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2141-2

Joint ICTP-IAEA Workshop on Nuclear Reaction Data for Advanced Reactor Technologies

3 - 14 May 2010

Introduction to Advanced Reactor Technology Development
IAEA Perspective

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Technology Development for Advanced Reactors

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Topics

- The role of nuclear power today
- Different Reactor Types
- IAEA activities
- Conclusions

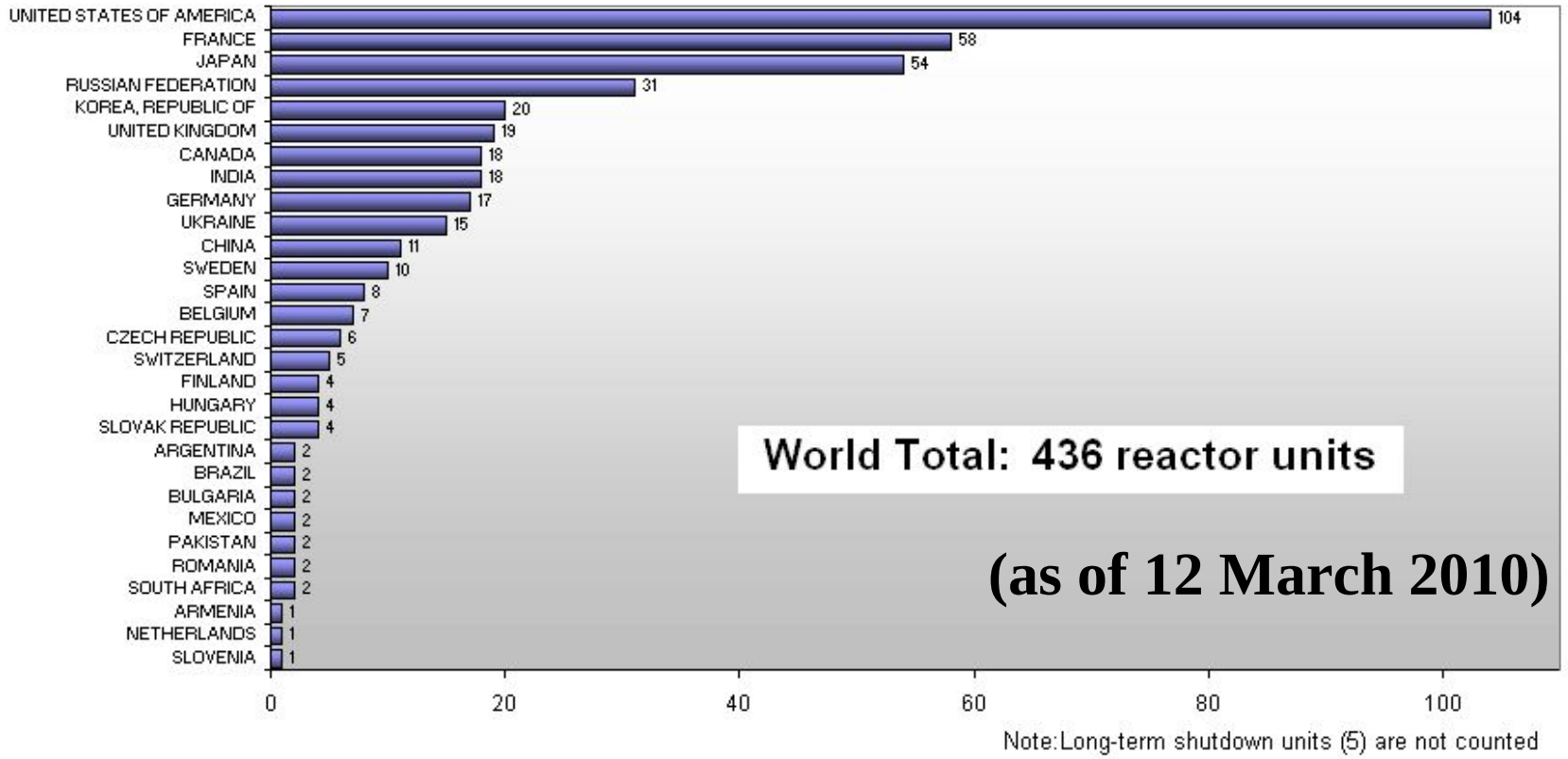
Background

- Growing world population with increasing energy needs, especially in the developing countries
- Security of supply concerns
- Threat of global warming due to CO_2 emissions demands non-fossil electricity production
- Nuclear will have to be part of a sustainable mix of energy production options

Energy and Poverty

- Overwhelming correlation between energy consumption and poverty
  - Sweden / Germany / India / Tanzania: 16’000 / 6’500 / 460 / 100 kWh_{el} per person and year
- Of the planet’s ~6.7 billion population
  - 1/4 are without electricity
  - More than 1/3 rely almost exclusively on traditional biomass as their principal energy source
  - Roughly 1/2 live in poverty
  - More than 1/5 are severely undernourished

Number of Reactors in Operation Worldwide



In Operation: 436 **Capacity: 370.5 GWe**

Under Construction: 56 **Capacity: 51.9 GWe**

Operating Experience (up to 31 December 2007): 13036.4 RYs

2007 Electricity Production: 2608.1 TWh (14 % global electricity share)

(world totals include 6 reactors in operation in Taiwan, China)

Beginning Of A Renaissance?

- The 1970s - average 25 construction starts/year
- Last ten years - construction starts:
  - 1998: 3 China (2), Japan (1)
  - 1999: 5 China (1), Rep. of Korea (2), Taiwan, China (2)
  - 2000: 5 China (1), India (2), Japan (2)
  - 2001: 1 Japan
  - 2002: 6 DPRK (1), India (5)
  - 2003: 1 India
  - 2004: 2 Japan (1), India (1)
  - 2005: 3 China (1), Finland (1), Pakistan (1)
  - 2006: 4 China (2), Rep. of Korea (1), Russia (1)
  - 2007: 7 China (2), France (1), Rep. of Korea (2), Russia (2)
  - 2008: 10 China (6), Rep. of Korea(2), Russia (2)
  - 2009: 11 China (9), Rep. of Korea(1), Russia (1)

Nuclear Power will probably grow, but its share of global electricity may fall

- Some countries have phase-out policies
- Others see advantages for energy security
- Some plan to increase nuclear capacity (e.g. China, India, Japan, Republic of Korea)
- IAEA predicts growth from 2598 TW(e)h in 2008 (low-high estimates):
  - 2732 - 2785 TW(e)h by 2010
  - 3261 - 3962 TW(e)h by 2020
  - 3771 - 5930 TW(e)h by 2030
- However, the percentage of electricity produced by nuclear power will decrease from 14.0 % in 2008 (low-high estimates):
  - 14.3 - 14.4 % by 2010
  - 13.5 - 14.6 % by 2020
  - 12.6 - 15.9 % by 2030

Further Statistical Info

- IAEA Power Reactor Information System (PRIS) www.iaea.org/programmes/a2
- Energy, Electricity and Nuclear Power Estimates for the Period up to 2030, REFERENCE DATA SERIES NO. 1, 2009 Edition
- STI/PUB/1304, Energy, Electricity and Nuclear Power: Developments and Projections - 25 Years Past and Future

Several Factors Will Influence Nuclear Energy's Future Contribution

- The degree of global commitment to greenhouse gas reduction
- Continued vigilance in safety
- Continued vigilance in safeguards
- Technological advances; economic competitiveness; and financing arrangements for new NPPs
- Implementation of nuclear waste disposal
- Public perception, information & education

