The fission reactor and the spallation source

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ILL PhD seminars – 10 Feb 2015
Overview

Nuclear reactor: operational principles
Research Reactors
The ILL research reactor

Spallation neutron sources: operational principles
The ISIS spallation neutron source
Energy Gain through Fission

http://en.wikipedia.org/wiki/Nuclear_binding_energy
Energy Gain through Fission

When splitting a heavy nucleus into two fragments we gain energy:

\[ E = m \cdot c^2 = m(236U) - [m(\text{frag1}) + m(\text{frag 2})] \approx 200\text{MeV} \]

which is shared between excitation energy and kinetic energy

Due to the rapid potential changes the process is not adiabatic
-> single particle excitations

\[ \Delta t = 10^{-22} \ldots 10^{-21} \text{s} \]

from Herbert Faust, 2005
Massive Energy Gain through Fission – The Bomb

http://en.wikipedia.org/wiki/Nuclear_chain_reaction
Of course, Fermi and his crew!

![Drawing of Chicago Pile 1](http://en.wikipedia.org/wiki/Chicago_Pile-1)
Natural Nuclear Reactor in Oklo, Gabon

Geological situation in Oklo, Gabon leading to natural nuclear fission reactors
1972 discovery of only 0.600% U-235 in natural U from Oklo sparked investigation.

http://en.wikipedia.org/wiki/Natural_nuclear_fission_reactor
Natural Nuclear Reactor in Oklo, Gabon

- Today: 0.7202% U-235 in natural uranium

- 700 Myr ago – 1.3%; 1.70 Gyr ago – 3.1%; 2.10 Gyr ago – 4.0% and up to 17% when the solar system was created

- half-life of U-235 – 710 Myr; of U-238 – 4.51 Gyr

- The Great Oxidation Event about 2.2 Gyr ago (biological activity of cyanobacteria increased the oxygen content in the atmosphere of Earth by about a factor of a hundred); allowed uranium to be oxidized from its insoluble uranium(IV) form to its soluble uranium(VI) form

- Oklo went critical about 1.7 Gyr ago and lasted for several 100 kyr

Reactor Types

By moderator material
- Graphite (Chicago Pile-1, X-10 @ ORNL, RBMK)
- H2O
- D2O
- Molten salt (LiF, BeF2)
- Liquid metal (Li+Bi)

By coolant
- H2O/D2O (Pressurized water reactors, boiling water reactors)
- Liquid metal (Na, NaK, Pb, Pb+Bi)
- Gas cooled reactors (He, CO2, N2)

By generation
- Generation-I: first commercialised power plants of various designs (gas-cooled / graphite moderated, or prototype water cooled & moderated)
- Generation-II: standard light-water pressurised and boiling water reactors in operation today
- Generation-III: evolution of current LWR technology, improved performance and extended design lifetimes
- Generation-IV: fast neutron reactors, use of fissile U^{238} breeding Pu^{239}, increasing the sustainability of nuclear power in a scenario of dwindling uranium reserves.
Example Fission Reactions

\[ ^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n \]

- Fissile vs. fissionable

http://chemwiki.ucdavis.edu/Physical_Chemistry/Nuclear_Chemistry/Thermodynamic_Stability_of_the_Atomic_Nucleus
Decay Products
The Neutron Life Cycle

Physical Principles of a Nuclear Reactor

- \( k \equiv \frac{N_2}{N_1} \)
- \( v \approx 2.5 \)
- \( 40 \times 2.5 = 100 \)
- 200 MeV/fission
- 2 MeV
- 1 eV
- Fission
- Leakage
- Fast fission
- Resonance abs.
- Non-fissile abs.
- Non-fuel abs.

from Brissot, 2008
The Four- and Six-Factor Formula

\[ k_{\infty} = \eta f p e \quad k = \eta f p e P_{FNL} P_{TNL} \]

