Research Reactors: Purpose and Future

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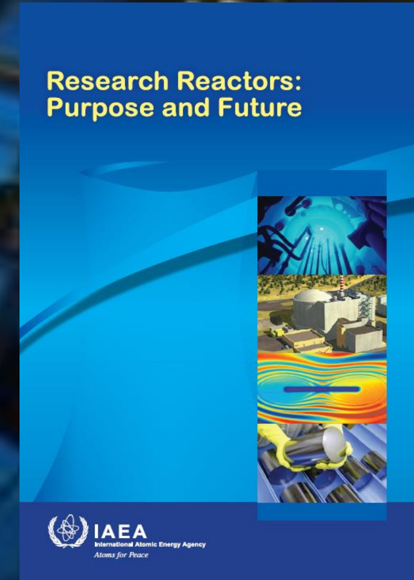
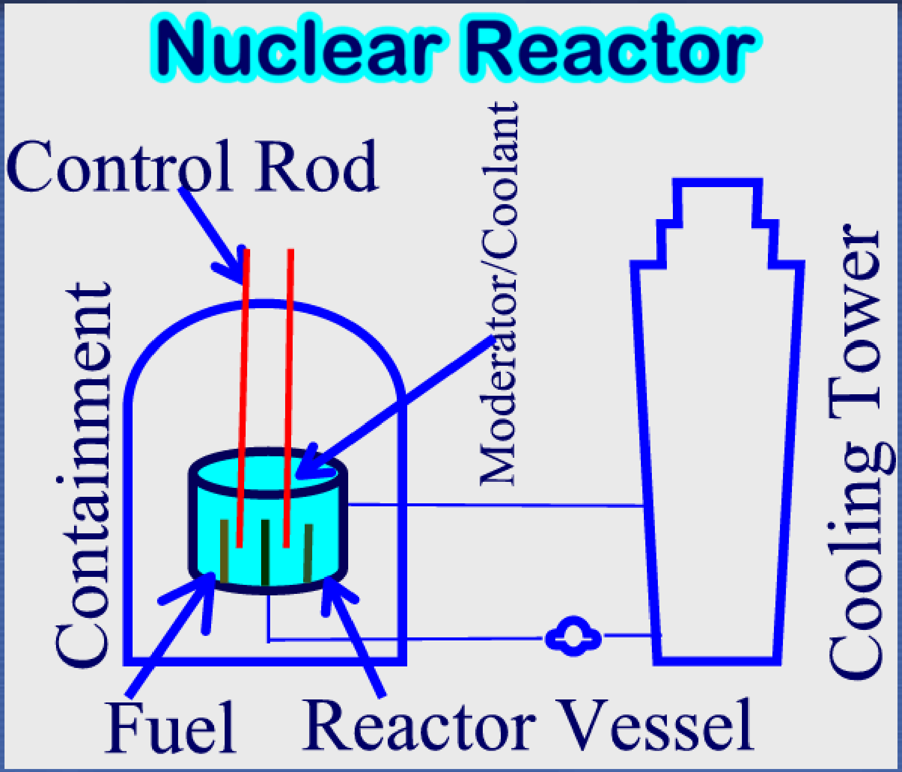
Outline

- Historical background
- Applications of Research Reactors
- Future perspectives
- List of references



Background



Main Components of Research Reactor

FUEL	Natural Uranium / Enriched Uranium
FORM	Metal, Alloy, Oxide, Silicide
CLAD	Aluminium, Zirconium, Stainless Steel
MODERATOR	H_2O, D_2O, 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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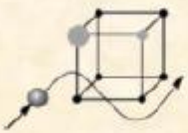
Basics on neutron scattering research

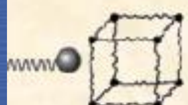
Why Neutrons?

1. Neutrons have the right wavelength

2. Neutrons see the Nuclei



3. Neutrons see Light Atoms next to Heavy Ones

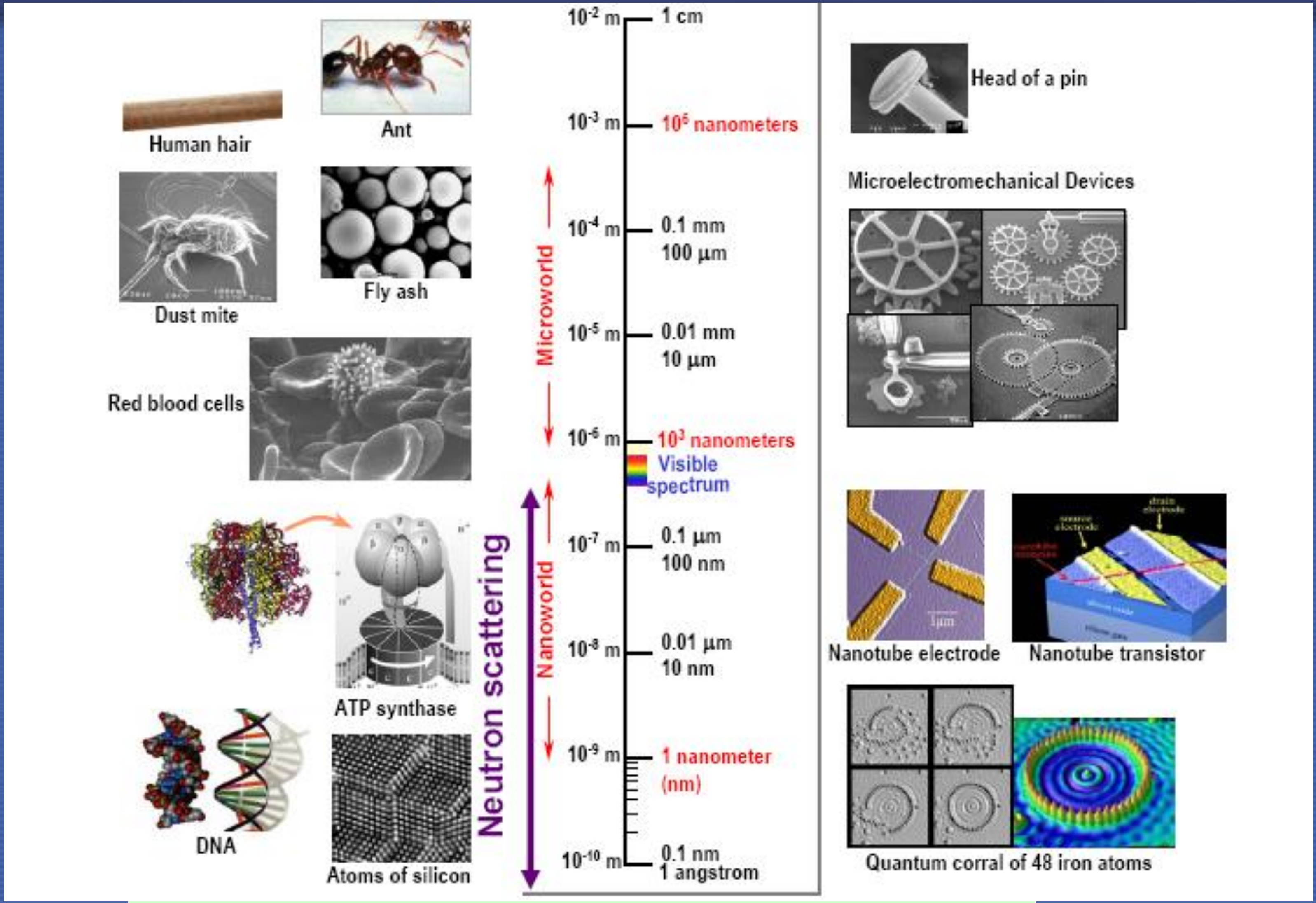


4. Neutrons measure the Velocity of Atoms

5. Neutrons penetrate deep into Matter

6. Neutrons see Elementary Magnets

→ Neutron scattering (1)



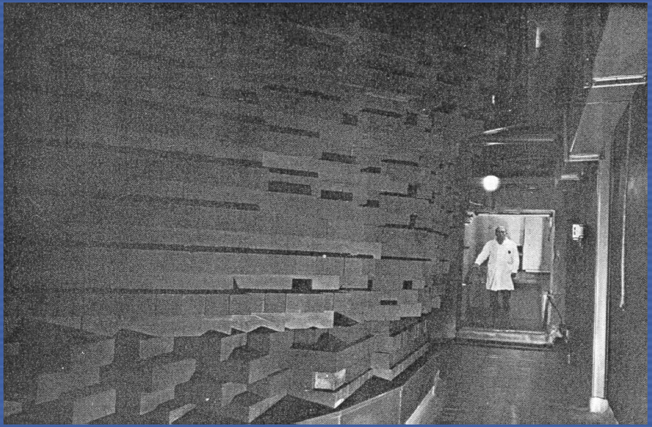
Neutrons: microns to angstroms!

Background

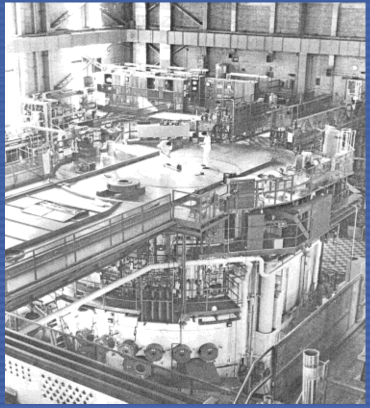
Some historical facts

- 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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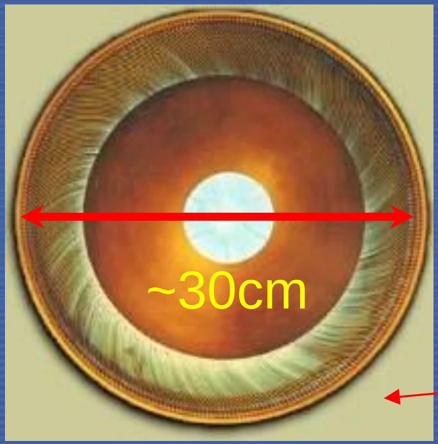
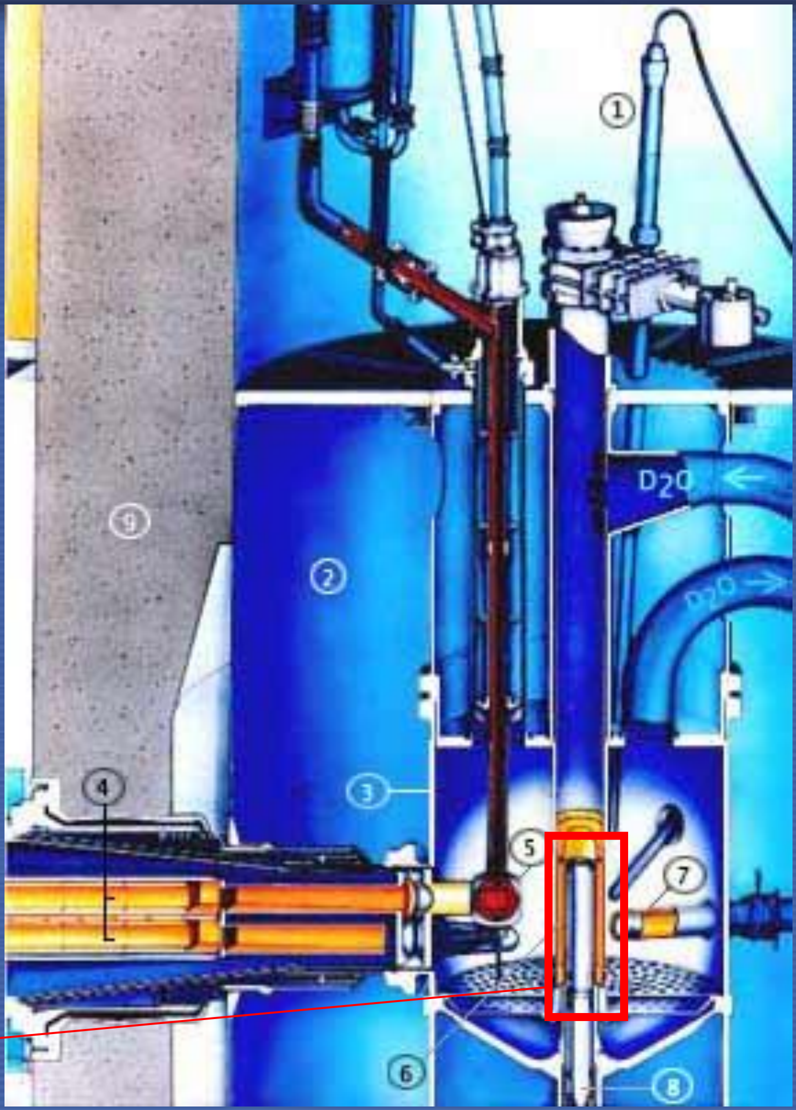
Background