Electricity Production With Nuclear Energy

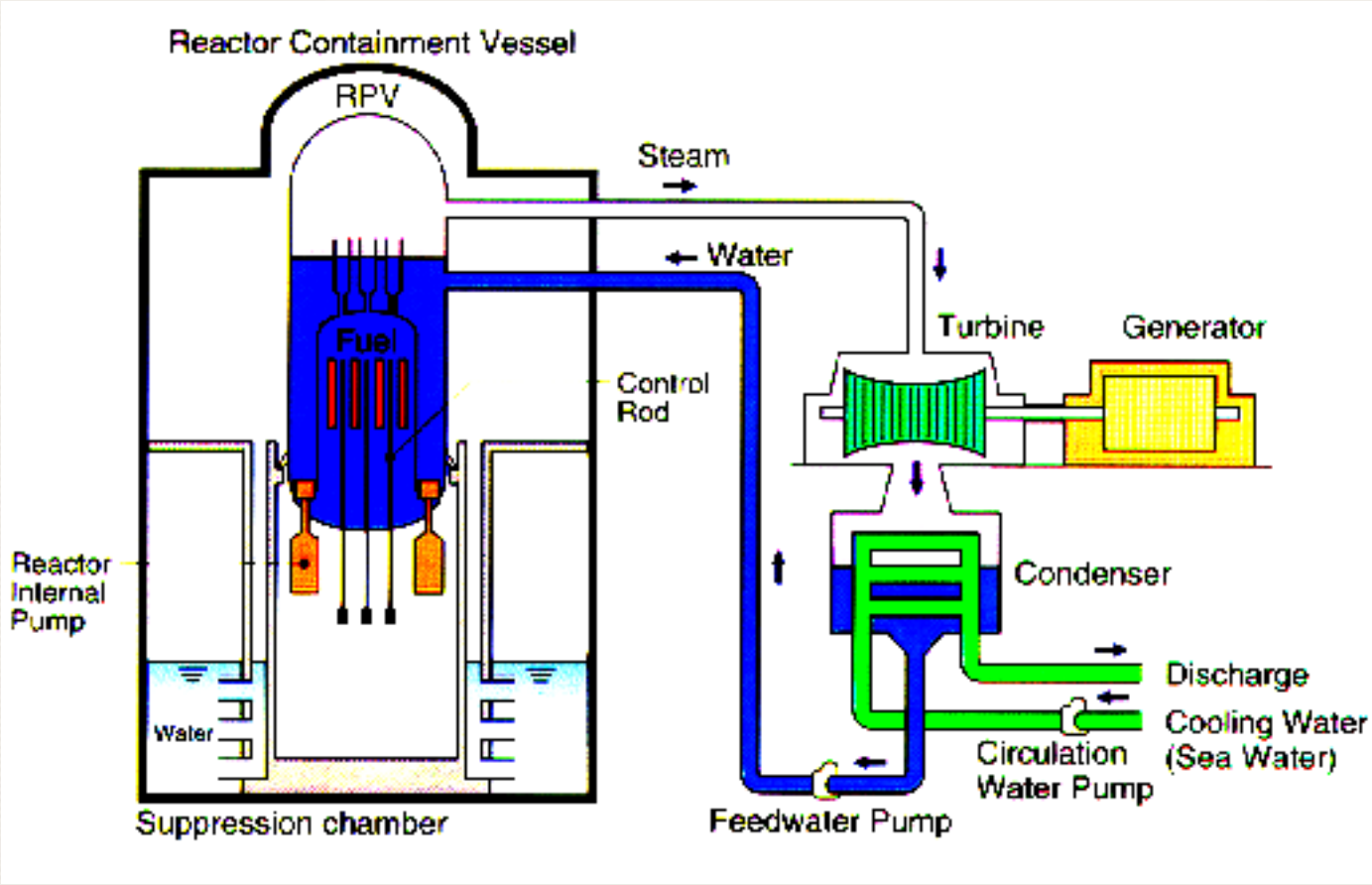
- Principle
- Main reactor types

Almost All Electricity Is Produced By Turning An Electric Generator

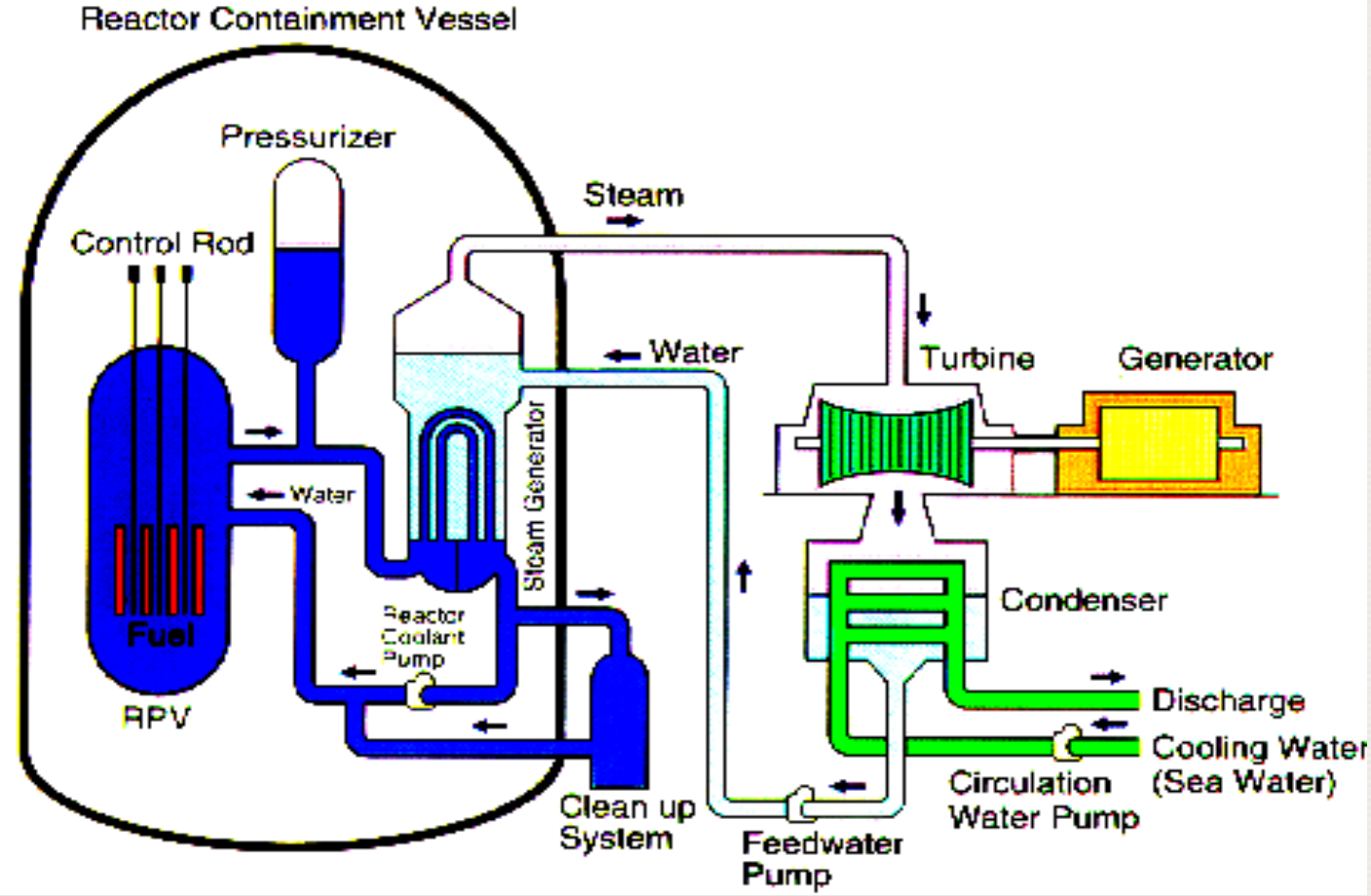
Reactors Are Classified By Their Coolants

- Water Cooled Reactors
  - Light Water
  - Heavy Water
- Gas Cooled Reactors
  - CO_2
  - Helium
- Liquid Metal Cooled Fast Reactors
  - Sodium
  - Heavy Liquid Metals (Pb, Pb-Bi eutectic alloy)

