ELSMOR

Towards European Licensing of Small Modular Reactors

Advanced and innovative safety features of LW-SMRs

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- Systems for
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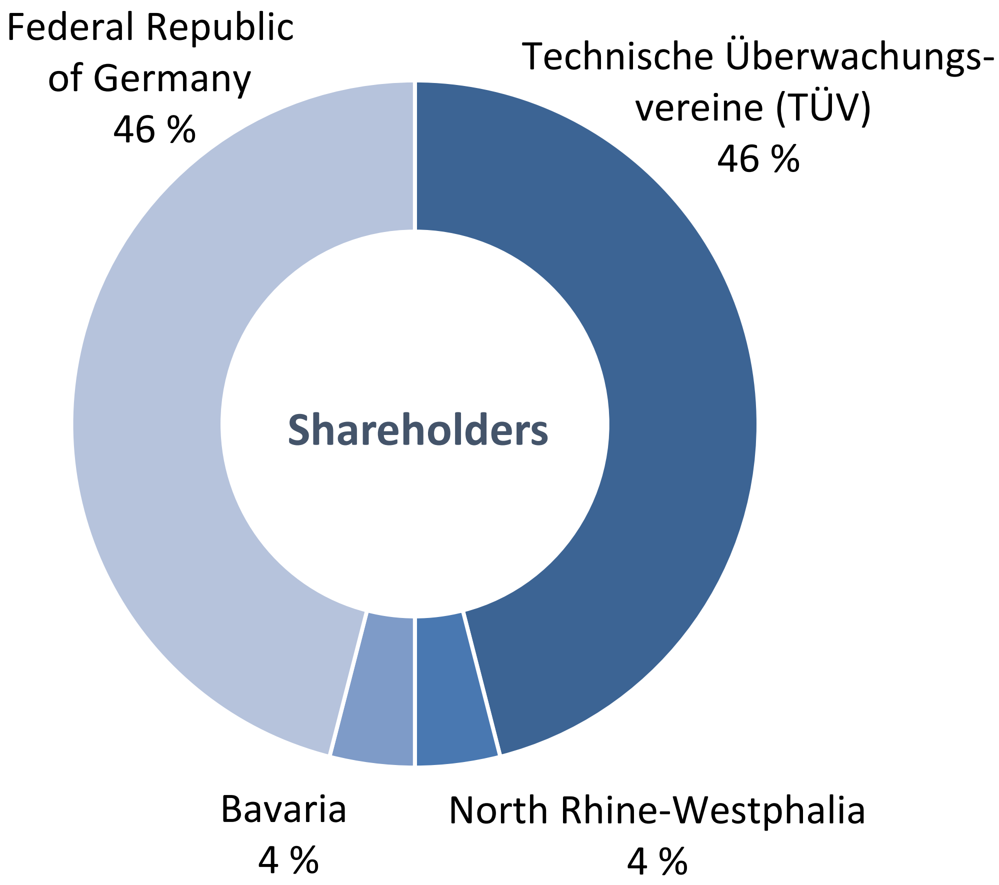
Overview GRS

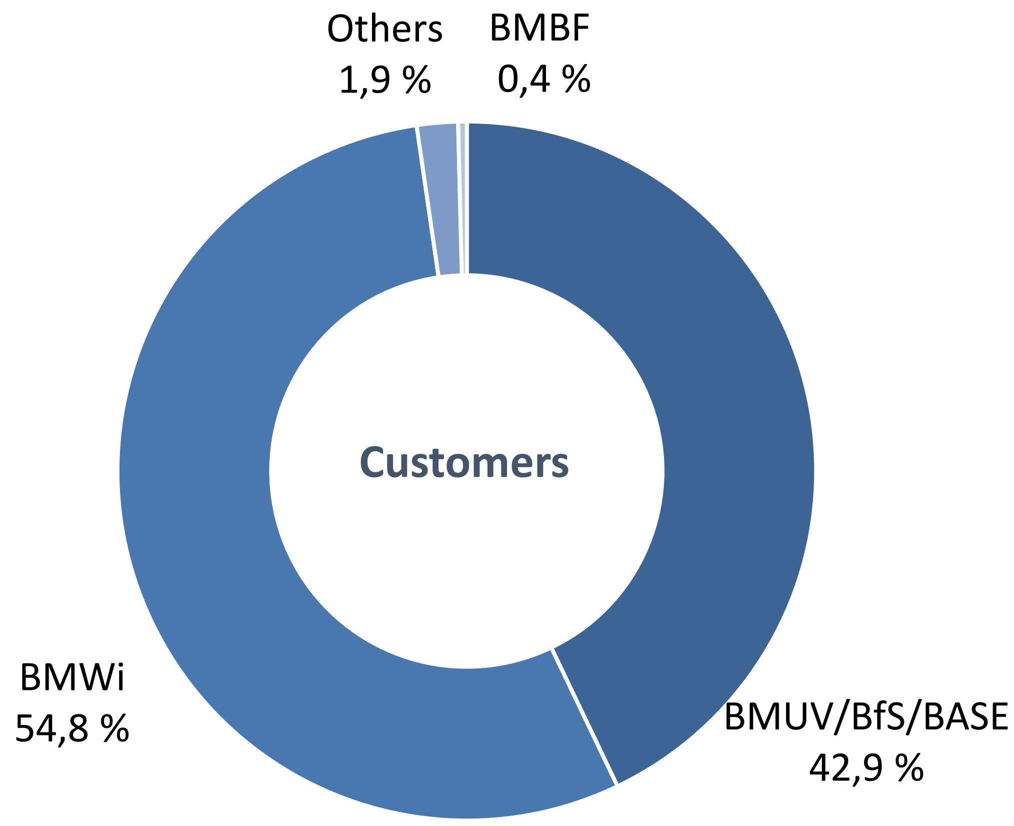
GRS – Company and Stakeholders

- Germany's central expert organisation in the field of nuclear safety since 1977
- Non-profit and independent research organisation
- German Technical Safety Organisation (TSO) and member of European Technical Safety Organisations Network (ETSON)



GRS – Customers

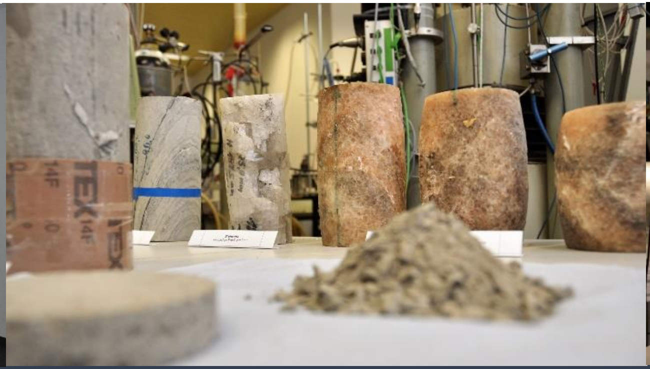
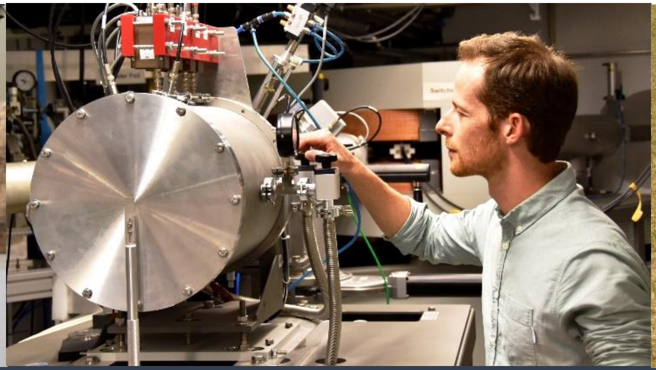
- Main customers are Ministries (e.g. Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection) and Federal Offices (e.g. Federal Office for Safety of Nuclear Waste Management)
- International: European Commission, nuclear regulatory authorities of various countries
- Annual volume of orders around 53 Mio. € (2020)



GRS – Competencies

We carry out research and developent and provide expert advice to authorities in the fields of:

- Reactor safety
- Storage and final disposal of radioactive waste
- Decommissioning & Dismantling
- Physical protection
- Radiation protection
- Environment & Energy


