes e.g.
  – Vitrification
  – Ceramics

Environmental

Economics
The challenge to the technology is to prove that transmutation can deliver.

The viability of transmutation will depend on economics and political decisions.

Technically validated solutions are needed to allow decision makers to have options.

International collaborations in transmutation needed to enable quick success.
Maximise Use of Energy Potential

- Energy source must be secure
- Energy source must be sustainable
- Efficient use of uranium is needed
- The choice of fuel cycle is important to maximise use of energy potential
Potential for Long Term Use of Uranium

![Graph showing the potential for long-term use of energy sources, with Uranium (FBR) significantly longer than other sources such as Oil, Nat Gas, Coal, and Uranium.]
Public Acceptability is Key

- The benefits of nuclear power outweigh the disadvantages
- The biggest challenges are social & political
- We must encourage and inform the debate
Several Fuel Cycle Options Exist
Diagram shows natural development for gas cooled systems & technology challenges to be addressed.
Multiple Uses for the Heat from High Temperature Reactors

- Glass
- Cement
- Hydrogen
- Styrene, ethylene
- Oil desulfurisation
- Wood pulp
- Urea synthesis
- Desalination, district heating

Temperature °C
- VHTR: 1500
- HTR (PBMR): 900
- AGR: 650
- LMF BR: 550
- LWR: 320
Optimise Use of Nuclear Power by Hydrogen Generation

DAY

NIGHT

Hydrogen Storage
Fuel Cycle will be Needed in the Future

• The need for a fuel cycle will come back in the long term due to
  – limited uranium
  – costs of uranium
  – resurgence of nuclear
  – the need to act against global warming

• BUT the industry must focus on social and political issues as well as technical issues to allow the right decision to be made

• Both evolution of current systems and a revolution to the next generation of systems are needed for reactors and fuel
Achievements and Prospects for Advanced Reactor Design and Fuel Cycles

Roberto O. Cirimello
Argentina

Advanced Designs

Consist of evolutionary designs and design requiring substantial development effort. It can range from moderate modifications of existing design to entirely new design concepts.

Evolutionary Design

Advance design achieving improvements over existing designs through small or moderate modifications (strong emphasis on maintaining proven design features to minimize technological risks)

Innovative Design

Advanced design that incorporates radical conceptual changes in design approaches or system configuration in comparison with existing practice.

Cost of Development

- Engineering + Confirmatory Testing
- Substantial R&D + Engineering + Confirmatory testing + prototype / demonstration plant
Let's them believe...
Evolutionary designs or third-generation reactors have:

- A standardized design for each type to expedite licensing, reduce capital cost and reduce construction time,
- A simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- Higher availability and longer operating life - typically 60 years,
- Reduced possibility of core melt accidents,
- Minimal effect on the environment,
- Higher burn-up reduce fuel use and the amount of waste,
- Burnable absorbers ("poisons") to extend fuel life.

Improved Safety
Low cost electricity
High fuel efficiency
60 years plant life, 48 m construction
Less waste

Light and Heavy Water Reactors

AP600

NRC CERTIFIED
September 2004

ACR-700

CANADA

AP1000

USA

Improved Safety
Low cost electricity
High fuel efficiency
60 years plant life, 48 m construction
Less waste

INDIA

AHWR


**Gas Cool Reactors**

**GT-MHR**
- USA - Rusia

**JAPAN**
- HTTR

**SOUTH AFRIKA**
- PBMR

**Modular Plants**
- Low cost
- Direct cycle gas turbine
- High fuel efficiency
- Passive safety features

Also: Russia - Japan - India - Canada

- Modular Plants
- Passive features
- Non-electrical application
- 36 m construction
- 1000 $/KW install
Fast reactors

JAPAN

RUSIA

BN-350

CHINA

CEFR

INDIA

@ Recycling Pu
@ Actinide burning
@ Desalination
@ Th Cycle

UA-US FRANCE

SUPERPHENIX

FRANCE

# Key research areas of NRC’s Advanced Reactor Research Program

- **1. Accident Analysis** - risk assessment techniques, human factor tools, models to address advancements in instrumentation and control (I&C).
- **2. Reactor Systems Analysis** - thermal-fluid dynamics, nuclear analysis, and severe accident codes and models.
- **3. Fuels Analysis** - methods to assess coated fuel particle performance and higher burnup fuels.
- **4. Materials Analysis** - codes and standards to address metallic and graphite components under high temperature operating and accident conditions.
- **5. Structural Analysis** - methods to assess aging, degradation and impact of external events.
- **6. Consequence Analysis** - tool enhancements to address differences in the mix of radionuclides and chemical forms.
Safety goals for future NPP from IAEA’s Safety Standards and INSAG documents:

- 1. A reduction in core damage frequency (CDF) relative to current plants;
- 2. Consideration of selected severe accidents in the design of the plants;
- 3. Ensuring that the releases to the environment in the event of a severe accident are kept as low as practicable with the aim of providing a technical basis for simplification of emergency planning.
- 4. Reduction of the operator burden during an accident by an improved man-machine interface.
- 5. The adoption of digital instrumentation and control.
- 6. The introduction of passive components and systems.

**Advanced technologies in the Front end of the NFC**

- Fuel assembly structure with internal water channel enables optimum moderation and thus best fuel utilization
- ULTRAFLOW™ spacer for excellent dryout performance
- Part length fuel rods for optimum axial fuel distribution and favorable stability performance
- High efficiency FUELGUARD™ debris filter

- Spacer grids with optimized swirl vanes provide enhanced thermal-hydraulic performance
- HTP spacer grids featuring line contact provide improved fretting resistance
- Reinforced structure provides high margins with respect to assembly bow (MONOBLOC™ guide tubes)
- High efficiency bottom nozzles (FUELGUARD™, TRAPPER™) effectively retain debris thus preventing fretting damage to the fuel rods
- Advanced cladding material IM5™ provides outstanding margins with respect to corrosion, hydriding as well as creep and growth


Advanced technologies in the Front end of the NFC

PWR
BWR

Year of discharge

Average Discharge Burnup of the Peak Reload Batch [MWh/kgHM]

Fuel Assembly Design...

DUPIC cycle anticipated benefits:

- Save of Unat for CANDU due to the reuse of PWR spent fuel.
- Removal of PWR spent fuel
- Reduction of CANDU spent fuel due to the increase of burnup
- Environmental benefit due to the transmutation effect of burning again PWR spent fuel.

DUPIC can be apply in countries with LWR and HWR at the proportion of 4 by 1.

PROSPECT...

Gaze Into The Crystal Ball...

Generation IV nuclear energy systems will:

- Provide sustainable energy generation that meets clean air objectives and promote long-term availability of systems and effective fuel utilization for worldwide energy production.

- Minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment.

- Increase the assurance that they a very unattractive and least desirable route for diversion or theft of weapon-usable materials.

- Excel in safety and reliability.

- Have a very low likelihood and degree of reactor core damage.

- Eliminate the need of offsite emergency response.

- Have a clear life-cycle cost advantage over other energy sources.

- Have a level of financial risk comparable to other energy projects.
Comparative advantages include: reduced capital cost, enhanced nuclear safety, minimal generation of nuclear waste, and further reduction of the risk of weapons materials proliferation. The purpose of Gen IV is to develop nuclear energy systems that would be available for worldwide deployment by 2030 or earlier.

... is a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374 degrees Celsius, 22.1 MPa, or 705 degrees Fahrenheit, 3208 psia).

... is a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle.
The GFR’s and SFR’s fast spectrum also makes it possible to use available fissile and fertile materials (including depleted uranium) considerably more efficiently than thermal spectrum reactors with once-through fuel cycles.
New enrichment technologies currently being developed
• atomic vapor laser isotope separation (AVLIS)
• molecular laser isotope separation (MLIS).
• Each laser-based enrichment process can achieve higher
  initial enrichment (isotope separation) factors than the
  diffusion or centrifuge processes can achieve. Both AVLIS
  and MLIS would be capable of operating at high material
  throughput rates.

• In 1985 the US Government backed it as the new technology
to replace its gaseous diffusion plants. After some US$ 2
  billion in R&D, it was abandoned in USA in favor of SILEX, a
  molecular process.

• Development of AVLIS, and the French SILVA began in the
  1970s.

• French work on SILVA has now ceased but continuo the
  MLIS technology evaluation.

Pyrometallurgical processes:

- Molten salt bath (LiCl+KCl or LiF+CaF₂)
- Fuse Metals (Cd, Bi, Al)
- Electrochemical separation

New approach of reprocessing are needed for:

- P & T or P & C
- NFC for FR
- ADS
INPRO (INternational PROyect on Innovative Nuclear Reactors and Fuel Cycle) objectives are:

- Help to ensure that nuclear energy is available to contribute in fulfilling energy needs in the 21st century in a sustainable manner, and to
- Bring together both technology holders and technology users to consider jointly the international and national actions required to achieve desired innovations in nuclear reactors and fuel cycles.
INPRO (INternational PROyect on Innovative Nuclear Reactors and Fuel Cycle)

Development of a Methodology for the Assessment of suitable INS for future deployment (Basic Principles, User Requirements and Criteria on Economics, Sustainability and Environment, Safety, Waste Management, Proliferation Resistance and Infrastructure)

Methodology Assessment throughout National and Individual Case Studies 2003/2004

INPRO PHASE II

DEFINITION OF REGIONAL SCENARIOS AND METHODOLOGIES

WORLDWIDE INVENTORY OF ONGOING R & D IN “INS” AND RELATED TECHNOLOGIES

INPRO METHODOLOGY APPLICATION TO REGIONS AND COUNTRIES UPON REQUEST

COORDINATION OF R & D IN NON-COVERED AREAS AND/OR IN NON-GEN IV COUNTRIES

FINAL REPORT

AVAILABLES “INS”

Dilemma!!!

Who is first?

• Burnup Increase increasing the enrichment. Only improved the Zry use.
• High Reactor efficiency with the results of higher cost of the NFC/Reactor system.
• Waste Storage is better at 700 m deep in isolate areas than in protected areas. Urge the decision of transport the spent fuel.
...is a technology that enters the market providing a product which has lower performance than the incumbent, but exceeds the requirements of certain segments thereby gaining a foothold in the market.
Disruptive technologies in INS!

- Disruptive Concept Gas Cool Reactor
- Disruptive Concept Spent Fuel Dry Storage
- Disruptive Concept Gaseous Diffusion Enrichment Plant
- Modular Plant

- 500 U$S/KW
- Three time less expensive than metal casks
- 50 U$S/SWU
- Proliferation resistant
"Those who believe in progress run the risk of being born too early"

Oscar Wilde

Thank you very much...  ...for your attention.
Holistic Consideration of Fuel Cycle Systems for Sustainable Development

Yumi Akimoto Dr. Sc.
Nuclear Energy: Pioneer for a Recycle-oriented Society

- Holistic concepts started off the peaceful use of nuclear energy
- Why was there a focus on recycling?
- LWR as the de facto leaving behind the backend cycle as necessary evil
- Sustainability of the nuclear power system: Scapegoat for the nuclear deterrence
### Tasks involving the resource and environment

**Conventional Concept**
- Obtaining and using energy resources lavishly
- Transient use of the cheapest energy resources
- Back fitting of environmental countermeasure

**Sustainable Concept**
- Do not leave the bill for future generations to pay.
- Planned use of limited resources
- Minimizing the environmental impact for developing resources
## Development policy of advanced reactor

<table>
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<th>Conventional Concept</th>
<th>Sustainable Concept</th>
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<td>Priority on the reactor performance</td>
<td>Priority on consistency with the cycle backend</td>
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<td>Cost competitiveness with light water reactors</td>
<td>Complement the shortcomings of LWR system</td>
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<td>Cycle development as an extrinsic technology to reactor development</td>
<td>Reactor development as an element of a cycle</td>
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<td>Unified development of cycle and reactor</td>
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Fig.6  Effect of Actinides Recycle
-Reduction of Radiotoxicity of HLW-
From a non-proliferation standpoint, MOX fuel is safer than enriched uranium fuel.
MOX

Fig. 8 Pu Balance in LWR
Development of Fuel Cycle System
- Non Proliferation System
- Partitioning & Transmutation Process

Recycling of TRU Nuclides (Pu, Np, Am, Cm)

