New Approaches in Nuclear Energy

A comprehensive view on Gen III & IV developments

Hans-Josef Allelein
Head of Institute for Reactor Safety and Reactor Technology, RWTH Aachen
&
Head of Institute for Energy Research 6, Research Center Jülich
Presentation Outline

• Opening comments
• Reactor Systems of Generation III
• Reactor Systems of Generation IV
• Summary and Conclusion
Nuclear Power in Nature

Nuclear Reactor Sun (Fusion)

Natural Nuclear Reactors

Nuclear Reactor Earth (Radioactive Decay)

Magnetic Field

Ozone (UV-Radiation-Shield)

Climate Change

Soil Radiation

Greenhouse Gases (IR-Radiation-Trap)

Cosmic Radiation

7th Energy Day – Nuclear Energy and Energy from Wind & Water
10th December 2009 in Eindhoven
Total Primary Energy Supply

Energy [EJ]

<table>
<thead>
<tr>
<th>Component</th>
<th>Energy [EJ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPES</td>
<td>503.6 EJ</td>
</tr>
<tr>
<td>Nuclear Electricity</td>
<td>29.43 EJ</td>
</tr>
<tr>
<td>Nuclear CHP</td>
<td>0.26 EJ</td>
</tr>
</tbody>
</table>

$1 \text{ EJ} = 10^{18} \text{ J}$

Data Source: Key World Energy Statistics 2009, IEA
### Deployed Reactors Worldwide

<table>
<thead>
<tr>
<th>Reactor Type</th>
<th>Number</th>
<th>Gross Power (Mwe)</th>
<th>Net Power (Mwe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR</td>
<td>214</td>
<td>216357</td>
<td>205640</td>
</tr>
<tr>
<td>PWR-WWER</td>
<td>54</td>
<td>38970</td>
<td>36802</td>
</tr>
<tr>
<td>BWR</td>
<td>94</td>
<td>88208</td>
<td>84625</td>
</tr>
<tr>
<td>Candu</td>
<td>40</td>
<td>21959</td>
<td>20549</td>
</tr>
<tr>
<td>GGR</td>
<td>8</td>
<td>2490</td>
<td>2284</td>
</tr>
<tr>
<td>AGR</td>
<td>14</td>
<td>9112</td>
<td>8380</td>
</tr>
<tr>
<td>LWGR</td>
<td>16</td>
<td>12348</td>
<td>11404</td>
</tr>
<tr>
<td>D2O-PWR</td>
<td>1</td>
<td>357</td>
<td>335</td>
</tr>
<tr>
<td>SNR</td>
<td>3</td>
<td>1130</td>
<td>1039</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>444</strong></td>
<td><strong>390931</strong></td>
<td><strong>371058</strong></td>
</tr>
</tbody>
</table>

Source: ATW, volume 52, issue 7 (2007)

7th EnergyDay – Nuclear Energy and Energy from Wind & Water
10th December 2009 in Eindhoven
Nuclear Reactor Generations

First Reactors

Current Reactors

Advanced Reactors

Future Systems

Generation I

Generation II

Generation III

Generation IV


7th EnergyDay – Nuclear Energy and Energy from Wind & Water
10th December 2009 in Eindhoven
History of Nuclear Power

- 1938 nuclear fission was discovered by Otto Hahn
- 1942 Enrico Fermi built the research reactor CP-1 and reached the first controlled chain reaction
- 1951 first electricity generated from nuclear energy
- 1960 first criticality in the Netherlands at LFR in Petten
- 1969 the nuclear power station Dodewaard (BWR) started commercial operation with a net capacity of 55 MWe
- 1973 the nuclear power reactor Borssele (PWR) started commercial operation at net capacity of 482 MWe
- Approx. 2018 a new reactor will start its commercial operation in the Netherlands
REACTOR SYSTEMS OF GENERATION III
Demands for a new Reactor Generation

- Higher safety standard
- Better fuel utilization
- Reduction of investment costs
- Higher availability
How to satisfy these Demands?