General Overview

General Overview

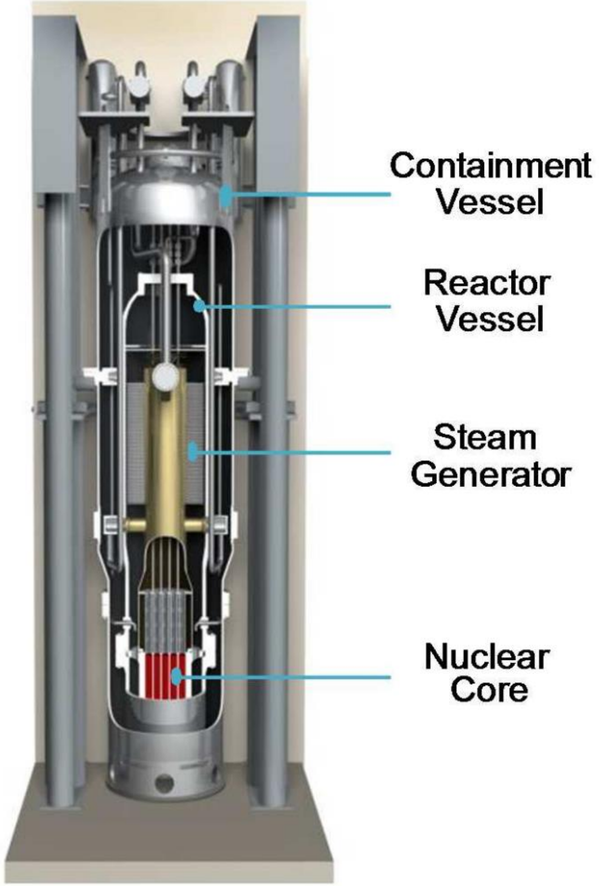
- Cost reduction driving force for
  - Smaller reactors
  - Simplification of the designs
- Protection against ionising radiation
  - Reactivity control
  - Cooling of the core
  - Confinement of radioactive material

- Inherent safety features
- Passive safety features
- Other innovative features

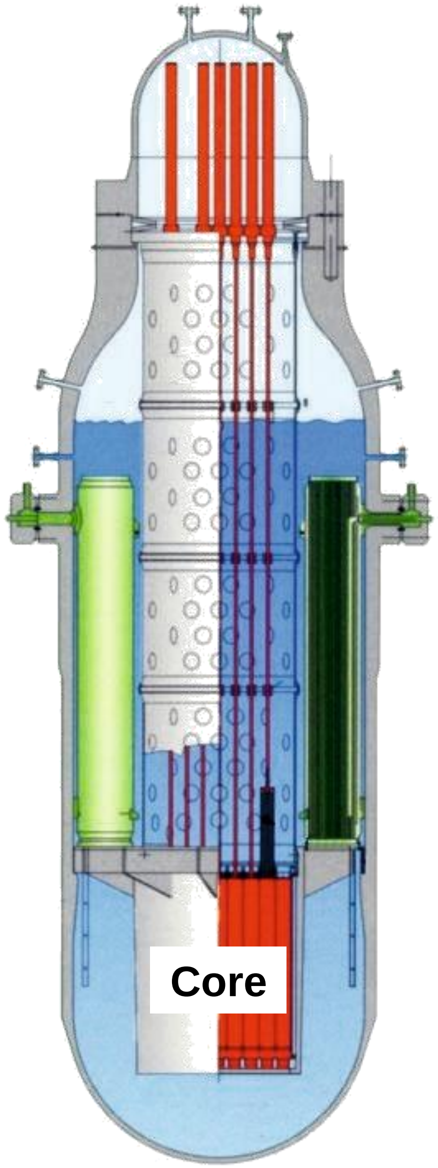
Inherent Safety Features

Inherent safety features - Core

- Low position of the core in the RPV
- Large water inventory above the core
  - Larger time during LOCA until core becomes dry
- Reliable, effective heat removal by
  - Reduced power density (- 25 % compared with current PWR)
  - Smaller distance between core and RPV wall
  - Larger surface to volume ratio



NuScale [1]



CAREM [2]

Inherent safety features - Core

- No dissolved boron in some designs (e.g. NUWARD, Rolls Royce SMR)
  - Elimination of deboration accident
  - Reactivity control by control rods and burnable absorbers only
    → Possible challenges for safety demonstration
    - Depletion of absorbers at end of cycle might lead to reactivity peaks
    - Prediction of depletion of heavy used control rods difficult
    - Quick depletion of common Ag-In-Cd control rods if inserted deep in the core
    - Heat conductivity and density of fuel changed if absorbers are integrated in the fuel
    - Higher effective rod worth of control rods in case of a REA

Inherent safety features - Core

- High burnups needed to reach long fuel cycles
  - Reached by heavy use of burnable absorbers and (in some designs) higher enriched fuels (> 5 %)
    → Proliferation issues

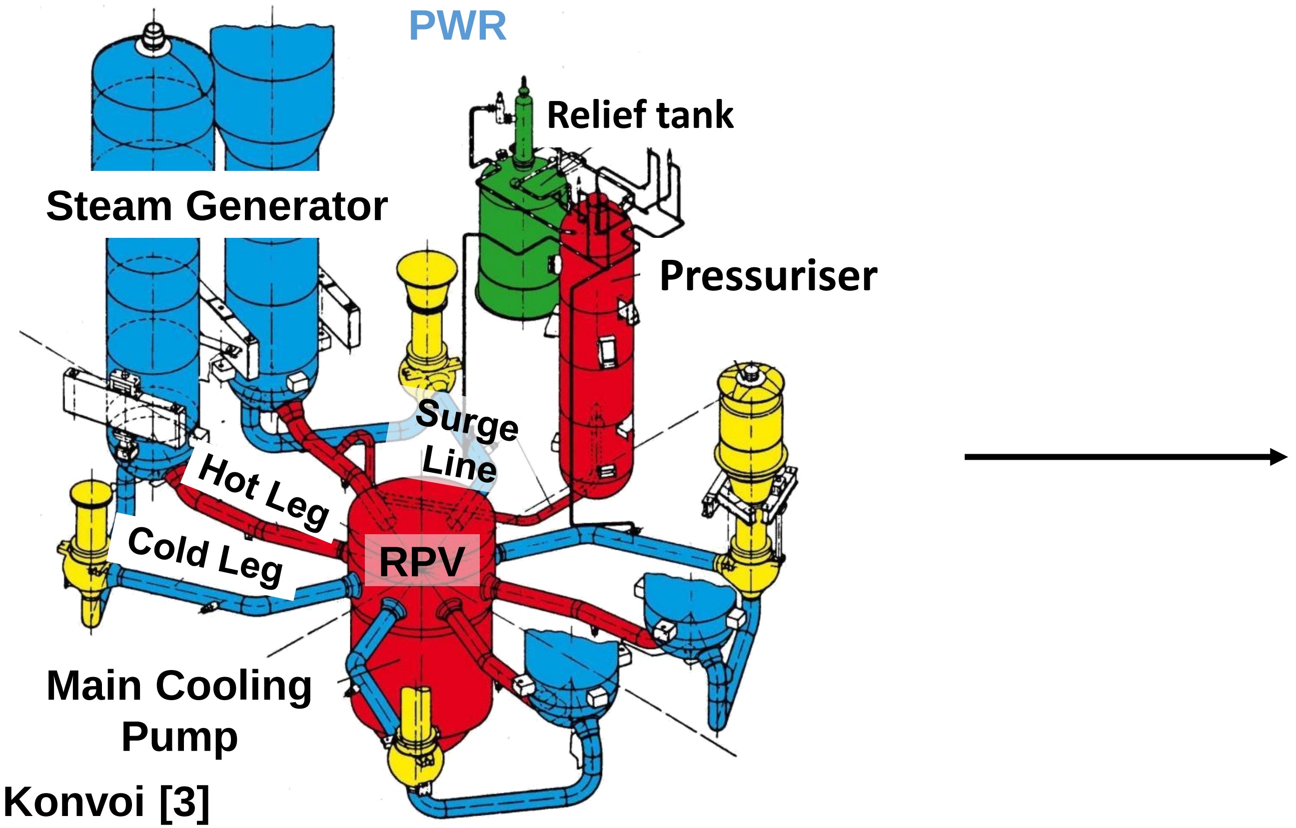
Name	Power $[MW_{th}]$	Boron Acid	Burnable Absorber	Planned FE-Cycle [M]	Planned Burnup $[MWd/kg_U]$	Power density [kW/l]	Enrich-ment
ACP100	385	x	x	24	< 52	?	< 4.95 %
ACPR50S	200	x	x	30	< 52	?	< 5.00 %
CAREM	100	x	x	18	24	?	3.1 %
KLT-40S	150	-	x	30 – 36	45.4	117.8	< 20 %
NuScale	160	x	x	24	30 – 50	?	< 4.95 %
RITM-200	175	?	?	54 – 84	68 – 51	?	~ 20 %
Rolls Royce SMR	1276	-	x	18 – 24	55 – 60	?	< 4.95 %
SMART	330	x	x	36	< 60	62.6	< 5.00 %
VBER-300	917	x	x	72	47	21.3	< 5.00 %
VK-300	750	-	x	72	41.4	?	4.00 %

