With new solutions towards sustainable nuclear power:
Gen-III, III+, and Gen-IV, as well as small- and medium size reactors (SMR)

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Overview

Some basic principles

Current status of nuclear energy

Development needs and possibilities

“Evolutionary”, safer reactors: Gen-III and Gen-III+

Small, modular reactors (SMR)

Sustainability: principally new solutions, Generation IV
Some basic facts

Fissile and fissionable ("fertile") nuclides (isotopes)

Fissile: odd mass (and neutron) number: U-235, U-233, Pu-239.
Easily fissioned by thermal neutrons ("thermal reactors")
In nature: only U-235

The Earth's resources consist nearly exclusively of "fertile" isotopes: Th-232 and U-238
These can be split only by fast (energetic) neutrons: (> 1 MeV).
But: with neutron capture, they are converted into fissile nuclides.

Natural uranium:
- 99.3 % U-238
- 0.7 % U-235

Enriched uranium

Fuel for thermal (=current) reactors
The fast neutrons, generated in fission, have to be slowed down below the resonance region, with the help of a slowing down material (moderator).
Breeding: from fissionable (“fertile”) nuclides, by neutron capture.

Requires excess neutrons in the core:

- plutionum fuel ($\nu = 3.2$) and hard (fast) neutron spectrum (“fast breeder”)
- external neutron source: “accelerator driven system”, ADS
Breeding and transmutation

Average number of neutrons in thermal fission:

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Mean number of neutrons per fission (ν)</th>
<th>Mean # of delayed n per fission</th>
<th>Fraction of delayed n (β)%</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-233</td>
<td>2.49 ± 0.01</td>
<td>0.0070 ± 0.0004</td>
<td>0.28 ± 0.02</td>
</tr>
<tr>
<td>U-235</td>
<td>2.42 ± 0.01</td>
<td>0.0158 ± 0.0005</td>
<td>0.65 ± 0.02</td>
</tr>
<tr>
<td>Pu-239</td>
<td>2.88 ± 0.01</td>
<td>0.0061 ± 0.0003</td>
<td>0.21 ± 0.01</td>
</tr>
</tbody>
</table>

Pu-239 fast fission: 3.2 neutrons/fission event

The transmutation of the ”nuclear waste” (actinides) is a similar process: fertile nuclides are transformed to fissile with neutron capture.

Both the breeding and the transmutation requires reprocessing. **Solution: fourth generation of reactors – Gen IV**
Spent fuel

Fission products (FP)
Short half lives (decay in about 500 years)

Transuranic elements (TRU)
Long half lives (hence less active)

Can be transformed to useful fuel with transmutation

But require fast reactors (Gen-IV).
The current situation

There are about 435 reactors in operation in 31 countries. Supply 16% of the world electricity (Europe: 28%).
60% PWR, 20% BWR.
60+ new reactors being built, +160 more planned
About 60% of the world’s reactors is a pressurised water reactor (PWR).
About 20% of the world’s reactors is a boiling water reactor (BWR)
Currently known economically extractable resources:

- Will last about 270 years in the current “once-through” (open cycle) reactors.
- Last about 8,000 years in fast breeders, with reprocessing Pu (closed fuel cycle).
- Last 48,000 years with full reprocessing.
- Even longer if thorium are also utilised.

![Diagram showing forecast of nuclear power plant life extension and new generation IV and III plants between 1975 and 2075.](image)
Evolution of nuclear power

**Generation I**
- Early prototype reactors
  - Shippingport
  - Dresden
  - Magnox

**Generation II**
- Commercial power reactors
  - PWRs
  - BWRs
  - CANDU

**Generation III**
- Advanced LWRs
  - CANDU6
  - System 80+
  - AP600

**Generation III+**
- Evolutionary designs
  - ABWR
  - ACR 1000
  - AP 1000
  - APWR
  - EPR
  - ESBWR

**Generation IV**
- Revolutionary designs
  - Enhanced safety
  - Minimisation of waste and better use of natural resources
  - More economical
  - Improved proliferation resistance and physical protection