• Passive safety systems
• Newest safety systems
• Simplified construction with modular design
• Simplified control systems
• Simplified maintenance
• Optimized fuel utilization (higher burn-up)
European/Evolutionary Pressurized Reactor (EPR)

- Advancement of the French N4 and the German KONVOI
- 4 times redundances of the most safety systems
- Spatial separation (KONVOI)
- Increased volume of reactor pressurized vessel (RPV)
- Enlarged water reservoir
- Steel neutron reflector to increase life time of RPV
- Double layer containment
- Core catcher
European/Evolutionary Pressurized Reactor (EPR)
European/Evolutionary Pressurized Reactor (EPR)

- In the case of a core melting the melt will enter the core catcher.
- 170 m² surface
- Cooling system to cool the melt and solidify it.
Advanced Passive Plant (AP-1000)

• Advancement of AP 600
  – Changes minimized to ease the licensing process

• Simplification of power plant design
  – Reduced number of components + modular design

• 18 months without changing fuel
  – High burn-up of 60000 MWd/t
Advanced Passive Plant (AP-1000)
Advanced Passive Plant (AP-1000)

- Passive core flooding system
- Passive cooler for decay heat removal
- Passive heat transfer out of the containment by natural convection
Advanced Boiling Water Reactor (ABWR)

- First Gen III reactor ever built (Commercial operation started in 1997)
- Development started in 1978
- Currently 4 units are operating, several are under construction
- Simple design
- 3 divisions of emergency core cooling systems
- Extra thick basalt fiber reinforced concrete to improve the containment
Advanced Boiling Water Reactor (ABWR)
SWR-1000/KERENA

- Development for a 1000 MWe started in the 90s by Siemens.
- Areva changed the concept from 1000 to 1250 MWe.
- 2009 the name was changed to KERENA.
- The aim is to replace active systems by passive ones.
- Large water pools are within the containment to gain more time in the case of accidents.
- Passive coolers for the RPV and the containment are foreseen.
- After core melting the RPV can be cooled from outside by a passive cooling system without RPV failure.
SWR-1000/Kerena

Source: Areva NP
SWR-1000/Kerena

Source: Areva NP
REACTOR SYSTEMS OF GENERATION IV
The Gen IV Roadmap

- 100+ concepts submitted for evaluation
- Classified by coolant: water, gas, liquid metal and non-classical
- 6 concepts were selected after 2 years:
  - Very-High-Temperature Reactor (VHTR) (Safety, Hydrogen Production)
  - Gas-Cooled Fast Reactor (GCFR) (Sustainability, Economics)
  - Lead-Cooled Reactor (LCR) (Sustainability, Safety)
  - Sodium-Cooled Reactor (SCR) (Economics)
  - Molten-Salt-Reactors (MSR) (Sustainability)
  - Supercritical-Water-Cooled Reactor (SCWR) (Economics)
Technological Goals for Gen IV Systems

• Gen IV goals:
  – **Sustainability**
    Focus on fuel utilization, waste management, and proliferation resistance and physical protection
  – **Safety and reliability**
    Focus on safe and reliable operation, investment protection, and essentially eliminating the need for emergency response
  – **Economics**
    Focus on competitive life cycle, energy production costs and financial risk

• **Purpose of the Goals:**
  – Define and guide the development and design of Gen IV systems
  – They are challenging and will stimulate the search for innovative nuclear energy systems
  – Serve as the basis for developing criteria to assess and compare the systems
Sodium Cooled Fast Reactors (SCR)

- The first power plant applying a sodium cooled reactor was the Sodium Reactor Experiment (SRE) in 1957.
- Experience with sodium as coolant in a lot of countries.
- France and Russia are the most important SCR stakeholder in Europe.
- By 2020 France wants to have a new SCR.
- By now 2 concepts are established:
  - 150-600 MWe reactor with uranium-plutonium-actinide-zirconium metal alloy fuel.
  - 600-1500 MWe reactor with uranium-plutonium-oxide dispersion fuel.
Sodium Cooled Reactor Concepts

• Small size loop reactor (50-600 MWe)
  – Uranium-plutonium-actinide-zirconium metal alloy fuel
  – With pyrometallurgical processing facility (on-site?)
• Large size pool reactor (600-1500 MWe)
• Both concepts:
  • Full recycling of actinides in a fast spectrum
  • Minimization of long-lived waste
• Utilization of $^{238}\text{U}$ by transmutation
  – Uranium-plutonium-oxide dispersion fuel
  – Advanced aqueous processing facility
Sodium as Coolant