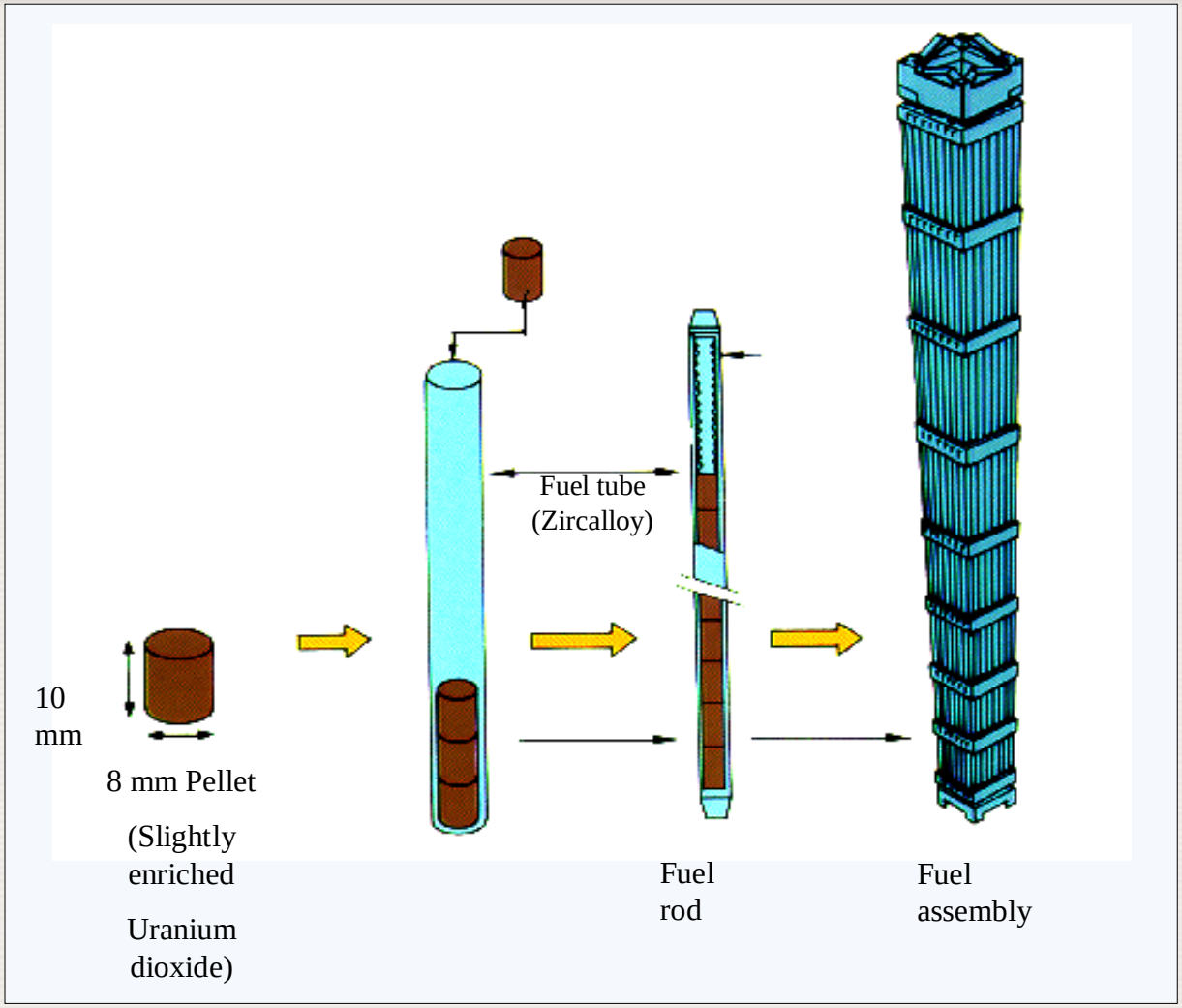
Boiling Water Reactor (BWR)



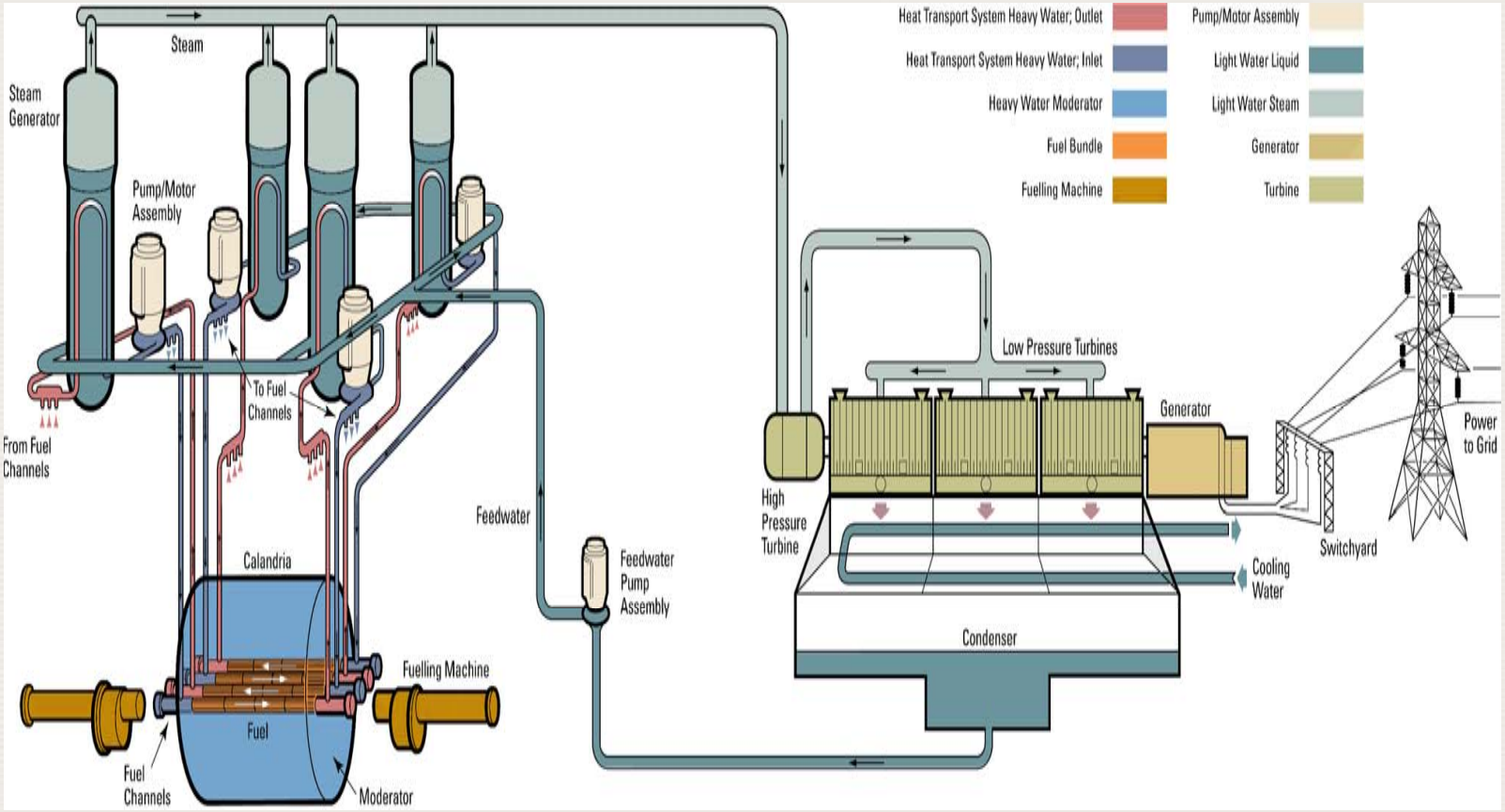
Pressurized Water Reactor (PWR)



