Applications of Research Reactors: Purpose and Future

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Department of Nuclear Applications and Sciences (NA)

IAEA, Vienna, Austria
Outline

• Historical background
• Applications of Research Reactors
• Future perspectives
• List of references
Main Components of Research Reactor

FUEL  Natural Uranium / Enriched Uranium
FORM  Metal, Alloy, Oxide, Silicide
CLAD  Aluminium, Zirconium, Stainless Steel
MODERATOR  H$_2$O, D$_2$O, 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
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
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

Typically, RR cores have small volume, many have powers less than 5 MW(t), higher enrichment than power reactors, natural and forced cooling, and pulsing capability.
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)**
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

http://nucleus.iaea.org/RRDB/
RRs world-wide

TOTAL: 737

Operational 247
Temp. shutdown 20
Under construction 3
Planned 8
Shutdown/Decommissioned 454
Cancelled 6

Operational RRs are distributed over 56 countries

<table>
<thead>
<tr>
<th>Region</th>
<th>Operational RRs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russia</td>
<td>65</td>
</tr>
<tr>
<td>USA</td>
<td>42</td>
</tr>
<tr>
<td>China</td>
<td>15</td>
</tr>
<tr>
<td>France</td>
<td>10</td>
</tr>
<tr>
<td>Japan</td>
<td>8</td>
</tr>
<tr>
<td>Africa</td>
<td>7</td>
</tr>
<tr>
<td>Americas</td>
<td>65</td>
</tr>
<tr>
<td>Asia-Pacific</td>
<td>49</td>
</tr>
<tr>
<td>Europe (with Russia)</td>
<td>126</td>
</tr>
</tbody>
</table>

Source: IAEA RRDB

Contact: D.Ridikas@iaea.org
# Involvement of 247 operational RRs

Indispensable to define priorities & plan the IAEA activities!

<table>
<thead>
<tr>
<th>Application</th>
<th>Number of oper. RR involved</th>
<th>Involved / Operational, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education &amp; Training</td>
<td>163</td>
<td>66</td>
</tr>
<tr>
<td><strong>Neutron Activation Analysis</strong></td>
<td>115</td>
<td>47</td>
</tr>
<tr>
<td>Radioisotope production</td>
<td>83</td>
<td>34</td>
</tr>
<tr>
<td>Neutron radiography</td>
<td>67</td>
<td>27</td>
</tr>
<tr>
<td>Material/fuel testing/irradiations</td>
<td>63</td>
<td>26</td>
</tr>
<tr>
<td>Neutron scattering</td>
<td>44</td>
<td>18</td>
</tr>
<tr>
<td>Nuclear Data Measurements</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>Si doping</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>Geochronology</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>Gem coloration</td>
<td>19</td>
<td>8</td>
</tr>
<tr>
<td>Neutron Therapy</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Other</td>
<td>120</td>
<td>49</td>
</tr>
</tbody>
</table>
RR stakeholders and users

Government:
- Intergovernmental agreements
- Economic Planning
- Industrial Competitiveness
- Expand National Science Capabilities
- Availability of Nuclear Medicine

Scientific Organizations
- New instruments
- New Facilities
- Study centre
- Student Education
- International cooperation

Policy / Funding / Development

Industry
- Metrology
- Radiography
- Materials Analysis
- Process efficiency
- Isotope Supplies

Science infrastructure & opportunity

NEW REACTOR

Output / Efficiency / Drought resistance

Better / Cheaper Health Care

Medicine
- New diagnostic procedures
- New treatment options
- Improved availability

Agriculture
- Radiotracers
- Trace element analysis

Energy:
- Education and training
- Nuclear Safety Culture
- TSO services

IAEA
Contact: D.Ridikas@iaea.org
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
→ Education & training (2)
Education & training (example)

Typical flow from Academics to Nuclear

Academic background

Nuclear training required

Population need estimates for 2 NPPs

<table>
<thead>
<tr>
<th>Level</th>
<th>Estimate</th>
<th>Training Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhDs</td>
<td>50+</td>
<td>+ 12 to 24 months</td>
</tr>
<tr>
<td>Engineers &amp; Masters</td>
<td>400+</td>
<td>+ 6 to 12 months</td>
</tr>
<tr>
<td>Bachelors &amp; Technicians</td>
<td>800+</td>
<td>+ 3 to 9 months</td>
</tr>
</tbody>
</table>

Neutron Activation Analysis (1)

Qualitative & quantitative analytical technique for the determination of trace elements/impurities

