International role of nuclear fission energy generation - status and perspectives

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Content

- Present status of nuclear electricity generation – observations worldwide and in Europe
- Boundary conditions for NPP deployment-Large reactors (LR)/ vs. small medium sized reactors (SMR)
  - Economic considerations
- Safety concept of a NPP
  - General safety approach
  - Design safety
  - Severe accident safety & measures
  - LR under development
  - SMR technologies
- Generation –IV -Transmutation
- Some concluding remarks
Present status – Some facts

  - 435 nuclear power plants commercially operated
  - 372 GWe net capacity
  - 72 reactors under construction
  - 240 research reactors in (56 countries), 180 nuclear powered civil ships

- Net electricity production 2370 TWh (2013)
  - ≈11% of global electricity production (almost constant since 2006)

© BP statistical Review of world energy, 2012
Present status – Some facts

- Plant Location - currently new builds
  - 72 new builds of which
  - 60 PWR’s
  - 68 GWel

- Reactor types - installed power
  - Focus on large scale units ~1GWe
  - Light water reactor (LWR)-types
  - Mainly pressurized water reactors (PWR)
Present status – Some facts

- Age distribution
  - Mean reactor age ~30y
  - Most reactors belong to Gen-II systems

- Nearly all current reactors operating are of LR-type
  - Installed mean power >1GWe
  - NPP operated as grid base load backbone
Present status - Germany

After March 11th 2011 Fukushima

- 9 NPP operating (12,068 GWel)
- 8 shut-down
- 16 in decommissioning phase

NPP electricity facts

- 97 TWhel produced
- Load factor (LF=) 92%
- Share in energy mix ~16%
- Difficult boundary conditions
  - Priority access of renewable energy sources (RES)
  - Nuclear fuel tax
  - Regulatory constraints („stress test“, licensing, ....)
Present status - Germany

Current German electricity share

- **RES share 24.9%**
- **Installed capacity RES**
  - 35.9GW Photovoltaics (PV)
  - 33.8GW Windpower
- **Delivered RES energy**
  - 30TWh PV (LF=9.5%)
  - 53TWh Wind (LF=18%)

⇒ Successful „Energiewende“ demands
  - transformation of grid **AND**
  - provision of mature, reliable storage technologies

Data, AGEB, 4th March 2014
Boundary conditions for NPP deployment

NPP deployment strongly dependent on national arguments

- Grid /electricity independence ➔ autarchy (resources, availability,…)
- Strategy of economic and ➔ industrialization goals
- social development ➔ acceptance, perception
- technological basis ➔ maturity, safety performance, infrastructures

Additional considerations: bridging technology ➔ long term option

General facts

- Cost share of electric power plants

![Cost share pie charts for Nuclear, Coal, and Oil/Gas](chart)

© M. Ricotti, Polytec. Milan
Boundary conditions for NPP deployment

Positive and negative effects in NPP erection

**POSITIVE**

Electricity Cost Sensitivity to Fuel Price Volatility

- Gas price x2: +75%
- Uranium price x2: < +5%

**NEGATIVE**

- Sensitivity to the Cost of Money
- Construction delays/regulatory burdens
- Capital intensive investment = exposure to market risk

ThD / 7 May 2007
Nuclear Power: Global Status and Prospects
Boundary conditions for NPP deployment

- High capital investments
- Long construction schedule
- High financial exposure
- Long Pay Back Time
- High investment risk

Consequences
- Long-term investment strategy
- stable energy politics environment
- societal economic stability AND acceptance

→ Especially for private operators in liberalized markets based on competition
Boundary conditions for NPP deployment

- Large reactors or Small Modular Reactors (SMR)?

**Arguments for SMR**
- flexible power generation ➔ wider user/application range
- replacement of fossil fired units
- enhanced safety margin by inherent and/or passive safety features;
- better affordability - freedom in upgrading
- Cogeneration & non electric applications (desalination-process heat),
- Hybrid energy systems composed of nuclear with RES.