Inherent safety features - Core

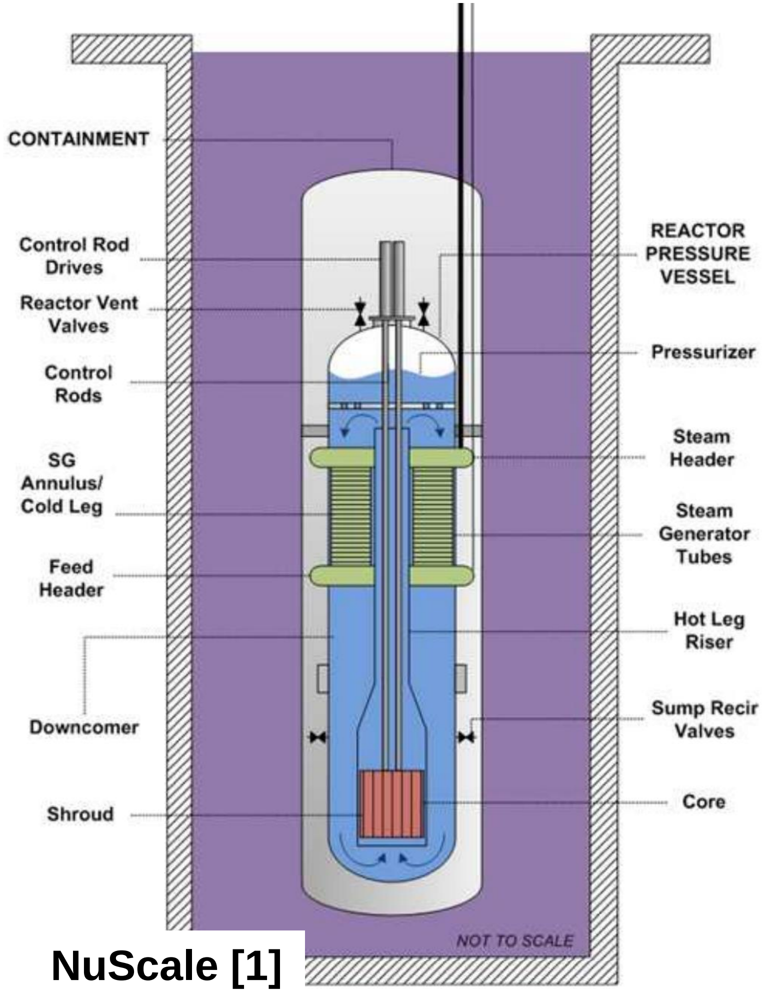
- Shorter cores (e.g. active height 4.2 m EPR, 2.0 m NuScale)
  - Correlations for critical heat flux depend on entry length
    → CHF might be less important
- Smaller cores (e.g. 241 FE in EPR → 37 FE in NuScale)
  - Higher leakage
    → Heavy reflector around the core necessary
    → Might affect validity of widely used diffusion approximation to neutron transport equation
- Use of accident tolerant fuel (ATF)
  - Potentially higher safety margins
  - Subject of active and ongoing research

Inherent safety features – Integral design

- Integration of all primary components into RPV



German Konvoi [3]



NuScale [1]

Inherent safety features – Integral design

- Integration of all primary components into RPV
  - Absence of large coolant pipes limits maximum possible LOCA size
    - Maximum break size PWR: DN800 → 1 m^2
    - Maximum break size CAREM: DN30 → 0.0014 m^2
  - Minimisation of number of connected pipes on RPV
  - Connection nozzles above core
  - High and narrow RPV → good for natural circulation
  - Integration of control rod drive mechanisms (CRDM) practically eliminates rod ejection accident due to lower pressure difference

Passive Safety Features

Passive safety systems

General

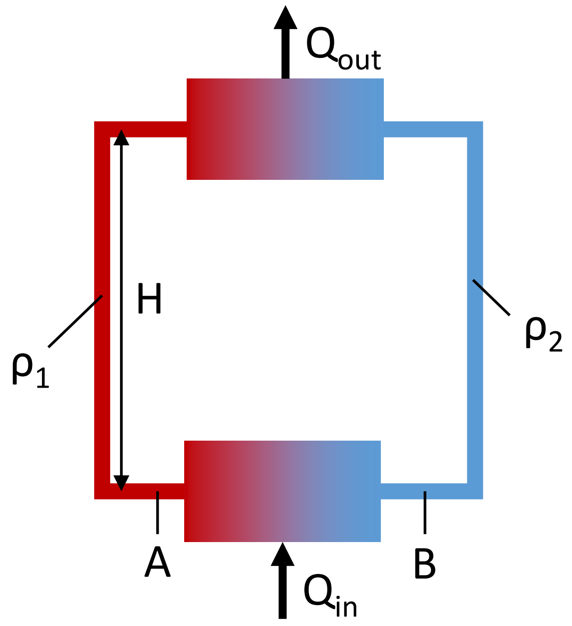
- No external power needed
- Based on small driving forces
  - Convection
  - Evaporation/condensation
  - Gravity
- Classification depends on national regulatory practice

Definition	Category			
IAEA	A	B	C	D
Moving fluid	-	x	x	x
Moving mechanical parts	-	-	x	x
Signals	-	-	-	x
External energy source	-	-	-	-
German Regulations	Passive system		Active system	

Passive safety systems

Natural circulation

- Both vertical pipes filled with fluids of different densities → one column heavier than the other
- Equalisation by flow of heavy media to lighter column
- No equalisation, if heat is added and removed
  - Steady flow
  - Heat source must be below heat sink
  - Pressure difference Δp drives the flow

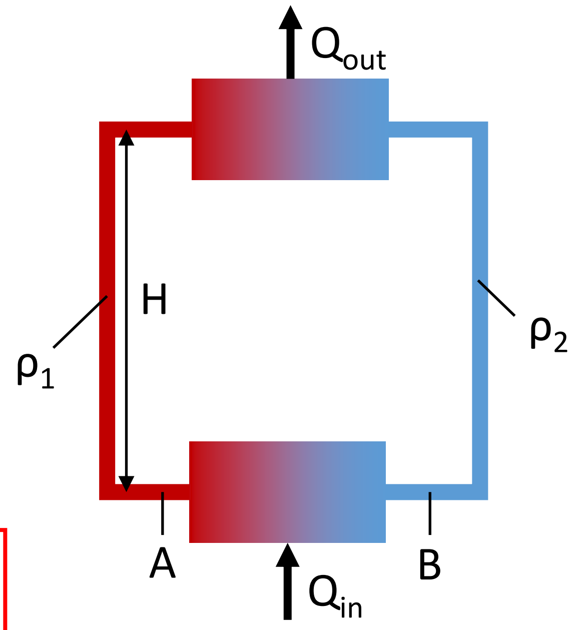


$$\Delta p = p_B - p_A = (\rho_2 - \rho_1) g H$$

Passive safety systems

Natural circulation

- Enhanced, if coolant is evaporated ($\rho_1 << \rho_2$)
- Balance of flow by pressure losses
  - Friction losses (on pipes, etc.)
  - Form losses
    - Bends
    - Flow path expansions/restriction
    - Valves
    - Blends
    - …



$$\Delta p = p_B - p_A = (\rho_2 - \rho_1) g H$$

$$\left(\lambda \frac{L}{D} + \sum \zeta\right) \frac{\rho}{2} v^2 = (\rho_2 - \rho_1) g H$$

$$v \approx \sqrt{\frac{2(\rho_2 - \rho_1) g H}{\left(\lambda \frac{L}{D} + \sum \zeta\right) \rho}}$$

