IAEA
International Atomic Energy Agency

Joint ICTP-IAEA Workshop on the
Physics and Technology of
Innovative Nuclear Energy Systems
20 – 24 August 2018, ICTP, Trieste, Italy

Workshop Introduction and
Development of Innovative Nuclear Energy Systems
at the IAEA

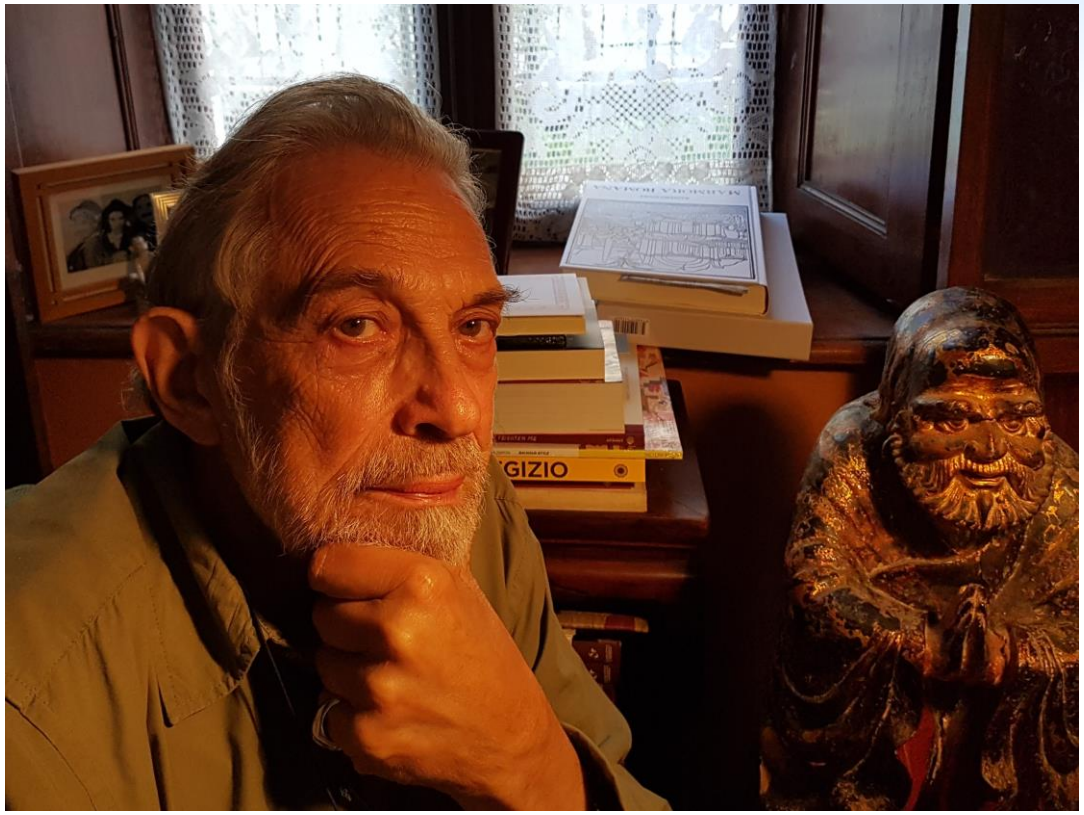
Vladimir Kriventsev, Chirayu Batra
Fast Reactor Development Team
Nuclear Power Technology Development Section
Department of Nuclear Energy
International Atomic Energy Agency - **IAEA**

Workshop Programme

- Lectured during the first half of the day
- Second half is devoted to group activities and poster sessions
- **Poster Session**: Please be present on the day assigned to you. The other groups and the lecturers will be invited to review the posters
- **Group Activities**

	Monday, 20 Aug	Tuesday, 21 Aug	Wednesday, 22 Aug	Thursday, 23 Aug	Friday, 24 Aug
08:30 – 09:00	- Registration	Students arrive and lecturers prepare			
09:00 – 10:30 (2)	- Opening - IAEA Activities on Innovative NES *Vladimir Kriventsev*	Fuel Cycle options for Innovative Nuclear Energy Systems *Massimo Salvatores*	Coolant Options for Innovative Nuclear Energy Systems *Christian Latge*	Thermal Hydraulics of Advanced Liquid Metal Cooled Reactors *Vladimir Kriventsev*	Safety of Fast Reactors: Phenomenology & Modelling Aspects *Konstantin Mikityuk*
10:30- 10:45	Coffee Break				
10:45 – 11:30 (1)	Group Photo History of Nuclear Energy: Young Gen Review *Chirayu Batra*	GIF: Gen IV Reactor Design Concepts *Konstantin Mikityuk*	*Coolant Options for Innovative Nuclear Energy Systems* *Christian Latge*	Thermal Hydraulics of Advanced Liquid Metal Cooled Reactors Vladimir Kriventsev	**Group Presentations** *All Participants*
11:30 – 12:30 (1)	Global Scenario for Nuclear Energy and Future of Innovative NES *Massimo Salvatores*	Innovative Nuclear Energy Systems: Core Design and Neutronics *Konstantin Mikityuk*	Innovative Nuclear Energy Systems: Reactor Design and Structural Designs *Masakazu Ichimiya*	Interaction between coolant and structures of liquid metal cooled reactors *Christian Latge*	**Group Presentations** *All Participants*
12:30 – 13:30	Lunch Break				
13:30 – 15:00 (2)	INPRO Scenario Analysis for Development of Nuclear Energy Systems *Galina Fesenko*	Simulation of Neutronics for Advanced Reactors *Konstantin Mikityuk* Digital Nuclear Reactor *Chirayu Batra*	Innovative Nuclear Energy Systems: Reactor Design and Structural Designs *Masakazu Ichimiya*	Fundamentals and Innovative Designs of Molten-Salt Reactors *Adriaan Buijs*	Final remarks, certificates distribution and closing session
15:00 – 15:15	Coffee Break				
15:15 – 16:00 (1)	INPRO Comparative Evaluation of Nuclear Energy System Options *Galina Fesenko*	**Group Activities: 1 & 3** *Chirayu Batra* *Konstantin Mikityuk* *Adriaan Buijs*	**Group Activities** Discussion Session *Chirayu Batra*	**Group Activities** *Chirayu Batra* *Konstantin Mikityuk* *Adriaan Buijs* *Galina Fesenko*	
16:00 – 17:00	Description and distribution of the **Group Activity 1** *Konstantin Mikityuk* *Chirayu Batra*	**Poster Session** *Massimo Salvatores* *Konstantin Mikityuk* *Christian Latge* *Masakazu Ichimiya* *Adriaan Buijs*	**Poster Session** Konstantin Mikityuk Christian Latge Masakazu Ichimiya Adriaan Buijs		

Our Lecturers: **Prof. Massimo Salvatores**



- Consultant in Reactor and Fuel Cycle Physics and Senior Scientific Advisor at the Idaho National Laboratory
- Former Head of the Reactor and Fuel Cycle Physics Division at CEA-Cadarache (France) and subsequently named Research Director
- Leader of several international studies on innovative fuel cycles; presently performing basic research on nuclear data measurements, sensitivity and uncertainty analysis, advanced simulation experimental validation and on theoretical methods for unusual reactor systems
- Awarded in 2002 the “Grand Prix Ampère” of the French Academy of Sciences and in 2005 of the ANS “E.Wigner” Award
- Fellow of the ANS and member of the International Nuclear Energy Academy
- Founder of the International Summer School in Reactor Physics “Frédéric Joliot/Otto Hahn” (FJOH)
- More than 250 peer-reviewed papers on various aspects of reactor physics.

Our Lecturers :
Prof. Christian Latge

- Graduated in chemical engineering from Institut National Polytechnique de Toulouse.
- PhD. Research Engineer in French CEA.
- Involved in SFRs (Superphenix, Phenix, Astrid) (Na technology, education and training) Fusion (fuel clean-up system, Isotopic Separation System, H safety..), ADS (Spallation target; director of Megapie project)
- Currently involved in several international bilateral or multilateral collaborations dedicated to Fast Reactors.
- Teacher in INSTN and several Universities.