But deployment & technology of SMR is not

simply a scale reduction = sum of the modules = different product & technology
Boundary conditions for NPP deployment

**LEVELIZED UNIT ELECTRICITY COST = LUEC**

- Calculated as “Lifetime levelized cost”
- Sum of cost items:
  - Investment cost including capital remuneration
  - Fuel cycle (front-end and back-end)
  - Operation & Maintenance (O&M)
  - Decontamination and Decommissioning (D&D)

- Modern design life-time 60Years!!
Status of Countries on Nuclear Energy Initiatives

Technology developer countries (with NPPs in operation)
Other countries with NPPs
Newcomer countries

Asia
Europe
Africa
Latin America

Which countries deploy SMRs?

© Subki, IAEA, 2012
Major aspects for nuclear reactor deployment

- Currently deployment of Gen III – reactors

Are they essentially new compared to running Gen-II types? - No

- Evolutions of the operating Gen 2 plants

Why?

- Low industrial risk:
  - Include feedback of experience of the global fleet
  - Designed on well proven physics principles
  - No technological leap necessary

- Performance vs. sustainability = Gen 2
Major aspects for nuclear reactor deployment

- **Hardened design objectives** for
  - **nuclear safety** (Severe accident integrated in design; limited radiological consequences, Core damage frequency \(<10^{-6}/y\), more robust defence in depth approach -diversity, specific measures for each DiD level, integration of external events and hazards in safety concepts)
  
  and

- **public acceptability** (No area submitted to off-plant emergency planning, Low environmental impact in normal operation and design basis after Chernobyl (1986), New York (2001) and Fukushima)

- **Hardened economic design objectives** (competition with other sources)
  - **profitability of project** (availability>90% along life-time, short refuelling- outages, long cycles, reduced investment ➔ large size, design simplification, construction duration)
  - **Investment protection** (lifetime 60-80 years, low rate of difficult-to-repair failures, low core melt frequency \(<10^{-5}\), proven technology ➔ no leaps)

- **Gen-III reactors are not Gen 4 !!!**
  - No design requirement(s) for sustainability (saving \(U_{235}\) resources)
  - No burning of minor actinides
Requirements quite well established & documented

Numerous standards posed in documents by

- utilities,
- national TSO,
- Regional within the EU and
- worldwide collaborations
- and through IAEA

and continuously updated.
### Safety concepts of NPP's-General

**Major protection goals for NPP to be matched by design**
- Confinement of radionuclide inventory
- Coolability at any time irrespective of origin and source
- Control of reactivity

**Defence in Depth (DiD) approach**

#### Assignment of safety levels

<table>
<thead>
<tr>
<th>lev.</th>
<th>cond.</th>
<th>aim</th>
<th>measures</th>
<th>consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>normal</td>
<td>prevention of anormal operation or failures</td>
<td>Conservative design, high quality construction, qualified personnel</td>
<td>No measures</td>
</tr>
<tr>
<td>2</td>
<td>operational failure</td>
<td>condition control, detection/identification of reason</td>
<td>Control, limitation/ protection measures and survey functions</td>
<td>After short time restart</td>
</tr>
<tr>
<td>3</td>
<td>Design basis accident (DBA)</td>
<td>control of DBA within design (e.g. multiple failures of safety functions)</td>
<td>Engineering safety charact. and implementation of controlled accident measures</td>
<td>Planned restart anticipated (after inspection, repair, qualification)</td>
</tr>
<tr>
<td>4</td>
<td>Severe accident (BDBA)</td>
<td>Control of critical plant states incl. prevention of propagation</td>
<td>Complementing measures and accident management</td>
<td>Re-start not required</td>
</tr>
<tr>
<td>5</td>
<td>Post severe accidents</td>
<td>Mitigation of radiolog. consequences</td>
<td>Off-plant emergency measures</td>
<td>No plant re-start assumed</td>
</tr>
</tbody>
</table>
Safety approach - Risk informed safety philosophy

