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TRENDS AND DEVELOPMENTS FOR FAST NEUTRON REACTORS AND RELATED FUEL CYCLES

International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios

Frank Carré – CEA/Nuclear Energy Division

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Outline

- From FR09 to FR13
  - Safety, Security, Economics, Sustainability, Public acceptance
- FR13 Program Highlights
  - Progress of Fast Neutron Reactor Technology *(near and longer terms)*
  - Fast Reactor Safety Design Criteria (Panel-1)
  - Sustainability of Advanced Fuel Cycles (Panel-2)
  - Young Generation Event
- Perspectives

FAST REACTORS AND RELATED FUEL CYCLE
FR-09 Challenges and Opportunities

FR-09, Kyoto – December 7-11, 2009
(IAEA, JAEA et al.)

- Revival of large international conferences on FNRs (1970s → 1991 (Kyoto)) & Support to Monju
- 380 + 200 participants, 130 papers & 160 posters
- Challenges and Opportunities
  - Sodium-FR + Lead-FR & Gas-FR
  - Pool vs Loop designs
  - Oxide, Metal, Carbide, Nitride Fuels
  - Minor Actinide Management (Np, Am, MA…)
  - Reprocessing & Recycling (Hydro-, Pyro-)
  - Training & Knowledge management
  - Enhanced safety & Improved management of severe accidents
  - Advanced materials for Fuels, Structures and Components
  - Basic science and simulation *(safety, materials, fuels, reprocessing…)*

→*Panel-1: Economics & Performance of Fast Neutron Systems*
→*Panel-2: International activities, collaborative programs, harmonization of prototypes, sharing of facilities & standardization*
→ *Young Generation Event*

A few highlights of international Fast Reactor Development

- 2010, May/August – Japan: Restart of MONJU
- 2009-2010 – EU SNE-TP – ESNII (2011): ASTRID, ALFRED, ALLEGRO & MYRRHA & R&D FP7: CP-ESFR, LEADER, GoFastR, EVOL, ADRIANA, F.BRIDGE, FAIRFUELS…
- 2011 – Generation-IV International Forum: *Fast Reactors Common Design/Safety Criteria*
- 2011, March – Japan: Tsunami in Tohoku & *Nuclear Accident at Fukushima* Dai-ichi
- 2011, July 21 – China: CEFR goes into operation → CFFR-600 (600 MWe) in 2025
- 2012, Dec – France: End of Basic Design Phase-1 of Technology Demonstrator ASTRID & Report on 4th Generation Nuclear Systems → ASTRID in 2020s
- 2012, Nov. 14-15 – Generation-IV International Forum Symposium (ANS W. Mtg, USA)
- 2012-2013 – France – National Debate on Ecology/Energy Transition
  → Displacing fossile energies & Calling nuclear power into question
  → Integration of nuclear power with renewable energies into a low carbon energy system
- 2013 – France – National Debate on Geological Repository (CIGEO) for HLLLW
  2013- end FY – Japan: MONJU performance tests & Safety upgrade
- 2014 – India: PFBR enters into operation
- 2014 – Russia: BN-800 (Beloyarsk-4) start-up & entering into operation in 2015
  → BN-1200 in 2020s

SODIUM-COOLED FAST REACTORS IN THE WORLD

18 experimental or prototype Sodium Fast Reactors so far
~400 Reactor x Years of cumulated operation in 2012

United States

- *EBR-1* *1951*
- *EBR-II (20 MWe)* *1963 → 1994*
- *FFTF (400 MWth)* *1980 → 2000*
- *Clinch River Project cancelled in 1983*

Europe

- *Rapsodie (20 MWth) 1967 → 1983*
- *DDFR (60 MWth)*
- *KNK-II (17 MWe)* *1978 → 1991*
- ***Phénix (250 MWe)*** ***1973 → 2009***
- *PFR (250 MWe)* *1975 → 1994*
- *SNR300 (300 MWe) never started*
- *Superphenix (1200 MWe) 1986 → 1998*
- *EFR Project cancelled in 1998*