Our Lecturers: **Prof. Masakazu Ichimiya**

- Consultant in Department of Nuclear Engineering and Management School of Engineering, The University of Tokyo
- Former Director General of FBR Engineering Center of JAEA (Japan Atomic Energy Agency).
- Former Professor at Research Institute of Nuclear Engineering in University of FUKUI
- Professional Experiences:
  - activities on MONJU project during 1979-1999
  - activities on Japanese Demonstration Reactor Project during 1999-2010
  - activities on SFR SSC (System Steering Committee) of GIF during 2001-2010, and Chair of SFR SSC during 2008-2010
- Published four books, one for structural design of nuclear facility and three for fast reactors. Most recently published one is “Fast Reactor System Design,” (Springer)

Our Lecturers: **Dr. Konstantin Mikityuk**

- PhD, 2002, from PostGraduate School of Russian Research Centre “Kurchatov Institute”
- Advanced Nuclear Systems Group Leader at Paul Scherrer Institute, Switzerland
- Coordinator of the Horizon-2020 ESFR-SMART project devoted to the safety of the European Sodium Fast Reactor
- Representative of Switzerland at
  - Generation-IV International Forum Experts Group and
  - International Atomic Energy Agency Technical Working Group on Fast Reactors

- Research interests:
- safety of Generation-IV fast reactors
- advanced modelling of coupled neutronics and thermal hydraulics
- sodium boiling in low-void SFR core

Our Lecturers: **Prof. Adriaan Buijs**

- Professor of Engineering Physics at McMaster University, Hamilton, Canada
- Prof. Buijs specializes in nuclear reactor core physics of existing designs such as CANDU reactors and research reactors at Canadian Nuclear Laboratories (ZED-2) and McMaster (NMR), and future reactor designs, such as the Advanced CANDU reactor (ACR-1000), the Canadian Supercritical Water Reactor, and Molten Salt Reactors
- Prior to becoming professor at McMaster, Adriaan was the manager in charge of the reactor core design of the ACR-1000 at Atomic Energy of Canada, Limited
- Before coming to Canada, Mr Buijs was professor in experimental particle physics at Utrecht University, participating in experiments at LEP and the design of experiments at the Large Hadron Collider
- Prof. Buijs is a fellow and past-president of the Canadian Nuclear Society

Our Lecturers: **Dr. Galina Fesenko**

- Since 2013 Nuclear Engineer at the IAEA, International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)
- Scientific secretary for collaborative projects on scenarios and pathways to sustainable nuclear energy development and studies on architecture for innovative nuclear energy systems
- Responsible officer for IAEA publications, co-authored several conference and journal papers on topics relevant to the collaborative projects
- Supporting the INPRO education and training activity
- Awarded in 2017 by IAEA for outstanding performance
- Before joining the IAEA: more than 20 years contributing to nuclear physics education and science in Obninsk technical university for nuclear power engineering in Russian Federation, including lecturing and scientific research in nuclear physics and nuclear power development

IAEA Lecturers:

Mr. Chirayu Batra

- Since 2015, Nuclear Engineer in Fast Reactor Technology Development Team, IAEA
  - Chirayu supports all IAEA activities on fast reactors, such Coordinated Research Projects (CRPs), Education and Training Workshops, International Conferences, etc.
  - Awarded by IAEA for outstanding performance in 2018
- Double MS from UPC-Barcelona Tech and INSTN CEA-Saclay in 2013
- Chirayu has been working in nuclear engineering and fast reactor technology for last 5 years
- President of UN-Nuclear Young Generation

Dr. Vladimir Kriventsev

- Since 2016, Team Leader of Fast Reactor Technology Development Team, IAEA
  - Vladimir serves a Scientific Secretary for the IAEA activities on fast reactors, such Coordinated Research Projects (CRPs), Education and Training Workshops, International Conferences, etc.
- PhD from Obninsk Inst. For Nuclear Engineering in 1994
- Dr. Engineering from Tokyo Institute of Technology in 1999
- Vladimir has been working in nuclear engineering and fast reactor technology in
  - IPPE (Obninsk)
  - TITech (Tokyo Inst. of Technology)
  - JNC (JAEA now)
  - INPE (Obninsk) and
  - KIT (Germany, former FZK).

IAEA
International Atomic Energy Agency

IAEA goals, mandate and assistance to the IAEA Member States

This is the IAEA

IAEA: Main Work Areas

Nuclear Technology & Applications

Nuclear Energy

Nuclear Sciences & Applications

Technical Cooperation

Nuclear Safety & Security

Nuclear Safety & Security

Safeguards & Verification

Safeguards

By the Numbers

Founded in 1957: **62 Years** of international service

168 Member States (as of February 2016)

~2500 Professional and support staff

Regular Budget (2016) ~ €360M

Extra-budgetary (voluntary) ~ €50M

Technical Cooperation Fund contributions (voluntary) **~ €90M** in 2016

12 international laboratories (Vienna, Seibersdorf and Monaco) and research centres

1+ million documents, technical reports, standards, conference proceedings, journals and books in the IAEA Library

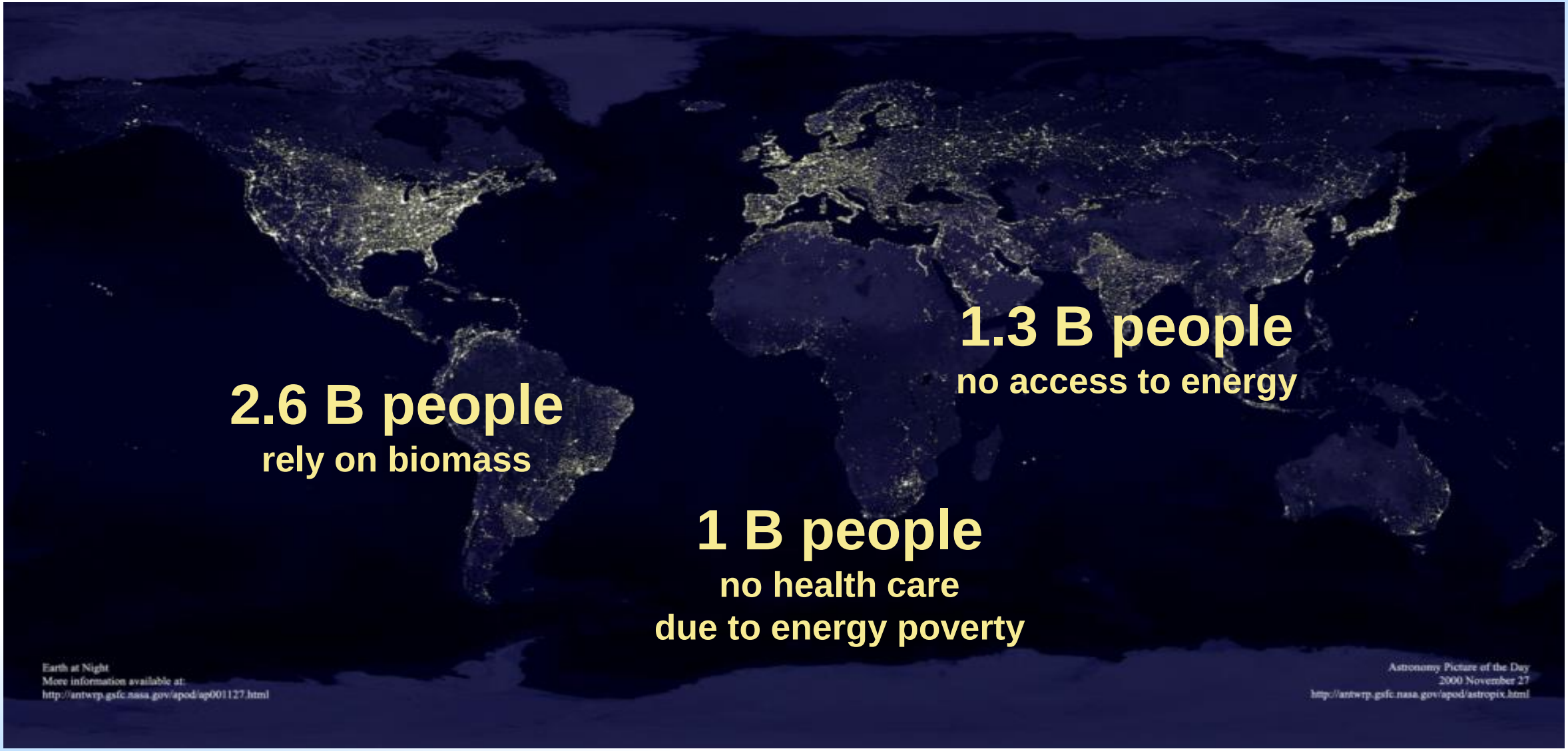
IAEA
International Atomic Energy Agency

A more Sustainable World: the peaceful applications of Nuclear Power and the Sustainable Development Goals

IAEA & UN SDGs

(Sustainable Development Goals)