- Defense in Depth Concept (DiD)
  - Deterministic Success Criteria
  - Probabilistic Success Criteria
- Risk informed Safety Requirements for Design
- Basic Safety Functions
- Technical Protection Goals
Design basis safety: Gen II and Gen-III Reactors

Main challenges for risk informed safe design:
- Neutronic, thermal hydraulic, mechanical design – ALL ARE COUPLED
- Passive safety systems for ECC and decay heat removal
- Control of severe accidents (core-catcher, passive containment cooling, PAR)

NPP: Complex System with Multi-physic and Multi-scale Phenomena
Design basis – safety

Enlarged computational capabilities and resources allow for
- more detailed local analyses in the reactor design
- improved design safety of new plants (Gen III)
- retrofitting of running plants (Gen II)

Recipe to solve the sophisticated problem involve:
- Multi-scale problems
- Multi-physics problems
- Multi-scale and multi-physics
- including transients
- A very challenging problem with numerous feedbacks!
Design basis – safety

TH- problem – „classic route“
- Fast running real time capability
  - reactor operation
  - principle design

Real World
VVER-1000 Reactor

Coarse 3D Mesh

System code level

Real world
Design basis -safety

TH- multi-scale –problems –CFD
Flow in reactor pressure vessel (RPV)

- micro ➞ macro scale
- Down comer and lower plenum:
- Computing effort 2 weeks CPU time (12 processes parallel) for 1800s transient
- Development chain
  - $\Delta p$ obtained from standalone full detail model (3 Mio cells / column)
  - Implementation of $\Delta p$ coefficient in the coarser RPV model (5000 cells / column)

VVER-1100 reactor
Design basis - safety

TH - multi-scale - problems
RPV ➝ Primary loop (VVER-1000)

- RPV
- Heat exchanger
- Primary loops:
  - Steam generators and pumps
  - Pipes
  - Valves

© M. Böttcher, INR
Design basis -safety

- TH Validation essential corner-stone ➔ IAEA –Benchmarks

Example:

- OECD/NEA Benchmark: Pump Trip exercise
  - Void fraction
  - Pressure drop
  - Critical power

![Diagram](Image)

Fuel assembly (FA)

Design basis - safety

Advanced methodologies for the analysis of PWR and BWR Transients

- Coupled thermal-hydraulics and neutronics
- High-fidelity / multi-physics developments: from FA to pin-based solutions
  - Direct prediction of local safety parameters at cell level
  - Reduction of conservatism

![Diagram showing Neutronic and Thermalhydraulic connections with PIN Cross Sections and POWER flow](image-url)
Design basis -safety

Actual Trend: Multiphysics and multiscale problems

“Two routes”

- Fuel Assembly level simulations ➔ conservative safety parameters
- Pin level simulations ➔ local safety parameters, but costly

⇒ economic AND save designs demand high spatial resolution on core level
Design basis -safety

Actual Trend Multi-/scale -physics
- local FA or even pin data
- Mesh super-position at FA level with pin-power- reconstruction
- Demanding High Performance Computing (HPC) and parallelization

NURESIM- Platform: Code coupling Strategy

COBAYA3D
Neutronic

Data Exchange Model (DEM)

SUBCHANFLOW
Thermal
Hydraulics

SALOME

Based on:
- Geometry
- Meshes
- Feedback parameters

Application Programming Interface

API

INPUT
OUTPUT

INPUT
OUTPUT

Total reactivity ($$)

COBAYA-

0 2 4 6 8 10
Time (s)

-16 -14 -12 -10 -8 -6 -4 -2 0 2

1

PWR Boron Dilution Transient

© Calleya PhD Thesis 2013
Design basis - safety

- Actual Trend: Multiphysics and multiscale problems

1 - 2

Hybrid schemes
- Nodal in most of core
- Local pin resolution

Predicted Nodal/cell power

Pin resolution
- Computational demanding

Next steps underway
- Tracking each neutron
- Monte Carlo methods

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Beyond design basis - safety

- Integral part of Gen-III reactor design

What to be avoided?
- Fukushima (➔ radiolog. consequences)

Design options
- Design, core catcher, PAR,
- Barriers,…….