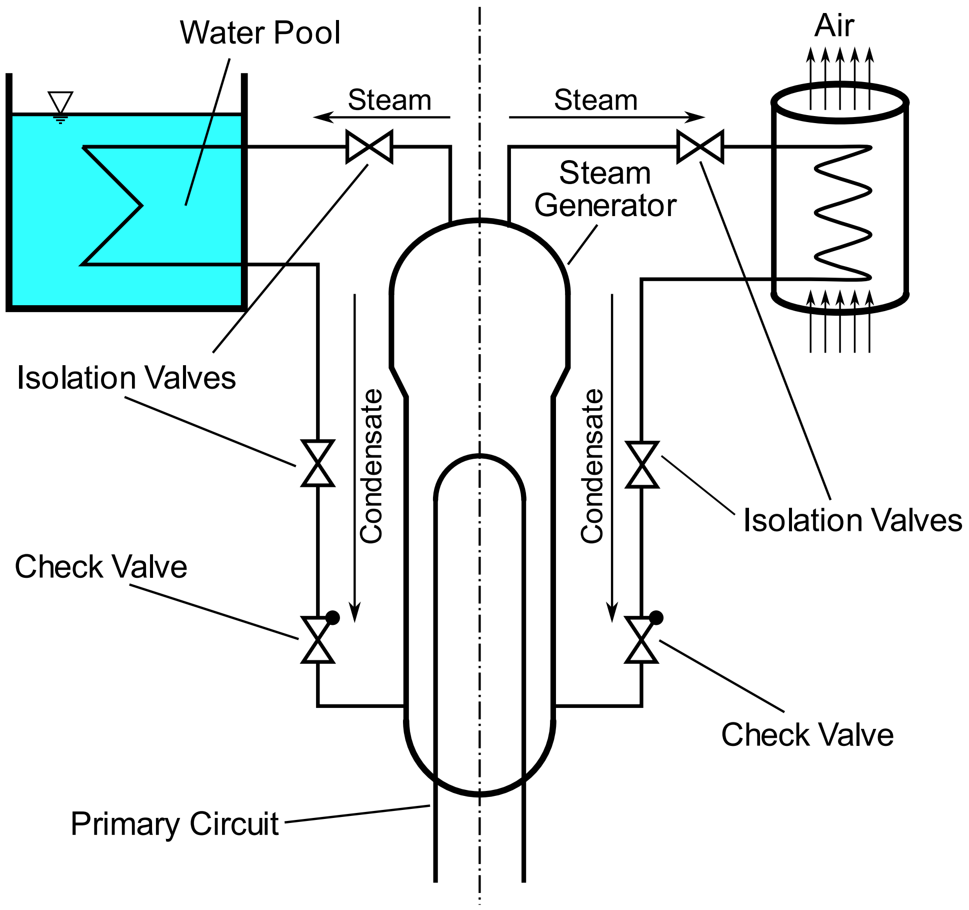
Passive safety systems

- Safety demonstration can be challenging
  - Small driving forces with high uncertainties
  - Small changes in boundary conditions can influence the system behaviour
  - Non-linear characteristics can lead to several distinct operating regimes depending also on overall plant feedbacks
  - Testing under plant conditions needed but difficult sometimes
  - Non-condensable gases affect heat transfer
  - Model uncertainties in evidence tools (simulation codes)
  - Lack of high-precision models (e.g. pressure losses, heat transfer) in simulation
  - Too efficient operating regimes can be as problematic as ineffective one (e.g. a subcooling transient)

Residual Heat Removal

Residual heat removal

- Cooled by secondary side
  - Passively within water pool
    - ACPR50S, CAREM, IMR, IRIS, KLT-40S, NuScale, RITM-200, SMART, VBER-300, VK-300
  - Passively on air
    - IMR, mPower, NuScale, RITM-200
  - Actively by main heat sink
- Primary side
- Other active systems



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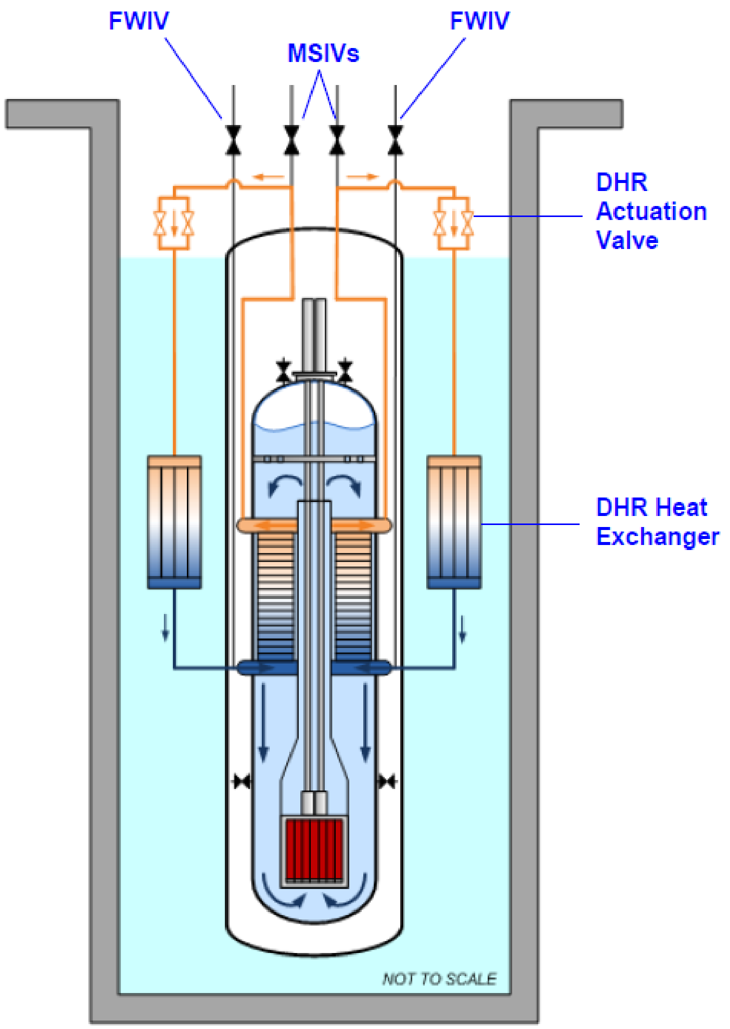


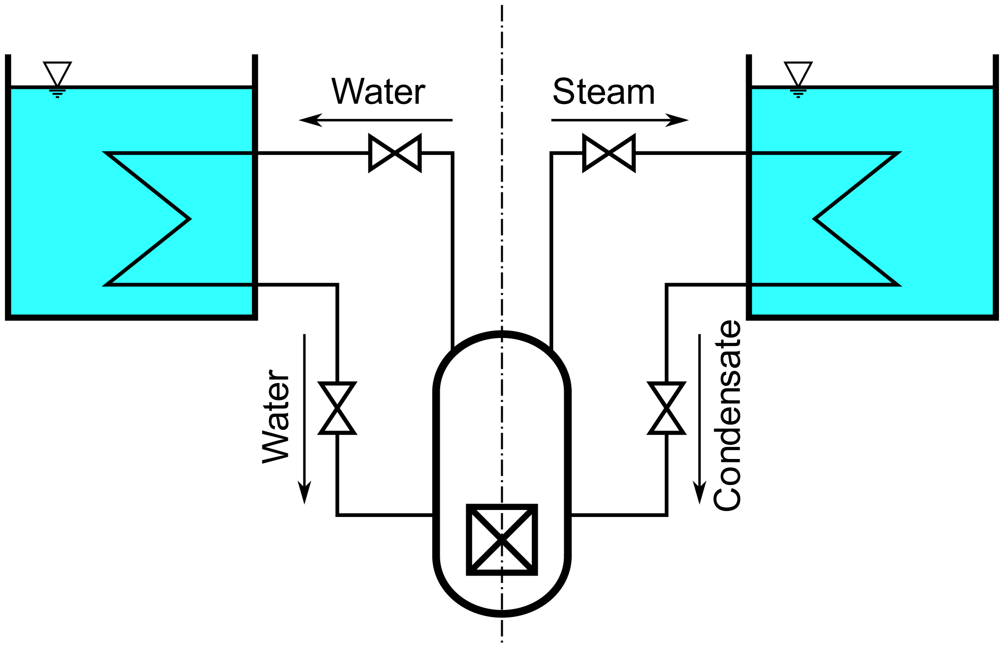
NuScale [4]

Residual heat removal

- Cooled by secondary side
  - Passively within water pool
  - Passively on air
  - Actively by main heat sink
    - All
- Primary side
- Other active systems