- Criticality condition: \( k = \text{#of n in generation 2} / \text{#of n in generation 1} = 1 \)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Meaning</th>
<th>Formula</th>
<th>Typical Thermal Reactor Value</th>
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<tr>
<td>( \eta )</td>
<td>Thermal Fission Factor (Eta)</td>
<td>The number of fission neutrons produced per absorption in the fuel.</td>
<td>( \eta = \frac{\nu \sigma^F_F}{\sigma_a} )</td>
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<td>( f )</td>
<td>The thermal utilization factor</td>
<td>Probability that a neutron that gets absorbed does so in the fuel material.</td>
<td>( f = \frac{\Sigma^F_F}{\Sigma_a} )</td>
<td>0.71</td>
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<td>( p )</td>
<td>The resonance escape probability</td>
<td>Fraction of fission neutrons that manage to slow down from fission to thermal energies without being absorbed.</td>
<td>( p \approx \exp \left( \frac{-\sum_{i=1}^{N} N_i I_{r,i} A_i}{(\xi \Sigma_p)_{mod}} \right) )</td>
<td>0.87</td>
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<tr>
<td>( c )</td>
<td>The fast fission factor (Epsilon)</td>
<td>( \frac{\text{total number of fission neutrons}}{\text{number of fission neutrons from just thermal fissions}} )</td>
<td>( c \approx 1 + \frac{1 - p}{p} \frac{u_t \nu_f P_{FNL}}{\nu_a P_{TNL} P_{TNL}} )</td>
<td>1.02</td>
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<td>( P_{FNL} )</td>
<td>The fast non-leakage probability</td>
<td>The probability that a fast neutron will not leak out of the system.</td>
<td>( P_{FNL} \approx \exp \left( -B_g^2 \tau_{th} \right) )</td>
<td>0.97</td>
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<tr>
<td>( P_{TNL} )</td>
<td>The thermal non-leakage probability</td>
<td>The probability that a thermal neutron will not leak out of the system.</td>
<td>( P_{TNL} \approx \frac{1}{1 + L_{th}^2 B_g^2} )</td>
<td>0.99</td>
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Delayed Neutrons and Reactor Control

- Reactivity is a measurement of this relative deviation from unity: \( \rho = \frac{k-1}{k} \)

- Prompt neutron lifetime \( \tau_p \) is the average time between the birth of prompt fission neutrons and their final absorption, order of \( 10^{-4} \) s
  -> prompt control not possible

- Avg. emission time \( \tau_d \) of delayed neutrons of the order of 12 s

Brissot, 2008
Delayed Neutrons and Reactor Control

- 6 groups of delayed neutrons

Delayed Neutron Data for Thermal Fission in U-235

<table>
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<tr>
<th>Group</th>
<th>Half-Life (s)</th>
<th>Decay Constant (s⁻¹)</th>
<th>Energy (keV)</th>
<th>Yield, Neutrons per Fission</th>
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<td>0.00052</td>
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<td>2</td>
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<td>0.00546</td>
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<td>6</td>
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<td>0.000273</td>
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</table>

- Power reactors operate in the delayed supercriticality region between 
k = 1 and k = 1/(1-β)

\[
\beta = \frac{\text{precursor atoms}}{\text{prompt neutrons} + \text{precursor atoms}}. \quad \beta = 0.0064 \text{ for U-235}
\]

Lamarsh, Introduction to Nuclear Engineering
Reactivity Feedbacks

- Reactivity change may be induced by:
  - An increase of water temperature
  - An increase of fuel temperature
  - A loss of coolant
  - A control rod displacement

\[ \text{Doppler effect} \]
Reactivity Feedbacks

- 1.25 gram of U-235 ~ 1 MWD (24000kWh)

- negative reactivity through insertion of boric acid in order to mitigate higher reactivity of fresh fuel rods

Brissot, 2008
Fission Products

http://en.wikipedia.org/wiki/Nuclear_fission
Fission Products Need to be Contained

- This is the result of a heating and quenching test under extreme conditions, not under regular reactor operating conditions!

Figure 4-26 Ballooned region with relocated fuel in the Halden IFA-650.2 test (Ref. 61)
Fission Products Need to be Contained

Figure 4-36 Neutron radiography of test IFA-650.11 (Ref. 50)

Figure 4-7 Pre (top) and post (bottom) LOCA transient fuel fragmentation for low-burnup rods (2.5 GWd/MTU, left) and medium-burnup rods (35 GWd/MTU, right) (Ref. 19)
Fission Products Need to be Contained

Avg. rod burnup:
192: 68.2 GWd/TU
193: 69.3 GWd/TU
Max. allowed:
62 GWd/TU in BoilingWR
60 GWd/TU in PressWR

Figure 4-40  Particle size distribution from six integral LOCA tests

Figure 4-41  Images of fuel particles collected from test rod (a) 192 and (b) 193 revealing a very small, sand-like fragmentation size

The Pressurized Water Reactor (PWR)
The Boiling Water Reactor
## Power Reactors vs. Research Reactors

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<th>Fission Power reactors</th>
<th>Research reactors</th>
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<td><strong>Thermal Power</strong></td>
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<td>0.1-100 MW</td>
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<td><strong>Power density</strong></td>
<td>0.1 MW/liter a)</td>
<td>1 MW/liter</td>
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<td><strong>Enrichment of 235U</strong></td>
<td>2 – 4% b)</td>
<td>20 – 93 %</td>
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<tr>
<td><strong>Pressure</strong></td>
<td>80-150 bar</td>
<td>1-20 bar</td>
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<tr>
<td><strong>Temperature</strong></td>
<td>350 °C</td>
<td>50 °C d)</td>
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<td><strong>Moderator</strong></td>
<td>H₂O b)</td>
<td>D₂O / Beryllium</td>
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<td><strong>In-pile material</strong></td>
<td>Zircaloy / steel</td>
<td>Aluminum /Zircaloy</td>
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<td><strong>Length of cycle</strong></td>
<td>1 year</td>
<td>1-2 months</td>
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<tr>
<td><strong>Major concern</strong></td>
<td>Heat after shut down c)</td>
<td>Rupture of beam tubes</td>
</tr>
</tbody>
</table>