Timeline:
- Gen I: 1950
- Gen II: 1960
- Gen III: 1970
- Gen III+: 1980
- Gen IV: 1990
- Gen III+: 2000
- Gen IV: 2010
- Gen III+: 2020
- Gen IV: 2030
# Aspects of nuclear power being discussed

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
</table>
| Safety (accident, fuel damage, release of radioactivity) | Passive safety  
                                        Core catcher  
                                        Material development |
| Economy                                      | Better thermal efficiency;  
                                        More efficient fuel utilisation  
                                        Improved plant availability |
| Fuel resources                               | Higher burnup, MOX fuel  
                                        Breeder technology (Gen-IV) |
| Waste, spent fuel                            | Better conversion  
                                        Transmutation |
| Proliferation, safeguards                    | Harder diversion routes  
                                        Safeguards policy |
Generation 3 and 3+ Plants

Same technology (thermal neutron spectrum, enriched uranium) as today’s reactors, but:

• Reduced possibility for core meltdown: passive and inherent safety diversified, redundant safety systems
• Survive 72 hrs after shutdown without intervention
• Enhanced containment of meltdown (core catcher)
• Resistance to serious damage (earthquake, aircraft impact)
• Higher burnup: better fuel utilisation and less waste
• Higher thermal efficiency
• Higher availability and longer operation time (60 years)
• Simpler design, simpler building and operation
• Simpler licensing procedure
Generation III and III+ Plants

- Areva: EPR, Atmea1, Kerena
- Westinghouse/Toshiba: AP1000, ABWR
- GE-Hitachi: ABWR, ESBWR, PRISM
- Candu: EC6
- KHNP: APR1400
- Mitsubishi: APWR
- Rosatom: AES-92, AES-2006 etc
- CNNC & CGN: ACPR1000, ACP1000

Source: World Nuclear Association
Some generation 3 och 3+ reactors available on the market today

<table>
<thead>
<tr>
<th>Type</th>
<th>Model</th>
<th>Electric power</th>
<th>Supplier</th>
<th>Country of origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>BWR</td>
<td>ABWR</td>
<td>1400 – 1600 MW</td>
<td>GE/Hitachi, Toshiba/W</td>
<td>USA, Japan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ESBWR</td>
<td>1550 MW</td>
<td>GE/Hitachi</td>
<td>USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PWR</td>
<td>EPR</td>
<td>1600 – 1750 MW</td>
<td>Areva</td>
<td>France / Germany</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>AP1000</td>
<td>1100 MW</td>
<td>Westinghouse</td>
<td>USA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>APWR</td>
<td>1700 MW</td>
<td>Mitsubishi</td>
<td>Japan</td>
</tr>
</tbody>
</table>

Source: New Nuclear Power Plants - courtesy of Nils-Olov Jonsson
Areva’s European Pressurized Reactor (EPR)

- High power: 1600 MWe
- 60 years lifetime
- 37% thermal efficiency
- Redundant safety systems (4x100% capacity) – partly diversified. Active systems (electric driven, motors, pumps, valves, control)
- Handles core melt-down without releases
- Handles terror attacks including airplane crash
- Being built in Finland, France and China (Taishan)
- Will be built in the USA
- Negotiated for UK application
Areva EPR

Source: New Nuclear Power Plants - courtesy of Nils-Olov Jonsson
Areva EPR in Olkiluoto (Finland 5)
Areva EPR in Olkiluoto (Finland 5)
Westinghouse AP1000

- 1100 MWe
- 60 year life-time
- Passive emergency core cooling systems
- Passive containment cooling
- Large reduction of the number of safety classified pumps, valves, piping and equipment for power supply and control

Source: New Nuclear Power Plants - courtesy of Nils-Olov Jonsson
Westinghouse AP1000

- Westinghouse AP1000
  - 1150 MWe, Pressurized Water Reactor
  - Uses the forces of nature and simplicity of design to enhance plant safety and operations and reduce construction costs
  - 50 percent fewer valves, 83 percent less piping, 87 percent less control cable, 35 percent fewer pumps, and 50 percent less seismic building volume than a similarly sized conventional plant
  - Has a site construction schedule of 36 months from first concrete to fuel loading
  - U.S. Design Certification Received in 2006!