Enriched UO_2 Pellets Are The Fuel For Water-Cooled Reactors

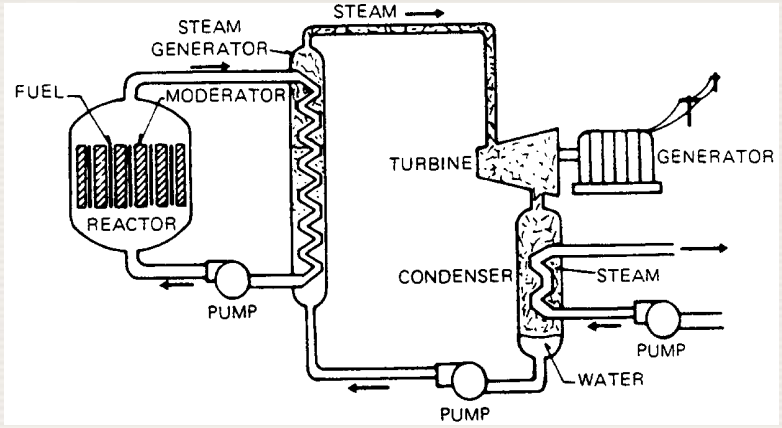


Heavy Water Reactor (HWR)

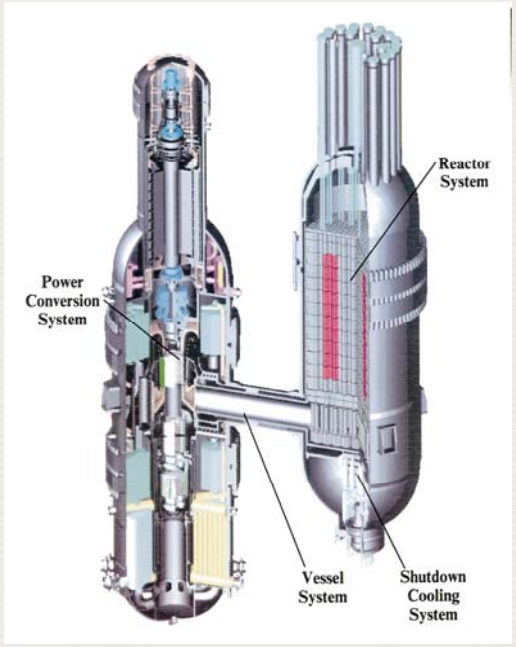


HWR
fuel bundle

There are Different Types of Gas Cooled Reactors

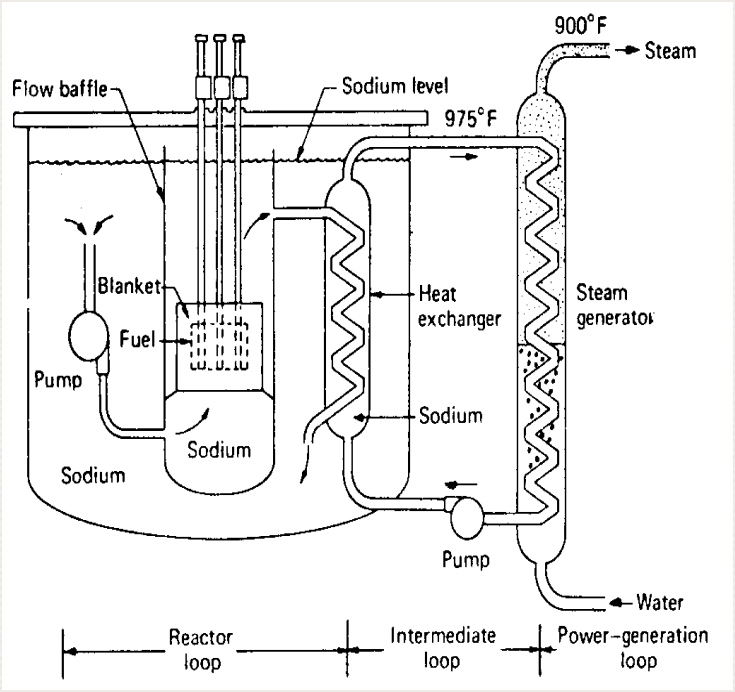


CO_2 Cooled Reactor

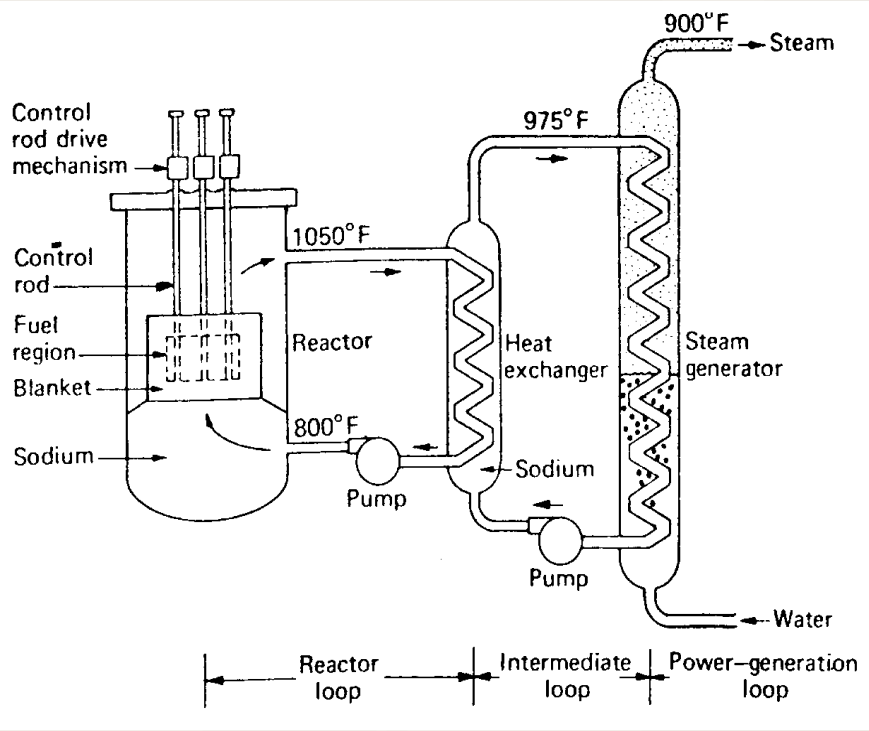


Helium Cooled Reactor

There are Different Types Of Liquid Metal Cooled Reactors

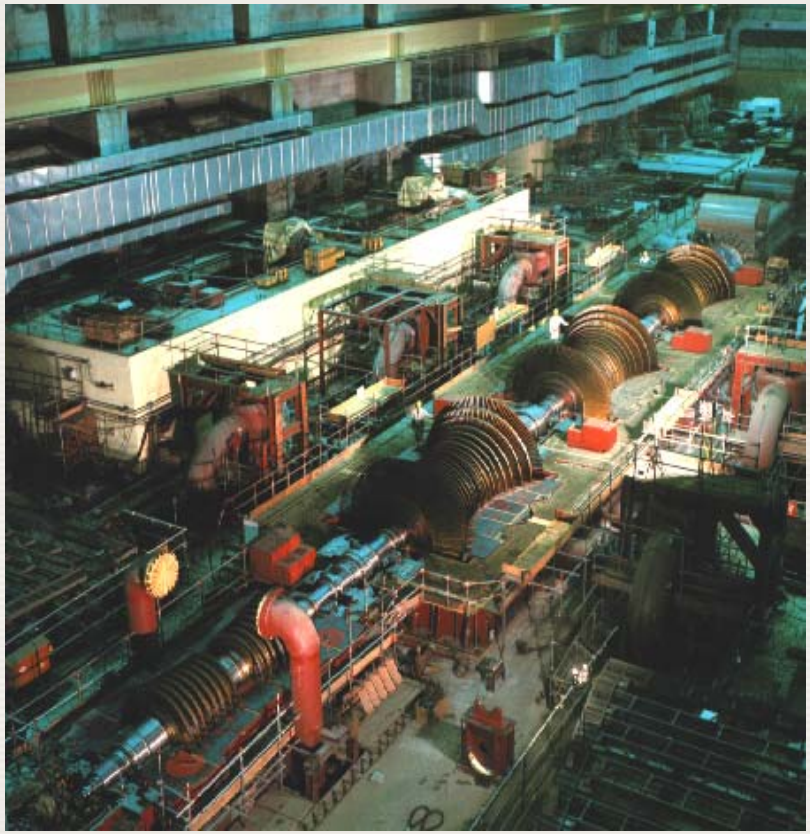


Pool Type

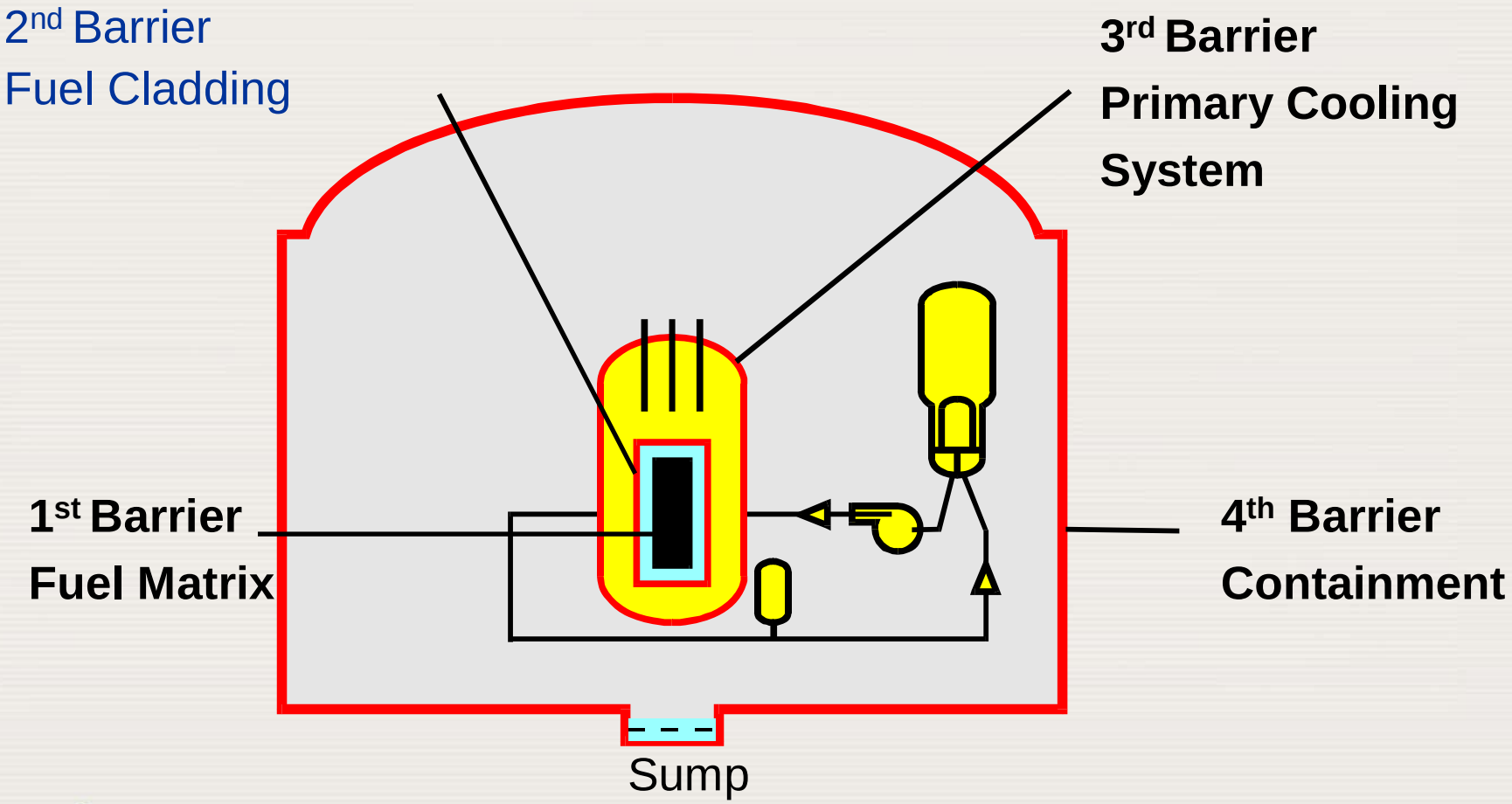


Loop Type

All Power Reactors Have A Turbine Generator



There Are Several Physical Barriers To Release Of Radioactivity



IAEA Fast Reactor Technology Development Activities

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Framework

- **Technical Working Group on Fast Reactors, TWG-FR**
  - **Promote exchange of information on national and multi-national fast reactor and transmutation system programs (e.g. ADS)**
  - **Stimulate and facilitate collaborative research and development (Coordinated Research Projects, CRPs)**
  - **Coordinate activities with other Agency projects (e.g. in Safety), and international organizations (EC, ISTC, and OECD/NEA)**
  - **Membership: Belarus, Brazil, China, France, Germany, India, Italy, Japan, Kazakhstan, Republic of Korea, Russia, Switzerland, United Kingdom, and United States of America, as well as the EU (EC), ISTC, and OECD/NEA; Observers: Belgium, Sweden**

Information Exchange and Training

- Advanced Workshop on “Model Codes for Spallation Reactions”, collaboration with ICTP, 4 – 8 Feb 2008, Trieste, Italy
  - Intern. Nucl. Data Committee Report 0530
- Workshop on “Nuclear Reaction Data for Advanced Reactor Technologies”, collaboration with ICTP, 19 – 30 May 2008, Trieste, Italy
  - Lecture notes on http://cdsagenda5.ictp.trieste.it/full_display.php?smr=0&ida=a07153

Information Exchange and Training

- **International Topical Meeting on "Nuclear Research Applications and Utilization of Accelerators", Vienna, 4 – 8 May 2009**

  - ***Topics***
