Karlsruhe Institute of Technology

DPG Tagung
17-21.März 2014, Berlin

International role of nuclear fission energy generation - status and perspectives

R. Stieglitz, J. U. Knebel, W. Tromm

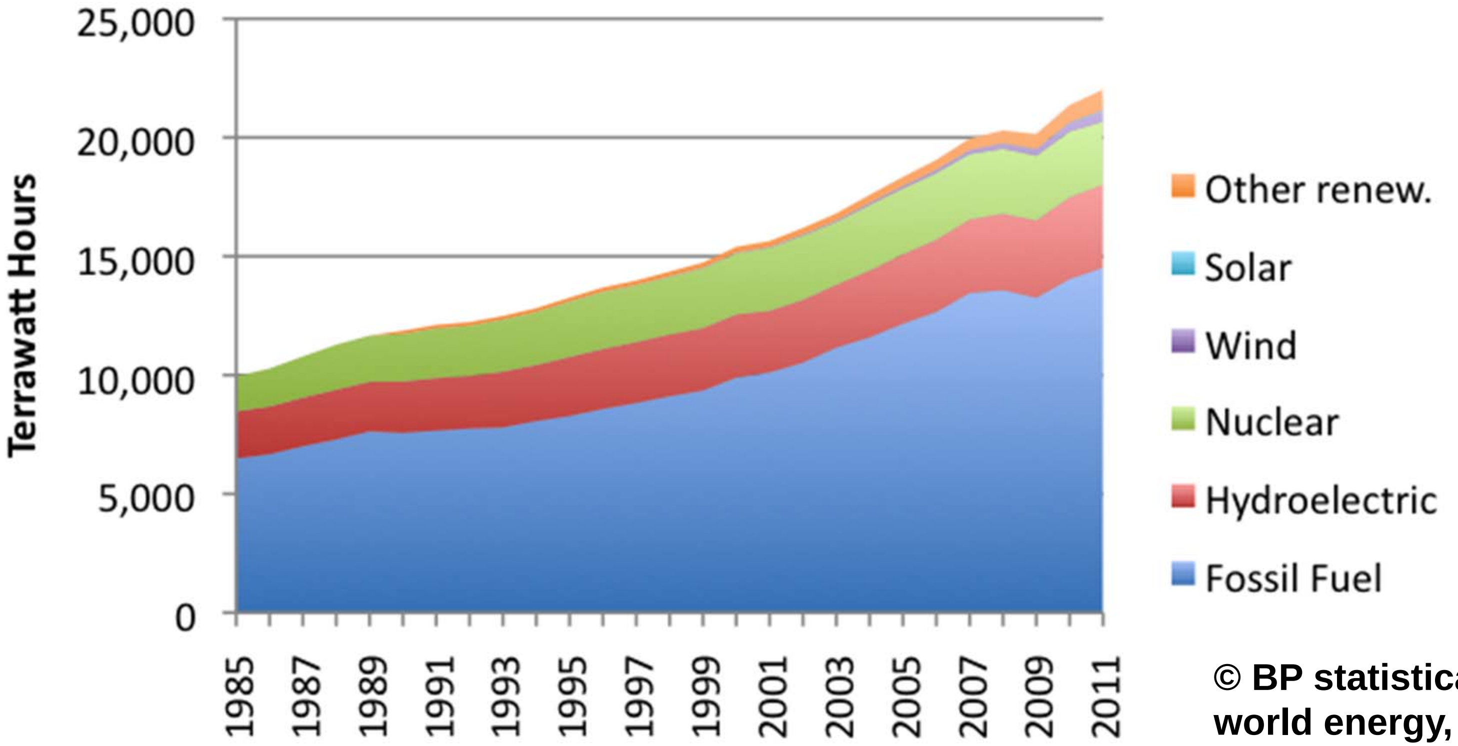
Content

- 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

- NPP worldwide currently operating (3/2014, www.iaea.org/pirs/):
  - 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)

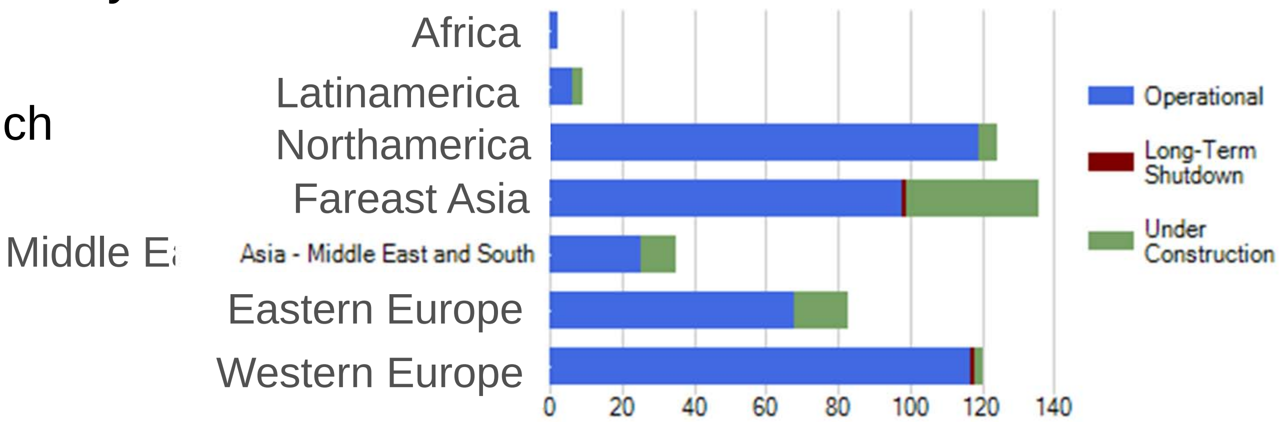
➡ ≈11% of global electricity production (almost constant since 2006)



Present status –Some facts

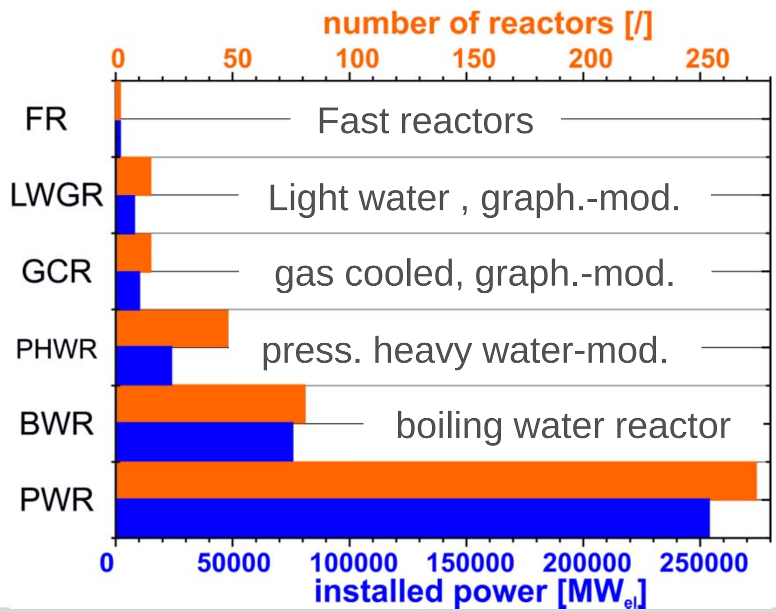
- Plant Location-currently-new builts

  - ➡ 72 new builts of which
  - ➡ 60 PWR´s
  - ➡ 68 GW_{el}



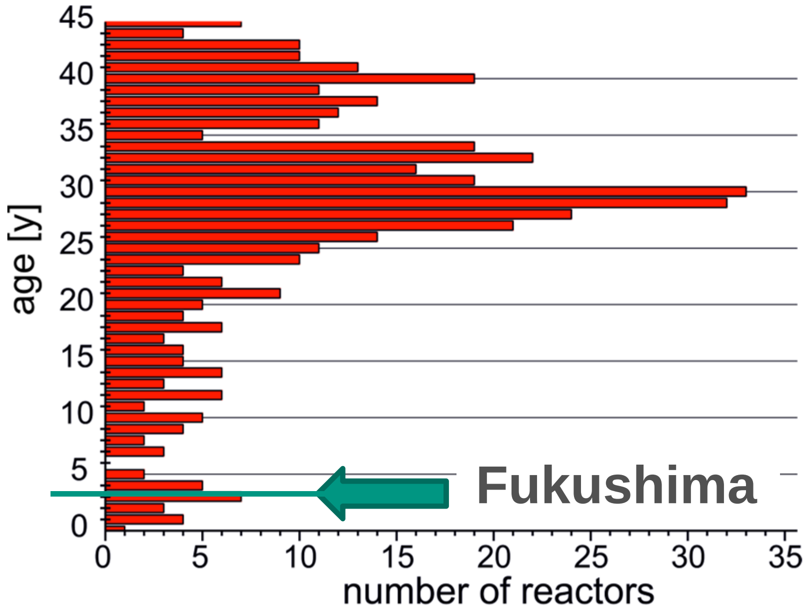
- Reactor types-installed power

  - ➡ focus on large scale units ~1GWe light water reactor (LWR)-types
  - ➡ mainly pressurized water reactors (PWR)

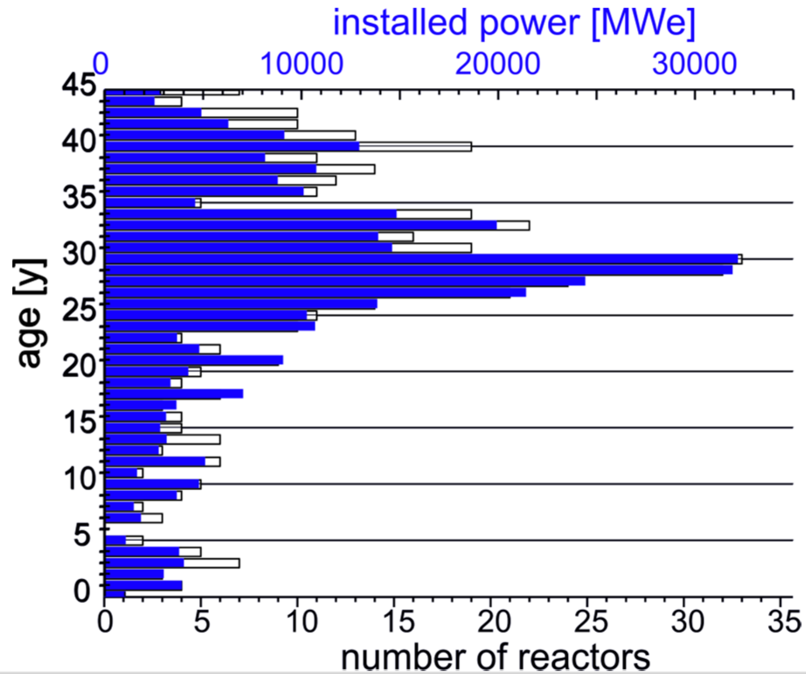


Present status –Some facts

- 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



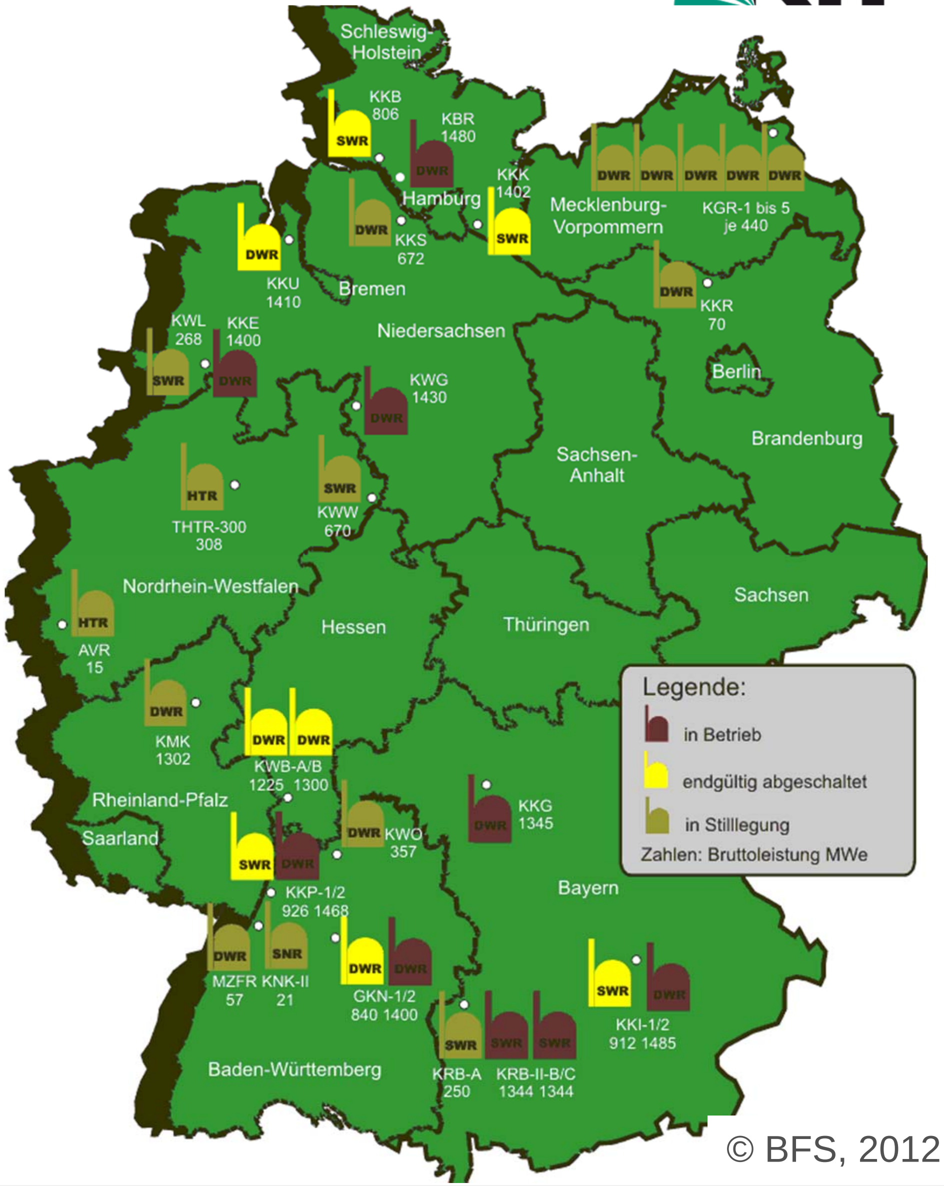
Present status- Germany

After march 11th 2011 Fukushima

- 9 NPP operating (12,068GW_{el})
- 8 shut-down
- 16 in decomissioning phase

NPP electricity facts

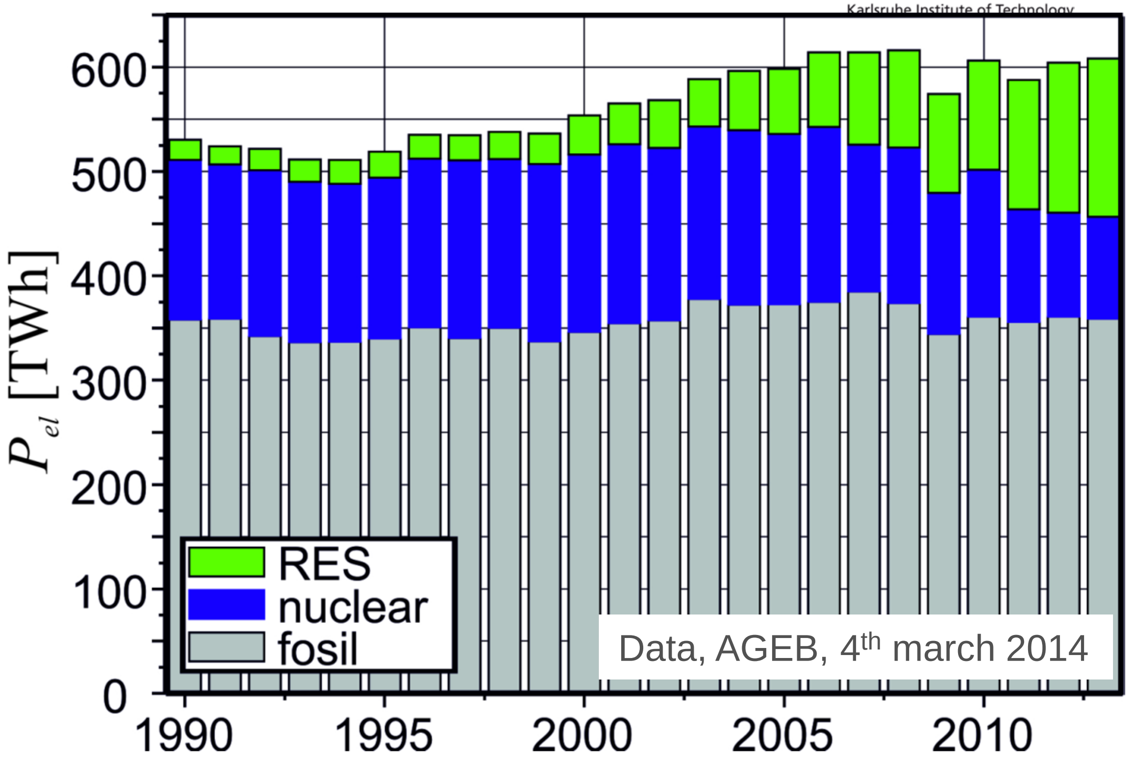
- 97TWh_{el} produced
- ➡ load factor (LF=) 92%
- Share in energy mix ~16%
- Difficult boundary conditions
  - Priority access of renewable energy sources (RES)
  - nuclear fuel tax
  - Regulatory contraints („stress test“,licensing, ….)