Other general information: features

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





SOME OF THE MORE POWERFUL MTRs IN USE

Reactor	Country	Power	Start-up
LVR15	Czech Republic	10 MW	1957
HBWR	Norway	20 MW	1959
BR2	Belgium	100 MW	1961
SM-3	Russian Federation	100 MW	1961
HFR	Netherlands	45 MW	1963
HFIR	United States of America	85 MW	1965
Osiris	France	70 MW	1966
ATR	United States of America	250 MW	1967
MIR.M1	Russian Federation	100 MW	1967
JMTR	Japan	50 MW	1968
BOR-60	Russian Federation	60 MW	1968

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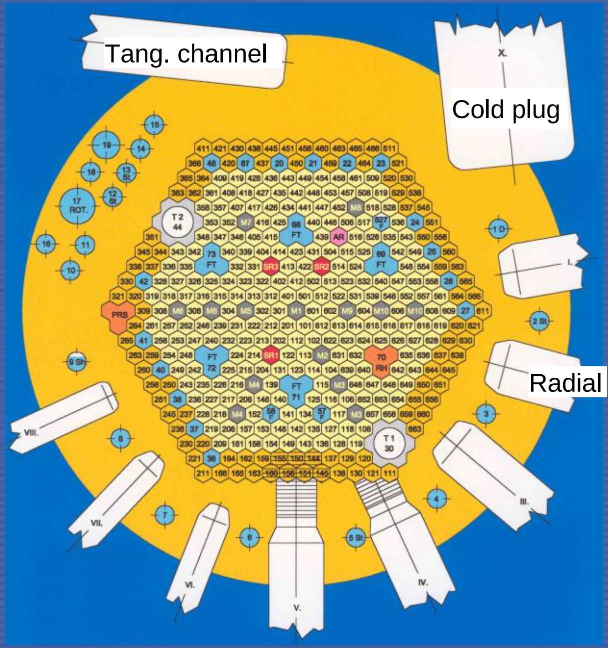
Background

Other general information: purpose

- Produce and provide access to the neutrons
- Access can be provided:
  - inside core, along core boundary and from external beams
- Typical Power range 100kW to 10MW
- Typical Steady-State Neutron Flux → 10^{12} to 10^{14} n/(cm^2 s)



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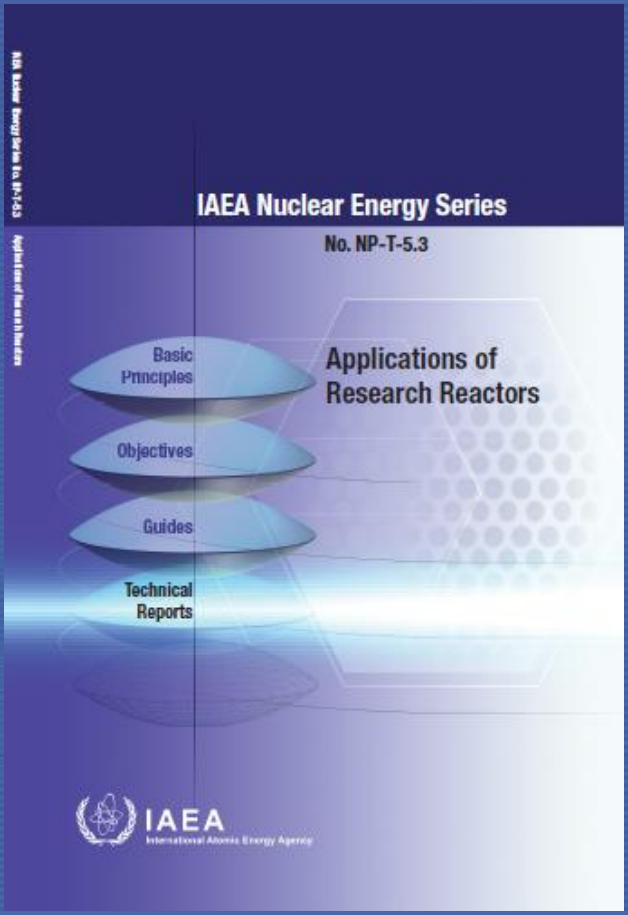
Applications of Research Reactors

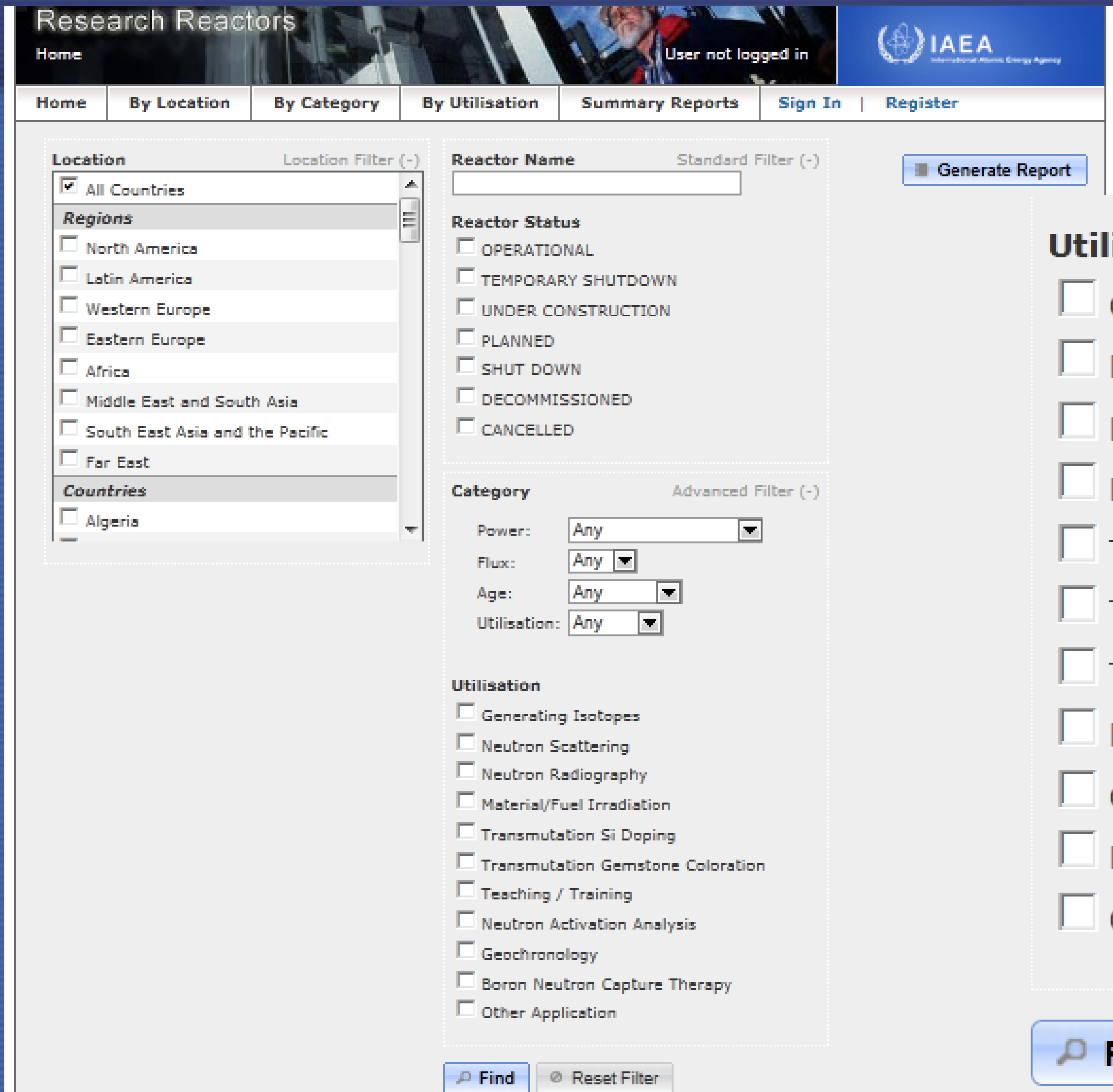
Other general information: purpose (continued)

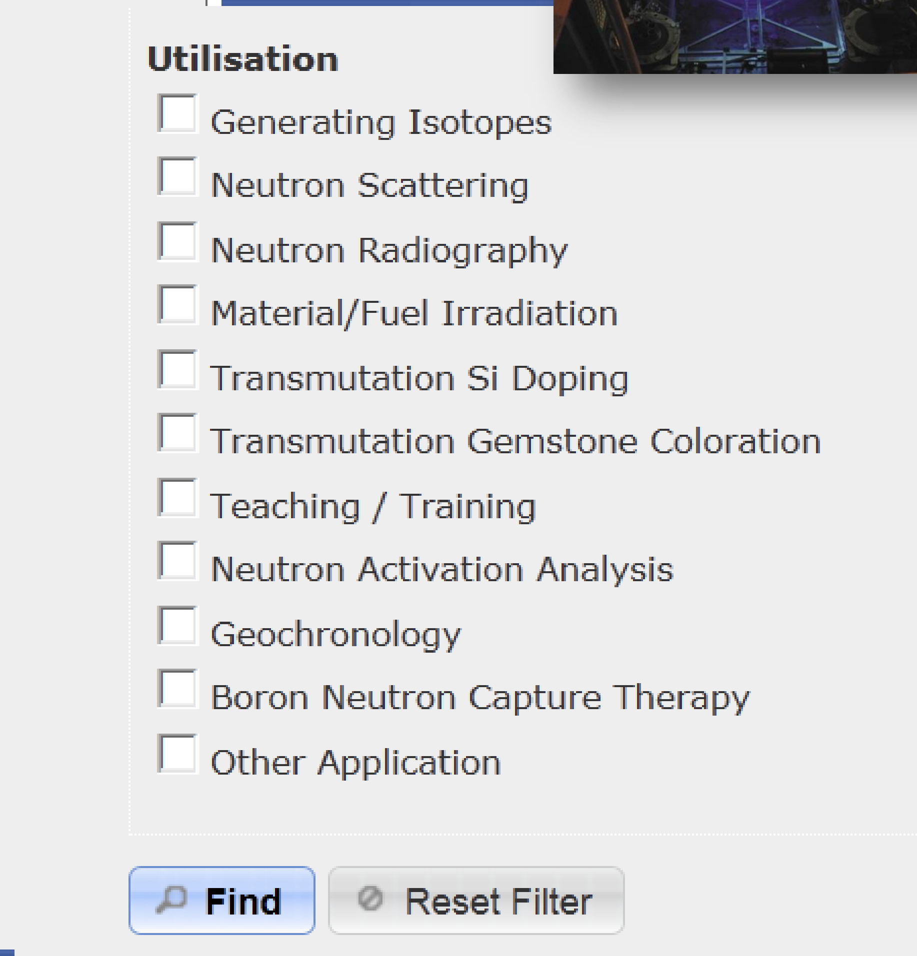
- Education & Training
- Neutron Activation Analysis
- Radioisotope Production
- Geochronology
- Neutron transmutation doping
- Neutron Radiography
- Neutron Scattering
- Positron source
- Neutron capture therapy
- Fuel/material testing and qualification
- Nuclear data measurements
- Computer code validation
- …