    - ✓ **Accelerator applications including nuclear materials research**
    - ✓ **Accelerator Driven Systems (ADS)**
    - ✓ **Accelerator technology**
  - ***240 participants from 50 IAEA Member States and 4 international organizations***
  - ***153 oral papers and 145 posters***

Information Exchange and Training

- **School on *Physics, Technology and Applications of Innovative Fast Neutron Systems***
  - **Organized by IAEA's Department of Nuclear Energy, Department of Nuclear Sciences and Applications, in collaboration with ICTP, 9 – 20 November 2009, Trieste, Italy**
  - **Syllabus**
    - ✓ **Physics and Design Studies**
    - ✓ **General Concept Studies**
    - ✓ **Sub-system Studies**
    - ✓ **Nuclear Data**
    - ✓ **Fuel Development**
    - ✓ **Fuel Recycling**
    - ✓ **Fuel Cycle Studies**
    - ✓ **Impact of Transmutation Scenarios on High-level Waste Repositories**
    - ✓ **…**

Information Exchange and Training

- **International Conference on "Fast Reactors and Related Fuel Cycles - Challenges and Opportunity (FR09)", Kyoto, 7 – 11 December 2009**

  - ➢ **Exchange of information on new developments and experience covering all areas of reactor and fuel cycle research and technology**
  - ➢ **622 participants from 20 countries and 3 intl. or org.**
  - ➢ **150 oral papers and 154 posters**

FR09 Highlights

- Scope covered key scientific and technological areas in which innovation is pursued to ensure that next generation's fast reactor and fuel cycle achieve their potential
  - Core design
  - Fuels and materials development
  - Safety
  - Advanced simulation
  - Component and system design
  - Coolant technology
  - Fuel cycles
- Open issues identified, R&D programs to resolve them outlined
- Importance of international collaboration and continuous efforts to harmonize concepts to pool resources, avoid duplication, make best use of synergies and aim for complementarities
- Need for fast reactor safety standards
- Establish the FR International Conference as a series every 3 years
- Next FR International Conference FR12 hosted by France?