Present status- Germany

Current German electricty 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%)



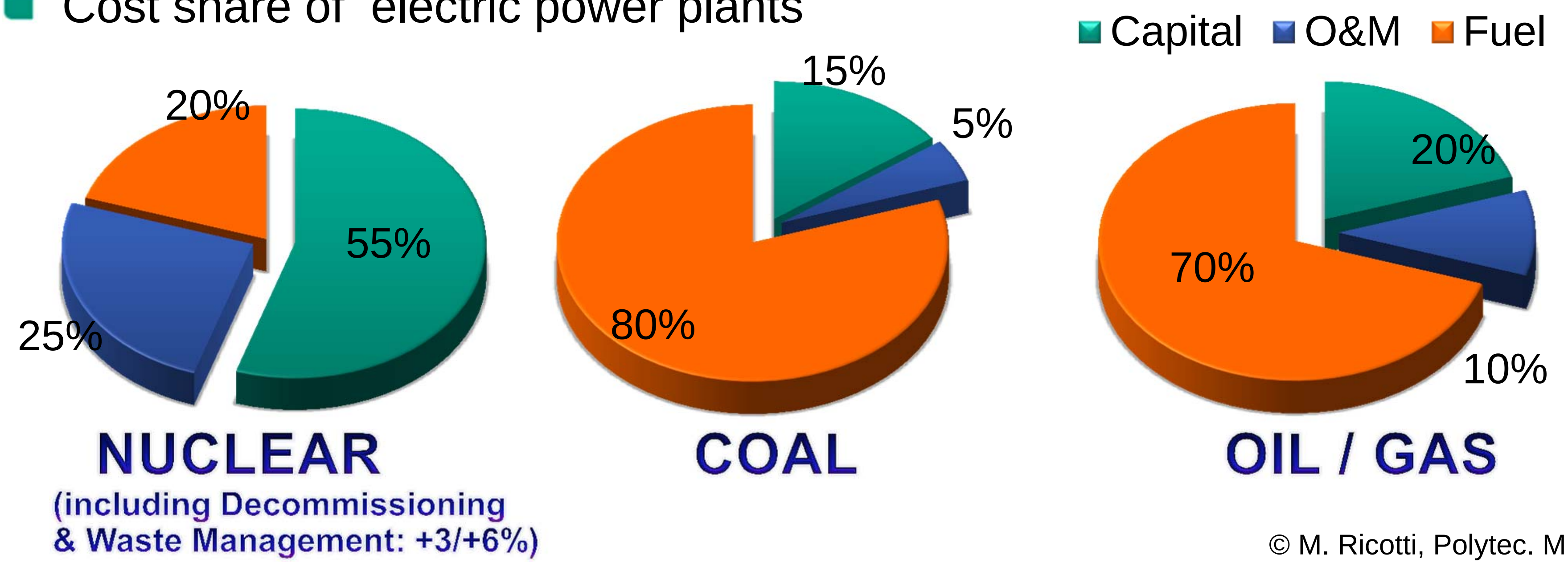
➡ Successful „Energiewende“ demands
  - transformation of grid **AND**
  - provision of mature, reliable storage technologies

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

<u>General facts</u>

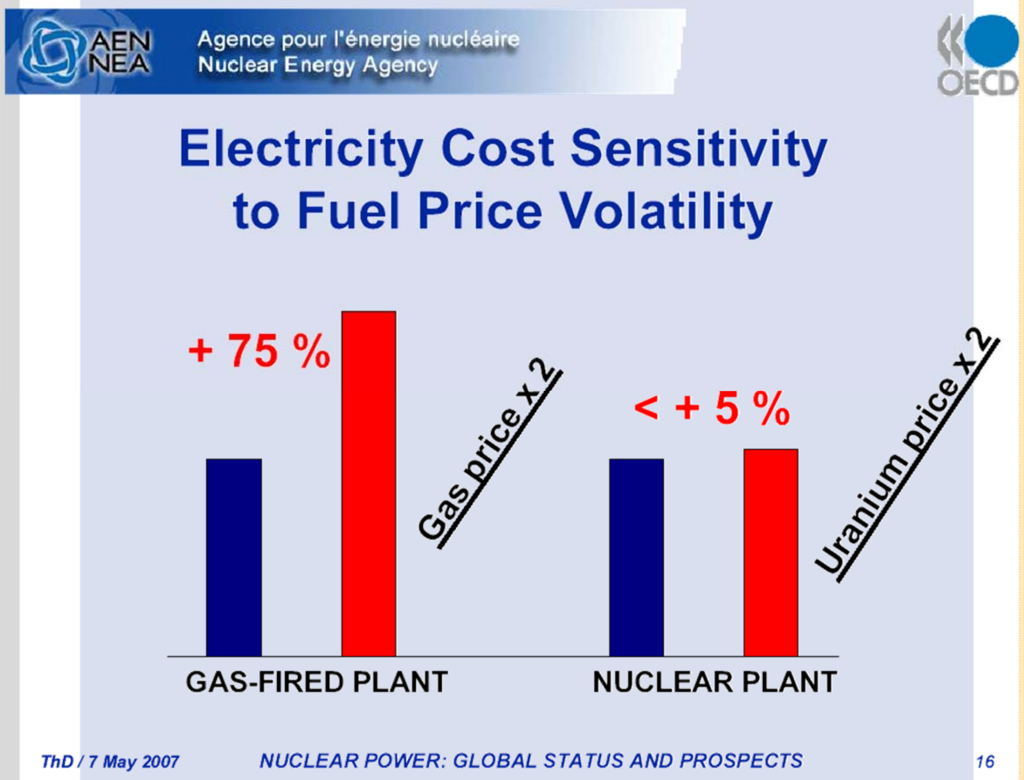
- Cost share of electric power plants



Boundary conditions for NPP deployment

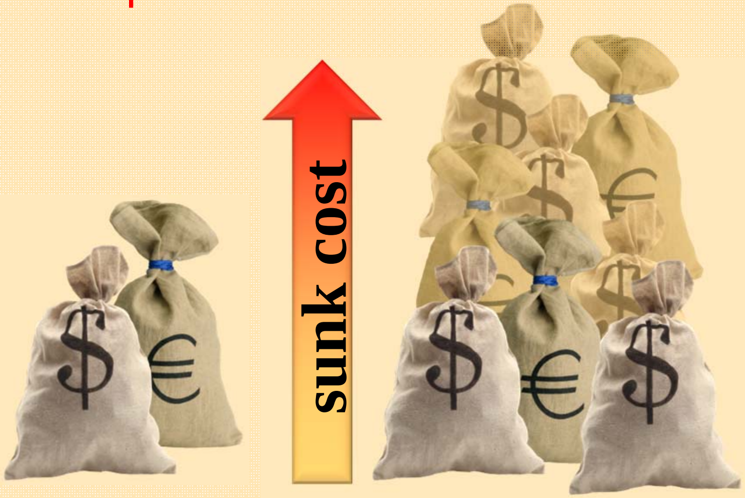
- Positive and negative effects in NPP erection

POSITIVE



NEGATIVE

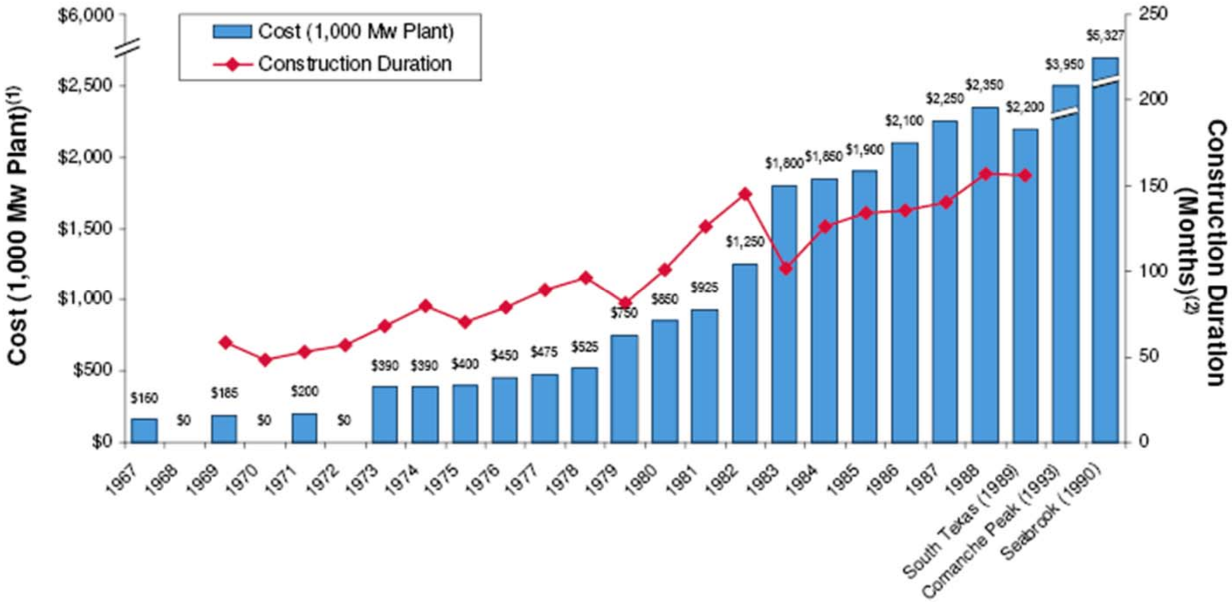
- Sensitivity to the Cost of Money
- construction delays/regulatory burdens
- capital intensive investment = exposure to market risk



Boundary conditions for NPP deployment

- High capital investments
- Long construction schedule

- High financial exposure
- Long Pay Back Time
- High investment risk



© Booz & Company, 2009

Consequences

- Long-term investment strategy
- stable energy polictics 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

