The Abdus Salam International Centre for Theoretical Physics

2473-22

Joint ICTP-IAEA School on Nuclear Energy Management

15 July - 3 August, 2013

Nuclear Infrastructure for Research, Development and Applications I

D. Ridikas
IAEA, Vienna, Austria

Lecture 1

Nuclear Infrastructure for R&D and Applications:

Research Reactors

19 November 2012

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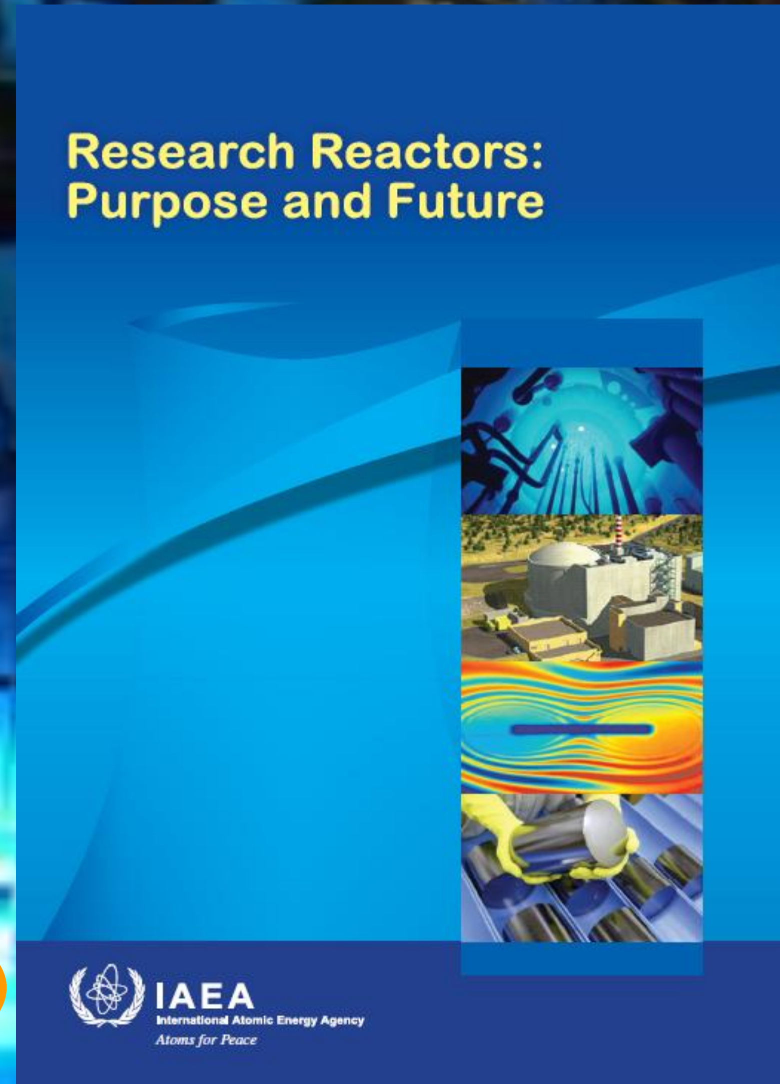
IAEA

International Atomic Energy Agency

Outline

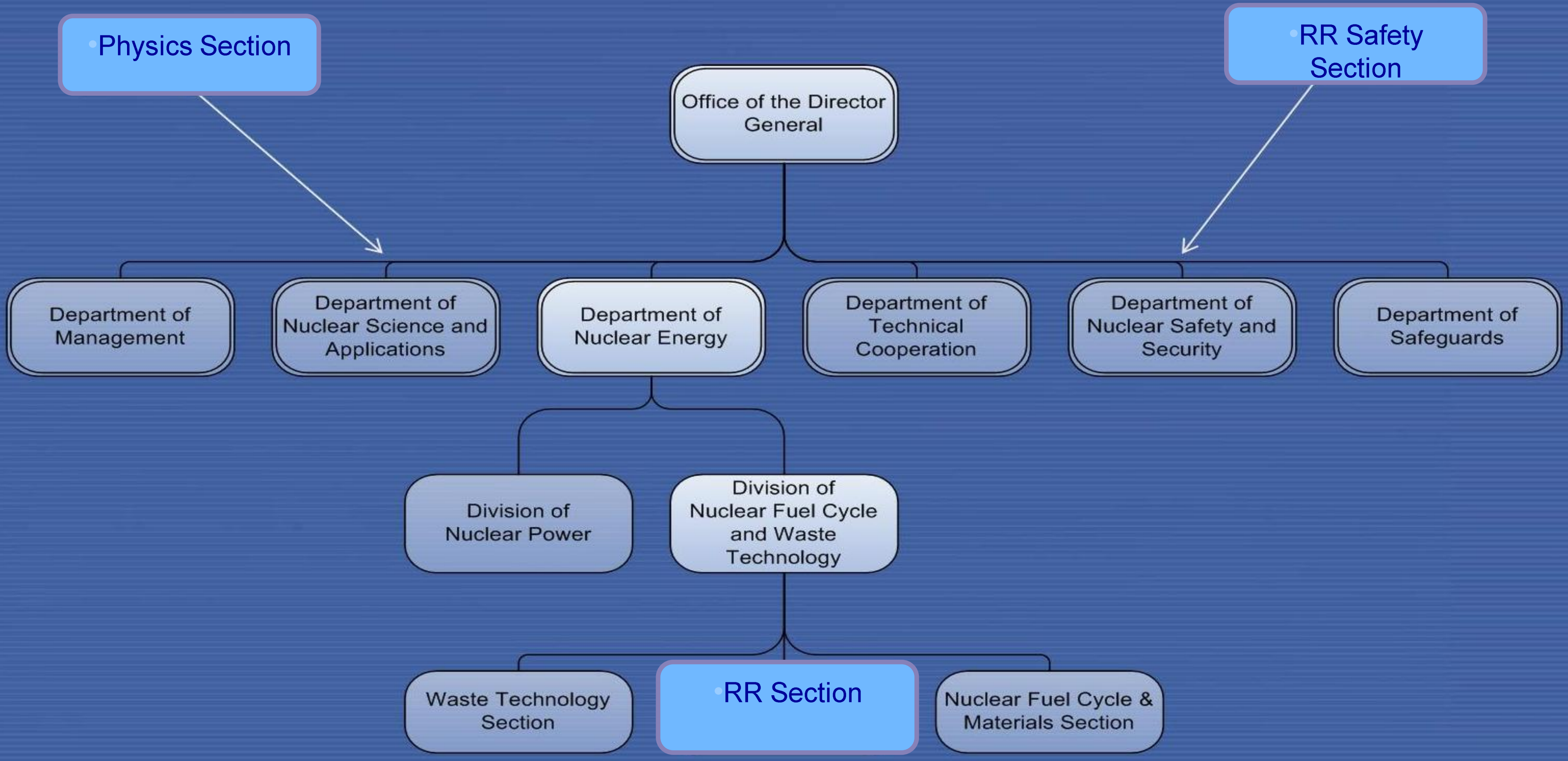
- Background
- IAEA RR Data Base
- Latest news on RRs
- Key Issues and challenges
- Role of RRs in Development of Nuclear Infrastructure
- (Applications of RRs TECDOC-1234, 2001)



http://www-naweb.iaea.org/napc/physics/research_reactors/

Research Reactors: organization within the IAEA

- http://www-naweb.iaea.org/napc/physics/research_reactors/
- http://www-ns.iaea.org/tech-areas/research-reactor-safety/



- http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/

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Major Activities within Physics Section

Assistance and support of Member States in the field of

1. **Accelerators**
2. **Research Reactors**
3. Controlled Fusion
4. Nuclear Instrumentation
5. Cross-cutting Material Research

Based on Member States needs, requests & recommendations

- Planning & implementation of P&B activities
- Proposal and implementation of CRPs
- Management of Data Bases
- Organization of Conferences, Technical & Consultancy Meetings
- Organization of ICTP workshops, training schools and courses
- Support of TC projects
- Promotion of Nuclear Sciences, Applications and Technologies

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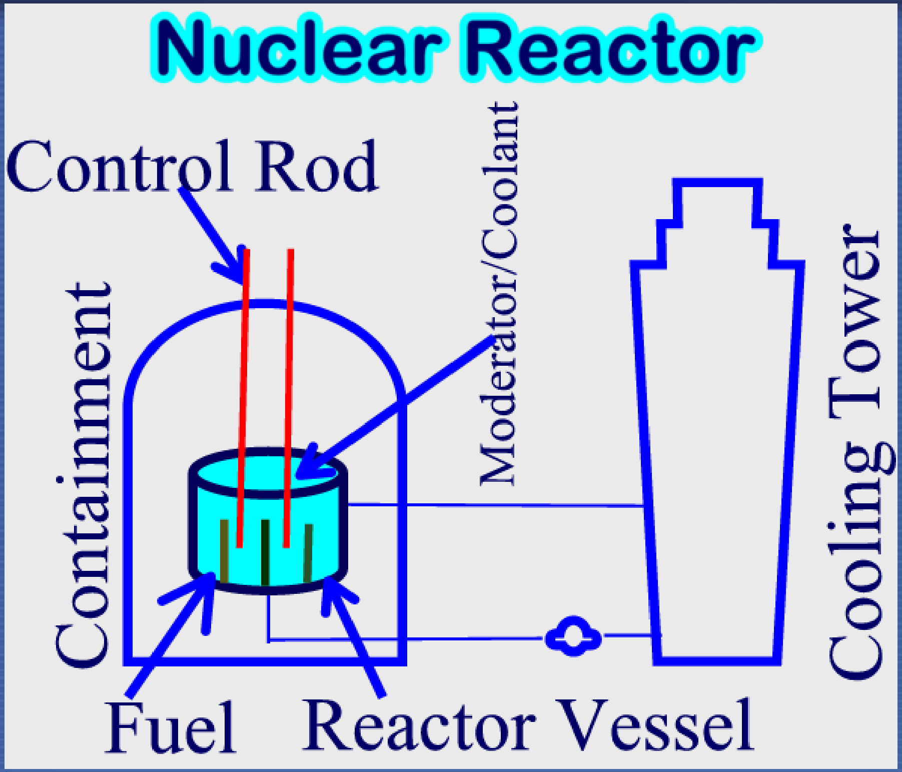
Introduction



Main Components of Research Reactor

FUEL	Natural Uranium / Enriched Uranium
FORM	Metal, Alloy, Oxide, Silicide
CLAD	Aluminium, Zirconium, SS
MODERATOR	H2O, D2O, Graphite, Beryllium
CONTROL	Boron, Cadmium, Nickel
COOLANT	Water, Gas, Sodium, PbBi
VESSEL	to contain all components

Basic Nuclear Physics

Interaction of neutrons with matter (fission, capture, scattering)
Criticality, role of delayed neutrons, radiocative decay
Basics of thermohydraulics

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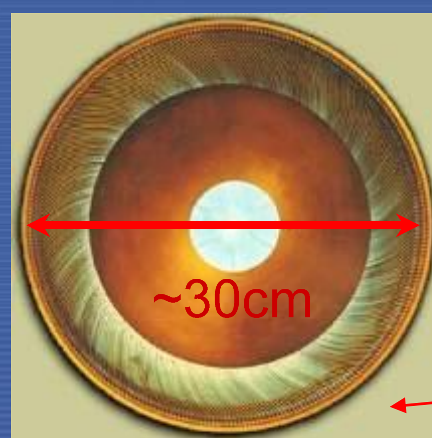
Introduction

Other general information: features

- Typically, RR cores have small volume
- Many have powers less than 5 MW(t)
- Higher enrichments than power reactors
- Natural and forced cooling
- Pulsing capability

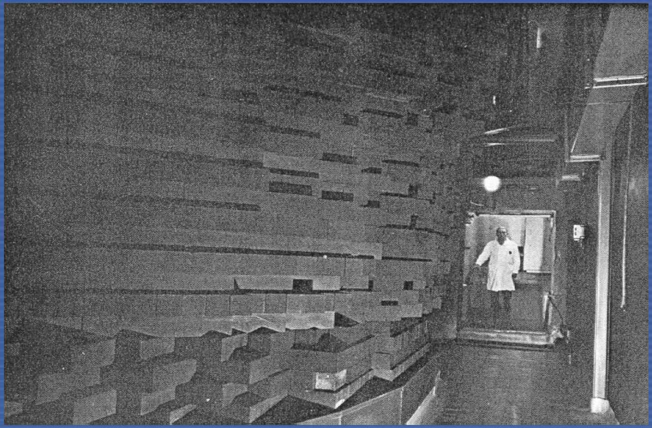


Background

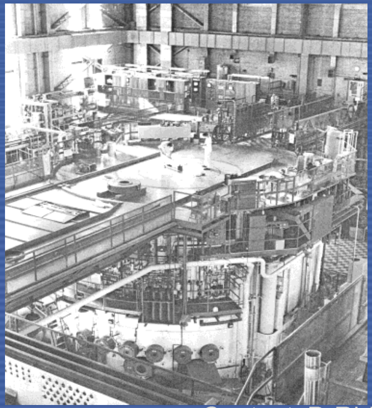
Some historical facts

- USA, Dec. 1942: Chicago Pile (CP1), E. Fermi
  - Objective: neutron source for Pu production