Coordinated Research Projects (CRPs)

- ***Studies of Innovative Reactor Technology Options for Effective Incineration of Radioactive Waste (2003 – 2008)***
  - **17 institutions in 13 Member States & EC (JRC)**
  - **Transient behaviour of advanced transmutation systems, both critical and sub-critical**
  - **Papers at PHYSOR 2006, ICENES 2007, and GLOBAL 2007**
  - **Final CRP report to be published in 2009**

Coordinated Research Projects (CRPs), cont'd

- ***Analytical and Experimental Benchmark Analyses of Accelerator Driven Systems (2005 – 2010)***
  - **Participation from 27 institutions in 18 IAEA Member States**
  - **Papers at AccApp2007, and PHYSOR2008**

Coordinated Research Projects (CRPs), cont'd

- **Scope of the CRP**
  - ✓ **Computational and experimental benchmarking**
  - ✓ **ADS and non-spallation neutron source driven sub-critical systems**
  - ✓ **Work domains in the first stage**
    - o **YALINA Booster**
    - o **Kyoto University Critical Assembly (KUCA)**
    - o **Pre-TRADE**
    - o **FEAT and TARC**
    - o **ADS kinetics analytical benchmarks**
    - o **Actinides cross sections**
    - o **Spallation targets**
    - o **ADS performance**

Coordinated Research Projects (CRPs), cont'd

- ***Analyses of, and Lessons Learned from the Operational Experience with Fast Reactor Equipment and Systems (2007 – 2010)***
  - **Three Work Domains**
    - ✓**Steam Generators**
    - ✓**Fuel & Blanket Subassemblies**
    - ✓**Structural Materials**
  - **Retrieval of the documentation and feedback information**
  - **Producing bibliographic catalogues of these documents**
  - **Publishing national synthesis reports**
  - **Publishing joint synthesis (lessons learned)**
  - **Contributes to the IAEA Fast Reactor Knowledge Preservation Initiative**

Coordinated Research Projects (CRPs), cont'd

- ***Benchmark Analyses of Sodium Natural Convection in the Upper Plenum of the MONJU Reactor Vessel*** **(2008 – 2012)**
  - **First stage based on thermal stratification measurements performed in MONJU (1995 trip tests)**
  - **Specific research objectives for first stage**
    - ✓ **Validation of multi-dimensional fluid dynamics codes**
    - ✓ **Identification of weaknesses (e.g. turbulence models, reactivity feedback models etc), and of the R&D needs to resolve them**
  - **Possibility to extend CRP activities to similar tests during MONJU start-up experiments in 2009**
  - **Participants: China, India, France, Japan, R. of Korea, Russia, USA**
  - **Kick-off RCM held in September 2008**

Coordinated Research Projects (CRPs), cont'd

- ***Control Rod Withdrawal and Sodium Natural Circulation Tests Performed During the PHENIX End-of-Life Experiments*** **(2008 – 2011)**
  - **Research objectives of the CRP: perform preparatory analyses, blind calculations, and post-experiment analyses for two PHENIX EOL tests**
    - ✓**Control Rod Withdrawal Test**
    - ✓**Sodium Natural Circulation Test**
  - **Participants: China, India, France, Japan, R. of Korea, Russia, Switzerland, USA**
  - **Kick-off RCM held in September 2008**

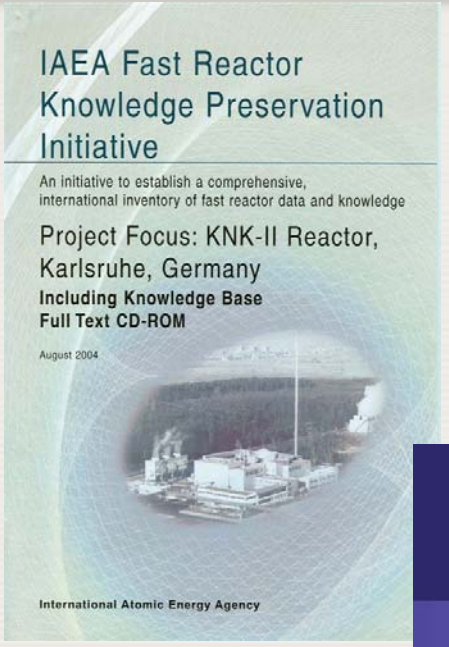
IAEA Fast Reactor Knowledge Preservation (FRKP) Initiative

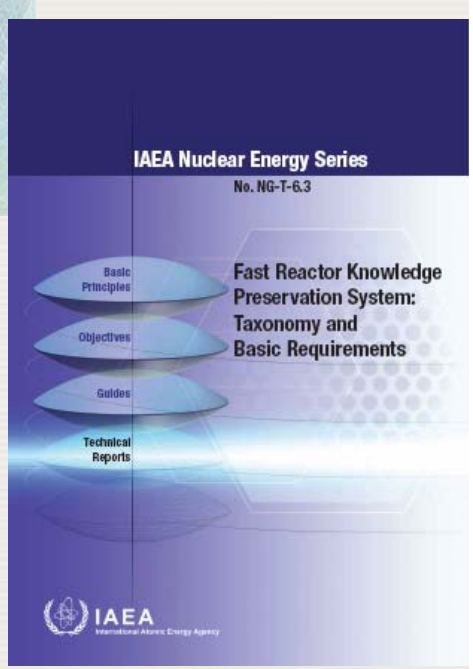
❑IAEA Contributions

- Own FR data and knowledge: 40+ years of activities (IWG-FR/TWG-FR)
- Creation of FRKP network
- Support and coordination of FRKP in MS through and with the help of the TWG-FR
- Coordinated Research Projects (CRPs), and technical coordination meetings
- Development of FR taxonomies, creation and maintenance of the FRKP WWW-Portal

IAEA Fast Reactor Knowledge Preservation (FRKP) Initiative, cont'd

- Support for retrieval and archiving (using INIS capabilities) of data and information related to the German experimental fast reactor KNK-II (dismantled)
- Work started on IAEA FRKP WWW-Portal
  - *Fast Reactor Knowledge Preservation System: Taxonomy and Basic Requirements*, IAEA NE Series Report NG-T-6.3 (2007)





Technical Publications

- "BN-600 Hybrid Core Benchmark Analyses. Results from a Coordinated Research Project on Updated Codes and Methods to Reduce the Calculational Uncertainties of the LMFR Reactivity Effects" (IAEA-TECDOC-1623)
- "Decommissioning of Fast Reactors After Sodium Draining" (IAEA-TECDOC-1633)
- "Advanced Reactor Technology Options for Utilization and Transmutation of Actinides in Spent Nuclear Fuel" (IAEA-TECDOC-1626)

IAEA Gas Cooled Reactor Technology Development Activities

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CRP-5 “HTGR CORE & TRANSIENT ANALYSIS METHODS”