=

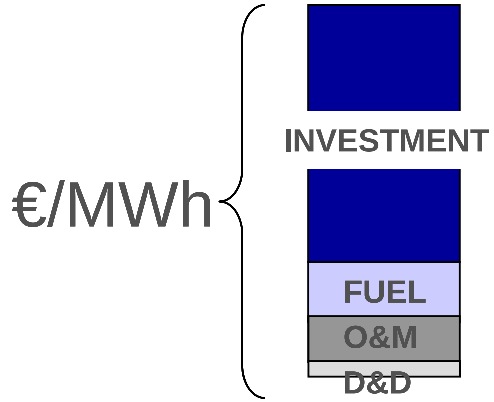
sum of the modules

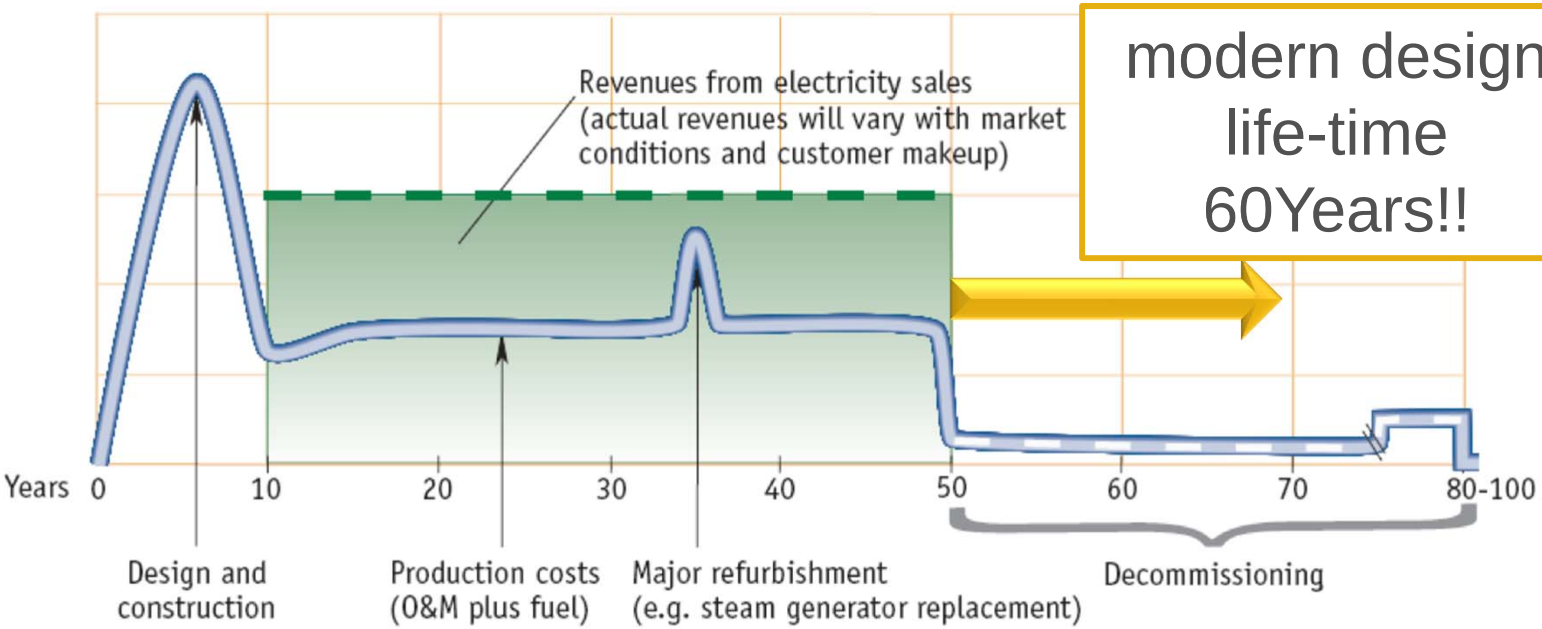
= different product & technology

Boundary conditions for NPP deployment

LEVELIZED UNIT ELECTRICITY COST = LUEC

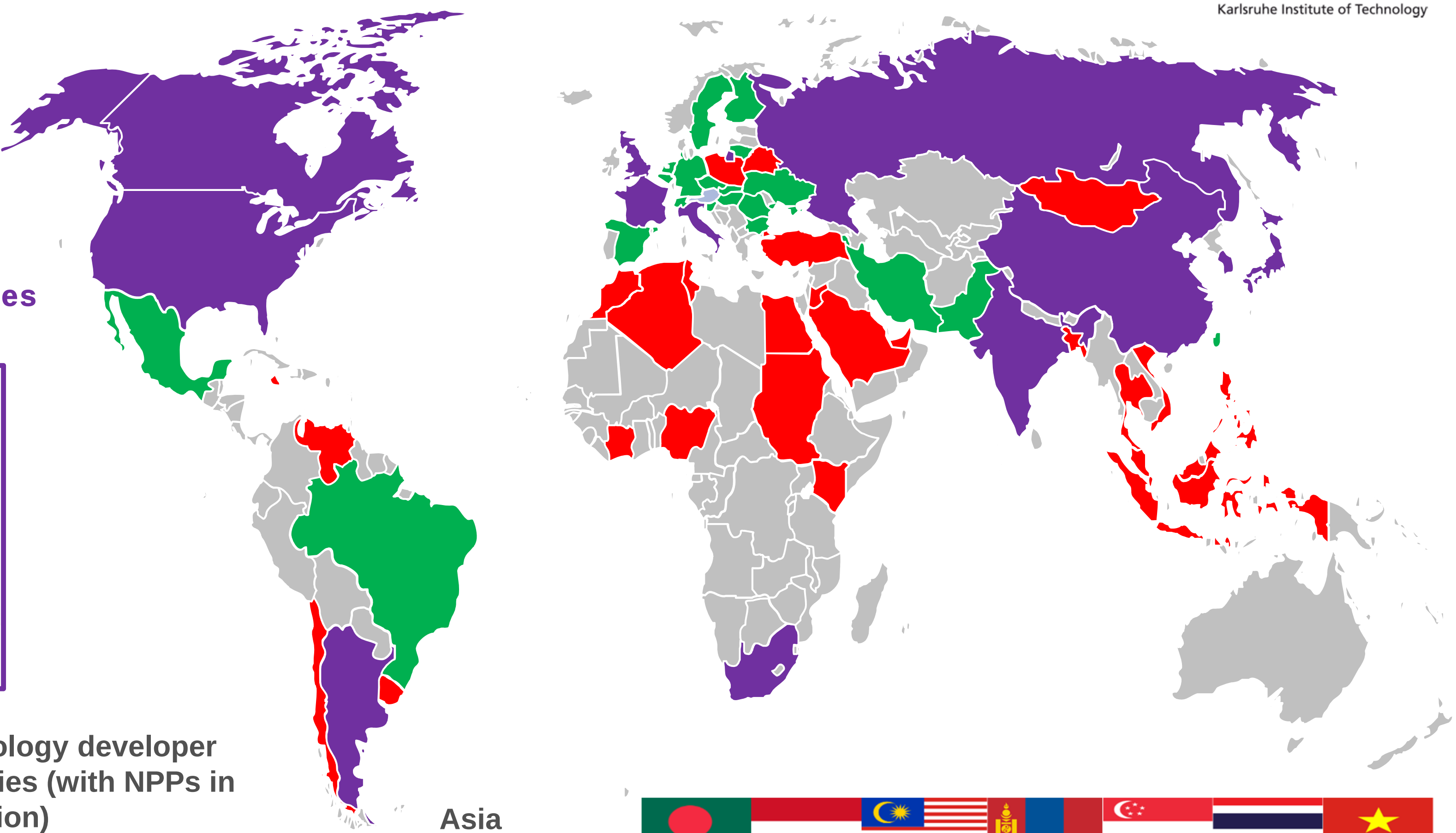
- Calculated as “Lifetime levelized cost”
- Sum of cost items:
  - Investment cost including capital remuneration
  - Fuel cycle (front-end and back-end)
  - Operation & Maintenance (O&M)
  - Decontamination and Decommissioning (D&D)





modern design
life-time
60Years!!

Status of Countries on Nuclear Energy Initiatives



Which countries deploy SMRs?

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

Asia

Europe

Africa

Latin America

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), NewYork (2001) and Fukushima
- Hardened **economic design objectives** (competition with other sources)
  - **profitability of project** (availability>90% along life-time, short refuelling- outages, long cycles, reducedinvestment ➡ 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)

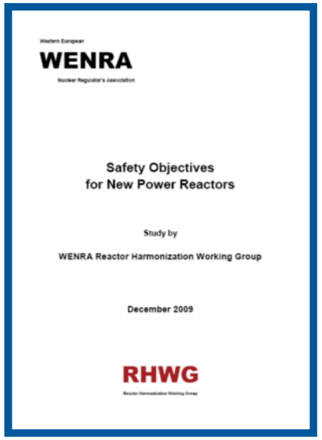
➡ **Gen-III reactors are not Gen 4 !!!**
  - **No design requirement(s) for sustainability (saving U_{235} resources)**
  - **No burning of minor actinides**

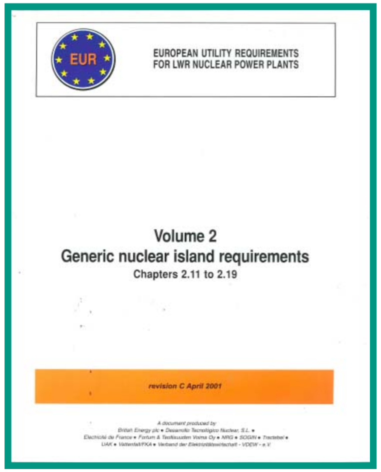
Requirements quite well established & documented

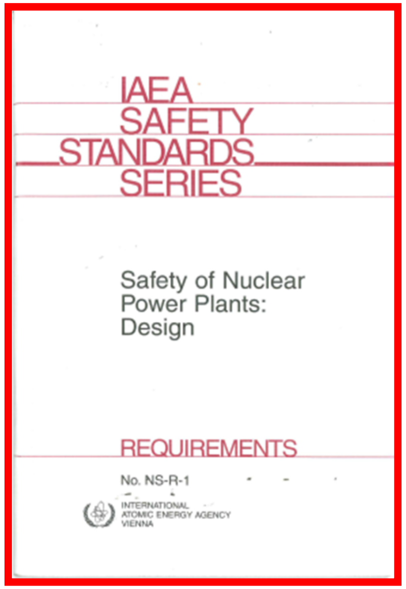
Numerous standards posed in documents by

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

and continuously updated.







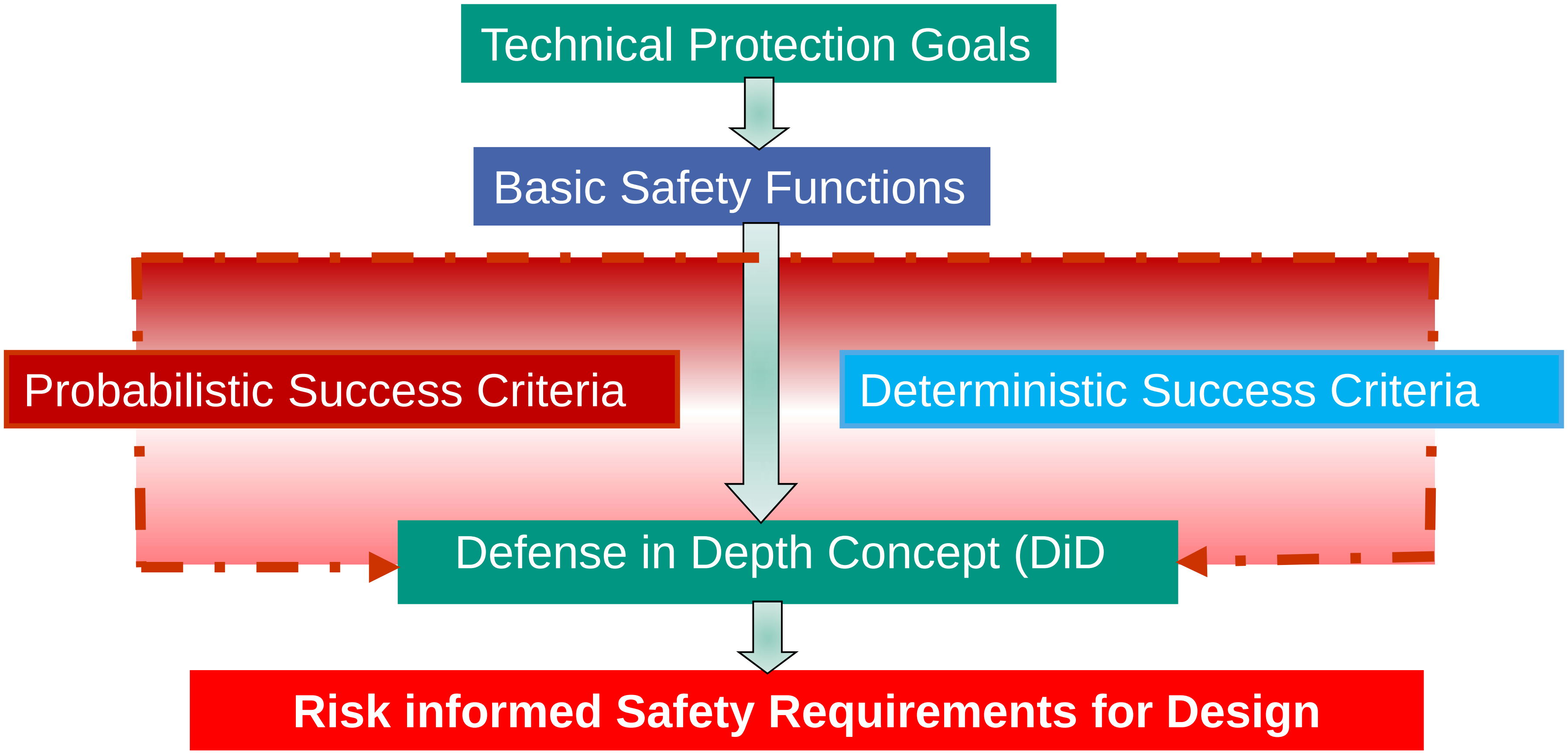
Safety concepts of NPP´s-General

Major protection goals for NPP to be matched by design

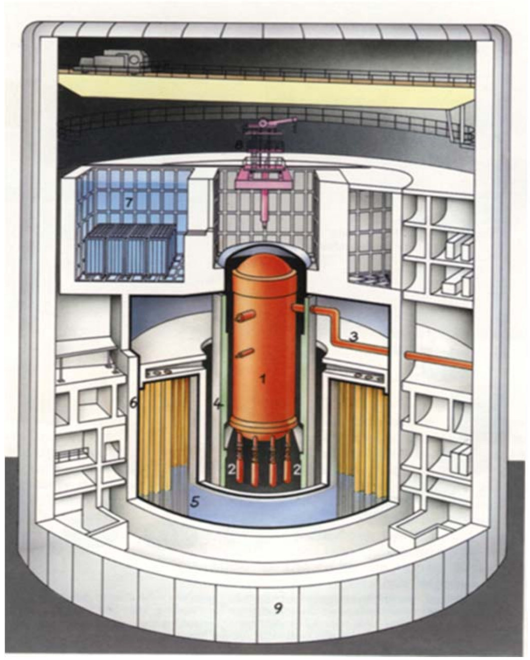
- Confinement of radionuclide inventory
- Coolability at any time irrespective of origin and source
- Control of reactivity
- ➡ Defence in Depth (DiD) approach ➡ assignment of safety levels

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

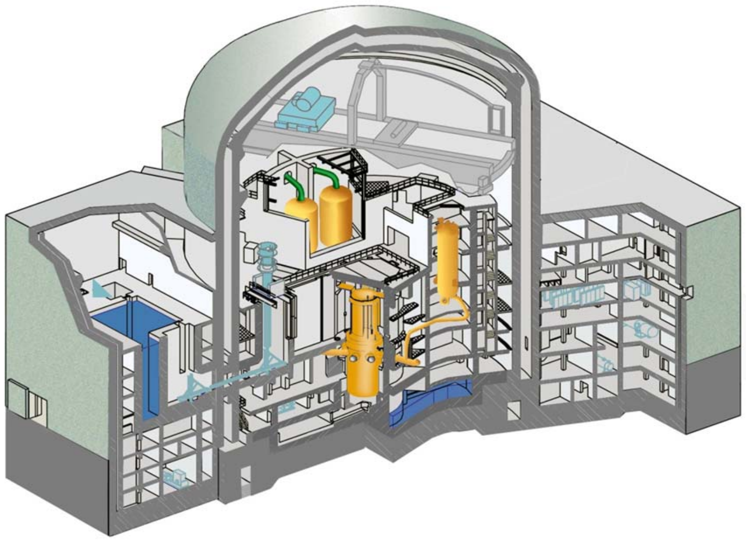
Safety approach- Risk informed safety philosophy



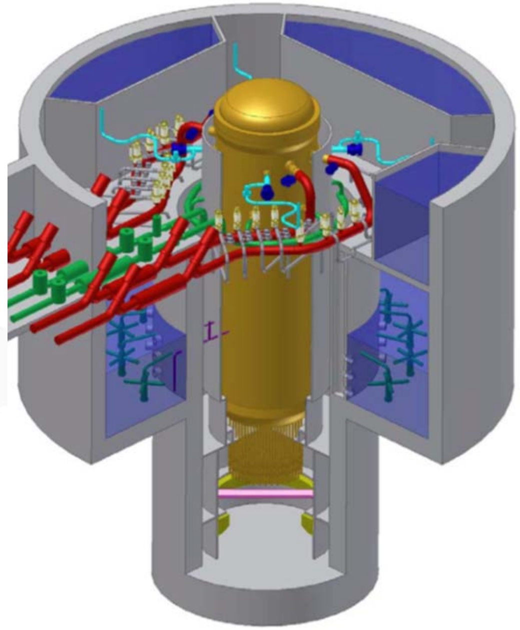
Design basis safety: Gen II and Gen- III Reactors



- BWR



- EPR-PWR



- ESBWR

NPP: Complex System with Multi-physic and Multi-scale Phenomena

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)**

Design basis – safety

Enlarged computational capabilities and ressources allow for

- ➡ more detailled 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 envolve:

- Multi-scale problems
- Multi-physics problems
- Multi-scale and multi-physics
- including transients
- ➡ **A very challenging problem with numerous feedbacks !**

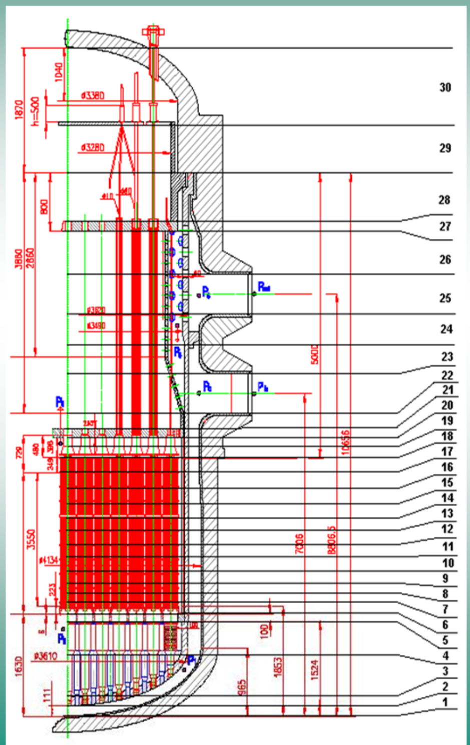
Design basis – safety

TH- problem – „classic route“

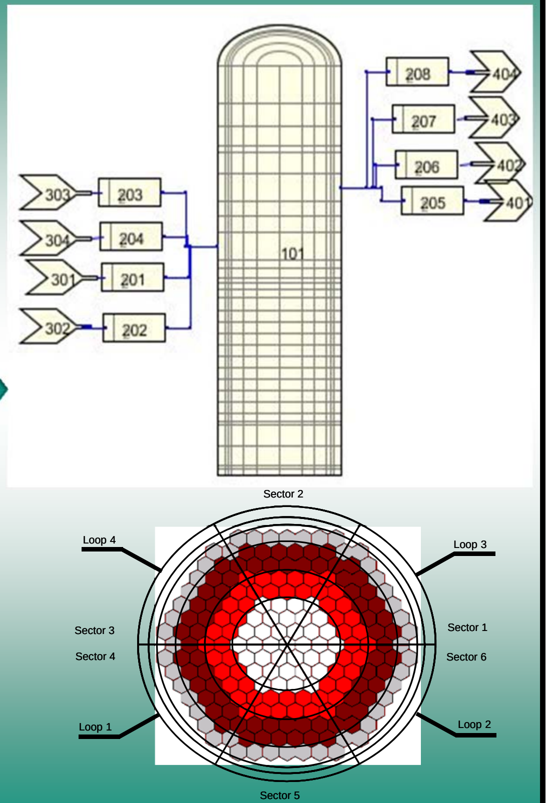
- Fast running real time capability
  - reactor operation
  - principle design