Source: New Nuclear Power Plants - courtesy of Nils-Olov Jonsson
Westinghouse AP1000 in the USA and China under construction

- VC Summer (South Carolina), 2 units
- Vogtle (Georgia), 2 units
- China, Sanmen and Haiyang, 4 units

Source: World Nuclear Association
SMRs: an alternative

• Conventional nuclear power plants are expensive to build, which can be a serious obstacle to their construction in developing countries.

• Small and medium reactors (SMRs) could be built for a fraction of the cost of the current large-scale ones and could be installed at remote places without the need to also build an extensive and expensive power grid.

• The idea is not new, SMRs were around in one form or another, mostly as plans.
Small and medium: definitions (IAEA)

- Small reactors: < 300 Mwe
- Medium reactors: between 300 - 700 Mwe

According to this definition, nearly half of the existing commercial power reactors would classify as SMR. Most of these are, however, downscaled versions of the large reactors.

By SMR one means special designs that are different from the existing power reactors.
Key features of SMRs I

Construction

- Small physical size
- Small footprint on environment
- Factory construction, transport to and assembly on spot
- Compact (integral) construction
  - internal pumps
  - internal steam generators
  - internal pressurizer
  - internal control rods
Compact construction: SMART (KAERI)
Key features of SMRs II

Safety

- Reduced source term (radioactive inventory)
- Smaller accident vulnerability:
  integral construction = better confinement
  large coolant pipes eliminated
  total inventory of coolant is large
  heat exchangers above core: better natural circulation
- Better decay heat removal (larger surface/volume ratio)
Key features of SMRs III

Operational flexibility

- Site selection (closer to demand)
  process heat (shale oil)
  desalination
- Less coolant water needed (small rivers)
- Better load follower
- Better grid stability
Key features of SMRs IV

Plant economy

- Total investment smaller
- Can be built up in smaller units, fitting the demand
- Economy of scale: somewhat larger than that of “large” reactors
SMRs on the design board

- IRIS (DoE initiative, Westinghouse Electric development)
- mPower (Babcock and Wilcox)
- WSMR (Westinghouse)
- PRISM (GE and Hitachi)
- NuScale (NuScale Power)
- SMART (KAERI)
- Super Safe Small and Simple (4S) (Toshiba)
- Next Generation Nuclear Plant (NGNP, Next Generation)
IRIS: International Reactor Innovative and Secure (DoE -> Westinghouse)

- Scalable power 100 – 350 MWe
- Integral construction (everything is inside the pressure vessel)
- 17 x 17 UO₂ PWR fuel, 3.5 years cycle, 50,000 MWd/t burnup

mPower: Babcock and Wilcox

- 180 MWe
- Integral reactor vessel
- Produces superheated steam

WSMR: Westinghouse SMR

- 225 MWe
- Descendant of AP1000
- Same passive safety systems

PRISM: GE/Hitachi

- Based on the EBR-II construction
- 300 MWe
- Metallic fuel (pyroprocessing)
- Sodium cooled
- Suitable for breeding and plutonium incineration
- Considered by the UK to reduce/eliminate the plutonium stockpile

Sustainability

• Definition by the Brundtland commission:

To satisfy the needs of the current generation without worsening the chances of future generations

• For nuclear energy, this means:

- do not exhaust the raw materials (only use renewables or inexhaustible sources)

- do not pollute the biosphere (handling of spent fuel)
Current nuclear energy

Is not sustainable:

• Uses only a fraction of the uranium resources (U-235, only 0.7% of natural uranium)
  With such a method, the known, economically extractable resources last about 200-300 years.