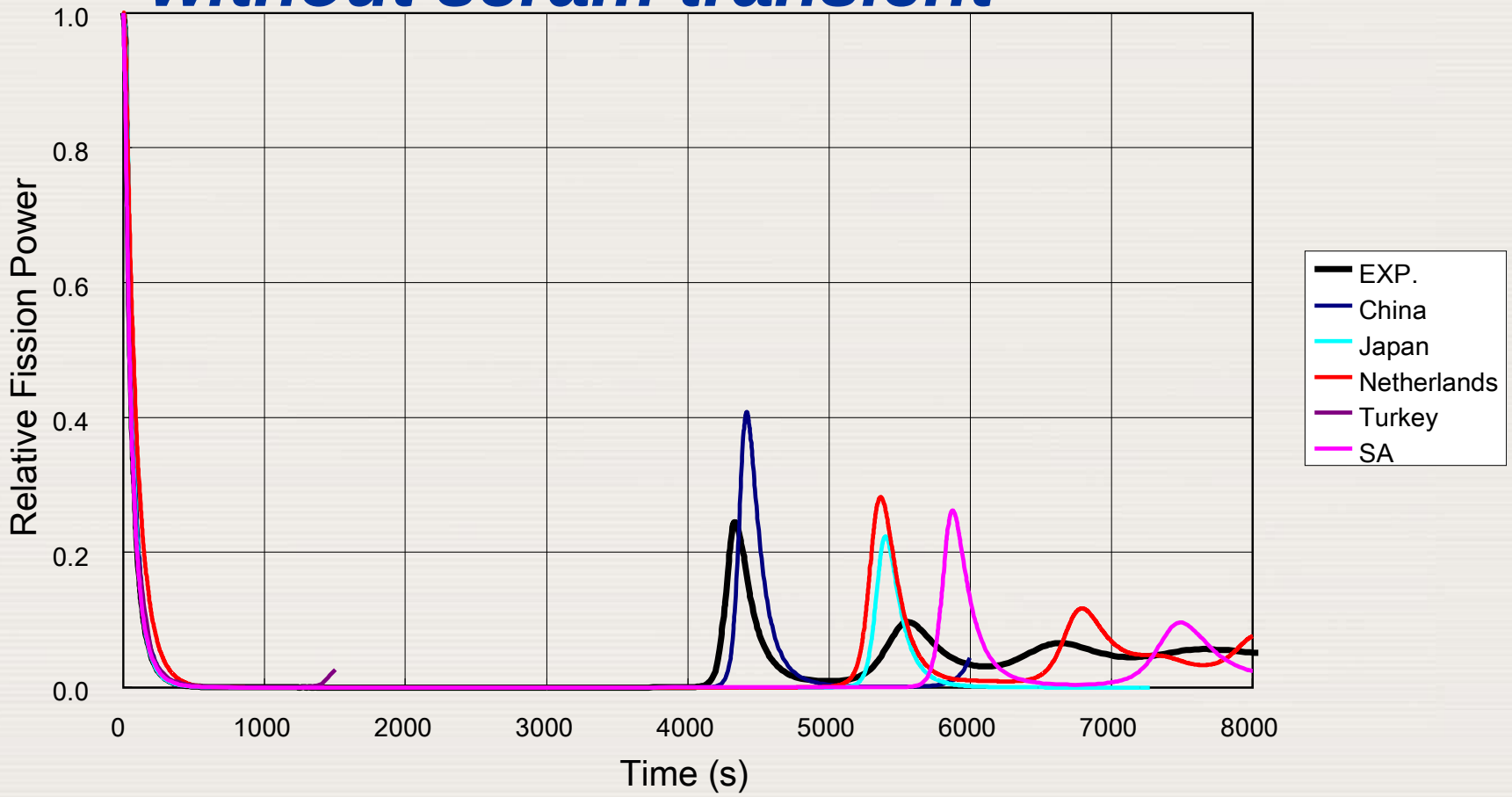
- 12 institutes from China, France, Germany, Indonesia, Japan, Rep. of Korea, Netherlands, Russia, South Africa, Turkey, USA
- Objectives
  - Validation of codes and performance models (code-to-code and experimental validation)
  - HTR-10, PBMR, GT-MHR and the ASTRA benchmarks [e.g. GT-MHR and PBMR-400 gas turbine, three shaft gas turbine micro-model (PBMM), …]
  - Demonstration of HTGR safety characteristics

CRP-5 “HTGR CORE & TRANSIENT ANALYSIS METHODS”, cont’d

- **Status of CRP-5**
  - **Phase I: Preliminary HTTR and HTR-10 core physics evaluation and selected HTTR thermal hydraulics benchmarks IAEA-TECDOC-1382 (2004)**
  - **Phase II: Benchmark analyses related to the Pebble Bed Modular Reactor (PBMR-400), PBMR Micro Test module (PBMM), Gas Turbine-Modular Helium Reactor (GT-MHR), HTR-10 test reactor, and the ASTRA Critical Facility**

Example: HTR-10 Loss of Flow

Power through 8000s after loss of flow without scram transient



CRP-6 “ADVANCES IN HTGR FUEL TECHNOLOGY”

- 10 institutes from China, France, Germany, Japan, Rep. of Korea, Netherlands, Russia, South Africa, Turkey, USA
- Objectives
  - Fuel design and fabrication
  - Fuel characterization
  - Fuel irradiation and PIE
  - Fuel performance modelling
  - QA/QC and licensing issues

Characterization Techniques and Advanced QA/QC Methods

- Supply of specimens to all participants
- Analysis of state-of-the-art techniques in a round-robin measurement exercise
- Development and study of advanced QA/QC
- Results of characterization from large-scale fuel production (Germany, Japan, China)
- Results to be shared with GIF

CRP-8 “Irradiation Creep in Nuclear Graphite: Mechanism and Model”

- **Motivation**
  - Fast neutron irradiation of graphite leads to displacement of atoms and the creation of vacancies
  - Interstitials (and vacancies at higher temperatures) are mobile and contribute to new structures which disrupt the ordered structure of the graphite
  - The consequence: crystal strain, changes in internal porosity, dimensional change (leading to component cracking, distortion of graphite stacks, inability to move fuel or control rods in and out of the core, …) and the generation of local stresses

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CRP-8 “Irradiation Creep in Nuclear Graphite: Mechanism and Model”

- Ultimate objective: Development of universally acceptable creep model applicable over wide temperature and doses ranges
- Participants’ contributions
  - USA for NGNP as part of GIF: Experiments and Modelling
  - UK (British Energy/EdF Energy) for AGR support: Experiments and Modelling
  - South Africa for PBMR Support: Experiments and Modelling
  - China for HTR-PM Support (and through them Toyo Tanso Co. as graphite supplier)
  - Japan for future development (HTTR): Modelling
  - The Netherlands: As host to UK experiment and independent HTR design interest
  - Germany: through consultancy services to HTR designers
  - Ukraine: Advances in their graphite manufacturing plans (more experiments)
  - ...also intend to ‘tap into’ modelling and experimental experience from Russia, if possible

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PLANNED CRP
Uncertainty Analysis in HTGR Modeling

- **Sensitivity and uncertainty analyses (SA, UA) needed for quantification of the impact of uncertainties on performance and safety parameters**
- **Assessment of coupled neutronics / thermal hydraulics simulations for reactor design and safety analysis with the help of SA and UA**
- **Comparison and further development of SA and UA methodologies will be compared**
- **Validation of uncertainty propagation methodology**
- **Unified benchmark to estimate the uncertainty propagation**
- **Kick-off meeting to narrow down scope and objectives of the CRP at University of Pisa, Italy (15 – 17 June 2010)**

Information Exchange

- **Technical Meeting on Licensing Experience for Past HTGRs and Challenges for future HTGR (30 Aug. – 3 Sept. 2010)**
  - **Identify regulators' and designers' expectations**
  - **Involvement of the few remaining experts from pat HTGR plants (Peach Bottom 1, FSV, THTR, …)**
- **Technical Meeting on Performance of Test Reactors and Use of Data for Benchmarking (6 – 9 Sept. 2010)**
  - **Review performance data from experiments in tests reactors (e.g. AVR, THTR, HTR-10, HTTR, …) and evaluate its usefulness for new designs (e.g. NGNP, PBMR, …)**
  - **IAEA technical publication planned**

IAEA Small & Medium Size Reactor Technology Development Activities

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Activities in Support of Advanced SMR Deployment

- Adjust regulatory rules (technology neutral and risk-informed approach)
- Quantify reliability of passive safety systems
- Justify reduced or eliminated Emergency Planning Zones (proximity to users)
- Justify reliable operation with long refuelling interval
- Demonstrate SMR competitiveness for different applications