Karlsruhe Institute of Technology

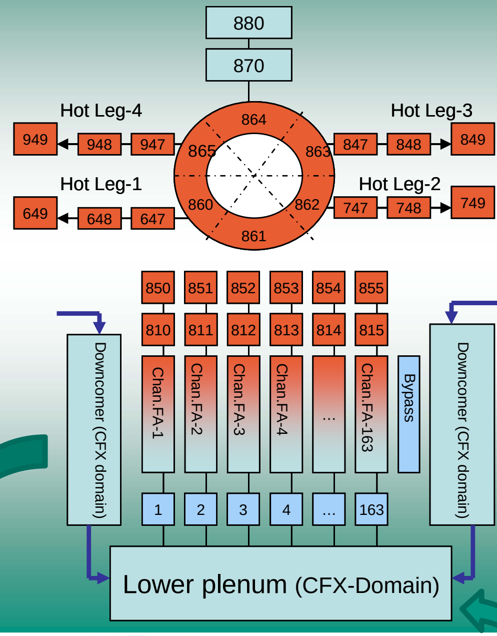
Real World VVER-1000 Reactor

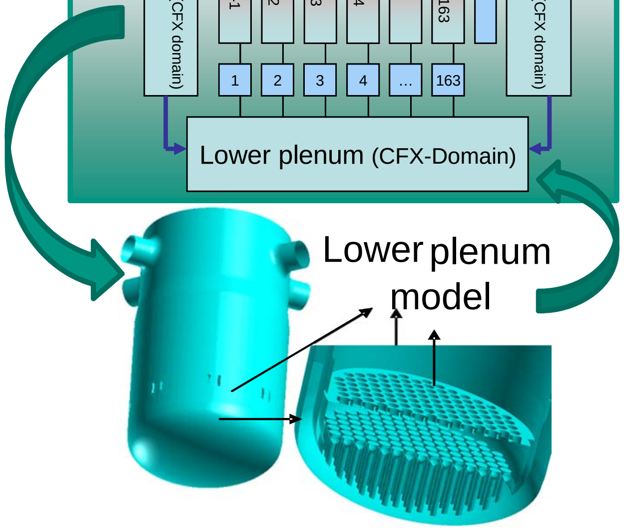


Coarse 3D Mesh



System code level





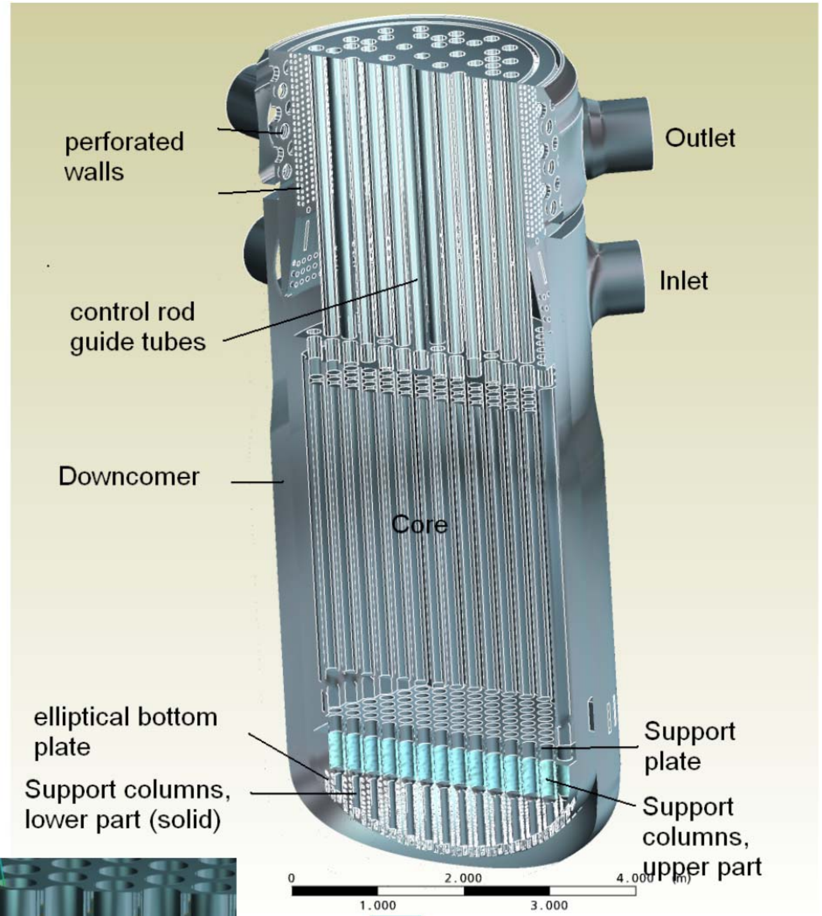
Design basis -safety

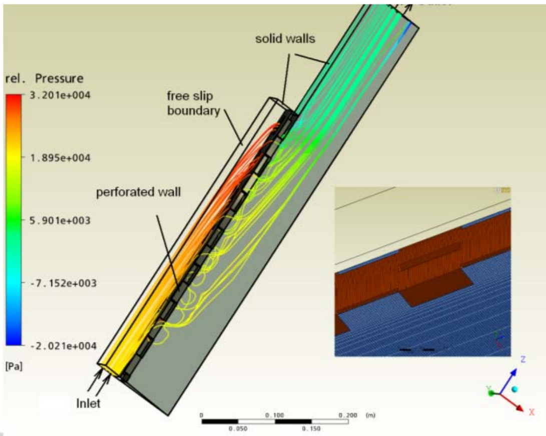
TH- multi-scale –problems –CFD

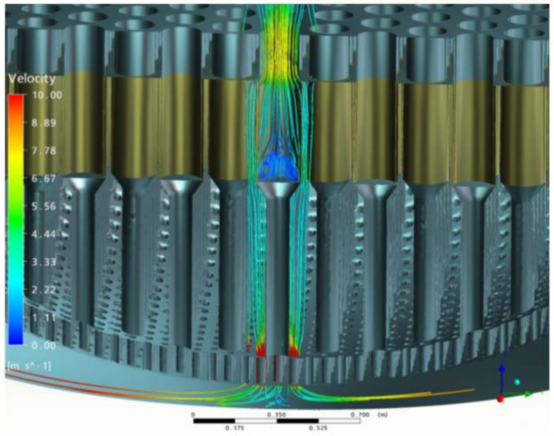
Flow in reactor pressure vessel (RPV)

micro ➡ macro scale

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





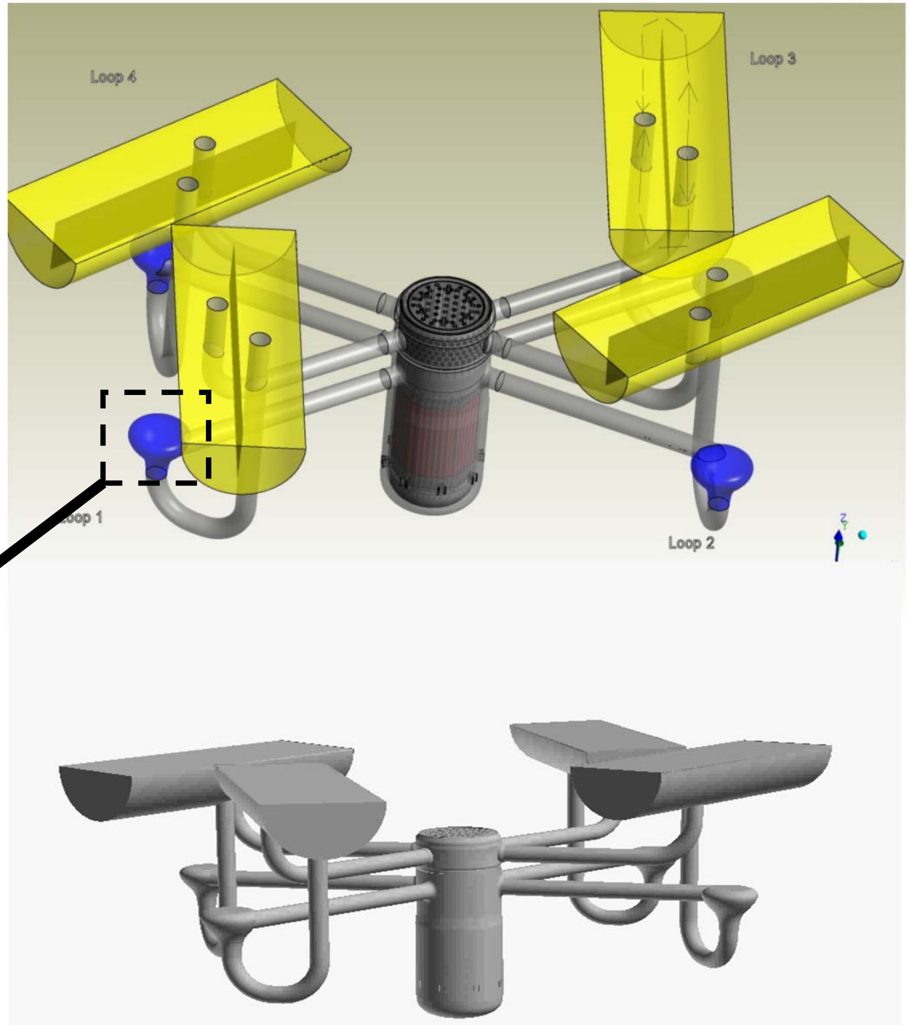


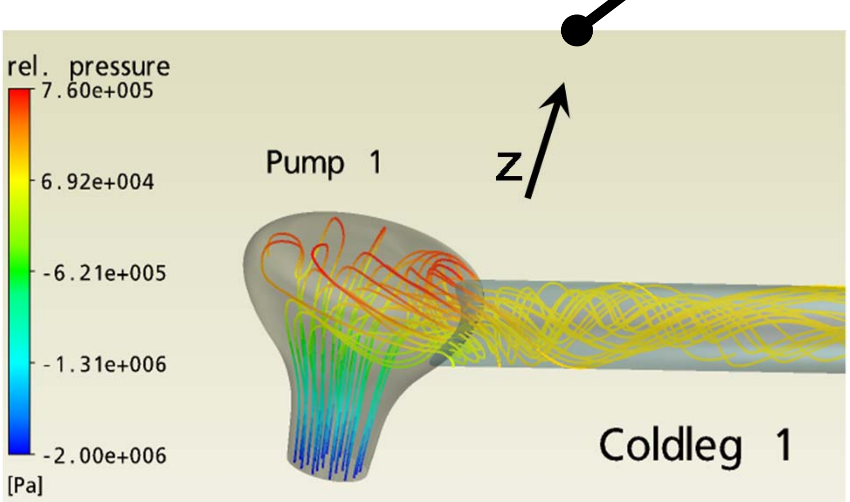
VVER-1100 reactor

Design basis -safety

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

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



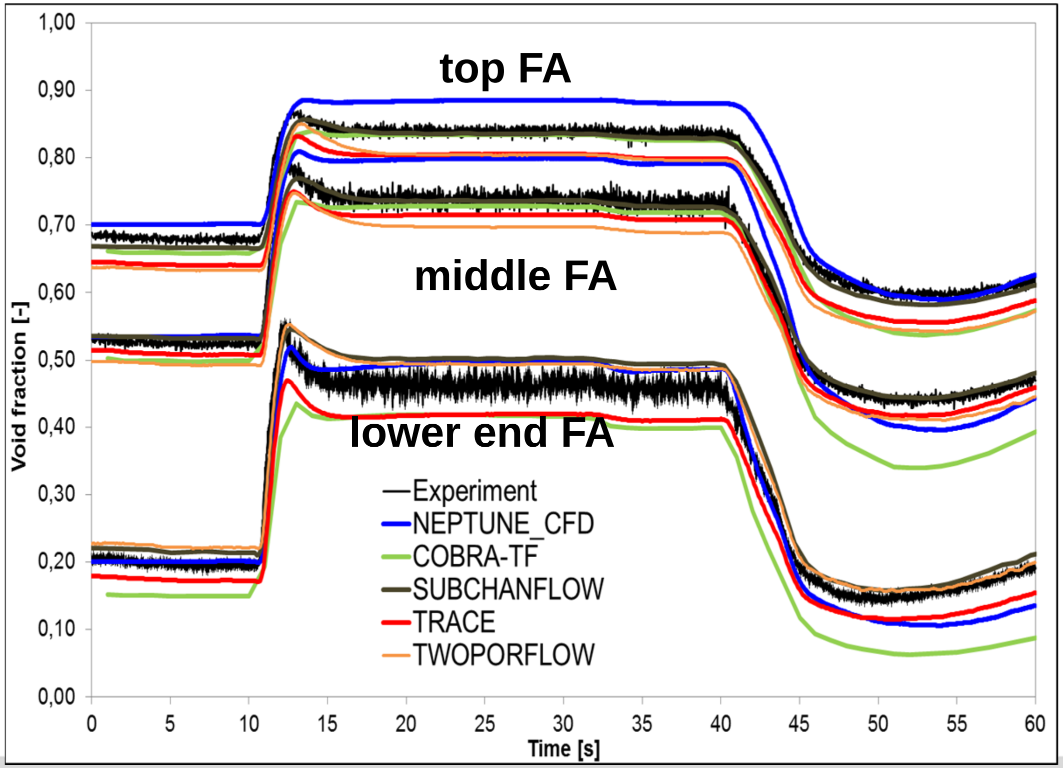


Design basis -safety

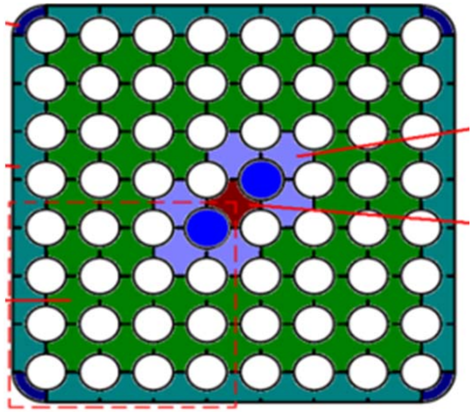
- **TH Validation essential corner-stone ➡ IAEA –Benchmarks**

Example:

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



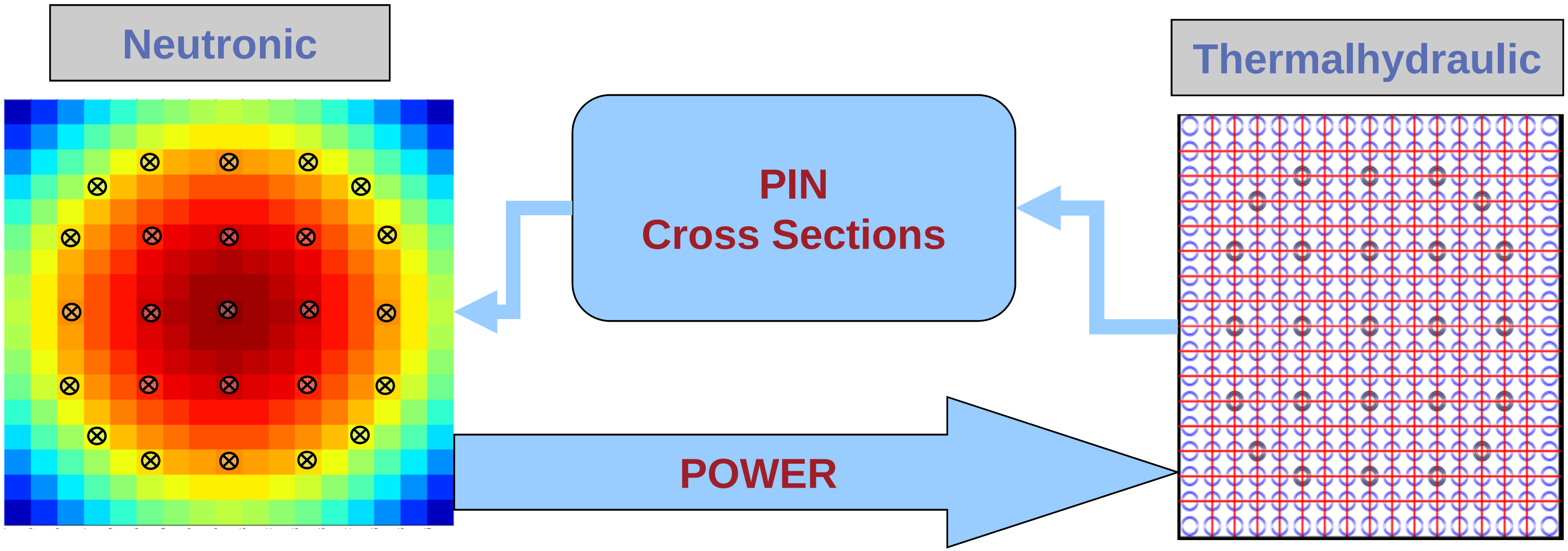
Fuel assembly (FA)



