Containment systems (cont'd)
Cooling of NPPs

Reactor technology
Lecture 5

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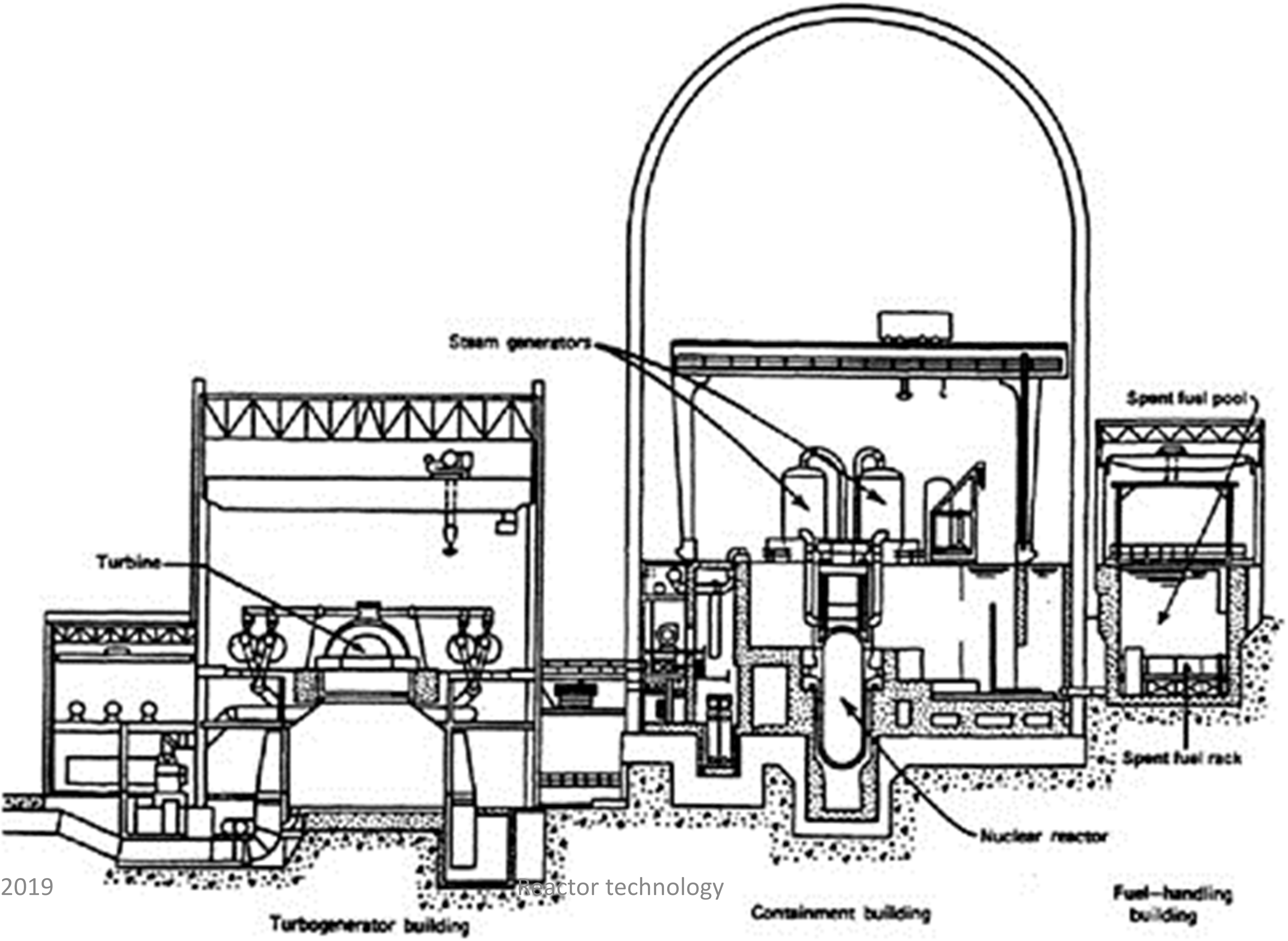
CONTAINMENT SYSTEMS

Containment system



Containment system

- Function of the containment system:
  - (a) Confinement of radioactive substances in operational states and in accident conditions,
  - (b) Protection of the plant against external natural and human induced events,
  - (c) Radiation shielding in operational states and in accident conditions.
  - (d) Housing the technology
- Containment system includes:
  - Leaktight structures
  - Associated systems for pressure and temperature control
  - Features for isolation, management and removal of fission products, hydrogen, oxygen, etc.
- Important parameters: free volume, P_d, T_d, design leakage rate, number of penetrations, etc.

Design of containment systems for DBA

- Design basis: usually an LB LOCA accident
- In case of LOCA event, parameters for acceptance criteria:
  - Mass and energy flow from the RCS into the containment (quantity and time duration)
  - Heat transfer between the containment structure and the technology
  - Mechanical loads
  - Release of radionuclides into the containment
  - Release of radionuclides from the containment -> leakage rate!
  - Generation of explosive gas mixture

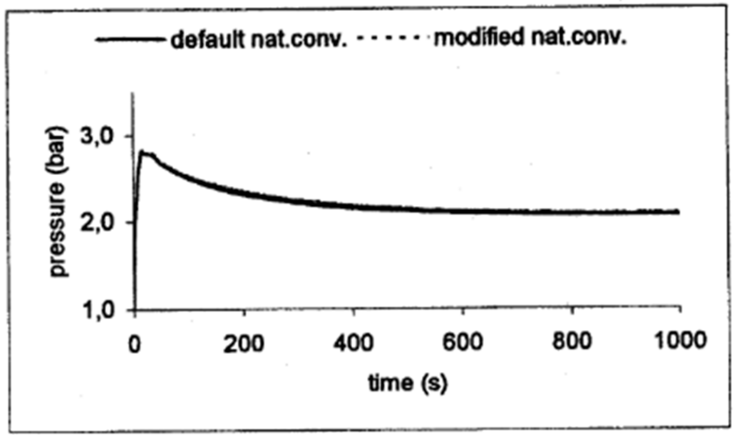


FIGURE 2. Pressure in containment main compartment for base case and modified input (natural convection model from Rohsenow et al., 1985).

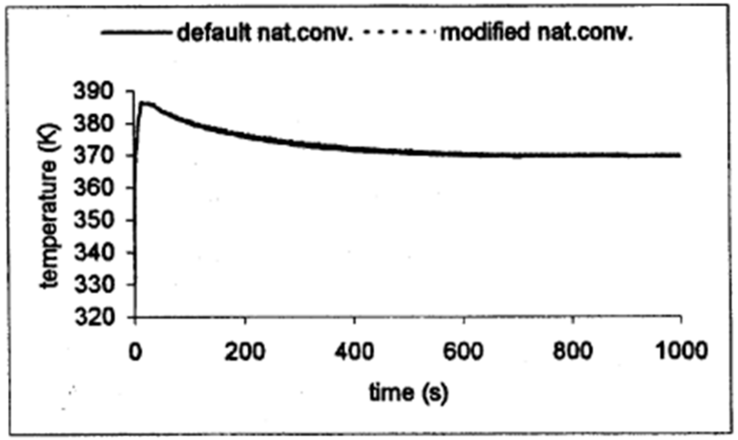
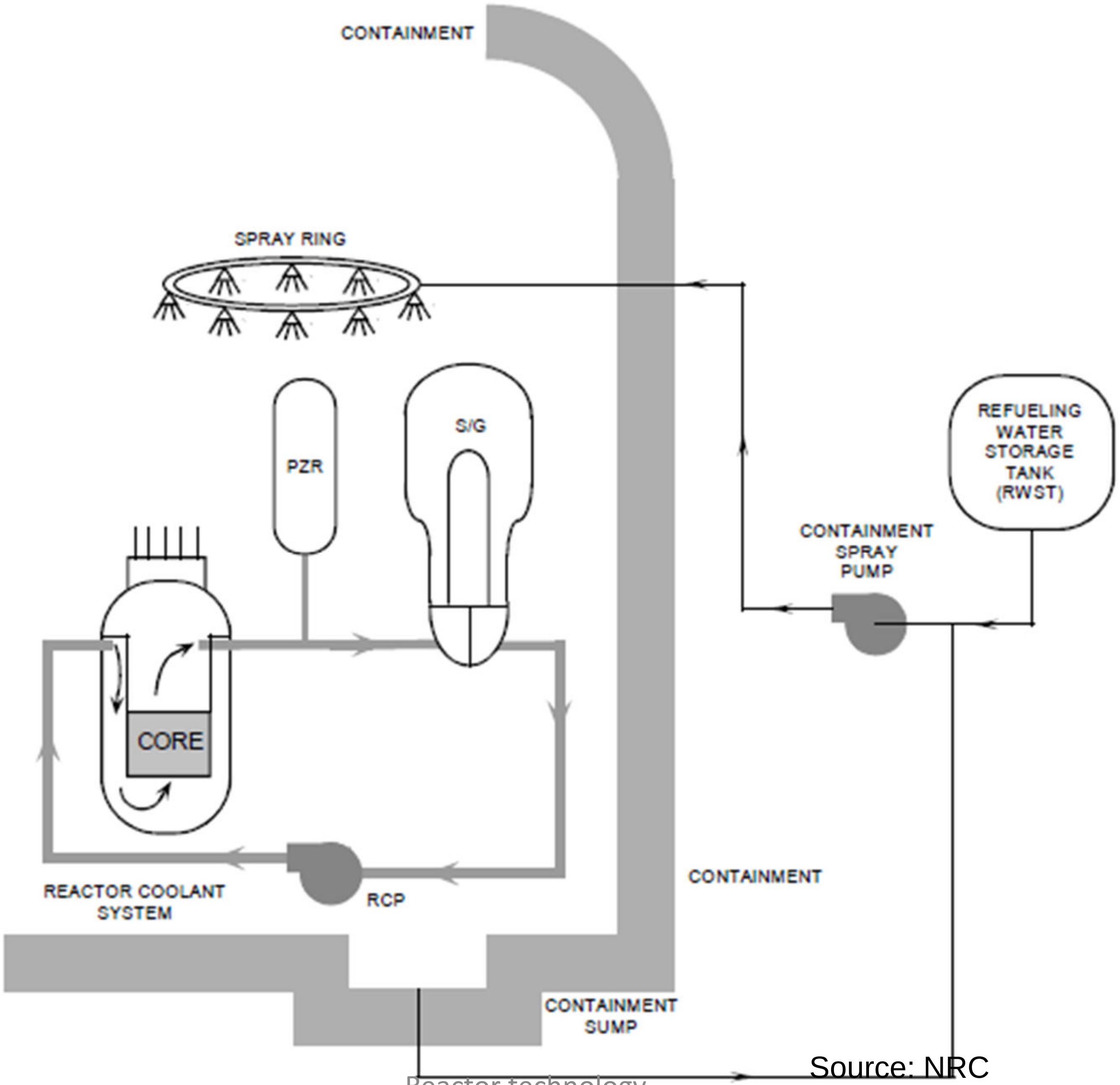


FIGURE 3. Temperature in containment main compartment for base case and modified input (natural convection model from Rohsenow et al., 1985).

Source: Tiselj, Kljenak, Prosek: Simulation of containment response during a large-break LOCA scenario with the CONTAIN code

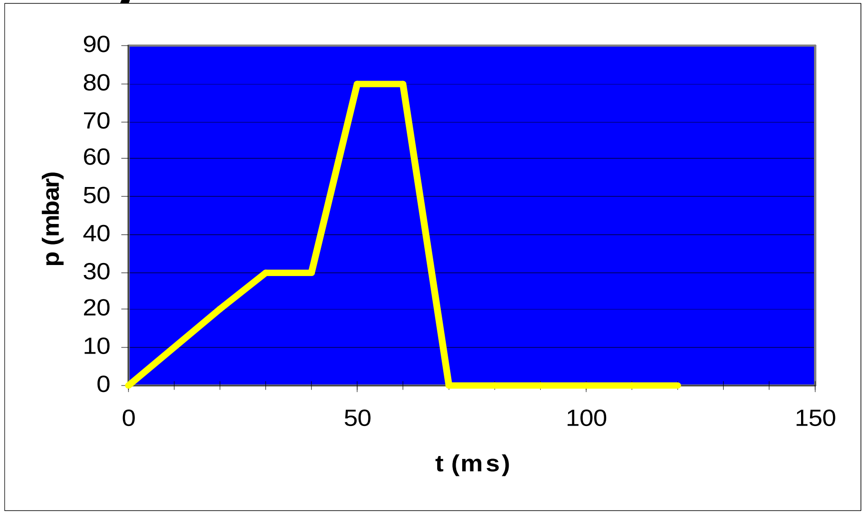
Containment spray system



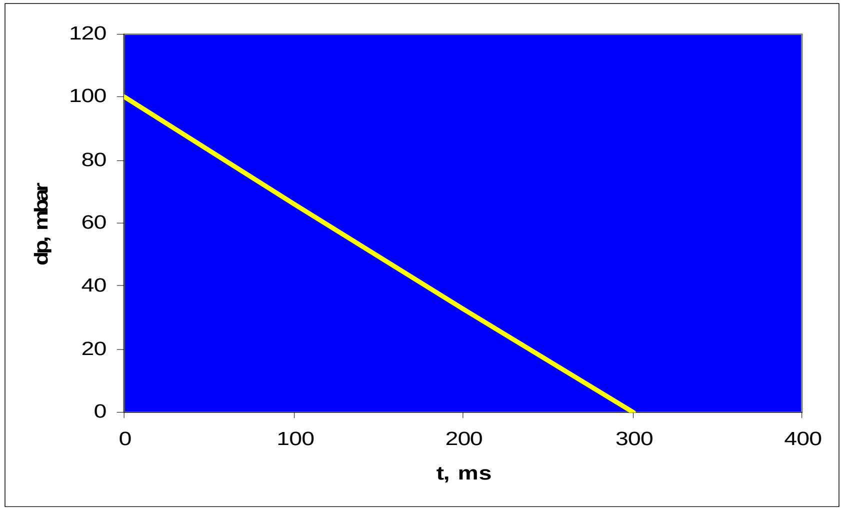
Source: NRC

Design of containment systems for SA

- Severe accidents
  - For operating plants:
    - Re-evaluation of safety
    - analysis with deterministic and probabilistic analysis to identify reasonably practicable preventive or mitigatory measures
  - For new plants, severe accidents should be considered at the design stage of the containment systems
  - Requirement for new plants: practically eliminating the large release of radioactivity