• Melting point: 97.82 °C
• Boiling point: 883 °C
• Low vapor pressure: ~1 kPa (at 550 °C)
• Density: 0.968 g/cm³
• Heat conductivity: ~140 W/(m K)
• Ignite on contact with wet air
• Violent reaction with water (Producing hydrogen)
• No neutron moderator – for the moderation from 1 MeV to thermal energies ~207 collisions are needed
Sodium Activation Characteristics

\[ ^{23}\text{Na}(n,\gamma)^{24}\text{Na} - T_{1/2} = 14,959\text{h} \]

\[ ^{23}\text{Na}(n,2n)^{22}\text{Na} - T_{1/2} = 2602\text{y} \]
Sodium Cooled Reactor Concepts

Liquid Metal cooled Fast Breeder Reactors (LMFBR)

"Pool" Design
- Control Rods
- Flow Baffle
- Coolant Level
- Fissile Core
- Breeder Blanket
- Reactor Pool Pump
- Biological Shielding
- Liquid metal coolant
- Heat exchanger
- Steam generator
- Steam (to power turbine)
- Water (from power turbine)

"Loop" Design
- Control rods
- Fissile Core
- Breeder Blanket
- Biological Shielding
- Liquid metal coolant
- Heat exchanger
- Steam generator
- Steam loop (primary coolant)
- Intermediate loop
- Power-generation loop
- Intermediate loop
- Reactor loop (primary coolant)

Source: wikipedia
Passive Decay Heat Removal System for Pool Type Reactor

- Passive Decay Heat Removal System is connected with a chimney to reach a natural convection.
- For lead cooled systems 2 MW decay heat should be removed by this system.
Advantages of Liquid Metal Cooled Reactors

- High power density (Economy)
- Sustainable, due to breeding capabilities (Sustainability)
- Experience available in a few countries
- Possible burning of minor actinides (Waste Reduction)
- Closed fuel cycle (Sustainability)
Supercritical Water Cooled Reactor

Year

coal power plants

PWR power plants

Net Efficiency

25%
30%
35%
40%
45%
50%


critical pressure

Source: Schulenberg

7th EnergyDay – Nuclear Energy and Energy from Wind & Water
10th december 2009 in Eindhoven
Concepts for SCWR

- **Europe: High Performance Light Water Reactor**
  - Thermal LWR
- **Japan: Super Fast Reactor**
  - Fast LWR
- **Canada: CANDU SC**
  - Thermal heavy water moderated reactor
Steam Cycle of HPLWR

2188 MW_th
25 MPa
508°C
1113 kg/s

280°C
282°C

193 kg/s
78 kg/s
3.7 MPa
245°C

485°C
724 kg/s

1000 MW_e
\( \eta = 44\% \text{ net} \)

5 kPa
33°C
547 kg/s

37 MW_e
138°C

7 MW_e

Source: Schulenberg

7th EnergyDay – Nuclear Energy and Energy from Wind & Water
10th december 2009 in Eindhoven
Flow Concept in HPLWR

- Heat up in 3 steps with mixing in the upper and lower plenum
- 500°C outlet temperature with 600°C hot channel temperature
Technical Implementation of the Flow Concept

- Upstream flow in evaporator fuel element
- Downstream flow in superheater 1 elements
- Upstream flow in superheater 2 elements
- Additional moderator water between fuel elements and in water channels
HPLWR Core Concept

Evaporator upstream

Superheater 1 downstream

Superheater 2 upstream

Source: Schulenberg
Fuel Element Concept

Fuel bundle of 3x3 fuel elements with:

- 40 fuel rods with 8 mm diameter
- $p/d = 1.18$
- Wire spirals as spacers
- FE-boxes with thermal insulation
- Water channel with thermal insulation

Source: Schulenberg
Containment Design of HPLWR

4 Containment condensator

4 core flooding pools with 1100 m³ water

4 low pressure pumps

Automatic pressure release system

steam pipe

Water pipe

1 condensation chamber with 900 m³ water

Cooling water

Source: Schulenberg
Size comparison of BWR and HPLWR

BWR
Gundremmingen

HPLWR 1000 MWe

Source: Schulenberg
Advantages of SCWR Concept

• High fresh vapor enthalpy results in:
  – High turbine output (Economy)
  – High thermal efficiency (Economy)

• Supercritical pressure, therefore no departure from nucleate boiling (Safety)

• Prevailed Technology in coal fired power plants, therefore „only“ a new reactor design is needed
Experience with Gas cooled Reactors