- Russia, Dec. 1946, F-1, I. Kurchatov
  - Objective: excess neutrons for Pu production



- Canada, Jul. 1947, Chalk River Laboratories
  - NRX – National Research Experiment
  - Reached 20MW(t) in 1949
  - Used for basic research
  - Contributed to nuclear x-section data



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Background

Some historical facts (continued)

- Obninsk, Russia, 1954 APS-1: Institute of Physics and Power Engineering
  - First reactor to generate appreciable electric power, 5 MW(e)
  - Start of nuclear energy…

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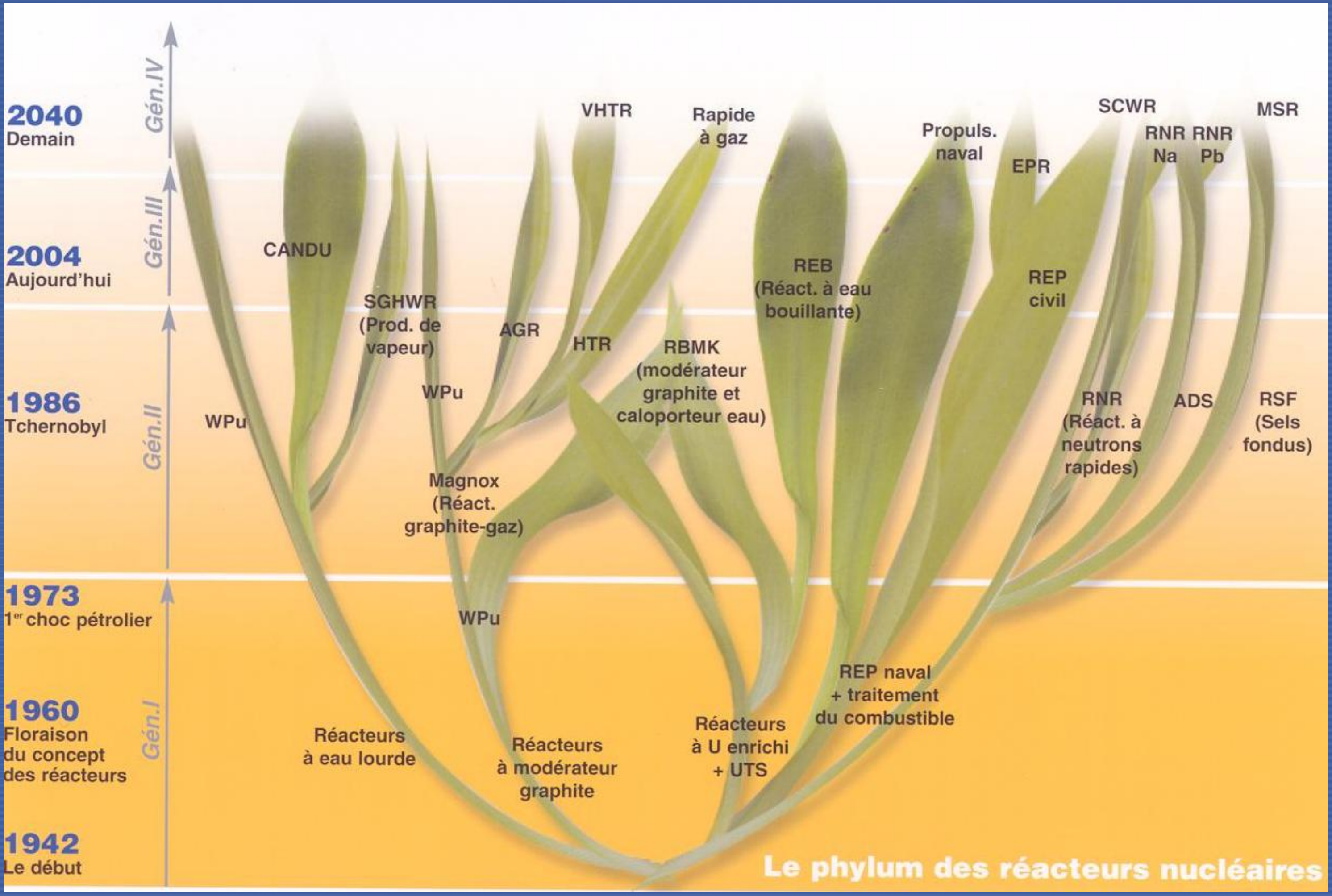
Background

« If any species do not become modified and improved in a corresponding degree with its competitors, it will soon be exterminated » ***Charles Darwin. The origin of species, 1859***



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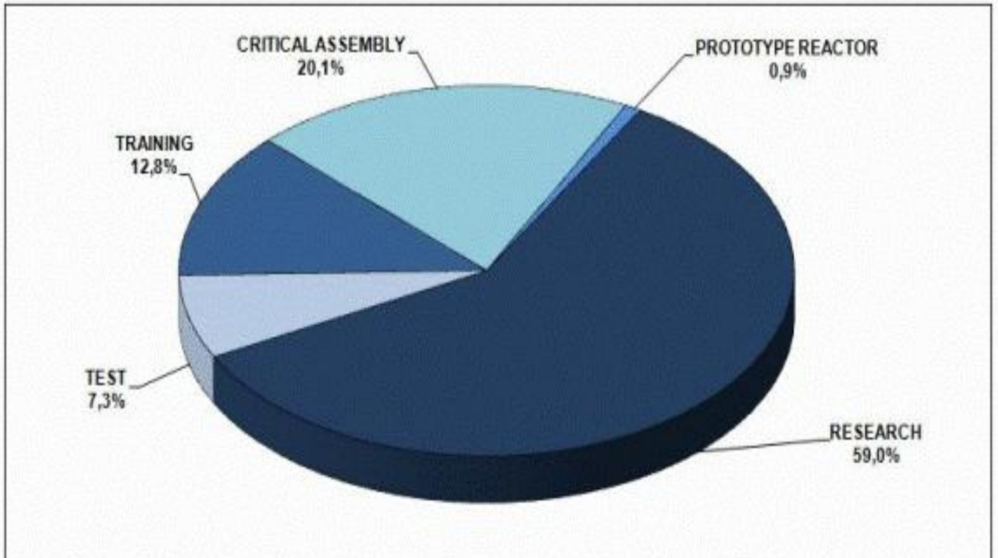
Background

Status of RR as of today (IAEA RR Data Base): type of RRs

- Huge variety, no easy categorization, 26 different types
- Manufacturer types: Slowpoke, MNSR, Argonaut, TRIGA, IRT, WWR
- Coolant/moderator: heavy water, pool, light water, liquid metal, organic
- Fuel: plate, TRIGA, rods, homogeneous
- Purpose: critical assembly, research, test, training, prototype



Research reactors in operation: Categories & number of facilities

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Background

Source: IAEA RRDB, January 2012

TOTAL:	679
Operational	231
Temp. shutdown	13
Under construction	3
Planned	2
Shutdown/Decommissioned	424
Cancelled	5
Unverified	1

Operational RRs are distributed over 56 countries

Russia	47
USA	39
China	15
Japan	13
France	10

Region	Operational RRs
Africa	8
Americas	64
Asia-Pacific	53
Europe (with Russia)	106

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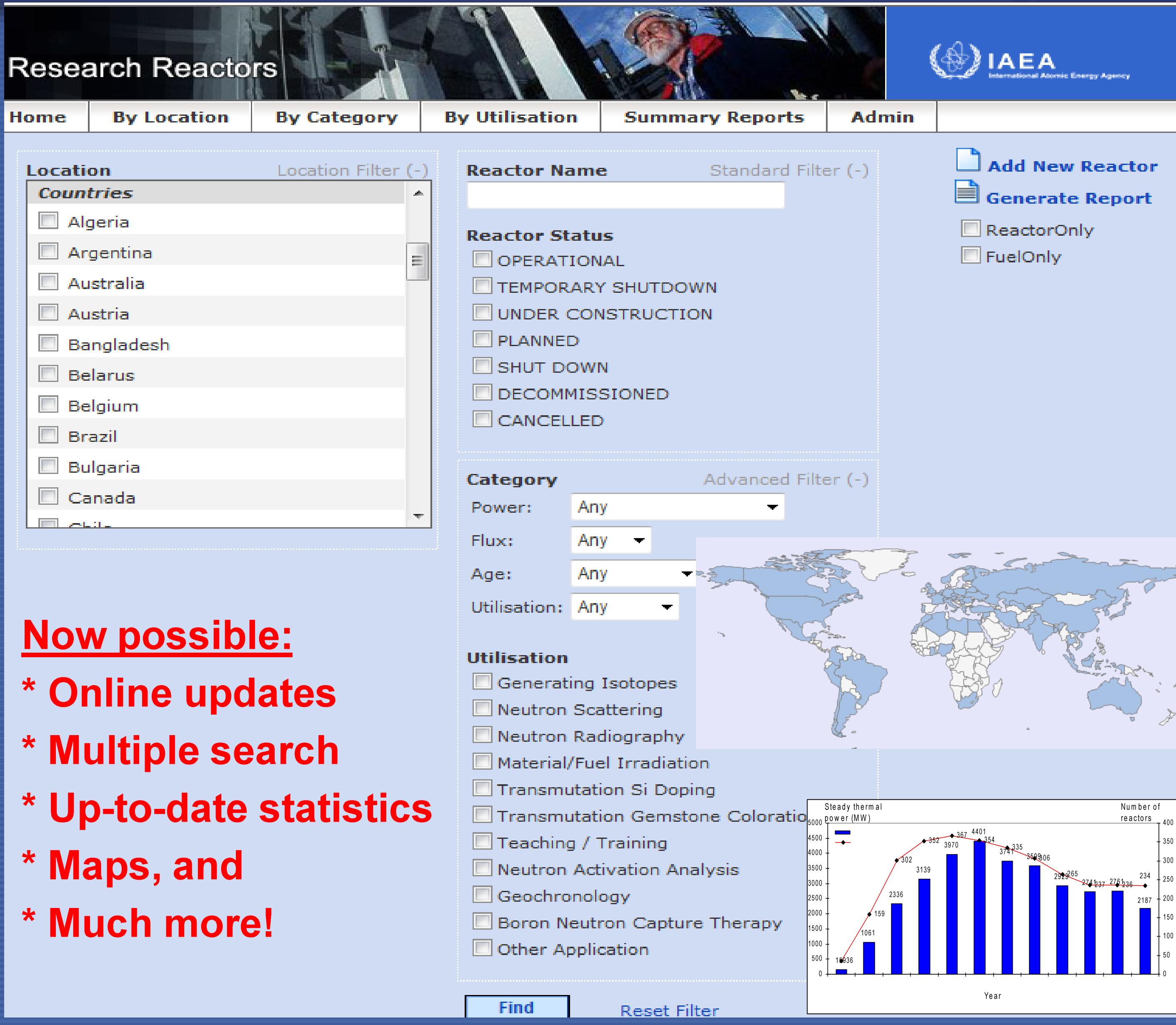
IAEA Research Reactor DataBase (RRDB)

http://nucleus.iaea.org/RRDB/



Includes:

* Detailed information of 680 facilities
* Operational status
* Reactor data
* Fuel data
* Utilization records
* …

Jointly coordinated and managed by NAPC & NEFW.

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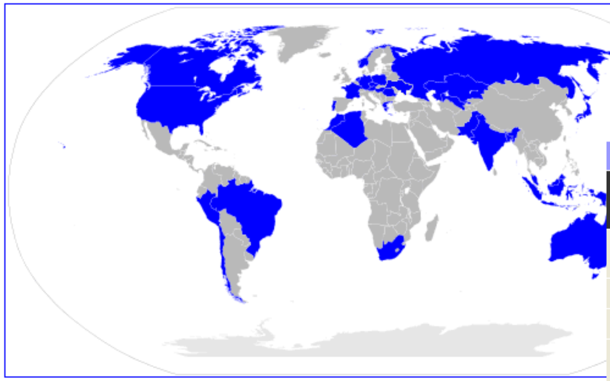
Now possible:

* Online updates
* Multiple search
* Up-to-date statistics
* Maps, and
* Much more!

