DE LA RECHERCHE À L'INDUSTRIE

Seminar on Coolants for Fast Neutron Reactors

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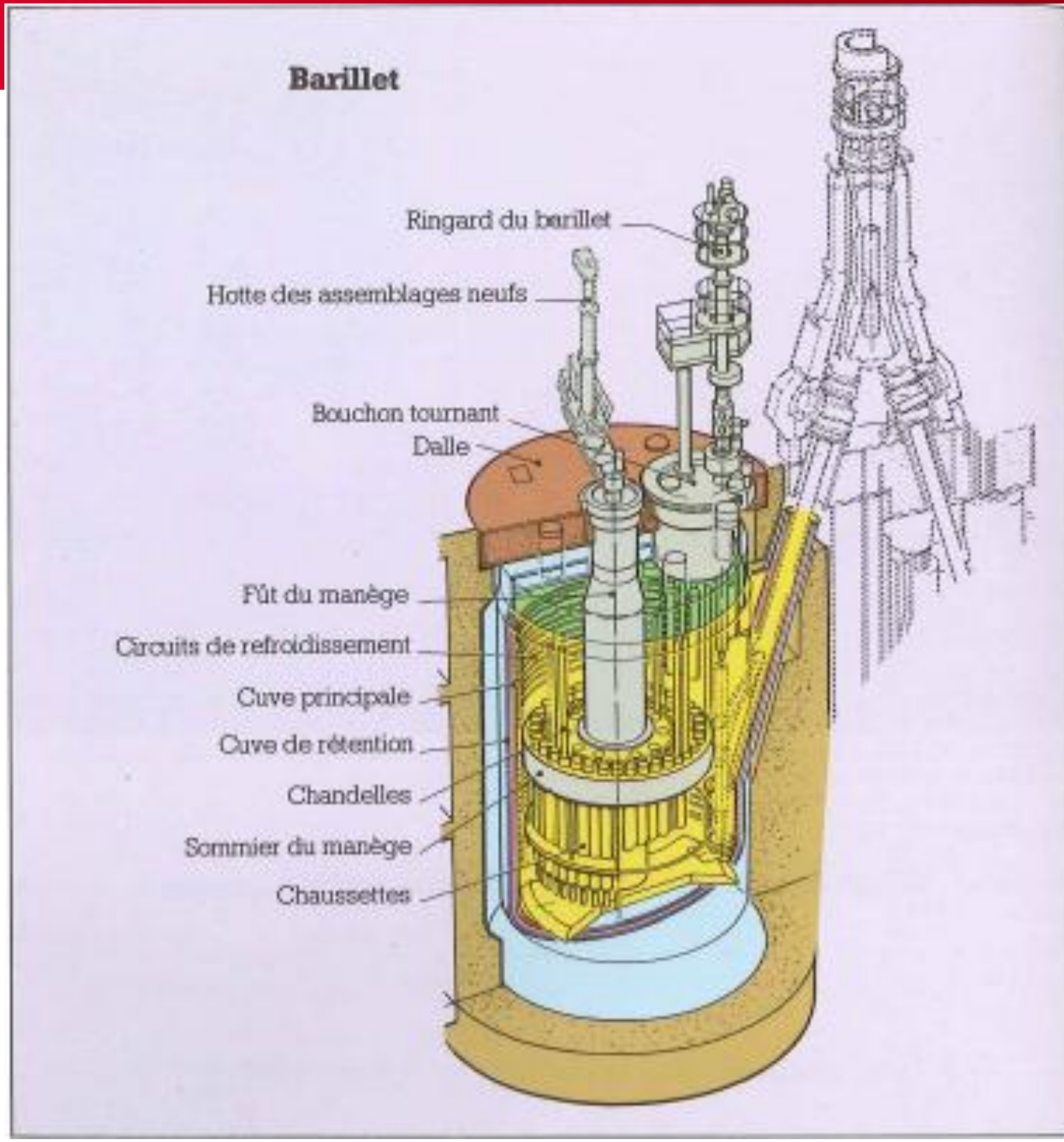
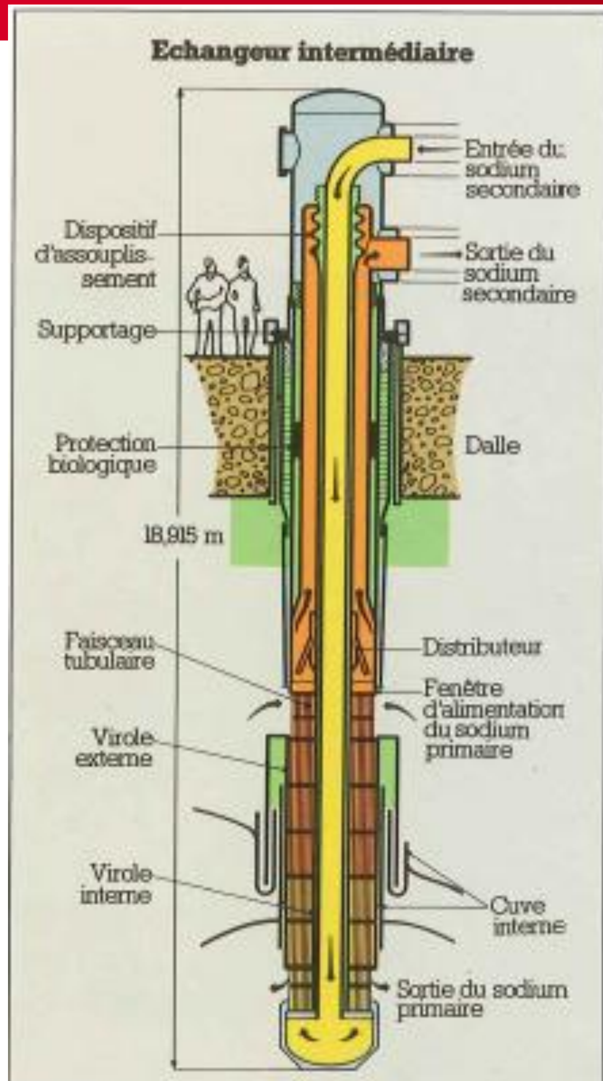