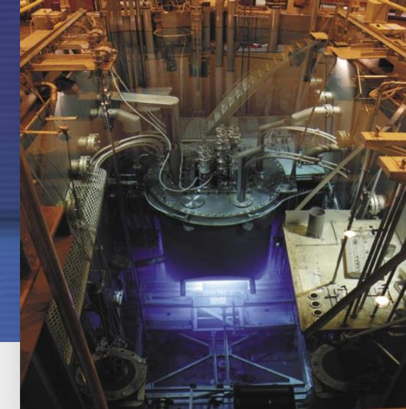
→ For more information see



Contents of the IAEA RRDB







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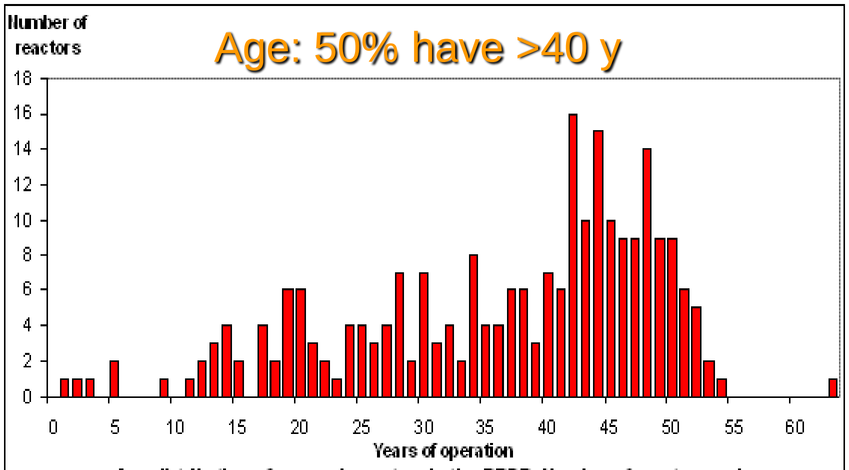
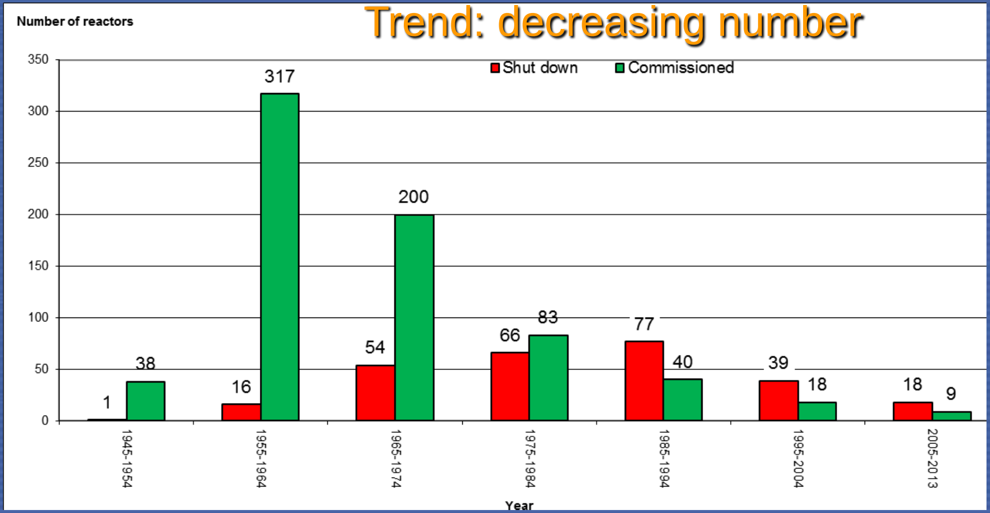
http://nucleus.iaea.org/RRDB/

Background

TOTAL	>770
Operational	**218**
Temp. shutdown	**22**
Under construction	**9**
Planned	10
Extended shutdown	8
Permanent shutdown	128
Decommissioned	356
Under decommissioning	16



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



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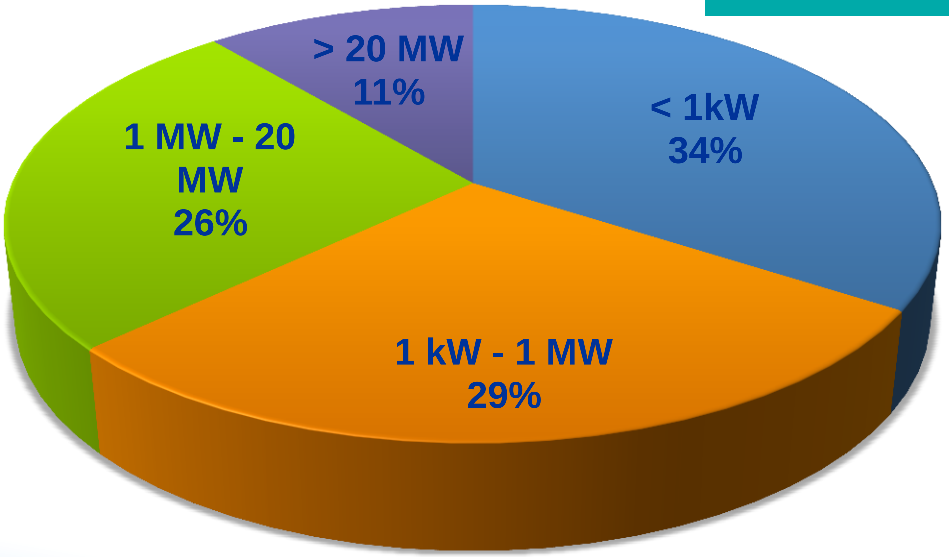
Background

- ~240 RR in operation in 55 MSs
  - ~119 (49%) Europe
  - ~50 (20%) Asia and Pacific
  - ~49 (20%) North America
  - ~17 (7%) Latin America and the Caribbean
  - ~8 (3%) Africa



Power distribution of operational RRs

Background

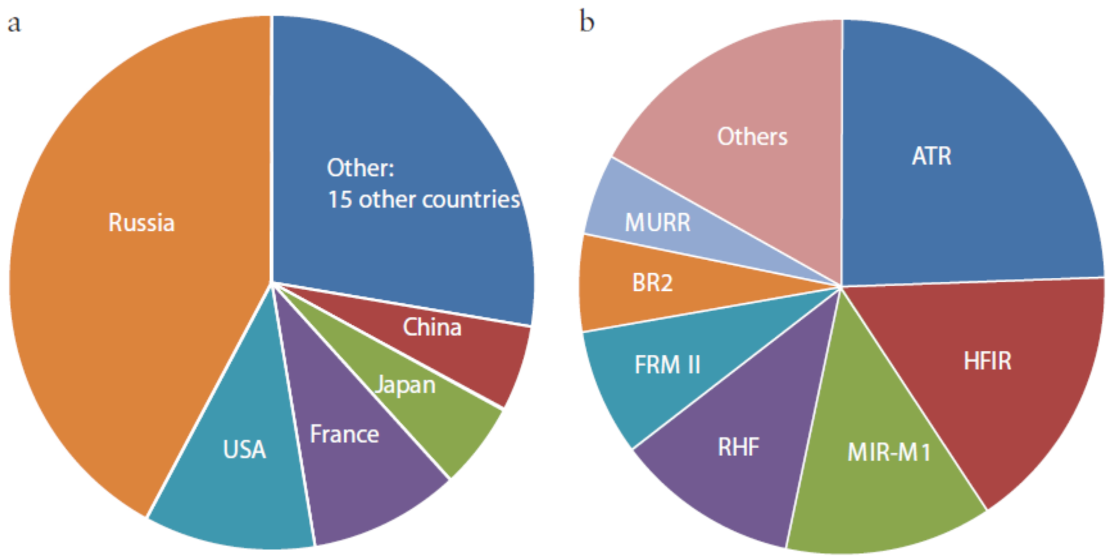


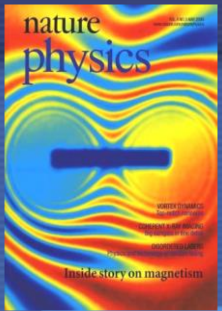
FIGURE 2.3 Distributions of civilian research reactors currently using HEU fuel (a) by country (see Table 2.2) and (b) by approximate HEU annual consumption. Figure 2.3a identifies countries with four or more reactors; 15 countries have three or fewer research reactors currently operating with HEU fuel. In Figure 2.3b, three of the top seven are in the United States (ATR with 120 kg, HFIR with 80 kg, and MURR with 24 kg approximate annual consumption), three are in Europe (RHF/ILL with 55 kg, FRM-II with 38 kg, and BR2 with 29 kg approximate annual consumption), and one is in Russia (MIR.M1 with 62 kg annual consumption). SOURCE: Table 2.2 and Meyer (2006).

- 74 operating or under construction RRs in 18 countries are using HEU
- High-density LEU U-Mo fuel not yet qualified
- Efforts to convert Mo-99 production from HEU to LEU
- Fresh fuel supply issues (TRIGA and non-TRIGA)
- Dead-line for US origin RR SNF repatriation 2016-2019
- Majority of MS are lacking a strategies for RR SNF management/disposition

Background

Fuel Type	Fuel Element Geometry	Fuel Element (Assembly) Dimensions, mm	Fuel meat	Clad	Enrichment in 235U, %
EK-10	Rod	880	UO2-Mg	Al	10
IRT	Rod	880	UO2-Al	Al	19.7 - 36 - 90
MTR	Plate	N/A	UAlx-Al, U3Si2-Al, U3O8-Al	Al 6061, Al 1100	19.75 ÷ 93.0
VVR	concentric fuel tubes, hexagon	750 - 865	UO2+Al U-Al dispersed	Al	19.7 - 36 - 80 - 90
TRIGA 102	Rod	755 X 3.65	U-Zr-H	Al	19.9
TRIGA 104	Rod	755 X 3.56	U-Zr-H	SS304	19.9
TRIGA 106	Rod	755 X 3.75	U-Zr-H	SS304	19.9
TRIGA 108	Rod	755 X 3.75	U-Zr-H	SS304	19.9

RR stakeholders and users



Government
- Intergovernmental agreements
- Economic planning
- Industrial competitiveness
- Expand national R&D capabilities
- Availability of nuclear medicine
- International recognition

Scientific Organizations
- Universities
- Research centres
- Private sector
- New facilities
- New instruments
- International cooperation

Industry
- Metrology
- Radiography
- Materials testing
- Process efficiency
- Radioisotope supplies
- Elemental analysis

Policy / Funding / Development

Science infrastructure & opportunity

RESEARCH REACTOR

Industrial efficiency / Competitiveness

Better / Cheaper healthcare

Output / efficiency / drought resistance

Competencies / Technical Recourses

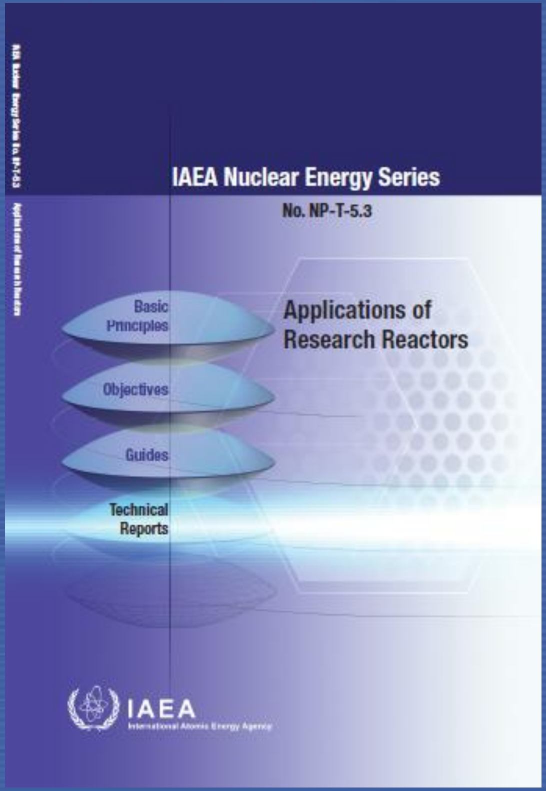
Medicine
- Radioisotope supplies
- New treatment options
- Improved availability

Agriculture
- Radiotracer techniques
- Elemental analysis
- Sterilization services

Energy
- Education and Training
- TSO services
- Nuclear Safety Culture

RR utilization: applications

Application	Number of RR involved	Number of countries
Education & Training	166	53
Neutron Activation Analysis	120	53
Radioisotope production	97	43
Material/fuel testing/irradiations	60	27
Neutron radiography	72	38
Neutron scattering	48	31
Si doping	28	18
Geochronology	26	22
Gem coloration	21	12
Neutron Therapy	17	12
Nuclear energy research	16	11
Nuclear Data Measurements	4	4
Other	130	38