a) Except for fast breeder (1 MW/liter)

b) Except for CANDU reactors (natU + D₂O moderation), MAGNOX/AGR

c) typ. 1% of nominal power directly after shut down from radioactive decays;

d) The low pressure demands a low temperature to avoid vapor bubbles at the fuel plates; (cooling!)
Research reactors in the world

247 Reactors Found (for OPERATIONAL)
Research reactors in the world

61 Neutron Scattering Facilities

Overview Reactor List Additional Information

This database contains 61 Research Reactors performing Neutron Scattering distributed over 37 Member States. Note that this view includes Reactors of the following status: (check this to include all) OPERATIONAL, TEMPORARY SHUTDOWN, UNDER CONSTRUCTION, PLANNED, SHUT DOWN, DECOMMISSIONED, CANCELLED
Research reactors: utilisations
Research reactors: utilisations

Isotope Production
Research reactors: utilisations

Isotope Production
Neutron Scattering
Research reactors: utilisations

- Isotope Production
- Neutron Scattering
- Neutron Radiography
- Material Irradiation
Research reactors: utilisations

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- Transmutation (Si-doping, Gemstone coloration)
Research reactors: utilisations

Isotope Production
Neutron Scattering
Neutron Radiography
Material Irradiation
Transmutation (Si-doping, Gemstone coloration)
Neutron Activation Analysis
Geochronology
Nuclear Data Measurement
Research reactors: utilisations

- Isotope Production
- Neutron Scattering
- Neutron Radiography
- Material Irradiation
- Transmutation (Si-doping, Gemstone coloration)
- Neutron Activation Analysis
- Geochronology
- Nuclear Data Measurement
- Neutron Therapy
Research reactors: utilisations

- Isotope Production
- Neutron Scattering
- Neutron Radiography
- Material Irradiation
- Transmutation (Si-doping, Gemstone coloration)
- Neutron Activation Analysis
- Geochronology
- Nuclear Data Measurement
- Neutron Therapy
- Innovative Nuclear Energy Research
- Training/Teaching
# Neutron scattering facilities in the world

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<td>1,000,000</td>
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<td>HEAVY WATER</td>
<td>15,000,000</td>
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<td>Chile</td>
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<tr>
<td>China</td>
<td>CARR</td>
<td>TANK IN POOL</td>
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<td>Czech Republic</td>
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<td>TANK WWR</td>
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<tr>
<td>France</td>
<td>HFR</td>
<td>HEAVY WATER</td>
<td>58,300,000</td>
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<td>POOL</td>
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<td>Germany</td>
<td>FRMZ</td>
<td>TRIGA MARK II</td>
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<td>DHRUVA</td>
<td>HEAVY WATER</td>
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<tr>
<td>Indonesia</td>
<td>RSG-GAS</td>
<td>POOL, MTR</td>
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</table>
ILL High Flux Reactor - Historical Remarks -

- **1967**: The ILL is founded on January 19th by France and Germany

Louis Néel

Heinz Maier-Leibnitz
ILL High Flux Reactor - Historical Remarks -

- **1967**: The ILL is founded on January 19th by France and Germany
- **1969**: Start of work on the reactor floor and walls
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- **1972**: First experiments

![Graph](image-url)  
**FIG. 2.** Results of a const-Q scan, no background subtracted. The instrumental resolution is given by a Gaussian.
ILL High Flux Reactor - Historical Remarks -

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- **1971**: Construction complete. The reactor went critical on August 31, ramping to full power on December 16-21
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- **1972**: First experiments
- **1973**: The UK becomes an Associate on January 1st

- **2015**: International Partnership for Science

**Associates Founding countries**
- France
- Germany
- United Kingdom

**Scientific Member Countries**
- Spain
- Austria
- Italy
- Czech Republic
- Sweden
- Hungary
- Belgium
- Slovakia
- Poland
- India
- Denmark
ILL High Flux Reactor
ILL High Flux Reactor - the core -
Core
Fuel element, moderator and coolant

Fuel element (93% HEU) sits in the centre of a tank of 2.5 m diameter containing D2O as moderator. Moderation and cooling obtained by D2O circulation. The moderator partly reflects thermalised neutrons back towards the fuel element.