Energy 2017


1.3 B people
no access to energy
2.6 B people
rely on biomass
1 B people
no health care
due to energy poverty
Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap001127.html
Astronomy Picture of the Day
2000 November 27
http://antwrp.gsfc.nasa.gov/apod/astropix.html

Goal 2 – Zero Hunger

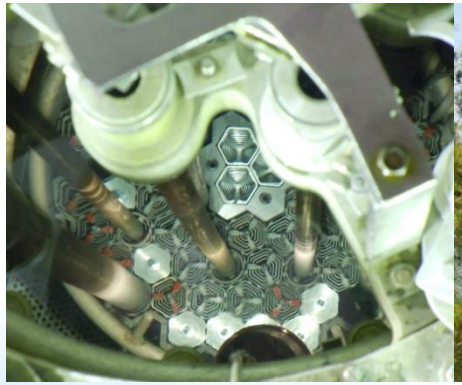
- Food safety
- Insect pest control
- Livestock production
- Crop improvement
- Water and soil management

Goal 3 - Health

- Cancer prevention and control
- Nuclear medicine & radiation oncology
- Zoonotic disease monitoring
- Nutrition

Goals 7 & 9 – Energy / Industrialization

- Energy planning
- Introduction of nuclear power (milestones)
- Nuclear fuel cycle
- Research reactors
- Industrial applications




Goals 6 & 14 – Clean Water and Sanitation / Life below water

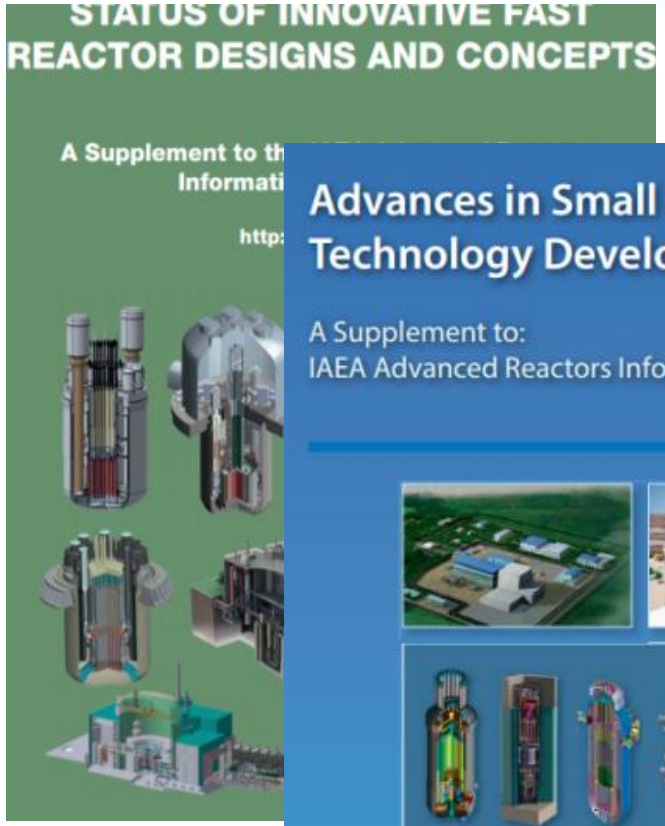
- Water resources management (isotope hydrology)
- Marine, terrestrial and coastal environment protection
- Water & soil management

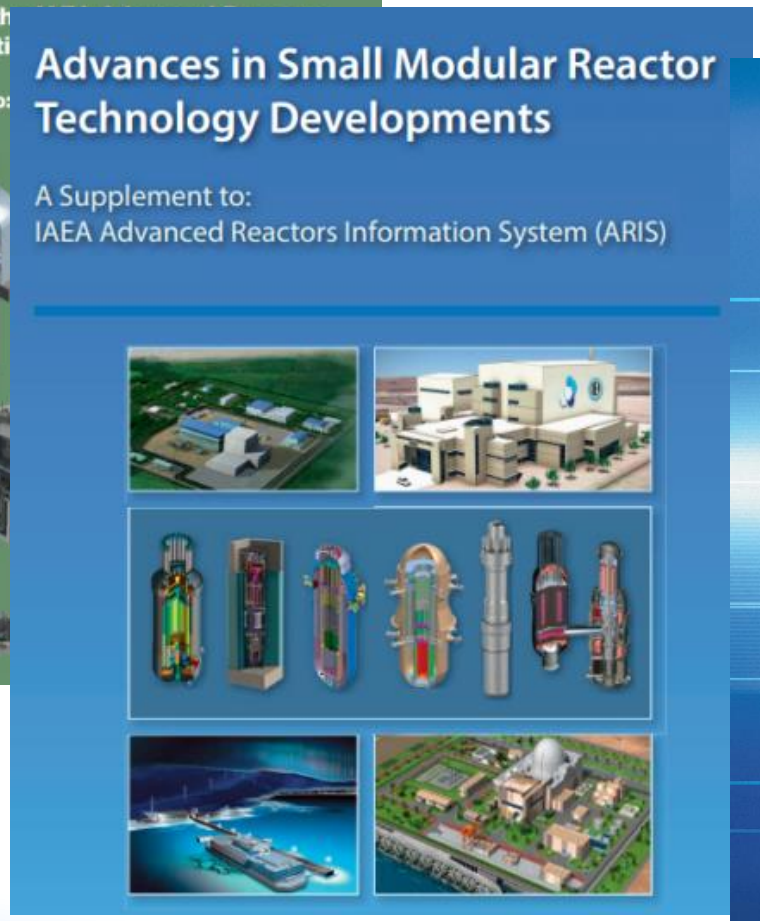


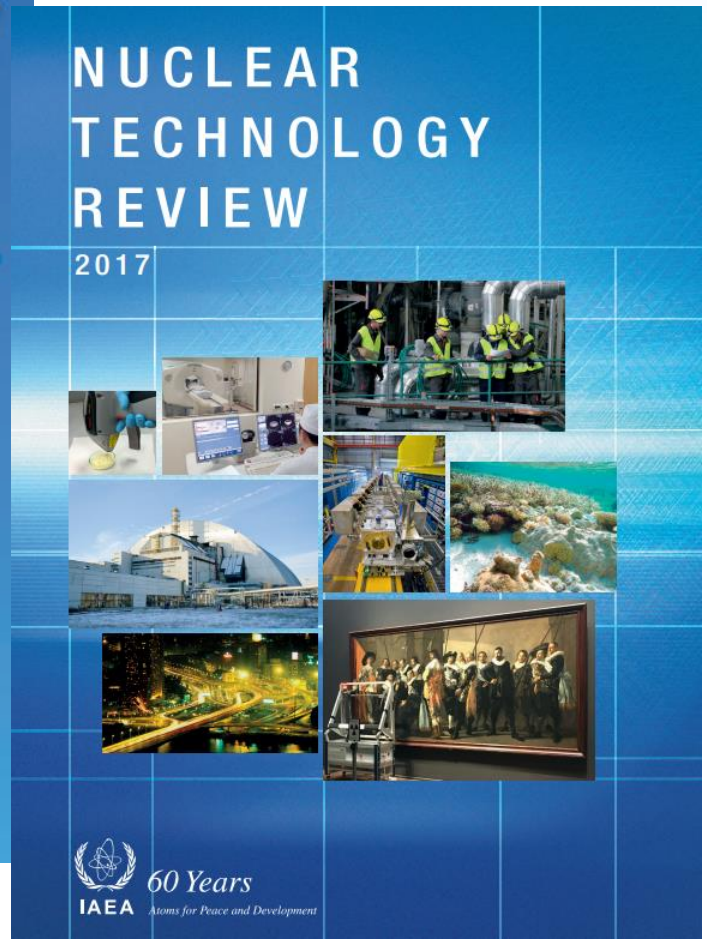

Goals 13 & 15 – Climate action / Life on Land

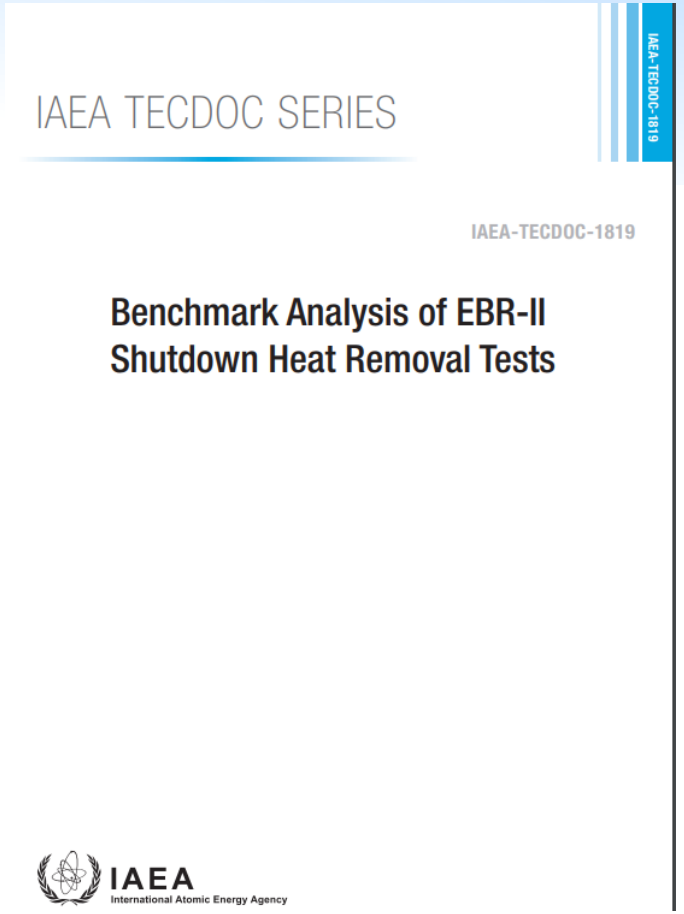
- Climate change monitoring, pollution mitigation
- Soil studies
- Safety & radioactive waste management and disposal