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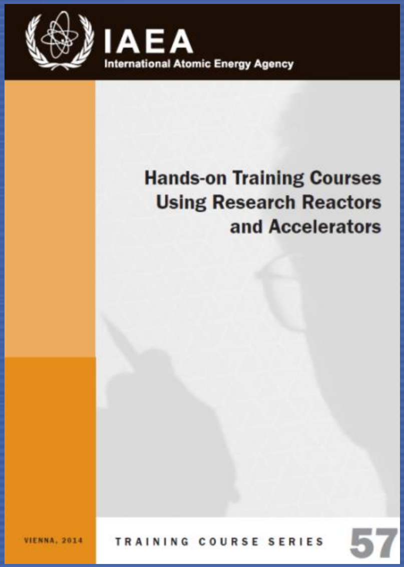
→ Education & training (1)

- **Public tours & visits**
- **Teaching physical and biological science students**
- **Teaching radiation protection & radiological engineering students**
- **Nuclear engineering students**
- **Nuclear power plant operator training**

→ Can be potential source of income



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→ E.g. hands-on-training using RRs

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E.g. Internet Reactor Laboratory (IRL) project

PULSTAR Reactor NCSU/ U.S

Reactor Parameters →

Audio/ Video data ↔

Nucl. Eng. Department JUST/Jordan

Ongoing projects with host RRs in Argentina and France

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E.g. training of nuclear utility staff

Typical flow from Academics to Nuclear

Academic background → **Nuclear training required**

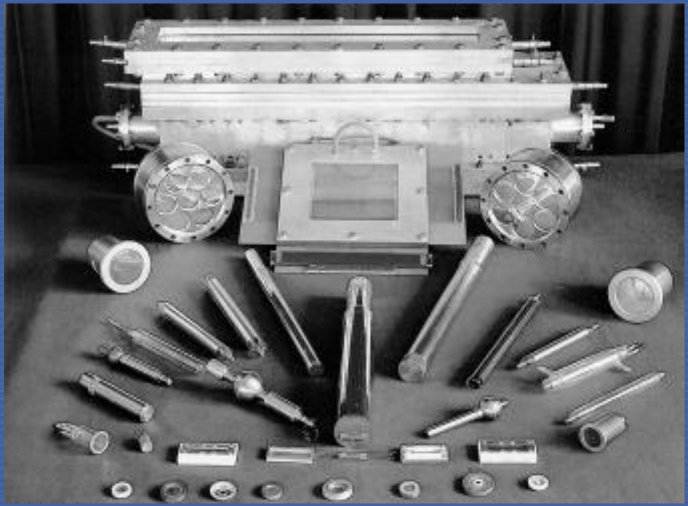
Academic background	Population need estimates for 2 NPPs	Nuclear training required
PhDs	50+ Experts	+ 12 to 24 months
Engineers & Masters	400+ Project + M&O staff	+ 6 to 12 months
Bachelors & Technicians	800+ Construction & Operating staff	+ 3 to 9 months

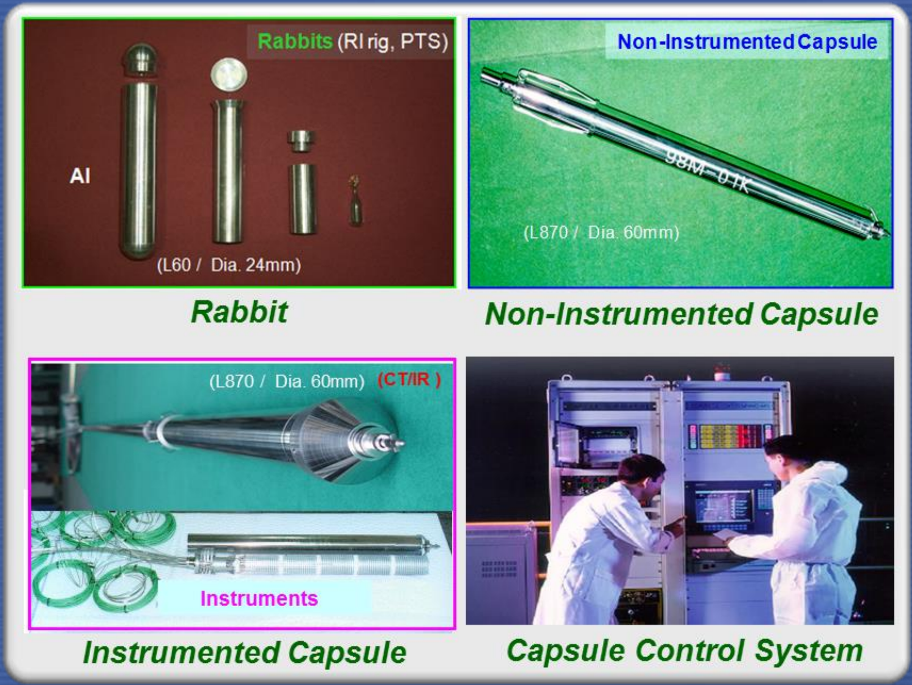
Population need estimates for 2 NPPs

Courtesy: AREVA, France, 2009.

→Fuel/Material/detector testing/qualification (1)

- Instrument development, testing, calibration, qualification
- Fuel/material testing (ageing, corrosion, irradiation)
- Fuel/material qualification (temperature, pressure, irradiation)
- Development of new fuels/materials (actinide fuels, high temperature reactors, fast reactors, fusion reactors, …)





Irradiation at High Flux RR of 50 days is equivalent to 10 years irradiation at a typical NPP!

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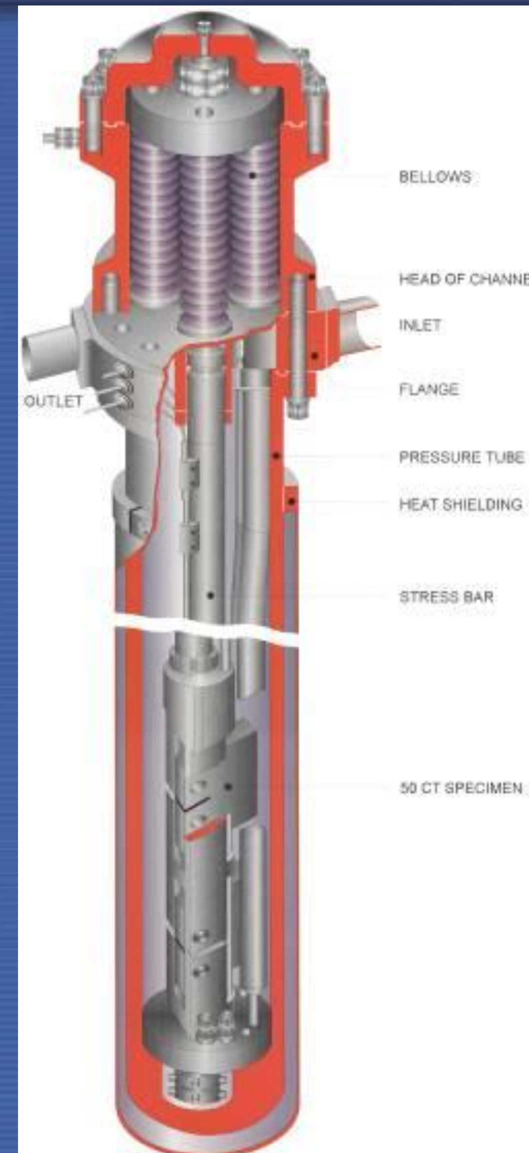
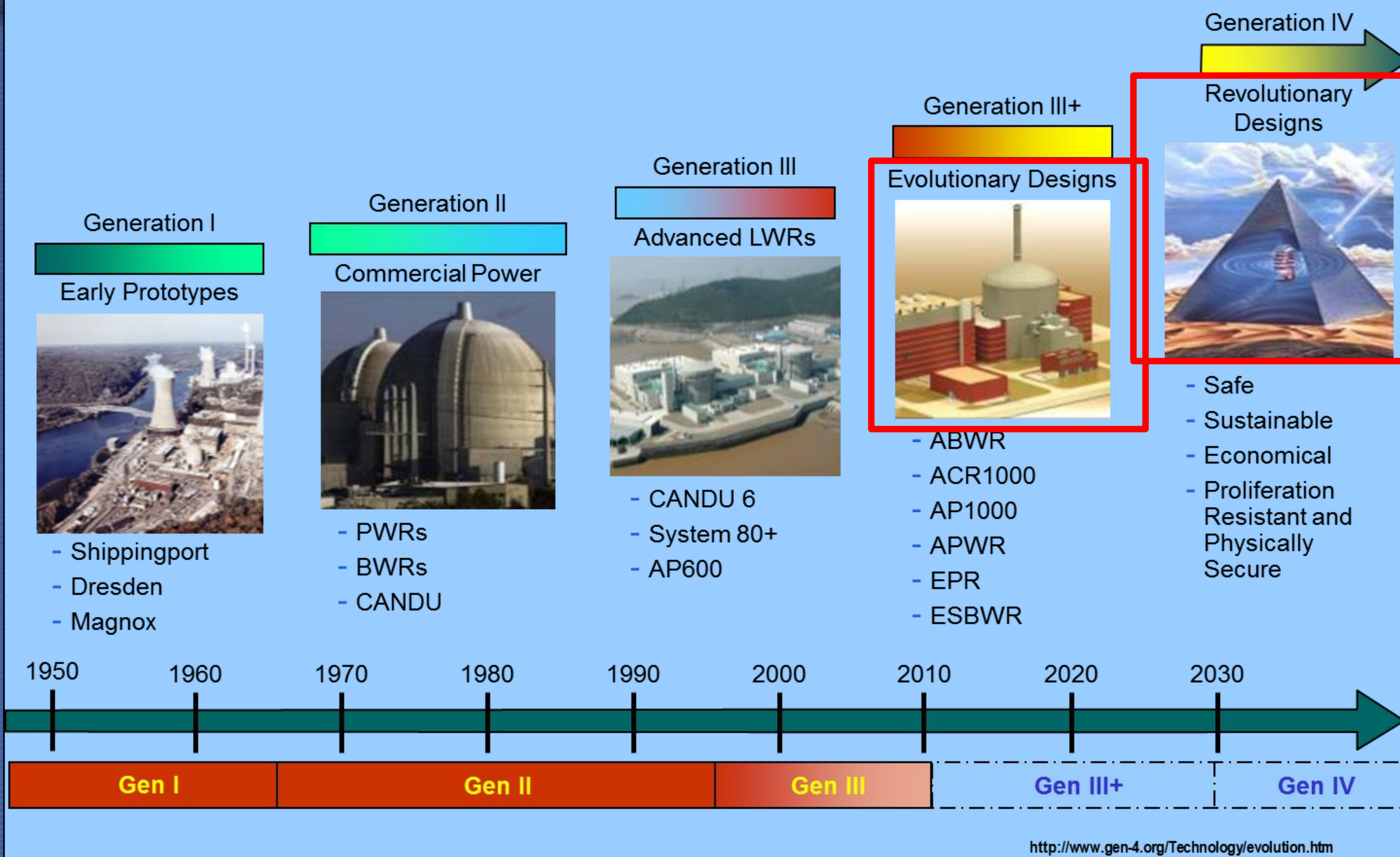
→Fuel/material testing/qualification (2)

- Equipped irradiation rigs
- Independent/controlled heating
- Thermocouples
- Neutron monitoring
- Irradiation loops (p, T, neutrons)
- Hot laboratories
- Mechanical tests
- Visual examination
- Radiochemistry