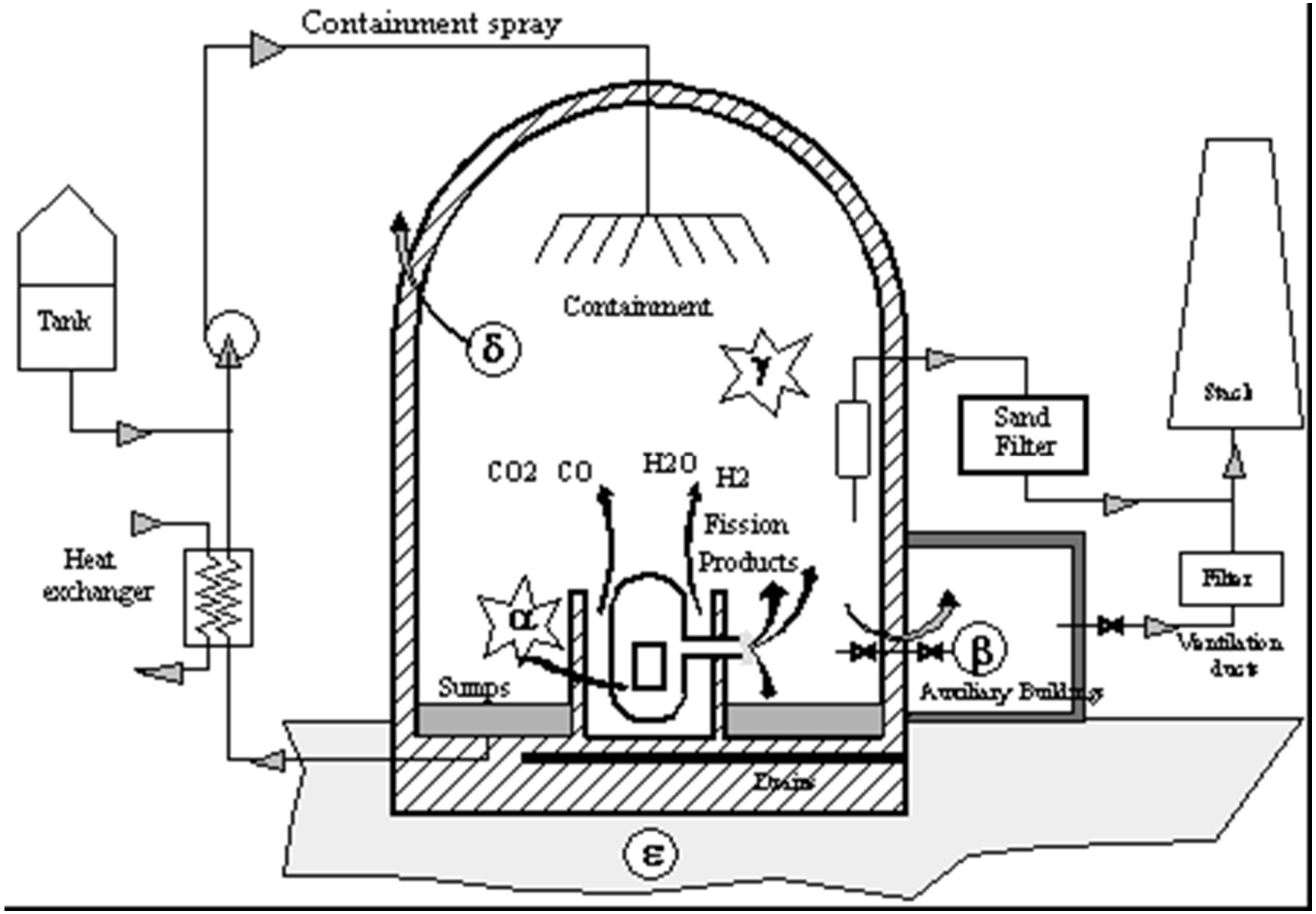


Typical loads during an aircraft crash



Typical explosion load

Containment failure processes during SA



Mode α: steam explosion in the vessel or reactor pit, inducing loss of containment integrity in the short term;
Mode β: initial or fast-induced loss of integrity;
Mode γ: hydrogen explosion;
Mode δ: slow overpressurization;
Mode ε: basement melt-through by the corium.

Source: IAEA

Containment types

PWR full pressure containment

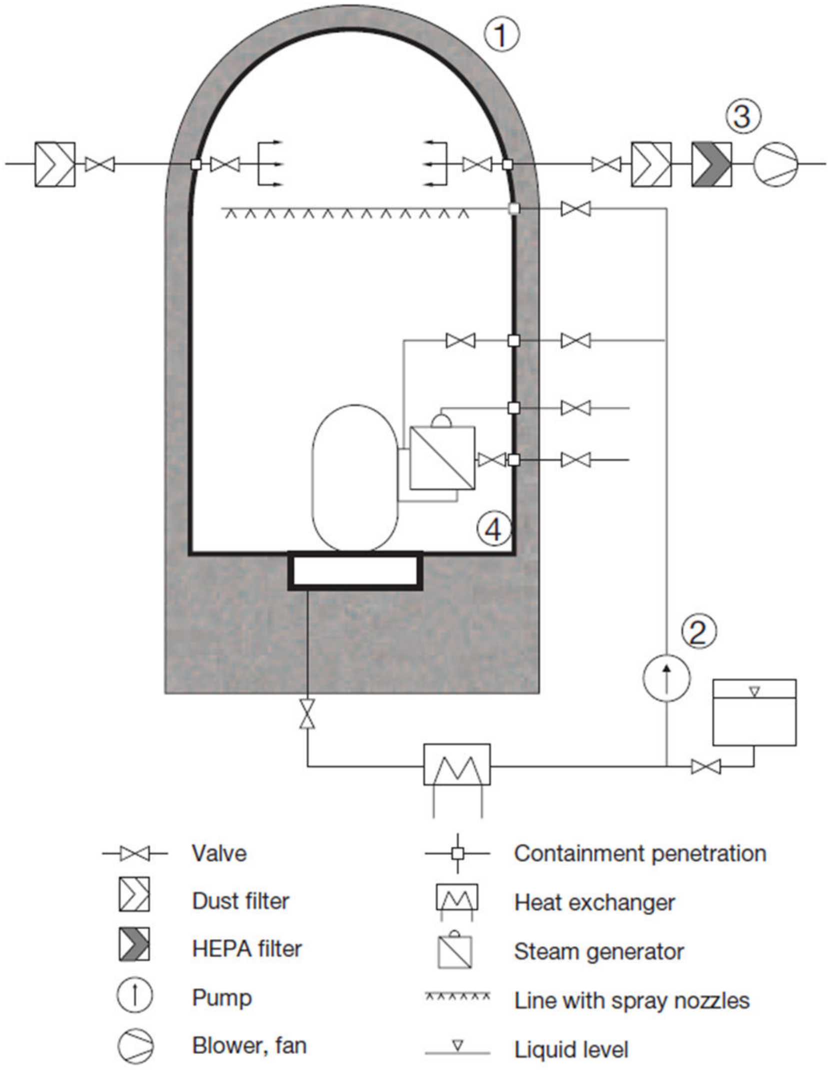


FIG. I–1. Schematic diagram of a full pressure dry containment system for a pressurized water reactor: 1, containment; 2, containment spray system; 3, filtered air discharge system; 4, liner.

Source: IAEA

PWR full pressure double wall containment

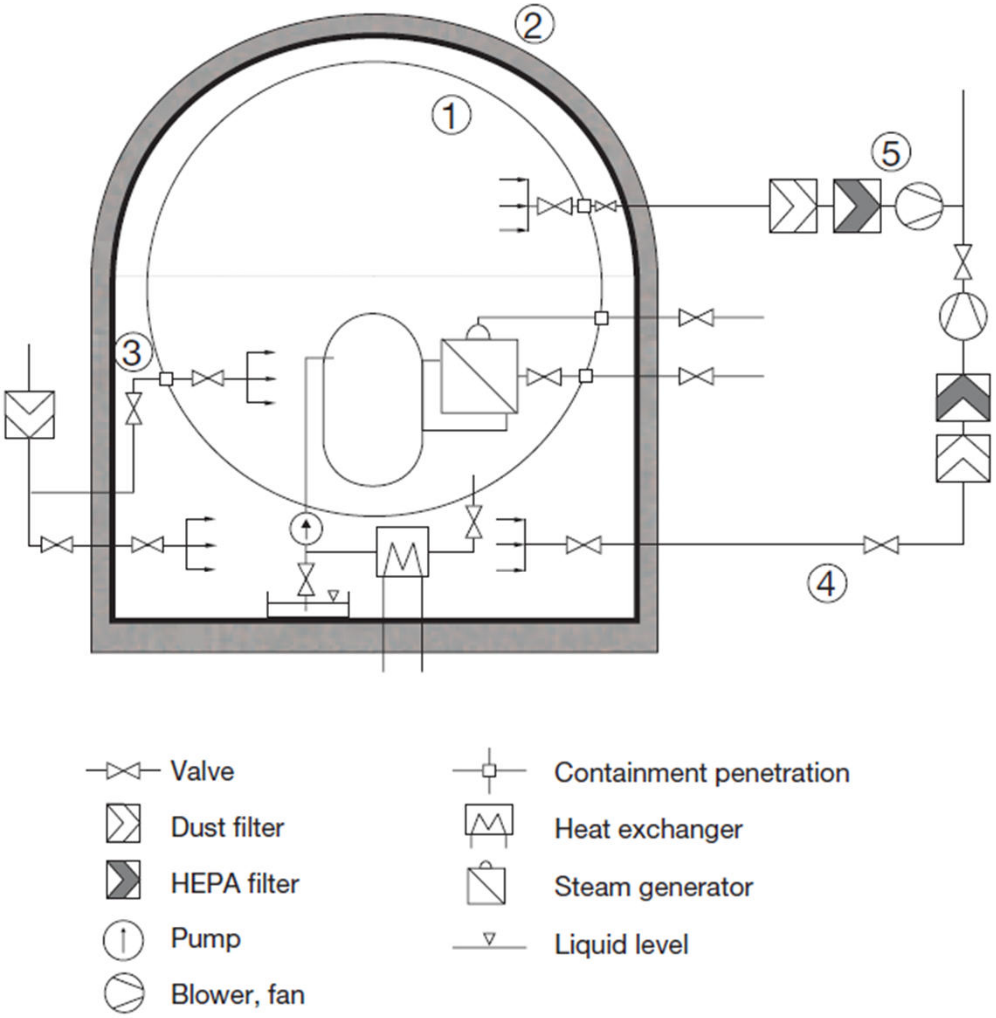


FIG. I–2. Schematic diagram of a full pressure double wall containment system for a pressurized water reactor: 1, full pressure containment; 2, secondary confinement; 3, annulus; 4, annulus evacuation system; 5, filtered air discharged system.