• 1400 reactor-years experience
• CO2 cooled
  – 18 reactors (Magnox and AGRs) generate most of the UK’s nuclear electricity
    (23 more have been shut down)
  – Have also operated in France, Japan, Italy and Spain
• Helium cooled
  – Have operated in UK(1), Germany(2) and the USA (2)
  – Current test reactors
    • 30 MW(th) HTTR (JAEA, Japan)
    • 10 MW(th) HTR-10 (Tsinghua University, China)
  – In South Africa ~165 Mwe plant is being designed
  – In China, the HTR-PM will be constructed this year
  – US is designing NGNP for hydrogen and electricity production
Fuel Concepts of HTRs

- Germany, China, Russia
- USA
- Japan

Fuel Element

Fuel Rod

Fuel Element

Fuel Compact

Fuel Rod

Fuel Element

7th Energy Day – Nuclear Energy and Energy from Wind & Water
10th December 2009 in Eindhoven
Elemental Composition of Fuel elements

Large amounts of graphite heat capacity -> safety

-> waste volume: 10.000t / module
The (V)HTR fuel
History & near-term Concepts of HTRs

**Experimental Reactors**

- DRAGON (U.K.)
  - 1963 - 1976
- AVR (FRG)
  - 1967 - 1988
- HTTR (Japan)
  - 1998 - Present

**Demonstration of Basic HTGR Technology**

- PEACH BOTTOM 1 (U.S.A.)
  - 1967 - 1974
- FORT ST. VRAIN (U.S.A.)
  - 1976 - 1989
- THTR (FRG)
  - 1986 - 1989

---

Pebble Bed Modular Reactor (PBMR)

Modular HTGR Concept
- General Atomics

ANTARES
- AREVA NP

Source: B. Tyobeka, IAEA
Main VHTR Features

- Extension of prismatic modular reactor (PMR) and of pebble bed modular reactors (PBR)
- Thorium cycle was already tested in Germany
- Higher coolant core outlet temperatures to enhance process heat applications
- Direct Brayton cycle energy conversion
  - He coolant, >900°C outlet temperature
  - Efficient electricity generation and/or H₂ production for hydrogenations
- Thermochemical water splitting
- Deployment in crude oil refining and petrochemistry by substituting process heat
- Coal gasification, oil sand / shale retorting
- Production of aluminium oxide and metals
The Gen IV VHTR Concept
Advantages of VHTR Concept

- Helium is transparent for neutrons. (Safety)
- Reactor outlet temperature is high enough for process heat applications. (Economy)
- Experience with HTRs in some countries available
- R&D demand is not as high as for other Gen IV reactors.
- Reactor size fits also for countries with small electricity grid.
Gas Cooled Reactor Fuel Concepts

- Coated-Particles
- Plate Fuel
- Cladded Pellets

HTRs

%vol. of actinides compound in the volume dedicated to fuel
The GCFR Fuel

- Power Density: 100 MW/m$^3$
- Fuel temperature: \(~1000\,^\circ\text{C}\)
- Burn up %FIMA: 7.5 at%
- Radiation damage: 40 dpa
The Gen IV GCFR Concept
Lead cooled reactor history

Prototype nuclear submarine Project 645 (1963)

Pb-Bi test setup (1951)

Nuclear submarine-705 demo (1971)

Nuclear submarine-705 serial (1976-1996)

~80 reactor years experience
The Gen IV LCFR Concept
The Gen IV MSR Concept

Reactor

Multi-Reheat Helium Brayton Cycle

Primary Salt Pump

Secondary Salt Pump

Off-gas System

Coolant Salt

Graphite Moderator

Heat Exchanger

Fuel Salt

Purified Salt

Freeze Plug

Critically Safe, Passively Cooled Dump Tanks (Emergency Cooling and Shutdown)

Chemical Processing (Collocated or off-site)

Generator

Recuperator

Gas Compressor

Cooling Water
The Gen IV MSR Concept
Summary and Conclusion

• We are at the beginning of the deployment of Gen III reactors all over the world.
• Gen III reactors are more safe and reliable than current Gen II reactors, due to their passive safety systems.
• But, due to the reduction of loops, the redundancy is reduced.
• The passive safety performance might suffer with the scale-up of reactor power (AP600 → AP1000).
• By the mid of this century first Gen IV reactors will be a mature technology.
• Due to the intensive investigation of sodium cooled reactors, it is very likely that the first Gen IV reactor will be a SCR.
• The other Gen IV systems will probably be build later or forsaken.