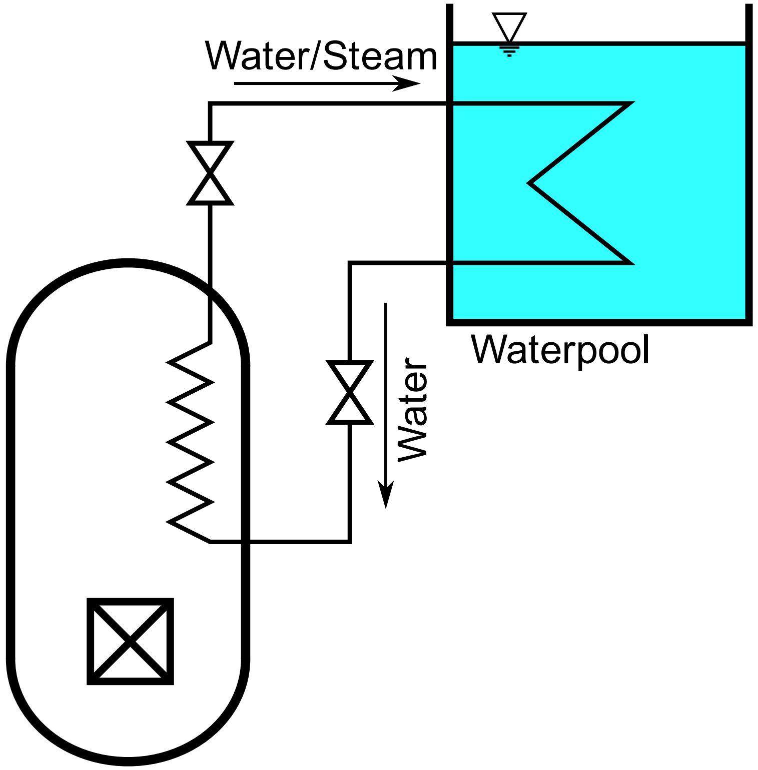
Residual heat removal

- Cooled by secondary side
- Primary side
  - Passively within water pool
    - ACP100, Flexblue, mPower, DHR-400
  - Passively with extra circuit
  - Actively by purification system
- Other active systems



Residual heat removal

- Cooled by secondary side
- Primary side
  - Passively within water pool
  - Passively with extra circuit
    - SMR-160, Westinghouse SMR, NUWARD
  - Actively by purification system
    - RITM-200
- Other active systems
  - Flexblue, IMR, Rolls Royce SMR



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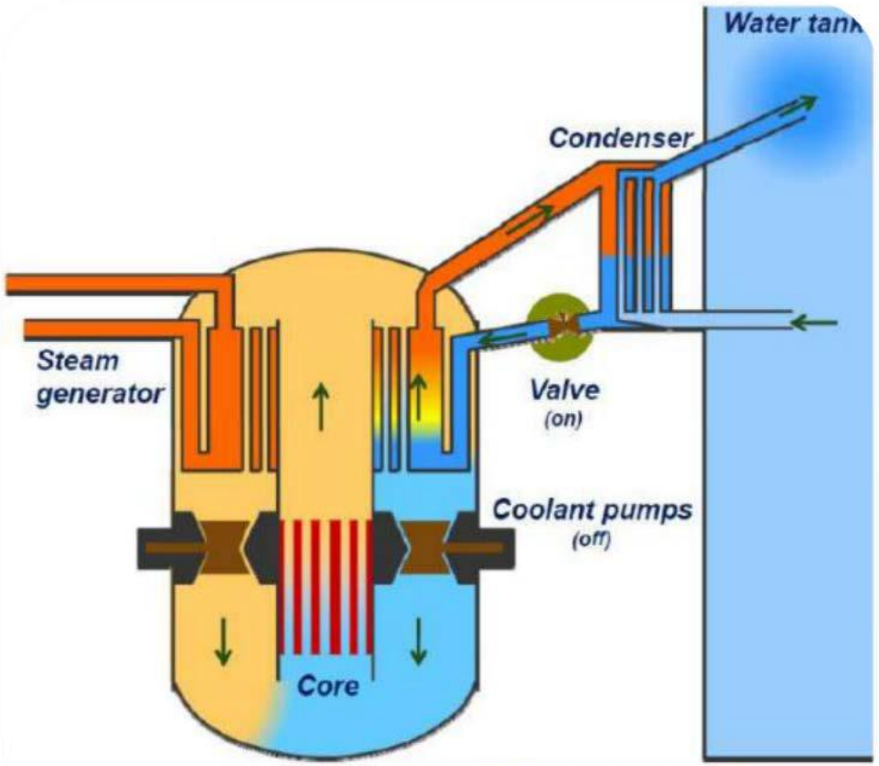

Passive residual heat removal system

Emergency Core Cooling

Emergency core cooling

- Active systems
  - CAREM, Flexblue, KLT-40S, VBER-300, VK-300, SMR-160, RITM-200, SNP350
- Passive systems
  - Accumulators
  - Make-up tanks
  - Elevated tanks
  - Long term cooling from sump/pit

Emergency core cooling

- Active systems
- Passive systems
  - Accumulators
    - ACP100, ACPR50S, CAREM, Flexblue, IMR, IRIS, KLT-40S, mPower, NUWARD, RITM-200, VBER-300, VK-300
  - Make-up tanks
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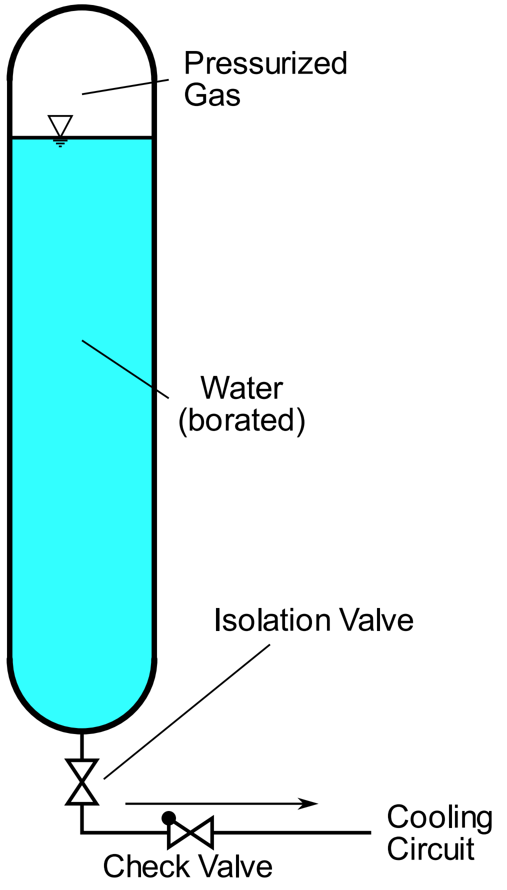

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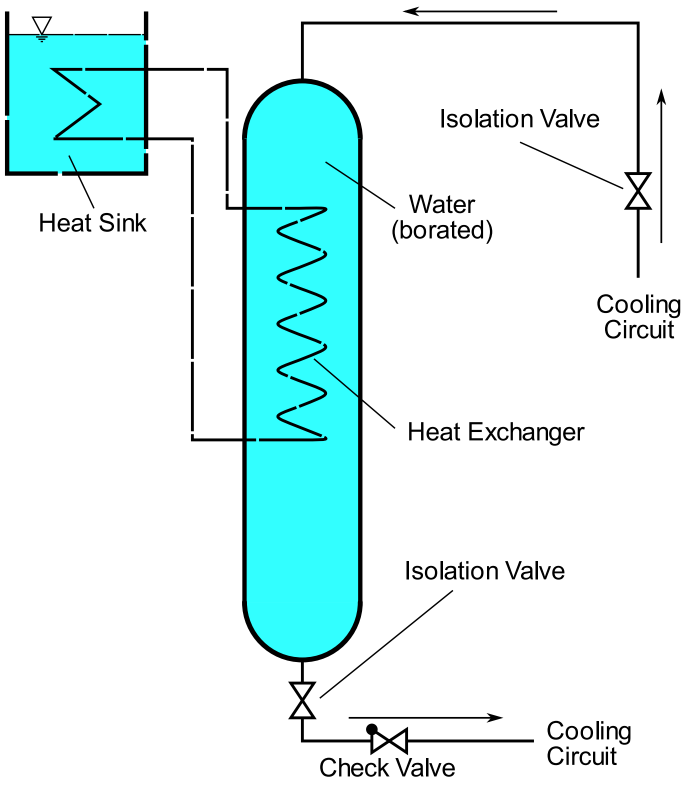