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



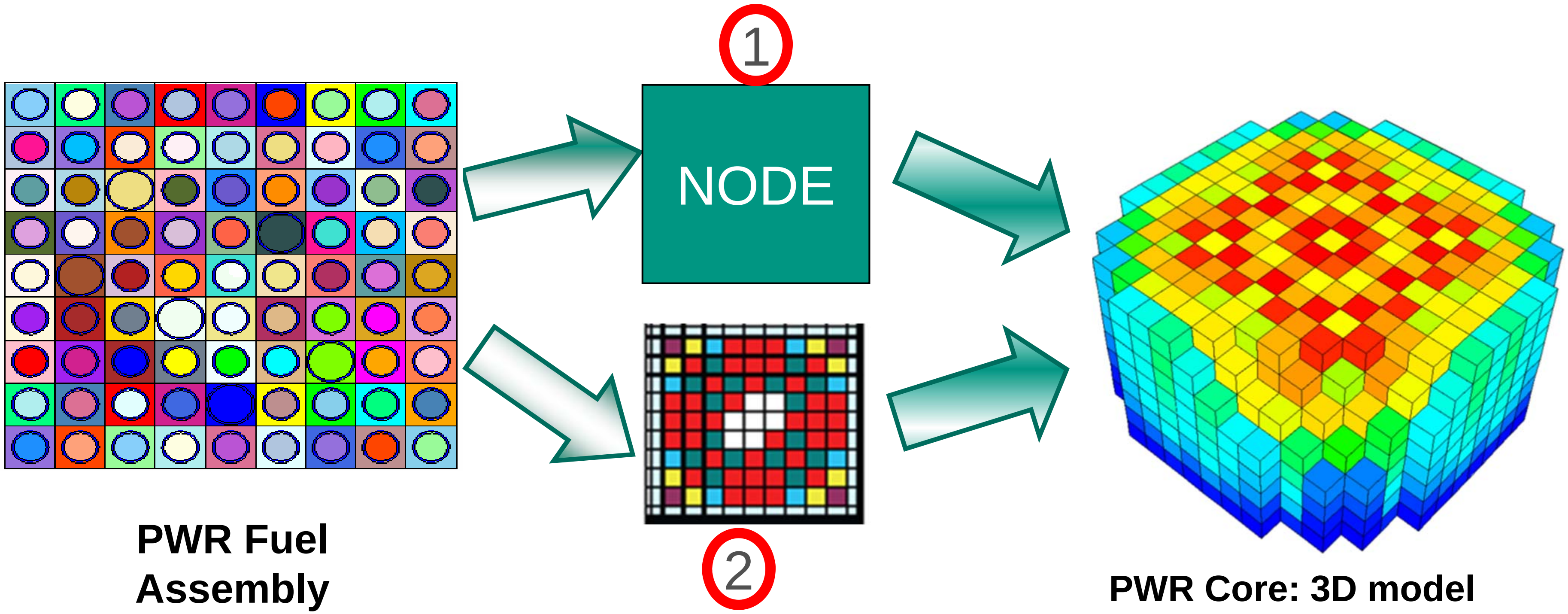
Design basis -safety

- **Actual Trend: Multiphysics and multiscale problems**

“Two routes”

- Fuel Assembly level simulations ➡ conservative safety parameters (1)
- Pin level simulations ➡ local safety parameters, but costly (2)

➡ economic AND save designs demand high spatial resolution on core level



PWR Fuel Assembly

PWR Core: 3D model

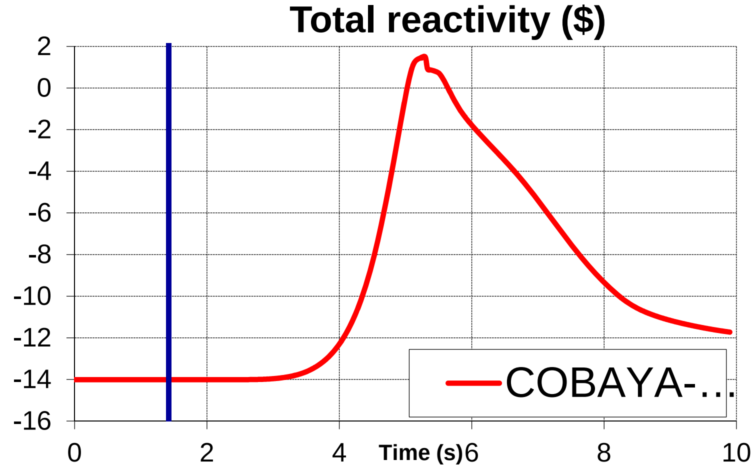
Design basis -safety

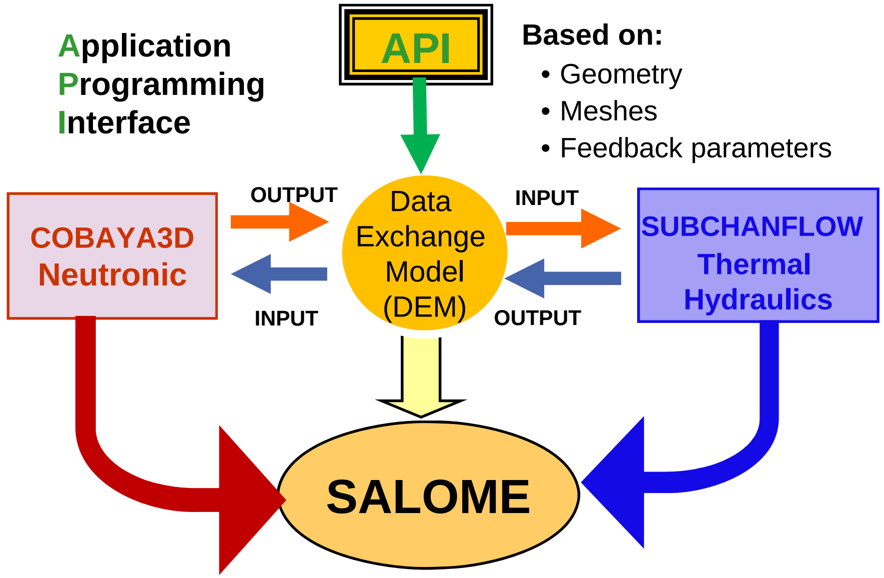
PWR Boron Dilution Transient

Actual Trend Multi-/scale -physics ①

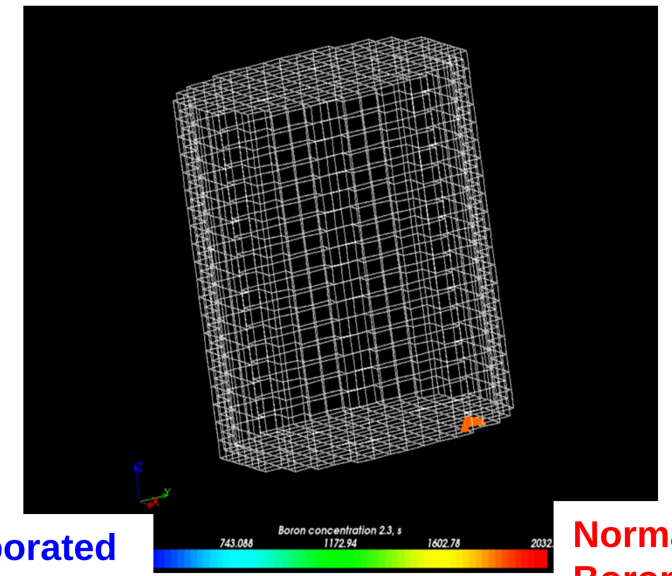
➡ local FA or even pin data

- Mesh super-position at FA level with pin-power- reconstruction
- Demanding High Performance Computing (HPC) and parallelization





NURESIM- Platform: Code coupling Strategy



Unborated Slug

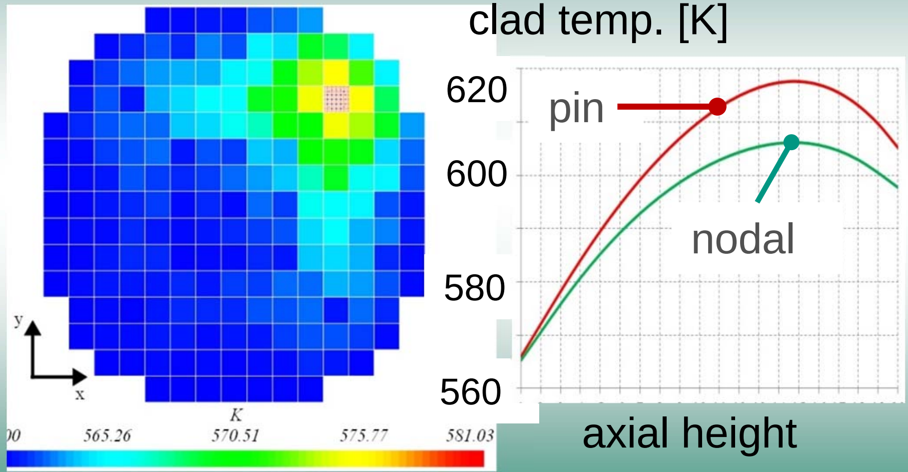
Normal Boron Conc.

Design basis -safety

- **Actual Trend: Multiphysics and multiscale problems**

1 - 2

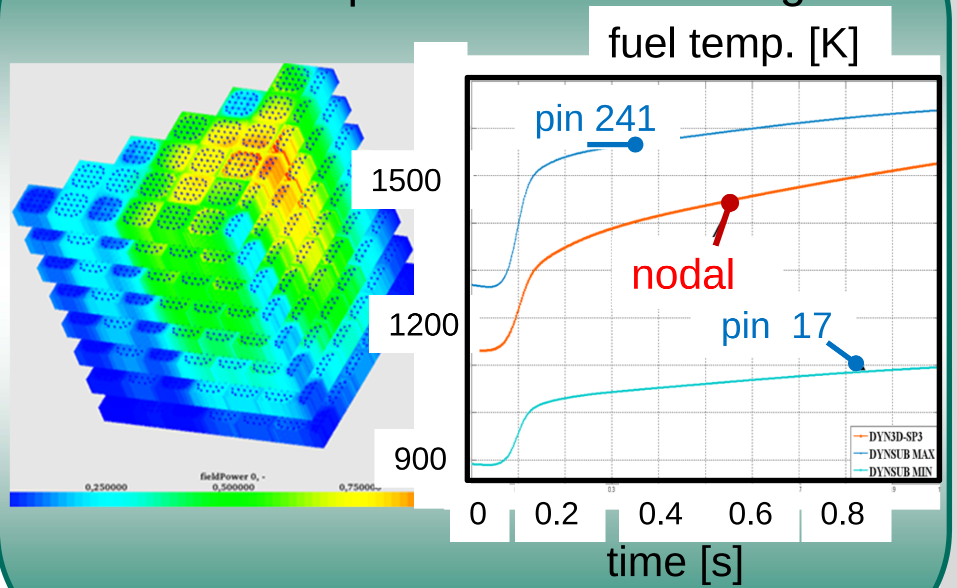
Hybrid schemes
- Nodal in most of core
- Local pin resolution



Predicted Nodal/cell power

2

Pin resolution
➡ computational demanding



Next steps underway ➡ tracking **each** neutron ➡ **Monte Carlo methods**

Beyond design basis -safety

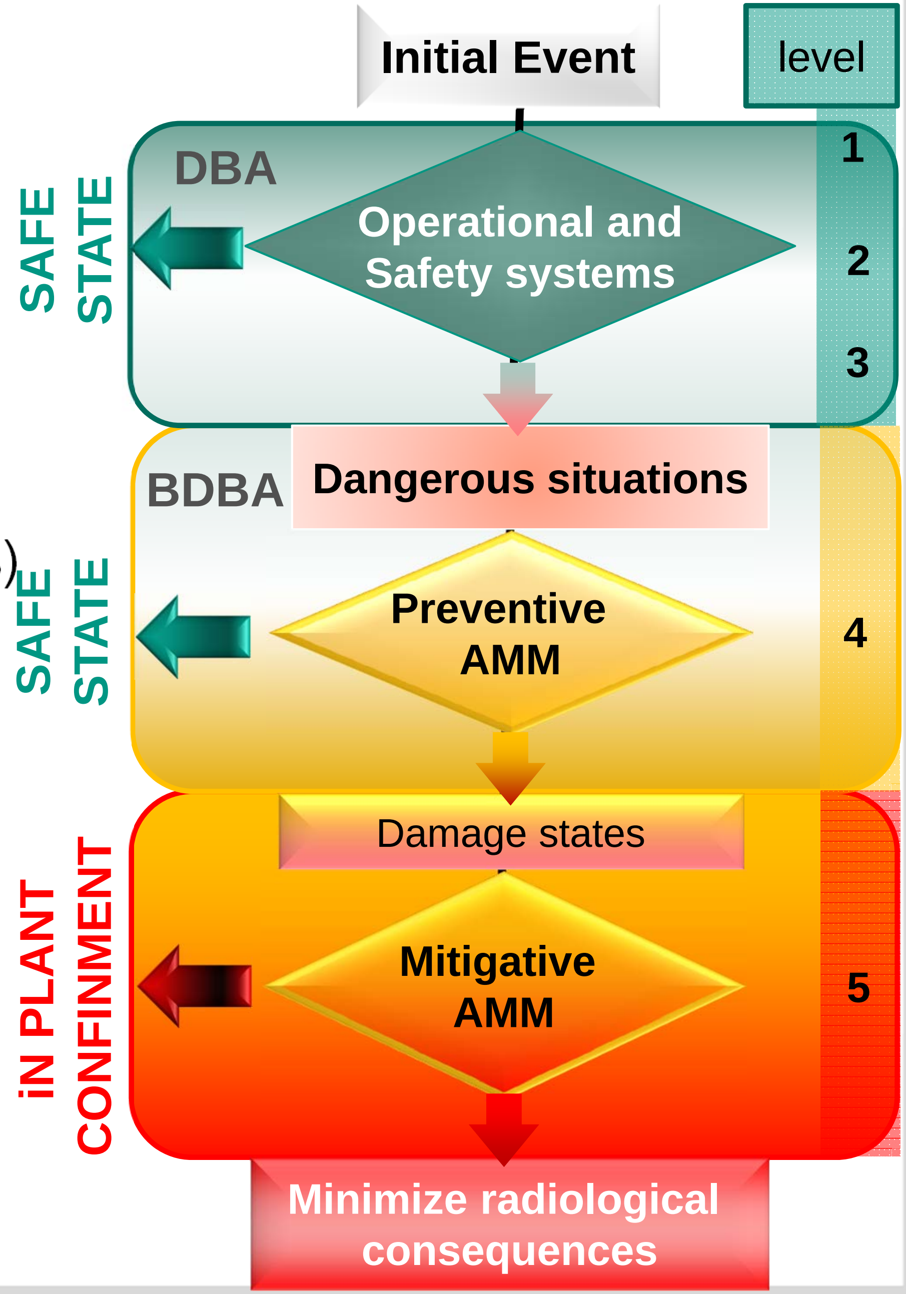
- Integral part of Gen-III reactor design

What to be avoided ?