Japan

- ***JOYO (140 MWth)***
- ***MONJU (280 MWe)*** ***1995 →***

Russia & Kazakhstan

- ***BOR-60 (60 MWth)***
- *BN-350 (90 MWe)* *1973 → 1999*
- ***BN-600 (600 MWe)*** ***1980 →***
- ***BN-800 (800 MWe)*** ***2014***

India

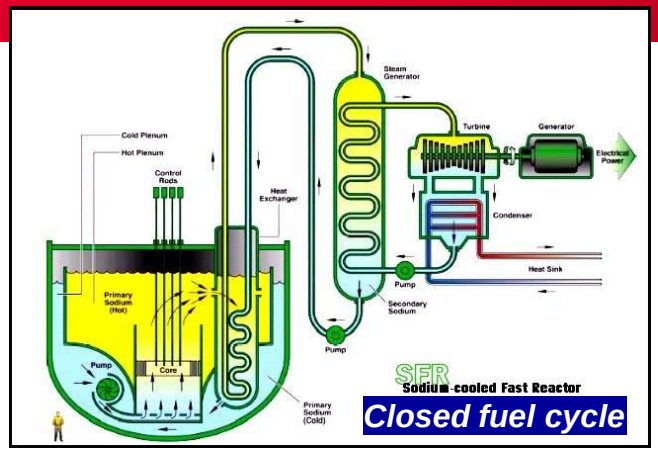
- ***FBTR (40 MWth)*** ***1985 →***
- ***PFBR (500 MWe)*** ***2014***

China

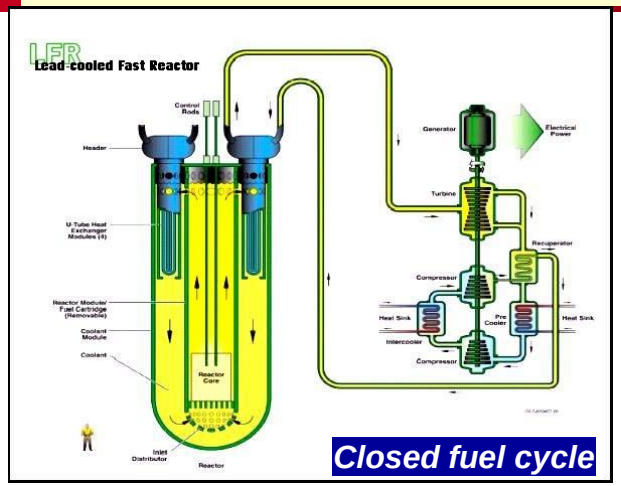
- ***CEFR (20 MWe)*** ***2011***
- ***CFR-600 (600 MWe)*** ***2025***