Reduction of Radiotoxicity of HLW
- Removal of LLFP (I-129, Tc-99, Cs-135)
- Removal of Heat Source (Sr-90, Cs-137)

Size Reduction of Reactors & Fuel Cycle Facilities

Efficient Use of HLW Disposal Facility

Fig.9  FBR Cycle Development Strategy (JNC Program)
- Optimum Coordination with Reactor and Fuel Cycle System -
Fig. 10  Effect of FBR Recycle System
- Reduction of glass solidified waste -

Number of Glass Solidified Waste/Gwy

LWR, Reprocessing & Pu Separation

FBR, Reprocessing & TRU Recycle

FBR, Reprocessing & TRU Recycle & FP(Sr,Cs) Separation
Example of Transition Scenario from LWR to FR Cycle

- 2015: Certification of Technical Feasibility
- 2020: Demonstration of Plant Technologies
- 2030: First Deployment Plant
- 2040: Commercial Plants (1500 MWe x2)
- 2050: Commercialization
- 2060: [Depending on social needs]

**Fast Reactor**
- Monju (280 MWe)
- Pilot Plant
- LWR/MOX

**Fuel Cycle**
- Rokkasho Reprocessing Plant (800 t/y)
- LWR/MOX Fuel Fabrication Plant (100 t/y)
- Plutonium Fuel Production Facility
- Fuel Cycle Engineering Test Facility
- [LWR/MOX Fuel]
- Hybrid Type Fuel Cycle Plant (Integration of reprocessing & fuel fabrication)
- [FR Fuel Reprocessing, Improvement of LWR Fuel Reprocessing]
- FR & LWR/MOX Fuel Reprocessing
- LOW-DF TRU Fuel Fabrication
- Implementation of LWR Head-end Process
- Scale-up of FR Process
- DF: Decontamination Factor

Fig. 11 Example of Transition Scenario from LWR to FR Cycle
Comparison of Reactor Building Volume

**Prototype FBR MONJU**
- Thermal Output: 714 MWt
- Electricity Output: 280 MWe
- Reactor Building Volume: 810,000 m³

**Experimental FBR JOYO**
- Thermal Output: 140 MWt
- Reactor Building Volume: 200,000 m³

**Advanced Large-scale FBR**
- Thermal Output: 3570 MWt
- Electricity Output: 1500 MWe
- Reactor Building Volume: 130,000 m³

Ref.(a) Comparison of Reactor Building Volume
Comparison of Nuclear Fuel Cycle Facilities

- LWR Reprocessing Facility (800 tHM/y) (Rokkasho plant) 37 ~ 42 GWe / year
- FBR Advanced Aqueous Reprocessing Facility (200 tHM/y) (15 ~ 25 GWe / year)

Ref.(b) Comparison of Nuclear Fuel Cycle Facilities
International cooperation

Conventional Concept
- Pursuit of national interest by monopolizing information
- Development of strategies and systems by individual country

Sustainable Concept
- Pursuit of mutual interest by sharing information
- Cooperative development for increasing speed and reducing costs
- Development of strategies and systems through international cooperation
Alien Power into Accustomed Power

• Reaction of 9.11
• Distance of Public
  from Nuclear Society
  from Aviation Society
  from Automobile Society
• Education for Next Generation
“Sleep Peacefully as we Never Repeat the Mislead”

• The first and last nuclear-bombed country: A model of an advanced nuclear power country independent from weaponry world

• No oil, No coal, No choice: The current situation in France and Japan, tomorrow’s situation of the world

• Energy for the short term or energy for supporting the generations to come?
Fig. 12 Portion of Domestic & Nuclear Energy

(Source: IEA Energy Balances of OECD/Non OECD Countries, 2000-2001)
### Purpose of nuclear reactors development

<table>
<thead>
<tr>
<th>Conventional Concept</th>
<th>Reduction of direct power generation cost by improving reactor performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable Concept</td>
<td>Improvement of reactor performance in accordance with the needs of the cycle and reduction of total power generation costs</td>
</tr>
</tbody>
</table>

### Approach of nuclear reactors development

<table>
<thead>
<tr>
<th>Conventional Concept</th>
<th>Jump up to a fast breeder reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable Concept</td>
<td>Gradual progress from LWR-MOX, Pu/MA burner fast reactor to fast breeder reactor</td>
</tr>
</tbody>
</table>
## Review of the Mission (2)

### Function of Reprocessing

<table>
<thead>
<tr>
<th>Conventional Concept</th>
<th>Sustainable Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolation and effective use of nuclear fuel substances</td>
<td>• Waste management acceptable to society</td>
</tr>
<tr>
<td></td>
<td>• Use of nuclear fuel substances in a manner of proliferation resistance</td>
</tr>
</tbody>
</table>

### HLW management

<table>
<thead>
<tr>
<th>Conventional Concept</th>
<th>Sustainable Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent Disposal in accordance with geological time scale</td>
<td>Management and disposal in accordance with societal time scale</td>
</tr>
</tbody>
</table>
Fig. 1  Long Term Energy Demand and Fossil Fuel Supply

(Source: Energy Technology and Society, 2003)
Fig. 2 Energy Balance Ratio of Various Generation System in Japan

(Source: Uchiyama, Criepi Report Y94009, etc.)
Fig. 3  Life Cycle Assessment of CO2 Emissions for Generation Systems

(Source: Uchiyama, Criepi report Y94009(1995))
Fig. 4 Expansion of Nuclear Energy vs. Decrease of CO2 Emission Rate in 1973-1995

(TPES: Total Primary Energy Supply, TC/TOE: ton of carbon/ton of petroleum)
Fig. 5  Uranium Spot Price  (Source: CAMECO)
Fig. 1  Long Term Energy Demand and Fossil Fuel Supply

(Source: Energy Technology and Society, 2003)
Fig. 2  Energy Balance Ratio of Various Generation System in Japan

Energy Balance Ratio, Output/Input
(Source: Uchiyama, Criepi Report Y94009, etc.)

Power Generation Resources

- Nuclear with Diffusion Enrichment
- Nuclear with Centrifuge Enrichment
- Solar, Generation Plant
- Solar, Home System
- Solar, Heat
- Sea Wave
- LNG
- Wind
- Sea Tide
- Difference of Ocean Temperature
- Hydro
- Oil
- Coal
- Geothermal
- Solar, Heat
Fig. 3  Life Cycle Assessment of CO2 Emissions for Generation Systems

(Source: Uchiyama, Criepi report Y94009(1995))
Fig. 4 Expansion of Nuclear Energy vs. Decrease of CO2 Emission Rate in 1973-1995
Fig. 5  Uranium Spot Price  (Source: CAMECO)
Ingestion Radiotoxicity/1000MWey

![Graph showing the effect of actinides recycle on reduction of radiotoxicity of HLW. The graph includes lines for LWR Spent Fuel and FBR Cycle, with a natural uranium level indicated. The x-axis represents year after irradiation, and the y-axis represents ingestion radiotoxicity. The data shows a significant reduction in radiotoxicity with actinides recycle, particularly with a 99.9% recycle rate.]

Fig. 6 Effect of Actinides Recycle
-Reduction of Radiotoxicity of HLW-
From a non-proliferation standpoint, MOX fuel is safer than enriched uranium fuel

Fig. 7 MOX Fuel from a Non-Proliferation Standpoint
Pu kg/tonHM

Pu increase

Pu t 0kg
Pu t 11kg
(Pu f 7.5kg, 68%)

Pu t 23kg (Pu f 16kg)
Pu t 23kg
(Pu f 12kg, 52%)

Pu t 70kg (Pu f 48kg)
Pu t 45kg
(Pu f 22kg, 48%)

Pu t 11kg
(Pu f 7.5kg)

Pu t 0kg
(Pu f -4kg)

Pu t -25kg
(Pu f -26kg)

Fig.8  Pu Balance in LWR
Fig. 9  FBR Cycle Development Strategy (JNC Program)
- Optimum Coordination with Reactor and Fuel Cycle System -
Fig. 10  Effect of FBR Recycle System
- Reduction of glass solidified waste -
Example of Transition Scenario from LWR to FR Cycle

**Fast Reactor**
- Monju (280 MWe)
  - ▼ Pilot Plant
- Rokkasho Reprocessing Plant (800 t/y)
- LWR/MOX Fuel Fabrication Plant (100 t/y)
- Plutonium Fuel Production Facility
  - [LWR/MOX Fuel]
- Fuel Cycle Engineering Test Facility
  - [High-DF FR/MOX Fuel, TRU Fuel]
  - [FR Fuel Reprocessing, Improvement of LWR Fuel Reprocessing]

**Fuel Cycle**
- Hybrid Type Fuel Cycle Plant
  - (Integration of reprocessing & fuel fabrication)
- FR & LWR/MOX Fuel Reprocessing
- LOW-DF TRU Fuel Fabrication
- Scale-up of FR Process
- Implementation of LWR Head-end Process
- DF : Decontamination Factor

**Certification of Technical Feasibility**
- 2015

**Demonstration of Plant Technologies**
- 2030

**Commercialization**
- 2040
- 2050
- 2060

**Commercial Plants (1500MWe x2)**
- [Depending on social needs]

Fig. 11  Example of Transition Scenario from LWR to FR Cycle
Fig. 12 Portion of Domestic & Nuclear Energy
(Source: IEA Energy Balances of OECD/Non OECD Countries, 2000-2001)
CHALLENGES & DIRECTIONS IN FUEL CYCLE RESEARCH AND DEVELOPMENT

Anil Kakodkar
Department of Atomic Energy
INDIA
New Technologies & Approaches needed for the Growth of Nuclear Power

Innovative nuclear energy systems

i) INPRO project

(15 nations, including India)

methodology for assessing innovations in reactor systems as well as fuel cycles being established)

ii) GIF - Generation IV International Forum

10 Nations, 6 Reactor concepts

(4 of these are fast reactors)
Fuel Cycle: A **vital & integral** component of nuclear technologies. It is intimately linked to a) choice of the reactor systems & b) national policies.

**CLOSED FUEL CYCLE ALONE CAN PROVIDE SUSTAINABLE NUCLEAR ENERGY OVER LONG TERM WITH REDUCED IMPACT ON ENVIRONMENT**

**THREE STAGES OF INDIAN NUCLEAR POWER PROGRAMME**

**STAGE 1**
- **PHWR**
  - Natural Uranium
  - 10 GWe, 40 y
  - ELECTRICITY

**STAGE 2**
- Pu FUELLED FAST BREEDERS
  - Th
  - Pu
  - 530 GWe, 100 y
  - ELECTRICITY

**STAGE 3**
- U-233 FUELLED BREEDERS
  - Th
  - U-233
  - 150,000 Gwe·y
  - ELECTRICITY
Key Performance Indices for Nuclear Fuel Cycle

- Safety
- Economy
- Environmental impact
- Sustainability &
- Proliferation resistance

BENEFIT TO SOCIETY

ECONOMY

SUSTAINABILITY through CLOSED FUEL CYCLE with MINIMUM IMPACT ON ENVIRONMENT

IMPROVEMENTS IN SAFETY

IMPROVEMENTS IN WASTE MANAGEMENT

PROLIFERATION RESISTANCE

IMPROVEMENTS IN WASTE MANAGEMENT
R&D TARGETS FOR IMPROVING FUEL CYCLE

- Increase in burn-up to reduce mining milling and other processing requirements – *better economy and sustainability* and less impact on environment

- Increased remotisation of fuel cycle operations to permit processing of short cooled / recycled fuel

- Partitioning and transmutation of minor actinides & long lived fission products and recovery of fission products of commercial value (eg. $^{137}$Cs, $^{90}$Sr and noble metals) to reduce long term radiation hazards and create wealth from waste
R&D TARGETS FOR IMPROVING FUEL CYCLE

- Compact plants, simplified processes, higher emphasis on automation and co-location of facilities to improve economy of fuel cycle
- New processes and approaches to minimise waste and reduce secondary waste generation
- R & D to augment strategies to enhance public acceptance of waste management philosophies: Robust process and matrix for immobilization of waste, technologies for surveillance of waste, comprehensive modeling to ensure long term stability