Project Publications

- Innovative Small and Medium Sized Reactors: Design Features, Safety Approaches, and R&D Trends, IAEA-TECDOC-1451 (May 2005)
- Advanced Nuclear Plant Design Options to Cope with External Events, IAEA-TECDOC-1487 (February 2006)
- Status of Innovative Small and Medium Sized Reactor Designs 2005: Reactors with Conventional Refuelling Schemes, IAEA-TECDOC-1485 (March 2006)
- Status of Small Reactor Designs without On-site Refuelling, IAEA-TECDOC-1536 (March 2007)

Project Publications

- IAEA Nuclear Technology Review 2007, "Progress in Design and Technology Development for Innovative SMRs“ (Appendix 4)
- Design Features to Achieve Defence in Depth in Small and Medium Sized Reactors, NUCLEAR ENERGY SERIES REPORT NP-T-2.2 (July 2009)
- Approaches to Assess Competitiveness of SMRs, NUCLEAR ENERGY SERIES REPORT (to be published in 2010)
- Final Report of the CRP on Small Reactors Without On-site Refuelling, IAEA-TECDOC (to be Published in 2010)
- SMR Inputs for Web-based Electronic Database of Advanced Reactor Designs (in progress)

Ongoing CRP on "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"

- Objective: determine a common analysis-and-test method for reliability assessment of passive safety system performance
- Such a method would facilitate application of risk-informed approaches in design optimization and safety qualification of the future advanced reactors, contributing to their enhanced safety levels and improved economics

Ongoing CRP on "Development of Methodologies for the Assessment of Passive Safety System Performance in Advanced Reactors"

- Participants: Argentina (CNEA), France (CEA), Italy (ENEA and University of Pisa), India (BARC and IGCAR), Russia (OKB "Gidropress"), USA (Idaho State University); observers from Japan and Sweden
- First Research Coordination Meeting, 31 March-3 April 2009 (Vienna)
- Detailed work plan defined
- Second Research Coordination Meeting 16 – 19 March 2010 (Vienna)

IAEA Non Electric Applications Development Activities

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Coordinated Research Projects

- CRP on "Optimization of the Coupling of Nuclear Reactors and Desalination Systems" (1998-2003)
  - Nuclear reactor design
  - Optimization of thermal coupling
  - Performance improvement of desalination systems
  - Prospects of advanced desalination technologies for the application of nuclear desalination
  - Results published in IAEA-TECDOC-1444 (2005)

Coordinated Research Projects, cont'd

- CRP on "Economic Research on, and Assessment of, Selected Nuclear Desalination Projects and Case Studies" (2002-2006)
- Overall objective: enhance prospects for the demonstration, and eventually, successful implementation of nuclear desalination
- Specific objectives
  - Evaluate economic aspects and investigate competitiveness of nuclear desalination under specific conditions
  - Identify innovative technologies leading to further cost reduction of nuclear desalination and refine economic assessment methods and tools
  - Results published in IAEA-TECDOC-1561 (2007)

Coordinated Research Projects, cont'd

- **CRP on "Advances in Nuclear Process Heat Applications" (2007-2009)**
  - **Overall objective: investigate the prospects of using waste heat generated in High Temperature Reactors**
  - **Specific objective: evaluate the potential of all advanced reactor designs for process heat applications**

Coordinated Research Projects, cont'd

- New CRP on "New Technologies for Seawater Desalination using Nuclear Energy"
  - Kick-off meeting 27-28 October 2009
  - Still open to participants
- Objectives
  - R&D support to nuclear desalination technologies
  - Assistance to developing countries interested in nuclear programmes to master applications of nuclear energy for seawater desalination and cogeneration option
  - Introduction of innovative technologies aiming at making nuclear desalination more safe and economical

Conclusions

- Nuclear energy contributes significantly to the world's electricity supply
- Several countries have rising expectations
- New NPP designs are being developed to meet high performance and safety goals
- Nuclear power can also be used for desalination of seawater, hydrogen production, process heat
- Nuclear power faces challenges, including
  - Maintaining high safety levels
  - Continuing vigilance in safeguards
  - Implementing waste disposal strategies
  - Improving public acceptance
  - Continuing innovation efforts to assure economic competitiveness and ever higher safety standards

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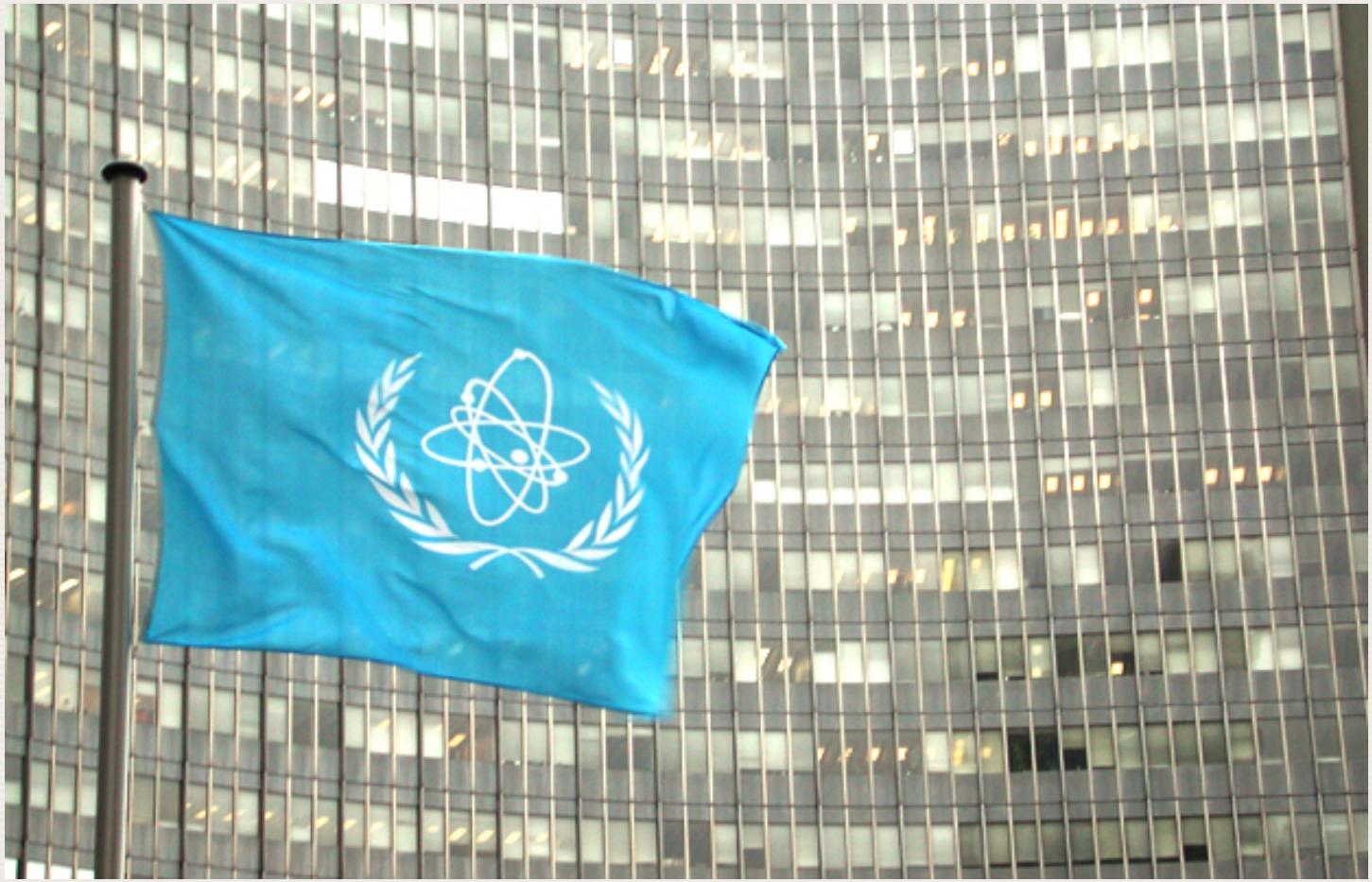

…Atoms for Peace