- Samples from mg to kg, detected concentration ~ppb
- Uses: Archaeology, Biomedicine, Environmental Science, Geology and geochemistry, Industrial products, Nutrition, Quality assurance of analysis & reference materials
  - Rocks, minerals, and soils
  - Atmospheric aerosols
  - Archaeological artifacts
  - Tree rings
  - Dust in ice cores
  - Hair, nails, skin, etc.
  - Plant and animal matter
  - Coal
- Can be a potential source of income

Soil mapping using NAA in Jamaica
Neutron Activation Analysis (2)

- Sampling
- Pre-irradiation sample treatment
- Irradiation
- Radioactivity measurement
- Elemental concentration calculation
- Critical evaluation of results and preparation of the NAA report

Radiochemical separation in P or DNAA

Radiochemical separation in RNAA

Prompt-ray counting in PGNAA

Cyclic NAA
Radioisotope Production (1)

Used in
- Medicine (diagnostic and therapy), but also
- Industry, agriculture & research

- Most used:
  - in medicine Mo-99 (85% of all procedures), and
  - in industry Co-60

- Potential source of **income, big demand**

- Also produced in particle accelerators
Radioisotope Production (2)

<table>
<thead>
<tr>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target fabrication</td>
</tr>
<tr>
<td>Irradiation in reactor</td>
</tr>
<tr>
<td>Transportation of irradiated target to</td>
</tr>
<tr>
<td>radioactive laboratory</td>
</tr>
<tr>
<td>Radiochemical processing (separation) or</td>
</tr>
<tr>
<td>encapsulation in sealed source</td>
</tr>
<tr>
<td>Quality control</td>
</tr>
<tr>
<td>Transportation to end users</td>
</tr>
</tbody>
</table>

Fission:
- Short lived fission products: $^{99}$Mo, $^{131}$I
- Long lived fission products: $^{137}$Cs, $^{147}$Pm

Capture:
- $(n,\gamma)$:
  - $(n,\gamma) \rightarrow \beta^-$:
    - $^{59}$Co + n $\rightarrow$ $^{60}$Co + $\gamma$
    - $^{130}$Te + n $\rightarrow$ $^{131}$Te* + $\gamma$ $\rightarrow$ $^{131}$I + $\beta^-$

Threshold reactions:
- $(n,p)$:
  - $^{32}$S + n $\rightarrow$ $^{32}$P + p
- $(n,\alpha)$:
  - $^{6}$Li + n $\rightarrow$ $^{3}$H + $^{4}$He

Multistage reactions:
- $^{186}$W $(n,\gamma)$ & $^{187}$W$(n,\gamma)$ $\rightarrow$ $^{188}$W

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Geochronology (1)

- Dating method of small (mg) quantities of minerals
  - Actinide free
  - Including actinides

Geologic studies on the origin and thermal histories of:

- mineral deposits, emplacement, cooling
- uplift history of plutonic rocks
- formation of metamorphic belts
- development of volcanic terraces
- formation and amalgamation of the Earth's crust
- age and development of the landscape
- timing of catastrophic events in earth history

Age range from 2000 years to 4.6 billion years

Scoria cone erupted on an ancient fluvial terrace of Rio Chico, Argentina
Geochronology (2)

- Dating method of small (mg) quantities of minerals
  - Actinide free
  - Decay of natural potassium $^{40}\text{K} \rightarrow ^{40}\text{Ar}$
  - Ratio $^{40}\text{Ar}/^{39}\text{Ar}$ from $^{40}\text{Ar}/^{39}\text{Ar}$ via $^{39}\text{K}(n,p)^{39}\text{Ar}$, $E_{\text{th}}=1.2\text{MeV}$
  - Use of gas extraction spectrometry systems

- Including actinides (apatite, zircon)
  - Use of fission track method
  - The age is determined by

$$N_{\text{fissionU5}} = f(N_{\text{U5}})$$

$$N_{\text{U5}} \rightarrow N_{\text{U8}}(t=0)$$

$$N_{\text{fissionU8}} = f(N_{\text{U8}}(t))$$
Transmutation effects (1)

- Silicon transmutation doping

  - Single crystal silicon ingot
  - In-core treatment
  - Silicon slice semiconductor fabrication

- Gemstone coloration

  Colourless topaz (left) and blue topaz (right)
Transmutation effects (2)

- **Silicon transmutation doping**
  - $^{30}\text{Si}(n,\gamma)^{31}\text{Si} \rightarrow ^{31}\text{P}$
  - Source of income

- **Gemstone coloration**
  - Improve gemstone properties (e.g. colour)
  - Source of income
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, …)
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
Provision of nuclear data (1)

- Fission & capture cross sections
- Branching ratios
- Neutron multiplicities
- Fission yields
- Decay data
  (half-lives, branching ratios, decay particles, heat)
- Delayed neutrons
- ...