Innovation & Technology Development



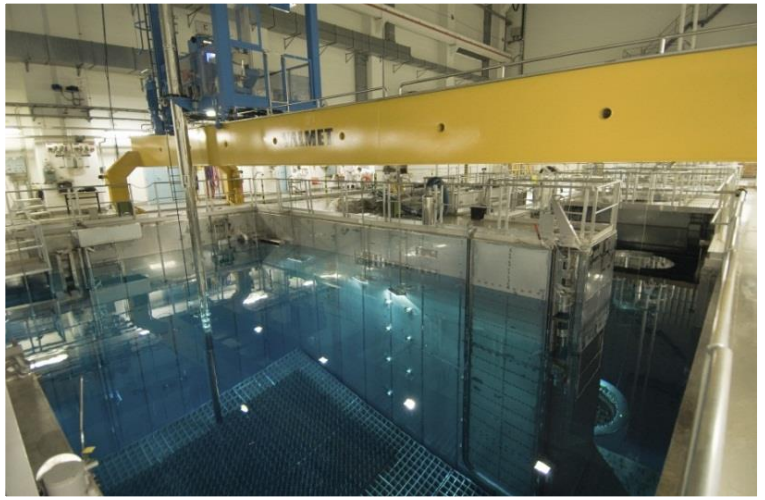






What Makes Nuclear Power Unique

- Long-term Government Commitment needed
- Long-term nuclear waste management
- Capital intensive investment
- Well-trained human resources
- High level of safety and security
- Control of nuclear materials
- Public perception



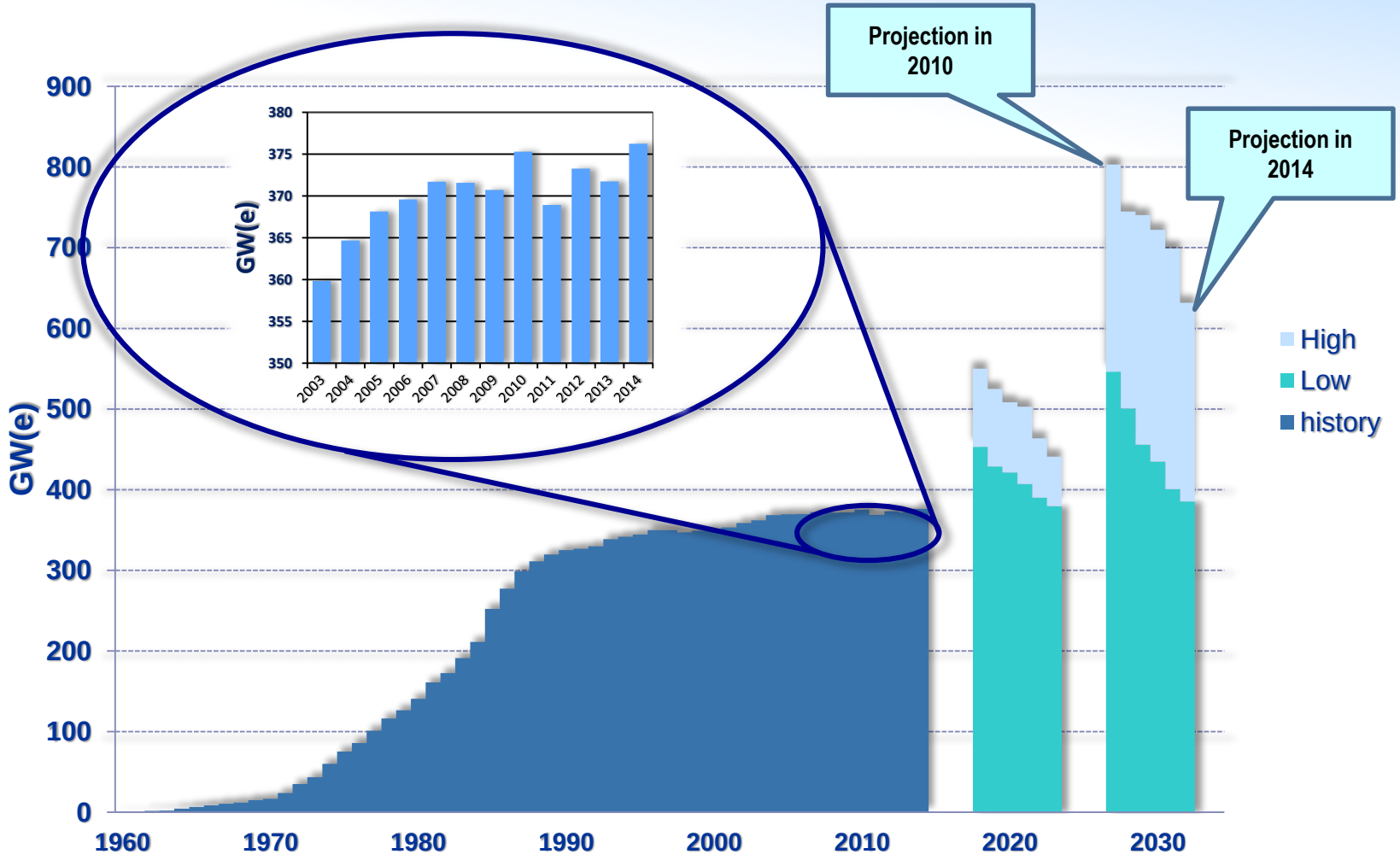
Nuclear Power Reactors Today

In 2014 nuclear power reactors generated 2410 TWh of electricity

Today* there are 441 nuclear power reactors (~382 GWe) in operation in 30 countries