Generations of Nuclear Reactors



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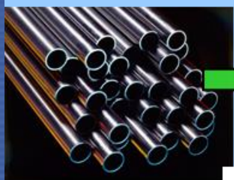
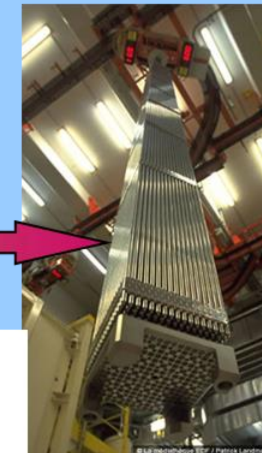
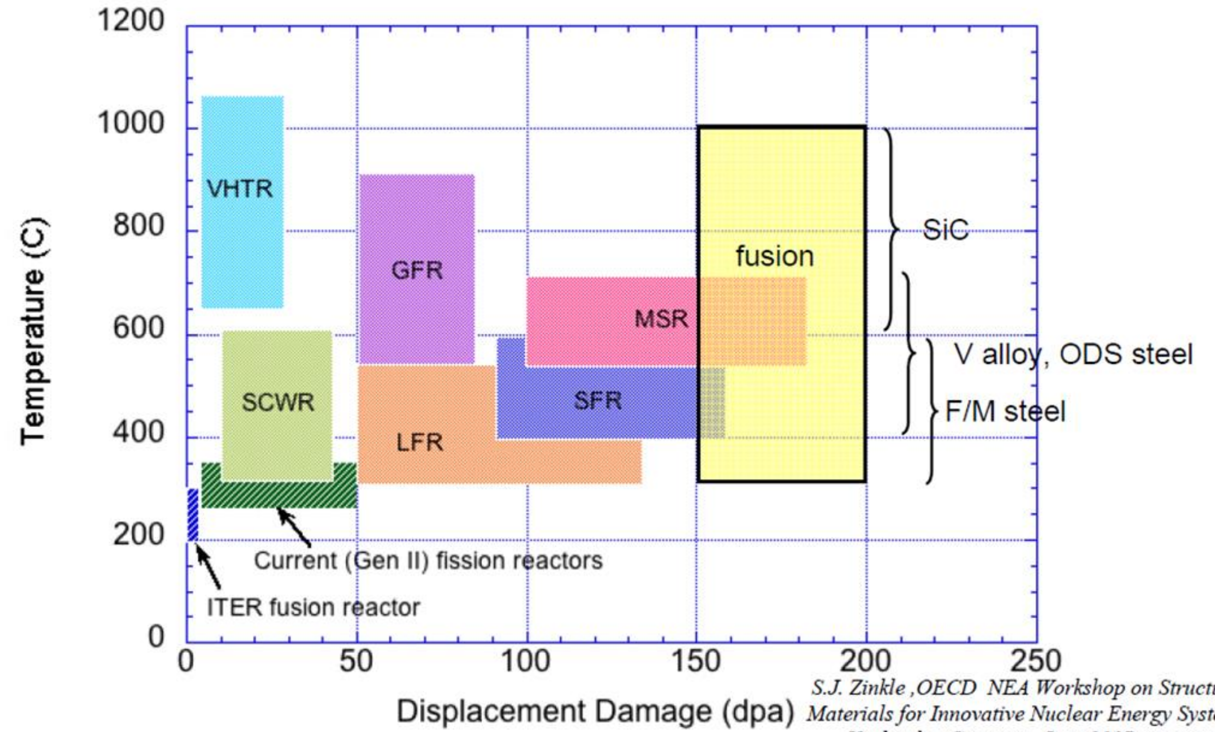
Material development in nuclear industry



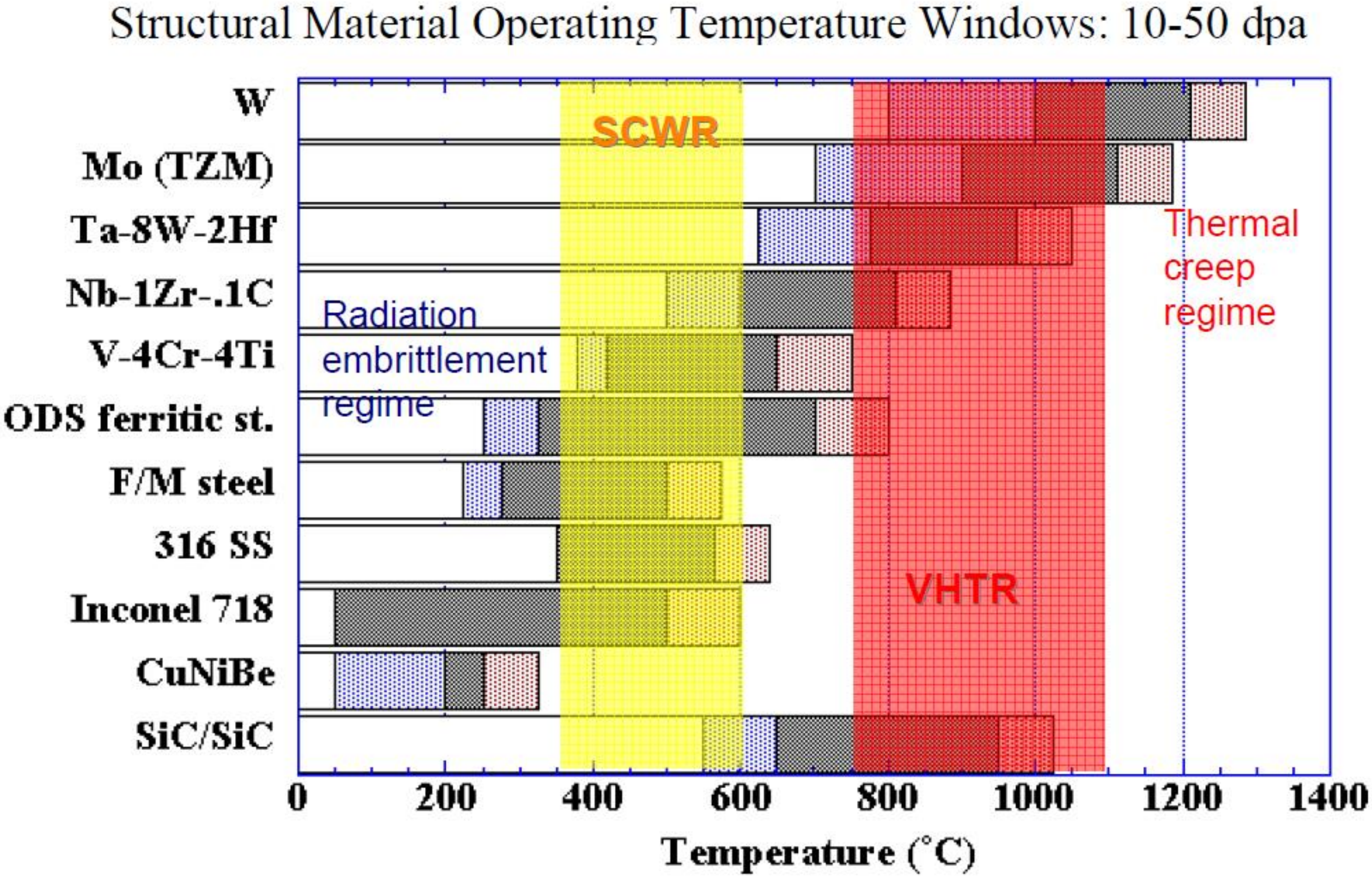
Selection → Characterisation → Qualification





S.J. Zinkle ,OECD NEA Workshop on Structural Materials for Innovative Nuclear Energy Systems, Karlsruhe, Germany, June 2007, in press

New structural materials with temperature windows >300°C are needed for efficient development of Gen IV concepts



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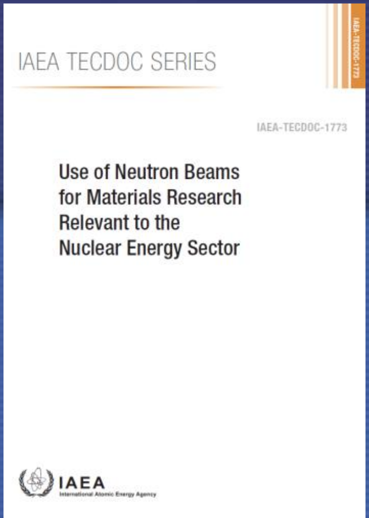
→ Neutron scattering (3)


IAEA TECDOC SERIES
IAEA-TECDOC-1773
Use of Neutron Beams for Materials Research Relevant to the Nuclear Energy Sector
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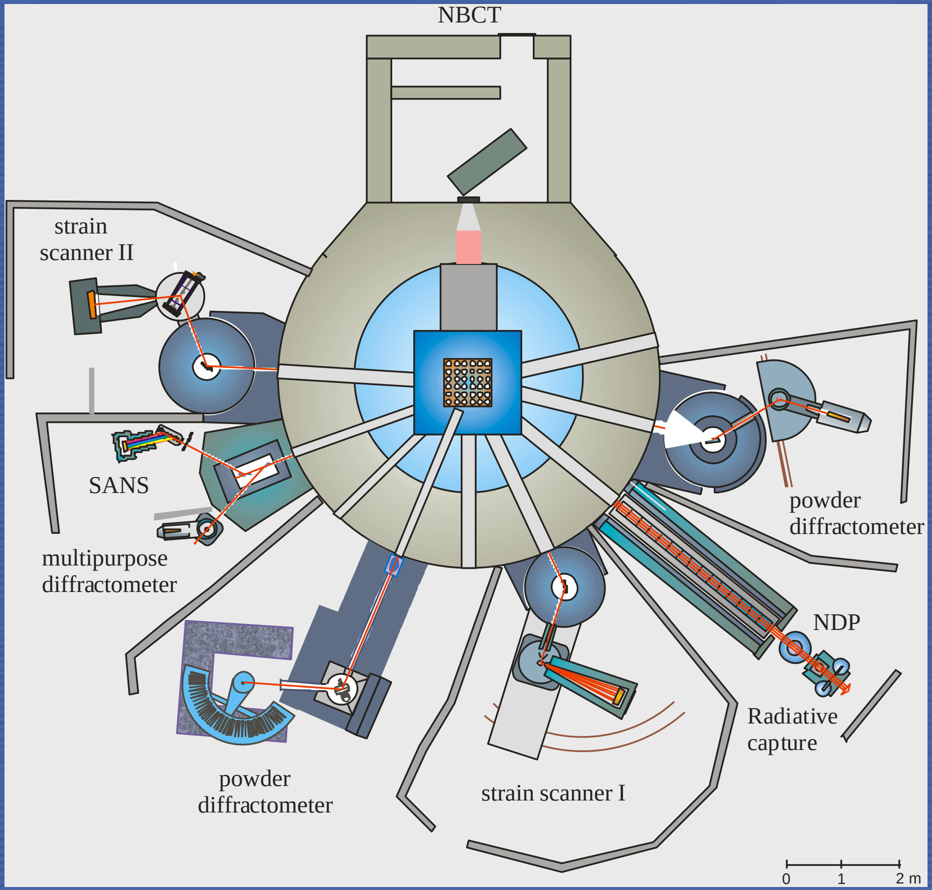
Experimental facilities installed @ LVR-15



Guide hall II @ HZB

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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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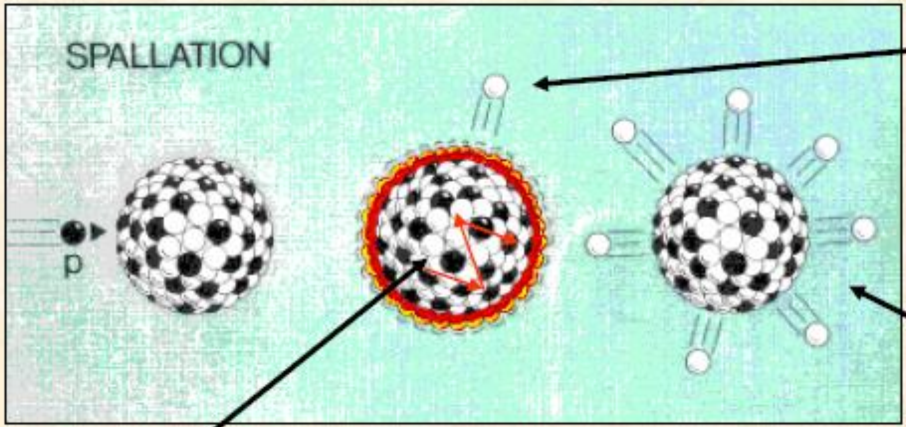
How do we produce neutrons?