GEN-IV INTERNATIONAL FORUM: 6 SYSTEMS FOR R&D

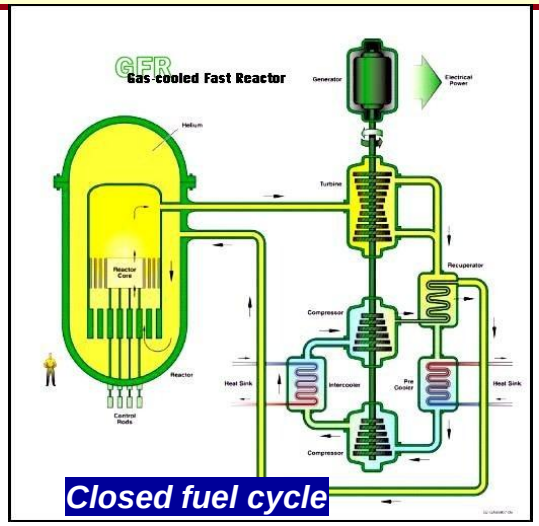
GIF Selection of six Nuclear Systems



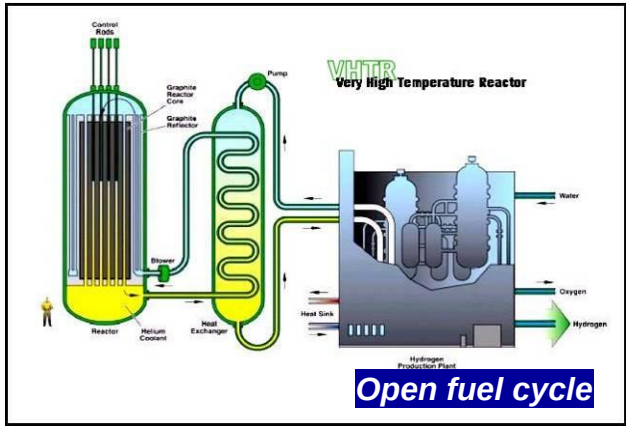
Sodium Fast Reactor



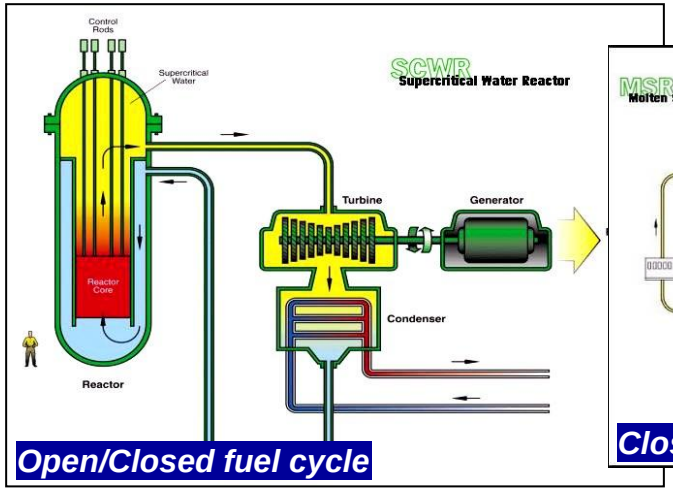
Lead Fast Reactor



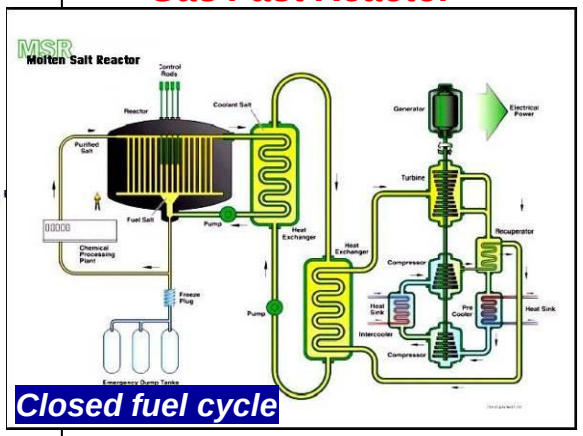
Gas Fast Reactor



Very High Temperature Reactor



Super Critical Water Reactor



Molten Salt Reactor

Recognition of the major potential of fast neutron systems with closed fuel cycle for breeding (fissile re-generation) and waste minimization *(minor actinide burning)*

FAST REACTORS AND RELATED FUEL CYCLE
FR13 – Safe technologies and Sustainable Scenarios

FR-13, Paris – March 4-7, 2013
(IAEA, CEA et al.)

- Updates since FR09, current programs and future prospects
- > 600 participants, 34 countries, 378 papers & 187 posters
- Safe Technologies & Sustainable Scenarios
  - Sodium-FR + Lead-FR & Gas-FR
  - T1&2 - Advanced reactor designs & Technologies
  - T3 - Enhanced safety & Improved mgt of severe accidents
  - T4&5 - Advanced materials for Fuels, Structures & Components
  - T6- Reprocessing & Recycling (Hydro-, Pyro-) & Minor Actinide Management (Np, Am, MA…)
  - T7 – Data, Experiments & simulation *(safety, materials, fuels, reprocessing…)*
  - T8 – Deployment, scenarios & economics
  - T9 – Operation and decommisioning
  - T10 - Professional development & Knowledge management

→ *Panel-1: Safety Design Criteria*
→ *Panel-2: Sustainability and Advanced Nuclear Fuel Cycle*
→ *Young Generation Event*

FAST REACTOR DESIGNS & TECHNOLOGIES: GOALS AND PATHS OF PROGRESS (TRACKS-1&2)

Integrating SFR feedback experience into near term projects & Preparing the longer term future with Gen-IV Nuclear Systems

- Main goals and challenges ahead:
  - Safety, Security, Economics, Sustainability, Public acceptance
  - Improved performances *(availability, operability, fuel burnup, power conversion…)*