Measured (n,γ) x-section, leading to $^{210}$Po

Decay type: $\alpha$ - 1 %, $\beta$ - 52 %, $\gamma$ - 47 %

Repartition of decay heat of spent MOX fuel

Measured FF mass distribution
Provision of nuclear data (2)

Fission $\mu$-chamber
Positron source (1)

Use of positron sources:

- as particle probe to detect defects in materials
- as particle probe to examine defects in lattices
- in solid state physics for surface sensitive analysis

- 3D irradiation defect mapping
- Examination of lattice defects
- Elemental dependence
- Surface contamination
→ Positron source (2)

- Activation method

\[ ^{63}\text{Cu} (\text{n},\gamma)^{64}\text{Cu} \rightarrow ^{64}\text{Ni} + e^+ + \nu_e \ (12.8\text{h}) \]

1. n & \gamma are emitted from reactor core
2. (n,\gamma) on Cd produce additional \gamma
3. Pair creation in W
4. Moderated positrons are emitted

- Hard Gamma Ray Direct Converter Method
Neutron Capture Therapy (1)

Four years after the discovery of neutrons in 1932 by J. Chadwick of Cambridge University, a biophysicist, G.L. Locher of the Franklin Institute at Pennsylvania introduced the concept of Neutron Capture Therapy (NCT).

3 figures of merit in terms of advantage:
• depth
• dose ratio
• depth-dose rate
and… remaining questions! In total <1000 patients treated, mainly in Finland and Japan
Neutron Capture Therapy (2)

Dose phantom

Clinical treatment: patient’s position
Neutron Radiography (1)

- Provide static or dynamic “picture” in 2D or 3D
- Non-destructive technique down to 10 μm level
- Various applications
  - Potential income

- Application to plants
- Mineral distribution in stones
- Lubricates in engines
- Voltage sources/cells
- Medical applications

H₂O → D₂O
Neutron Radiography (1) continued

- Polarised neutron tomography

Cultural heritage:
Photo, x-ray, radiography, tomography

Brasing connections
Neutron radiography (2)

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

What do neutrons do?

Nobel Prize in Physics 1994 - Shull and Brockhouse

Neutrons show where atoms are.....

...and what atoms do
Neutron scattering (2)

- Cold, thermal, hot neutron sources
- Neutron beams, neutron guides, mirrors and ports
- Neutron scattering instruments (diffractometer, spectrometer, interferometer, strain scanner,…)
- Data acquisition, analysis and interpretation systems

FIG. 10. The neutron scattering methodology.
Neutron scattering (2)

Experimental facilities installed @ LVR-15

Guide hall II @ HZB
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:

$\sim 3 \times 10^{16}$ fissions/s $\rightarrow \sim 0.8 \times 10^{17}$ n/s

Spallation Neutron Source of 1MW:

$(1 \text{GeV};1 \text{mA};\text{protons}) \rightarrow \sim 25 \text{n/p} \times 6.25 \times 10^{15} \text{p/s} \rightarrow \sim 1.6 \times 10^{17} \text{n/s}$
How do we produce neutrons?

a) Fission Reactions

\[ n^1 + U^{235} \rightarrow 2 \text{ fission fragments} + 2.5n^1 + 200 \text{ MeV} \]

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

1 neutron \rightarrow 2 \text{ to } 3 \text{ neutrons}

Example: 20 MW Research Reactor

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

generates \( 1.5 \times 10^{18} \) neutrons/sec in the whole reactor volume
New RRs considered in many developing countries

Example: Jordan Research & Training Reactor (JRTR),
Under construction by KAERI-Daewoo Consortium, operation planned in June 2016

- 5 MW (upgradable to 10MW), neutron flux $\sim 1.5 \times 10^{14} \text{n/(s cm}^2\text{)}$
- Fuel: $\sim 19.75\% \text{U-235, U}_3\text{Si}_2\text{-Al, Coolant & Moderator: H}_2\text{O, Reflector: Be}$
- Multipurpose RR: radioisotope production, Si doping, neutron beams, NAA, E&T, etc.
- 1st step to the national NPP programme

Contact: D.Ridikas@iaea.org
How do we produce neutrons?

b. Artificially accelerated particles

(iii) Spallation with Protons

1. Internal Cascade

2. Inter Nuclear Cascade

3. Evaporation

Up to 40 neutrons per incident proton

Contact: D.Ridikas@iaea.org
J-PARC = Japan Proton Accelerator Research Complex

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

Nuclear Transmutation

Materials and Life Science Experimental Facility (Neutron & Muon)

Hadron Beam Facility

Multi-Purpose Facility

Linac 181 MeV (400MeV)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

@ Tokai, Ibaraki

Neutrino to Kamiokande

Contact: D.Ridikas@iaea.org
Neutron Instruments (Beamlines)

18 beamlines have been working or budgeted, of the 23 available ports.