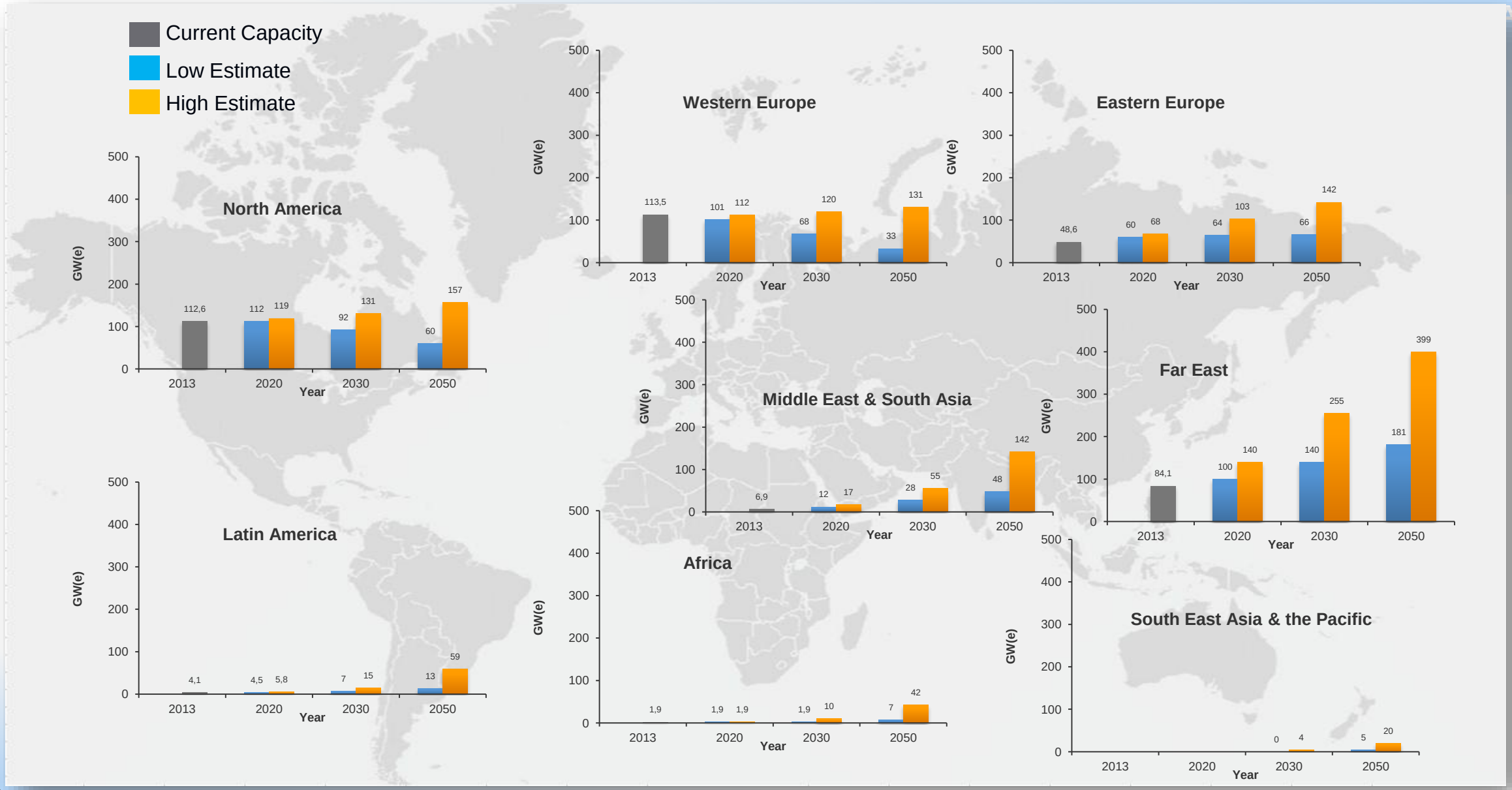
As of January 2016 there are 67 NPPs under construction in 15 countries (2 newcomer countries)

Nuclear Capacity 2020 – 2030: Projections



Ref.: Energy, Electricity and Nuclear Power Estimates for the Period up to 2050, 2015 Edition, IAEA

Regional Development of Nuclear Power



Working at the IAEA

IAEA
International Atomic Energy Agency

Fast Reactor Technology Development Team:

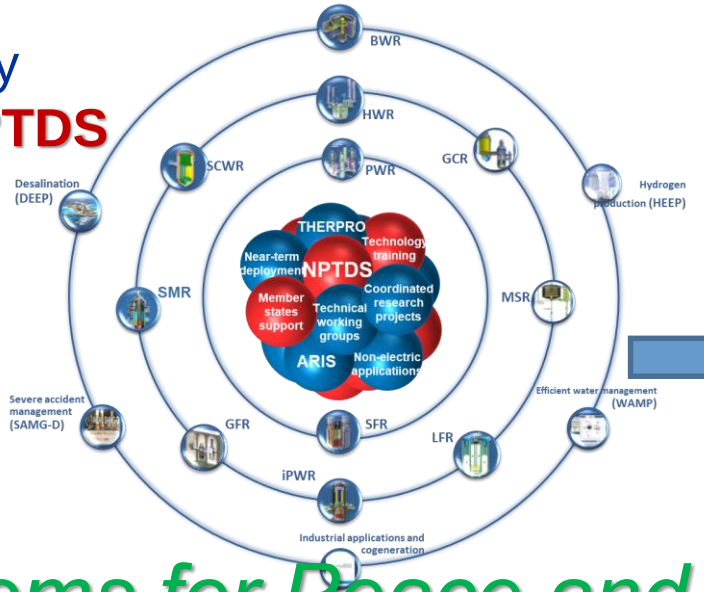
Advanced Technology of Innovative Nuclear Energy Systems

IAEA Fast Reactor Technology Development Team

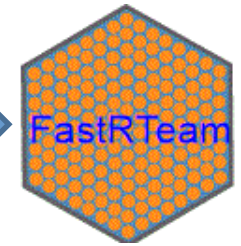
DDG: Mikhail Chudakov

DIR: Dohee Hahn

Nuclear Power Technology
Development Section **NPTDS**
Head: Stefano Monti



Fast Reactor Technology
Development Team



"Atoms for Peace and Development"

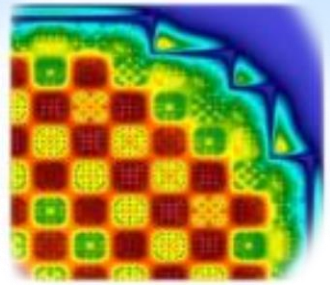
Main Activities on Fast Reactor Technology in 2017-2018

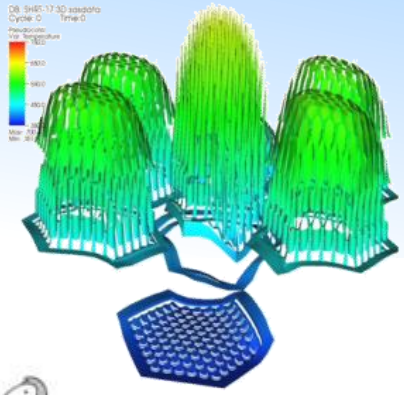
- FR17 Conference in Yekaterinburg
- CRPs/Benchmarks
  - 2 Ongoing: **NAPRO** and **PSFR Source Term**
  - 2 New: **CEFR Start-Up Tests** and **FFTF ULOF**
  - Study on **Passive Shutdown Systems** for Fast Reactors
- Technical Working Group on Fast Reactors
  - 50th TWG-FR Meeting in Vienna, May 2017
  - 51st TWG-FR Meeting in Hefei, China, 21-25 May 2018
- GIF-IAEA Workshops on Safety of SFR/LMFR
  - Continuous in-depth discussions on the development of SFR SDC/SDG
  - 7th GIF-IAEA Workshop on LMFR Safety: 27-29 March 2018
    - Review of GIF Report on Safety Design Guidelines on Safety Approach & Design Conditions for GEN-IV SFRs
  - 8th GIF-IAEA Workshop on LMFR Safety: 27-29 March 2018
- LMFNS Experimental Facilities Database
- Training Courses and Workshops
  - Joint ICTP-IAEA Workshop on the Physics and Technology of Innovative Nuclear Energy Systems for Sustainable Development (2016, Trieste, Italy)
  - Next Workshop: 20 – 24 August 2018, Trieste, Italy

Fast Reactors: Key Activities

Modelling and Simulations

- Coordinated Research Projects (CRPs)
  - ***EBR-II*** *(Shutdown Heat Removal Tests)*
  - ***NAPRO*** **(Sodium properties)**
  - ***PSFR*** Source Term
  - ***CEFR*** Start-Up Tests: **NEW**
  - ***FFTF*** ULOF Test: **NEW**





Knowledge Preservation

- Fast reactor knowledge preservation portal **(*FRKP*)**
- Liquid metal cooled fast neutron system database (***LMFNS***)

Education and Training

- **SFR Simulator** for Educational Purposes
- **ICTP-IAEA Workshops** on the Physics and Technology of **Innovative Nuclear Energy Systems**

Safety

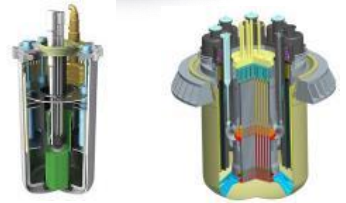
- Joint **IAEA-GIF** Workshops on LMFR Safety
- **Passive Shutdown Systems** for Fast Neutron Systems – NES Publication

Technology Support

- ***NAPRO*****:** CRP
- ***LMFNS*** Catalogue

Information Exchange

International Cooperation



Fast Reactors: *Coordinated Research Projects*

CRPs on Fast Reactors Technology

CRP recently completed

- BN-600 MOX Core Benchmark
- Analytical and Experimental Benchmark Analysis of ADS
- PHENIX – EOL Tests
- MONJU – Na Natural Convection

CRP currently on-going

- **NAPRO** – Na Properties and Safe Operations of Exp. Facilities
- **PSFR Source Term** – Radioactive Release Under Severe Accident Conditions

New CRPs

- MONJU – Turbine Trip Test
- **Neutronics Benchmark of CEFR Start-Up Tests** (27 participants)
- Benchmark Analysis of **FFTF** Loss of Flow Without Scram Test