Barillet
Ringard du barillet
Hotte des assemblages neufs
Bouchon tournant
Dalle
Fût du manège
Circuits de refroidissement
Cuve principale
Cuve de rétention
Chandelles
Sommier du manège
Chaussettes


Echangeur intermédiaire
Entrée du sodium secondaire
Sortie du sodium secondaire
Dispositif d'assouplis-sement
Supportage
Protection biologique
Dalle
18,915 m
Faisceau tubulaire
Distributeur
Fenêtre d'alimentation du sodium primaire
Virole externe
Virole interne
Cuve interne
Sortie du sodium primaire

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Maturity of Fast Reactor Types

Sodium fast reactor

- **~400 reactor.year of operating experience**
- **+ specific requirements to be Gen-IV relevant**

Design features	R&D
Core designed for low coolant void reactivity effect	Heterogeneous fertile/fissile fuel Low swelling cladding steel (AFMA, ODS…) Detection of gas bubbles
Practical elimination of core compaction & prompt criticality	Core design specific provisions Understanding of Phenix negative reactivity events
Reliable operation + 60 y lifetime High availability factor	Improved (dpa, HT) resistant structural materials Master corrosion *(even hidden under thermal insulators), Mastering stress corrosion cracking of steels* Short fuel handling outage, reliable equipment
Flexible actinide management (+ Breeding?) High fuel burnup / Long fuel irradiation campaign	Minor Actinide bearing fuels High fuel burnup
Power conversion system with steam Elimination of big sodium fire, big sodium-water reactions and big sodium-water- air reactions	Robust steam generator design Fast detection of sodium/water interaction Specific Na issues
Power conversion system with gas turbine	Compact sodium/gas & gas/gas HX Helium technology, Test benches, System loop ? Management of IHX failure

Maturity of Fast Reactor Types

Design features	R&D
Severe accident mitigation	Advanced core catcher design & materials Sacrificial materials for core catcher
Protection against large airplane crash Earthquake, flooding…	Specific design features
Efficient & Reliable decay heat removal	Avoid risks of coolant freezing Diversification Active/Passive
Extended surveillance/monitoring/safeguards	Innovative instrumentation *(optical fibers, LIBS, in core FC, US thermometers…)* + post accident instrumentation
Clean primary cooling system	Mitigation of sodium activation (^{24}Na, ^{22}Na) Efficient purification and purity control / Instrumentation
In service inspection & Repair	Instrumentation (US, Xtomography…) Under sodium imaging
Improved cladding failure detection	Innovative fuel cladding failure detection
Improved prevention, detection & repair of coolant leaks	Innovative sodium leak detection Mastering sodium fires & Sodium aerosols hazards
Simplification of spent fuel handling process	Novel spent nuclear fuel fuel handling process
Dismantling: minimization of waste, dose to workers…	Advanced dismantling techniques Disposal for waste generated

Maturity of Fast Reactor Types

Lead Fast Reactor

- **~70 reactor.year of operating experience for naval applications**
- **SVBR 75/100 & BREST-300 projects in Russia**
- **+ specific requirements to be Gen-IV relevant**