- Wide range of reactor types and candidate technologies
  - Sodium Fast Reactors as currently best available technology
  - → Integrating SFR feedback experience into near term projects
  - → Preparing the advent of a new generation of SFR *(w. prototypes in 2020s)*
  - Lead alloy-, gas-, molten salt- cooled fast reactors…
  - → Assessing the potential of other types of Fast Neutron Reactors
  - Pool/Loop designs, Power conversion system…
  - Nuclear fuel: oxide, metal, carbide, nitride…
  - Unit size

→Diversity & Complementarity of National Programmes

FAST REACTOR DESIGNS: GOALS AND PATHS OF PROGRESS (TRACK-1)

New Builds and New Projects of Fast Neutron Reactors

- Near term projects of SFRs:
  - India: PFBR (500 MWe) (2014, Kalpakkam) + *2 CFBR units (500 MWe)*
  - Russia: BN-800 (800 MWe) (2014, Beloyarsk-4) → *BN-1200*
    MBIR (150 MWth) (~2019)
  - China: CFR-600 (600 MWe) (2023)

- Near term projects of LFRs:
  - Russia: SVBR-100 (100 MWe) (2017)
  - Russia: BREST-300 (300 MWe) (~2020, Tomsk) → *BREST-1200*

- Gen-IV Systems Technology Demonstrators & Prototypes
  - France: ASTRID (~ 600 MWe SFR) (2020s) → *ESFR (1500 MWe)*
  - Europe: MYRRHA (~50-80 MWth LBE-FR) (~2020, Mol Belgium)
  - USA: SMFR (50 MWe)
  - Rep. of Korea: KALIMER (600 MWe)
  - Europe: ALFRED (~300 MWth LFR) → ELFR
  - Europe: ALLEGRO (~70 MWth GFR) (> 2025, CZ, SK, HR + PL)
  - …

FAST REACTOR SAFETY: POST-FUKUSHIMA LESSONS & GOALS FOR NEXT-GENERATION REACTORS (TRACK-3)

Track-3 & Panel-1

- FNRs to match at least safety goals anticipated for contemporary Gen-III LWRs
- Gen-IV nuclear systems safety goals
- Make best use of past and present reactors' operating feedback
- Improve prevention, management and mitigation for severe accidents
  - Severe nuclear accidents
    - *Low reactivity effect of coolant void*
    - *Practical elimination of core compaction & prompt criticality*
    - *Efficient & Reliable decay heat removal*
    - *Advanced core catcher technology*
  - Large chemical accidents
    - *Sodium/Water, Sodium/Water/Air*
    - *→ Robust protection of sodium systems and steam generator technologies?*
    - *→ Gas power conversion systems: nitrogen, SC-CO_2…? Related R&D needs?*
- Post Fukushima lessons
  - Better integrate external hazards/events into safety analysis *(air plane crashes, earthquakes, flooding…)*
  - Revisiting safety framework *(beyond design basis accidents, residual risks, practical exclusion, cliff-edge effects…)*
  - Improve emergency preparedness *(off-site power supply and cooling capabilities)*

FAST REACTOR SAFETY: POST-FUKUSHIMA LESSONS & GOALS FOR NEXT-GENERATION REACTORS (TRACK-3)

Track-3 & Panel-1

- Enhanced Safety/Reliability of operation
  - Enhanced/Extended principles of Defence-in-Depth principles
  - Extended surveillance/monitoring/safeguards
  - In Service Inspection & repair (ISIR)
  - Redundant & diversified safety systems *(Active, Passive, "Natural safety"…)*
  - Improved detection *(gas bubbles, sodium/water interaction, cladding failure…)*
  - Improved prevention, detection & repair of sodium leaks

  → *Innovative instrumentation + Post accidental instrumentation*

- Examples of application of extended safety approaches
  - MONJU Safety upgrade + Safety demonstrations
  - JSFR, BN-1200, ASTRID…
  - ALFRED → ELFR
  - …

- Progress toward a harmonized safety framework

  → Gen-IV Forum Initiative on SFR "Common Design/Safety Criteria"
  - Enhancing international cooperation on safety related research