RRDB: Utilization and Application Oriented, new capability

Neutron Scattering Facilities - "Click here for details"



This database contains 44 research reactors performing Neutron Scaterring distributed over 3

44 RRs employ neutron beams; they are distributed over 30 MSs

Neutron Scattering Facilities

No.	Country	Name	Reactor Type	Thermal Power, kW	Thermal Flux, n/cm²/s	Fast Flux, n/cm²/s	Criticality Date
1	Algeria	ES-SALAM	HEAVY WATER	15000	2.1E14	4.2E12	1992-02-17
2	Algeria	NUR	POOL	1000	5.9E12	4.0E12	1989-03-24
3	Australia	OPAL	POOL	20000	3.0E14	2.1E14	2006-08-12
4	Austria	TRIGA II VIENNA	TRIGA MARK II	250	1.0E13	1.7E13	1962-03-07
5	Bangladesh	TRIGA MARK II	TRIGA MARK II	3000	7.5E13	3.8E13	1986-09-14
6	Brazil	IEA-R1	POOL	5000	4.6E13	1.3E14	1957-09-16
7	Canada	MNR MCMASTER UNIV	POOL	3000	1.0E14	4.0E13	1959-04-04
8	Canada	NRU	HEAVY WATER	135000	4.0E14	4.5E13	1957- Temp
9	Chile	RECH-1	POOL	5000	7.0E13	5.0E13	1974-
10	Czech Republic	LVR-15 REZ	TANK WWR	10000	1.5E14	3.0E14	1957-
11	France	HFR	HEAVY WATER	58300	1.5E15		1971-
12	France	ORPHEE	POOL	14000	3.0E14	3.0E14	1980-
13	Germany	BER-II	POOL	10000	2.0E14	1.4E13	1973-
14	Germany	FRG-1	POOL	5000	1.4E14	4.5E13	1958-
15	Germany	FRM II	POOL	20000	8.0E14	5.0E14	2004-
16	Greece	DEMOKRITOS (GRR-1)	POOL	5000	1.0E14	4.5E13	1961- Temp
17	Hungary	NUCL. BUDAPEST RES.	TANK WWR	10000	2.5E14	1.0E14	1959-

Utilization

Hours per Day	24
Days per Week	7
Weeks per Year	21
MW Days per Year	2160
Materials/fuel test experiments	NO
Isotope Production	99Mo, 131I,192Ir, 32P
• Total Activity (GBq)	33741
Neutron Scattering	HRPD, NRF, HRSANS, FCD/TD, SANS, PD
• On-line beam hours	2100
Neutron Radiography	On-line beam hours: N/A
Neutron capture therapy	NO
Activation Analysis	INAA
• number of samples irradiated	300
Transmutation	NO
Geochronology	NO
Teaching	Number of students: N/A
Training	Number of operators/experimenters trained: 13
Other Uses	NO

Available at: http://nucleus.iaea.org/RRDB/

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RR application-oriented functions of RRDB

Application	Number of RR involved	Involved / Operational, %	Number of countries
Education & Training	161	67	51
Neutron Activation Analysis	122	51	54
Radioisotope production	90	37	44
Neutron radiography	68	28	40
Material/fuel testing/irradiations	60	25	25
Neutron scattering	48	21	32
Nuclear Data Measurements	42	18	20
Gem coloration	36	15	22
Si doping	35	15	22
Geochronology	26	11	21
Neutron Therapy	20	8	13
Other	95	40	29

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Indispensable to define priorities and plan our activities!

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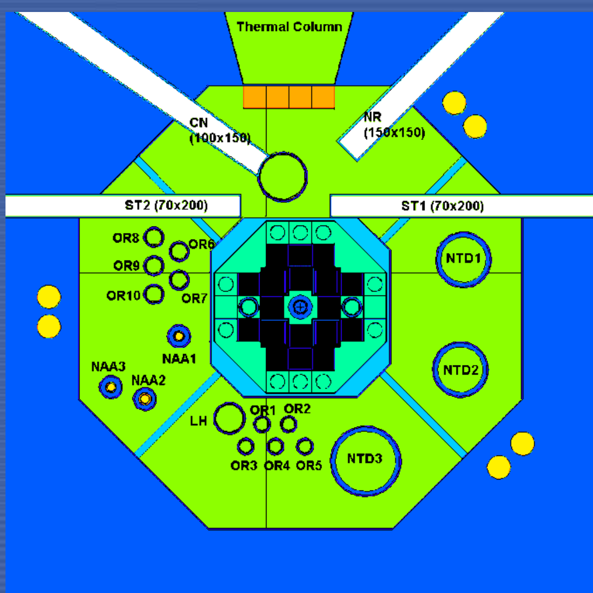
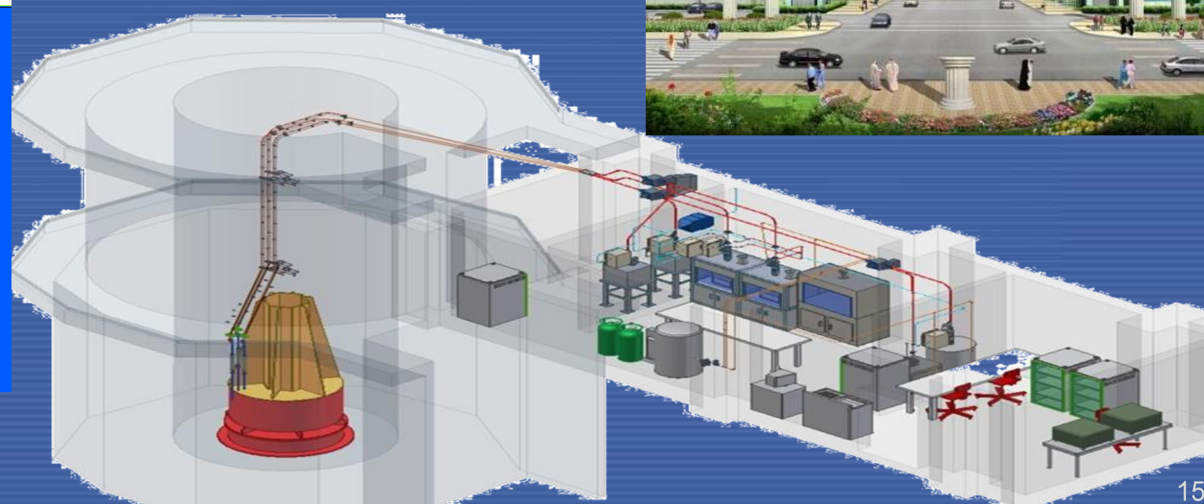
Activity: New RRs

Jordan Research & Training Reactor (JRTR)

In the detailed design stage, construction is about to start

- 5 MW (upgradable to 10MW), neutron flux ~1.5*10^{14} n/(s cm^2)
- Fuel: ~19.75 % U-235, U_3Si_2-Al, Coolant & Moderator: H_2O, Reflector: Be
- Multipurpose RR: radioisotope production, Si doping, neutron beams, NAA, E&T, etc.
- 1^{st} step to the national NPP programme





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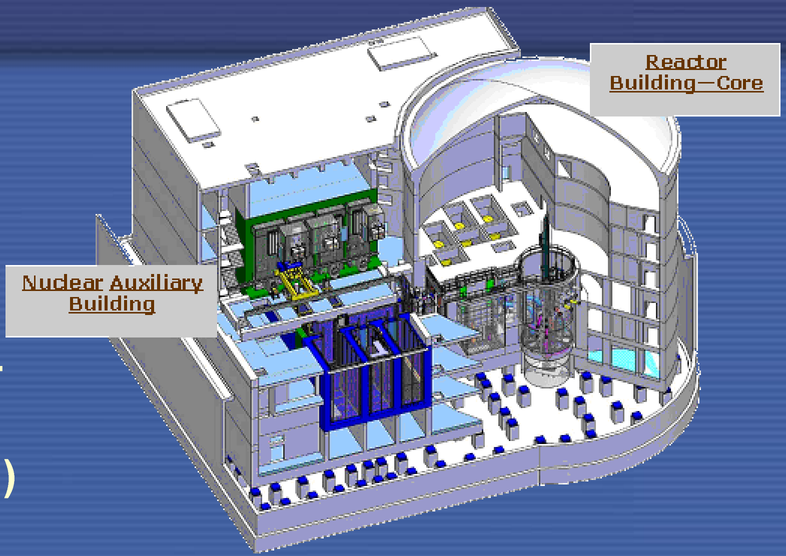
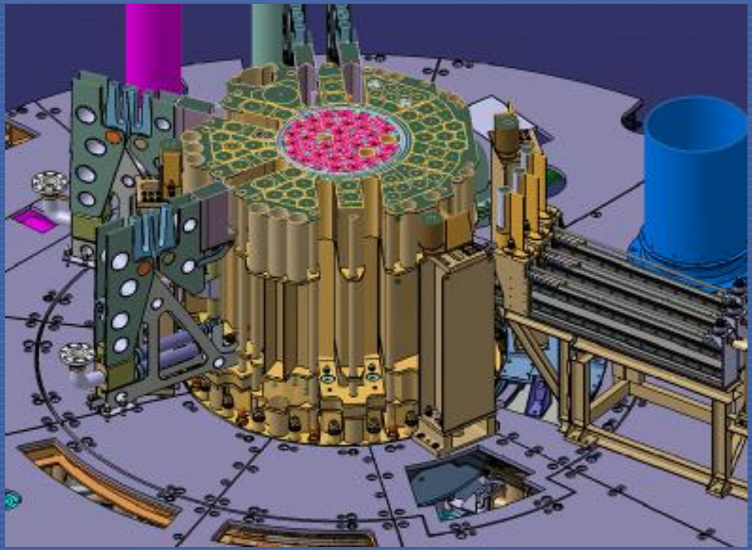
Activity: New RRs

RR under construction

JHR, France, operation expected in 2015



- MTR pool, 100 MW, in core flux ~$1*10^{15}$ n/(s cm^2)
- Fuel: Ref. UMo LEU, Backup: U_3Si_2 27 % U-235
- In support of future nuclear power, Gen3+ & Gen4
- Dedicated for material/fuel irradiation and testing
- Other applications envisaged (isotope production)
- International consortium



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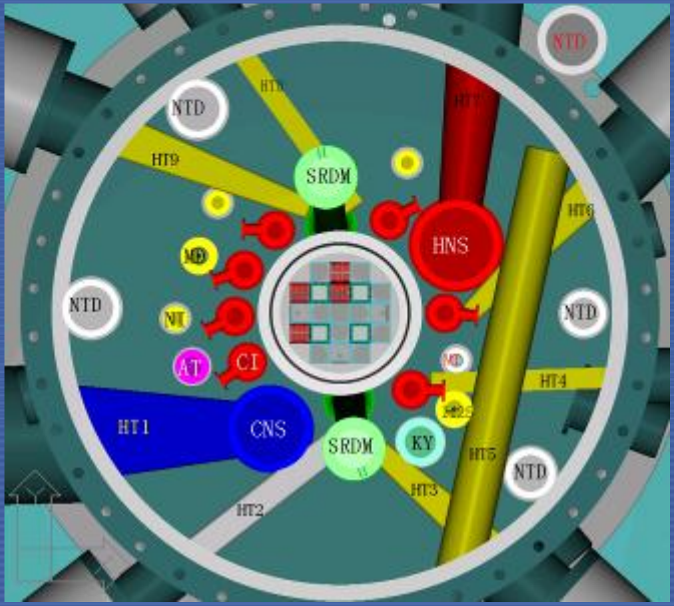
Activity: New RRs

CARR, China

1st criticality in May 2010; full power reached in 2012

- 60 MW, in core flux ~$1*10^{15}$ n/(s cm^2)
- Fuel: 19% U-235, Moderator: H_2O, Reflector: D_2O
- Replacement for 10MW HWRR (2007)
- Multipurpose RR with the main objectives in basic research
- Open to users from universities, governmental laboratories, industry

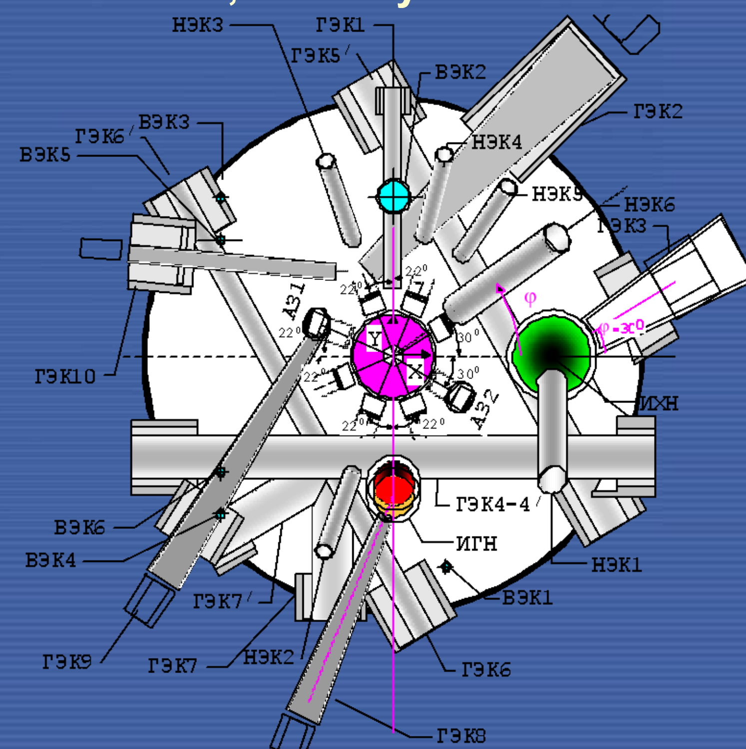


Activity: New RRs

PIK, Russian Federation

1st criticality in March 2011, full power expected in 2013

- 100 MW, in neutron trap flux ~$4.5*10^{15}$ n/(s cm^2)
- Fuel: ~90% U-235, Moderator & Reflector: D_2O
- Replacement for WWR-M (18MW)
- Multipurpose RR with the main objectives in basic research
- Open to users from universities, governmental laboratories, industry