Cumulative worldwide spent fuel arisings, reprocessing and storage 1990-2015 (IAEA)
Large scale deployment of uranium, plutonium mixed oxide fuel is one of the directions in utilization of Pu stockpile in water reactors. This demands R&D for critical evaluation of novel recycle technologies (co-precipitation, sol-gel microsphere pelletisation, coating / impregnation, remote fabrication, etc) to reduce waste generation and reduce man-rem exposure.
FAST REACTORS

IMPORTANT CANDIDATES FOR NEXT GENERATION REACTORS

- Development of clad and structural components for increasing the burn-up to a value of 200,000 MWd/t
- Integrated fuel cycle facilities to reduce cost and enhance proliferation resistance
- Development and Demonstration of matrices for deep burning of Pu
- Improved aqueous reprocessing schemes for processing high burn-up short-cooled fuel
- Development of pyrochemical processing route on industrial scale for oxide, metallic & other fuels
- Development and performance evaluation of Vibro-pac fuels: towards reduction in waste and man-rem exposure

MICROGRAPHS OF IRRADIATED (U, Pu) MIXED CARBIDE (70 % Pu) FUEL AT DIFFERENT BURN-UPS

FBTR Fuel subassembly
R & D TARGETS for FBRs

METALLIC FUELS WITH PYROCHEMICAL PROCESSING

- Higher burn-ups (up to 20 at % achieved)
- Greater degree of Passive safety
- Potential for high breeding
- High resistance to proliferation

PYROPROCESSING – PROCESS AT JPC, TOKAI, JAPAN
R & D Targets related to Metallic fuels for Fast Reactors

- Development of comprehensive data base on physicochemical properties of metallic fuel
- Modeling
  - Safety studies on reactor size optimization
- Transmutation of minor actinides – characterisation and chemistry of recycled fuel to be studied
Pyrochemical Processing

Developmental needs:
- Corrosion-resistant materials
- Remote handling techniques
- Characterization techniques & Waste management

Lower Melting & Less Expensive Electrolytes

Electrorefining of actinide oxides

Pyro-electro-metallurgical process for UO₂
Salient features of thorium based fuels

- Thorium is an excellent host for Pu
- Makes the fuel cycle more sustainable and proliferation resistant
- Enables much deeper plutonium burning with manageable reactor characteristics even when the entire core is loaded with Pu bearing fuel assemblies
- Th-U fuel cycle has the advantage of absence of production of minor (heavy) actinides
THORIUM BASED FUELS
R& D issues

Fuel Fabrication:

- New technologies for the production of U-Th and Th-Pu oxide fuels (sol-gel, Impregnation, etc.)
  
  Reduction in sintering temperature, Improvement of homogeneity

Fuel Reprocessing:

- Dissolution without use of HF?
- Three component separations U, Th, Pu
- $^{233}$U clean-up (removal of $^{232}$U) by laser separation
ACTINIDE PARTITIONING AND TRANSMUTATION

- **Partitioning flow sheets**
  Comprehensive techno-economic evaluation to consider:
  i) Secondary waste production,
  ii) Need for An/Ln separation,
  iii) Utility value of actinides
  iv) Simplification in alpha waste management

- **Transmutation**
  Fast reactors or Accelerator driven sub-critical systems?

- **Choice of ADS fuel cycle**
  would be influenced by its goal:
  Actinide Breeding / Actinide burning/
  Power production

- **Burning in fast reactors**
  choice of fuel cycle would depend on matrix:
  metal / oxide / nitride
AQUEOUS FUEL REPROCESSING

Increase in plant life

Use of corrosion resistant materials to withstand high concentrations of nitric acid and high temperatures in high radiation environment

- Systematic studies on corrosion behaviour of materials
- Development of special coatings on materials
- On-line monitoring of health of the equipment

Nitric acid loop for corrosion studies

Micrograph of corrosion resistant Ti-5Ta-1.8 Nb

AFM IMAGE OF CORROSION RESISTANT NANO-COATING
Simplified plant maintenance through development of remote handling tools

Reduction in man-rem exposure through increased remotisation of equipment and operations
AQUEOUS FUEL REPROCESSING

- Reduction of waste generation: Adoption of salt-free processes for reducing secondary wastes (new organic soluble reductants for Pu; electrochemical and photochemical steps)
- Minimising loss of actinides to waste streams & discharges to environment
- Development of new extractants and resins
- Comprehensive on-line monitoring of Pu (at low as well as high concentrations) to improve process control and safety
New extractants: higher loadings, higher decontamination, lesser degradation & economical manufacturing.

Comprehensive fuel reprocessing flow sheet: Near-Quantitative Extraction of actinides, and recovery of minor actinides & valuable fission products.

**Variation of $D_{\text{Am}}$ with nitric acid concentration; Diluent: n-dodecane; Temperature: 25°C**

- 0.1M TODGA
- 30% TRPO
- 1.0M DMDBTDMMA
- 0.2M CMPO + 1.2M TBP

![Diagram of fuel reprocessing flow sheet](image-url)

**TODGA**
AQUEOUS FUEL REPROCESSING

- Development of comprehensive modeling capability to design improved processes and equipment.

- Development of equipment with reduced maintenance.

Variation of maximum aqueous Pu concentration inside the HC contactor: SIMPSEX results for 70%U+30%Pu flowsheet with feed concentration of 72 g.L⁻¹ (U+Pu).

Pu loss in organic phase in HC Contactor: SIMPSEX results for 70%U+30%Pu flowsheet with feed concentration of 72 g.L⁻¹ (U+Pu).

Accurate metering of crucial streams.

Rotary Semi-Continuous Dissolver
R & D on glass and ceramic matrices to adapt to fast reactor fuel reprocessing waste

Processes benign to environment: *Supercritical extraction*

Processes which generate minimum or no secondary wastes

Electrochemical and photochemical steps

Ultrafiltration, Supported liquid membranes, Microwave techniques
INTEGRATED FUEL CYCLE FACILITIES

Objectives

R& D Targets

Oxide fuels:

i) Integration of Fuel Fabrication & Reprocessing
   (by adopting sol-gel vibro pac or SGMP process)

ii) Sol-gel process to be demonstrated on commercial scale

Metallic fuels:

i) Integrated fuel fabrication plant

ii) Very little liquid waste,

iii) Compact size,

iv) Economy

Reduction in number of process steps
Minimization of waste generation
Economy of operation
Reduction in man-rem exposure
CONCLUSIONS

- Closed Fuel Cycle and Th utilisation – sustainable long term strategy for nuclear energy

- Cost Reduction of Nuclear Fuel Cycle – R & D is vital; Key issues – plant life, safety & reduced burden on environment

- R & D emphasis should be on innovative approaches for reactor systems as well as fuel cycle
Thanks
Nuclear Fuel Cycles Issues and Challenges
2004 IAEA Scientific Forum

Session 2 – Waste and Spent Fuel Management Issues
Panelist - Jose Rubens Maiorino, IPEN-CNEN (Brazil)
Title of the Notes- P&T An option for spent fuel and waste management using a Double Strata Fuel Cycle with a dedicated Waste Burner Reactor

Notes

• The present time commercial reactors (LWR, CANDU, etc.) operate in a Once Through Fuel Cycle OTC, and based in a feed of uranium. From around 400 operating reactors a large stock pile of radioactive waste are being produced, mainly long lived TRU- Plutonium, MA (Am, Np, Cm), and Long Lived Fission Products, LLFP, such as I-129, Te-99, Cs-135 etc. It is estimated around 300,000 t of the spent fuel be produced in this decade, with 1% of Pu (3,000 tons), 0.1% MA, 300t, and 400tons of LLFP.

• The build up of radioactive stock piles, besides the concern of waste disposal (radio toxicity), also brings the issue of proliferation. To overcome these issues, the next generations of nuclear reactors are considering concepts that coupled with a closed fuel cycles in many new initiatives, such as GIF and INPRO. This is main point I which to note, that is P&T is sustainable option for spent fuel and HLW management, considering the renascence of Nuclear Energy for the next decades. Some issues such as safety, economics had already been almost solved. Also the contribution of nuclear energy to avoid the threat of global warming due to CO₂ emissions in short term is also a positive point. So the only point which still remain as a controversy issue for a complete acceptance of Nuclear Energy, is what is going to be done with the HLW (long term hazard). We need to give answers acceptable for the public, and as established in the Joint Convention for Safety Spent Fuel Management and Radioactive Waste Management to protect the people, the society, and the environment presently and in the future in such way that the needs from present generation be satisfied without compromising the future needs of the future generations.

• The scheme illustrated in the slide, summarizes almost all possibilities of waste and spent fuel management. First we notice that in a present OTC cycle, only uranium is being used as a fuel. So a first point we wish to make is that the utilization of thorium based fuel cycle is an option to reduce long lived radio toxicity and constrain plutonium even in a present time reactors (LWR, CANDU), or in the concepts under development such as Molten Salt Reactors, Gas Cooled Fast Reactors, HTR, considered in INPRO and GIF initiatives. In fact initiatives to utilize thorium as fuel in several cycles had been studied and proposed all around the world, as the Radowisk Light Water Thorium Nuclear Reactor Concept (seed blanket fuel element), and the utilization in CANDU Reactors. The IAEA, has promoted several technical meetings, coordinated research projects related with Thorium utilization, as reported in the recent TECDOC-1319, Thorium Fuel
Utilization (2003), and TECDOC-1349, Potential of thorium based fuel cycle to constrain plutonium and reduce long lived waste toxicity (2003).

- The second point, I wish to make is that OTC assumes that the final solution for HLW is the geological repository for thousand of years (>10,000 y). Although this solution looks as the most attractive and economical competitive, and adopt by countries like USA (Yucca Mountain), Sweden, Finland, still a lot of controversies still remain, and the acceptability by the public is still an unsolved issue. First some questions need to be answered, such as i) is possible to control physically by engineering design and natural barriers for such long period of time (10,000-100,000 y), ii) the security is possible for such long time period. We must realize that 10,000 y is the time of man history, and from the time man start civilization in history to now empires, nations, culture, social organization etc have changed, and it is impossible to predict how society is going to be 10,000 y from now (there are prognostics that a new glacial age could start 15,000 y from now). Also, for instance in the USA, Yucca was designed to accept 70,000 HM, and if there is a renaissance or even the present time reactors have its life extended, probably new repositories is going to be constructed. This paradox is also true for other countries. So to have a sustainable nuclear energy development for the centuries to come, a hundred folds should reduce the time of confinement. That is the Advanced Fuel Cycle, or P&T has to give as an answer.

- The second fuel cycle option, already implemented or in planning by countries like France, Japan, Russia, etc. Is the aqueous reprocessing fuel cycle with vitrification of HLW. In fact LWR-MOX is already in use in Western in Europe (France, German, Switzerland and Belgium) in LWR( the advanced EPR will use MOX fuel), and are a first step in a global closed fuel cycle scenario. The PUREX aqueous process is well established, and reprocessing of Plutonium and uranium is available in France, UK, Japan, India, Russia, and China., and the recycling of these major actinides(U, Pu-99.9% are extracted). For the innovative reactors under consideration RFC is an option, and if we include in cycle the possibility to separate MA( pyroreprocess), and burn in fast reactors than the goal to reduce the requirement in the repository by a hundred fold could be achieved. I would like to add, the possibility to use thorium in a closed fuel cycle with aqueous reprocessing( THOREX), with Fast Reactors, as also an option to reduce the burden in the repository, besides to increase the utilization of natural resources( thorium is 3 times more abundant than U in the earth crust, 6.000 ppb), in a sustainable nuclear energy scenario.