Source: IAEA

PWR ice condenser containment

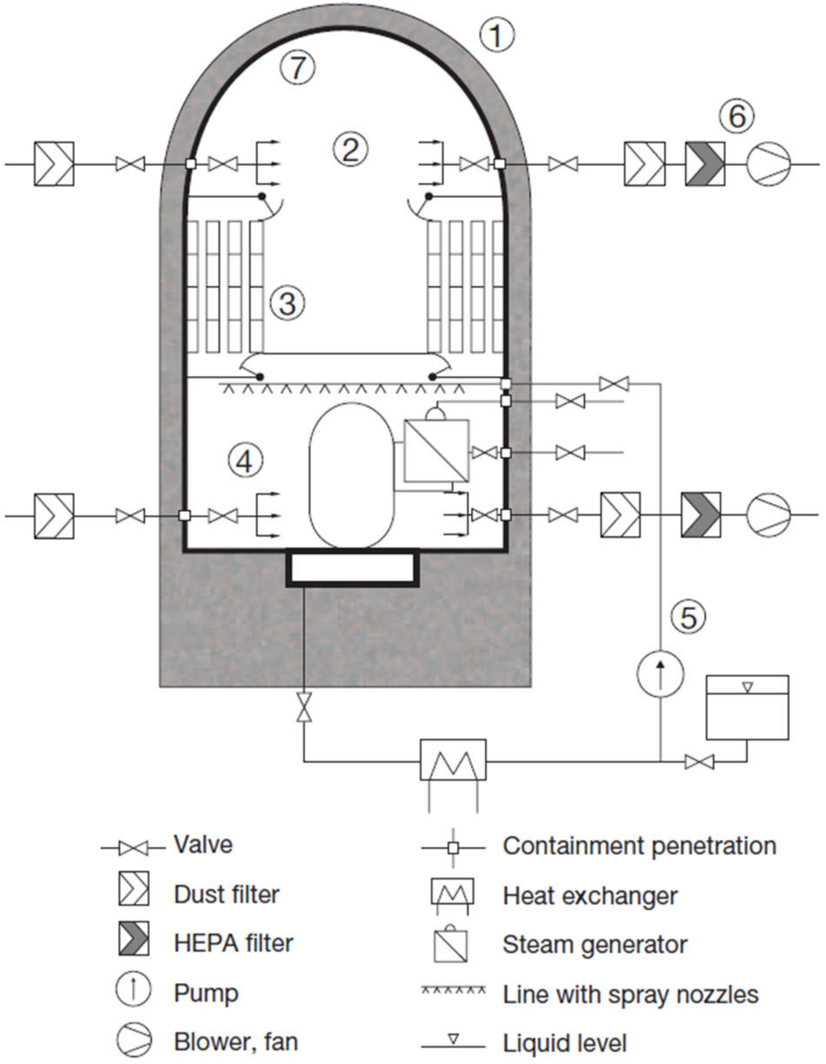
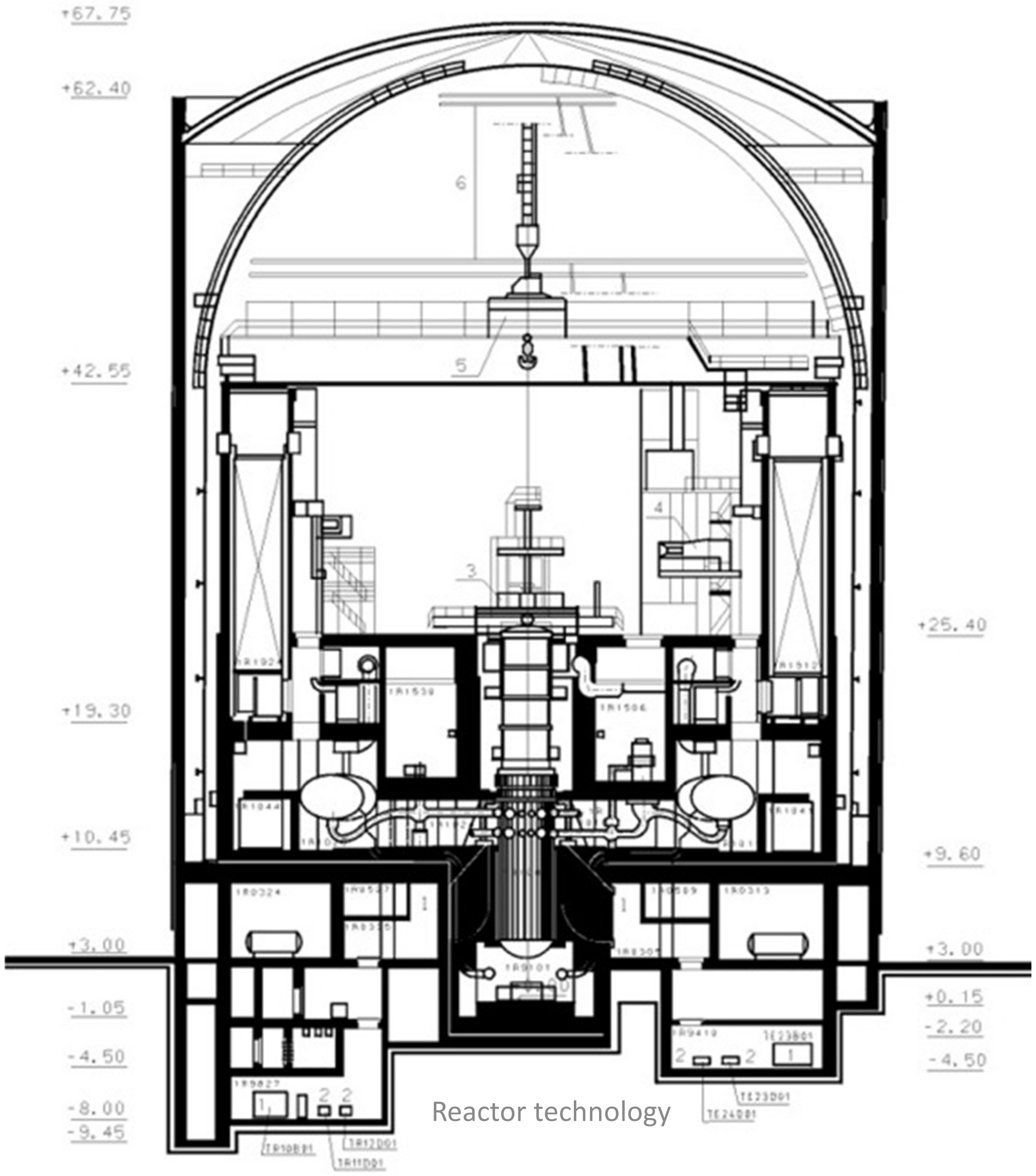


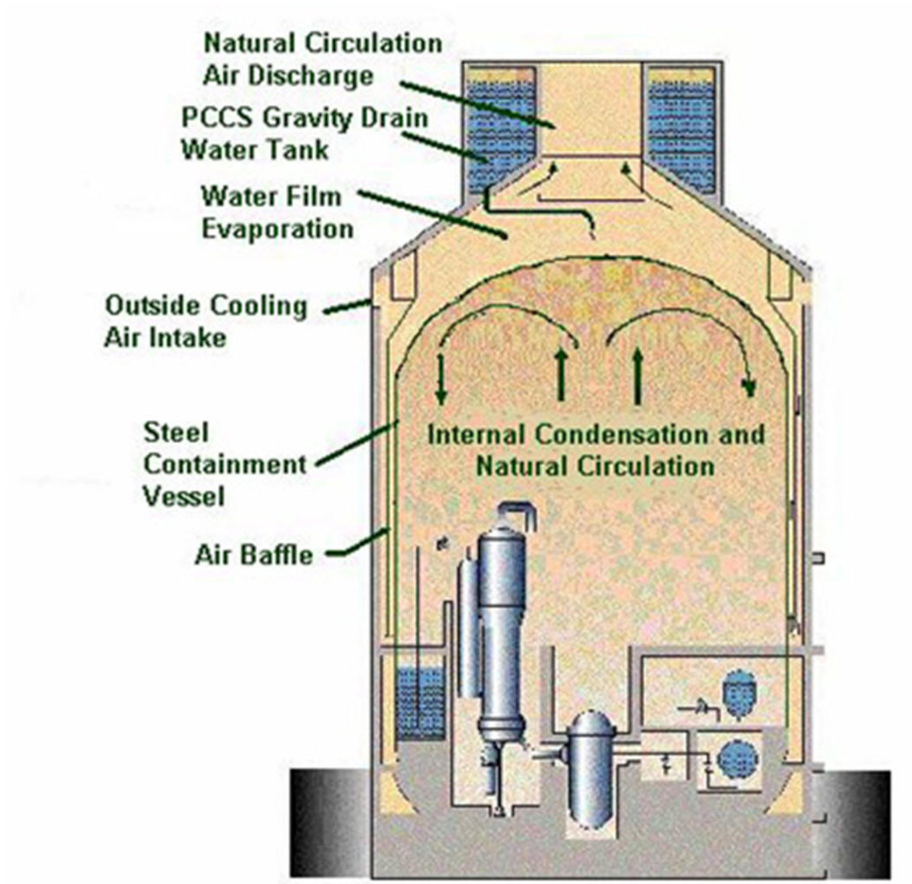
FIG. I–3. Schematic diagram of an ice condenser containment system for a pressurized water reactor; 1, containment; 2, upper containment volume; 3, ice condenser; 4, lower containment volume; 5, lower containment spray system; 6, filtered air discharge system; 7, liner.

Source: IAEA

PWR ice condenser containment



AP-1000 passive containment



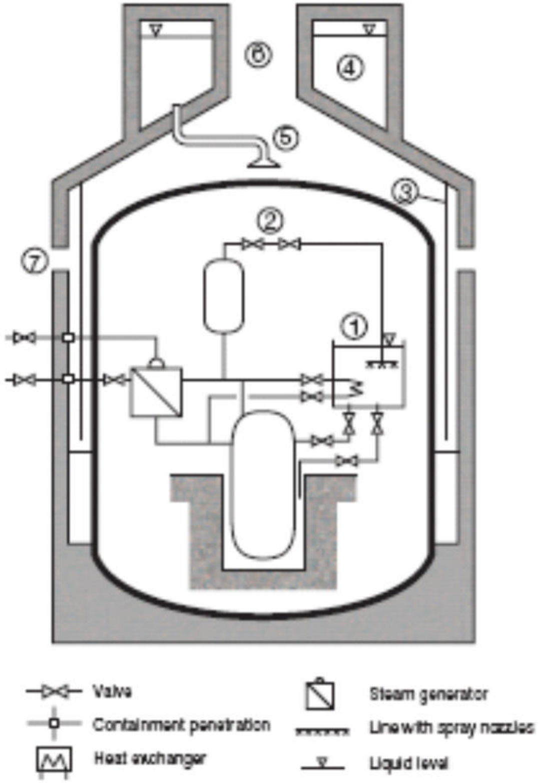
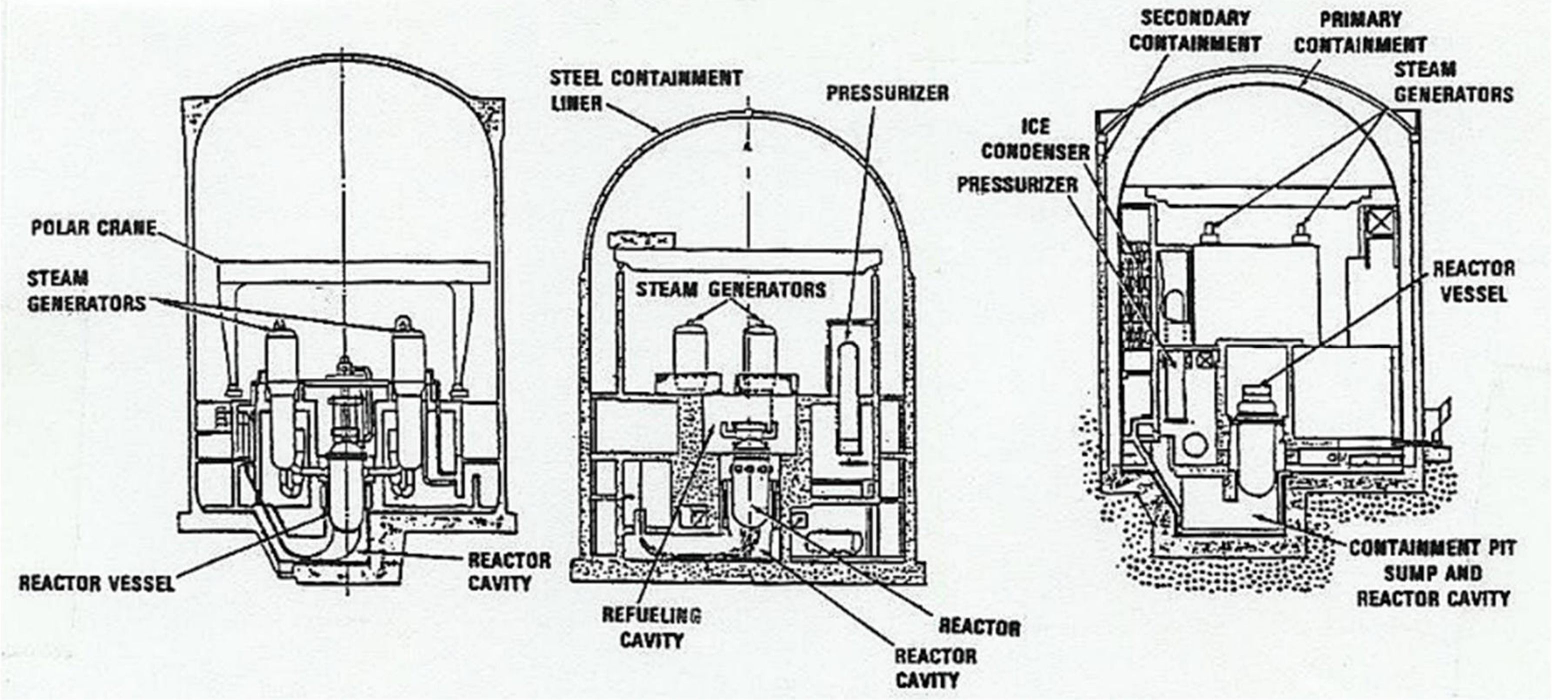


FIG. I–11. Schematic diagram of a passive simplified pressurized water reactor: 1, in-containment refuelling water storage tank; 2, primary circuit depressurization system; 3, air baffle; 4, passive containment cooling system: gravity drain water tank; 5, containment vessel gravity spray; 6, natural convection air discharge; 7, natural convection air intake.