AMM=Accident management measures
Standard NPP Safety Systems- Gen II

Control
- Control rods
- Borated water

Purely passive and safety related Emergency core cooling systems (ECCS)
- Core make-up-tanks (borated water)
- Accumulators (water replacement)
- Coolant make-up from IRWST by gravity
- PRHR gravity based

© Example Westinghouse, AP1000, 2014
Evolutionary Safety Systems- Gen III

- Several severe accident strategies
- In-vessel retention
- ex-vessel by means of „core catcher“
Beyond design basis – safety – Severe accidents

- Numerous phenomena

- Subject of international cooperations and networks

Goal: reliable physics description ➔ predictive tool development

Beyond design basis – safety – Severe accidents

Hydrogen generation mechanisms
- clad melt @ reflodding
- hydrogen induced clad rupture
QUENCH prog. @KIT

Behavior of core melt in lower plenum
- hydrogen safety @KIT
LIVE prog. @KIT

Hydrogen distribution in large containments
- scale demonstration
- concrete sensitivity
MOCKA prog. @KIT

ex-vessel Molten Core
Concrete interaction
- behavior in reactor pit
- direct containment heating
DISCO prog. @KIT
Large Gen-III Reactors currently deployed (PWR)

- **AP 1000 (Westinghouse – Toshiba)**
  - 2 SG, 4 Pumps, 1100MWe
  - Compact core Passive safety features
  - China, US

- **APR 1400 (Korea)**
  - 2 SG, 4 Pumps, 1400MWe
  - 2 act. safety system, no high press. injection
  - Mixed severe accident strategy
  - Korea, UAR

- **APWR 1000 (MHI)**
  - 4 SG, 4 Pumps, 24m fuel cycle,
  - 1000MWe
  - Instead safety diesels, gas turbine

- **EPR (AREVA)**
  - 4 SG, 4 Pumps, large core, ->1600MWe
  - Core catcher, 24m fuel cycle, CDR10⁻⁷/y
  - FIN, FRA, VRC

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Large Gen-III Reactors currently deployed (PWR)

- **AES** (Russia)
  - 4 SG, 4 Pumps, 1070MWe, Horizontal HEX,
  - Passive safety features, Core catcher, soda injection system
  - BUL, RUS

- **ATMEA** (MHI-AREVA)
  - 3 loop, 1150MWe,
  - 3-safety trains
  - 2 stage accumulator,
  - heavy airplane crash design
  - 100% MOX fuelling possible,
  - 24m fuel cycle
  - interests but no built

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Large Gen-III Reactors currently deployed (BWR)

- **AB 1600 (Toshiba)**
  - PCCS (passive containment cooling system)
  - GDCS, (gravity based core cooling system).
  - Core catcher
  - in licensing

- **ABWR (Hitachi-GE)**
  - 1350MWe, high operation flexibility
  - high core safety CDR <10^{-7}/y
  - short erection time 37m, full MOX capability
  - JAP, TAIWAN

- **ESBWR (GE)**
  - 4 passive safety trains (nat. circulation)
  - 1500MWe, CDR CDR <10^{-8}/y
  - licensed in US, no current projects

- **Kerena (AREVA)**
  - all passive safety sytem, compact, 1250MWe
  - flexible operation, designed for severe acc.
  - Airplane crash resistant , no current projects

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SMR operating/ under development (water cooled)

- **CAREM-25**
  - PWR
  - 87MWe
  - Primary system in vessel

- **SMART**
  - Korea, Republic of
  - 100MWe
  - Primary system in vessel
  - Passive DHR

- **NuScale**
  - PWR
  - 45MWe
  - Natural circulation cooled
  - DHR via containment