- Finally, the Advanced Fuel Cycle with Partining of MA could be a sustainable option for spent fuel and HLW management. So P&T objective is to reduce the LONG TERM HAZARD of spent fuel or HLW by transforming long lived radio nuclides(MA, LLFP) into short lived nuclides and reduce the radio toxicity by a factor of 100. Of course P&T demands a lot of development in dry processing( pyro), fuel fabrication, and new innovative dedicated transmute reactor. Accelerator Driven System(ADS), Thorium fueled(Th-TRU), Helium or lead bismuth cooled could be such reactor. In fact a lot of R&D effort are being put in P&T in all technical aspects, pyro processing, fuel fabrication, ADS concepts using solid or fluid fuels( MSR). The European Community, the USA, Russia, China, Republic of
Korea, France etc. are involved in P&T, and have programs in it. The IAEA through the technical Working Group of Fast Reactors have reported several technical documents related with P&T, such as IAEA TECDOC 1365(2003)- Review of National ADS programs for P&T. A NEA OECD 2003 report (Comparative Study on ADS and FR in Advanced Nuclear Fuel Cycles), made an excellent and consistent study comparing the sustainability( cost effectiness, environmental friendly, resource efficiency) of several fuel cycles scheme(Pu Burning in LWR-FR, Heterogeneous MA recycling LWR-FR, TRU burning in FR, TRU burning in ADS, MOX recycling LWR-ADS, Double Strata LWR-FR-ADS, only FR), using U-Pu-MA solid fuels, and compare with OTC. The main conclusions were that? 1) P&T WILL NOT REPLACE THE NEED FOR APPROPRIATE GEOLOGICAL DISPOSAL OF HLW THE CLOSED FUEL CYCLE WITH P&T, USING ADS OR FR, WILL REDUCE IN A HUNDRED FOLD THE TIME REQUIREMENT FOR THE REPOSITORY, 2) THE COST OF ELETRICITY IN SUCH CYCLES WILL INCREASE 10-20%, 3) NEEDS A R&D EFFORT FOR THE DEVELOPMENT OF THE NECESSARY TECHNOLOGY.
IAEA Scientific Forum 2004

P&T: An option for Spent Fuel and Waste Management using a Double Strata Fuel Cycle with a dedicated waste burner reactor (ADS)

J.R. Maiorino

---

**P&T OBJECTIVE IS TO REDUCE THE LONG TERM HAZARD OF SPENT FUEL OR HLW BY TRANSFORMING LONG-LIVED RADIONUCLIDES (MA, LLFP) INTO SHORT-LIVED NUCLIDES (REDUCE THE RADOTOXICITY)**

---

Feed U or Th

Conversion Enrichment Fuel Fabrication

Thermal Reactor LWR, HTR

Processing?

Storage

No

Purex, Thorrex Aqueous

Waste

Yes

Fast Reactor (Na, Pb-Bi, He), MA burner

Waste

Reduced Radio toxicity Factor ~100

---

First Strata

Second Strata

Energy

Accelerator

---

Pu, MA, LLFF

PARTITION PYRO Processing Fuel Fabrication

Pu, MA, LLFF

TRANSFORMATION (Dedicated Reactor) ADS -Th, TRU; He or Pb-Bi

---

Energy

---

OTC - Once Through Fuel Cycle

RFC - Aqueous Reprocessing Fuel Cycle with Vitrification of high-level liquid waste

REPOSITORY Long Term Radio toxicity >10,000 years

REPOSITORY Reduced Radio toxicity Factor ~100
A Century of Spent Fuel Management
“A View from the Halfway Mark”

International Atomic Energy Agency Scientific Forum 2004
Vienna, Austria

September 21, 2004

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Nuclear Fuel Cycle – Growing Complexity Associated with Spent Fuel Management
Spent Nuclear Fuel Management System
“Managing the Complex Interdependencies”

- Transportation
- Nonproliferation
- Safeguards
- Stakeholders
- Nuclear Power Plants
- Reprocessing
- Very-High-Temperature Reactor
Serve the peaceful pursuits of mankind . . .
. . . provide abundant electrical energy in power starved areas of the world
Encourage world-wide investigations with the most effective peacetime uses of fissionable material
Create international controls to prevent proliferation (IAEA)
“Obviously, if the [nuclear] industry is to grow in a healthy way, it must be a “good neighbor” . . . having harmonious relations with the rest of the community”

. . . “Should we think primarily in terms of problems in the United States or should we take a wider [global] view”

“The problem was extremely complex . . . extending to many years waste will constitute a serious problem”

“‘It is an encouraging possibility that in the future people can produce wastes that can be gotten rid of more easily . . . it takes teamwork over a wide spectrum in order to put the problem in the proper light to evaluate all aspects”
International Spent Fuel Management Programs

- Yucca Mountain Project, USA
- La Hague, FRANCE
- Potential Host Rock Studies, TAIWAN
- Grimsel Underground Rock Laboratory, SWITZERLAND
- Olkiluoto, FINLAND
- Gentilly Dry Storage, CANADA
- Spent Fuel Container, RUSSIA
Waste Isolation Pilot Plant (WIPP)  
“Insights and Perspective”

Deep Geological Repository for Transuranic Waste

- Transformation of “Science to Compliance” to Support Significant Regulatory Interactions
- Compliance Basis Founded in Safety Analyses and Performance Assessments
- Significant Stakeholder Initiatives Local–State–National Engagement
- National and International Reviews of Technical and Regulatory Outcomes
Yucca Mountain Project

- Site Recommendation Report - February, 2002
- Yucca Mountain Site Approved - “Site Characterization Phase is Complete” - July, 2002
- License Application for Construction Authorization - Submittal Expected - December, 2004

Environmental Protection Agency - 10,000-Year Compliance Standard Court Ruling - July, 2004
Spent Fuel Management System
“Suggestions for the Next 50 Years”

• Pursue a multi-national nuclear fuel system that fully integrates standardized reactor designs and fuel forms, approaches to reprocessing and ultimately disposal.

• Pursue a multi-national repository that provides significant safety, security, economic and non-proliferation advantages.

• IAEA lead efforts to develop standards and approaches for confidence building through public involvement and enhanced transparency measures consistent with approaches developed for reactor safety, proliferation prevention, and nuclear materials management.
Advances in Treatment of Wastes from Reprocessing of Spent Fuel

P. Bernard

Director of Nuclear Development and Innovation
Reprocessing & Recycling, a cornerstone for future energy needs

- Extract the maximum energy from the fuel
- Drastically minimize radiotoxicity of the waste

Valuable materials (96%)
Uranium (94 to 96 %)

Wastes (4%)
Fission Products (3 to 5 %)
Minor Actinides (0.1 %)

Reprocessing & Recycling

Pu stockpile stabilisation: the Pu produced is consumed in LWR

Radiotoxicity after 1000 years

- Plutonium
- Minor actinides
- Fission products

IAEA Scientific Forum - September 21, 2004
R&D for long term management of HLLW in France

3 areas of R&D set out by law of December 30, 1991:

- **minimization** of the **quantity** and **toxicity** of **waste**, by **partitioning** and **transmutation**,

- packaging and **conditioning**, for safe long lasting containment, and also studying **long term surface storage**,

- feasibility of **deep geological disposal**, whether reversible or irreversible.

≤ 15 years of R&D ⇔ ≤ 2006 ; evaluation by National Evaluation Commission
At present time:

1) Significant results have been produced by R&D since 1991,

2) Technical solutions do exist, that can be implemented in a progressive manner.
Evolution of the radiotoxicity

- Natural uranium ore
- Spent Fuel (Pu + MA + FP)
- FP
- MA + FP
• **SUSTAINABLE NUCLEAR ENERGY WITH REPROCESSING AND RECYCLING**

  ✓ Recover and recycle valuable materials
  ✓ Minimise waste: volume/5, radiotoxicity/10
  ✓ No plutonium in ultimate waste
  ✓ Vitrification of ultimate waste: very safe conditioning providing long lasting confinement of radioactive waste
  ✓ Open strategy to the future

• **MATURE INDUSTRIAL IMPLEMENTATION AND COMPETITIVE**

  ✓ > 18 000T reprocessed at La Hague
  ✓ 20 reactors in France recycling plutonium
Minimisation of the quantity and the toxicity of waste

**Partitioning**

* Minimisation of the volume of solid waste and of the activity of liquid releases

Volume of solid waste reduced by 3
Activity of liquid releases divided by 10

Feasibility of partitioning

Evaluation report

Industrial stage ~ 2030

Conception and test of molecules
Qualification
Technological demonstration of process

Spent fuel

REPROCESSING

+ Partitioning

Very selective molecules
Partitioning performances > 99%

FP
Glass

UP u

REPROCESSING

UP u

REPROCESSING

Actinides

NP Am Cm
Transmutation

* Physics and scenarios studies

Evaluation report

Industrial stage

~ 2040

Physics

91

98

01

scenarios

and systems

04

Physics

Gain in radiotoxicity, reduction compared to open cycle

Integral recycling of plutonium and minor actinides

Recycling of plutonium

Open cycle

ECRX (2.75 g of Am)

0498

Scenarios

Physics

Evaluation

report

Feasibility of transmutation

Interactive stage

~ 2040

Feasibility of transmutation

91

Physics and

scenarios studies

Physics

91

Industrial

stage

~ 2040

Physics and

scenarios studies

Physics

91

Industrial

stage

~ 2040

Physics and

scenarios studies

Physics

91

Industrial

stage

~ 2040

Physics and

scenarios studies

Physics

91

Industrial

stage

~ 2040

Physics and

scenarios studies

Physics

91
Conditioning and long term interim storage

**Conditioning**
- *processes*
- Development and qualification of processes
- Technological qualification
- Evaluation Report

**Technological qualification**
- Processes available for various categories of waste

**Alteration of glass by water**

**Operational models**

**Long term behaviour of waste packages**
- Phenomenology - modelisation
- Evaluation report

Nuclear Energy Division
IAEA Scientific Forum - September 21, 2004
* Containers

**CECER**
(Centre d'Expertise sur le Conditionnement et l'Entreposage des matières Radioactives) at Marcoule

Containers for spent fuel

- **Functional demonstrators**
  - Specification, fabrication of demonstrators
  - Evalutation report

- **Technological demonstrators**
  - Internal barrel in ceramics

Containers for ILLW

- Storage
- Internal barrel in ceramics
- Internal barrel in enameled steel

Storage - Disposal

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Long term storage

Report to Government: storage in subsurface

Progress report: surface and subsurface

Preliminary design of concepts

Feasibility report concepts, qualification

Concepts

Storage in surface

Storage in subsurface

Nuclear Energy Division

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Deep geological disposal

Meuse-Haute-Marne Underground Laboratory

General architecture of the laboratory
Closing the fuel cycle has a major impact on:

- Minimization of waste
- Resources Extension
- Reprocessing and recycling for sustainable nuclear energy
- Quite advanced processes (minimisation of volume and radiotoxicity, safe conditioning) at competitive industrial maturity
- Recycling of plutonium in present LWR is demonstrated at large scale; further possible improvements with 3rd generation LWR type reactors

**Next steps for the future**
- 4th generation systems with closed fuel cycle for integral recycling of actinides

⇒ **HLLW decay within some hundred years**
- Safe long term management of waste
- Geological disposal of ultimate waste = long term burden free solution, taking benefit from the most important reduction of the quantity and toxicity of waste brought by closed fuel cycle
- Storage of radioactive material ⇒ flexibility
A drastic minimization of ultimate waste:
- Very small volumes,
- Decrease the heat loading
- Hundreds of years versus hundreds of thousands

An optimal use of energetic materials
Fuel cycle: Perspective for actinides management

- **Pu recycling in LWRs (MOX fuel)**
- **Global Actinide Extraction**
- **Recycling of LWR Pu and MA in Gen 4 FR**
- **Global Actinide Management (extraction and recycling) in Gen 4 FR**

- Gen 2&3 LWR
- Gen4 FR
- GAM (U,Pu,MA)
ADVANCES IN REPROCESSING OF SPENT FUEL: PARTITIONING

A. Mayorshin
SSC RIAR, RUSSIA
Fuel cycle in nuclear power engineering of the 21 century

**Principles**

- Closed fuel cycle
- Optimization of technological system
- Maximum level of inherent safety
- Minimum quantity of wastes
- Optimization of fuel cycle costs
Advanced Closed Fuel Cycle

Principles

- Optimization of technological systems
- Maximum level of “inherent” safety
- Minimization of wastes flows
- Optimization of fuel cycle cost

Requirements

- High level of safety
- Minimal impact on environment (radiation-migration equivalent for disposal of nuclear power engineering wastes)
- Maximum utilization of natural resources
- Non-proliferation

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Requirements of new technologies of the fuel cycle

The future technologies, which can significantly extend the oxide fuel potential and improve technical-economical indices of the fuel cycle with regard to the present-day requirements, are of great interest.