Source: IAEA

Comparison of PWR containments



Large dry cont. *Sub-atmospheric cont.* *Ice condenser cont.*

Type	Material	Ref. Plant	Int. Diam. (m)	Free Volume (10000 m3)	Design pressure (bar)	Design Leakage Rate (%Vol/day)
Large dry	RC Hemi. Dome	Indian Point	41	74	3.2	0.1
Large dry	St. Cyl. Hemi. Dome	Davis Besse	40	81	2.8	0.5
Large dry	PC shallow dome	Zion	43	81	3.2	0.1
Large dry	PC Hemi. Dome	Trojan	38	57	4.1	0.2
Ice condenser	St. Cyl. Hemi. Dome	Sequoyah	32	---	0.7	0.5
Subatmospheric	RC Hemi. Dome	Surry	38	51	4.1	0.1

Bubbling condenser containment

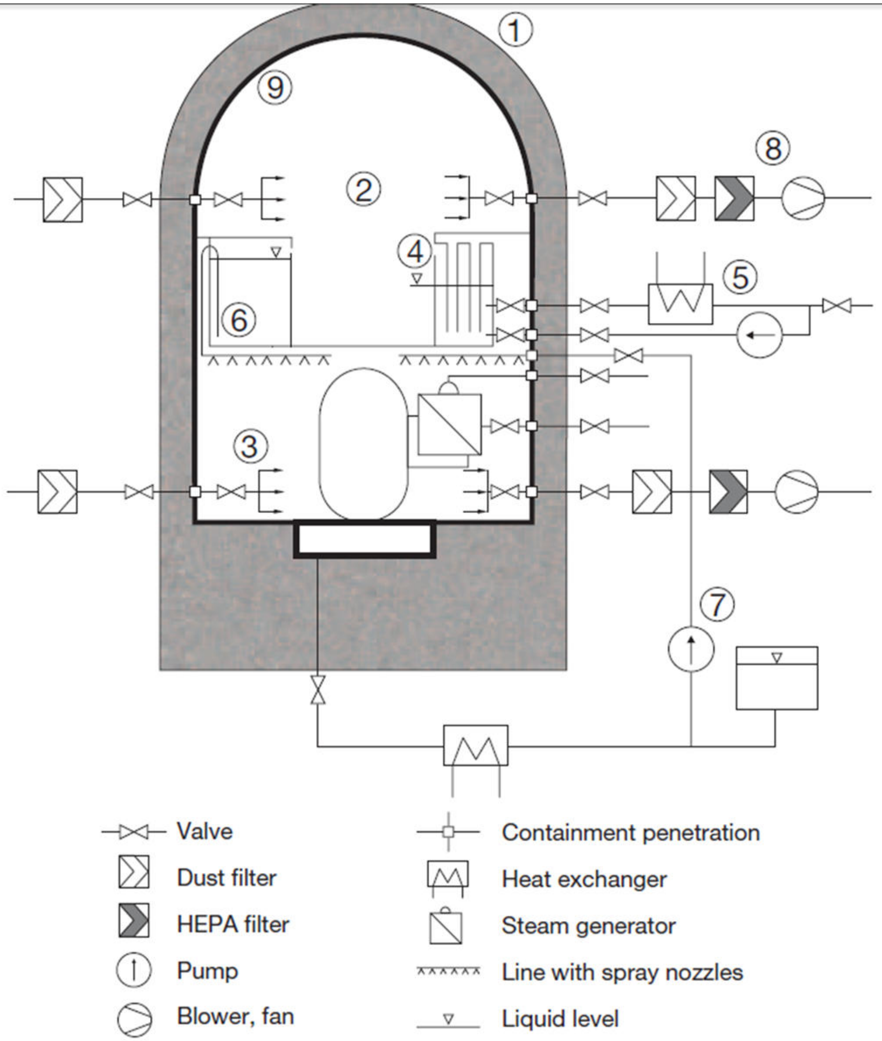
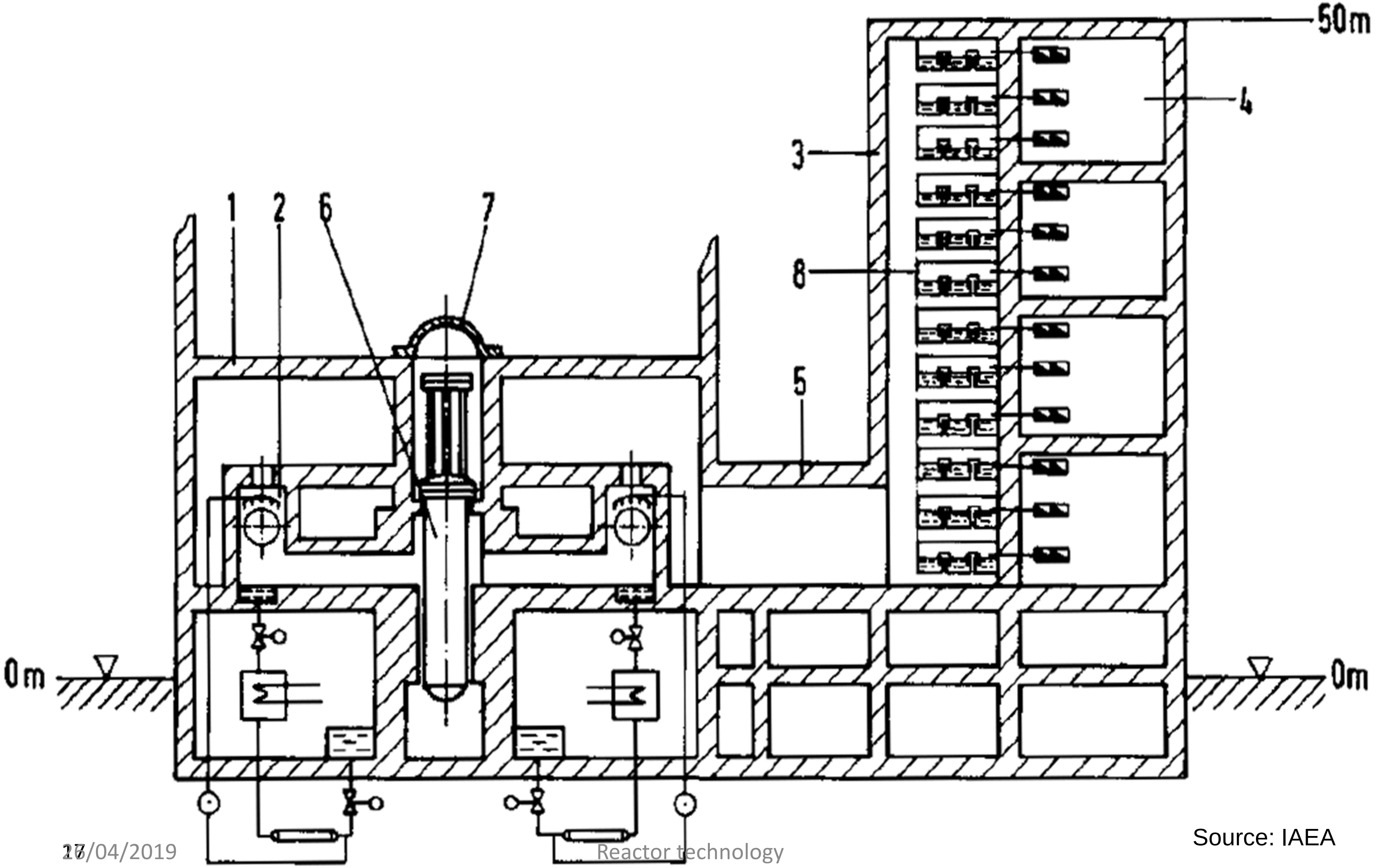


FIG. I–4. Schematic diagram of a bubbling condenser containment system for a pressurized water reactor: 1, containment; 2, upper containment volume (wet well); 3, lower containment volume (dry well); 4, bubbling condenser system (suppression pool); 5, suppression pool cooling system (not required if the heat capacity of the condenser system (4) is sufficiently large); 6, passive spray system; 7, active spray system; 8, filtered air discharge system; 9, liner.

- Similar to BWR
- 3 main compartments with bubbling condenser
- Designed for LOCA accidents
- Passive containment spray system

VVER-440/213 (Paks)



Source: IAEA

VVER-440 pressure suppression system

VVER-440 pressure suppression system

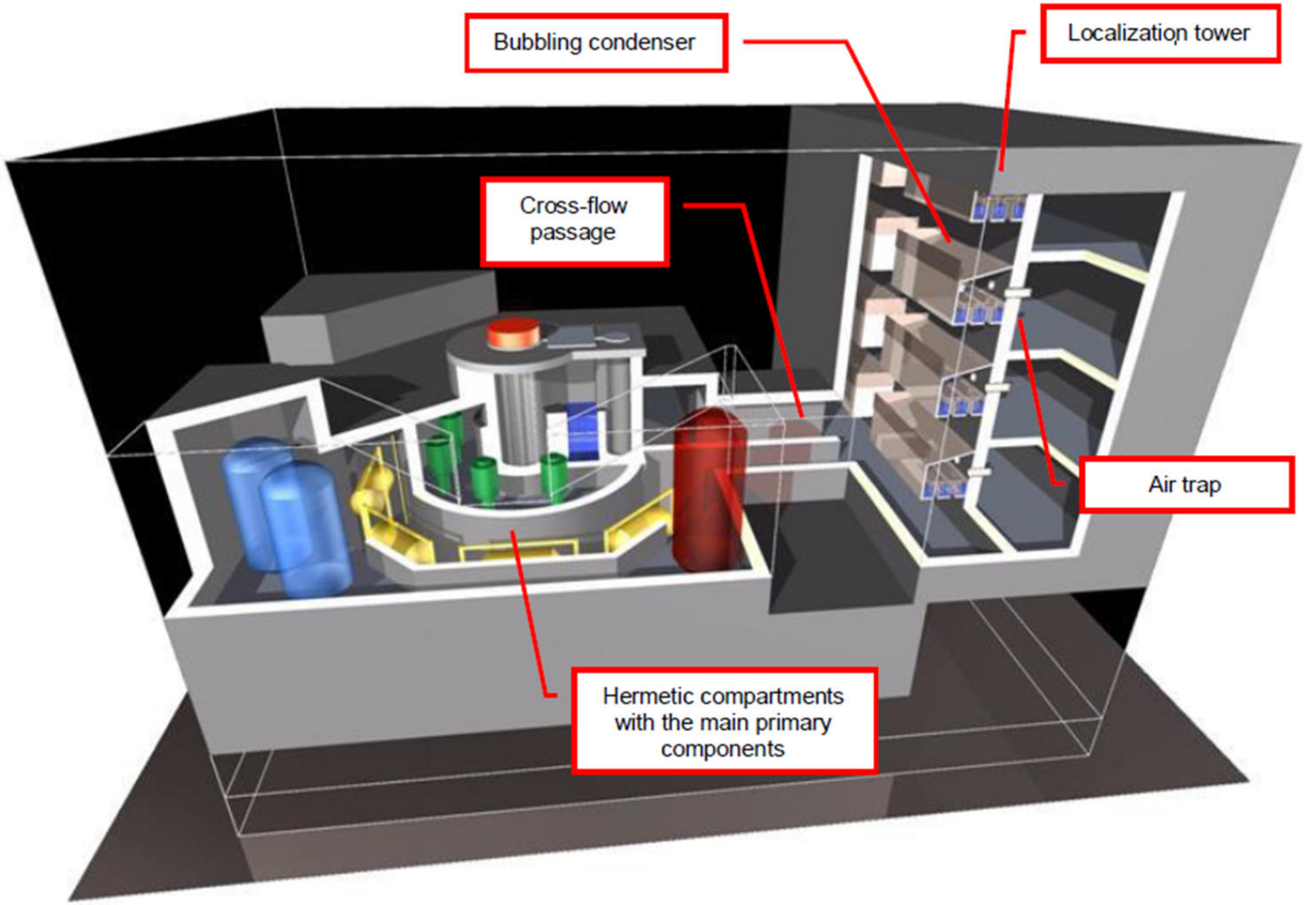
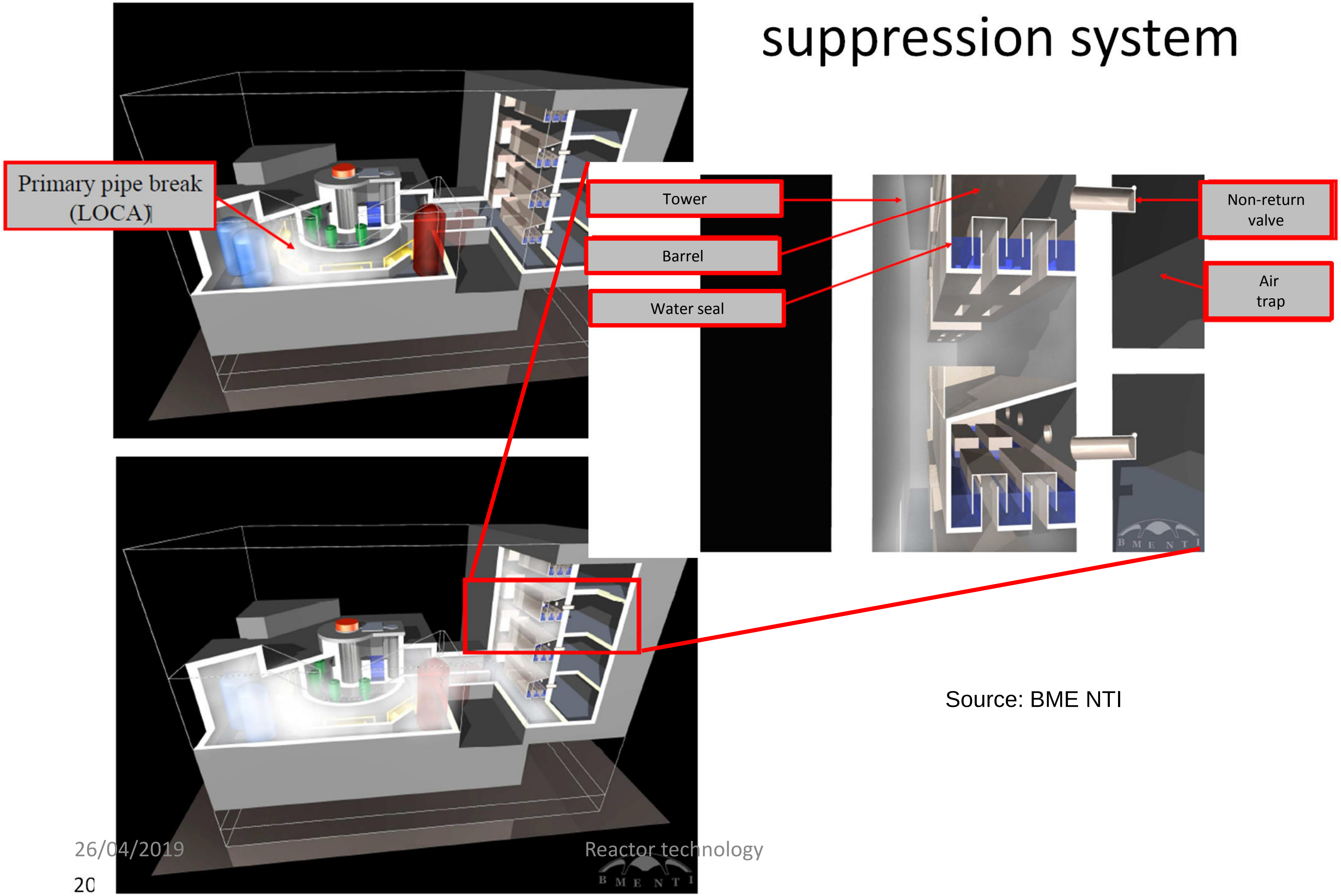