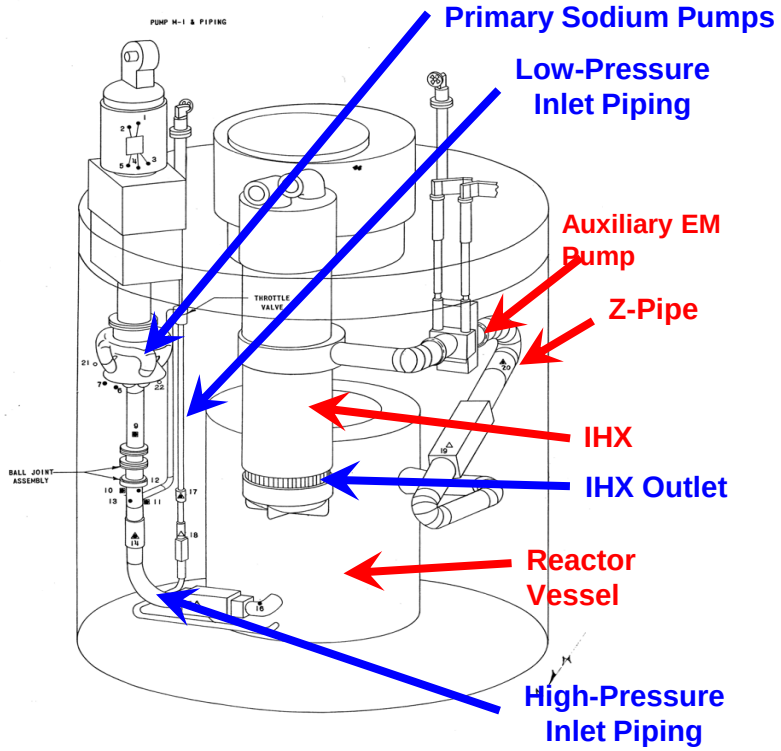
EBR-II Shutdown Heat Removal Tests (published in 2017)

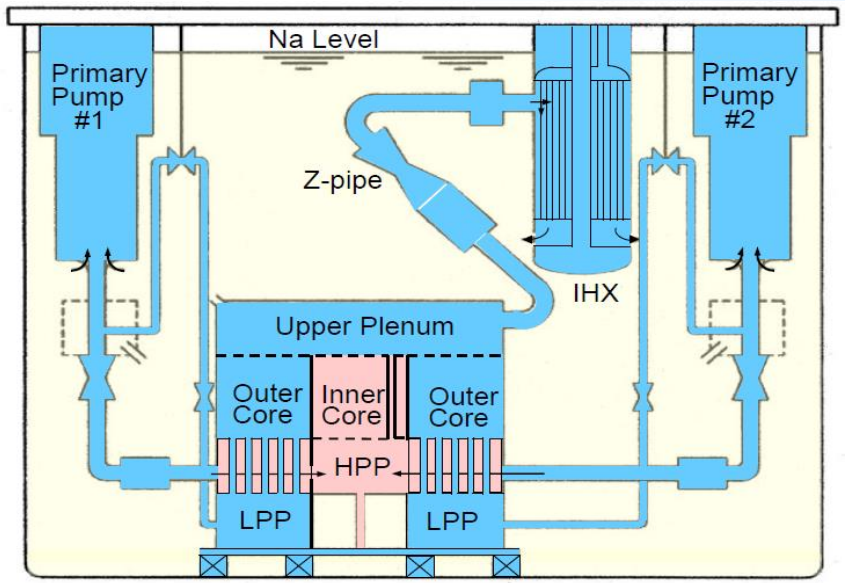
IAEA TECDOC SERIES

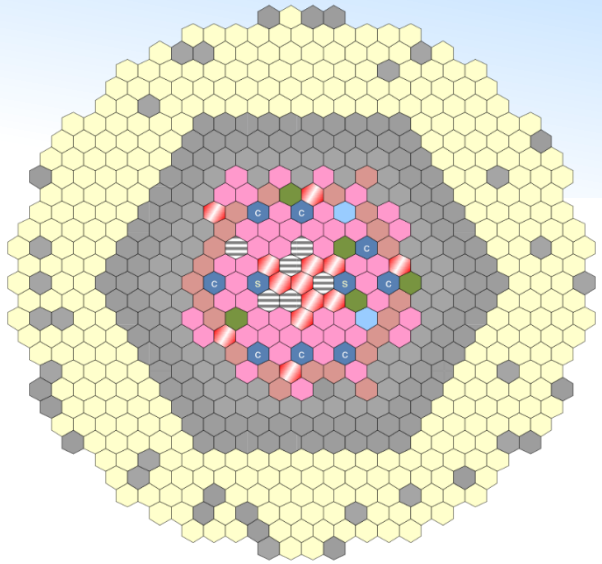
IAEA-TECDOC-1819

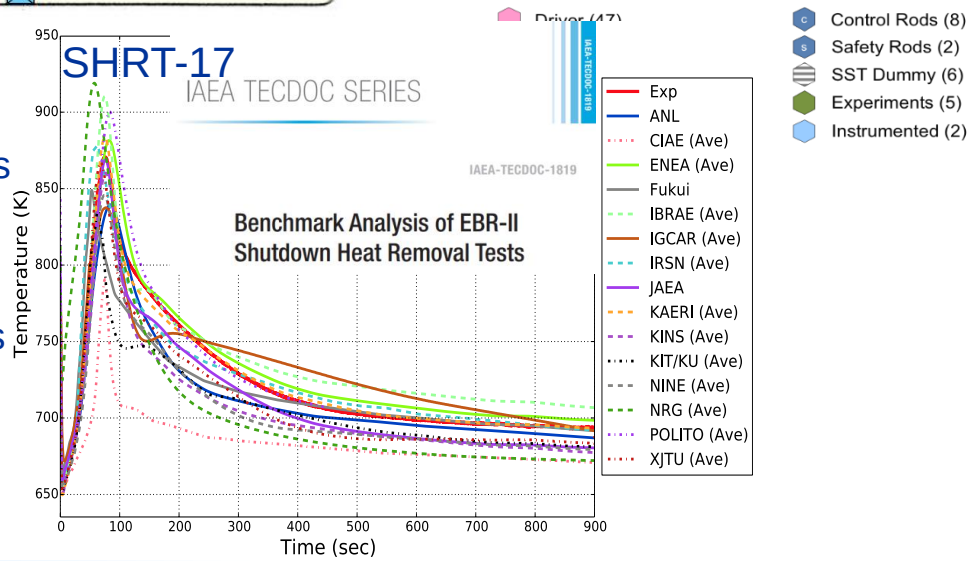
Benchmark Analysis of EBR-II Shutdown Heat Removal Tests

CRP on Benchmark Analysis of *EBR-II* Shutdown Heat Removal Test (*2012-2016*)



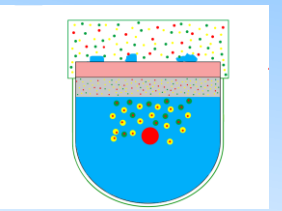






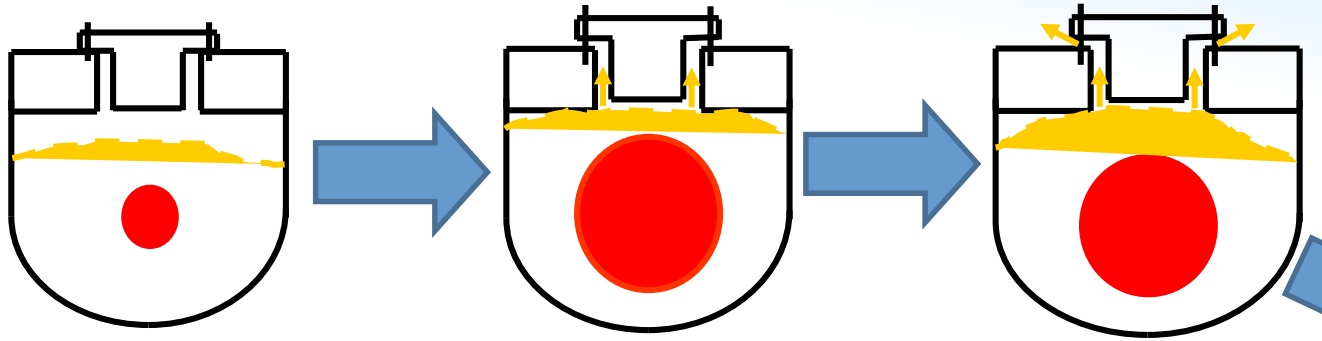
- Coupled Neutronics and Thermalhydraulic Transient Simulations
- SHRT-17 (Protected): Loss of normal and emergency pumping
- SHRT-45 (Unprotected): Loss of normal flow, scram disabled, station blackout
- 20 Organizations from 12 Countries jointly produced simulations predicting most plant parameters with acceptable accuracy
- Neutronics benchmark was an added dimension to the CRP