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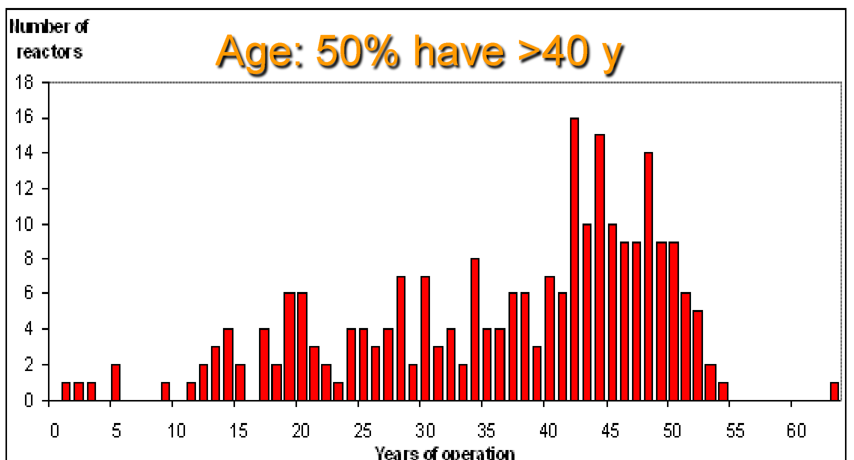
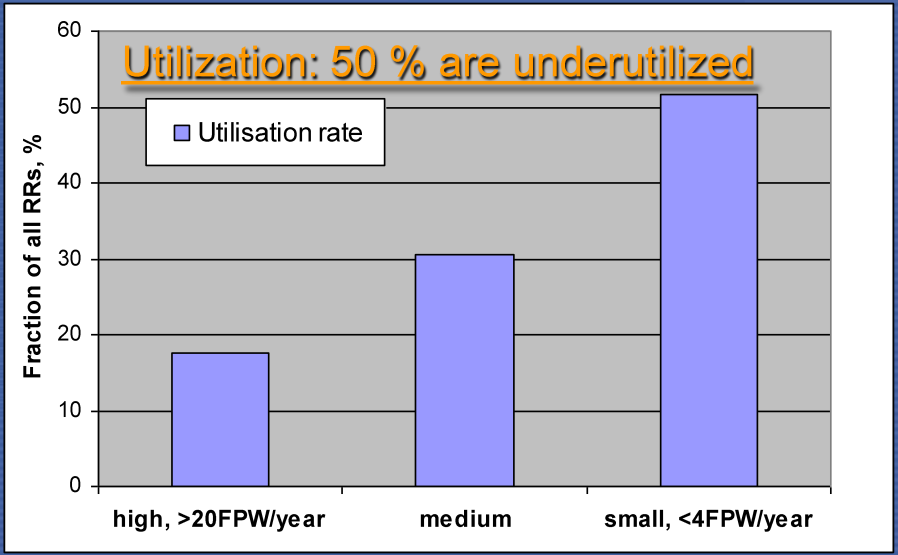
Key issues and challenges

Source: IAEA RRDB, February 2011

- RR underutilization
- Ageing & needs for refurbishment
- Fuel cycle issues
- Requests for new RRs
- Safety & security
- …



Age distribution of research reactors in the RRDB: Number of reactors and years in operation



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Key issues and challenges: underutilization

- **Lack of purpose** (and strategy) objectives formulated long time ago; no new/clear strategy available
- **Lack of budget** (and staff); prefer operate on "survival" level rather than shut-down and decommission; no plan/funds for decommissioning
- **Lack of pro-activity** (and motivation); no action to search for new users/clients; no action to analyse/penetrate the market for potential commercial products & services
- **Lack of QA/QC** (and Integrated Management System); decreased confidence from major stakeholders (funding and regulatory authorities); decreased chance to go commercial; no courage for re-organization
- …

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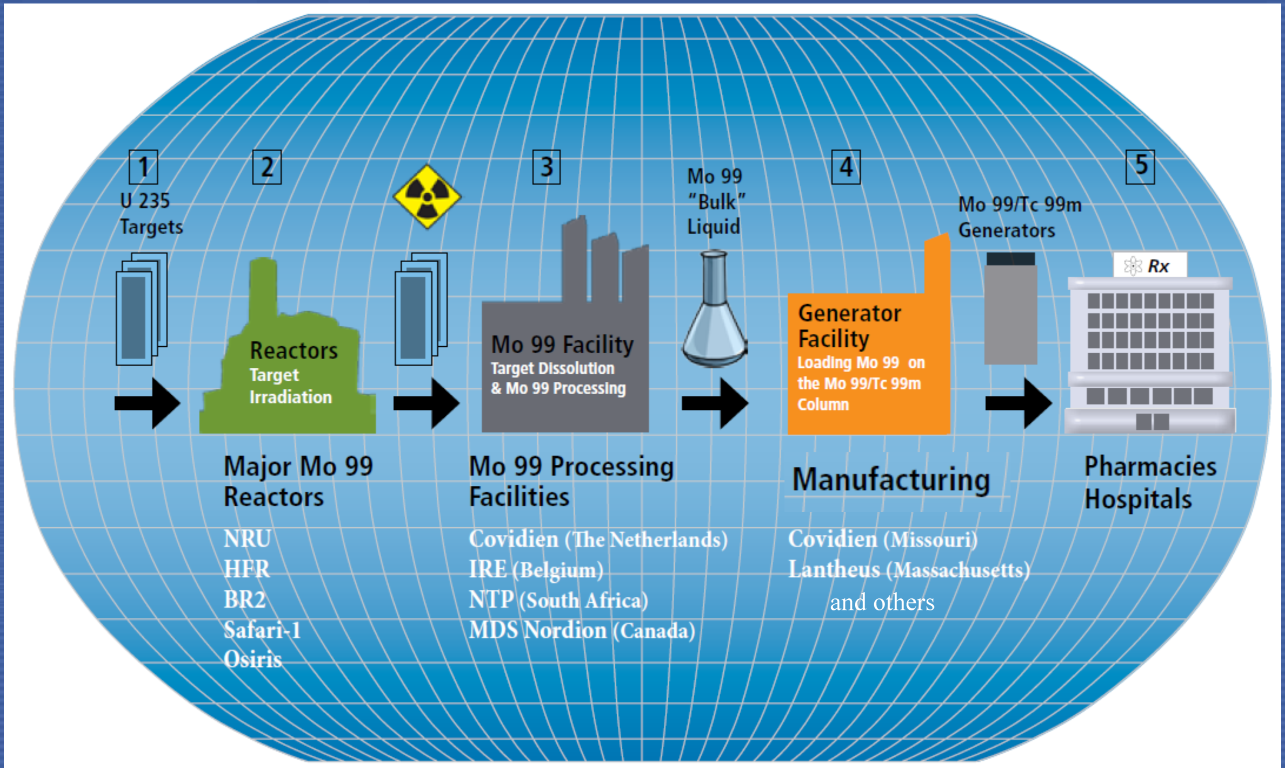
Key issues and challenges: supply of Mo-99

- Over 80% of diagnostic nuclear medical imaging uses radiopharmaceuticals containing technetium-99m (^{99m}Tc), entailing over 30 million investigations per year

- Over 95% of the ^{99}Mo required for ^{99m}Tc generators is produced by the fission of uranium-235 targets in nuclear research reactors

Source: IAEA NTR 2010, Annex



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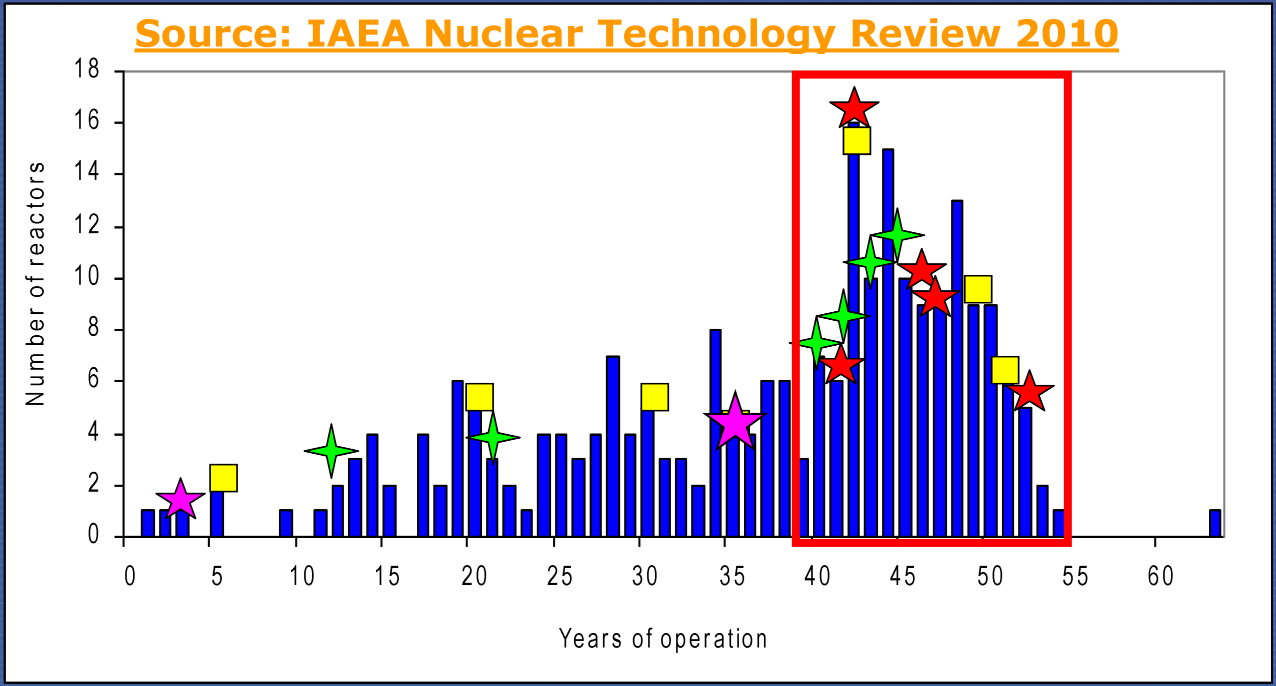
Key issues and challenges: supply of Mo-99



- The five major RR currently producing more than 95 % of ^{99}Mo
- The OPAL (Australia) and Maria (Poland)
- Existing RR that are already used by regional ^{99}Mo producers or for which commissioning is underway
- Existing RR which are now studying the feasibility of providing irradiation services.

Latest news:

NRU (Canada) and HFR (Netherlands) are back to operation!

Maria (Poland) & LVR-15 (Czech) have entered as new important players!

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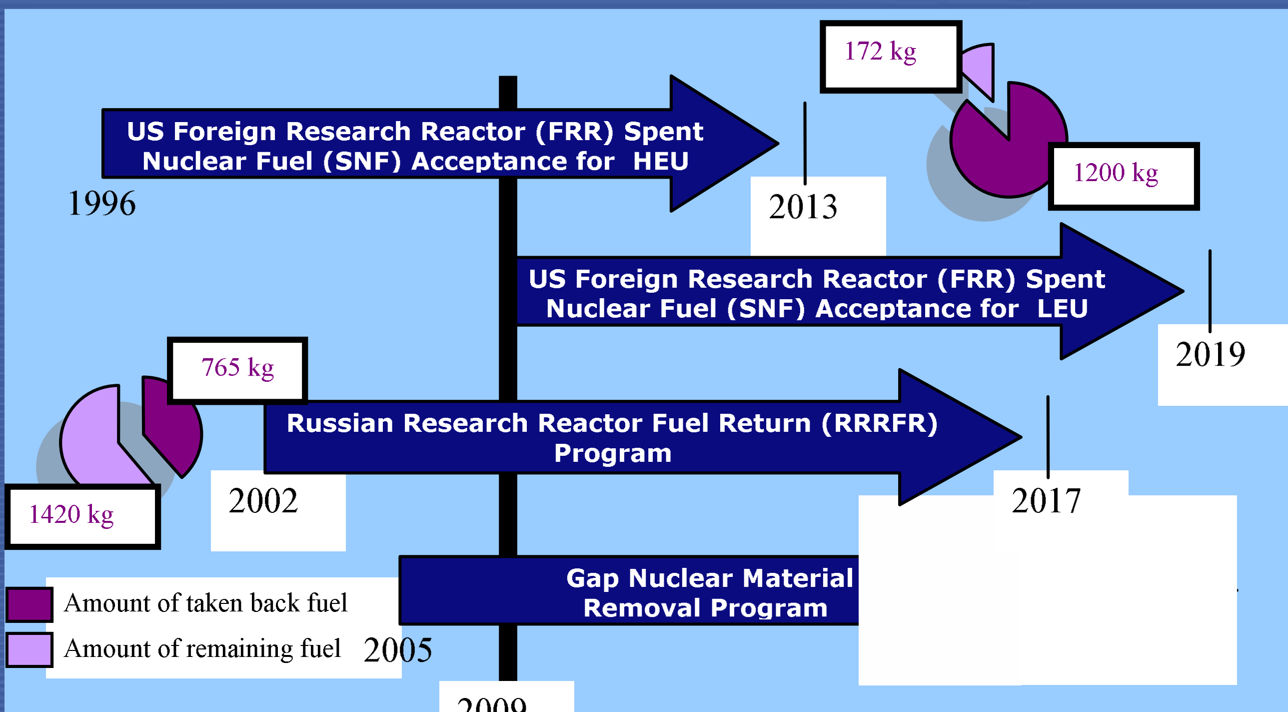
Key issues and challenges: reduction of HEU

- Reduction of HEU through the Global Threat Reduction Initiative (GTRI)
  - 76 RR cores converted to LEU, ~20 RR are expected/on-going
  - Spent and fresh fuel take back programmes



Latest news:

- 2500 kg of Russian-origin HEU spent fuel has been removed from Serbia
- SAFARI-1 is entirely LEU!