Figure 1-11: Hermetic compartments with the passive pressure reducing system (simplified)

Source: BME NTI

VVER-440 pressure suppression system



Primary pipe break (LOCA)

Tower

Barrel

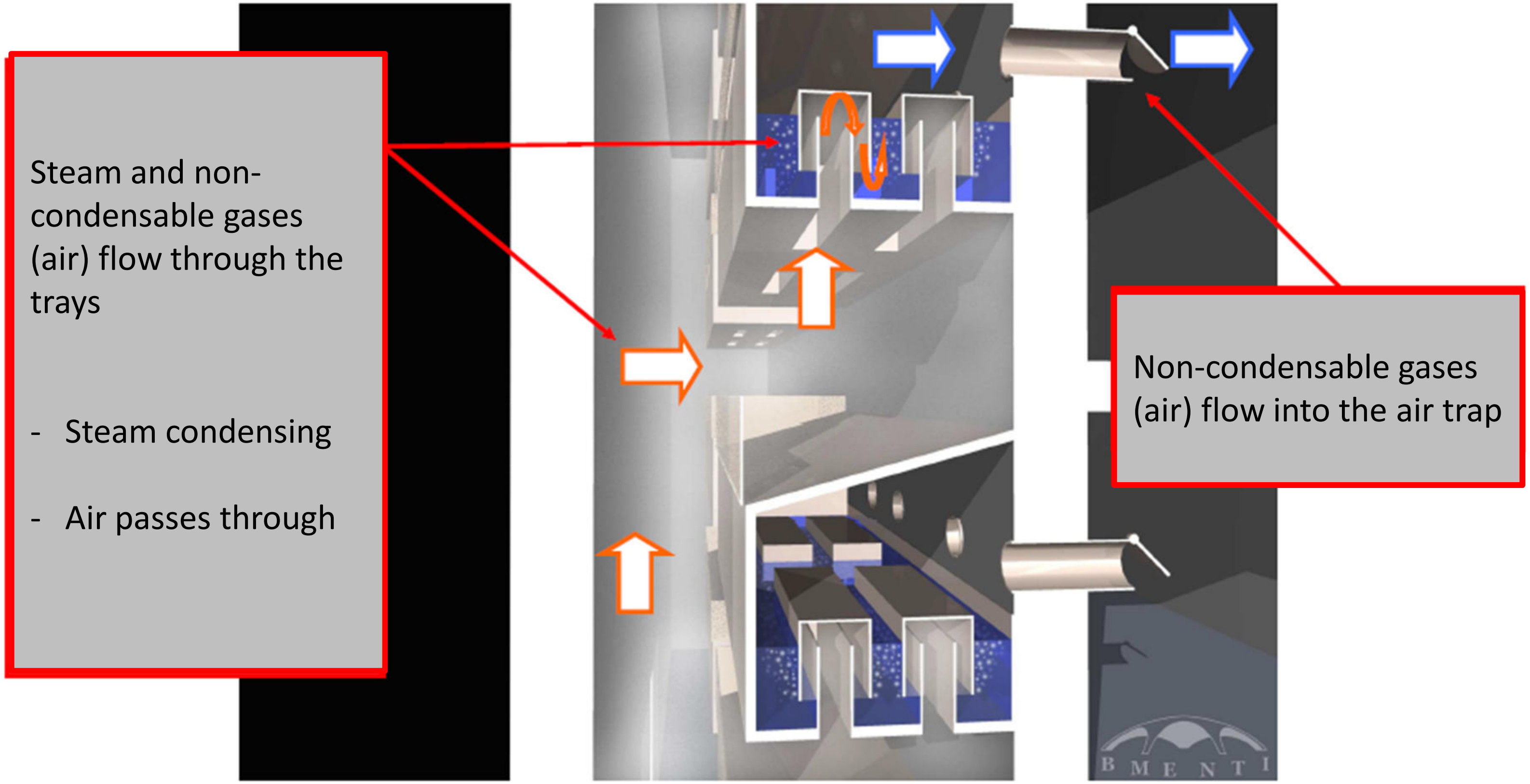
Water seal

Non-return valve

Air trap

Source: BME NTI

VVER-440 pressure suppression system



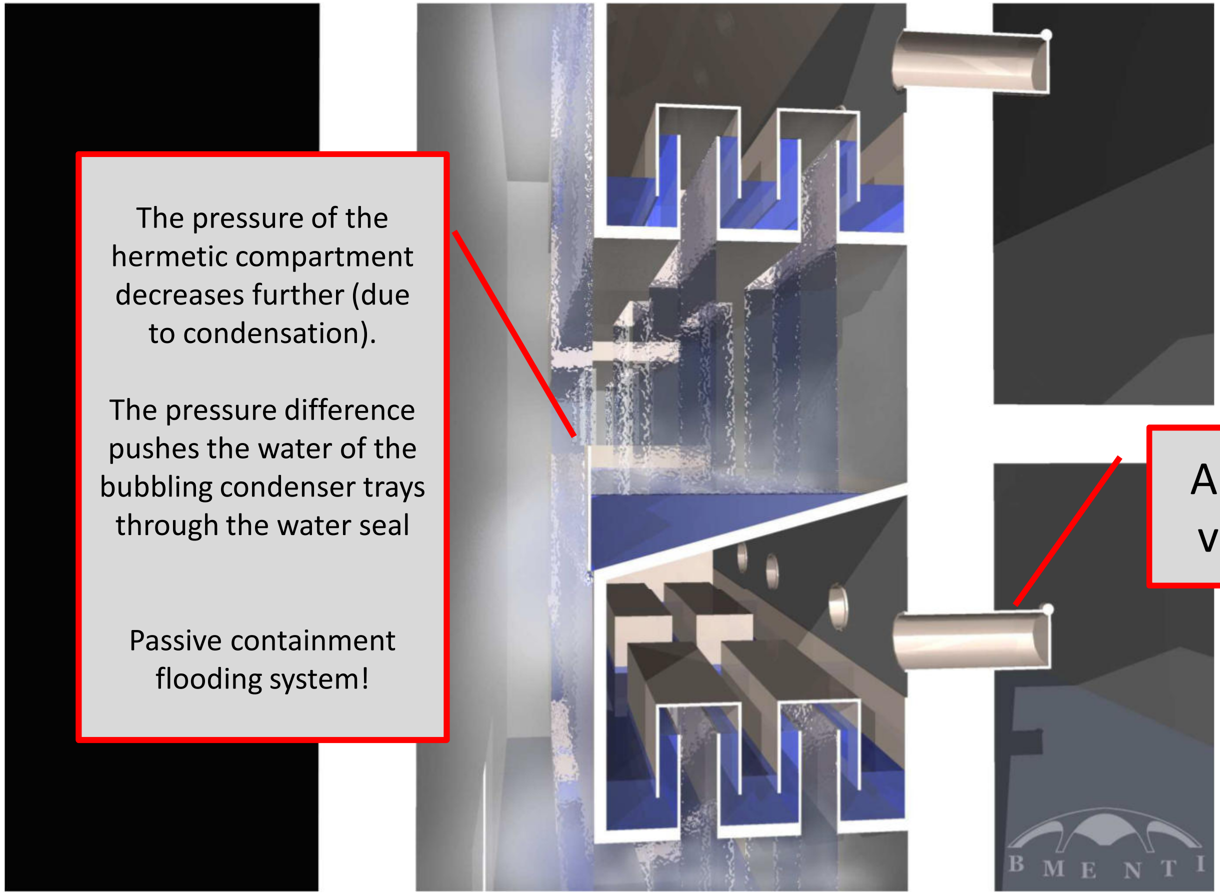
Steam and non-condensable gases (air) flow through the trays

- Steam condensing
- Air passes through

Non-condensable gases (air) flow into the air trap

Source: BME NTI

VVER-440 pressure suppression system



The pressure of the hermetic compartment decreases further (due to condensation).

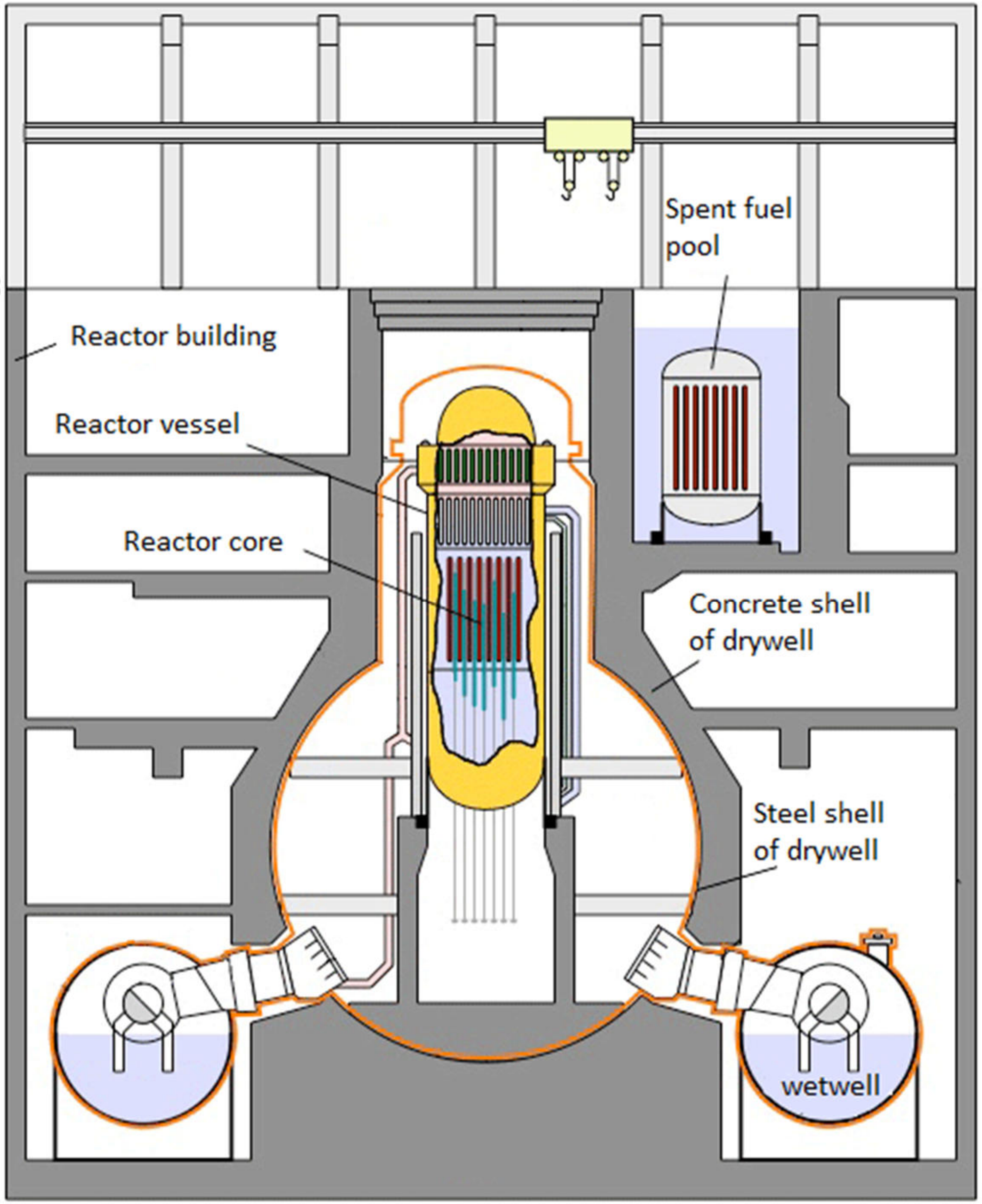
The pressure difference pushes the water of the bubbling condenser trays through the water seal

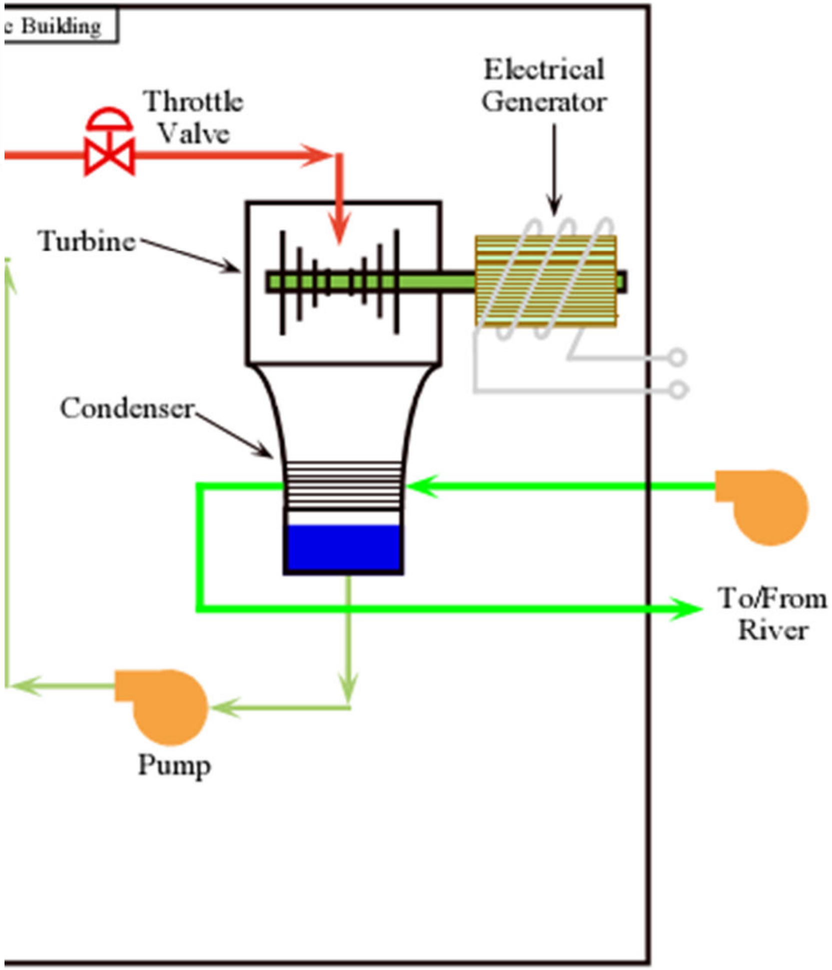
Passive containment flooding system!