Al-based alloy fuel cladding

- Internal diameter: 39 cm
- Height: 80 cm
- Total $^{235}$U: 8.57 kg
Control rod space
- Neutron absorbing material Ni
- Rod pulled out downward over the cycle to control the fission rate

280 Fuel element plates
“Al-sandwich configuration” (involute) to maintain a constant distance between the plates
- Homogeneous flowing of D2O
- Avoid mechanical deformation stresses due to unbalanced internal forces
Safety rods and reactor pool
Safety rods and reactor pool

5 safety rods
- Pulled inward in case of emergency
- Absorbing material
- Silver, Indium, Cadmium alloy

H2O reactor pool
- Cherenkov blue-radiation
[Cherenkov radiation]

- High-energy gamma rays coming from the core produce fast Compton $e^-$ in H2O
[Cherenkov radiation]

- High-energy gamma rays coming from the core produce fast Compton $e^-$ in H2O
- If $c/n < v_e < c$ -> Medium polarised and mechanically disturbed

$c$ speed of light in vacuum
$c/n$ speed of light in the medium
$n$ refractive index
[Cherenkov radiation]

- High-energy gamma rays coming from the core produce fast Compton $e^-$ in H$_2$O
- If $c/n < v_e^- < c$ -> Medium polarised and mechanically disturbed
- Energy lost by the $e^-$ radiates as a coherent shockwave -> Cherenkov radiation!

\[
\frac{c}{n} t \\
\text{Light path after } t
\]

\[
\theta \\\n\text{Particle path after } t
\]

- $c$ speed of light in vacuum
- $c/n$ speed of light in the medium
- $n$ refractive index
- $\beta = v_e^-/c$
Cherenkov radiation: a sonic boom for light!

- High-energy gamma rays coming from the core produce fast Compton e\(^{-}\) in H\(_2\)O
- If \(c/n < v_{e^-} < c\) -> Medium polarised and mechanically disturbed
- Energy lost by the e\(^{-}\) radiates as a coherent shockwave -> Cherenkov radiation!

- Supersonic aircraft propagating at a speed higher than the acoustic wave it generates
- Waves cannot propagate forward from the body -> shock front is formed
Safety rods and reactor pool

5 safety rods
- absorbing material
- Silver, Indium, Cadmium alloy

H2O reactor pool
- Cherenkov blue-radiation

<table>
<thead>
<tr>
<th>Moderator</th>
<th># collisions, from 2 MeV to 1 eV</th>
<th>Scattering mean free path $\lambda_s$</th>
<th>Absorption mean free path $\lambda_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>16</td>
<td>0.7 cm</td>
<td>52 cm</td>
</tr>
<tr>
<td>D$_2$O</td>
<td>29</td>
<td>3 cm</td>
<td>32700 cm</td>
</tr>
</tbody>
</table>
Neutrons energy distribution

REACTOR DESIGN:

- optimised to deliver the maximum thermal neutron flux to the beam tubes
- D2O moderation -> Maximum thermal flux @ about 40 cm from the core centre

\[ E = k_B T \]
\[ E_n = \frac{h^2}{2m\lambda^2} \]
\[ \lambda [\text{Å}] = 9.04 (E [\text{meV}])^{-1/2} \]
\[ T = 300 \text{ K} \ (\sim 25 ^\circ \text{C}) \]
\[ E \sim 25 \text{ meV} \]
\[ \lambda \sim 1.8 \text{ Å} \]
High Flux Reactor - Essential Data

- 1 cycle = 50 days
- Thermal power = 58.3 MW

Nuclear power **57 MW** at full power! (1.3 MW of heat from friction in the fuel element)

**NUCLEAR POWER --- > HOW MANY EMITTED NEUTRONS?**

\[ 57 \text{ MW} \Rightarrow 57 \times 10^6 \text{ J s}^{-1} \] of released nuclear energy

\[ n_{\text{thermal}} + ^{235}\text{U} \rightarrow 2 \text{ fission fragments} + 2.5 \text{ fast neutrons} + 180 \text{ MeV} \]

\[ 57 \times 10^6 \text{ J s}^{-1} / 180 \text{ MeV} \approx 2 \times 10^{18} \text{ fissions s}^{-1} \]

\[ 2 \times 10^{18} \text{ fissions s}^{-1} \times 2.5 \text{ n} = 5 \times 10^{18} \text{ n s}^{-1} \]
High Flux Reactor - Essential Data

VS

# of neutrons produced by 57 MW of nuclear power $\sim 10^{18} \text{ n s}^{-1}$

# of photons emitted by a 1 W bulb light $\rightarrow \sim 10^{18} \text{ photons s}^{-1}$
High Flux Reactor - Essential Data

# of neutrons produced by 57 MW of nuclear power $\sim 10^{18} \text{ n s}^{-1}$

# of photons emitted by a 1 W bulb light $\rightarrow \sim 10^{18} \text{ photons s}^{-1}$!

UNIQUE PROPERTIES OF NEUTRONS!!
Beam-tubes arrangement at the ILL-HFR

- Noses of beam tubes are located in the region where the thermal flux is maximum
- Blocks of other moderator materials at higher or lower T are used to obtain different wavelengths
Thermal, Hot and Cold sources
Hot source (HS)