Design features	R&D
Core designed for low coolant void reactivity effect	Less an issue than for SFR
Compact design for accomodating extreme weight	In vessel steam generator Provisions for resisting seismic events, sloshing…
Practical elimination of core compaction & prompt criticality	Core design specific provisions Specific R&D on severe accidents with HLM R&D & simulation of core relocation Reliable control rod shutdown *(Archimedes?)*
Reliable operation + 60 y lifetime High availability factor	Improved structural materials / Mastering corrosion Managing LM embrittlement + synergetic effects w. irradiation Control of oxygen potential / oxide film at interface Thermal management of lead Short fuel handling outage, reliable equipment Mastering erosion on pumps
Flexible actinide management (+ Breeding?) High fuel burnup	Minor Actinide bearing fuels Nitride fuel ?
Power conversion system with steam turbine	Robust steam generator design Fast detection of lead/water interaction Specific Pb or LBE issues

Maturity of Fast Reactor Types

Lead Fast Reactor *(cont'd)*

- **Specific requirements to be Gen-IV relevant**

Design features	R&D
Severe accident mitigation	Advanced core catcher design & materials Specific severe accident management scenarios
Protection against large airplane crash Earthquake, flooding…	Specific design features
Efficient & Reliable decay heat removal	Avoid risks of coolant freezing Diversification Active/Passive
Extended surveillance/monitoring/safeguards	Innovative instrumentation *(optical fibers, LIBS, in core FC…)* + post accident instrumentation
Clean primary cooling system	Efficient purification and purity control (^{210}Po, H_2…)
In service inspection & Repair	Instrumentation (US, Xtomography…) Under lead imaging
Improved cladding failure detection	Innovative fuel cladding failure detection
Improved prevention, detection and repair of coolant leaks	Innovative lead & LBE leak detection
Simplification of spent fuel handling process	Novel spent nuclear fuel fuel handling process
Dismantling: minimization of waste, dose to workers…	Advanced dismantling techniques Disposal for waste generated

Maturity of Fast Reactor Types

Molten Salt Reactor *(MSFR)*

- **Operation of MSRE**
- **+ specific requirements to be Gen-IV relevant** *(Fast neutrons…)*

Design features	R&D
Optimisation for achieving effective breeding with UTh fuel cycle	Optimisation of salt composition and core design Start of reactor operation with initial ^{233}U load ?
Management of salt Purification of salt from FP & Tritium	Reliable mastery of redox potential in « cold » and « hot » zones at the same time Salt reprocessing processes Novel processes (He bubbling..) Management of FP & Tritium
Reliable operation + 60 y lifetime High availability factor	Improved structural materials / Master corrosion + *Te-induced corrosion* Reliable equipment
Heat exchangers (MS/gas, MS/water…)	Materials, technology, manufacturing, inspection…
Flexible actinide management ??	Control of molten salt composition
Power conversion system with steam turbine	Robust steam generator design Detection of salt/water interaction

Maturity of Fast Reactor Types

Molten Salt Reactor *(MSFR)* ***(cont'd)***

- **Specific requirements to be Gen-IV relevant**

Design features	R&D
Severe accident mitigation	Reference severe accident (bounding event TBD)
Protection against large airplane crash Earthquake, flooding…	Specific design features
Efficient & Reliable decay heat removal	Molten salt draining Avoid risks of salt freezing Diversification Active/Passive
Extended surveillance/monitoring/safeguards	Innovative instrumentation *(optical fibers, LIBS, in core FC…)* + post accident instrumentation
Clean primary cooling system	Efficient purification and purity control
In service inspection & Repair	Instrumentation & Equipment
Coolant leaks: early detection, quick localisation & repair	Innovative sodium leak detection
Dismantling: minimization of waste, dose to workers…	Advanced dismantling techniques Disposal for waste generated

Maturity of Fast Reactor Types

Gas fast reactor

- A new concept of Gas-cooled Fast Reactor (> GBR, GCFR)
- Experience of HTR operation and technology

Design features	R&D
Core designed for a safe management of cooling accidents	Robust fuel / Integrity up to 1600°C)? UPuC fuel & SiC cladding Prestressed primary pressure boundary ?
Practical elimination of core compaction & prompt criticality	Core design specific provisions Phenomenology of SiC in case of severe accident
Reliable operation, 60 y lifetime, high availability factor	Improved (dpa, HT) resistant structural materials Master corrosion by impurities in helium
Safe management of cooling accidents Efficient & Reliable decay heat removal	Redundant and diversified safety systems (natural convection, accumulators…), active/passive
Flexible actinide management (+ Breeding?) High fuel burnup	Minor Actinide bearing fuels
Power conversion system with steam	Robust steam generator design
Power conversion system with gas turbine	Compact gas/gas HX Helium technology, Test benches, System loop ? IHX technology, fabrication, inspection… Management of IHX failure