Air trap check valves closed

Source: BME NTI

Boiling Water Reactor (BWR)





Comparison of BWR containments

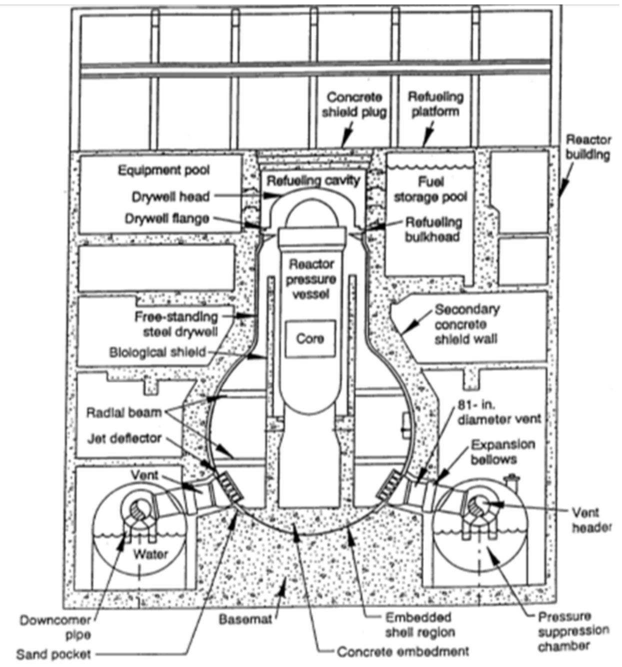


FIG. 2.1. GE-BWR Mark I design.

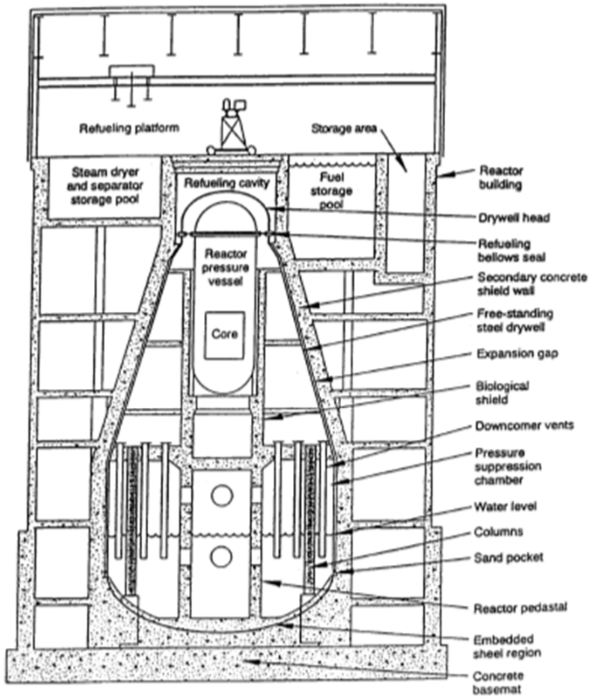


FIG. 2.2. GE-BWR Mark II design.

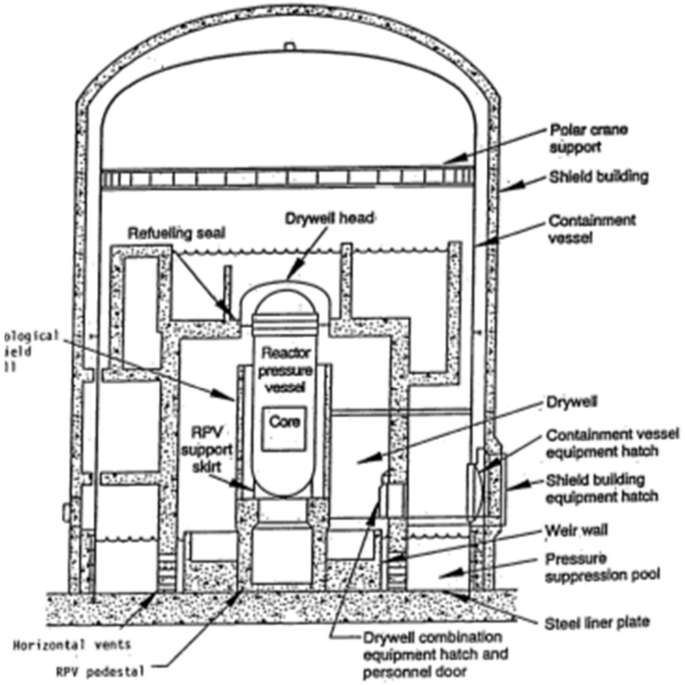


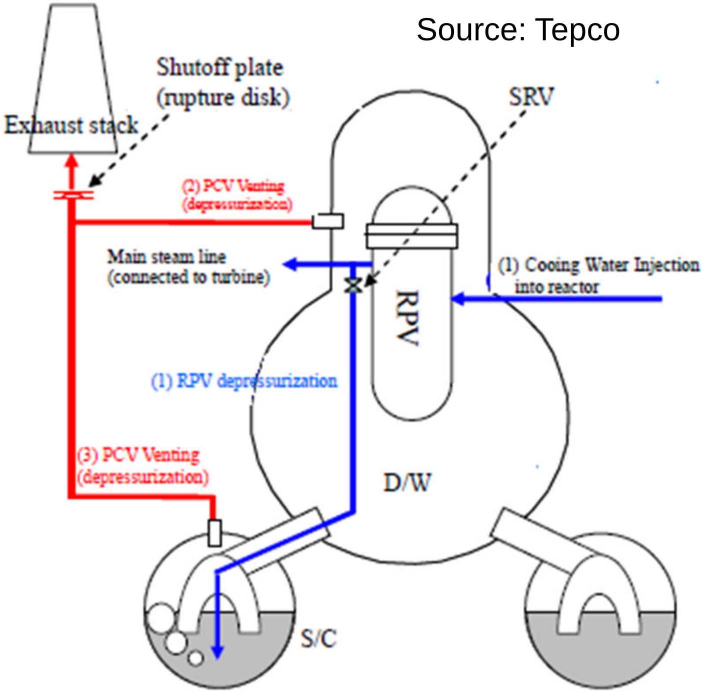
FIG. 2.3. GE-BWR Mark III design.

	Mark I	Mark II	Mark III
Drywell design overpressure (bar)	3.94–4.36	3.16–3.73	1.05
Drywell design temperatur (°C)	139–171	139–171	166
Drywell air volume (m^3) × 1000	3.7–5.0	5.7–8.6	7.1–7.9
Suppression chamber design overpressure (bar)	3.94–4.36	3.16–3.73	1.05
Suppression chamber design temperatur (°C)	139–155	100–139	74
Suppression chamber volume (m^3) × 1000	4.9–7.2	6.1–9.8	23.6–39.6

Containment venting

- A typical containment failure: slow overpressurization (see the Fukushima accident!)
- Preventing: containment depressurization
  - Containment cooling
  - Containment venting – releasing contaminated, radioactive atmosphere from the containment into the environment by controlled, filtered way
- Became an issue only in 80's
- At first mainly in the emergency operational procedures of BWRs
- NRC requirement in 1988: hardened venting for Mark I type containments
  - Hardened venting: stronger, more resistant piping, valves, remote-controlled valves
- Containment venting can be performed also after core melting through the wetwell

Source: Tepco



PCV: part comprising D/W and S/C

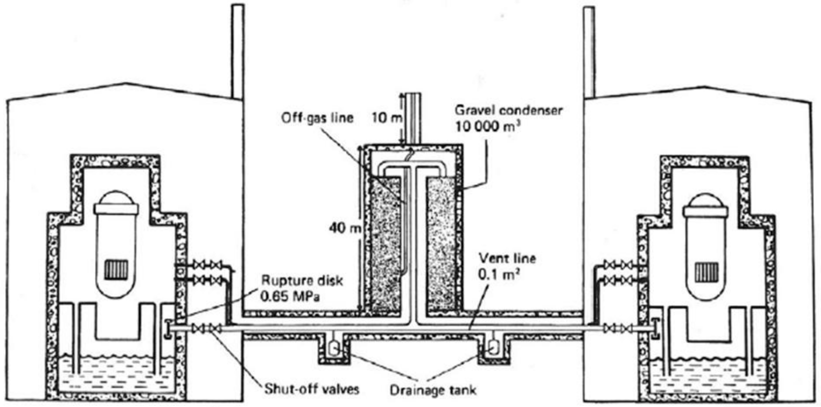
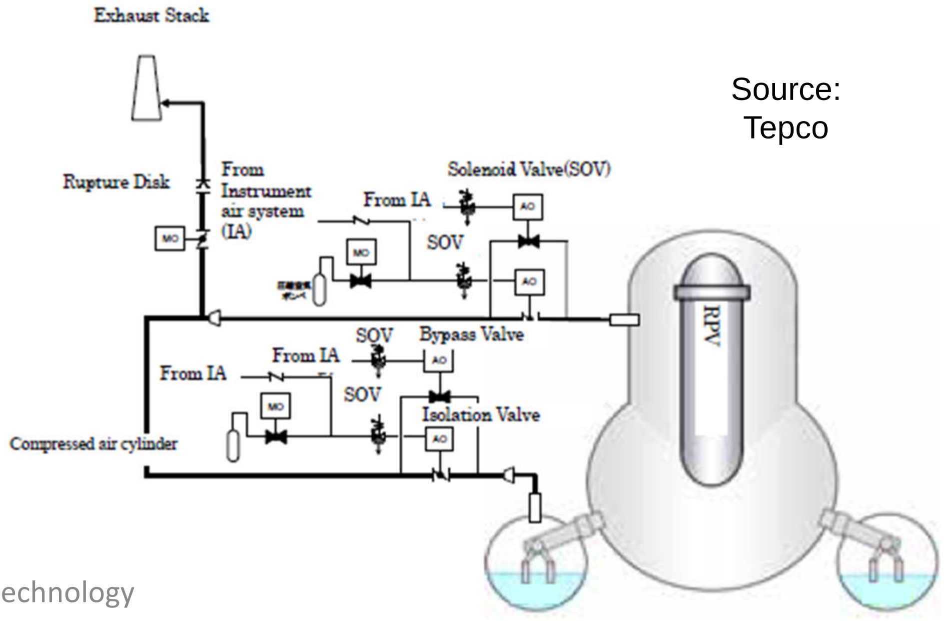


Figure 33. BWR Swedish Filtra venting system.