Non-aqueous methods are considered as possible alternative technologies for the closed fuel cycle.
Main recent trends for application of molten salts

- Fast reactors and other advanced reactors
- Reprocessing of oxide spent fuel (MOX, Th-based, etc.)
- Reprocessing of metallic and nitride fuel (U-Pu and others)
- Partitioning of HLW (Ln/Ac separation)
- Recycling of Molten Salt Reactor (or ADS) fluid fuel
RIAR activities in the field of fuel cycle

Since 1964 RIAR has been performing large-scale investigations in the following research lines:

- Development of dry fuel production and reprocessing technologies for different nuclear reactor types
- Development and testing of the fuel rod designs for different nuclear reactor types
- Investigation of the ways for waste management generated during production processes resulting from dry technologies
- Investigation of the actinide and fission product properties in different ion liquids
Basic research of the molten salt systems allowed for the development of technological processes for production of granulated uranium and plutonium oxides and mixed uranium and plutonium oxides. A distinctive feature of the pyrochemical technology is a possibility to perform all the deposit production operations in one apparatus - a chlorinator-electrolyzer.

Pyrochemical reprocessing consist of the following main stages:

- **Dissolution of initial products or spent nuclear fuel in molten salts**
- **Recovery of crystal plutonium dioxide or electrolytic plutonium and uranium dioxides from the melt**
- **Processing of the cathode deposit and production of granulated fuel**
Current status of pyrochemical process in RIAR:

- Fundamental studies
- Technological development
- Industrial implementation
Fundamental studies of pyrochemical process

Properties of U, Pu, Th and Np in molten chlorides were studied in detail.

The knowledge on physical chemistry and electrochemistry of basic FPs is enough for technological implementation.

Necessary direction for studies – chemistry of Am, Cm, Tc in molten chlorides.

Development of basis for new processes
- Reprocessing of nitride fuel
- Partitioning of HLW
From electrochemical point U and Pu oxides behave like metals. They are forming the complex oxygen ions MeO$_{2n+}$, which are reduced on cathode up to oxides.

Under high temperatures (> 400°C) UO$_2$ are electrically conductive.

In the molten alkali chlorides uranium has the stable ions U(III), U(IV), U(V), U(VI). Highest states of Pu oxidation Pu(V) and Pu(VI) are stable only in the definite field of ratios for oxidation reduction potentials of the system.
Technological development

For reprocessing and production of oxide fuel the main processes and equipment were developed and tested.

Total amount of produced fuel is about 6000 kg (MOX, UO₂, special types). About 30 kg of fuel from the BOR-60 and BN-350 reactors was reprocessed. The basis of technology was created. The feasibility study was carried out for industrial plant for closed cycle of the BN-800 reactor.
Pyroelectrochemical reprocessing of spent UO$_2$ and PuO$_2$ fuel

**CHLORINATION (Dissolution) (650°C)**

CATHODE: $\text{UO}_2^{2+} + 2e^- \rightarrow \text{UO}_2$

ANODE: $2\text{Cl}^- \rightarrow \text{Cl}_2 + 2e^-$

**UO$_2$ ELECTROLYSIS (650°C)**

$\text{Pu}^{4+} + \text{O}_2 + 2\text{Cl}^- \rightarrow \text{PuO}_2^{2+} + \text{Cl}_2$

$\text{PuO}_2^{2+} + 2\text{Cl}^- \rightarrow \text{PuO}_2 + \text{Cl}_2$

**PuO$_2$ PRECIPITATION (630°C)**

**ADDITIONAL ELECTROLYSIS (630°C)**

CATHODE: $\text{UO}_3^{2+} + 2e^- \rightarrow \text{UO}_3$

$\text{PuO}_2^{2+} + 2\text{Cl}^- \rightarrow \text{PuO}_2 + \text{Cl}_2$

ANODE: $2\text{Cl}^- \rightarrow \text{Cl}_2 + 2e^-$

**PURIFICATION of MELT (650°C)**
Pyroelectrochemical reprocessing of spent MOX fuel

**Chlorination (dissolution)**
(650°C)

- Spent fuel
- Pyrographite bath
- NaCl+CsCl
- **Cl₂**

**Additional electrolysis**
(630°C)

- Cathode
- Cl₂+O₂+N₂
- **UO₂**
- **PuO₂**
- **Na₃PO₄**
- MA, RE
- Ce⁴

**Purification of melt**
(650°C)

- Mixing device
- **Na₃PO₄**
- MA, RE
- Ce⁴
- (MA, RE)PO₂⁻
Main equipment for production

MOX-fuel

30 kg MOX-fuel

6 kg MOX-fuel

Crucible diameter 250 mm

Crucible diameter 380 mm

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Granulated MOX-fuel particles obtained by pyroelectrochemical process

Particle density – 10.8 g/cm³
O/M ratio - 2.0-2.03
Content of corrosion-active impurities, % no more:
Carbon- 18 \cdot 10^{-3}
Fluorine- 2 \cdot 10^{-3}
Chlorine- 7 \cdot 10^{-3}
Total content of cationic impurities, % no more- 0.5
Experience on pyrochemical reprocessing of the BOR-60 and BN-350 irradiated fuel

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Burn-up, %</th>
<th>Mass, kg</th>
<th>Data of Tests</th>
<th>Reactor</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO₂</td>
<td>7.7</td>
<td>2.5</td>
<td>1972..1973</td>
<td>BOR-60</td>
</tr>
<tr>
<td>(U,Pu)O₂</td>
<td>4.7</td>
<td>4.1</td>
<td>1991</td>
<td>BN-350</td>
</tr>
<tr>
<td>(U,Pu)O₂</td>
<td>21..24</td>
<td>3.5</td>
<td>1995</td>
<td>BOR-60</td>
</tr>
<tr>
<td>UO₂</td>
<td>10</td>
<td>5</td>
<td>2000</td>
<td>BOR-60</td>
</tr>
<tr>
<td>(U,Pu)O₂</td>
<td>10</td>
<td>12</td>
<td>2000-2003</td>
<td>BOR-60</td>
</tr>
</tbody>
</table>

PuO₂, UO₂ and MOX Decontamination factors (DF) from main FPs

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Main FPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ru- Rh</td>
</tr>
<tr>
<td>PuO₂ for BN-350 (test, 1991)</td>
<td>50</td>
</tr>
<tr>
<td>PuO₂ for BOR-60 (test, 1995)</td>
<td>33</td>
</tr>
<tr>
<td>UO₂ for BOR-60 (test, 2000)</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>(U,Pu)O₂ for BOR-60 (test, 2001)</td>
<td>20 - 30</td>
</tr>
</tbody>
</table>
Experience on pyrochemical reprocessing of the BOR-60 irradiated fuel

MOX cathodic deposit after pyro-process

Salt ingot after reprocessing test with the BOR-60 fuel
Pyrochemical processes

30 kg (U,Pu)O$_2$ deposit on cathode
Pyrochemical reprocessing of irradiated fuel

The following experiments were carried out:

- $\text{UO}_2$ SNF $\rightarrow$ granulated $\text{UO}_2$
- $\text{UPuO}_2$ SNF $\rightarrow$ granulated $\text{PuO}_2$
- $\text{UPuO}_2$ SNF $\rightarrow$ granulated $\text{UPuO}_2$

![Plutonium dioxide, BOR-60 spent fuel fraction <0.1mm](image)

Equivalent diameter, $\mu$m

Ratio of particles, %

0 5 10 15 20 25 30 35 40
10 30 60 70 90 110

Plutonium dioxide, BOR-60 spent fuel fraction <0.1mm
## Demonstration experiment on UOX and MOX fuel reprocessing

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Process ( \text{UO}_2 \rightarrow \text{UO}_2 )</th>
<th>Process ( \text{MOX} \rightarrow \text{MOX} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test For production line</td>
<td>Test For production line</td>
</tr>
<tr>
<td>Yield of fuel component, %</td>
<td>95,91 &gt; 99,6</td>
<td>94,83 &gt;99,5</td>
</tr>
<tr>
<td>Fraction of U and Pu in recycled products, %</td>
<td>2,90 Will be recycled</td>
<td>3,90 Will be recycled</td>
</tr>
<tr>
<td>Technological losses, %</td>
<td>1,19 &lt;0,4</td>
<td>1,27 &lt;0,5</td>
</tr>
<tr>
<td>DF in Cs</td>
<td>10000</td>
<td>&gt; 1000</td>
</tr>
<tr>
<td>DF in REE</td>
<td>&gt; 100</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>DF in noble metals</td>
<td>~ 10</td>
<td>~ 10</td>
</tr>
</tbody>
</table>
Recycle of reprocessed fuel in BOR-60

Vipacked UO$_2$+PuO$_2$ fuel (mixture) achieved burnup $\sim$ 15.1%,
PIE were performed for fuel pins with a burn-up of 4.8 and 9.8 % h.a.
Reprocessed MOX fuel was used for new fuel pins production and irradiation in BOR-60 started in June 2004

Microstructure and alpha-radiography of vibropacked fuel, the burnup of 9.8 %
Methods for separation of MA and LLFP

During solid fuel reprocessing by molten halide salt methods:

- Cs, Sr, I remain in salt
- Np mainly precipitates together with U and Pu
- Am and Cm accompany REE
- Tc is collected as part of noble metals fraction
  (Tc and I can migrate in gas phase during chlorination or fluorination)
**HLW flows after pyrochemical reprocessing**

Dry process → Salt removal → Salts

- **Na₃PO₄**
- Radioactive Cs
- FPs
- **Phosphates** (NdPO₄, CePO₄)
- **NaCl**, **CsCl**

<table>
<thead>
<tr>
<th>Wastes</th>
<th>Phosphates</th>
<th>Spent salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characte-</td>
<td>Phosphates, contained FPs and</td>
<td>Alkali chlorides</td>
</tr>
<tr>
<td>ristics</td>
<td>other impurities</td>
<td>High activity, high heat release</td>
</tr>
<tr>
<td>Basic</td>
<td>11 wt. % Nd,</td>
<td>82 wt. % CsCl</td>
</tr>
<tr>
<td>elements</td>
<td>4.4 wt. % Ce</td>
<td>18 wt. % NaCl</td>
</tr>
<tr>
<td>Expected</td>
<td>78 kg for 800 kg LWR fuel</td>
<td>14 kg for 800 kg LWR fuel</td>
</tr>
<tr>
<td>amount</td>
<td>43 kg for 300 kg FBR fuel</td>
<td>7 kg on 300 kg FBR fuel</td>
</tr>
</tbody>
</table>
## Experience on pyrochemical HLW treatment

### Vitrification of pyrochemical HLW

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Type of HLW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Phosphates</td>
</tr>
<tr>
<td>Glass-matrix</td>
<td>Pb(PO₃)₂, NaPO₃</td>
</tr>
<tr>
<td>Method for vitrification</td>
<td>vitrification, T=950°C</td>
</tr>
<tr>
<td>Amount of wastes in glass, wt.%</td>
<td>28</td>
</tr>
<tr>
<td>Leaching rate of ¹³⁷Cs on 7 day, g/cm² * day</td>
<td>7*10⁻⁶</td>
</tr>
<tr>
<td>Thermal stability, °C</td>
<td>400</td>
</tr>
<tr>
<td>Radiation stability</td>
<td>10⁷ Gr (for γ &amp; β)</td>
</tr>
</tbody>
</table>

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## Experience on pyrochemical HLW treatment

Ceramization of HLW arising from pyrochemical process

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Type of high-level wastes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type of ceramics</td>
</tr>
<tr>
<td></td>
<td>monazite</td>
</tr>
<tr>
<td>Method of introduction into ceramics</td>
<td>100</td>
</tr>
<tr>
<td>Quantity of waste introduced into ceramics, %</td>
<td>100</td>
</tr>
<tr>
<td>Leaching rate of $^{137}$Cs on 7-th day, g/cm² * day</td>
<td>$1*10^{-6}$</td>
</tr>
<tr>
<td>Thermal stability, °C</td>
<td>850</td>
</tr>
<tr>
<td>Radiation resistance</td>
<td>$5*10^8$ Gy (for $\gamma$ and $\beta$)</td>
</tr>
</tbody>
</table>
Other directions for Pyro-process application

Development of closed fuel cycle:
- Fuel cycle for actinide burner reactor – DOVITA
- Nitride fuel recycling for Fast reactors
- Molten salt reactor fuel recycling