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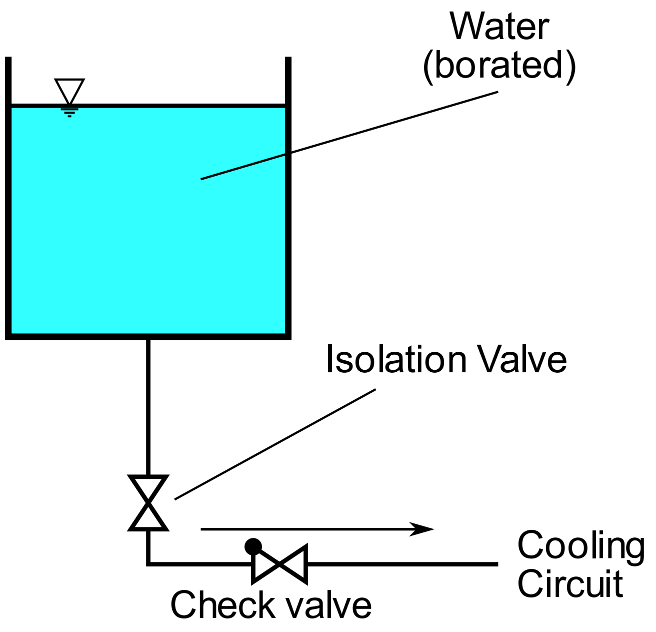

Emergency core cooling

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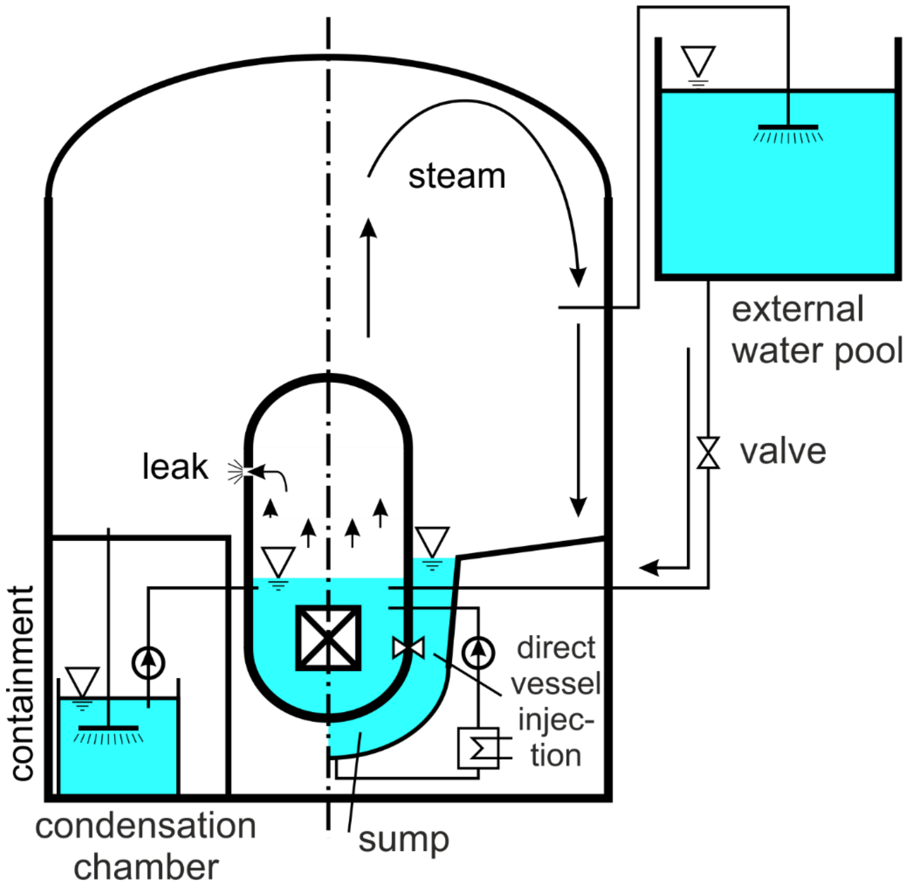

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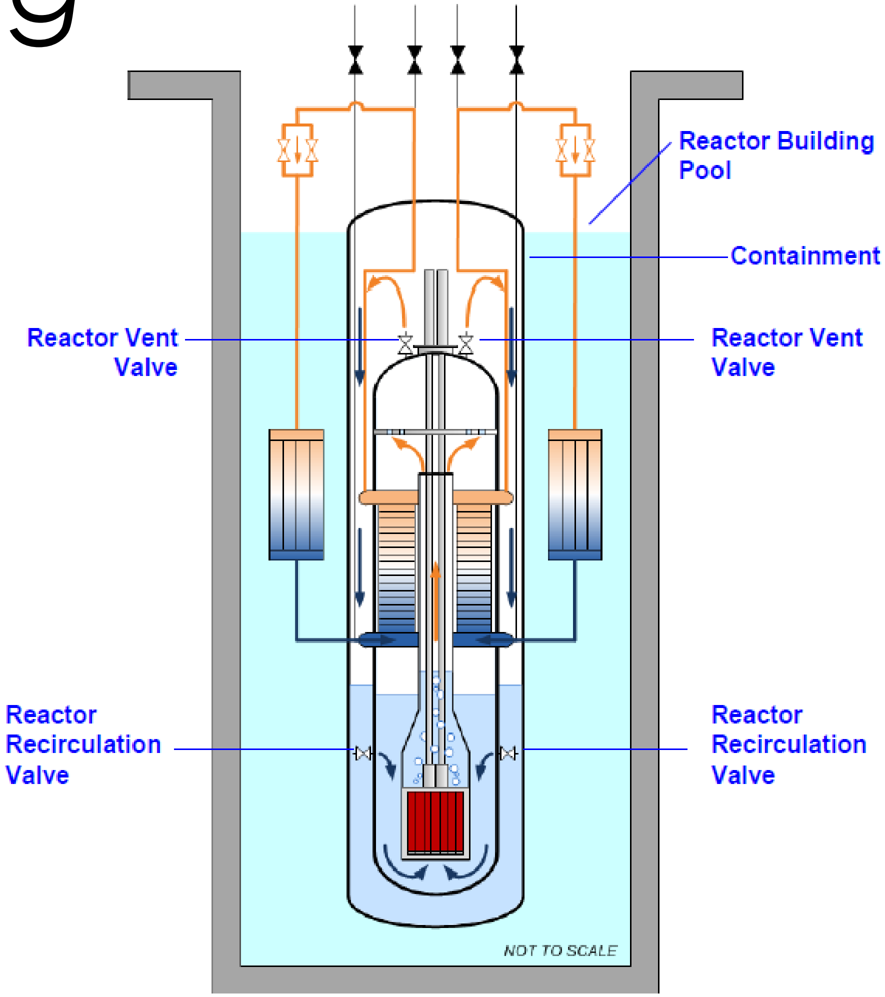
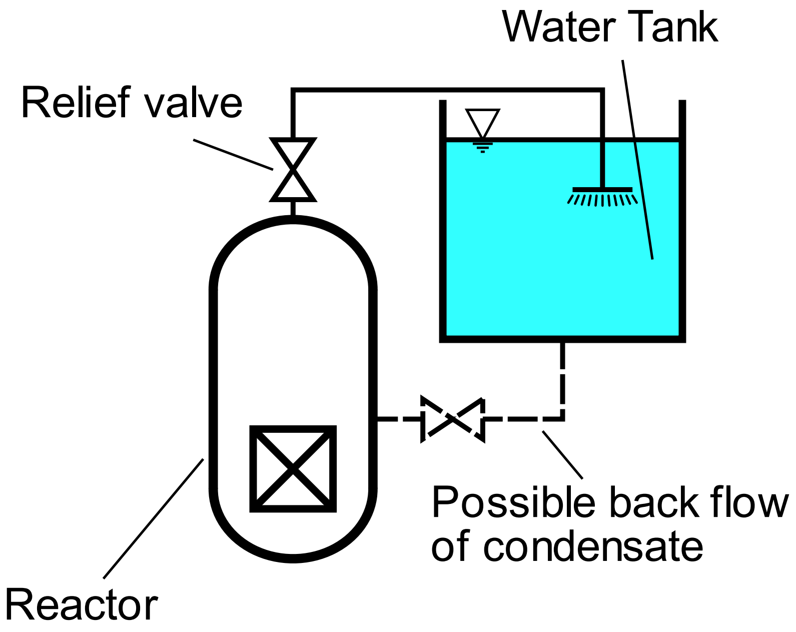