Other countries, where HEU is being removed:

Bulgaria, the Czech Republic, Germany, Hungary, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Uzbekistan, Vietnam, …

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Recommended strategy for enhanced RR utilization

Today existing or planned RR facilities should concentrate on three major issues:

Strategic Planning
&
Performance Monitoring

International Cooperation
&
Networking

Sustainability
through
Provision of Products & Services

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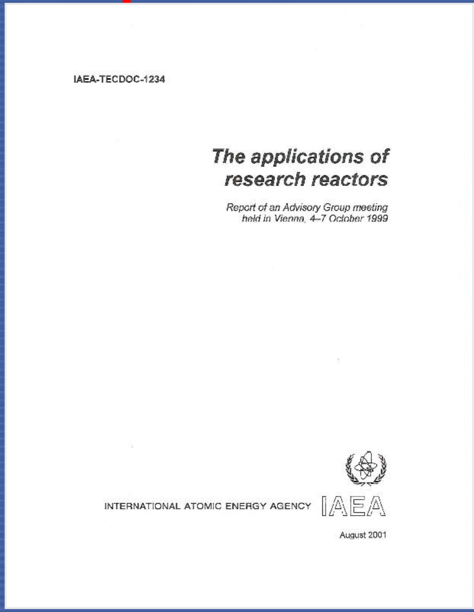
Activity: RR strategic & business plans

Preparation/revision of

- **Justification and Demonstrated Needs**
- **Strategic & Business Plans**

Facility Status	Current Stakeholder
Capabilities	Requirements/Needs
What can I do?	What should I do?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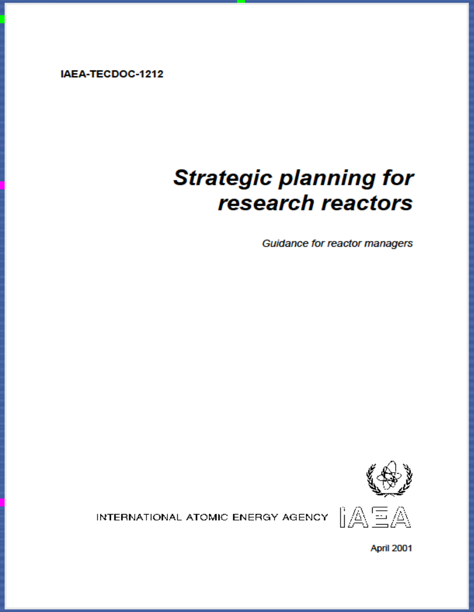
The applications of research reactors

Report of an Advisory Group meeting held in Vienna, 4–7 October 1999

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

August 2001

Production of a strategic plan supports an increase in utilization by increasing capabilities and creating new requirements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Strategic planning for research reactors

Guidance for reactor managers

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

April 2001

Support/assistance from the IAEA is dependent on having a demonstrated need, i.e. … a strategic plan

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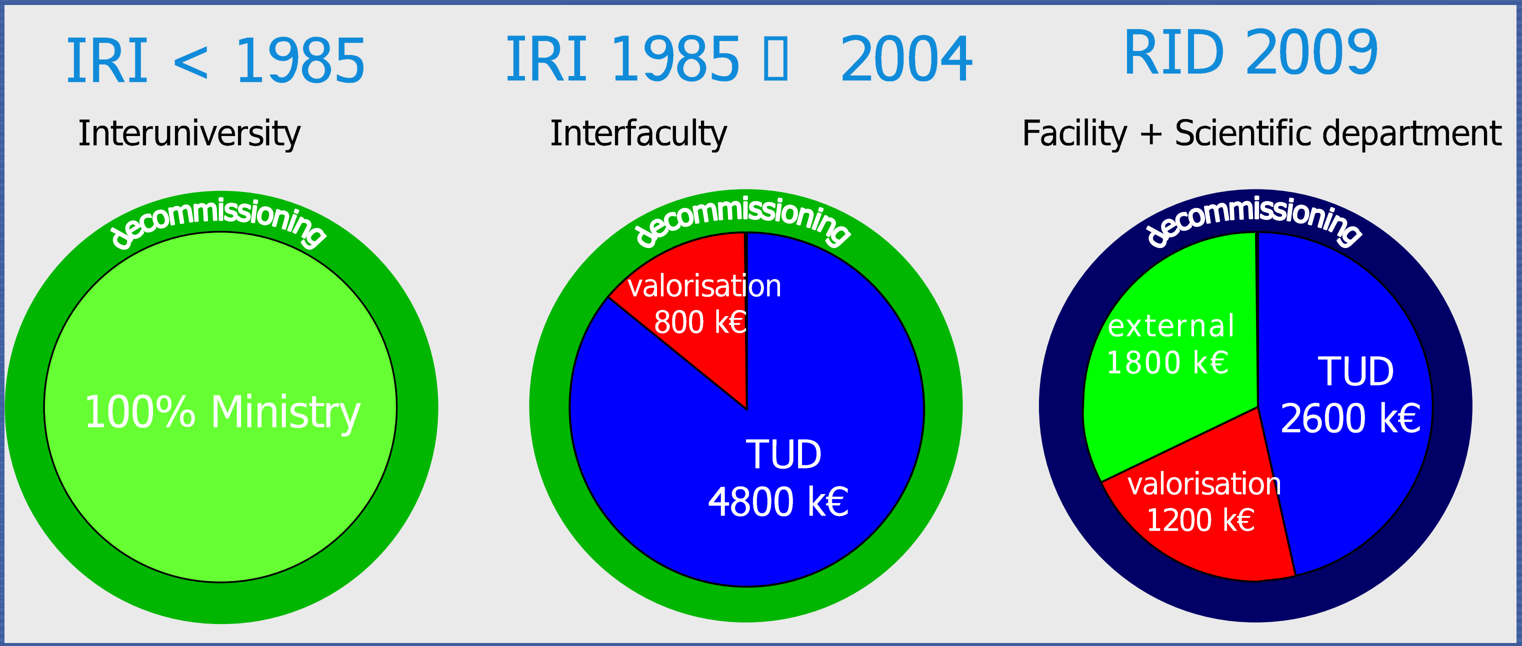
Example: 2MW RR, HOR of TU Delft

Today:

- It is a partially self sustained RR (operational costs ~6M Euros)
- Multipurpose RR
- NAA, neutron beams, positron source, E&T, isotope production
- Special efforts on QA/QM, accreditation, recognition, etc.



Future:

- New applications, advanced R&D, search for specific niche…

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Source: TU Delft, The Netherlands

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Activity: RR Networks and Coalitions

Objectives:

- increase utilization & sustainability
- promote regional/international cooperation
- access to RRs from Member States without RRs

Role of the IAEA

- Catalyst and facilitator towards self-reliance
- Preparation of strategic and business plans
- Initial support via regional TC projects

Performance indicators:

- Number of RR facilities forming networks
- Number of non-RR countries forming networks
- Number of RRs with new/updated strategic plans
- Number of RRs with increased utilization/revenues

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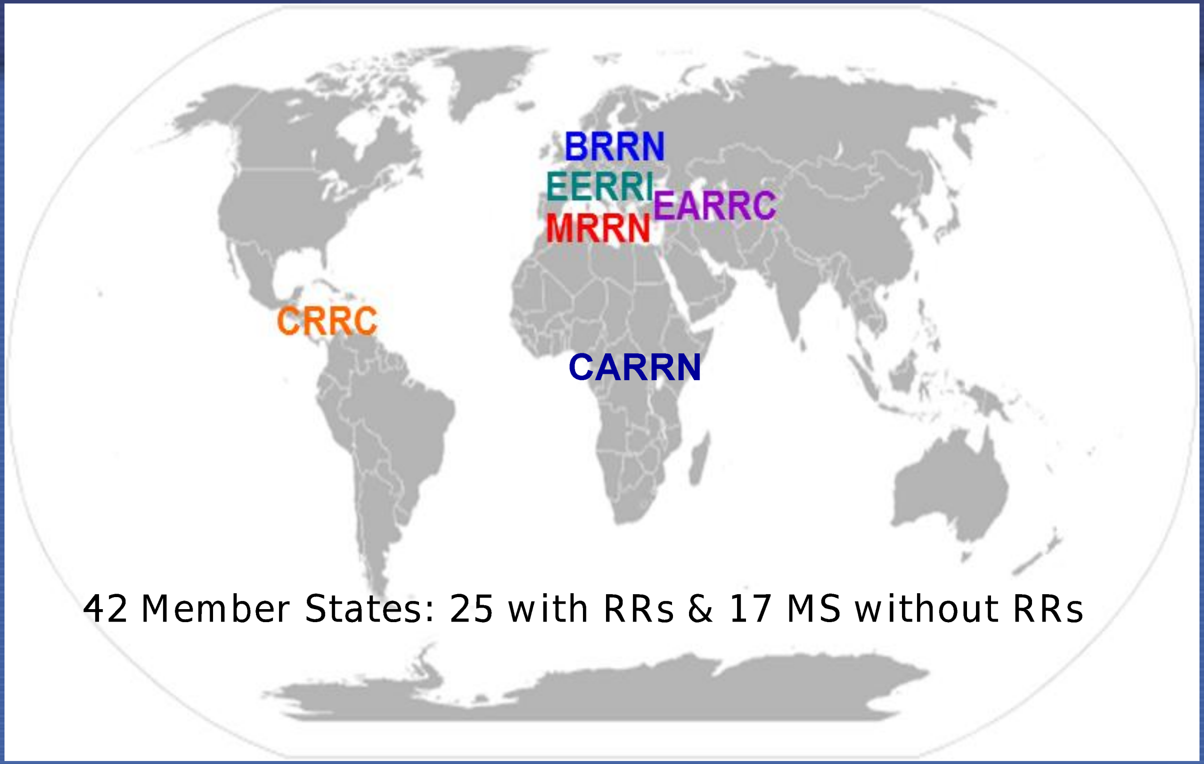
Activity: RR Networks and Coalitions, status



1. BRRN – Baltic Research Reactor Network, multipurpose, 10MS
2. EARRC – Eurasian RR Coalition, isotope production, 5MS
3. EERRI – Eastern European RR Initiative, multipurpose, 6MS
4. CRRC – Caribbean RR Coalition, mainly NAA, 3 MS
5. MRRN – Mediterranean RR Network, multipurpose, 12 MS
6. CARRN – Central Africa RR Network, multipurpose, 9 MS

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Activity: RR Networks and Coalitions, highlight

RR Group Fellowship Training Course (6 weeks):

- EERRI: organized by partners in Austria, Czech Republic, Hungary, & Slovenia
- IAEA: implementation and financial support through TC projects
- Contents: theoretical courses, hands on training, IAEA lectures, evaluations
- Participants: ~49 fellows trained during 6 courses
- Future: similar initiatives in other regions

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Internet Reactor Lab (IRL)

PULSTAR Reactor NCSU/ U.S

Reactor Parameters →

↔ Audio/ Video data

NE Department JUST/Jordan

Source: JUST, Jordan

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Similar initiatives in other regions

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Activity: TC projects and new RRs

Planned RRs as of today

- **Last TC cycle: more than 30 on-going IAEA TC projects related to RR utilization, safety, fuel cycle, refurbishment and modernization, etc.**

- **(2010-2011) 4 on-going projects to start the 1st RR in the country**
    1) Azerbaijan: Conducting a Feasibility Study for Planning and Establishing a RR
    2) Jordan: Establishing a RR
    3) Sudan: Sudan Nuclear RR Project
    4) GCC: Developing Regional Nucl. Training Centre for Capacity Building & Research

- **(2012-2013) similar number of all projects but already 8 new projects related to the 1st RR in the country**
- **Jordan, Lebanon, Kuwait, Philippines, Saudi Arabia, Sudan, Tunisia, and Tanzania** +

    new RR projects in Argentina, Brazil, Korea, the Netherlands, South Africa, Vietnam…