→ Papers from IAEA, Europe, India, Russia, USA…

Fast Reactor Materials: Achievements and New Challenges

- Structural materials with improved resistance *(HT, dpa, corrosion, 60y lifetime…)*
  - Advanced Austenitic Steels
  - Advanced Ferritic/Martensitic Steels
  - → Understanding ageing mechanisms *(creep, fatigue, creep-fatigue…)*
- Low swelling steels for fuel cladding
  - Advanced Austenitic Steels
  - Advanced Ferritic and Ferritic/Martensitic Steels
  - Oxide Dispersed Strengthened Steels *(ODS)*
  - SiC_fSiC
  - + Good internal and external corrosion resistance
  - + Compliance with reprocessing processes
- 9 Cr F/M steel for large components *(Steam Generator…)*
  - Codification research for mechanical design in progress
- Gen-IV systems specific materials issues
  - SFR: alternative coatings for the replacement of stellite
  - LFR: control of steel corrosion in lead-alloys
  - GFR: SiC_fSiC as fuel cladding, 9 Cr F/M steel for the vessel, Ni-alloys for HX…

Fast Reactor Fuels & Fuel cycle processes

- Flexible actinide management
  - Efficient Burning/Breeding of plutonium
  - Security *(Non-proliferation…)*
  - Managing minor actinides? *(cost/benefit…)*
- Nuclear fuel performance
  - High burn-up, long fuel irradiation campaign
  - Low swelling cladding steel *(F/M Steels, ODS…)*
- Novel fuel technologies
  - Heterogeneous fertile/fissile fuels
  - Metal *(USA, China, India, Rep. of Korea…)*
  - Carbide, nitride fuels
- Transmutation fuels
  - Minor actinide bearing fuels *(fabrication, performance, reprocessing…)*
- Timeline for Advanced Fuel Cycle Demonstrations?
  - Medium term (2020s…)
  - Long term for breakthroughs (~mid of 21st century)

Modelling & Numerical Simulation

- Advanced numerical simulation
  - Design studies *(neutronics & thermalhydraulics)*
  - Safety/Severe accidents Analyses
  - Nuclear fuel
  - Significant international benchmarks: AIEA, NEA, GIF, bilateral collaboration
  - More intensive and standard utilisation of Monte-carlo simulation techniques
  - Priority research on decay heat removal, prevention-mitigation of severe accidents
  - → Numerical demonstration of SFR passive core cooling by natural convection
  - Availability of reactor data *(Superphenix…)* to qualify computational tools used for operating transient analyses of Gen-IV SFR designs
- Path for progress
  - Multi-physics coupling
  - High performance computing
  - Reduction of uncertainties
- Modelling extension to more basic phenomena
  - Understanding and modelling of more basic phenomena
  - Extension of numerical simulation versatility and predictability
  - Adjustment of associated experimental programs *(analytical research, validation…)*

Fast Reactor Desirable Features & Plans for Deployment

- Economic competitiveness
  - Safe and reliable operation
  - 60 year lifetime with high availability factor
- Physical protection
- Non proliferation
  - Safeguards
  - International Centers of Fuel Cycle Services
  - Minor Actinide Management
- Plans for deployment
  - 100% FNRs or Symbiotic FNR/LWR fleet?
  - China: from CEFR (25 MWe) in 2011 to CFR-600 (600 MWe) in 2023 + CFR-1000 (1000 MWe) and 240 GWe in 2050 *(out of 400 GWe NPPs)*
  - Russia: from BN-600 & BN-800 to 14 GWe by 2030 & 34 GWe by 2050 *(out of 100-140 GWe NPPs)*
  - India: from FBTR to PFBR (500 MWe) + 2 x CFBR (500 MWe) + MFBRs (1000 MWe) from carbide to oxide fuels towards with metallic fuel w. pyroprocessing + Thorium?