NuScale [4]

Primary Depressurisation

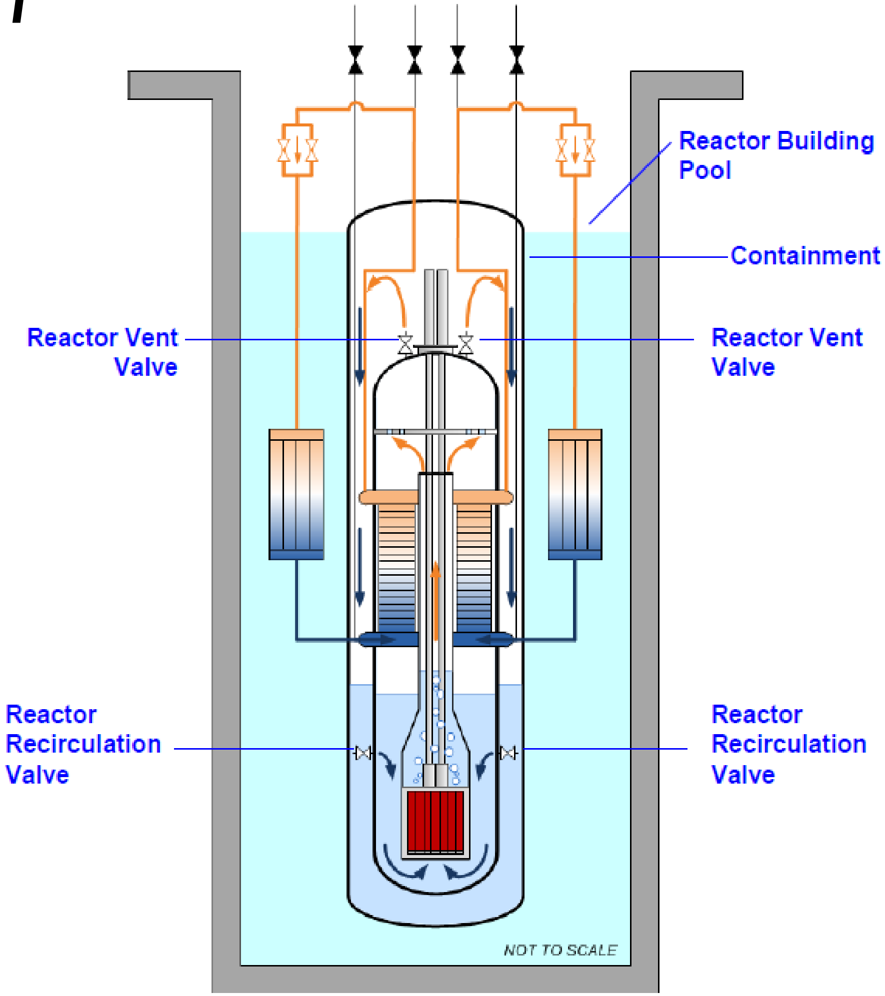
Primary depressurisation

- Depressurisation into pool
  - ACP100, ACPR50S, CAREM, Flexblue, IRIS, NUWARD, SMR-160, VK-300
- Depressurisation into containment
- Purification and cooldown system



Primary depressurisation

- Depressurisation into pool
- Depressurisation into containment
  - ACP100, IMR, mPower, **NuScale**, RITM-200, SMART, VBER-300, Westinghouse SMR
- Purification and cooldown system
  - KLT-40S, VBER-300

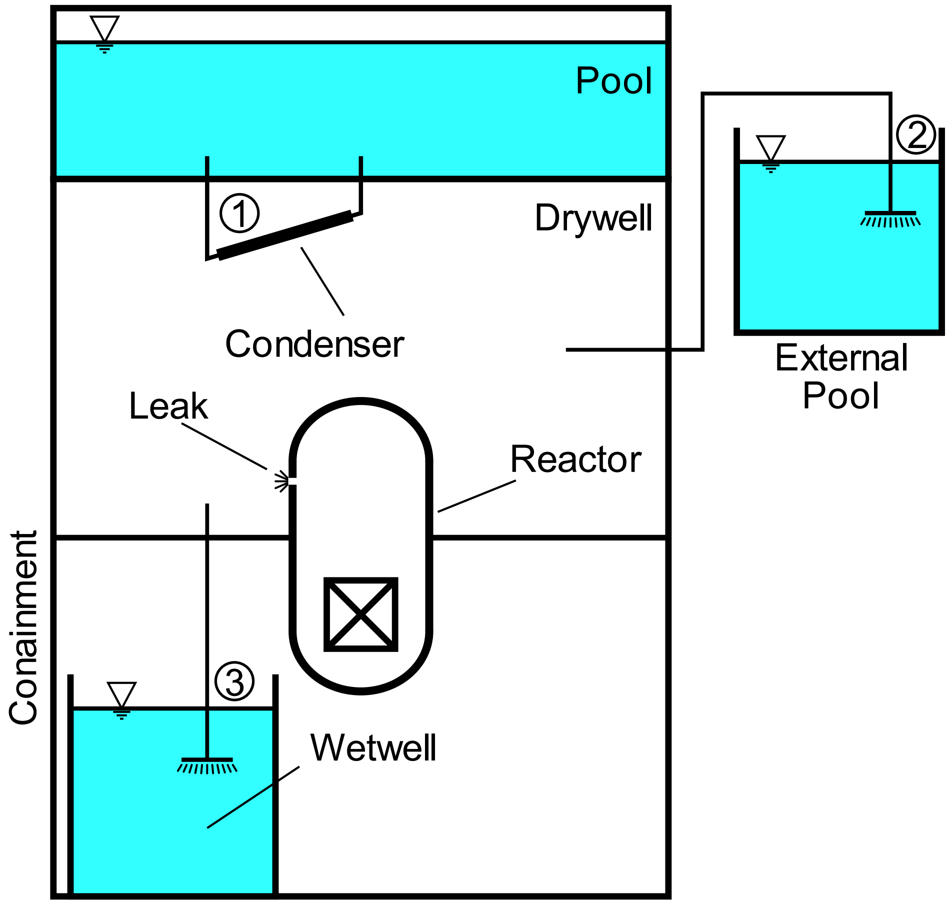


NuScale [4]

Containment Pressure Control

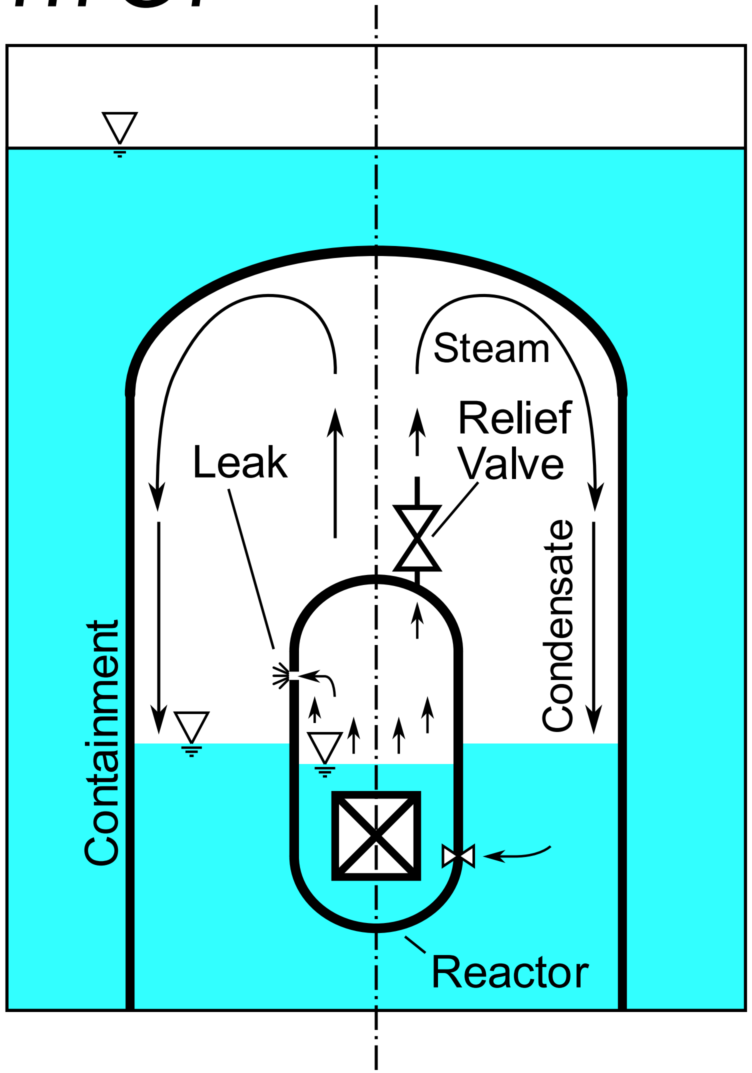
Containment pressure control

- Containment condenser (1)
  - ACP100, IRIS, KLT-40S, RITM-200, SMART, VBER-300
- Blowdown into pool (2) or wetwell (3)
  - Flexblue, CAREM, KLT-40S, VK-300