**In operation:** 9
**On-beam commissioning:** 3
**Under construction:** 3
**Funded:** 3
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
  - ...

Accelerator
(600 MeV – 4 mA proton)

Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Spallation source

Multipurpose flexible irradiation facility

Fast neutron source

Lead-Bismuth coolant

IGORR Conference, September, Knoxville, US
Combined applications of RRs and Accelerators:
Production of Super Heavy Elements

<table>
<thead>
<tr>
<th>Year</th>
<th>Element</th>
<th>Laboratory</th>
<th>Reaction</th>
<th>Number of atoms synthesized to date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>114</td>
<td>JINR, Russia(^1)</td>
<td>(^{48})Ca → (^{244})Pu (ORNL)</td>
<td>50 atoms</td>
</tr>
<tr>
<td>2004</td>
<td>113</td>
<td>JINR, Russia(^1)</td>
<td>Decay product of element 115</td>
<td>8 atoms</td>
</tr>
<tr>
<td>2004</td>
<td>115</td>
<td>JINR, Russia(^1)</td>
<td>(^{48})Ca → (^{243})Am (ORNL)</td>
<td>30 atoms</td>
</tr>
<tr>
<td>2005</td>
<td>116</td>
<td>JINR, Russia(^1)</td>
<td>(^{48})Ca → (^{248})Cm (RIAR/ORNL)</td>
<td>30 atoms</td>
</tr>
<tr>
<td>2006</td>
<td>118</td>
<td>JINR, Russia(^1)</td>
<td>(^{48})Ca → (^{249})Cf (ORNL)</td>
<td>3 – 4 atoms</td>
</tr>
<tr>
<td>2010</td>
<td>117</td>
<td>JINR, Russia(^2)</td>
<td>(^{48})Ca → (^{249})Bk (ORNL)</td>
<td>6 atoms</td>
</tr>
</tbody>
</table>

Source: ORNL (USA)
Generations of Nuclear Reactors

- **Generation I**: Early Prototypes
  - Shippingport
  - Dresden
  - Magnox

- **Generation II**: Commercial Power
  - PWRs
  - BWRs
  - CANDU

- **Generation III**: Advanced LWRs
  - CANDU 6
  - System 80+
  - AP600

- **Generation III+**
  - ABWR
  - ACR1000
  - AP1000
  - APWR
  - EPR
  - ESBWR

- **Generation IV**
  - Revolutionary Designs
  - Safe
  - Sustainable
  - Economical
  - Proliferation Resistant and Physically Secure

Timeline:
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010
- 2020
- 2030

Contact: D.Ridikas@iaea.org

http://www.gen-4.org/Technology/evolution.htm
Material development in nuclear industry

Selection - Characterisation - Qualification

Graph showing different reactor types and their temperature and displacement damage characteristics.

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International Fusion Material Irradiation Facility (IFMIF)

Accelerator
(125 mA x 2)

Source
140 mA D⁺
LEBT
100 keV
RFQ
5 MeV
MEBT
Half Wave Resonator
Superconducting Linac
9
14.5
26
40 MeV
HEBT
RF Power System

Lithium Target
25±1 mm thick, 15 m/s

Test Cell
Beam shape:
200 x 50 mm²

High
(>20 dpa/y, 0.5 L)
Medium
(>1 dpa/y, 6 L)
Low
(<1 dpa/y, > 8 L)

Typical reactions

\[ ^7\text{Li}(d,2n)^7\text{Be} \]
\[ ^6\text{Li}(d,n)^7\text{Be} \]
\[ ^6\text{Li}(n,T)^4\text{He} \]
Combined/comprehensive multi-disciplinary approach

High Flux Fast RRs for dpa generation (e.g. BOR60 in Russia)

Multi-ion beams for H, He and FF generation (e.g. JANNUS facility in France)

Use the best physics understanding through complex modelling of occurring phenomena

Contact: D.Ridikas@iaea.org
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

Contact: D.Ridikas@iaea.org
List of main references for RRs@IAEA

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


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

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