- Zircaloy cylinder of 29 cm diameter filled with a graphite @ T= 2400 K
- $\lambda < 0.8 \text{ Å}$
Vertical cold source (VCS)

- Al sphere (38 cm diameter)
- Filled with 20 litres of liquid D2 @ 25K
- Vertical service tube with a neutron guide to supply the cold neutrons turbine
- $\lambda > 3 \, \text{Å}$
Vertical cold source (VCS)

- Al sphere (38 cm diameter)
- Filled with 20 litres of liquid D2 @ 25K
- Vertical service tube with a neutron guide to supply the cold neurons turbine
- $\lambda > 3 \text{ Å}$
Horizontal cold source (HCS)

- Orthocylinder vessel 21 cm diameter
- Filled with liquid D2 @ 25 K
- Housed in a 23 cm diam. horizontal beam tube
- $\lambda > 3 \text{ Å}$
The ILL High Flux Reactor: Containment Building

3 BARRIERS SAFETY DESIGN

- Fuel cladding
- D2O/H2O + borate-concrete vessel
- Walls of the reactor building

$\Delta P = 150$ mbar over-pressure
How old is the ILL?
How old is the ILL?

- Founded 1967 -> criticality reached for the first time 1971
- Reactor lifetime -> aging of components due to irradiation damaging
- Al reactor parts need to be changed every 8 years \( \text{Al}^{27} + n \rightarrow \text{Al}^{28} \rightarrow \text{Si} \) (Less ductile)
- Research reactors are designed to be modular!

**1991-1995:** Replacement of the reactor vessel -> “restart of a new reactor”
Training Research Isotopes General Atomic

- TRIGA is a class of small nuclear reactors by General Atomic
- Most widely used research reactor in the world designed for universities, private commercial research
- Inherently safe reactor -> pool-type reactor that can be installed without a containment building
- Uranium-zirconium-hydride (UZrH) nuclear fuel -> "moderation" due to H mixed with the fuel.
- Power level -> 20 kw - 16 MW

TRIGA used as a neutron radiography reactor @ Idhao National Laboratory
Spallation Neutron Sources in the world

- SNS (Spallation Neutron Source) (Oak-Ridge, Tennessee)
- ISIS (Science & Technology Facilities Council) (UK)
- SINQ (Paul Scherrer Institut) (Switzerland)
- LANSCE (Los Alamos, New Mexico)
- (Japan)
Spallation

- “Spall” are flakes of a material that are broken off a larger solid body

-Nuclear spallation occurs naturally in Earth's atmosphere owing to the impacts of cosmic rays; \((\gamma, n)\) reactions, which undergo additional nuclear reactions:

- Concept of nuclear spallation was first coined by Glenn T. Seaborg in his doctoral thesis on the inelastic scattering of neutrons in 1937

Spallation Mechanism

- the uranium nucleus becomes transparent for the proton

- the proton interacts with individual nucleons of the target nucleus

- an intra-nuclear cascade develops

- the proton deposits only part of its energy in the target nucleus

- from the intra-nuclear cascade very fast particles (neutrons, protons, and mesons) leave the interaction zone and may initiate further spallation reactions in the target

from Faust, 2005
Spallation Products
Spallation Neutron Sources
Producing neutron exploiting spallation events

- ion source
- accelerator machines (LINAC, CYCLOTRON, SYNCHROTRON)
- target
- moderators
LINAC – Linear Accelerator

- Ion source (different possible designs)
- Pipe of cylindrical electrodes connected to a RF source
- In each gap the ion sees a difference in the voltage between the cylinders
- Ion accelerated in each gap -> cylinders have different lengths
- Limitation -> length of pipe!
LINAC – Linear Accelerator

- Ion source (different possible designs)
- Pipe of cylindrical electrodes connected to a RF source
- In each gap the ion sees a difference in the voltage between the cylinders
- Ion accelerated in each gap -> cylinders have different lengths
- Limitation -> length of pipe!
CYCLOTRON

• Charged particle injected in a plane perpendicular to a magnetic field
• Particle path along two “dees” (D-shaped electrodes) is bent by the Lorentz force
• RF alternating voltage tuned to accelerate the particle in the gap between the dees
• For relativistic particles -> tricks needed!
SYNCHROTRON

“Synchrotron” -> strength of magnetic field and frequency, amplitude and phase of RF all have to be synchronised!