- Fukushima (➡radiolog. consequences)

Design options

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



AMM=Accident management measures

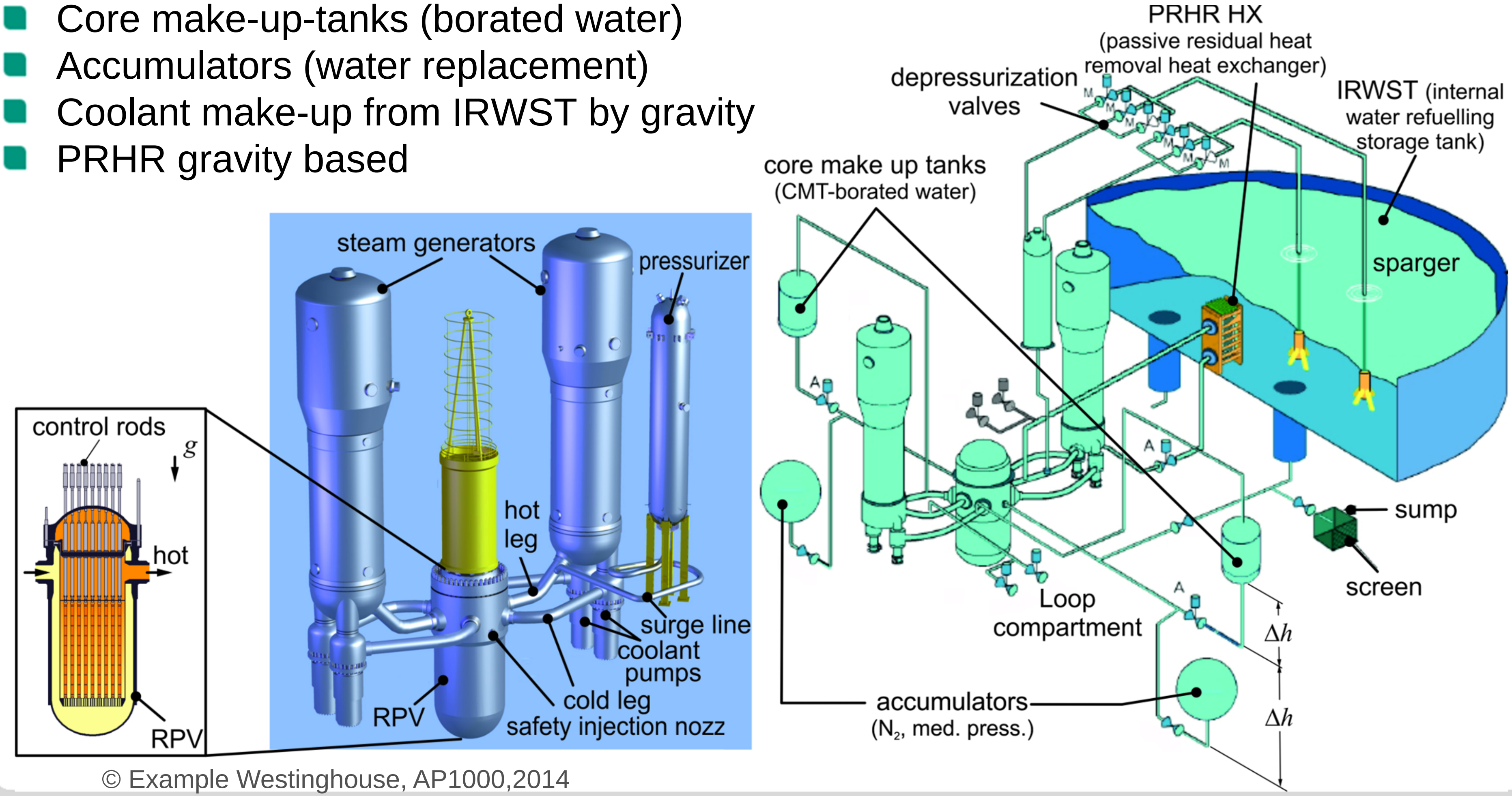
Standard NPP Safety Systems- Gen II

Control

- Control rods
- Borated water

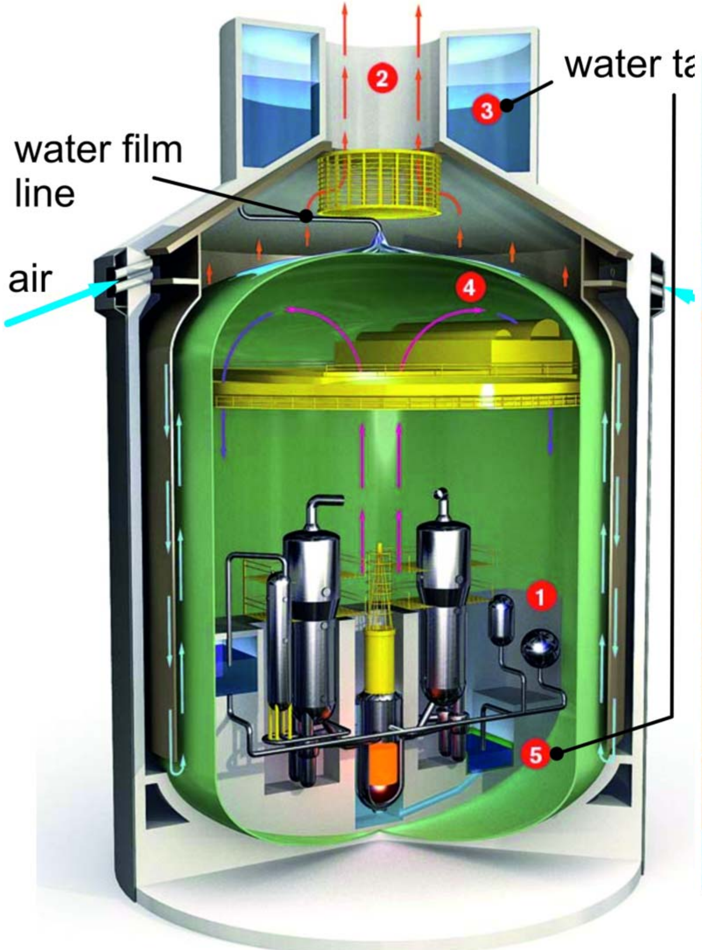
Purely passive and safety related Emergency core cooling systems (ECCS)

- Core make-up-tanks (borated water)
- Accumulators (water replacement)
- Coolant make-up from IRWST by gravity
- PRHR gravity based

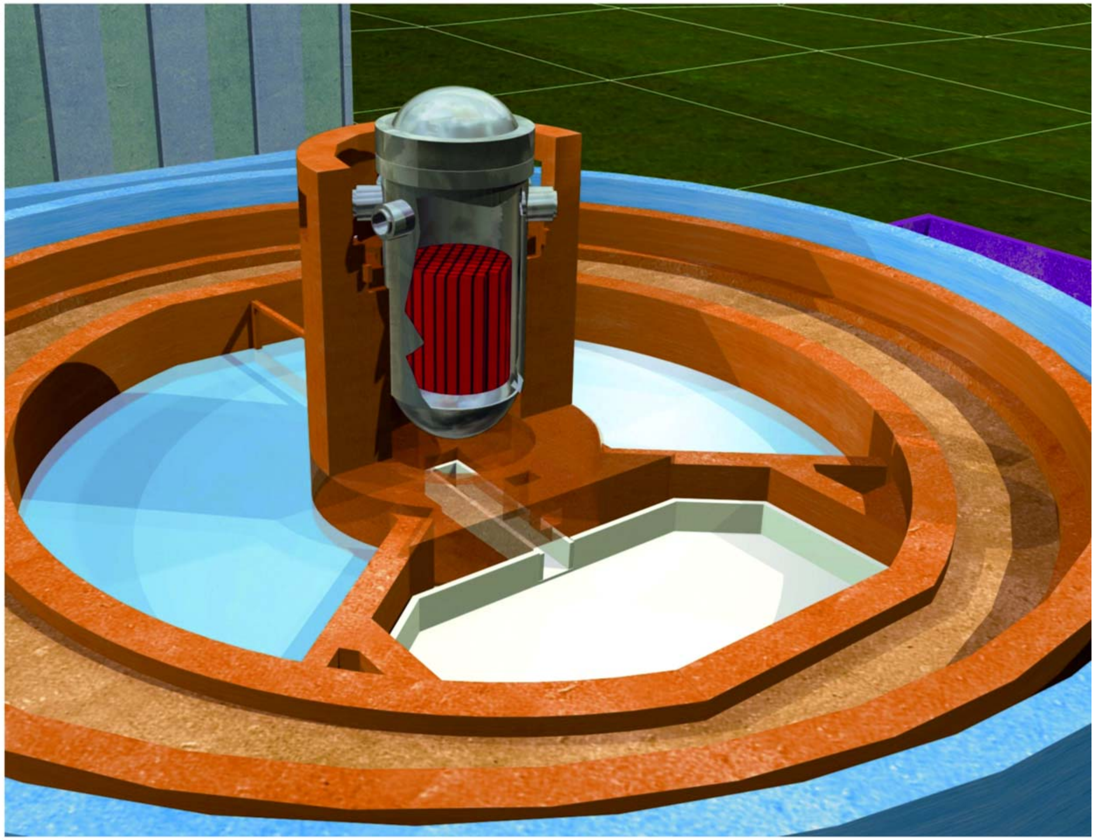


Evolutionary Safety Systems- Gen III

- Several severe accident strategies
- In-vessel retention
- ex-vessel by means of „core catcher"



© Westinghouse, AP1000,2012

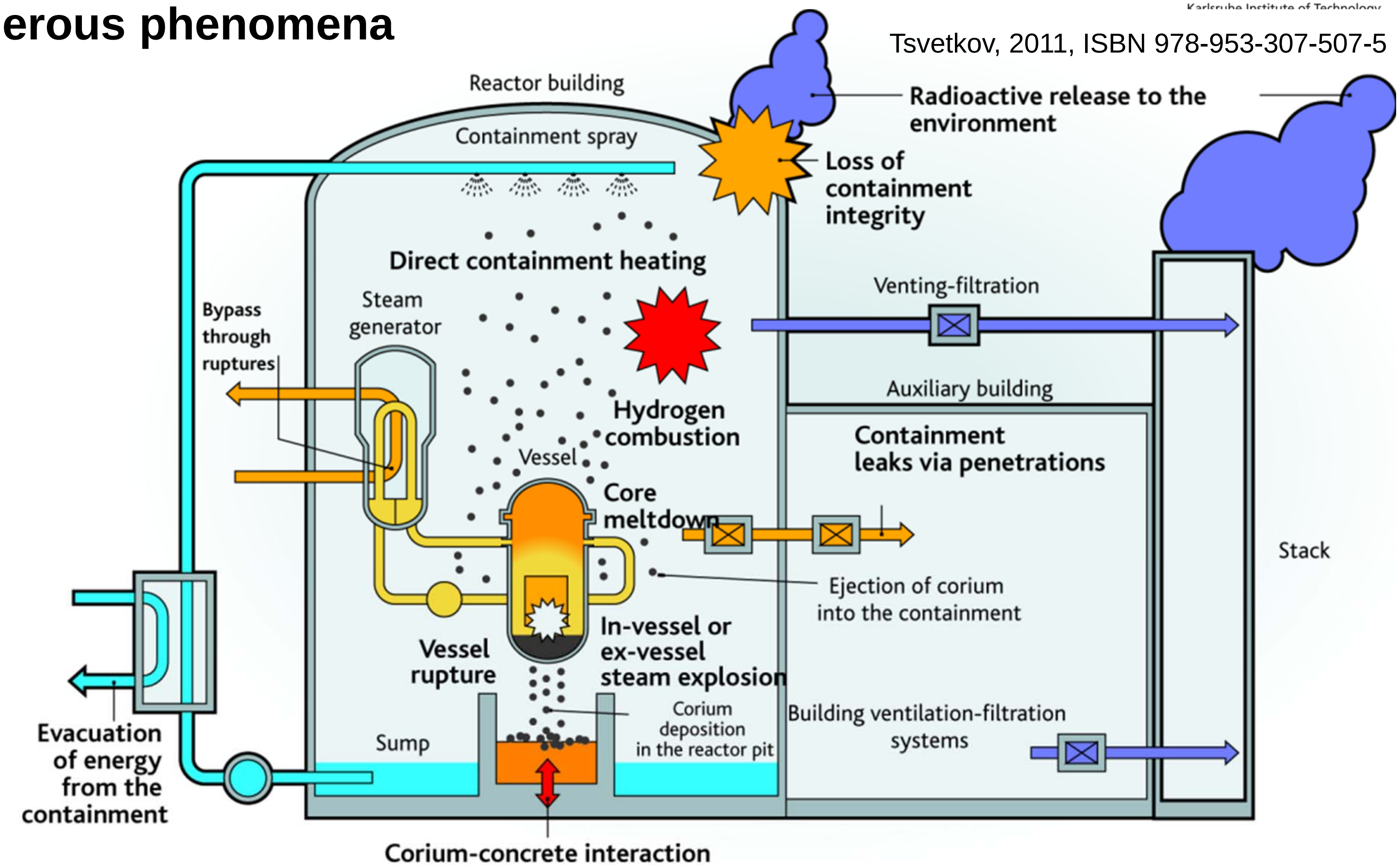


© AREVA-NP,2011

Beyond design basis –safety –Severe accidents

- **Numerous phenomena**

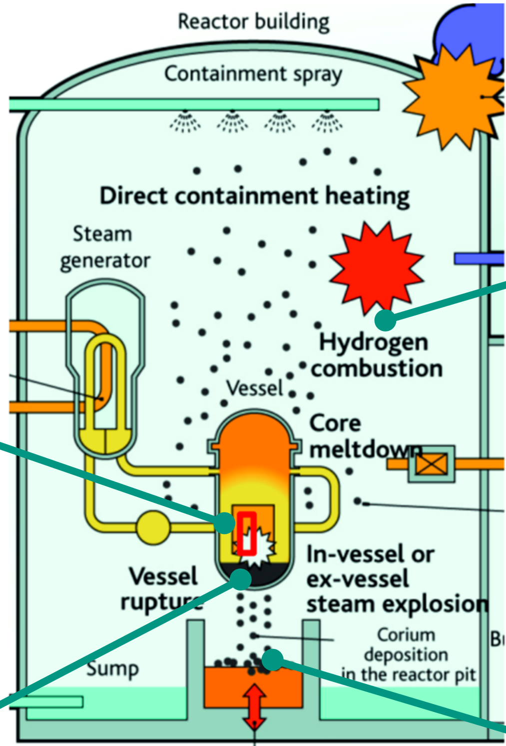
Tsvetkov, 2011, ISBN 978-953-307-507-5



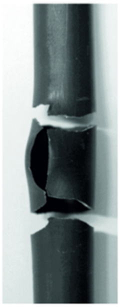
- **Subject of international cooperations and networks**

Goal: reliable physics description ➡ predictive tool development

Beyond design basis –safety –Severe accidents



Hydrogen generation mechanisms

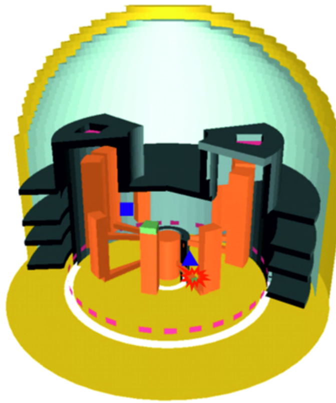


clad melt @ reflodding

hydrogen induced clad rupture

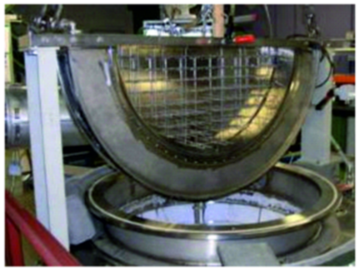
QUENCH prog. @KIT

Hydrogen distribution in large containments



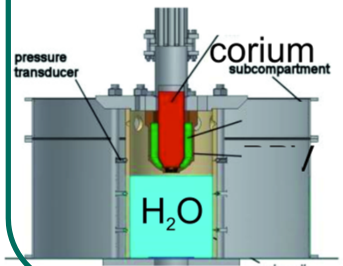
hydrogen safety @KIT

Behavior of core melt in lower plenum



LIVE prog. @KIT

ex-vessel Molten Core Concrete interaction



- behavior in reactor pit
- direct containment heating

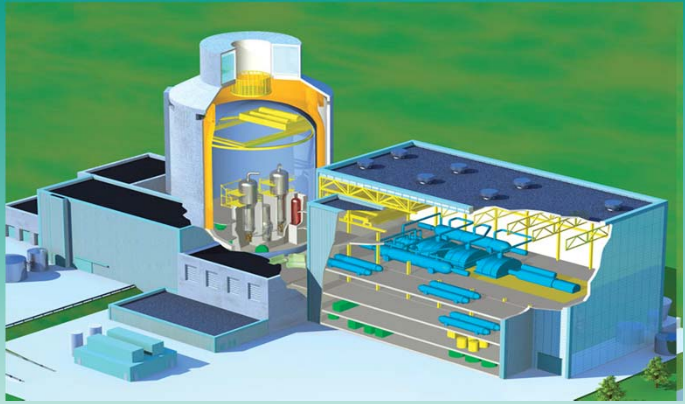
DISCO prog. @KIT

- scale demonstration
- concrete sensititvity

MOCKA prog. @KIT

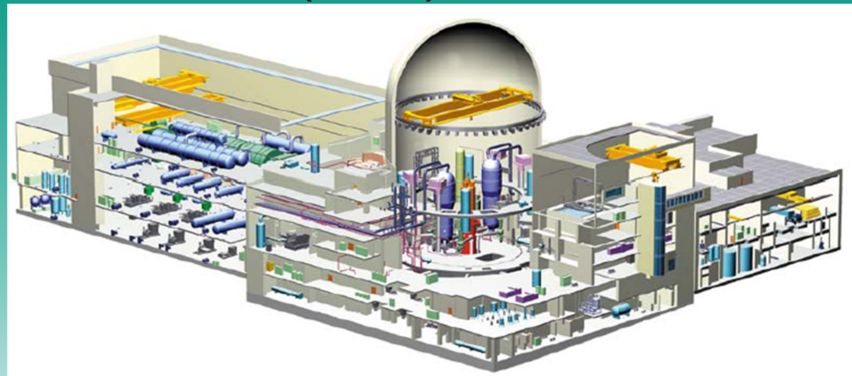
Large Gen-III Reactors currently deployed (PWR)