• It produces high level, long lived waste, which has to be separated from the biosphere for about 100,000 years ("once through" or "open fuel cycle").

If we used all uranium isotopes, the resources would last for 10,000 - 100,000 years.

To achieve better utilisation and less amount and shorter lived waste, one needs new technology: breeder reactors and reprocessing.

Closed fuel cycle: Generation IV reactors
The first reactor generating electricity was a fast breeder: the EBR-I, Idaho, USA (1951)

For the pioneers, the breeder technology was self-obvious!
Evolution of nuclear power
The Generation IV initiative established in 2001
12 countries and EU

Goals:
1. Safe, competitive and reliable production of energy products
2. Meet stringent safety requirements
3. Maximum use of fuel and produces minimum of waste
4. Proliferation resistant
5. Meet the public requirements on energy production units
Six Systems Chosen for Review and Evaluation

- Sodium cooled fast reactor (SFR)
- Lead cooled fast reactor (LFR)
- Gas cooled fast reactor (GFR)
- Molten salt reactor (MSR)
- Very high temperature reactor (VHTR)
- Water cooled reactor using supercritical pressure (SCWR)
Sodium-cooled Fast Reactor (SFR)

- Pool (Na) and loop designs
- Modular and monolithic designs
- Thermal efficiency about 40%
- Low pressure system
- 150-500 MWe with U-Pu-actinide-Zr metal fuel with re-cycling close to the site
- 500-1500 MWe plant using MOX-fuel and central re-processing for several plants
- 550 C exit temperature

Pool-type design example (The French program)
Sodium-cooled Fast Reactor (SFR)

European plans:
ASTRID, planned in France

Design fixed in 2015-16
Start-up in 2020-2025

Swedish participation within a co-operation agreement between CEA and the Swedish Research Council
Lead Cooled Fast Reactor (LFR)

- Pb or Pb/Bi coolant
- Exit temperature: 550 – 800 °C
- Passive safety: natural circulation
- High proliferation resistance
- 15 – 30 years core lifetime
- Modular (50 – 150 – 300 MWe) or large system (1200 Mwe)
- Load-follow capability
- Can generate either electricity or process heat (deslination, hydrogen production)
Gas Cooled Fast Reactor System (GFR)

- Appr 300 MW He-cooled with 850°C outlet temperature
- Closed fuel cycle. Integrated with reprocessing and re-fabrication of fuel close to the site
Chalmers University of Technology

Molten Salt Reactor (MSR)

- Molten/liquid fuel reactor
- High outlet temperatures
- Operates at atmospheric pressure
- Flexible fuel: no cladding
- Mix of sodium, zirconium and uranium fluorides
- Channels in graphite
- 1000 MWe
- Outlet temperature 700 - 800 C
- Closed fuel cycle burns Pu and actinides
- No need to manufacture fuel elements
Very-High-Temperature Reactor System (VHTR)

- Graphite moderated, He-cooled, outlet temperature 1000°C
- 600 MWth
- Core using prismatic blocks or fuel balls (pebble bed)
- Well-suited for hydrogen generation
- U/Pu-fuel
Challenges for Gen-IV reactors

Technical break-through and innovations are necessary for all Gen-IV reactor types

Most important areas:

Material science: new fuel, new construction materials:
- high temperature, aggressive chemical environment, high burn-up;
- Separation and transmutation technologies
The long-term program of the EU:

**Vision:** Sustainable Nuclear Energy Technology Platform (SNETP)

The planned infrastructure:

- **Jules Horowitz** high performance material test reactor in Cadarache (CEA). Start-up: 2015-16
- **MYRRHA** Mol, Belgium, fast spectrum, accelerator driven subcritical reactor/neutron source
- **ASTRID**, Gen-IV. Sodium cooled fast reactor, to be built in France. Start of construction 2015-16, start-up beyond 2020
- **VHTR**, a “first-of-a kind” very high temperature reactor, among others for hydrogen production.