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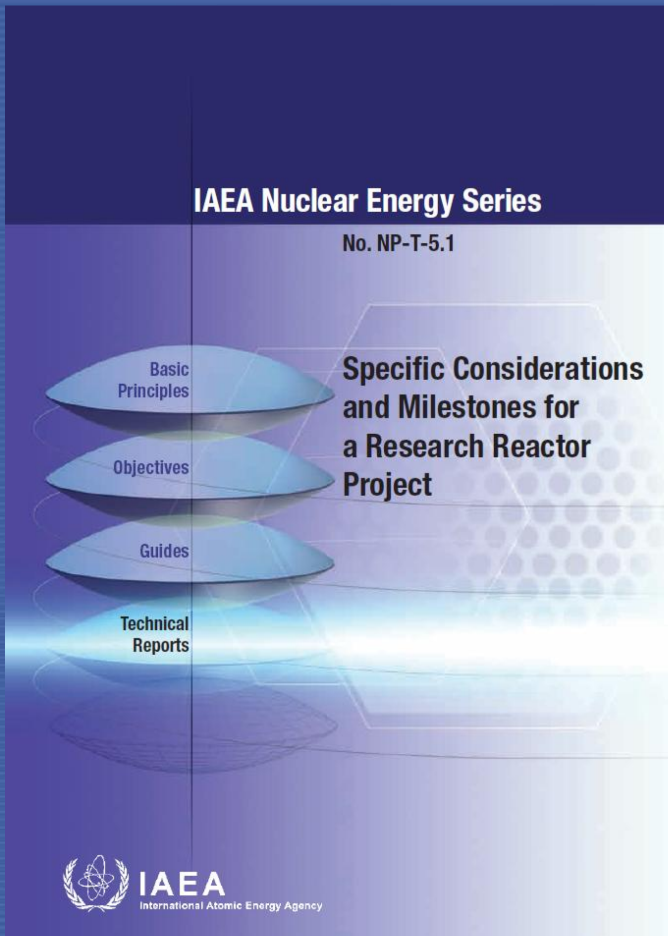
Contact: D.Ridikas@iaea.org

New Publications: NES NP-T-5.1 available



CONTENTS

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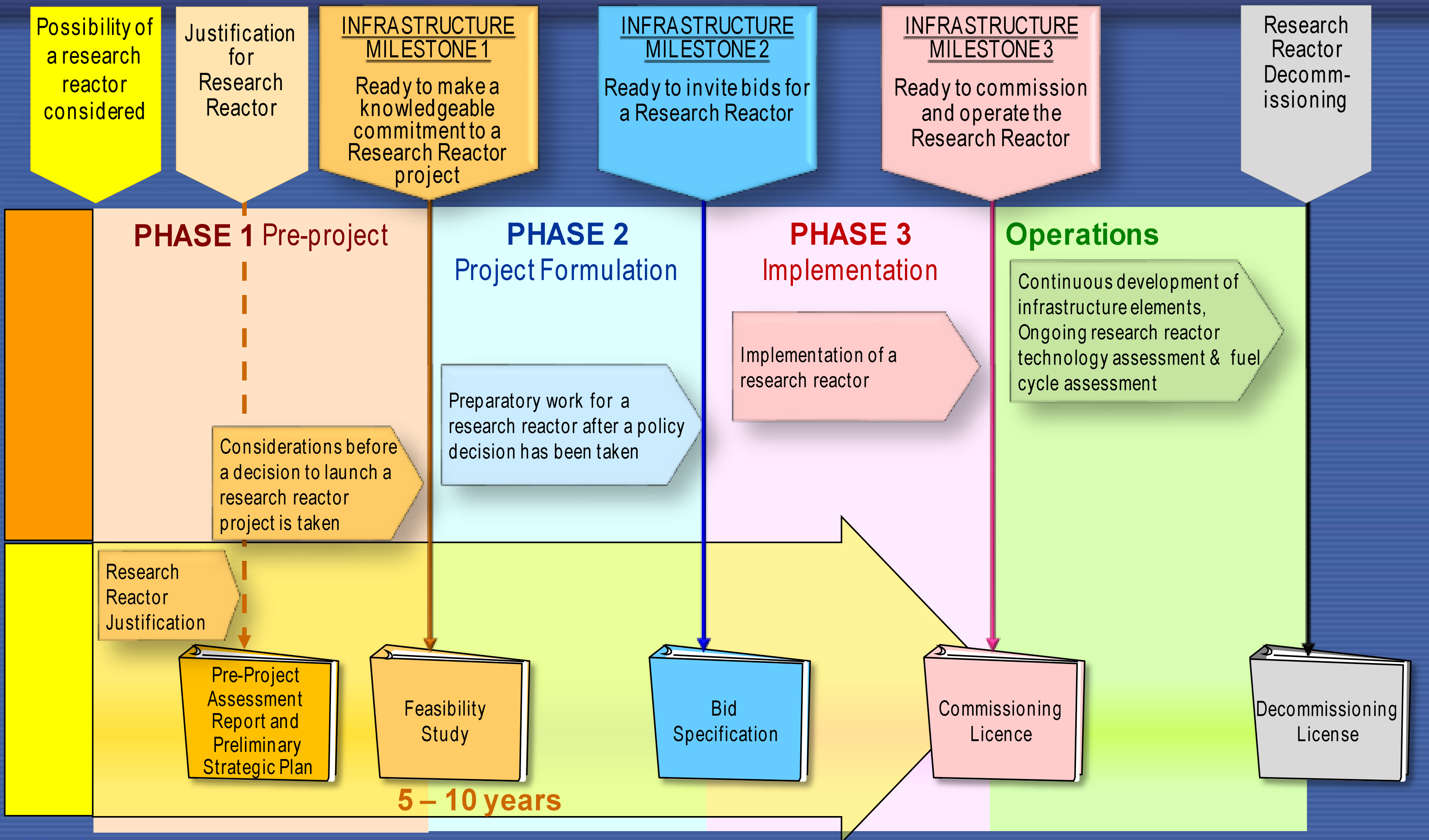
Activity: Newcomer Member States

Planning, Building and Operation of RR: phases/milestones



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Role of RR in E&T: ~164 RRs involved world-wide

- Public tours and visits
- Teaching physical and biological science students
- Teaching radiation protection and radiological engineering students
- Nuclear engineering students
- NPP operator training

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Role of RR in the context of national NPP programme

Typical flow from Academics to Nuclear

Academic background → **Nuclear training required**

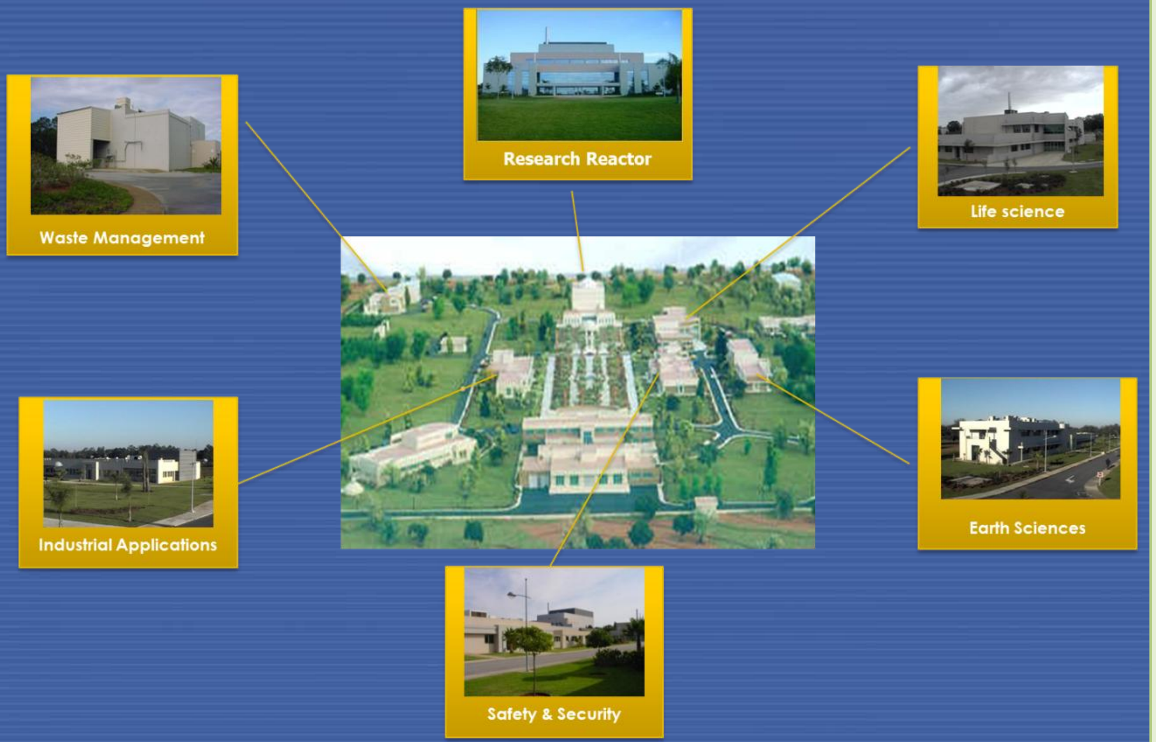
PhDs	50+ Experts	+ 12 to 24 months
Engineers & Masters	400+ Project + M&O staff	+ 6 to 12 months
Bachelors & Technicians	800+ Construction & Operating staff	+ 3 to 9 months

Population need estimates for 2 NPPs

Source: AREVA, France

Role of RRs in the context of national NPP programme

Example of Nuclear Research Centre in Morocco



Source: CNESTEN, Morocco

Issues (from Milestones Document)	Potential role of RR
1. National position	X
2. Nuclear safety	X
3. Management	
4. Funding and financing	
5. Legislative framework	X
6. Safeguards	X
7. Regulatory framework	X
8. Radiation protection	X
9. Electrical grid	
10. Human resource development	X
11. Stakeholder involvement	X
12. Site and supporting activities	X
13. Environmental Protection	X
14. Emergency planning	X
15. Security and physical protection	X
16. Nuclear fuel cycle	X
17. Radioactive waste	X
18. Industrial involvement	
19. Procurement	

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RR application-oriented functions of RRDB

Application	Number of RR involved	Involved / Operational, %	Number of countries
Education & Training	161	67	51
Neutron Activation Analysis	122	51	54
Radioisotope production	90	37	44
Neutron radiography	68	28	40
Material/fuel testing/irradiations	60	25	25
Neutron scattering	48	21	32
Nuclear Data Measurements	42	18	20
Gem coloration	36	15	22
Si doping	35	15	22
Geochronology	26	11	21
Neutron Therapy	20	8	13
Other	95	40	29

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Indispensable to define priorities and plan our activities!

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Revised RR power (~flux) - applications table

Power level	E&T	NAA	PGNAA (2)	Isotope production	Geochronology		Transmutation effects			Neutron imaging (2)	Neutron scattering (2)	Positron source (2)	BNCT (2)	Testing		
					Ar/Ar	Fission Track (1)	Silicon Doping (3)	Gamma irradiation	Gemstone Coloring (3)					I&C	Materials (3)	Fuels (3)
<1kW	F	S												S		
100kW	F	F	S	S	S	S		S		S	S		F	S		
1MW	F	F	S	S	S	S	S	S	S	S	S	S	F	F	S	
10MW	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	S
>10MW	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F
Time required, years	0.5- 1	2-3	2-3	0.5-5	0.5	0.5	3-5	0.5	2	2-4	3-10	5-10	5	0.5	3-5	3-10
Investment costs, US $k	5-80	150-300	200-600	50-5000	10	10	200-1000	10	100-500	150 – 1000	>1000*	500-700	2000-5000	1-20	>2000	>5000
Staff required, number	1-3	2	2	2-20	1	1	2-6	1	1-2	2-3	2-3*	2-3	2-3**	1	2-10	5-20

- S Some capability (e.g. R&D or demonstration capability)
- F Full capability (e.g. capable in commercial production)

- (1) Requires fully thermalized neutrons.
- (2) Requires a beam tube.
- (3) Requires a loop or special irradiation facility.