AP 1000 (Westinghouse –Toshiba)



- 2 SG, 4 Pumps, 1100MWe
- Compact core Passive safety features
- China, US

APR 1400 (Korea)

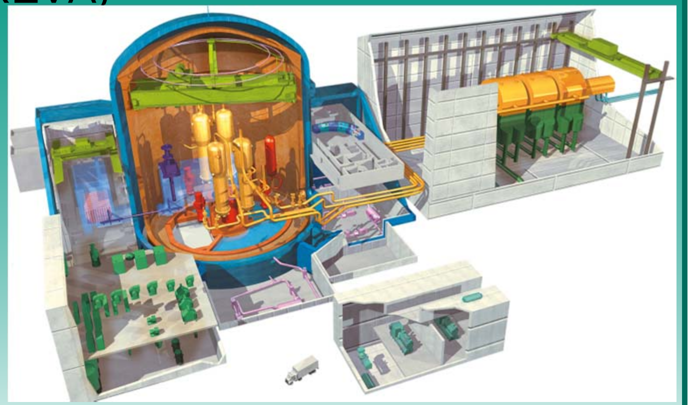


- 2 SG, 4 Pumps, 1400MWe
- 2 act. safety system, no high press. injection
- mixed severe accident strategy
- Korea , UAR

APWR 1000 (MHI)

- 4 SG, 4 Pumps, 24m fuel cycle,
- 1000MWe
- Instead safety diesels, gas turbine

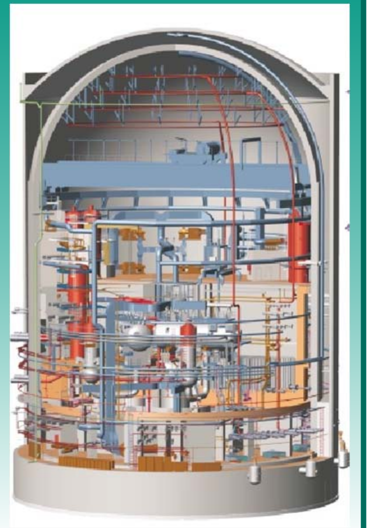
EPR (AREVA)



- 4 SG, 4 Pumps, large core , ->1600MWe
- Core catcher, 24m fuel cycle, CDR10^{-7}/y
- FIN, FRA, VRC

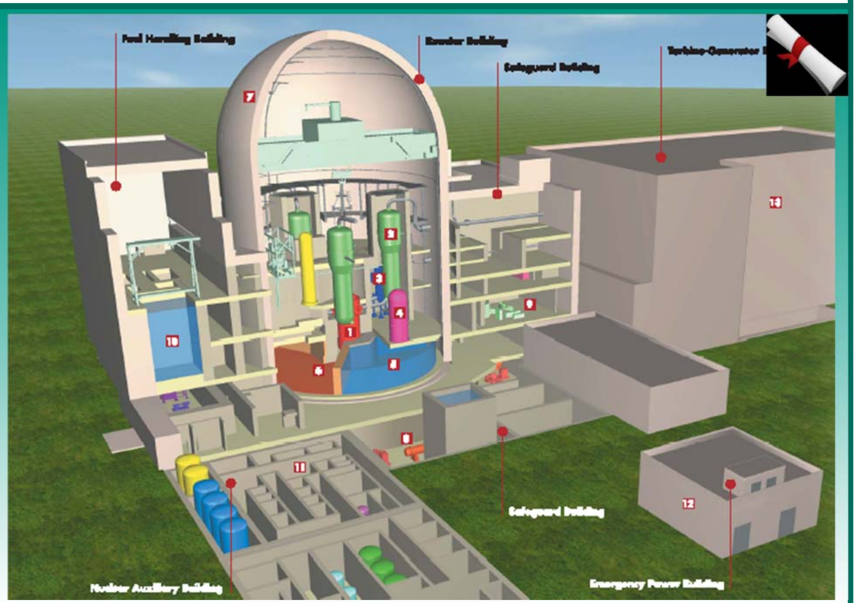
Large Gen-III Reactors currently deployed (PWR)

AES (Russia)



- 4 SG, 4 Pumps, 1070MWe, Horizontal HEX,
- Passive safety features, Core catcher, soda injection system
- BUL, RUS

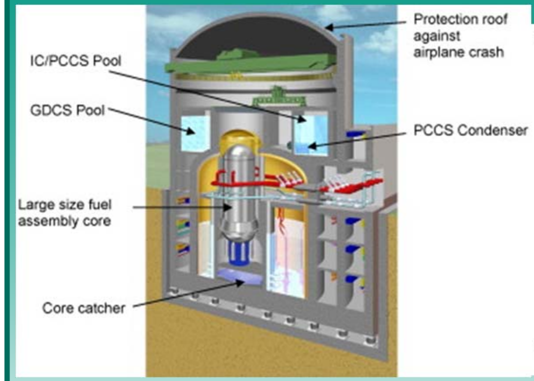
ATMEA (MHI-AREVA)

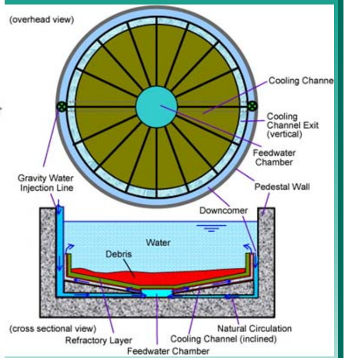


- 3 loop, 1150MWe,
- 3-safety trains
- 2 stage accumulator,
- heavy airplane crash design
- 100% MOX fuelling possible,
- 24m fuel cycle
- interests but no built

Large Gen-III Reactors currently deployed (BWR)

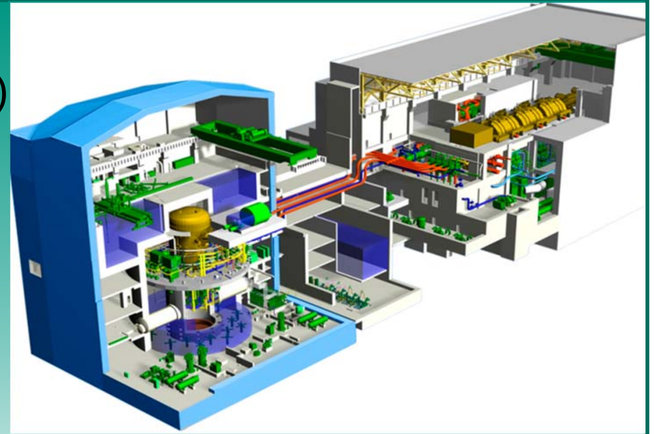
AB 1600 (Toshiba)





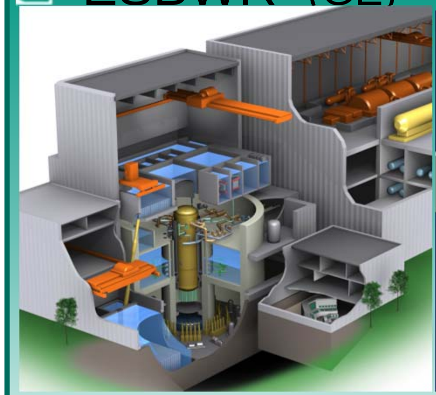
- PCCS (passive containment cooling system)
- GDCS, (gravity based core cooling system).
- Core catcher
- in licensing

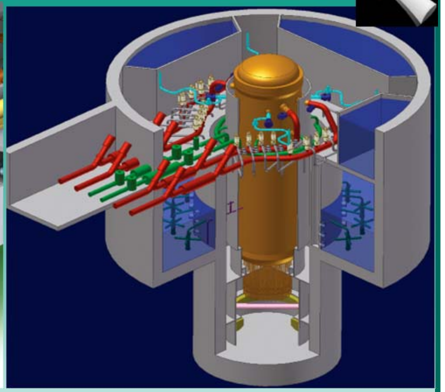
ABWR (Hitachi-GE)



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

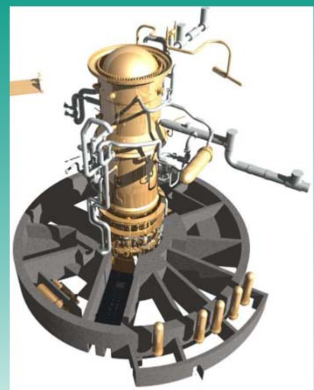
ESBWR (GE)

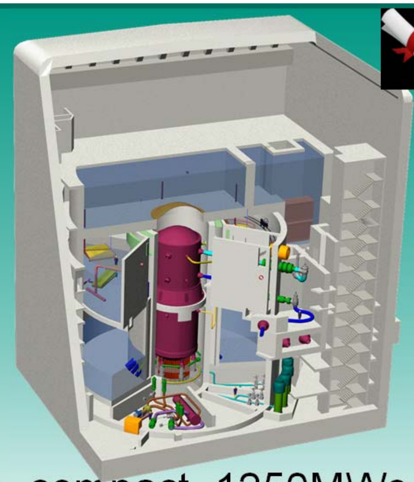




- 4 passive safety trains (nat. circulation)
- 1500MWe, CDR CDR <10^{-8}/y
- licensed in US, no current projects

Kerena (AREVA)

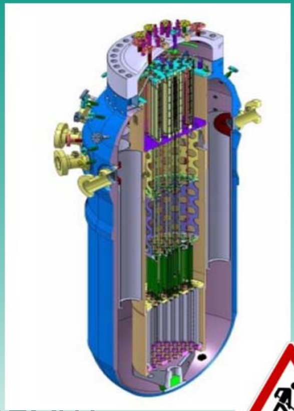




- all passive safety sytem, compact, 1250MWe
- flexible operation, designed for severe acc.
- Airplane crash resistant , no current projects

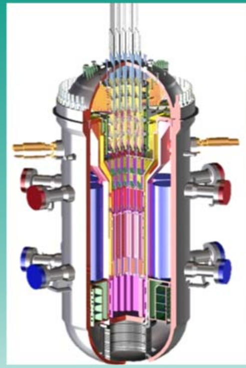
SMR operating/ under development (water cooled)

CAREM-25
PWR



- 87MWe
- primary system in vessel

SMART
Korea, Republic of



- 100MWe
- primary system in vessel
- passive DHR

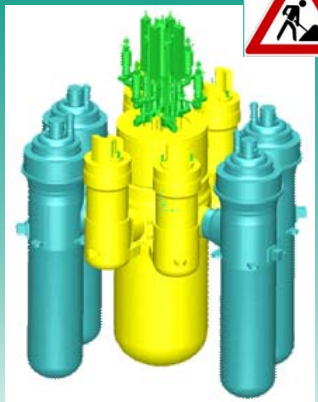
NuScale
PWR

- 45MWe
- nat. circ. cooled
- DHR via containment

mPower
PWR

- 180MWe
- low power density
- 48m fuel cycle
- Passive safety no diesels necess.

KLT-40s
PWR



- 70MWe
- 2 units constructed

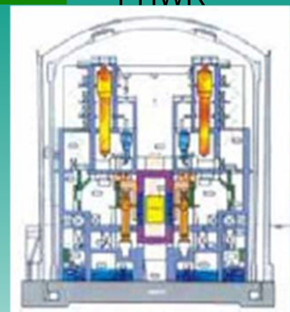
CNP-300
PWR

- 300MWe
- 2 loop system
- 3 plant operating
- 2 in construction

WWER-300
PWR

- 300MWe
- In-vessel core catcher

PHWR-family
PHWR



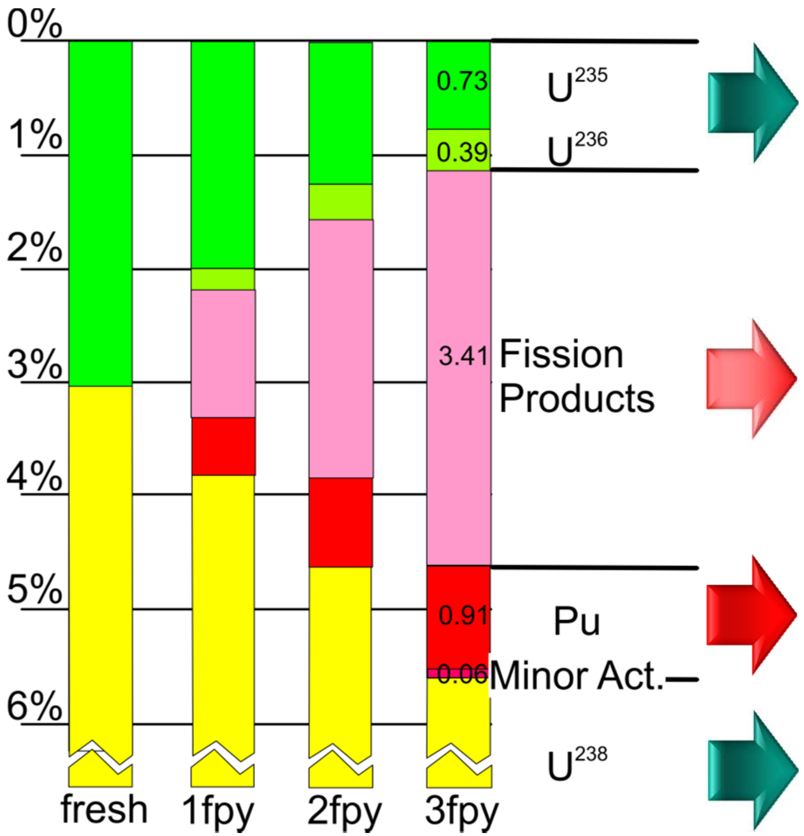
- 220-540MWe
- 2 –loop design
- Classic safety des.
- 16 operating plants

Nuclear Waste

Nuclear is a generation contract !!!! ➡ requiring accetance & 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

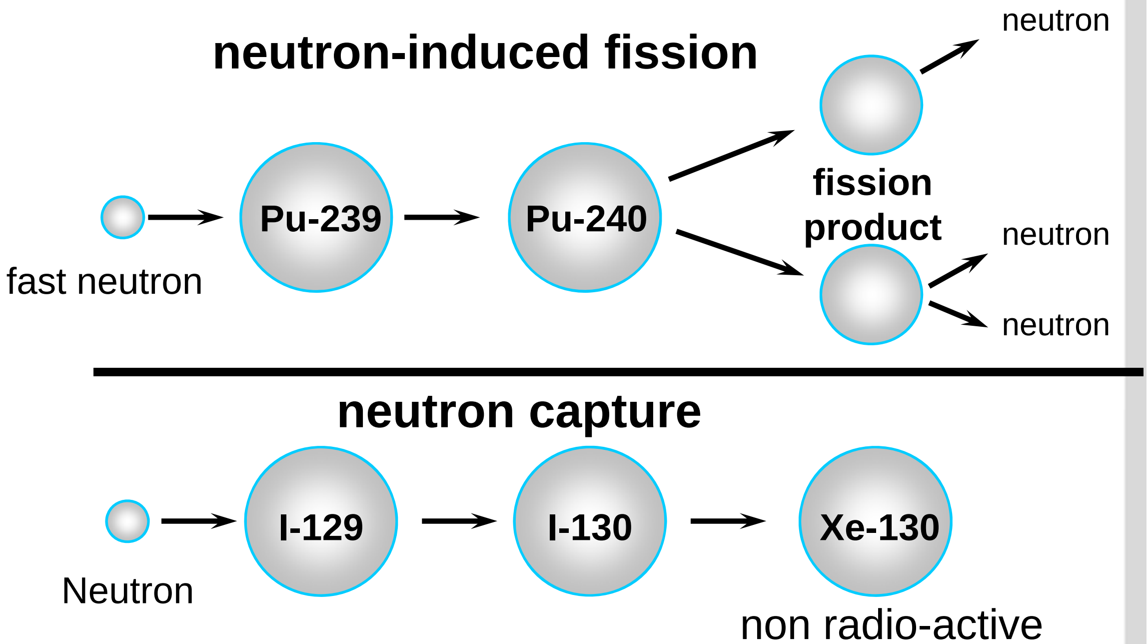
- Reprocessing, conditioning and transport mandatory