Applied directions:
- Weapon plutonium conversion
- U-Al fuel reprocessing
- U-Mo fuel reprocessing
Fuel cycle of actinide burner reactor

DOVITA fuel cycle
Activity on DOVITA Program

- $(U, \text{Np})O_2$ fuel – pyrochemical production, irradiation and PIE (burn-up 12.5% and 20%).
- $UO_2$-20%$PuO_2$-(3-6)%$NpO_2$ fuel – pyrochemical production, irradiation.
- $(U,Pu,Am)O_2$ fuel - pyrochemical production, irradiation.
- Targets with Am for transmutation in the BOR-60 reactor – pyrochemical production, vibropacking, irradiation.
- Pure actinide isotopes irradiation.
- Behavior of Np, Am, Cm in pyrochemical processes.
- Study of Am electrochemistry in molten chlorides.
Micro- and macrostructure of irradiated fuel

\((U,Np)O_2\) \((B=19.7\%)\)

Upper plane

Middle plane
Pyrochemical reprocessing of mixed nitride fuel

- Production of mononitride fuel from BREST reactor spent fuel on pyrochemical reprocessing stage
- Mononitride pellets production
- Manufacturing of fuel pins with Pb-bonding
- Assembling of fuel sub-assemblies for BREST reactor
## Development level for Oxide Fuel Pyro-process recycling technologies

<table>
<thead>
<tr>
<th>Method</th>
<th>Fundamental data</th>
<th>Laboratory testing</th>
<th>Pre-industrial testing</th>
<th>Industrial testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyro-process</td>
<td>available</td>
<td>For fresh and spent fuel</td>
<td>Only with pure MOX</td>
<td>Started for BN-600</td>
</tr>
<tr>
<td>Vibro</td>
<td>available</td>
<td>For fresh and spent fuel</td>
<td>Only with pure MOX</td>
<td>Started for BN-600</td>
</tr>
<tr>
<td>Waste</td>
<td>Studies is continued</td>
<td>Studies is continued</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Remote equipment</td>
<td>Tested at ORYOL Facility for BOR-60 and BN-600</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Since 1981 the BOR-60 reactor has been using vibropacked fuel produced by dry method.

The test facility for closing of the BOR-60 fuel cycle is under design.

BN-600 – 12 fuel assemblies with MOX fuel were irradiated, 3 LTAs are under irradiation.

Semi-industrial facilities are under modernization for future production of 50 BN-600 MOX FAs per year. The re-start of semi-industrial facilities will be in 2005.
Implementation prospects

Pu storage
- (weapon or civil)
- PuO₂ (civil)

Metal Pu
(weapon)

Depleted U
(oxides)

Granulated MOX-fuel

Pyro-process module – MOX production

Module for vibropacking and assembling

BN reactor

Spent FAs

Plant for spent fuel reprocessing (for LWR or other)

PuO₂ reprocessed

Granulated MOX-fuel

Pyro-process module – MOX production

Module for vibropacking and assembling

BN FAs

BN Reactor

Storage of spent VVER, RBMK fuel

Brainstorming plant for closed cycle (pyro-reprocessing and vibro-refabrication)

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Conclusion: ADVANCES IN REPROCESSING OF SPENT FUEL

Pyroprocess for reprocessing of spent fuel and vibropac technology can be used as basis for recycling and production of BN-type MOX fuel in different scenarios of future fuel cycles.
2004 Scientific Forum - Session 2 Summary

The growth of nuclear power, while providing many benefits, has also contributed to an increasing global challenge over safe and secure waste and spent fuel management. Over the past fifty years, the world has come to better understand the strong interplay between all elements of the nuclear fuel cycle, global economics, and global security. The nuclear fuel cycle can no longer be managed as a simple sequence of technological, economic and political challenges. Rather it must be managed as a system of strongly related issues...waste and spent fuel management cannot be relegated to the back-end of the fuel cycle as only a disposal or storage issue. There exists a wealth of success and experience with waste and spent fuel management that can be forged together with a global systems perspective to lay the framework for the future.

The three keynote speakers and four panellists for session 2 (waste and spent fuel management issues) of the 2004 Scientific Forum reviewed related experience to date, including approaches from direct disposal to the closed cycle. Regarding the latter, reprocessing of irradiated power reactor fuel was noted to be a mature, commercially available technology. Experience to date has demonstrated that commercial reprocessing can be compatible with security and non-proliferation requirements. There has also been a continuing reduction in the volume of waste arising from reprocessing. This trend will continue with the implementation of improved technology and operating practices. R&D programmes to study the partitioning and transmutation of environmentally significant radionuclides are being pursued to further enhance the effectiveness of waste minimization programmes.

Regarding direct disposal, session 2 participants described significant progress to date. As described in the Director General’s statement to the 48th session of the General Conference, Finland, the USA, and Sweden have all moved forward with their geologic disposal programmes. The majority of technological issues were noted to have been satisfactorily addressed, but social issues, including public acceptance and political endorsement remain problematic. Participants noted that safe and robust interim storage technologies are available to provide system flexibility while addressing longer term waste and spent fuel management issues.

Issues raised by the audience during the discussion period following the session presentations included the following:

•
Session 3 dealt with several aspects of the research reactor fuel cycle: the development and qualification of high-density LEU fuels as replacements for HEU fuels; utilization; interim spent fuel management; refurbishment; and ultimate decommissioning. Disappointment was expressed that no announcement has been made of the expected extension of the US Acceptance Program for foreign research reactor spent fuel. Utilization as the only good justification for the continued existence of any research reactor was questioned and argued to be insufficient without the approval of stakeholders. Semi-wet or semi-dry extended interim storage was demonstrated as a method, which through fuel encapsulation and return of the packages to the spent fuel pool, can control the corrosion of aluminium-clad spent fuel until such time as it can be returned to its country of origin or sent for ultimate disposition. Refurbishment was presented as a cost-effective method of life extension to enable continued utilization of an aged research reactor compared with the alternative of the construction of a new reactor. Problems of dealing with stakeholders, funding issues and waste management associated with the decommissioning of a low power research reactor were presented and discussed.

It was suggested that new research reactors would be required to investigate and develop the advanced fuel and core materials for many of the proposed innovative power reactor concepts, such as those under discussion in the INPRO and Generation IV programmes. Moreover the controversial assertion was made that some of these research reactors may have to be powered with HEU or plutonium fuels, to investigate the conditions that will prevail in fast reactors.
Important Features of Research
Reactors Fuel Cycle

N. Arkhangelski,
Rosatom, Russian Federation
Important Features of Research Reactors Fuel Cycle

- Using of HEU
- High accessibility of an active core
- Using of many types of fuel including exotic and experimental fuel
- Absence of the self-shielding property
- Location of facilities in large cities
- Insufficient funding of operating and shut down facilities
Refurbishing – A Cost Effective Option for Long Term Operation of Research Reactors

S.K. SHARMA, INDIA
e-mail address : sksharma@aerb.gov.in

In recent times it has been observed that the life time of research reactors can be significantly extended through implementation of appropriate refurbishing actions. This is feasible since the initially proclaimed design life of such facilities in most cases, is an arbitrary number. This aspect is applicable to research reactors, nuclear power plants and many nuclear fuel cycle facilities.

In India extensive refurbishing of the 40 MWt research reactor CIRUS was done during 1997 – 2002. Cirus is a vertical tank type reactor using natural uranium as fuel, light water as coolant, heavy water as moderator and graphite as reflector and became operational in 1960. Detailed ageing assessment of its systems, structures and components was done during 1992-1997 after the reactor had been in operation for about 30 years. The assessment included inspections, operating experience review, review of the Safety Analysis Report, seismic re-evaluation of structures and assessment of stored energy in the graphite reflector. A refurbishing plan was then drawn-up and preparatory work undertaken that included development of procedures, procurement of replacement items etc. The reactor was then shutdown, core unloaded and reactor systems were prepared for preservation during refurbishing. Extensive refurbishing was then carried out and the reactor brought back into operation successfully. During refurbishing, a low temperature vacuum evaporation based desalination unit was also coupled to the reactor to serve as demonstration of using waste heat from a research reactor for sea water desalination.

The scope of refurbishing of Cirus got considerably expanded as a result of identification of additional jobs during further inspections undertaken after reactor shut-down and core unloading. Consequently the refurbishing took about 5 years against the initially planned period of about 3 years. Inspite of this, the facility could be refurbished at a cost which is less than 10% of the cost of building a replacement reactor of similar capabilities. After refurbishment, the reactor is expected to operate with enhanced safety for a period of 20 years or even more. It can therefore be stated that refurbishing, based on Cirus experience, is a cost-effective option for long term operation of a research reactor facility.
REFURBISHING – A COST EFFECTIVE OPTION FOR LONG TERM OPERATION OF RESEARCH REACTORS –
S.K. SHARMA, INDIA

• RR Life Extension Feasible Through Refurbishing
• Initial Proclaimed Design Life – an Arbitrary Number

• Example of CIRUS Ref. In India
  - 40 MWt, Nat. U. fuelled, H₂O cooled, D₂O moderated, graphite reflected vertical tank type reactor
  - In operation since 1960
  - Availability started declining after 1990
  - Detailed ageing studies done.
CIRUS Ageing Studies; 1992-1997

- Detailed Inspection of SSCs
- Optg. Exp. Review
- Review of SAR
- Seismic Re-evaluation of Structures
- Assessment of Stored Energy in Reflector

Refurbishing Plan and Preparatory Work

- Development of Procedures and Special Tools
- Procurement of Replacement Items
- Identification of Work Execution Agencies
- PERT Network
- QA Plan
- Regulatory Review
CIRUS Refurbishing: 1997 – 2002

• Reactor S/D and core unloading
• Further Inspections – Considerable Expansion in Scope of work
• Preservation of Systems during Extended Outage
• Implementation of Ref. Actions
• Systems Commissioning and Testing
• Core loading and Restart
• Integration of a Low Temp. Vac. Evap. Desalination Unit

Conclusion

• Refurb. Took 5 Yrs. (Planned 3 Yrs.)
• Cost; Less than 10% of Replacement Reactor
• Reactor Expected to operate for 20 Yrs. Or even more
• Refurbishing is a Cost Effective Option
Fuel Issues: Replacement of HEU

Dr. Armando Travelli
Manager, RERTR Program

IAEA Scientific Forum
September 22, 2004

Argonne National Laboratory
A U.S. Department of Energy
Office of Science Laboratory
Operated by The University of Chicago
Research and test reactors play a vital role in medical, agricultural, and industrial applications and in fundamental scientific research. However, many of them use fuels or targets containing high-enriched uranium (HEU) that could be used to make nuclear weapons.

Since 1978, when the Reduced Enrichment for Research and Test Reactors (RERTR) program was established, the IAEA, the U.S. Congress and various U.S. Administrations have repeatedly expressed their strong support for converting research reactors to the use of low-enriched uranium (LEU) fuels and targets.

Over 250 research reactors are currently in operation throughout the world. Approximately half of these reactors use HEU fuel.
The RERTR program includes four major tasks:

- Fuel Development
- Mo-99 Target and Process Development
- Reactor Analysis and Conversions
- Support for the Russian RERTR Program
The key to reactor conversions is the development of fuels with greater uranium density, because approximately the same amount of U-235 must be loaded in the reactor core. Since LEU fuels must contain approximately four atoms of U-238 for every atom of U-235, the uranium density in LEU fuels must be significantly greater than in HEU fuels.

Several LEU dispersion fuels, culminating with uranium disilicide dispersion fuels with uranium densities up to 4.8 g/cm³, have been successfully developed and implemented. LEU TRIGA fuels developed by General Atomics with densities up to 3.7 g/cm³ have been demonstrated by the RERTR program.

These fuel types are appropriate for the conversion of approximately 90% of the existing HEU research reactors supplied by the West.
Qualified suppliers of RERTR LEU research reactor fuels have been established in many countries. Thousands of LEU elements of the types developed by the RERTR program have been fabricated and successfully used in new or converted reactors.