Circular machine -> particle injected from a LINAC

Main components:
• Bending magnets for deflection of particles round in circle
• RF electric fields for acceleration
• Quadrupole – sextupole magnets for beam focusing
ACCELERATORS @ ISIS
ISIS Pulsed Neutron Source

Some useful numbers for a case example

• Frequency of pulses -> 50 Hz -> 1 pulse every 20 ms

• Average protons current sent to the target -> 200 μA = 4 μC · 50 Hz

• Average # of protons sent to the target - > 200 μA / 1.6 · 10^{-19} C = 1.25 · 10^{15} protons s^{-1}
ISIS Pulsed Neutron Source

Some useful numbers for a case example

- Frequency of pulses -> 50 Hz -> 1 pulse every 20 ms
- Average protons current sent to the target -> 200 \( \mu \text{A} = 4 \mu \text{C} \cdot 50 \text{ Hz} \)
- Average # of protons sent to the target - > 200 \( \mu \text{A} / 1.6 \cdot 10^{-19} \text{ C} = 1.25 \cdot 10^{15} \text{ protons s}^{-1} \)

\[
(1.25 \cdot 10^{15} \text{ spallations s}^{-1}) \cdot (20 \text{ n/spallation}) = 2.5 \cdot 10^{16} \text{ n s}^{-1} \rightarrow \sim 1 \text{ MW reactor!}
\]
ISIS Pulsed Neutron Source

COMPARISON WITH A REACTOR CONTINUOUS NEUTRON SOURCE

\[
(1.25 \cdot 10^{15} \text{ spallations s}^{-1}) \cdot (20 \text{ n /spallation}) = 2.5 \cdot 10^{16} \text{ n s}^{-1} \Rightarrow \sim 1 \text{ MW reactor!}
\]

REACTOR CONTINUOUS SOURCES -> a fraction of neutrons in the beam is used (fixed -\(\lambda\))
PULSED SOURCES -> all neutrons are used (white beam) -> TOF instrumentation

REACTOR ENERGY SPECTRUM
Thermal region maximised

EPITHERMAL FLUX
Spallation Targets

- Older, lower power sources based on solid targets (W, Pb, Ta) with H2O or D2O cooling, e.g. ISIS: stationary W target, under a constant cooling load to dissipate the heat from the 160 kW proton beam

- Liquid targets superior over solid targets for high proton energies, because of higher average target density, Hg possible, heat removal by mass transport instead of conduction and convection

- Rotating targets: target revolves sufficiently that the beam strikes a cooled portion of the target while the heated portion moves onward and cools slowly

ESS website and Carpenter, ANL, 2012
Spallation Targets

- Ta and W are desirable target components

-W is better than Ta when afterheat questions arise (LOCA)

- Afterheat is mostly caused by radionuclides produced by thermal neutron capture

ESS website and Carpenter, ANL, 2012
Spallation Targets at ESS

- At ESS: rotating W target (decision taken in 2011), He cooling was evaluated as most viable option

- Metallic liquid PB-Bi eutectic is being retained as a comparative target for licensing purposes

- Both offer comparable neutron-yield performance and satisfy the ESS safety goals in terms of waste release and disposal under normal operation and in case of accidents

ESS website
Spallation Targets at ESS

- Two liquid-hydrogen moderators with a volume of about 2.5 l each, partially surrounded by water pre-moderators of comparable volume

- The moderators are placed inside an inner reflector of about 1 m3 of beryllium
Target Failure Mechanisms

- alpha-uranium targets develop cracks in the cladding because of grain growth with subsequent release of fission products, exacerbated after the event by corrosion

- Tungsten in contact with coolant water releases corrosion products into the coolant stream, requiring cladding

- Tantalum targets in ISIS have exhibited internal changes

- Tungsten and tantalum targets live much longer than the alpha-uranium targets employed to date

- liquid Hg targets suffer from high instantaneous pressure, can result in cavitation and erosion damage to the vessel

ESS website and Carpenter, ANL, 2012
Accelerator Driven Reactor

Concept:
• nuclear reactor that produces fission remaining subcritical
• neutrons produced by spallation of heavy protons using a particle accelerator

Motivation:
• ADR as a waste incinerator for heavy isotopes from used fuel of a conventional nuclear reactor
• Transmutation of long-lived actinides (neptunium, americium and curium) into shorter-lived radionuclides

The Belgian Nuclear Research Centre (SCK.CEN) is planning to begin construction on the MYRRHA reactor (Multipurpose Hybrid Research Reactor for High-tech Applications)
• @ Mol in 2015
• 57 MW ADS
• proton accelerator delivering a 600 MeV, 2.5 mA proton beam to a liquid
• lead-bismuth (Pb-Bi) spallation target
Acknowledgments

FOR TECHNICAL SUPPORT, USEFUL CONVERSATIONS AND MATERIAL
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Ulli Koester
Hannu Mutka

FOR USEFUL MATERIAL
ISIS Facility
LAM Group University of Bath
Eleonora Guarini (SISN)

ILL PhD seminars – 10 Feb 2015
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http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?filter=0
Yellow Book
Neutron Data Booklet
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http://neutrons.ornl.gov/

Back-up slides
Neutron Activation Analysis (NAA) is a qualitative and quantitative analytical technique for the determination of trace elements in a variety of objects, such as water, air, soil, fish, meteorites, rocks, and even agricultural products and plants. It is the most simple and widely used application of research reactors.