Containment venting

- Fukushima experiences with containment venting:
  - The measure designed for severe accident was not able to operate during the real severe accident!
  - Problems with valve actuation (high dose rates, loss of electricity, compressed air operated valves, etc.)
- Requirements after Fukushima for containment venting
  - NRC Task Force: reliable hardened venting instead of former hardened venting requirement (for Mark I and II)
  - Reliable hardened venting should be considered also for other containment types (**PWR!**)
  - Venting should be performed by passive controlling (pressure limiting) and by active (depressurization at selected time e.g. for activation of LPIS) as well
  - Ventilation of wetwell and drywell should be possible for long term without endangering the personnel
  - Common systems for more units in containment vent system should be avoided
  - Seismic resistance

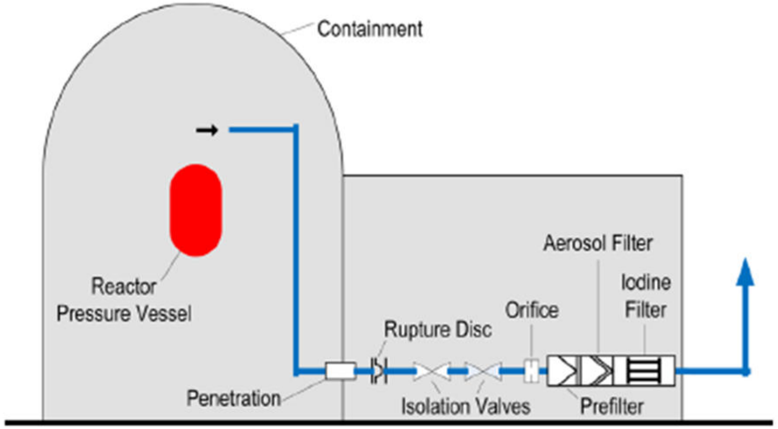
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment



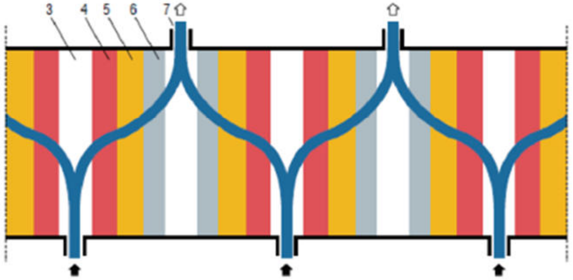
Source: Tepco

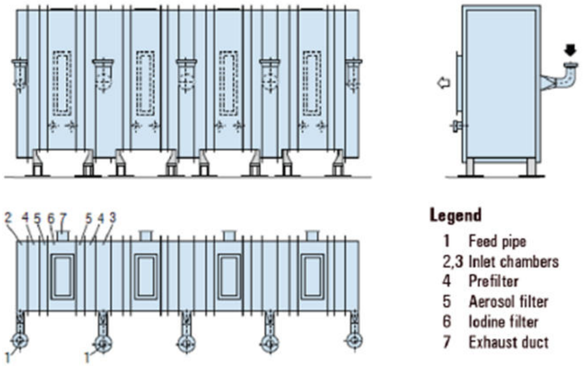
Containment venting

- Example: Westinghouse system for PWRs
  - Dry filter venting
  - Moisture separator at FCVS (Filtered Containment Venting System) inlet
  - Remove actuation (containment isolation valves) or with rupture disk
  - Can be realized with passive components
  - Aerosol filter: two stages for removal of particles
    - Pre-filter: metallic fibre with decreasing diameter (65-12 µm)
    - Main filter: metallic fibre with decreasing diameter (12-2 µm)
  - Iodine filter: molecule filter with zeolite (sorption of elemental and organic iodine)

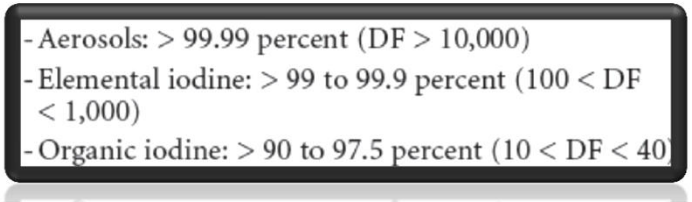


Schematic view of Dry Filter Method





DFM filter unit – Example of a 1300 MWe PWR



- Aerosols: > 99.99 percent (DF > 10,000)
- Elemental iodine: > 99 to 99.9 percent (100 < DF < 1,000)
- Organic iodine: > 90 to 97.5 percent (10 < DF < 40)

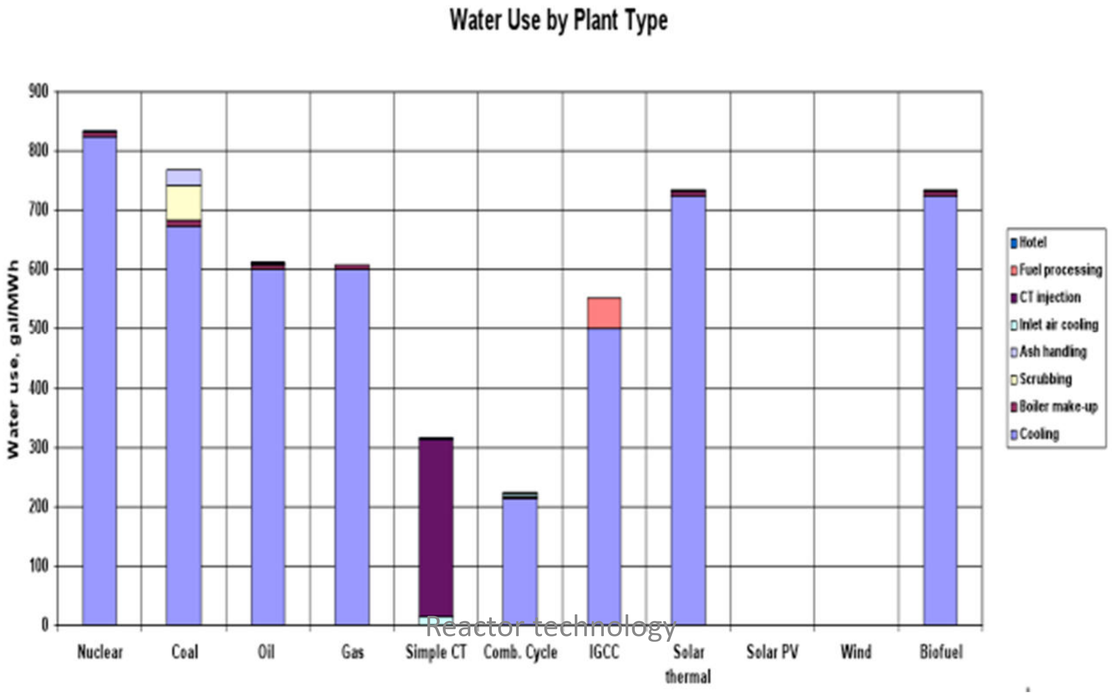
Source: Westinghouse

COOLING OF NUCLEAR POWER PLANTS

Condenser cooling

- Why is it a special nuclear plant problem?
- Because at 1000 MW unit power the heat to be removed into environment is:
    - nuclear plant: 2000 MW
    - thermal power plant: 1000…1300 MW
    - combined cycle: max. 700 MW

+ Safety!
(emergency cooling)



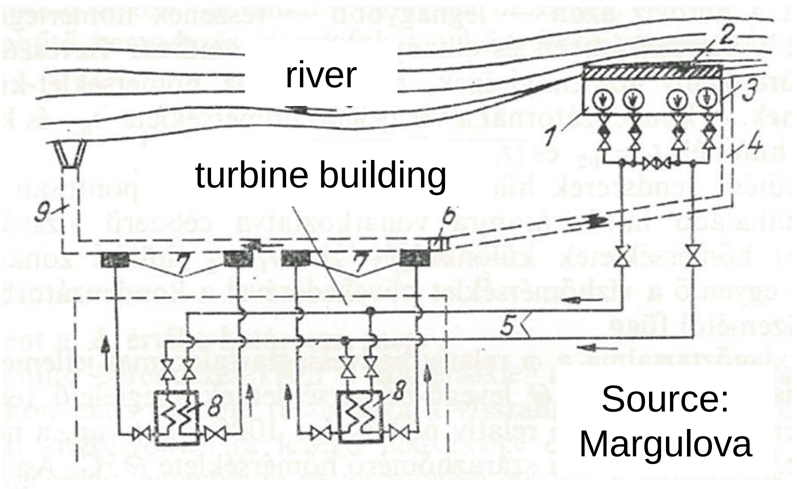
Condenser cooling

- Direct (once-through) cooling
  - River fresh water
  - Seawater cooling
- Recirculating or indirect cooling
- Dry cooling

E.g. USA, 104 units
60 direct cooling
35 wet cooling tower
9 mixed system

Condenser cooling – fresh water cooling

- Low temperature fresh water source needed with proper mass flow rate.
  - Condenser heat exchanger surface is determined by ultimate heat sink (UHS) temperature
  - Example: Turkey (1% difference in power output depending on the sea choice)
- This is the main aspect concerning the siting of NPPs (beside the safety aspects)
- Sea water cooling: more effective cooling is possible, but requirements for materials are more rigorous
- Limitation for coolant outlet temperature -> design limits
- USA: „clean water act” – fresh (river) water cooling practically eliminated

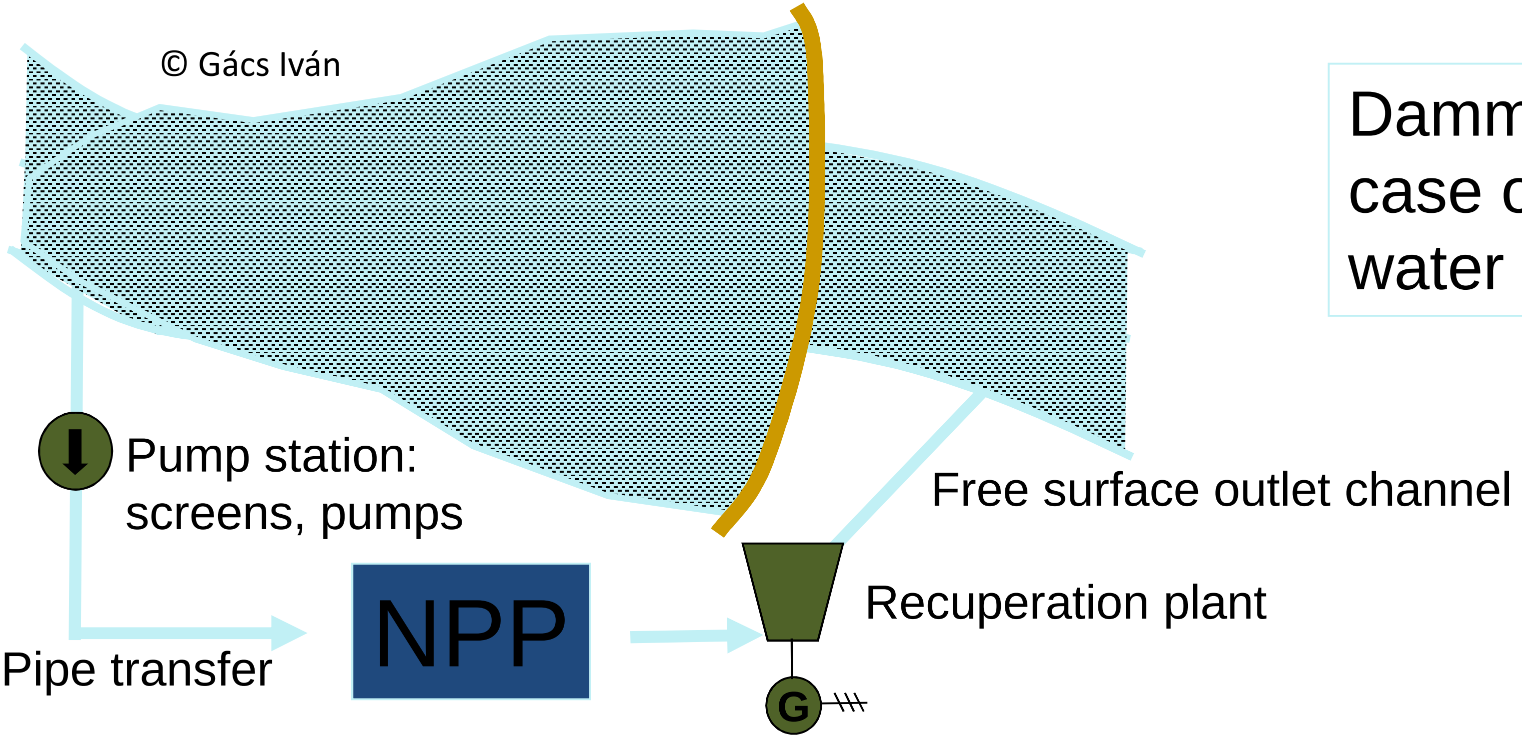


Source: Margulova

Scheme of fresh water cooled NPP

1. Water intake structures
2. Screens
3. Cooling pumps
4. Auxiliary hot channel
5. Coolant intake lines
6. Switching pit
7. Discharge pit
8. Condensers
9. Discharge channel

Fresh water cooling



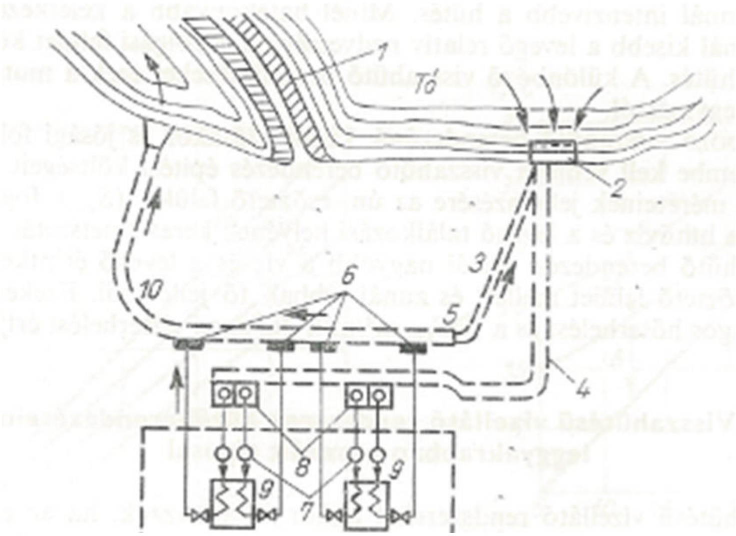
Damming in case of >30% water usage

Fresh water usage: from river: max. 1/3 of the flow rate

Problems: continuous condenser cleaning

Condenser cooling – cooling lake

- Advantages: (relatively) cheap and simple
- Low evaporation -> lower losses (than in spray ponds)
- Coolant pumps in bank pumping station or in turbine building
- Intake and offtake shall be separated
- Disadvantage: large area, large excavation work needed
- Loss: about 1 mm / day weeping to soil