**Actively Fabricating:**
- CNEA, Argentina
  - (U$_3$O$_8$-Al)
- CRL, Canada
  - (U$_3$Si-Al)
- CERCA, France
  - (U$_3$Si$_2$-Al, UZrH$_x$)
- BATAN, Indonesia
  - (U$_3$O$_8$-Al, U$_3$Si$_2$-Al)
- BWXT, United States
  - (UAI$_x$-Al, U$_3$O$_8$-Al, U$_3$Si$_2$-Al)

**Developing Capability:**
- IPEN, Brazil
  - (U$_3$O$_8$-Al)
- CCHEN, Chile
  - (U$_3$Si$_2$-Al)
- KAERI, South Korea
  - (U$_3$Si-Al)
Work is now in progress on LEU U-Mo materials, both in dispersion fuels (up to a uranium density of ~8 g/cm³) and monolithic fuels (up to a uranium density of ~16 g/cm³).

Approximately 150 samples of many variations of these fuels have been irradiated in the Advanced Test Reactor (ATR), in Idaho. Initial results have been very encouraging for both fuel types.

Recent irradiation tests on full-size plates/tubes by parallel French and Russian programs have revealed unexpected problems with the matrix of the dispersion fuel.

We are now concentrating our efforts on identifying and eliminating the problem with dispersion U-Mo fuel, while accelerating development of monolithic U-Mo fuel.
Samples of very high density U-Mo dispersion fuel are irradiated in the Advanced Test Reactor (ATR). Test results show the fuel behaved very well under irradiation.
Microstructure at center of fuel meat revealed excellent irradiation behavior of U-Mo dispersion fuel under irradiation conditions.
Interaction zone of a monolithic LEU U-Mo plate at 80% burnup
FISSION $^{99}\text{Mo}$ FROM LEU TARGETS

- An analytical/experimental program is in progress to determine the feasibility of using LEU instead of HEU in fission targets dedicated to the production of $^{99}\text{Mo}$ for medical applications.

- RERTR tests for an acidic process at BATAN (Indonesia) have been successful. A final demonstration of the system had to be postponed because of the 9/11 attacks.

- Cooperation with the CNEA (Argentina) is very active and has led to the successful implementation of a basic process applied to LEU targets.

- Cooperation with ANSTO (Australia) aims at the establishment of a successful acidic process based on the use of LEU targets.

- Cooperation with MDS Nordion (Canada) and its affiliates at AECL (Canada) and SGN (France) is centered on the development of a waste conditioning process compatible with the MDS Nordion process.
REACTOR ANALYSIS

◦ Methods and computer codes were developed or adapted for

  Neutronics,
  Fuel Cycle,
  Thermal-hydraulics,
  Transient Analysis, and
  Radiological Consequences

◦ Many generic and specific analyses have demonstrated the validity of these methods. The results were published in three IAEA Guidebooks:

  TECDOC-233 for H₂O-moderated reactors,
  TECDOC-324 for D₂O-moderated reactors, and
  TECDOC-643 for safety and licensing.

◦ The program’s computational and design capabilities for LEU reactors have created a standard which is internationally recognized and unsurpassed.
## CONVERSION PROGRESS

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<td>La Reina</td>
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<td>10 KW</td>
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<td>1988</td>
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</tbody>
</table>

* Conversion in progress
** Shut down after conversion
NEW RESEARCH REACTORS
USE LEU FUELS

With one single exception, all research reactors built by Western countries since 1978 with power of at least 1 MW have been designed for LEU cores.

- **Operational:**
  - Algeria (NUR, 1 MW)
  - Bangladesh (TRIGA, 3 MW)
  - Egypt (ETRR-2, 22MW)
  - Indonesia (RSG-GAS, 30MW)
  - Japan (JRR-3, 20 MW)
  - Korea, South (HANARO, 30 MW)
  - Malaysia (TRIGA Mark II, 1 MW)
  - Peru (RP-10, 10 MW)
  - U.S. (McClellan, 2MW)
  - U.S. (U. of Texas, 1MW)

- **Under design or construction:**
  - Australia (RR, 20 MW)
  - Canada (Maple-1, 10 MW)
  - Canada (Maple-2, 10 MW)
  - Canada (IRF, 20 MW)
  - France (RJH, 100 MW)
  - Morocco (MA-R1, 2 MW)
  - Thailand (MPR-10, 10 MW)

- **Cancelled after design:**
  - Taiwan (TRR-II, 20 MW)

The FRM-II (20MW), in Germany, is the only exception to this international norm.
THE RUSSIAN RERTR PROGRAM

- Twenty-eight Russian-supplied research reactors (14 in Russia and 14 exported) are fueled with HEU and are included in the RERTR program.

- Cooperation between the US RERTR program and the corresponding Russian program began in 1996. The major participating Russian institutes include RDIPE, VNIINM, NZChK, RRC "KI", RIAR, PNPI, and IRM.

- Five LEU WWR UO$_2$-Al tube-type fuel elements, suitable for conversion of reactors in Hungary, Ukraine, Vietnam, and Germany have been successfully irradiated to more than 70% burnup at PNPI (St. Petersburg).

- Pin-type LEU U-Mo dispersion fuel elements intended for conversion of WWR, IRT, and MR research reactors have been fabricated by VNIINM and are being irradiation tested at RIAR and PNPI.

- Tube-type U-Mo dispersion fuel elements have been fabricated by NZChK using Russian funds. These elements were tested successfully at IRM up to 40% equivalent burnup, but failed at 60% equivalent burnup.

- Joint reactor analyses and evaluations have been performed for many Russian-designed research reactors.
On May 26, 2004, U.S. Energy Secretary Abraham announced at the IAEA a new important initiative, the Global Threat Reduction Initiative (GTRI), to which $450 million will be assigned over 9 years.

GTRI aims to secure, remove, or dispose of, nuclear and other radioactive materials throughout the world that are vulnerable to theft by terrorists.

In addition to the RERTR program, GTRI includes the Foreign Research Reactor Spent Fuel Return Acceptance (FRRSNFA) program, the Russian Research Reactor Fuel Return (RRRFR) program, and the Radiological Threat Reduction (RTR) program.

In his speech, Secretary Abraham asked for cooperation from all countries, besides the U.S. and Russia, where these dangerous materials are located or from which they have originated.
# Conversion Status of HEU Research Reactors

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## Conversion Status of HEU Research Reactors (detail)

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</table>

### Notes
- **SUM** represents the total number of reactors converted, convertible, or not yet convertible.
ACCELERATED CONVERSION PLANS

The RERTR program plans to address the accelerated reactor conversions required by GTRI by:

- Qualifying both monolithic and dispersion LEU U-Mo plate-type fuels by 2010. Monolithic fuel, with a uranium density close to 16 g/cm³, can be used to convert all the ten research reactors that cannot use existing LEU fuels in the U.S. and Europe. Dispersion fuel can facilitate fuel disposal by reactors not requiring monolithic fuel.

- Assisting in the parallel development of LEU pin-type and tube-type fuel assemblies appropriate for use in Russian-designed reactors. The fuel elements contained in these assemblies may contain UO₂-Al or UMo-Al dispersions, or monolithic UMo.

- Procuring and irradiation testing LEU prototype fuel assemblies to facilitate their qualification.

- Engaging with all remaining reactors in the feasibility studies, tests, and safety documentation needed for their conversion decisions.

- Coordinating with other GTRI components to accelerate conversions.
SUMMARY AND CONCLUSION

◆ The RERTR Program has been very successful and has achieved many of its original goals. Thirty-eight reactors operating in 19 countries have been converted to the use of LEU. More reactors are in the process of converting.

◆ The most significant technical events of the past year concern the successful testing of monolithic LEU U-Mo fuel samples in the ATR, and the unexpected failures of full-size fuel plates/tubes of LEU U-Mo dispersion fuel in European and Russian reactors. Corrective actions are in progress.

◆ The events of September 11 and the new GTRI initiative require a special effort to eliminate HEU traffic and to conclude the conversion effort in the shortest possible time. The RERTR program plans to achieve this goal during the next nine years, in close collaboration with other GTRI programs, so that all HEU materials used in research reactors can be returned to their country of origin or properly secured in place.
Research Reactor Utilisation: A Justification for Existence?

CSB Piani

IAEA Scientific Forum (21-22 September 2004 Vienna)
If I can say:

“I have a Research Reactor able to provide Medical Isotopes, and have In-core Irradiation and Material Testing Rigs and Beam Port facilities for educational and R&D opportunities, etc…”

Is my Research Reactor justified?
ANSWER

“Your existence is only justified if your Stakeholders say so!”

Stakeholders:

“Person(s) and/or Institution(s) that have a direct or indirect interest or involvement in the operation of the facility”.
TYPICAL STAKEHOLDERS

- Government
- Upper Management
- Academic Institutions
- Commercial and Industrial Clients
- Regulatory Body
- Personnel
- Public
- IAEA....
10 POINT EVALUATION

JUSTIFICATION FOR SUSTAINED OPERATION

1. OPERATIONAL ABILITY (Technical Resources / Funding)
2. SAFETY
3. COMMERCIAL
4. INSTITUTIONAL
5. RERTR
6. SECURITY (Physical Protection)
7. ENVIRONMENTAL RESPONSIBILITY
8. WASTE (Back end Storage / Disposal)
9. REFURBISHMENT (Life Extension)
10. D & D Liability.

IAEA Scientific Forum (21-22 September 2004 Vienna)
OPERATIONAL ABILITY

• TECHNICAL RESOURCES
  • Personnel
  • Equipment
  • Support services

• FINANCIAL RESOURCES
  • Funds For Operation
    • Stakeholder provision / subsidy
    • Self sustaining.
SAFETY

• NUCLEAR SAFETY
  • Regulatory Control (Operational/Radiological)
  • Safety Analysis Report
  • PRA

• CONVENTIONAL SAFETY
  • Occupational Safety Acts
  • Industrial Safety (Design, etc.).
COMMERCIAL

• ISOTOPE MANUFACTURE
  • Supporting Processing Facilities
  • Marketability
  • Profitable

• IRRADIATION SERVICES
  • Target Irradiation
  • Materials Testing.
INSTITUTIONAL

• ACADEMIC RESPONSIBILITY
  • Educational - Tertiary
  • Post Graduate Research

• GOVERNMENTAL / INDUSTRIAL
  • Assistance Programs
  • Beneficial R&D.
RERTR

• U ENRICHMENT (HEU....LEU)
  • Fuel & Control Rods
  • Targets
  • Flux and operational impacts

• OPPORTUNITIES TO CONVERT
  • IAEA
  • ANL.
SECURITY (Physical Protection)

• THEFT:
  - U Materials (Proliferation)
  - Irradiated Materials (Dirty Bombs!)

• SABOTAGE:
  - Environmental Impact
  - Continuity of Operation.
ENVIRONMENTAL RESPONSIBILITY

- **CLEAN OPERATION**
  - Gaseous Discharge
  - Liquid Effluent
  - Solid Waste control

- **PUBLIC ACCEPTANCE**
  - Media Cooperation
  - ISO 14001.
WASTE
(Backend - Storage / Disposal)

• SPENT FUEL STORAGE
  • Spent fuel pool
  • Dry storage (cask /pipe)

• DISPOSAL ABILITY
  • US Take back program
  • Processing to LLW
  • National / Regional Depository.
REFURBISHMENT (Life Extension)

• MAINTENANCE (Continuous)
  • Nuclear Instrumentation
  • Mechanical Plant
  • Electrical Plant

• IN-SERVICE-INSPECTION
  • Vessel
  • Core Components / etc.
D & D Liability

• DECOMMISSIONING PLAN (REGULATORY)
  • Entombment (Not encouraged by IAEA)
  • Long Term Storage (Deferment)
  • Immediate Dismantling

• DECOMMISSIONING LIABILITY
  • Main Stakeholder (Government)
  • Financial and Regulatory Responsibilities.
What Now?