Options for subsequent treatment of radionuclides

- Disposal (geological w/o access, deep underground /near soil ,……)
- Transmutation

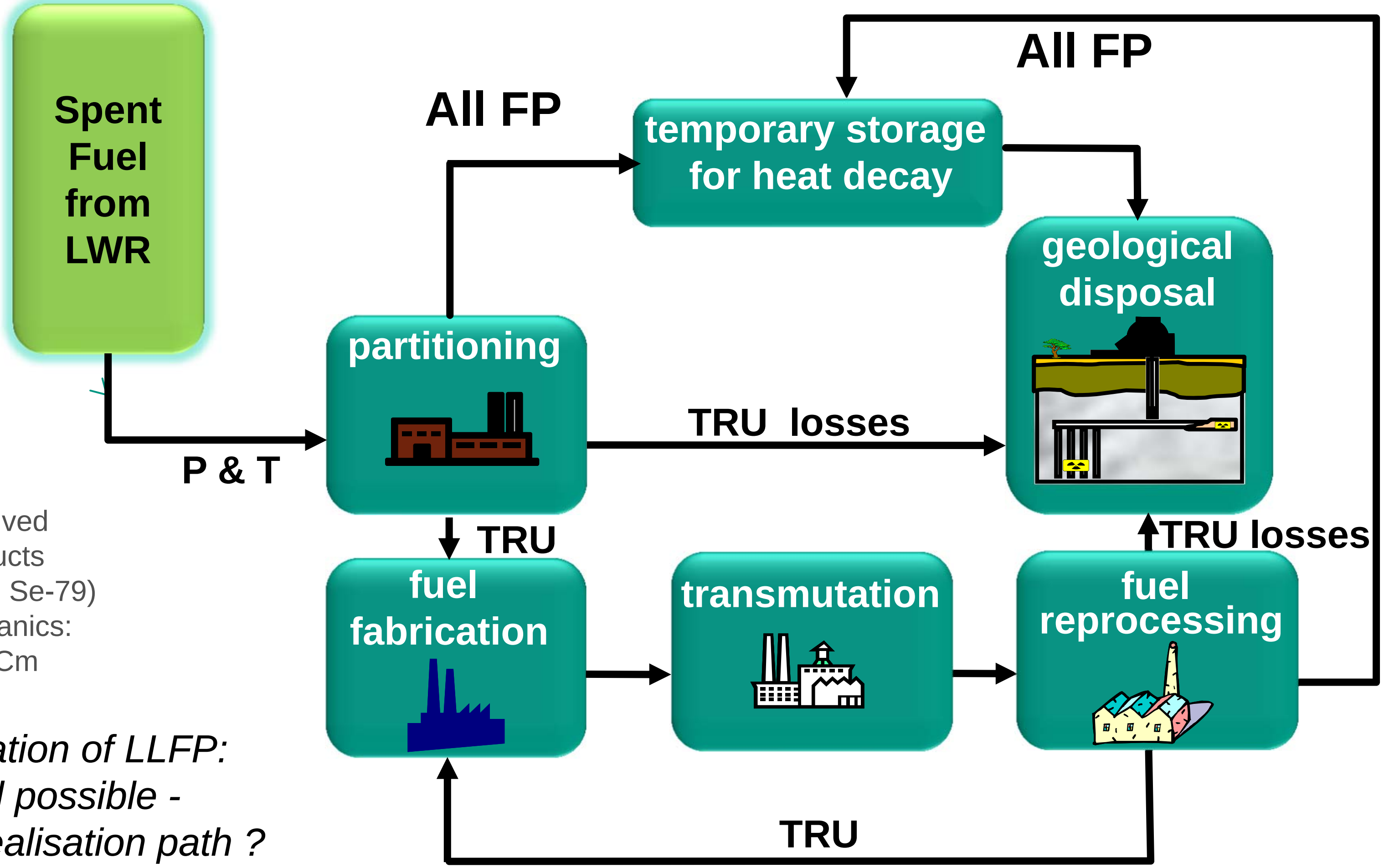
What is transmutation ?

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



Nuclear Waste -Transmutation

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



LLFP Long Lived Fission Products (Tc-99, I-129, Se-79)
TRU Transuranics: Pu, Np, Am, Cm

Transmutation of LLFP: theoretical possible - efficient realisation path ?

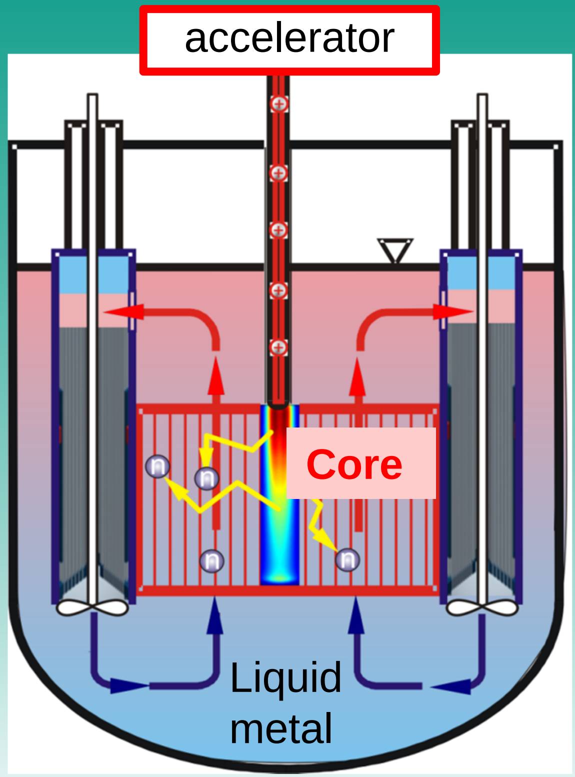
➡ **Final repository required but substantially smaller !**

Nuclear Waste -Transmutation

What type of fast neutron spectrum reactors ? –Two options

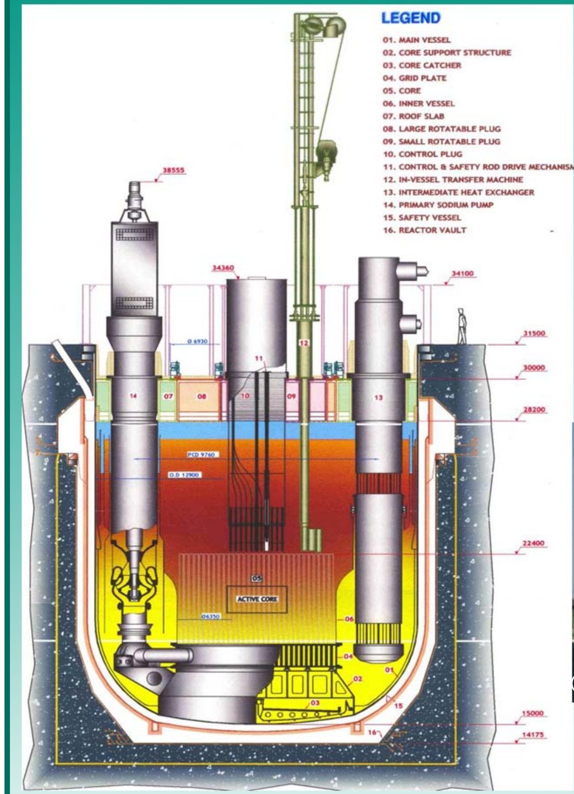
- **dependent on further nuclear utilization option !!!**

Accelerator Driven Systems



- Accelerator driven
- Sub-critical core ➡ simply burning

Fast reactors ➡ Gen-IV



© images pravasi today,2014

- breeding ➡ fissile regneration but also
- Burning ➡ transmutation of minor actinides
- critical core - different safety features (!)

International contributions to Generation IV

Strategic aims:

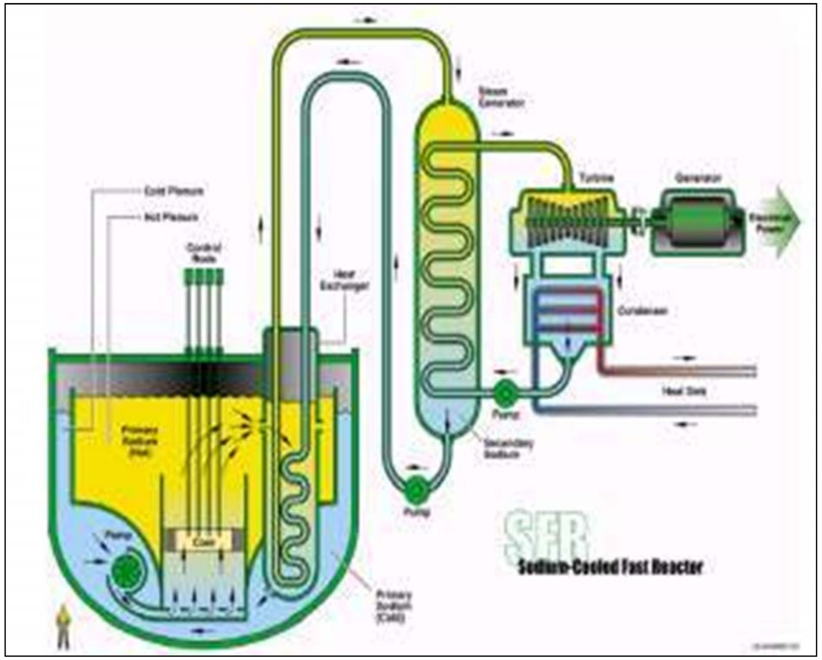
- development of new NPP by 2030 in internat. cooperation
- multifunctionality (electricity, desalination, hydrogen, heat)

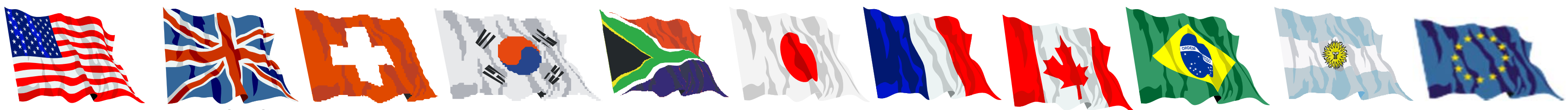
Technologic aims

- better economics
- improved sustainability
- increased safety
- enlarged proliferation resistance

Status

- continuous worldwide cooperation
- 6 dedicated concepts
- elaboration of standards





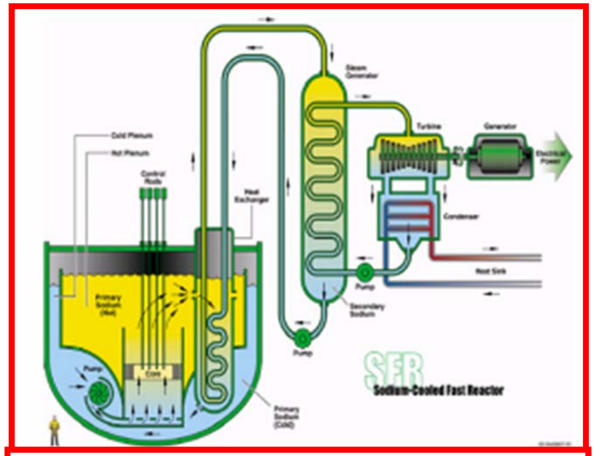
U.S.A. | United Kingdom | Switzerland | South Korea | South Africa | Japan | France | Canada | Brazil | Argentina | European Union

+China, Russia since 2006!

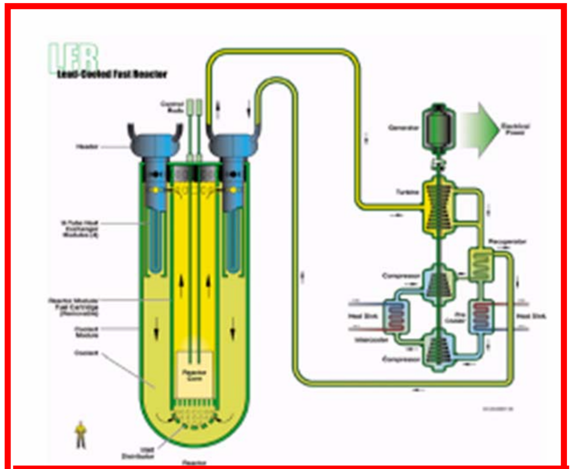
Gernmany ? –through EU

Generation IV Forum: selection of six nuclear systems

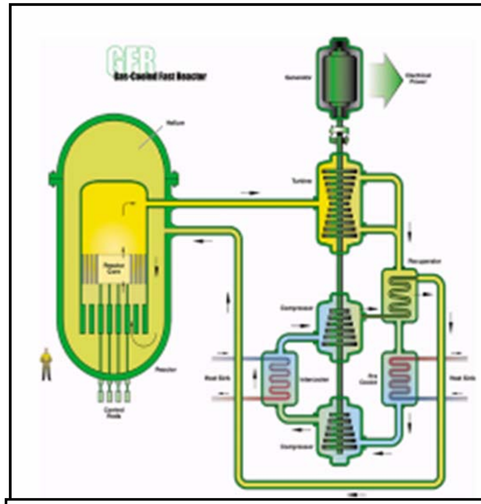
Karlsruhe Institute of Technology



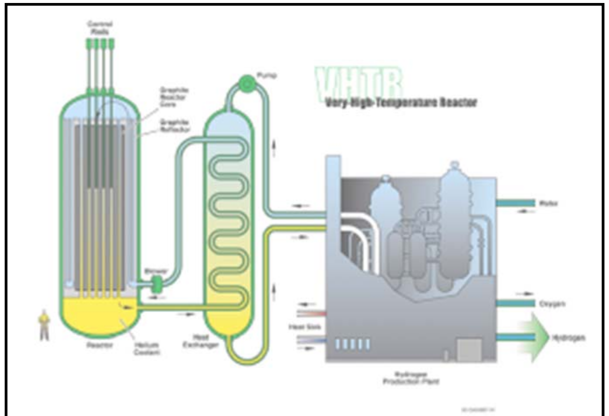
sodium-cooled fast Reactor



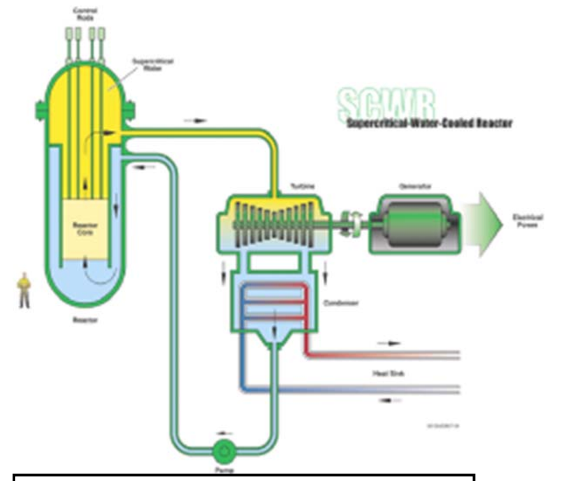
Lead-cooled Fast Reactor



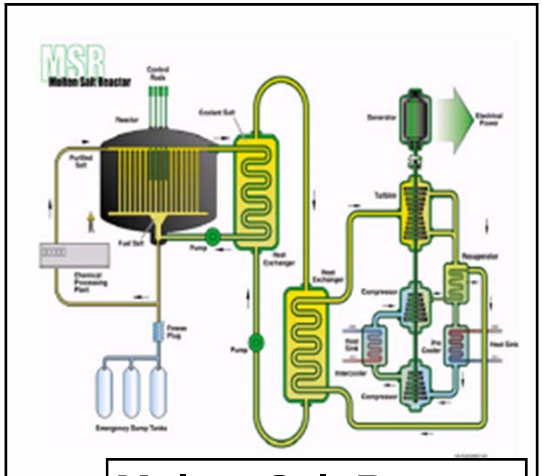
Gas-cooled Fast Reactor



Very High Temperature Reactor



Supercritical Water-cooled Reactor



Molten Salt Reactor

Summary and perspective

- fission energy fission **substantial part** of worldwide energy production.
- mostly generated by Gen –II NPP systems
- **fission pursued worldwide** in numerous industrial countries
- current deployment 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 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 assessement capability**.