- **mPower**
  - PWR
  - 180MWe
  - Low power density
  - 48m fuel cycle
  - Passive safety no diesels necessary

- **KLT-40s**
  - PWR
  - 70MWe
  - 2 units constructed

- **CNP-300**
  - PWR
  - 300MWe
  - 2 loop system
  - 3 plant operating
  - 2 in construction

- **WWER-300**
  - PWR
  - 300MWe
  - In-vessel core catcher

- **PHWR-family**
  - PHWR
  - 220-540MWe
  - 2 -loop design
  - Classic safety design
  - 16 operating plants

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Nuclear Waste

Nuclear is a generation contract !!!! → requiring acceptance & stability
- Capital investment
- Long living fission products
- Waste management strategies in all aspects

Why and what masses to expect ? → Fuel and activated material

- low radioactivity unused fuel
- high radioactivity, rapidly decaying FP´s (pot. products with economic apps. Mo)
- fairly radioactive, potential for consumption in reactor, driver for disposal concerns!
- very low radioactivity unused uranium

Origin: Burnup-33MWD/t, 1100day irr., 17x17 LWR assembly
Nuclear Waste

- Reprocessing, conditioning and transport mandatory

Options for subsequent treatment of radionuclides
- Disposal (geological w/o access, deep underground /near soil ,…….)
- Transmutation

What is transmutation?

- transfer of radionuclides by neutron induced fission or neutron capture in another element

**neutron-induced fission**

- fast neutron
- neutron

**neutron capture**

- Neutron
- non radio-active
Nuclear Waste - Transmutation

How to minimize radiologic burdens? **Fuel cycle required**

- Spent Fuel from LWR

**Fuel cycle:**

- TRU: Transuranics (Pu, Np, Am, Cm)

**Temporary storage for heat decay**

**All FP**

**TRU losses**

**TRU**

**Fuel fabrication**

**Transmutation**

**Geological disposal**

**Final repository required but substantially smaller!**

Transmutation of LLFP: theoretical possible - efficient realisation path?
Nuclear Waste - Transmutation

What type of fast neutron spectrum reactors? – Two options
- dependent on further nuclear utilization option!!!

Accelerator Driven Systems
- Accelerator driven
- Sub-critical core → simply burning

Fast reactors
- breeding → fissile regeneration but also
- Burning → transmutation of minor actinides
- critical core - different safety features (!)

Gen-IV
International contributions to Generation IV

Strategic aims:
- Development of new NPP by 2030 in international cooperation
- Multifunctionality (electricity, desalination, hydrogen, heat)

Technologic aims
- Better economics
- Improved sustainability
- Increased safety
- Enlarged proliferation resistance

Status
- Continuous worldwide cooperation
- 6 dedicated concepts
- Elaboration of standards

+ China, Russia since 2006!
Germany ? through EU
Generation IV Forum: selection of six nuclear systems

- Sodium-cooled Fast Reactor
- Lead-cooled Fast Reactor
- Gas-cooled Fast Reactor
- Very High Temperature Reactor
- Supercritical Water-cooled Reactor
- Molten Salt Reactor
Summary and perspective

- Fission energy is a substantial part of worldwide energy production.
- Mostly generated by Gen –II NPP systems.
- Fission is pursued worldwide in numerous industrial countries.
- Current deployment is focused on large scale LWR.
- Substantial scientific progress in last decade with respect to safety.
  - Interesting multi-physics and multi-scale phenomena.
  - Accurate description of transient processes in plants.
  - Internationalisation of research and development by collaboration, agreements and bi-lateral contracts.
  - Current deployment is focused on large scale LWR.

- Nuclear energy production is a generation contract!
- Nuclear waste management is an essential part of nuclear evolution.
- Transmutation in reactors is a credible option to minimize burden on future generations (both: fuel, repository demands).
- Irrespective of societal decision on use of nuclear fission energy research, development and education must be of vital interest to assure credible assessment capability.