b. Artificially accelerated particles

(iii) Spallation with Protons

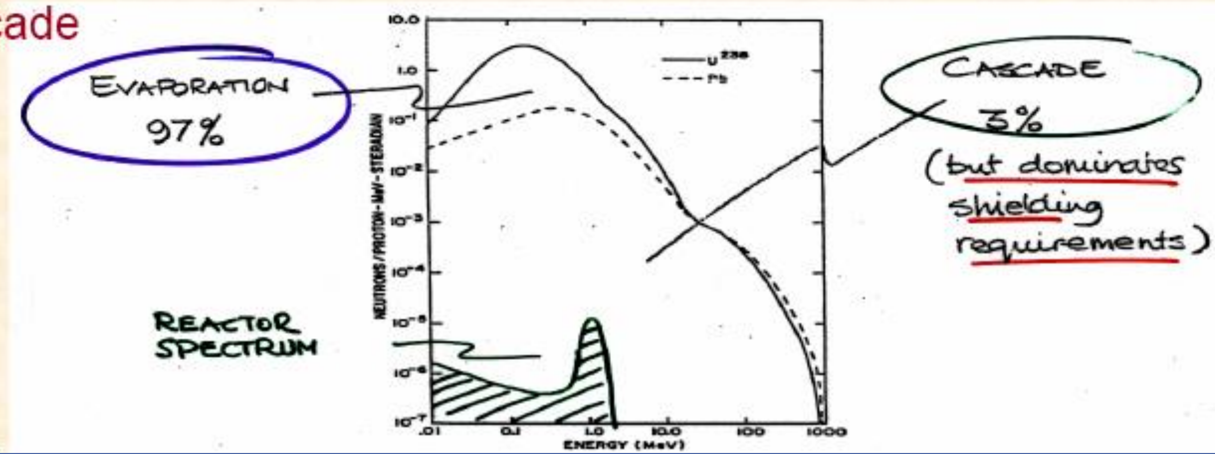


2. Inter Nuclear Cascade

Up to 40 neutrons per incident proton

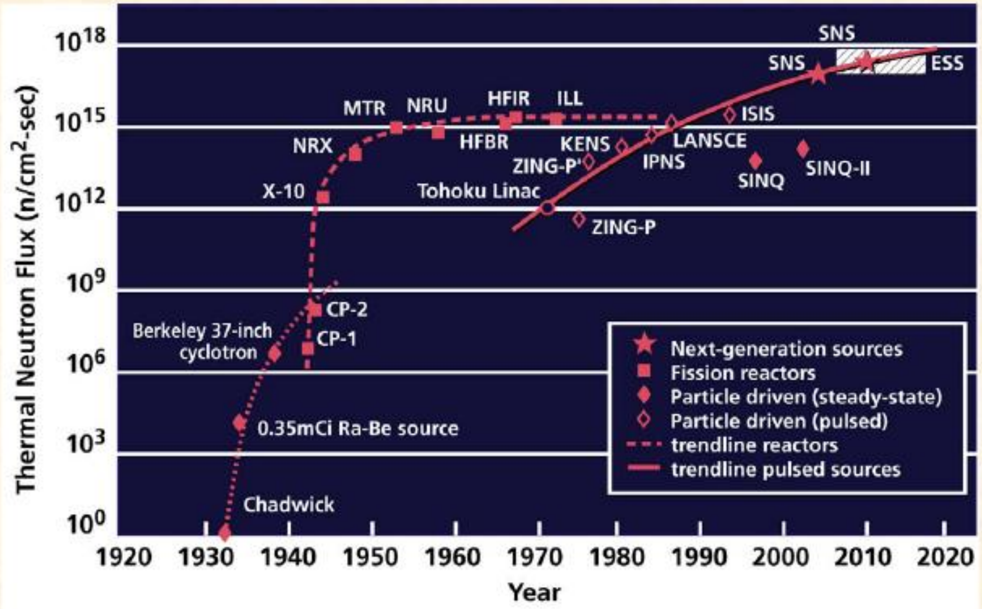
3. Evaporation

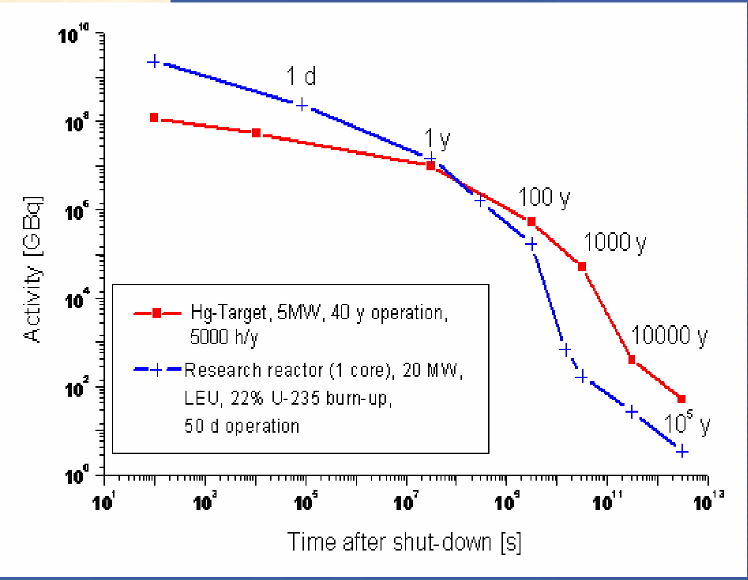
1. Internal Cascade



Neutron production: RRs or Accelerators?

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





Research Reactor of 1MW:

~3x10^{16}fissions/s → ~0.8x10^{17}n/s

Spallation Neutron Source of 1MW:

(1GeV;1mA;protons)→~25n/p * 6.25x10^{15}p/s →~1.6x10^{17}n/s

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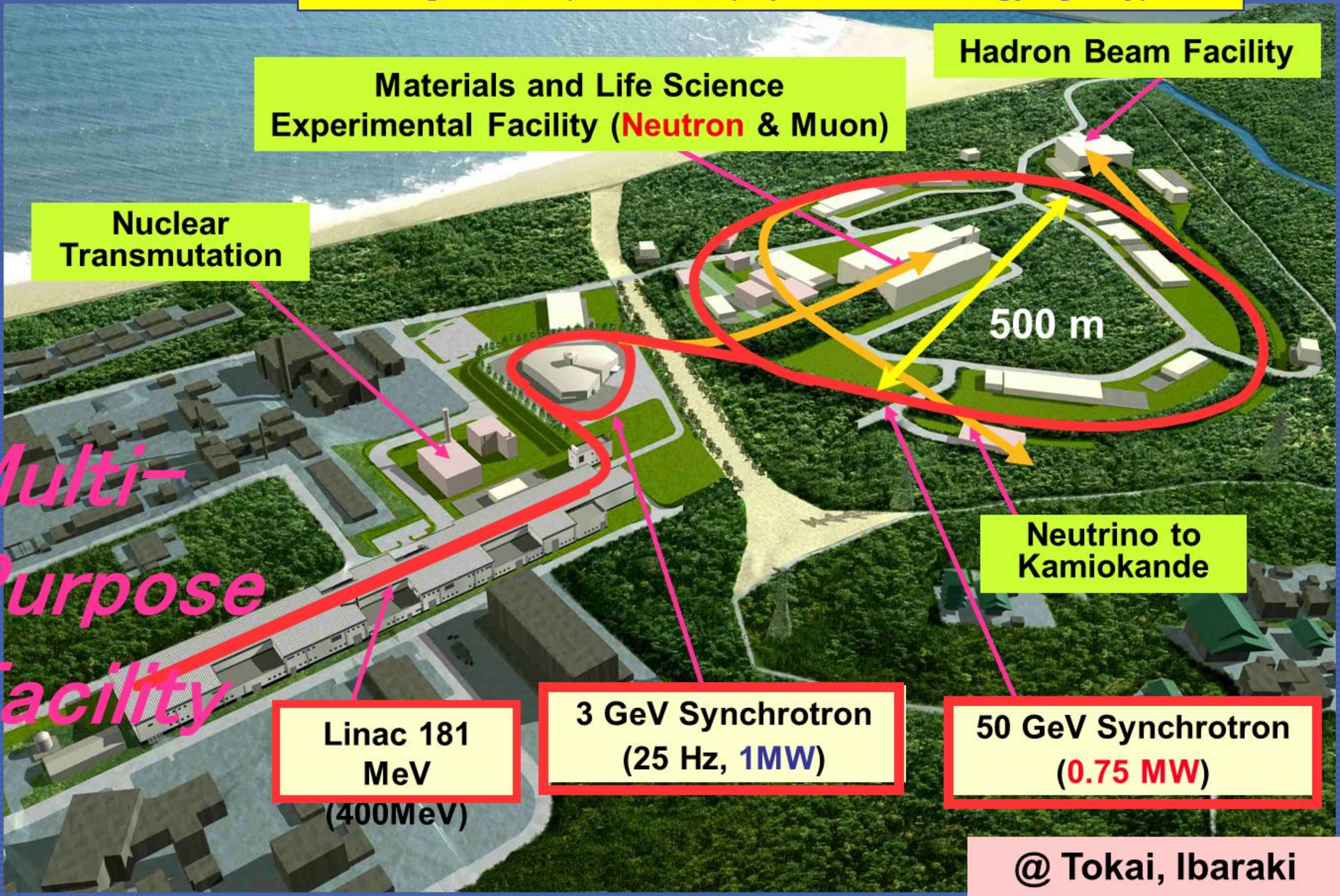
J-PARC = Japan Proton Accelerator Research Complex

Joint Project of **KEK** (High Energy Accelerator Research Organization) and **JAEA** (Japan Atomic Energy Agency)

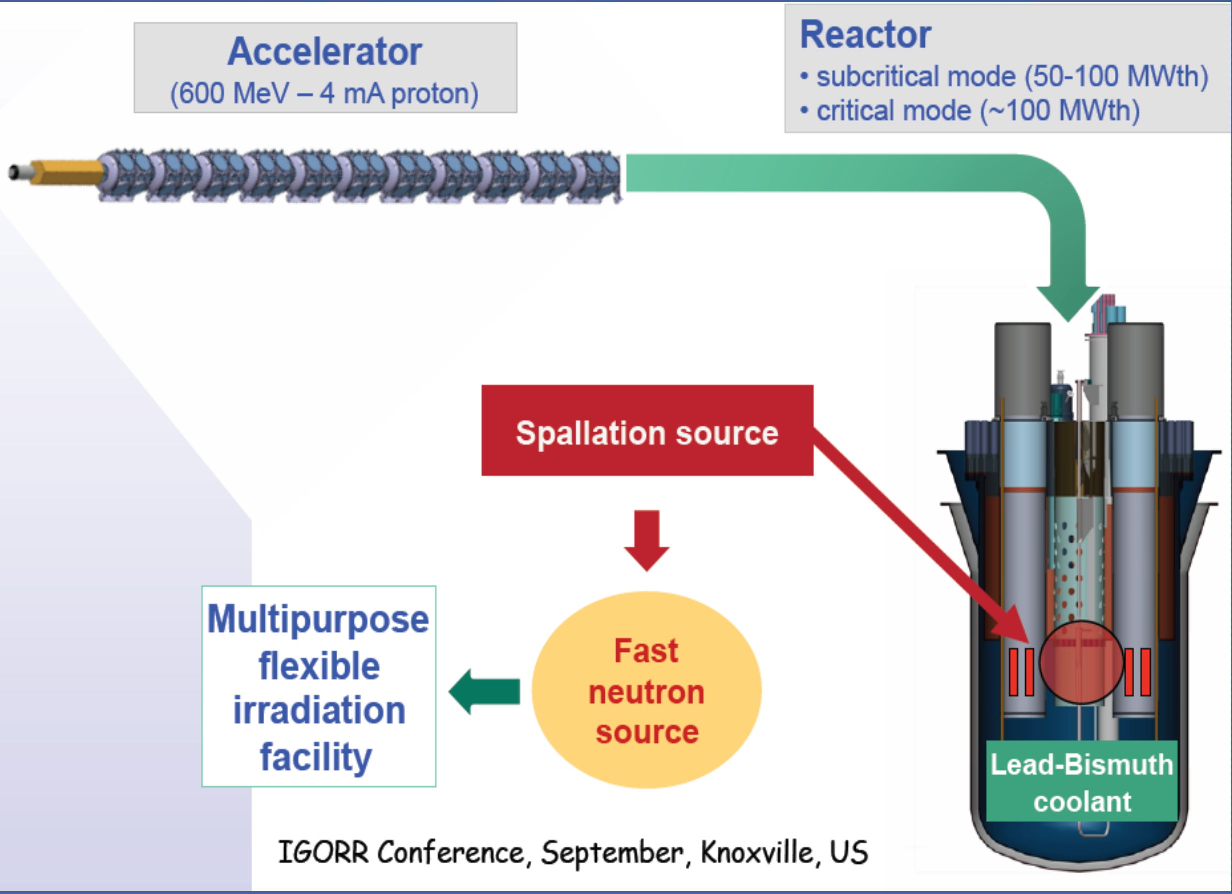


@ Tokai, Ibaraki

Combined applications of RRs and Accelerators:
ADS MYRRHA project in Belgium

Purpose:

- Prototype fast neutron ADS
- Demo for nuclear waste transmutation
- Fast & intense neutron source for
    - RI production
    - Si doping
    - Materials/fuel studies
    - Gen IV studies
    - R&D
    - E&T
    - …



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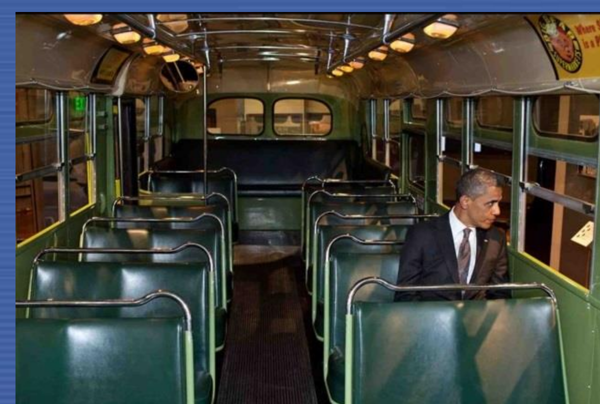
Challenge of low utilization: affects many RRs

“Busy”, well utilised RRs; ☺
1st crit. 1965

“Naked”, barely utilised RR; ☹
1st crit. 1979



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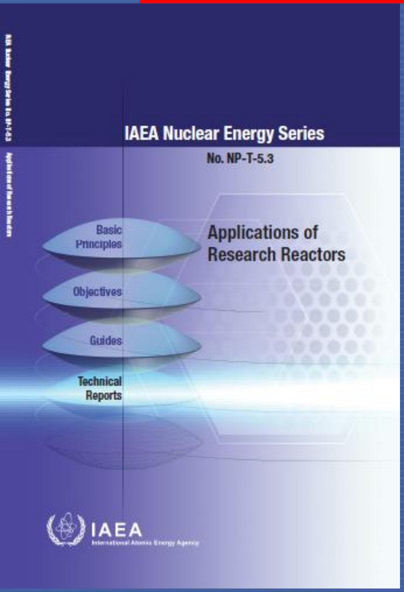
Strategy for enhanced utilization and sustainability

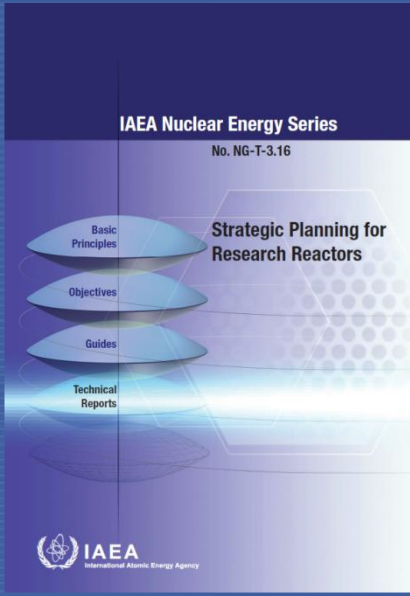
Basic approach for SP development

Facility Status
Capabilities
What can I do?

Current Stakeholder
Requirements/Needs
What should I do?

Production of a strategic plan supports an increase in utilization by increasing capabilities and creating new requirements





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

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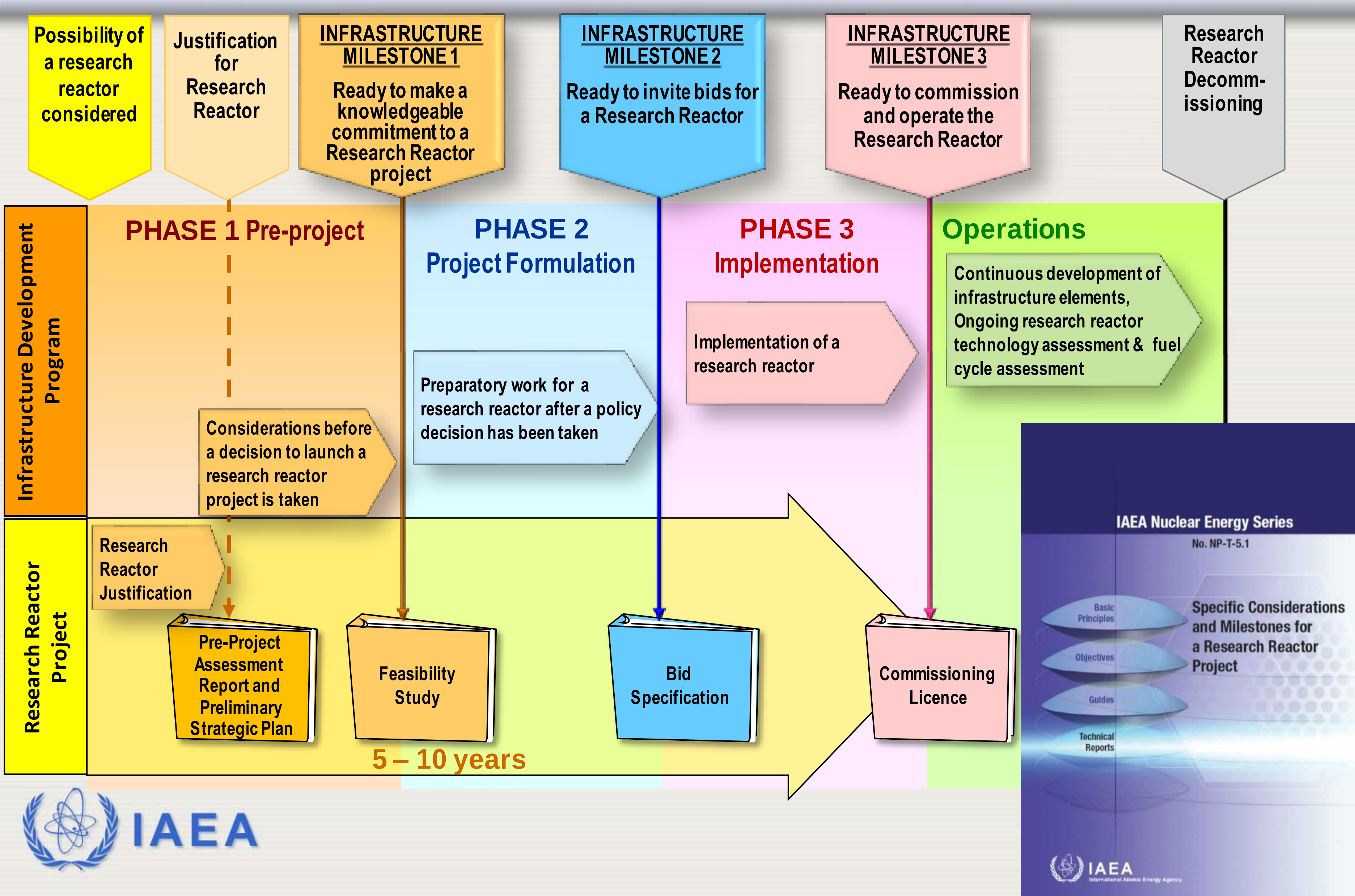
New RR Projects: *tentative overview*

Phase 1 (Consideration) Total: 23	Phase 2 (Preparatory Work) Total: 7	Phase 3 (Implementation) Total: 8
Azerbaijan	Belarus	Argentina
Bangladesh	Belgium	Brazil
China (2 facilities)	Bolivia	France (2 facilities)
Ethiopia	The Netherlands	Jordan
Ghana	Thailand (for BNCT at Univ.)	India
Japan	Vietnam	Republic of Korea
Kenya	USA	Russian Federation (3 facilities)
Kuwait		Saudi Arabia (Low Power RR)
Lebanon		
Malaysia		
Mongolia		
Myanmar		
Tajikistan		
Philippines		
Nigeria		
Saudi Arabia (Multipurpose RR)		
Senegal		
South Africa		
Sudan		
Tanzania		
Thailand (Multipurpose RR)		
Tunisia		
Zambia		

First criticality
(25 Apr. 2016)

RR Infrastructure: new RR project



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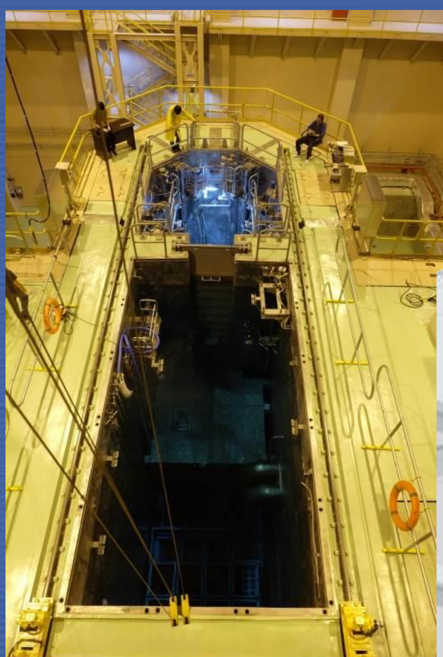
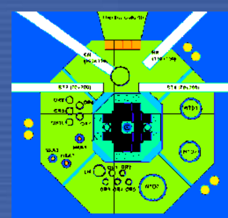
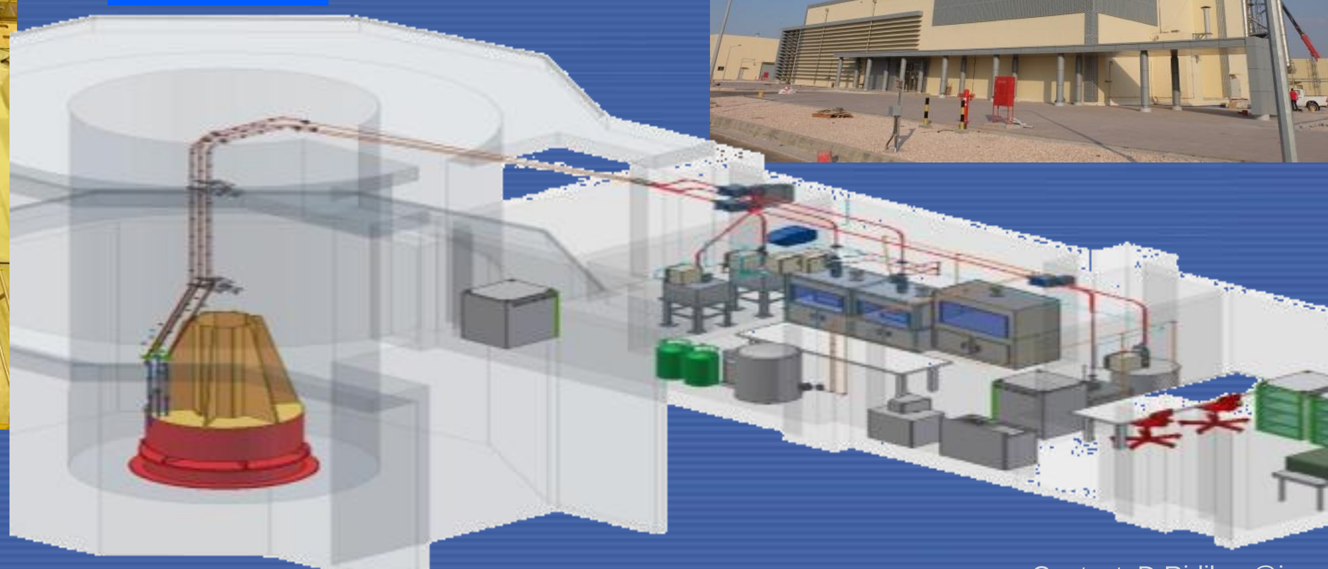
New RRs considered in many developing countries