The technique is non-destructive, unless the element of interest is lower than the detection limit, in which case chemical separations are necessary. The sample is irradiated in the reactor, and then its gamma radiation spectrum reveals its content.
Neutron, as X-ray, can explore matter, but in a different way thanks to its light elements sensitivity, whereas X-Rays are sensitive to heavier elements. The combination of the two techniques is very efficient in providing a detailed description of the inside of an object. Neutron radiography finds applications in various fields, such as archaeology, biology, aeronautics, car industry, material studies, etc.

Neutron radiograph of a transistor Radio (PSI, Switzerland)
As high flux research reactors are able to reproduce mechanical strains undergone by materials in power reactors, they provide an essential support to study the ageing of generation II power plants, to optimise the generation III plants and to test fuels and breeder capacities for generation IV (planned by 2050). Research concerning nuclear fusion is also important, since dedicated research and development is needed to find materials meeting needs for fusion: resistance against temperature of several million degrees and high-energy neutron irradiation.
One of the neutron beam applications, less frequently promoted and known is neutron medical treatment or neutron therapy. The property of neutrons that differentiates this therapy from more conventional radiation therapy techniques like high energy X ray, electron or high energy proton treatment is their ability to damages cells using so called high linear energy transfer (LET). This is achieved by creation of secondary recoil protons and alpha particles, which distinguish two branches of neutron therapy, fast neutron therapy (FNT) and boron neutron capture therapy (BNCT), respectively.

FNT has been administered to about 30 000 patients worldwide, and 5 facilities continue to operate (4 accelerator based and 1 reactor based). With curative intention, presently FNT is used to treat prostate and lung cancer, adenoid-cystic carcinoma of head and neck, especially of the major salivary gland tumours, breast and in some cases also thyroid cancers.

The total number of patients treated by the BNCT remains below 1000 with three-fourths of all patients administered in 3 research reactors, namely FiR-1 in Finland and KUR & JRR4 in Japan. Although clinical results indicate significantly increased survival times, the outcome has been palliative only.
Two different methods of geochronology allow geologists to date small quantities of minerals:

- The 1st one uses the radioactive decay of the natural Potassium 40, obtained from the ratio K40/K39. The reactor neutrons are utilised to transform Potassium into Argon, and then the ratio Ar40/Ar39 is measured.
- The 2nd one is convenient to date minerals that contain Uranium. The ratio U235/U238 is representative of the age and it is obtained by irradiating the mineral and counting fissions of U235, compared to the number of spontaneous fissions of U238.

To meet the growing demand from the electronic industry, research reactors are able to perform Neutron Transmutation Doping (NTD) of Si, and therefore to produce uniform silicon ingots doped with phosphorus, which is created by neutrons interacting with silicon and followed by a natural decay of the reaction product.
Research reactors have provided vast uses in the provision of **nuclear data** through utilization of their inherent capabilities for cross-section measurements, integral experiments, benchmarking and code validation analyses. Other fields in which nuclear data are needed relate to:

- Testing of materials required for innovative facilities;
- Evaluation of radioisotope production and their medical applications;
- Simulation using computer software of radiation doses to patients and advanced cancer therapies;
- Shielding experiments, mainly for neutron attenuation problems;
- Studies on transmutation of nuclear waste for safer disposal;
- Improvement of analytical techniques adopted for cultural diagnostics and material composition analysis.

Research reactors continue to occupy a visibly important place in these areas of study and application, along with dedicated accelerator based neutron sources. Some cross-section measurements for very short lived and on-line produced radioactive targets nuclei are possible only at research reactor facilities, given the high neutron fluxes available at some reactors.
High Flux Isotope Reactor

- 85 MW
- HEU-235 fuel
- Target loaded with Cm-244 and other transplutonium isotopes
- $\Phi_{\text{th in core}}: 4 \cdot 10^{15} \text{ cm}^{-2}\text{s}^{-1}$  
  $\Phi_{\text{th out core}}: 1.2 \cdot 10^{15} \text{ cm}^{-2}\text{s}^{-1}$
- “Flux-trap” principle -> moderation in the “island” -> isotope production
- H$_2$O cooling, Be/H$_2$O moderation
High Flux Isotope Research Reactor

- Core cross-section
Vertical cold source (VCS) H1
Hot source (HS) H3, H4, H8
Horizontal cold source (HCS) H5
Hot source (HS)

The HS is a double zircaloy cylinder of 29 cm diameter filled with a graphite block surrounded by carbon felt insulation at 2400 K. This hot source feeds three main beam tubes: H3, H4 and H8.