Extended Feedback of Sodium Fast Reactor Operation

- Operation of SFR is an industrial reality
  - 26 years of operation experience in FBTR,
  - 30 years of operation experience in BN 600,
  - Life extension in preparation for both reactors,
  - Reprocessing and multiple-recycling demonstrations in Phenix
  - Inspection and repair under sodium (Joyo…)
  - Replacement of large components (Phenix...)
- Targets for improvements
  - Low activation and purity control of primary sodium
  - In service inspection and repair *(Ultrasonic sensors, Xtomography…)*
  - Under sodium imaging
  - Shortened fuel handling outage *(simplication of process, reliable equipment…)*
  - Instrumentation *(surveillance, safety, safeguards + post accidental)*
- Significant feedback from SFR decommissioning
  - Minimization of radioactive waste and radioactive effluents
  - Minimization of doses to workers

  → *Advanced dismantling techniques*
  - Disposal of waste generated

SKILL CAPABILITIES, PROFESSIONAL DEVELOPMENT, KNOWLEDGE MANAGEMENT (TRACK-10)

Education & Training

- Active to support Education and Training on SFRs worlwide
  - Attractiveness of Gen-IV nuclear systems *(challenging scientific topics, projects of technology demonstrators and prototypes, international dimension…)*
  - Sharing information through experimental studies or operation feedback
  - Sharing a standardized information on safety
  - Development of dedicated simulators
  - → Supported by schools, seminars, workshops, exchanges of professors
- Knowledge preservation and management
  - Data preservation programs for FFTF in the U.S., Superphenix in France …
  - IAEA FR knowledge preservation inititiative (FR-KOS application)
  - How to attain higher levels of KM maturity in a FR R&D organisation?
- Examples of new Education & Training activities
  - The ENEN-III project: European Fission training schemes on GenIV reactors
  - Knowledge passing in France in the perspective of the next –generation SFR demonstrator ASTRID

SUSTAINABILITY OF ADVANCED FUEL CYCLES

Panel-2 (March 5, 15:30-17:30)

- Fast Neutron reactors with a closed fuel cycle
  - A vision of sustainable nuclear power: effective utilization of ^{238}U as Pu & mitigation of long lived high level waste burden
  - → An institutional priority for Uranium-poor nuclear countries
  - A vision of TRU burner for HLW minimization in Uranium rich countries
- Dimensions of sustainability
  - Effective utilization of uranium
  - Minimization of ultimate HLW burden *(decay heat, radiotoxicity…)*
  - Safety, Security (non-proliferation, resistance to external aggressions…)
  - Economics, social & environmental impacts, public acceptance…
- 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?*

YOUNG GENERATION EVENT

YGE (March 7, 13:30-15:10)

- FR13 Video Contest
  - Ksenia **Lipkina** *(Russia) – Inert Matrix Fuels*
  - Emmanuel **Mathe** *(France) – Sodium Aerosols: hazards & management*
  - Yoshiro **Nishioka** *(Japan) – Sodium Fast Reactor Safety*
  - Eugeny **Varseev** *(Russia) – Corrosion Control in Lead Fast Reactors*
  - Daniel **Weißbach** *(Gernany) – Another Look at Molten Salt Reactors*

- Young Generation "Side-Event" (March 6, 13:30-17:20)
  - Young Generation's visions for the future of nuclear power
  - Missions and role of Fast Neutron Reactors
  - Safety, Sustainability, Innovation, Public Acceptance, Simulation, International Cooperation, Education & Training…

  + Dinner hosted by CEA for participants in the Young Generation Side Event

- Young Generation Event (March 7, 13:30-15:10)
  - Reporting from the YG "Side-Event" in a plenary session
  - Debate with the audience
  - Conclusions reported during the closing ceremony

FR13 Conference

- FR13 – A unique and dedicated framework to share updates on national programs of Fast Reactor developments, projects of new builds and plans for the future
  - *Near term projects of sodium and lead-alloy Fast Reactors*
  - *Gen-IV visions of sodium-cooled and alternative types of Fast Neutron Reactors (GFR, LFR…)*
- FR13 – A special emphasis put on *Fast Reactor Safety*, *Sustainability of nuclear fuel cycle* and *Young Generation perspective*
- FR13 – A catalyst for further collaborations and alliances
  - *To share visions of goals and advisable options for future Fast Reactors and Nuclear Fuel Cycle*
  - *To share cost of R&D and large demonstrations (safety, security, recycling)*
  - *To progress towards harmonized international standards*
  - *To integrate national projects into a consistent international roadmap*