• If any of the responses to these 10 evaluations are negative – then the points should be addressed by means of Specific Objectives / Action Plans in your Strategic Planning process

• If negatives are not addressed – then the justification of existence of your RR could become questionable!
STRATEGIC PLANNING

- IAEA-TECDOC-1212:
  Strategic Planning for Research Reactors

- IAEA-TECDOC-1234:
  The Application of Research Reactors

- IAEA-Safety Series 35-G1:
  Safety Assessment of Research Reactors and Preparation of the Safety Analysis Report

- IAEA-INFCIRC/225:
  Physical Protection of Nuclear Material.
Summary (1)

• It's no longer sufficient to have an operational, well utilised RR....
• In fact it's not enough to also have a safe RR....
• You also need to ensure Compliance with:
  • RERTR needs
  • Physical Security
  • Backend disposal ability
  • Environmental acceptance
  • Life time maintenance ability
  • D&D Liability.
Summary (2)

• Justification of Sustained Operation - 10 Point Evaluation
• Select Requirements needed to Satisfy Stakeholders according to national / individual standards
• Apply Strategic Planning to focus on requirements
• Make use of IAEA (and other) assistance available.
Spent Fuel Management: Semi-dry storage

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IAEA Scientific Forum
20-22 September 2004
Vienna, Austria
Topics

• NSF’s storage practices and problems
• Introduction to the canning technology and equipment
• Canning in practice – movie clips
• Canning results at BRR
• Conclusions
Way to the canning

- **The storage practice**
  - Temporary storage (AR pool → decay+emergency, AFR pool → long time)
  - Wet storage technology (stored under water)

- **The problem → originated from long term wet storage**
  - Wet storage can be intermediate only (oldest for 40 years)
  - Transport: no decision no date (to ship final deposit place)
  - Signs of corrosion appeared

- **What to do? → Decreasing the corrosion process**
  - Change the storage mode from WET to SEMI-WET

- **The Solution → Canning**
  - Technology: encapsulation
    → Placing NSF into a tube, → drying, vacuuming, → filling up with inert gas, → hermetrical closing of this package
  - Requirements:
    - Ensure +50 years intermediate storage
    - Provide solution for both fuel types
    - Ensure easy monitoring after canning
    - Leave open all ways for final solution
3D-drawings of Canning Tube

Canning Construction
- Tube construction
- Al-alloy
- Thickness: 3 mm
- Length: 939 mm
- Diameter: Ø 100 mm

- Tube head
- Tube body
- EK-10 fuel
- Bottom weight
- VVR fuel
The Canning Equipment

- **Design philosophy:**
  - Easy handling – fuel manipulation before and after canning only → *compact container*
  - Closed technology → *PLC control*
  - Defective canning tube handling → *cropping machine*
  - Leave open all way for final solution → *shipment as package or unpacking*

- **Construction:** compact and mobile construction

1. **Canning Unit**
   - Canning Cask
     - Rotating Head
     - Cask Body
     - Transfer Pipe
   - Assembly Trolley
   - Control Unit
   - Power Supply
     - Electrical with UPS
     - Compressed Air
     - Nitrogen Supply System

2. **Cropping Machine**
   - Driving Unit
   - Cropping Container
     - Single-fuel nest
     - Triple-fuel nest
     - Tube Body nest
New ideas
1. Sucking up
2. Heating
3. Rotating head (compact container)
4. Welding under pressurized air (vacuum-tight sealing in the operation chamber of the container)
Canning cask
(assembling phase)

Membrane pump →

Rotating head →

Cask body →
(round shaped steel structure)

Stepping motors (3 items)

Transfer pipe driver
Canning cask
(assembling phase)

Cask body →

Transfer pipe (fix pipe section) →

Transfer pipe (movable pipe section) →
Canning container
(on its operation place)

Rotating head →
Welding unit →
Transfer pipe driver →

Cask body ←
Stepping motors ←
Cropping machine ←
Cropping machine

- Transmission bar
- Cropping container
- Single-fuel nest
- Triple-fuel nest
- Circular saw-disc
- Tube body nest
# Canning procedure

<table>
<thead>
<tr>
<th>Work phases</th>
<th>Activity</th>
<th>Time</th>
<th>Op.M.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prep. phase</td>
<td>NSF’s leg-cutting, capsule &amp; NSF are placed in the reception seat</td>
<td>≈ 20 min.</td>
<td>Manual op.</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; op. phase</td>
<td>float up the capsule with intensive water flow</td>
<td>≈ 3 min.</td>
<td>AUT op.</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt; op. phase</td>
<td>removing the water from the capsule</td>
<td>≈ 5 min.</td>
<td>Closed technology chain</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt; op. phase</td>
<td>drying and maintaining a given heat</td>
<td>≈ 70 min.</td>
<td></td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt; op. phase</td>
<td>vacuuming, filling up with nitrogen, and pressing in the capsule head</td>
<td>≈ 8 min.</td>
<td></td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt; op. phase</td>
<td>capsule head is secured by welding</td>
<td>≈ 4 min.</td>
<td></td>
</tr>
<tr>
<td>Control phase</td>
<td>welded seam inspected by CCTV, underwater observation (bubble test)</td>
<td>≈ 5 min.</td>
<td>Manual op.</td>
</tr>
<tr>
<td>Closing phase</td>
<td>✓ placing to its designated position X opening by cropping machine</td>
<td>≈ 5 min.</td>
<td></td>
</tr>
</tbody>
</table>

**TOTAL CYCLE TIME**  ≈ 120 min.
Canning mosaics

- Movie clips

From preparation phases
1. NSF assembly preparation – leg-cutting process (1:17)
2. Capsule preparation (1:04)

From operation phases
3. 1st phase: Float-up phase (0:18)
4. 2nd phase: Removing the water from the capsule (0:40)
5. 5th: Welding and control phase (0:58)
6. Float back of the package (0:27)

From closing phase
7. Deposition of the flawless package – 0:56)

Handling the defective closed capsule
8. Bubble test and cutting off (2:23)
NSF assembly preparation - leg-cutting process (1:17)
Capsule preparation (1:04)
1st phase: Float-up phase (0:18)
2nd phase: Removing the water from the capsule (0:40)
3rd and 4th phases

- Sorry, no movie clips 😞

Canning steps are carried out in the operation chamber (no observable)

3rd operation phase:
Drying and maintaining on a given heat
- Eddy current heating (48 VAC, 4.5 kVA)
- Warming up and min. 40 minutes maintaining on heat (130 °C)
- Total phase time: ≈ 70 minutes

4th operation phase:
Vacuuming, filling up with N₂ and pressing in the capsule head
- Vacuuming < 50 mbar
- Nitrogen: dry nitrogen (N₂ > 99.9999 %; H₂O < 5 ppm), overpressure: 2.5 bar

Steps: vacuuming (3 min.) → filling up with N₂ (1 min.) → vacuuming (3 min.) → filling up with N₂ (1 min.) → pressing in the capsule head (50 ms) → equal-warming (3 s, shrink fitting)
- Total phase time: ≈ 8 minutes
5th Welding and control phase (0:58)
Float back of the package (0:27)
Deposition of the flawless package (0:56)
Handling the defective closed NSF

- Un-pressed tube head
- Over-pressed tube head
- Defective welded NSF (extreme cases)

Defective canned NSF

KFKI Atomic Energy Research Institute, Budapest, HUNGARY
Bubble test and cutting off (2:23)
Canning record

\[ \Sigma = 342 \text{ cans} \checkmark \]
\[ \Sigma = 89 \text{ cans} \]

Monthly cans [items/month]

Validation period

Months of canning

Flawless  Defective
Q-factor

Accumulated flawless cans [%]

Validation period

100 % = 342 cans

Months of canning

Q-factor [%]

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

## Performance indicator

<table>
<thead>
<tr>
<th>NSF assembly</th>
<th>Quantity to be canned</th>
<th>Required encapsulation</th>
<th>Completed</th>
<th>Defective closed</th>
</tr>
</thead>
<tbody>
<tr>
<td>EK-10</td>
<td>82</td>
<td>82</td>
<td>82✓</td>
<td>66</td>
</tr>
<tr>
<td>VVR single</td>
<td>228</td>
<td>76</td>
<td>76✓</td>
<td>9</td>
</tr>
<tr>
<td>VVR triple</td>
<td>184</td>
<td>184</td>
<td>184✓</td>
<td>14</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>342</strong></td>
<td><strong>342✓</strong></td>
<td></td>
<td><strong>89</strong></td>
</tr>
</tbody>
</table>
How further?

**Status:** Phase 1 has completed. ✓
(encrypt all NSF irradiated before 1986)

1. **Closing activities:**
   - Conservation maintenance \(\rightarrow\) *Put it in stand by*;
   - Summary of the experiences \(\rightarrow\) *Closing report*.

2. **No decision to start Phase 2**
   It will be a periodic canning by 3-5 years \(\rightarrow\) depends on final solution.

3. **It is offered to fulfill any canning demand.**

**Improvement and upgrading (??):**
- No decision;
- Depends on outer demands and/or requirements.
Conclusions

- Technology and canning equipment are validated.
- Compact and closed technology that ensures safe reliable and effective encapsulation (demonstrated by 342 encapsulations).
- Cropping machine makes the technology complete (handling the defective canned packages).
- The canned storage technology leaves open all ways for a final solution.
- Human factor (3 operators form an optimum team).
- The experience demonstrates that the equipment provides a proper solution to the spent fuel storage problems of other research and training reactors (transportability, no contamination).
Thanks for your attention!
RESEARCH REACTOR DECOMMISSIONING

• ~ 800 constructed worldwide to date

• ~ 50% shut down
  • Due to design life, strategic, economic or regulatory considerations
  • Various stages of decommissioning

• ~ 50% Operational.
  • 27% of these are over 40 years old
DECOMMISSIONING?

• Staged process through which a nuclear facility, which has ceased normal operations, is taken out of service, including full or partial dismantling of buildings and contents’.

• It may include other operations such as the decontamination of buildings which are not to be dismantled and the remedial treatment or restoration of the land under and around the facility.

• Progressively removing the hazard the facility poses giving due regard to security, safety and protecting the environment.
DECOMMISSIONING?

- Reduce regulatory control

- Case by case basis
  - May be appropriate to delay decommissioning to take benefit from developing technologies and radioactive decay

- As soon as reasonable practicable taking into account all relevant factors as provided for in the relevant operator’s decommissioning Strategy and the Decommissioning Plan
DECOMMISSIONING PLAN

STRATEGIC ISSUES

- Waste Management
- Environmental impact
- Public safety
- Worker safety
- Site security
- Site stewardship
- Funding
- Cost effectiveness
- Skills/knowledge base
- Best practice
- Research/technology
- Stakeholders
DECOMMISSIONING PLAN

STRATEGIC ISSUES

- Waste Management
- Environmental impact
- Public safety
- Worker safety
- Site security
- Site stewardship

- Funding
- Cost effectiveness
- Skills/knowledge base
- Best practice
- Research/technology
- Stakeholders
FUNDING

• Cost Estimates
  – Benchmarking
  – Databases
  – Sharing experience

• Source
  – Owner/operator
  – Government

• Provision
  – Segregated
  – Fund
  – Account
WASTE

• Classification
  • High, Intermediate, Low/Very Low

• Minimisation
  • Delay/decay

• Storage
  • Local/national

• Clearance levels
  • Removal from regulatory control
STAKEHOLDER DIALOGUE

• Facilitates ‘Stepwise’ decision making process:
  – Meaningful involvement in planning process
  – Public reassurance
  – Higher levels of:
    • openness
    • transparency
    • reversibility

• Influences strategy

• Opposite to ‘Decide, Announce and Defend’
STAKEHOLDERS

• Comprehensive and diverse range required

• Operators and license holders

• Government Organisations:
  • Government Departments, Regulators and Environment Agencies
  • Regional and Local Government

• Non-Government organisations:
  • Trades Unions and Professional Bodies
  • General Public and Focus Groups
  • Anti-Nuclear Groups
Example

- UK BNFL Magnox Decommissioning Dialogue
- Independently facilitated by the UK Environment Council
  - Registered charity

- Regular meetings
  - Main Group, Coordination Group, Working Groups
  - Strategic Action Planning Group
  - Ground rules
  - Records
  - Expert advice

- Dialogue funded by BNFL
  - Travel and subsistence
  - Payments for NGO focus group attendance
    - Attendance time
    - Report writing
Summary

• Early and agreed strategy required covering all aspects of decommissioning, including funding, waste management and stakeholder dialogue.

• Whilst waste management is probably the most technically difficult issue, everything depends on adequate funding.

• Stakeholder dialogue becoming increasingly more important

• A Comprehensive Decommissioning Plan is required that encompasses the agreed strategy

• *Failing to plan = planning to fail!*