Containment pressure control

- Containment condenser
- Blowdown into pool or wetwell
- Spray into containment atmosphere
  - SMART, SNP350
- Condensation on containment inner wall
  - ACP100, ACPR50S, Flexblue, IMR, mPower, NuScale, SMR-160, Westinghouse SMR, CAP200, NUWARD



Containment pressure control

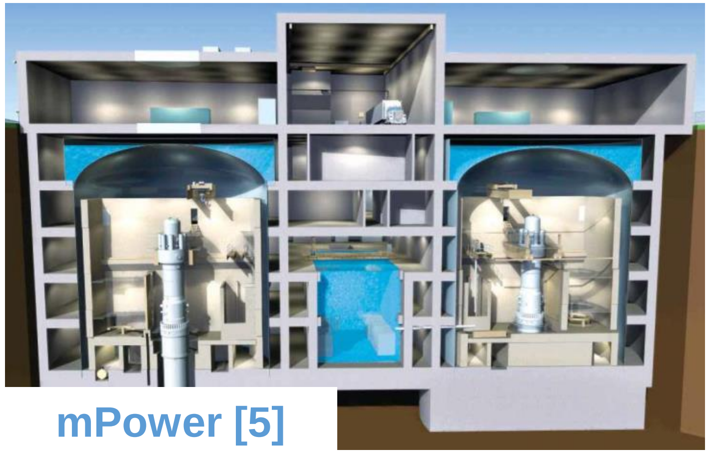
- Challenges for safety demonstration
  - Impact of non-condensables on condensation heat transfer
  - Natural convection on high containment walls when inside a water pool
  - Small containments
    → High pressures during LOCA expected
    → High loads on the containment wall
    (although limited LOCA size)
    - High design pressure for NuScale containment
    - Enhanced heat transfer due to spray, pool, etc.

Defence Against External Hazards

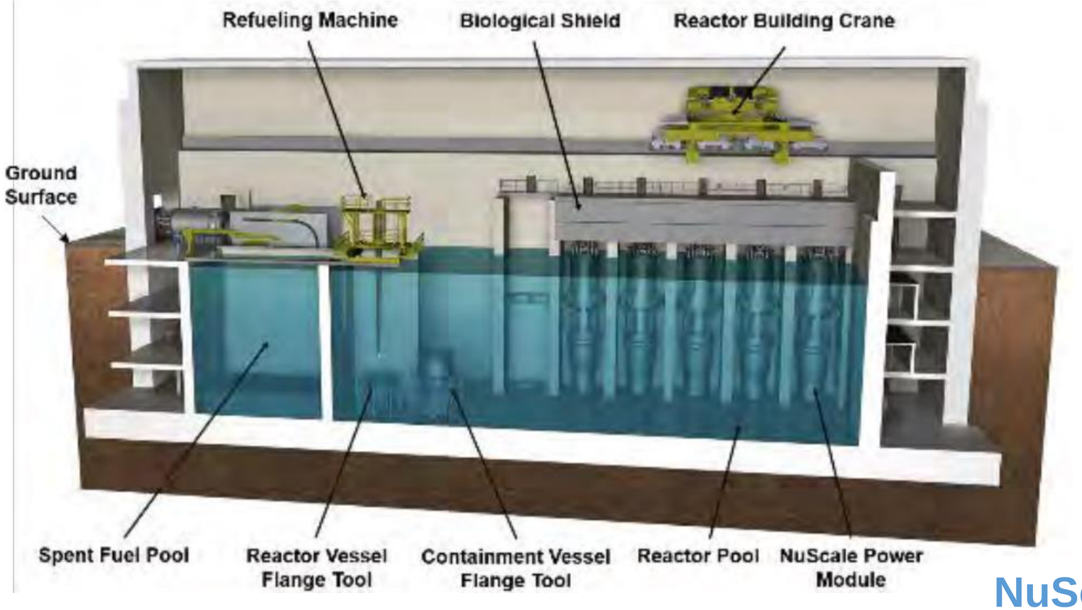
Defence against external hazards

Three different approaches against external hazards (earth quake, explosions, air plane crashes, flooding, etc.)

- Modules inside large water pools in caverns/below mounds



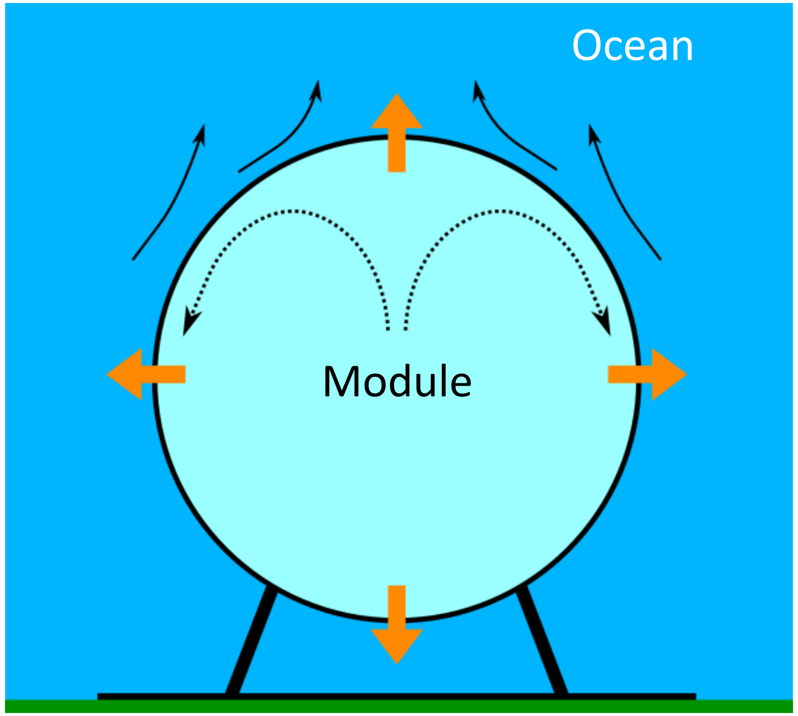
mPower [5]



NuScale [6]

Defence against external hazards

- Floating SMR
  - Depending on location no impact of earth quakes and tsunamis
  - Ocean works as unlimited heat source
  - Transport hazards to be considered
  - Sea motion → motion of the barge → impact of Coriolis force must be investigated
- SMR on ocean floor
  - Control rooms on-shore
  - Ocean works as unlimited heat source
  - Remote operation required



Flexblue [7]

Severe Accidents

Severe Accidents

- Sequences, events or situations to be practically eliminated which could lead to early and large releases
- Demonstration by:
  - Showing that the sequence is physically impossible by design
  - Demonstrate that the sequence is highly unlikely with high degree of confidence
- Severe accidents are still needed to be investigated, even if practically eliminated

Severe Accidents

- First conceptual versions of severe accident management should be derived during the design of the reactor
- In-vessel melt retention (IVMR) with external cooling preferred against ex-vessel melt retention in most designs
  - Difficult integration of core catcher into compact containment
  - Ex-vessel cooling with recirculation to the vessel already safety feature in some designs

Conclusions / References

Conclusions

- Large number of SMR designs currently under developed
- Simplification needed to reduce costs and increase safety
  - Size reduction, integration of components into RPV
  - Use of passive safety systems
- Innovative components and passive systems can challenge safety demonstration

References

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