- **Time required** for completion and implementation
- **Investment costs** for completion and implementation
- **Staff** required for operation (in addition to reactor operation team)

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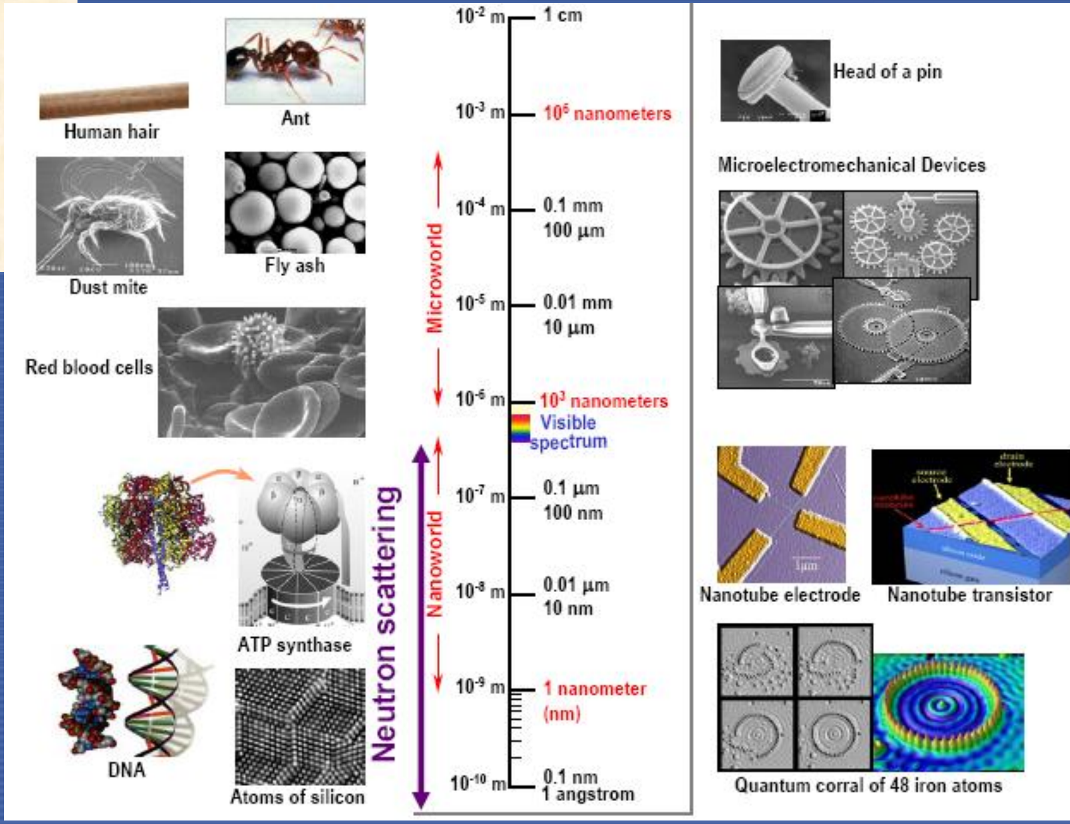
Basics on neutron scattering research

Why Neutrons?

1. Neutrons have the right wavelength
2. Neutrons see the Nuclei
3. Neutrons see Light Atoms next to Heavy Ones
4. Neutrons measure the Velocity of Atoms
5. Neutrons penetrate deep into Matter
6. Neutrons see Elementary Magnets



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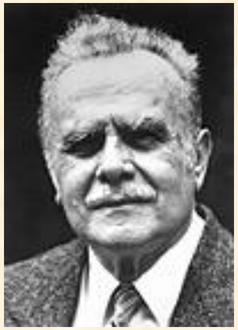
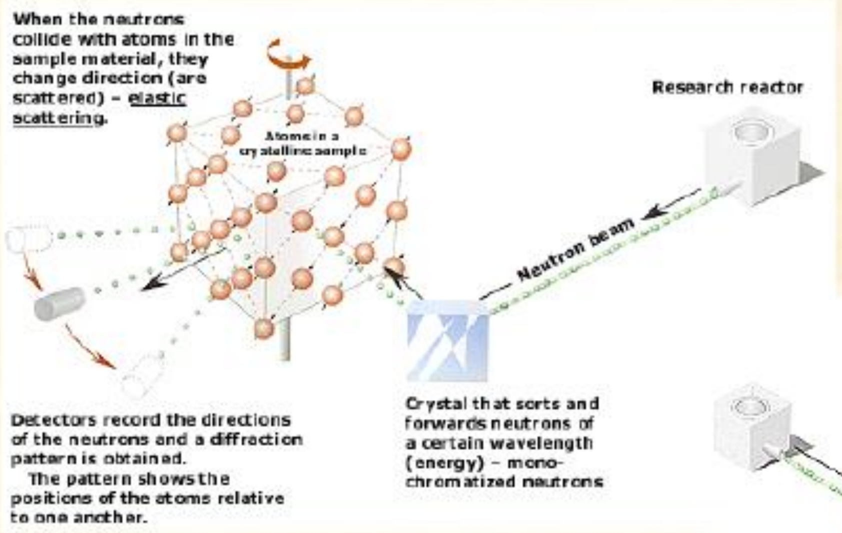
What do neutrons do?

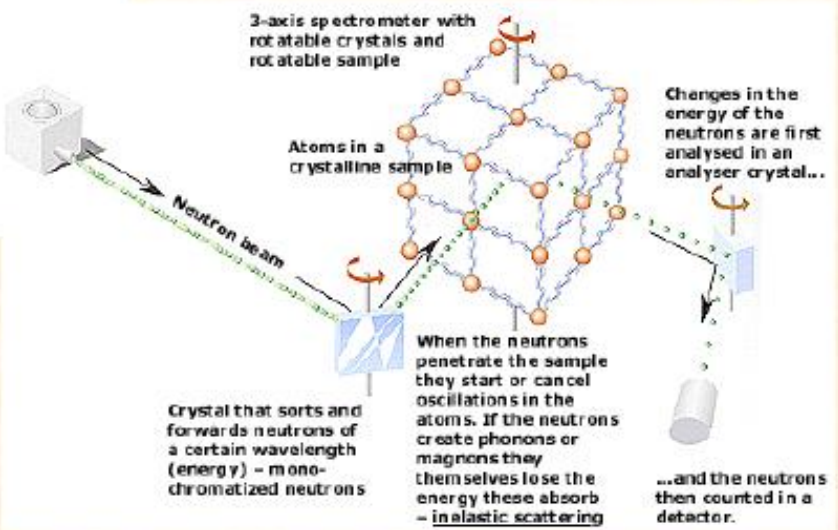
Nobel Prize in Physics 1994 - Shull and Brockhouse



Neutrons show where atoms are…..



… and what atoms do



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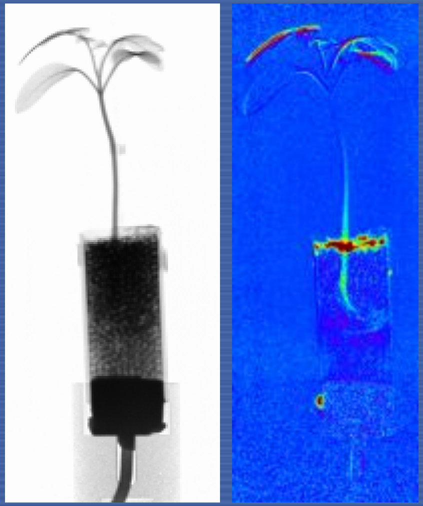
Neutron Radiography (1)

- Provide static or dynamic “picture” in 2D or 3D
- Non-destructive technique
- Various applications
  - Potential income

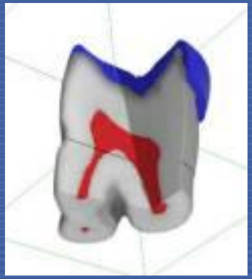
Mineral distribution in stones

Lubricates in engines

Application to plants

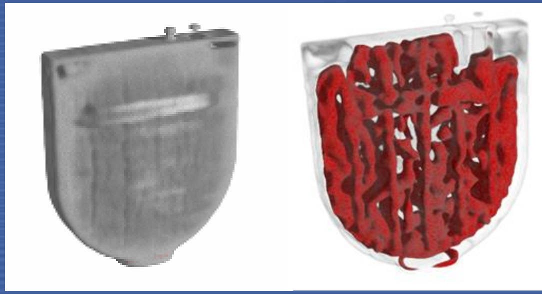


H_2O D_2O



Medical applications

Voltage sources/cells



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Courtesy to E. Lehmann (PSI) and N.Kardjilov (HZB)

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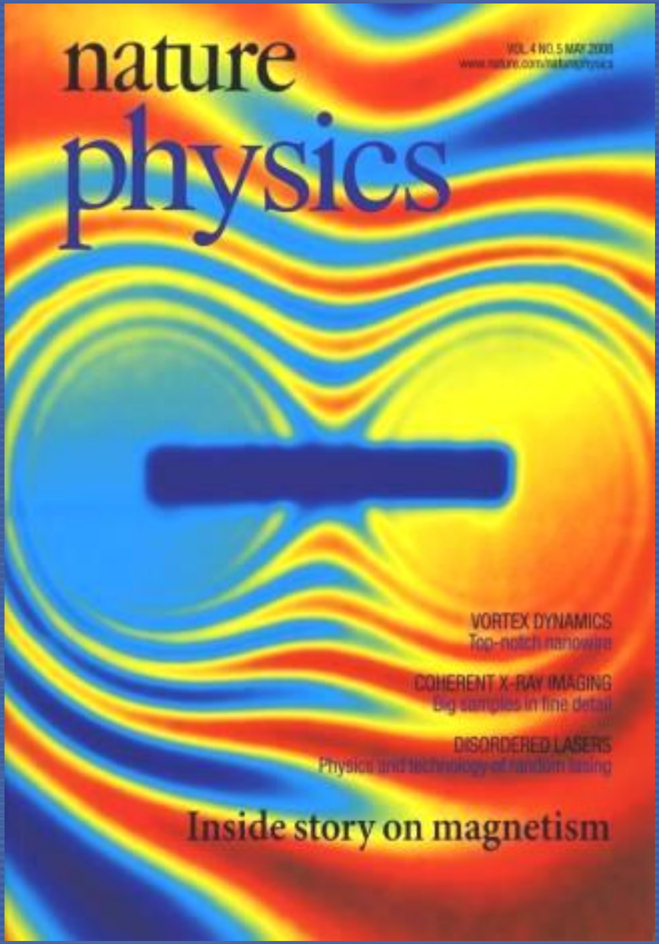
Neutron Radiography (1) continued

Cultural heritage:

Photo, x-ray, radiography, tomography

Brasing connections

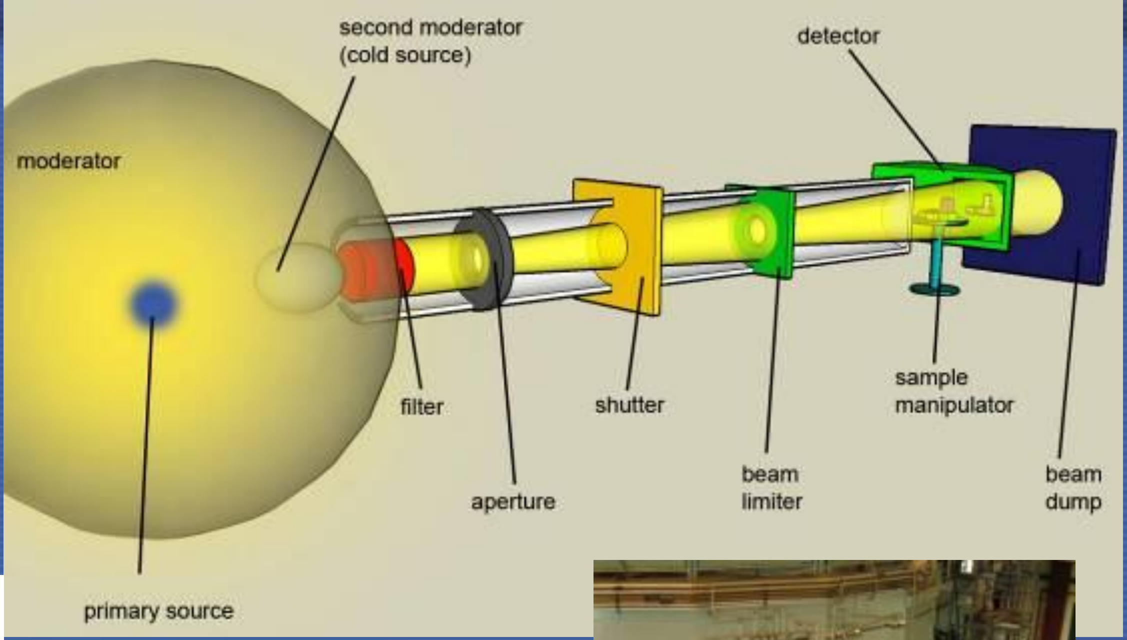
- Polarised neutron tomography

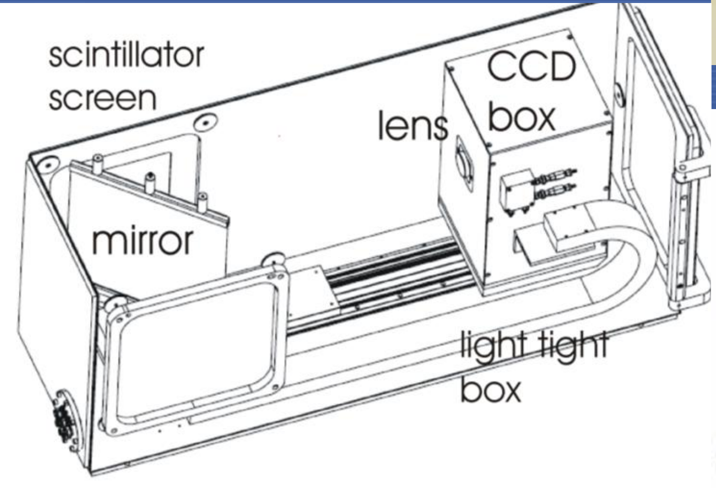


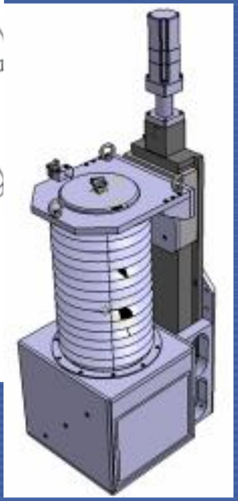
N. Kardjilov et al. Nature Physics 4 p. 399-403, (2008)