Vertical cold source (VCS)

The VCS is an aluminium sphere of 38 cm diameter filled with boiling liquid deuterium at 25 K. Its design features are:

- A sphere incorporating a re-entrant cavity 10 cm wide and 20 cm high with a penetration depth of 25 cm. The cavity is a magnesium vessel, filled with gaseous deuterium. Its design is optimised with respect to the six horizontal cold guides (3 x 20 cm).

- A vertical service tube, sufficiently large to incorporate a vertical neutron guide of 7 cm diameter constructed of aluminium and lined with a thin (0.15 mm) nickel tube. This is followed by a curved square guide (7 x 7 cm^2) with a radius of 13 m and length of 13 m. The guide supplies very cold neutrons (VCN) to the "neutron turbine". The turbine provides ultra-cold neutrons (UCN) to a number of experiments (see description of instrument PF2 p.112).

Horizontal cold source (HCS)

The HCS has the shape of an orthocylinder of 21 cm diameter filled with liquid deuterium. It is housed in a 23 cm diameter horizontal beam tube. This cold source feeds two main neutron guides:

- The first guide (H53 - instrument IN14 in the reactor hall, instruments IN16, EVA and PF1 in guide hall 2) has a width of 6 cm giving an enhanced flexibility for horizontal focusing.

- The other guide (H51) is divided into two parts: the upper part of 4 x 5.5 cm^2 is used as H512 for D22. The lower part is split into two guides by a beam splitter which consists of a 2 m long assembly of TiNi supermirrors deposited on a Si-substrate into: H513 (4 x 5.5 cm^2) is the transmitted beam, and H511 is the reflected beam which is fed into a polarising guide (4 x 5.5 cm^2 - instrument project IN15).
# High Flux Reactor - Essential Data

<table>
<thead>
<tr>
<th>ESSENTIAL DATA OF THE HFR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power</td>
<td>58.3 MW</td>
</tr>
<tr>
<td>Max. unperturbed thermal flux in the reflector</td>
<td>$1.5 \times 10^{15}$ neutrons cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Max. perturbed thermal flux at the beam tubes</td>
<td>$1.2 \times 10^{15}$ neutrons cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Coolant flow in fuel element</td>
<td>2400 m$^3$/h</td>
</tr>
<tr>
<td>Coolant velocity</td>
<td>17 m/s</td>
</tr>
<tr>
<td>Coolant pressure (outlet)</td>
<td>4 bar</td>
</tr>
<tr>
<td>Coolant temperature (outlet)</td>
<td>50 °C</td>
</tr>
<tr>
<td>Reactor cycle</td>
<td>50 days</td>
</tr>
<tr>
<td>Average consumption of $^{235}$U</td>
<td>36 %</td>
</tr>
</tbody>
</table>
The ILL High Flux Reactor: Containment Building

3 BARRIERS SAFETY DESIGN

- Fuel cladding
- D2O/H2O + borate-concrete vessel
- Walls of the reactor building

\[
\Delta P = 150 \text{ mbar over-pressure in between for defined flow}
\]
Fission and Spallation neutron sources

Currently active neutron sources for condensed matter research. (Flux of pulsed sources corresponds to the peak flux)

<table>
<thead>
<tr>
<th>Location</th>
<th>Country</th>
<th>Source</th>
<th>Type</th>
<th>Power (MW)</th>
<th>Thermal flux (10^{14} n cm^{-2} s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lukas Heights</td>
<td>Australia</td>
<td>HIFAR</td>
<td>Fission/continuous</td>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td>Chalk River</td>
<td>Canada</td>
<td>NRU</td>
<td>Fission/continuous</td>
<td>120</td>
<td>3.0</td>
</tr>
<tr>
<td>Grenoble</td>
<td>France</td>
<td>HFR</td>
<td>Fission/continuous</td>
<td>58</td>
<td>12.0</td>
</tr>
<tr>
<td>Saclay</td>
<td>France</td>
<td>Orphée</td>
<td>Fission/continuous</td>
<td>14</td>
<td>3.0</td>
</tr>
<tr>
<td>Berlin</td>
<td>Germany</td>
<td>BER-2</td>
<td>Fission/continuous</td>
<td>10</td>
<td>2.0</td>
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<td>Fission/continuous</td>
<td>5</td>
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<tr>
<td>Julich</td>
<td>Germany</td>
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Korea hanaro reactor
China carr reactor
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<th>Flux $\phi$/cm$^2$s</th>
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*Table 2* - The capture flux $\phi_c = \int (d\phi(\lambda)/d\lambda)(\lambda/1.8 \text{ Å}) d\lambda$ is measured with the activation of a gold foil at the outlet of the reactor shielding in the case of the beam tubes, and after one line of sight in the case of the guides (September 2003).