Maturity of Fast Reactor Types

Gas Fast Reactor *(cont'd)*

- **Specific requirements to be Gen-IV relevant**

Design features	R&D
Severe accident mitigation	Advanced core catcher design & materials Phenomenology of SiC/UPuC fuel degradation
Protection against large airplane crash Earthquake, flooding…	Specific design features
Extended surveillance/monitoring/safeguards	Innovative instrumentation *(optical fibers, LIBS, in core FC…)* + post accident instrumentation
Clean primary cooling system	Efficient purification and purity control Instrumentation
In service inspection & Repair	Instrumentation & Specific provisions
Improved cladding failure detection	Innovative fuel cladding failure detection
Improved prevention, detection and repair of coolant leaks	Innovative leak detection (leak before break)
Simplification of spent fuel handling process	Novel spent nuclear fuel fuel handling process
Dismantling: minimization of waste, dose to workers…	Advanced dismantling techniques Disposal for waste generated

Key Questions on Coolants for Fast Reactors

- **Sodium Fast reactor**
  - **- Frequency of nuclear fuel reloading**
  - **- In service inspection & repair**
  - **- Compatibility of sodium with materials**
  - **- Behaviour od structures** *(vibrations, stability,thermal gradients…)*
  - **- Prevention, detection & repair of sodium leaks**

- **Unit size?**

- **Power conversion systems?**

- **Tightness of pumps, valves & other components?**

- **Behaviour of welds** *(irradiation, corrosion…)***?**

Need for Science-driven Innovations & Technology Breakthroughs

Gen-IV Goals for Fast Neutron Reactors

- **Enhanced safety goals derived from strengthened requirements for Gen-III LWRs and lessons from Fukushima accident**
  + Need for robust safety demonstration *(margin, cliff-edge effects…)*
  - *Better prevention, control and mitigation of severe accidents*

    → *Improved reactivity control: low **coolant** void reactivity effect core design…*

    → *Risk preclusion /minimisation of large chemical accident (reactions between **coolant**/ turbine working fluid, **coolant**/air/water…)*
  - *Improved decay heat removal with redundent active & passive **cooling** systems*
- **Improved economic competitiveness & Operability** */ other power plants*
  - *Improved in-service inspection & repair technologies (instrumentation...)*
  - *Minimisation of **coolant** leaks & reaction with other plant working fluids*
  - *Improved compatibility of nuclear fuel with **coolant** & cladding failure detection*
  - *Modular design of **cooling** systems & components*
- **Improved security**
  - *Enhanced physical protection*
  - *Enhanced safeguards & intrinsic non-proliferation features in nuclear fuel cycle*

Candidate Coolants & Fast Reactor Types

Visions of Fast Neutron Reactors

- Historically the first means to produce weapon grade nuclear materials. Designed with the best available coolant technology *(Hg, NaK, Na)*
- A vision of sustainable nuclear power when fitted with a closed fuel cycle. An institutional priority for Uranium-poor nuclear countries: effective utilization of ^{238}U as Pu & mitigation of long lived high level waste burden
- A vision of TRU burner for HLW minimization in Uranium rich countries

Country-dependent goals

- **Breeding:** maximum for China, India (+ Russia ?)
  breakeven for France & other historical nuclear countries
- **Doubling time:** minimum for China, India (+ Russia ?)
  → High power density → Efficient cooling required
- **Fuel recycling:** recycle of UPu only
  + partial or integral recycle of Minor Actinides

→ Towards varied types of Fast Neutron Reactors & Closed fuel cycles?

Evolving Context for Fast Reactor Development

Towards harmonized safety & security criteria / standards

- Multinational Design Evaluation Program (MDEP) *(Safety, Codification…)*
- Gen-IV Forum initiative on *« Common Design/Safety criteria »*
- Non-proliferation / Safeguards + Physical Protection

→ *Demonstration of best available technologies / practices on prototype and experimental reactors*

- Conduct R&D today on Gen-IV Fast Neutron Nuclear Systems
  - *Build upon past prototypes to advance Sodium Fast Reactor technology and performances*
  - *Take benefit from international collaboration to advance alternative types of Fast Neutron Reactors (GFR, LFR…) in parallel*
- Stakes in international collaboration *(Generation-IV International Forum, IAEA-INPRO, EU-SNE-TP…)*
  - *To share cost of R&D and large demonstrations (safety, security, recycling)*
  - *To progress towards harmonized international standards*