CRP on Radioactive Release from Prototype SFR under Severe Accident Conditions



IAEA

CDA development and propagation in pool type SFR

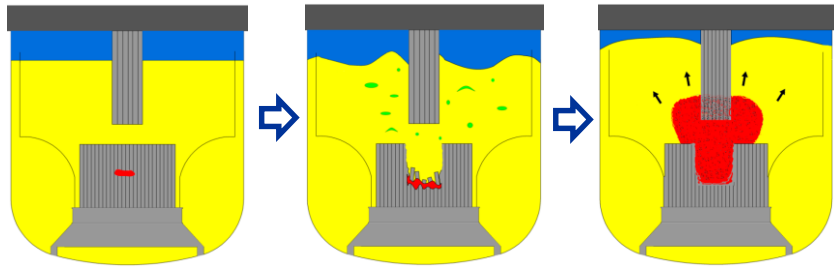


Initiation *(neutronics), and* ***Transition*** *(fuel relocation) Phases*

Core Melt/Bubble is formed

I. *Expansion Phase*

Core bubble expands in sub-cooled sodium



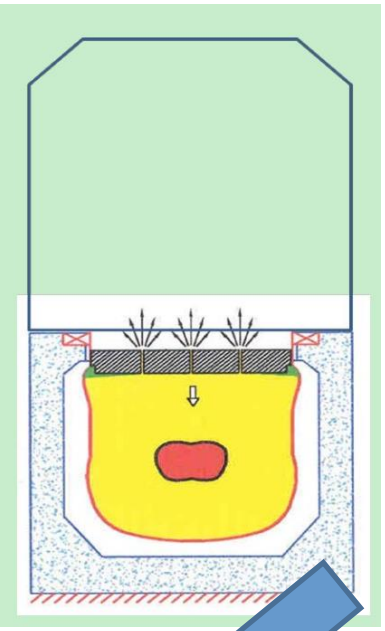
Incipient melting and early relocation

Extended relocation and core compaction

Rapid fuel vapor bubble expansion

II. *Quasi-static Phase*

Release of sodium to the Reactor Containment Building (RCB)



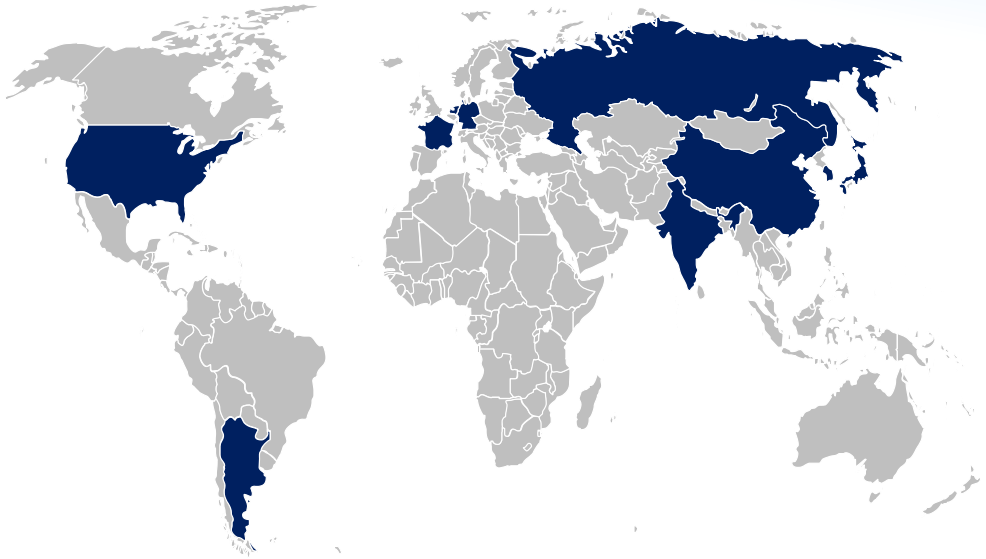
Reference design for the safety analysis:
500 MWe pool type PFBR

Very complicated multi-physics phenomenon
Can be a Standard Benchmark for Verification of Safety Analysis Codes and Models

III. *Containment Source Term*

- Evaluation of multi-component aerosol evolution is required
- Two typical sodium fire accidents:
- *sodium pool fire accident*
- *sodium spray fire accident*

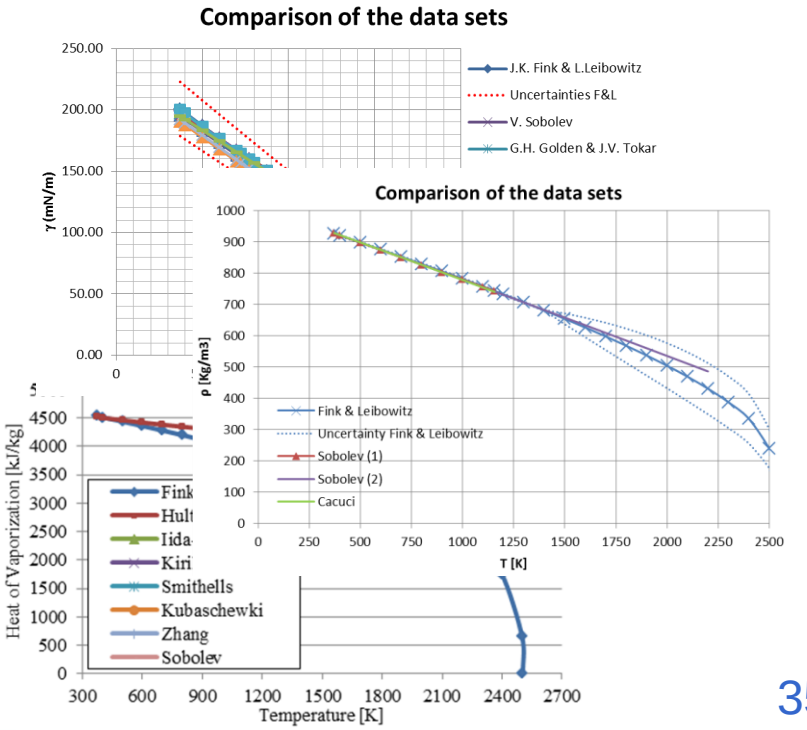
NAPRO CRP: Sodium properties and safe operation of experimental facilities in support of SFRs (2013-2018)



“Sodium properties and safe operation of experimental facilities in support of the development and deployment of SFR”

Argentina (CNEA)	China (CIAE)
France (CEA)	India (IGCAR)
Germany (KIT, HZDR)	Japan (JAEA)
Korea, Republic of (KAERI)	Netherlands (NRG)
Russian Federation (IPPE)	USA (ANL)

- **WP1**: Collection and assessment of sodium properties: harmonization of international data and correlations
- **WP2**: Design rules and best practice for Na exp. facilities
- **WP3**: Guidelines for the safe operation of Na exp. facilities
- 4th RCM in Vienna, 12 -14 June 2017
- Two TECDOCs and one NES to be published
  - TECDOC: Sodium Coolant Handbook: Physical and Chemical Properties (2018)
  - TECDOC: Sodium Coolant Handbook: Thermal-Hydraulic Correlations (2018)
  - NES: Design, Operation and Safety of Sodium Experimental Facilities (2019)