Neutron radiography (2)

- Neutron beam
- Detection system
- Manipulation system
- Computer system
- Image Reconstruction Software
- Image display
- Operator Interface







Courtesy to E. Lehmann (PSI) and N. Kardjilov (HZB)

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Neutron radiography (3)

Service	Flux, n/s cm^2	Facilities	Equipment	Staff	Budget
Neutron radiography & tomography	Thermal neutrons $>10^6$	Neutron beam, beam ports, filters, collimators, shielded room	Sample manipulator, mirrors, scintillation detector, CCD camera	Physicist, technician	Variable: from $50000 to $400000

See "Applications of RRs" TECDOC-1234 (2001) for all examples

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How do we produce neutrons?

a) www.ill.fr

a. Fission Reactions

$n^1 + U^{235} \longrightarrow$ 2 fission fragments + $2.5n^1$ + 200 MeV

thermal

- 1 neutron to maintain chain reaction
- 1 neutron escapes & is available for use
- 0.5 neutrons absorbed

1 neutron

2 to 3 neutrons

Example: 20 MW Research Reactor

No. of fissions/sec = $\frac{20 \times 10^6 \text{ watts}}{200 \text{ MeV/fission}}$ = 6×10^{17} fissions/second

generates 1.5×10^{18} neutrons/sec in the whole reactor volume

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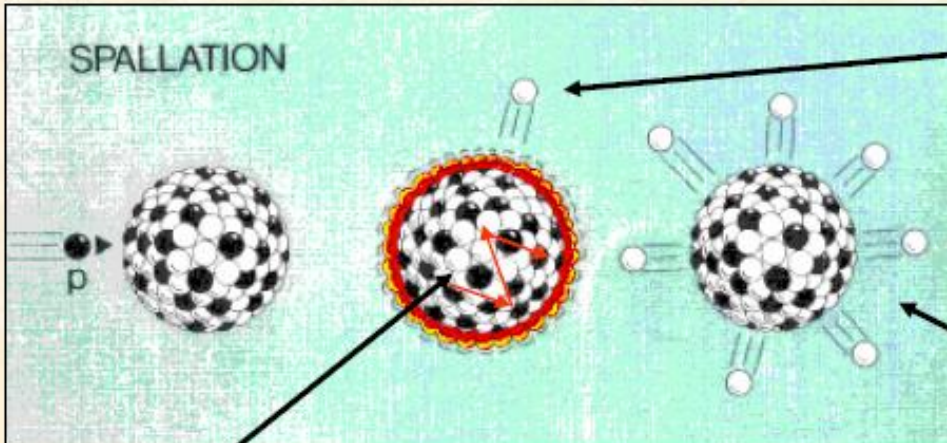
How do we produce neutrons?

b) www.sns.gov

b. Artificially accelerated particles

(iii) Spallation with Protons

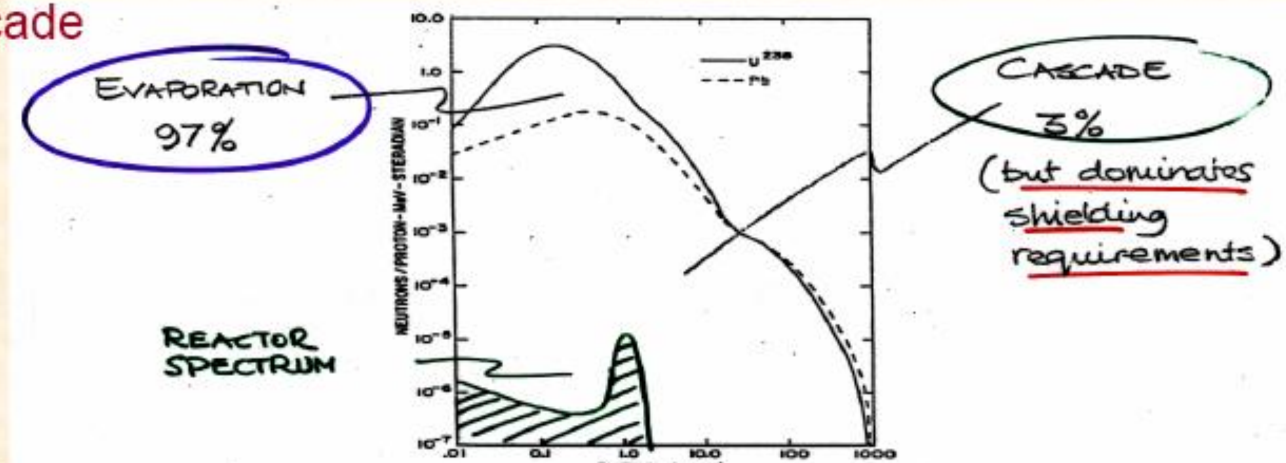


2. Inter Nuclear Cascade

Up to 40 neutrons per incident proton

3. Evaporation

1. Internal Cascade



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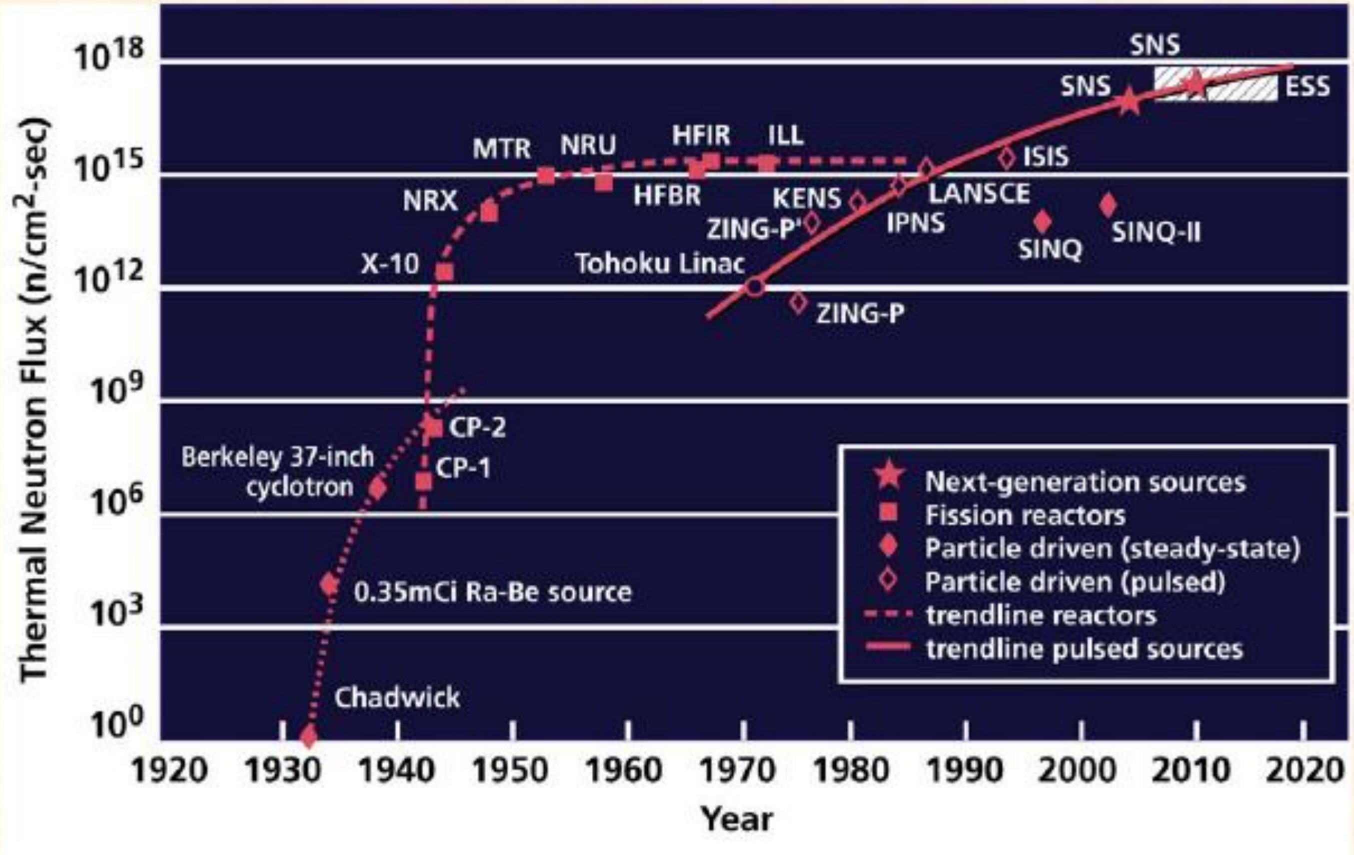
Higher neutron fluxes?

Reactors have reached the limit at which heat can be removed from the core
Pulsed sources have not yet reached that limit and hold out the promise of higher intensities



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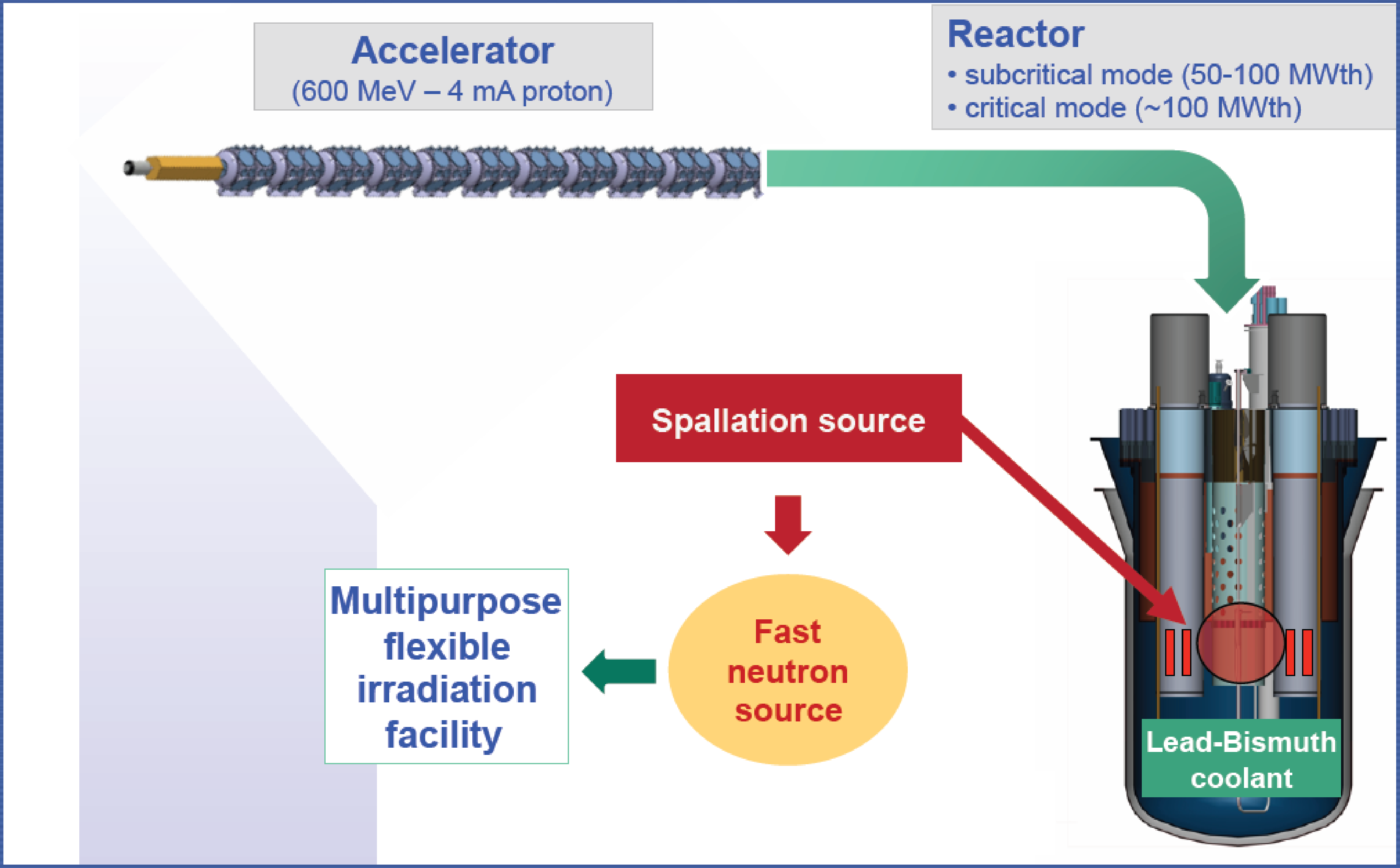
Accelerator Driven System: MYRRHA project in Belgium



Thanks for your attention and...

...we continue with accelerators later…

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