Example: Jordan Research & Training Reactor (JRTR),
Under commissioning by KAERI-Daewoo Consortium, 1st criticality in April 2016

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.
1st step to the national NPP programme







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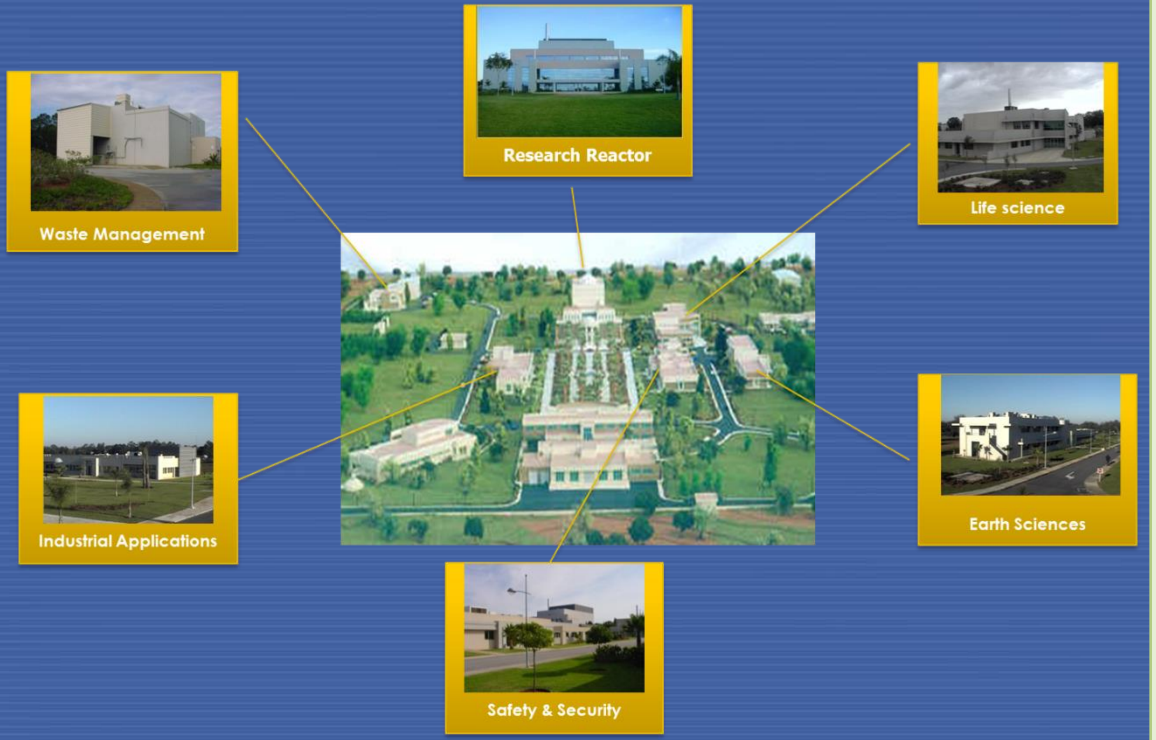
→ Role of RRs in the context of national NPP programme

Example of Nuclear Research Centre in 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	

Source: CNESTEN, Morocco

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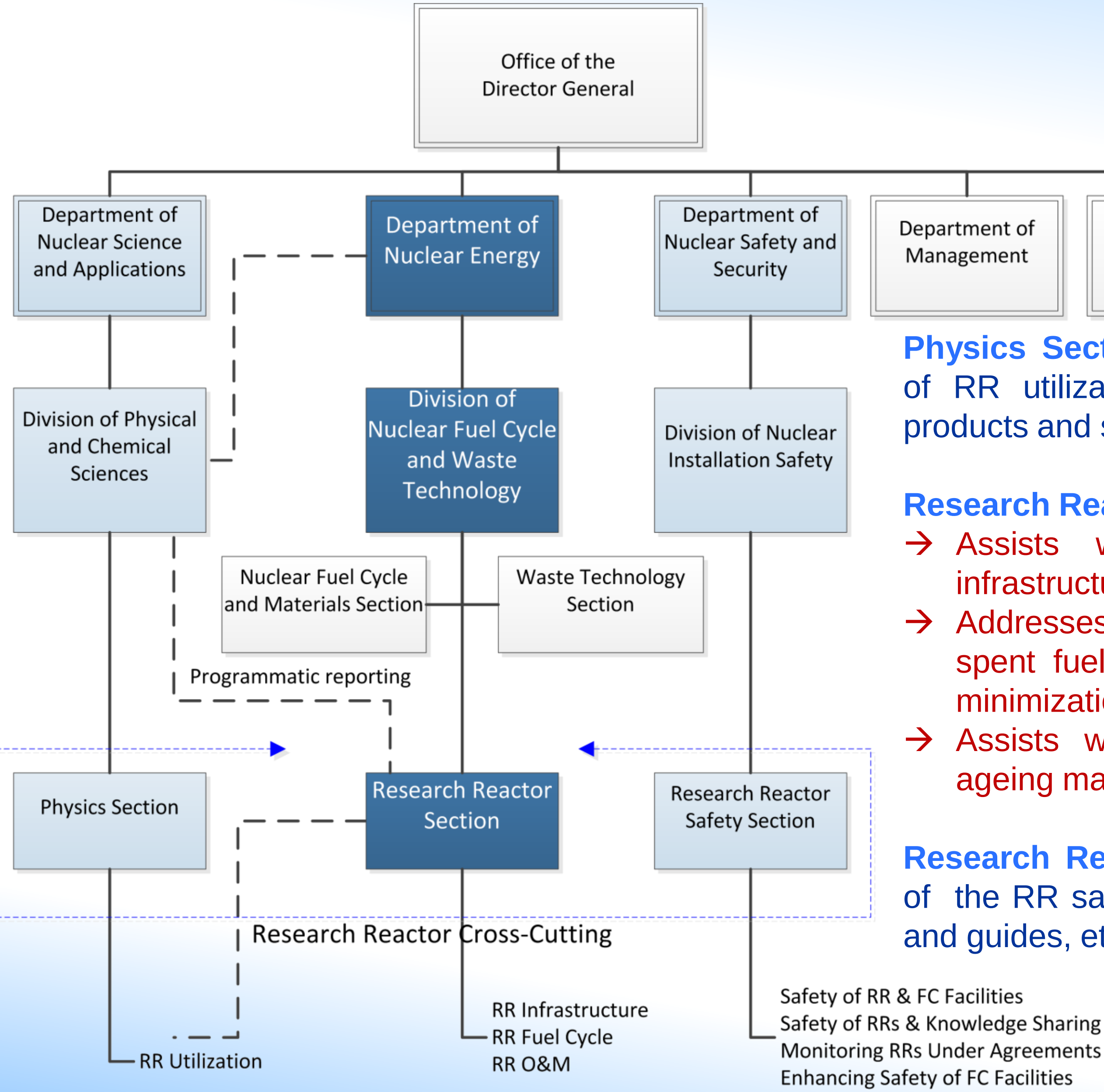
Field of activity RRs: cross-cutting



Physics Section: enhancement and improvement of RR utilization and applications; promotion of products and services; strategic planning.

Research Reactor Section:

→ Assists with new RR projects, including infrastructure development & capacity building;

→ Addresses RR fuel cycle issues (fuel supply, spent fuel management, HEU conversion and minimization);

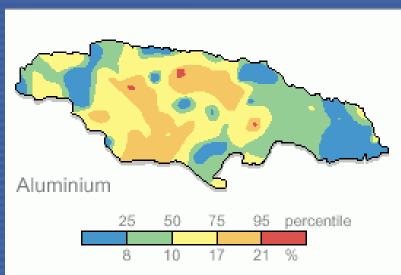
→ Assists with improvement of RR O&M and ageing management.

Research Reactor Safety Section: enhancement of the RR safety, development of safety standards and guides, etc.

Research Reactors will remain indispensable training, research and technological tools

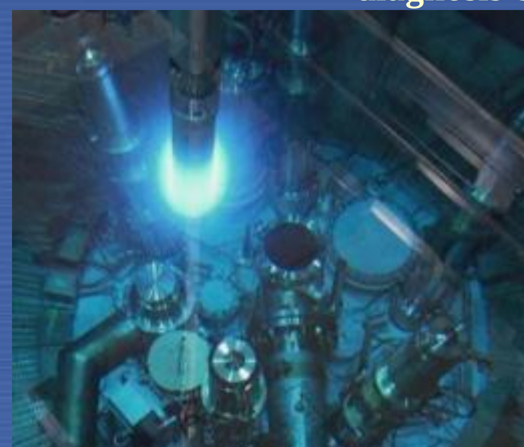
Radioisotopes for improved agricultural yields

Radioisotopes for medical diagnosis & treatment



Neutron activation analysis for geological & environmental studies

Neutron imaging for studying objects of national heritage



Irradiation effects
leading to added value of products

Education & training in nuclear science & technology

Neutron scattering for better materials & objects

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List of main references for RRs@IAEA

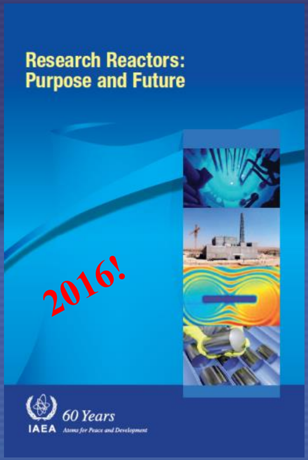
NA: http://www-naweb.iaea.org/napc/physics/research_reactors/

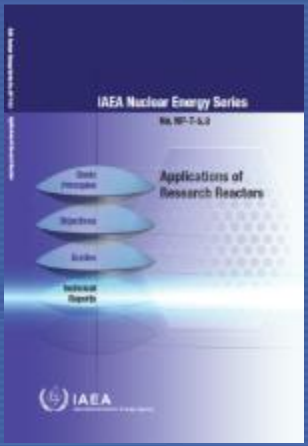
NE: http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/home.html

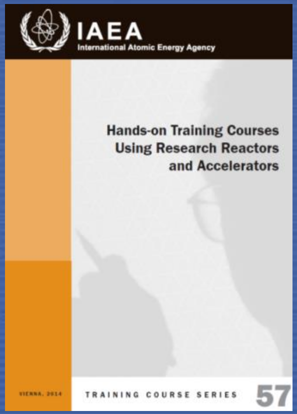
NS: http://www-ns.iaea.org/tech-areas/research-reactor-safety/

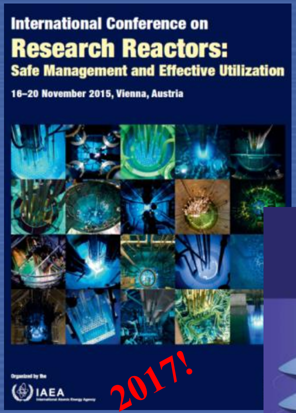
IAEA RRDB: http://nucleus.iaea.org/RRDB/

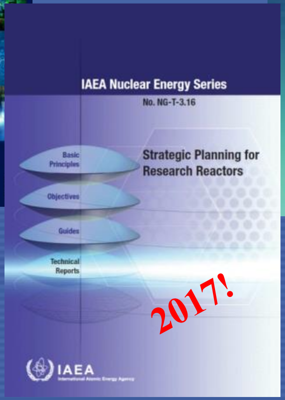
Bibliography:
http://www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/bibliography.html

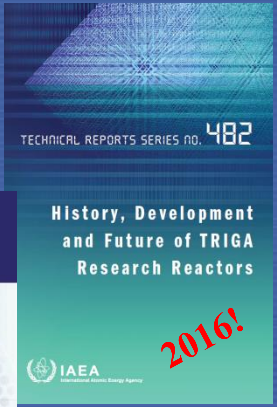


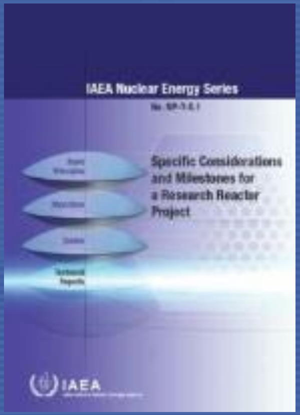












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