New CRP: **Neutronics Benchmark of CEFR Start-Up Tests**

中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

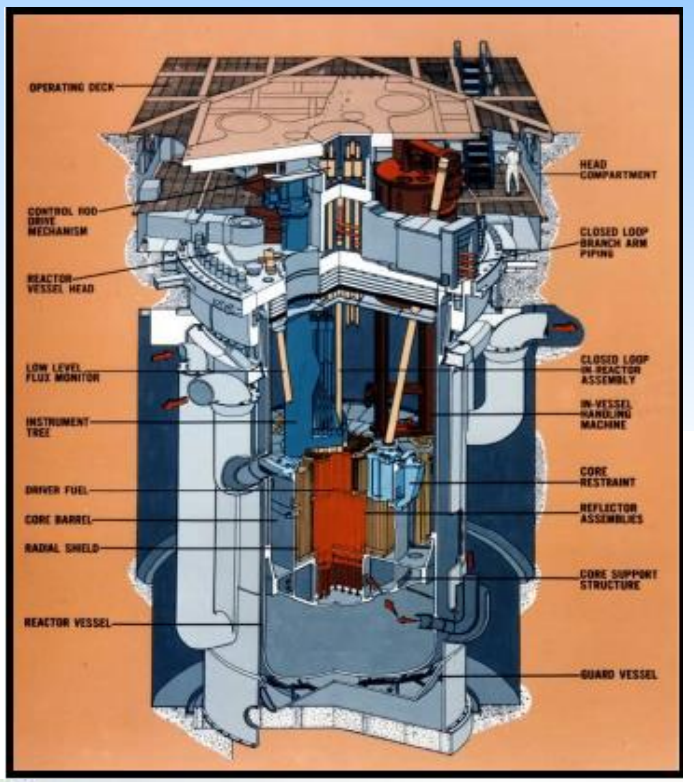
IAEA

- China Experimental Fast Reactor
  - Sodium-cooled fast reactor with nominal power of 65MW(th), 20MW(e)
  - Reached the first criticality in 2010
  - Generated electricity at 40% full power and was connected firstly to the grid in July 2011
  - Generated electricity at 100% power in December 2015 and operated for more than 40 effective full power days

CIAE at Consultants' Meeting November 2017, Vienna

New CRP: **Benchmark Analysis of FFTF Loss of Flow Without Scram Test**

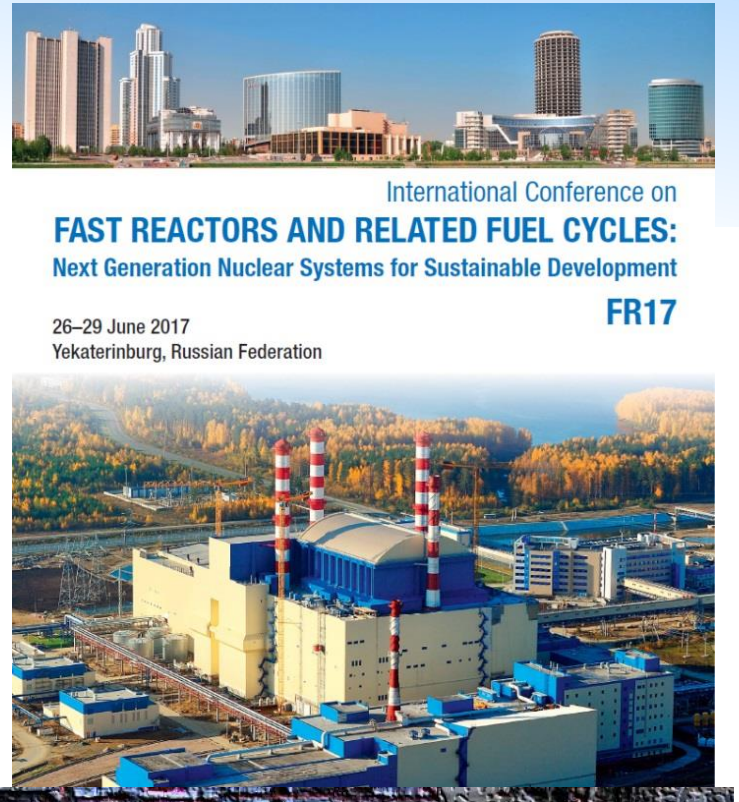
- FFTF Reactor:
  - 400 MWth sodium cooled fast test reactor
  - Mixed UO2-PuO2 (MOX) fuel
  - Loop type plant, axial and radial reflectors
  - Prototypic size
    - ~1m^3 core volume
    - ~91 cm high, ~120 cm diameter
  - Series of Passive Safety Tests
    - Demonstrated passive safety of SFRs
    - Demonstrated efficacy of negative reactivity insertion safety devises (GEMs)



PNNL/ANL at Consultants' Meeting
November 2017, Vienna

International Conference on Fast Reactors and Related Fuel Cycles:

Next Generation Nuclear Systems for Sustainable Development FR17



FR17: Young Generation Event

YGE Panel **13:30-15:30** **Young Generation Event**

Venue: Plenary Hall

Next Generation Nuclear Systems: "The Force Awakens"

Chair: **C. Xerri**
Moderator: **C. Batra**

Thursday 29 June 2017

Time	Presenter	Country	Title
13:30	C. Batra	IAEA	Introduction of the Panel
13:35	L. Lebel	Canada	How the Next Generation of People will shape the Next Generation of Nuclear
13:50	K. Gladinez	Belgium	Innovative cold trap filtration technologies for reliable and economical exploitation of lead-bismuth eutectic cooled systems
14:05	E. Bissen	France	Stability and bifurcation analysis of sodium boiling in a GEN IV SFR reactor core
14:20	S. Aravindan	India	Development of Reverse Flow Blockage Device for Primary Sodium Pumps of Fast Breeder Reactor
14:35	E. Pettersen	Switzerland	Developing an open-source multi-physics tool for simulating advanced nuclear reactors
14:50	B. Sreenivasulu	India	Development of Tri-iso-Amyl Phospahte (TiAP) based solvent extraction process as an alternate method for the processing of metallic alloy fuels (U-Pu-Zr and UZr)
15:05	***General Discussion***		

Watch event

https://www.facebook.com/iaeaorg/videos/10154480978397062/?t=0

LMFNS Experimental Facilities Database

Experimental Facilities in support of Development and Deployment of Liquid Metal cooled Fast Neutron Systems

Includes an overview as well as detailed information on 150 experimental facilities under design, construction or operation

19 institutions from 14 IAEA Member States contributed

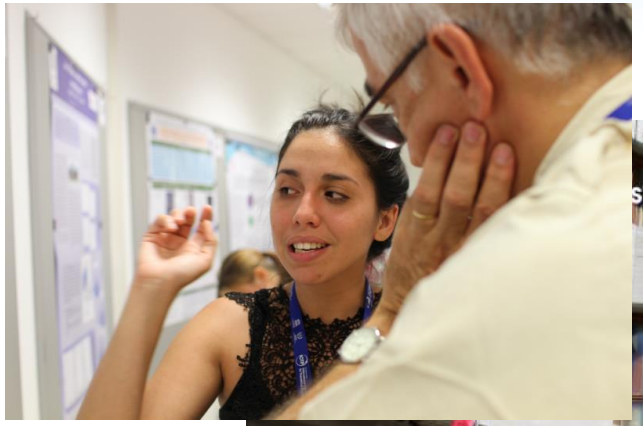
Freely Available at iaea.org: Search for "IAEA LMFNS"

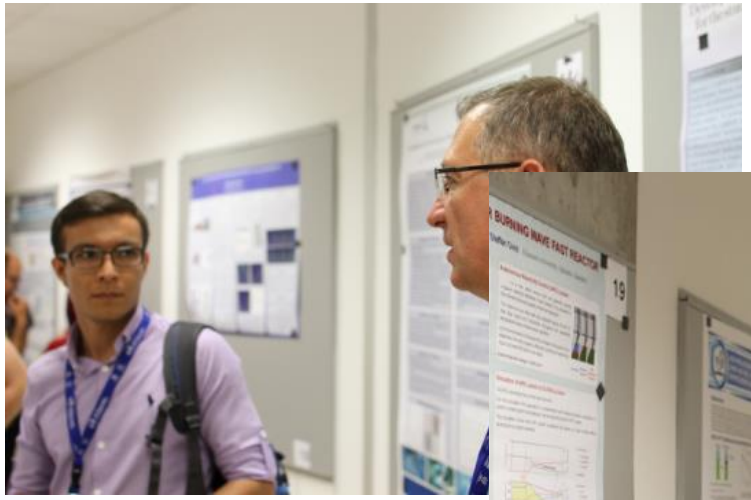
- A comprehensive Catalogue providing detailed information on experimental facilities currently designed, under construction or operating
- Facilities Designed to support the development and deployment of innovative liquid metal-cooled (sodium, lead and lead-bismuth) fast neutron systems (LMFNS), both critical and subcritical
- Identifies existing or future operational experimental facilities able to support innovative LMFNS
- Expected to facilitate cooperation using existing and planned experimental facilities for LMFNS, and enhance their utilization by providing end-users with detailed information
- Encourages international collaborations

Training Courses and Workshops

- **IAEA Workshops and Schools on Innovative Nuclear Energy Systems**
- **2016 WS:** 2016, Trieste, Italy
- **ICTP-IAEA Workshop on Physics and Technology of Innovative Nuclear Energy Systems**

  20 – 24 August 2018, Trieste, Italy





Thank You and Welcome to Trieste!