Scheme of cooling lake cooled NPP

1. Directing dam
2. Water intake structures
3. Auxiliary hot channel
4. Gravitational coolant intake lines
5. Switching pit
6. Offtake pit
7. Cooling pumps
8. Intake pits
9. Condensers
10. Offtake channel

Source: Margulova

Condenser cooling – cooling lake

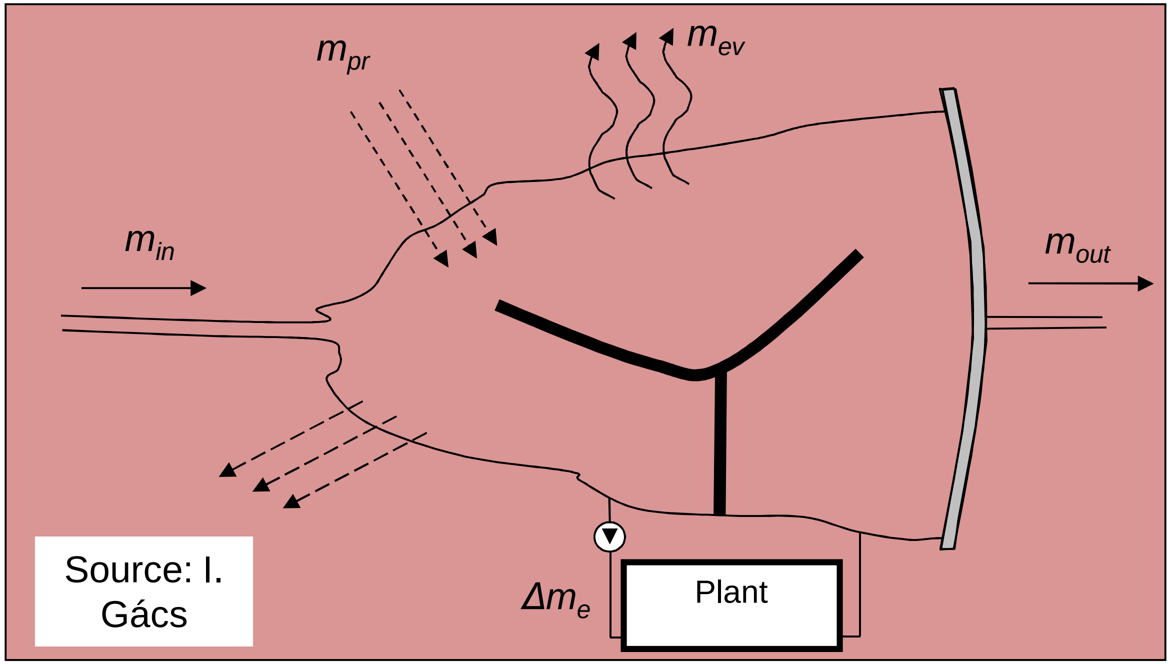
$$m_{in} + m_{pr} = m_{leak} + m_{ev} + m_{out} + \Delta m_e$$

water mass balance

$$m_{in} \cdot c_{in} = (m_{leak} + m_{out} + \Delta m_e) \cdot c$$

Dissolved material (salt) mass balance

$$m_{in,min} = (m_{ev}+\Delta m_e-m_{pr})/(1-c_{in}/c)$$



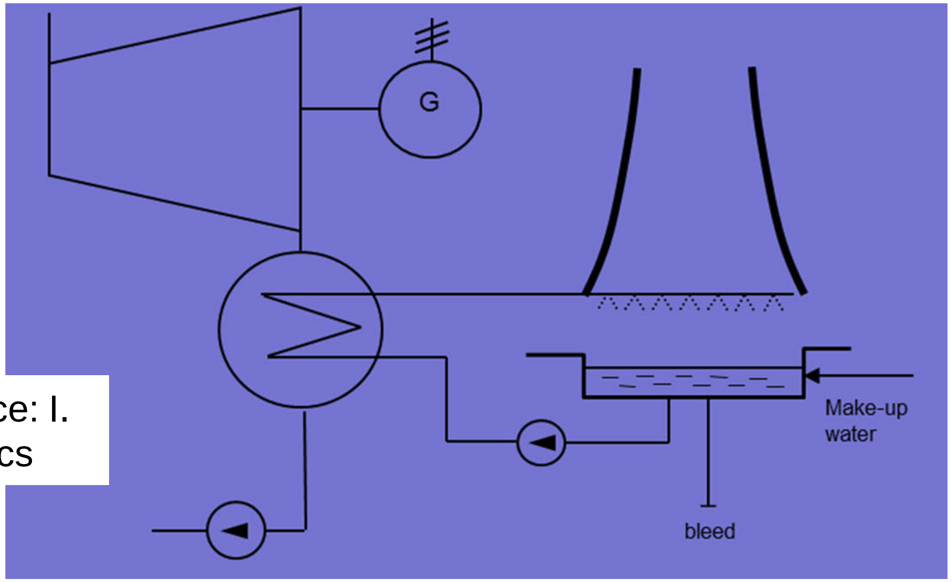
Source: I. Gács

Necessary surface:
1 MW$_e$ ÷ 1 ha

Cooling lake – South Ukrainian NPP

(Photo: AA)

Condenser cooling – wet cooling towers



Source: I. Gács

- Natural draft
- Forced draft

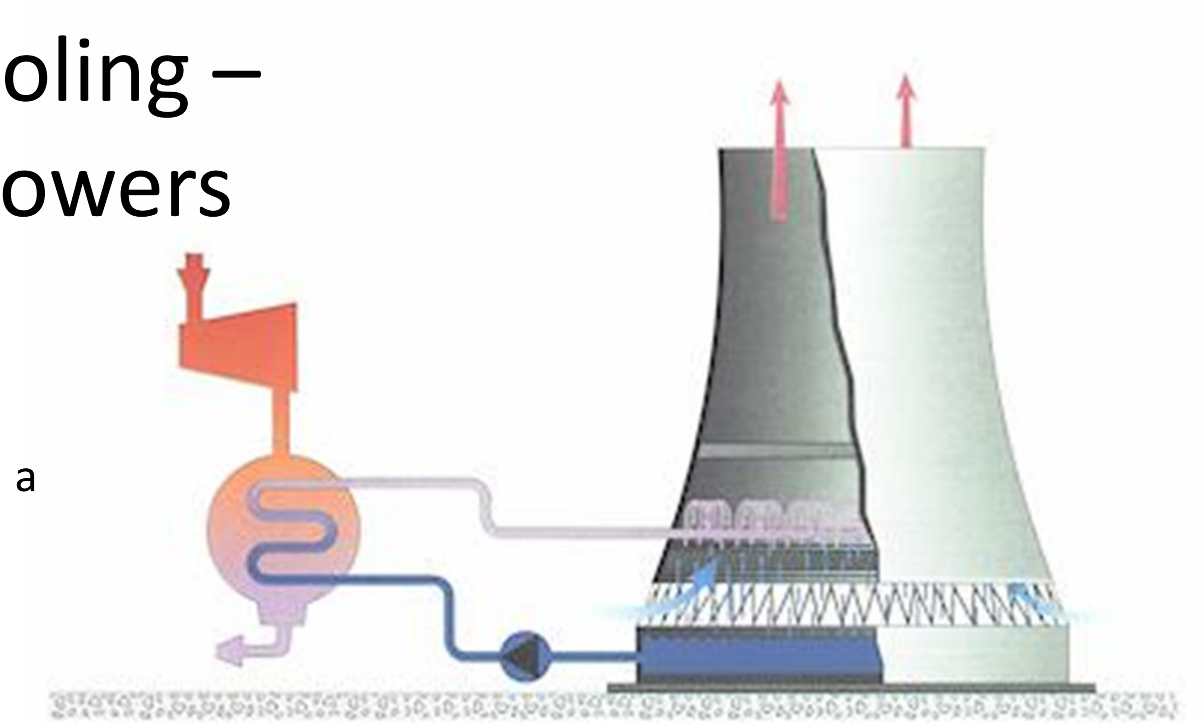
Wet cooling tower

Prairie Island NPP, Minnesota, USA

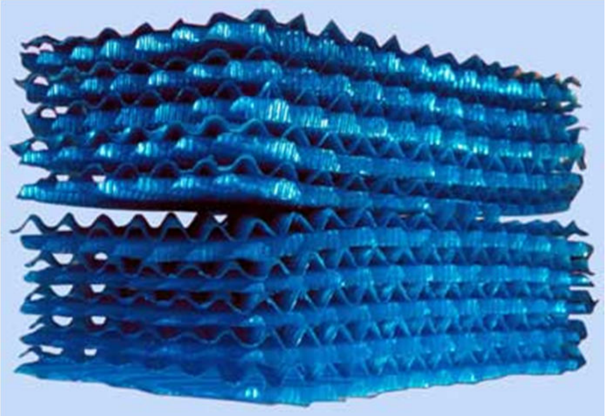
Leibstadt NPP,
Switzerland

Condenser cooling – wet cooling towers

- Natural draft cooling towers
  - large concrete shell with a heat exchange 'fill’
  - effective cooling with large air-water surface
- Up to 120-200 m height
- Advantage: low area, no large water flow (river) necessary
- Disadvantage: high construction cost and water losses (about 3%)
- Counterflow and crossflow types



http://www.gea-energytechnology.com

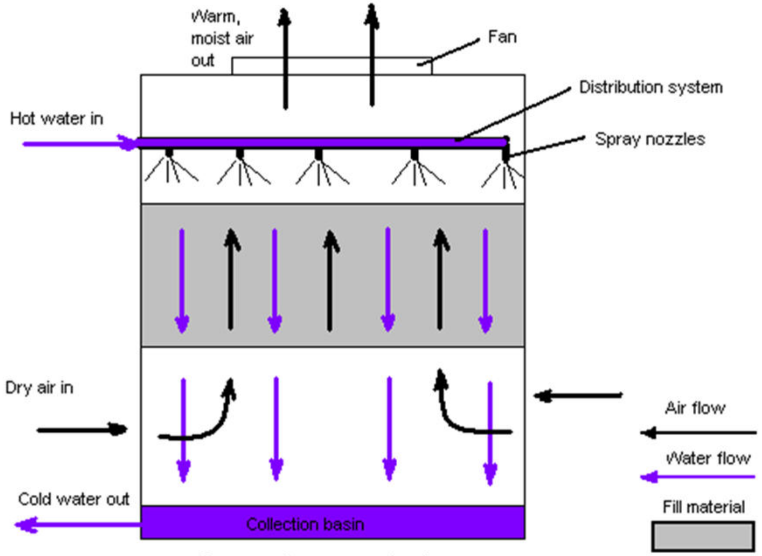


Source: http://raicoolingtower.com

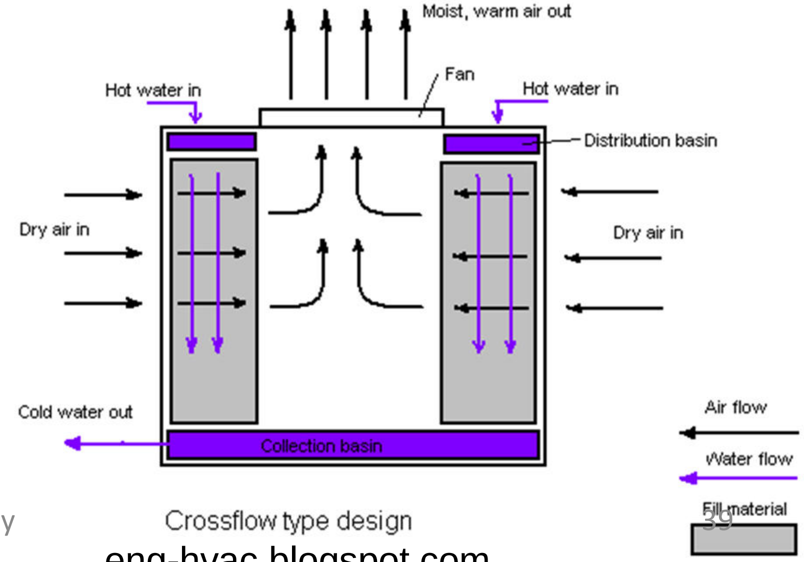
Condenser cooling – wet cooling towers

- Mechanical draft cooling towers
  - have large axial flow fans
  - Can provide lower water temperatures
  - auxiliary power needed: typically about 1-1.2% of the output
  - Height: max. 50 m
  - used typically in Central and Western USA (because of extreme weather conditions)
  - Cooling towers are ~40% more expensive than a direct, once-through cooling system

Chinon B



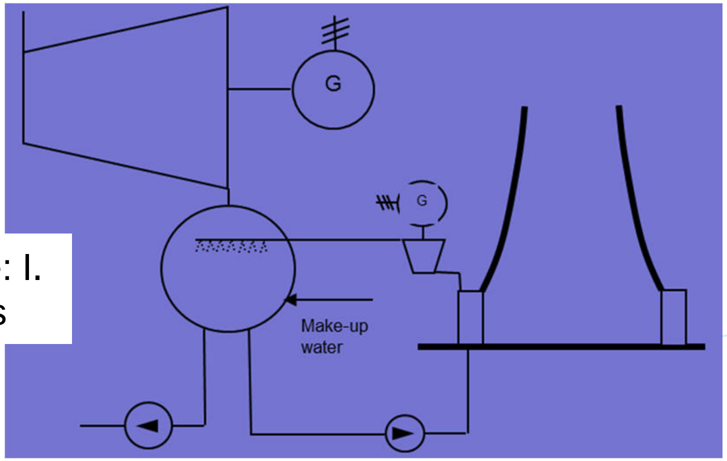
Counterflow type design



Crossflow type design

eng-hvac.blogspot.com

Condenser cooling – dry cooling towers



Source: I. Gács

Finned tube heat exchanger

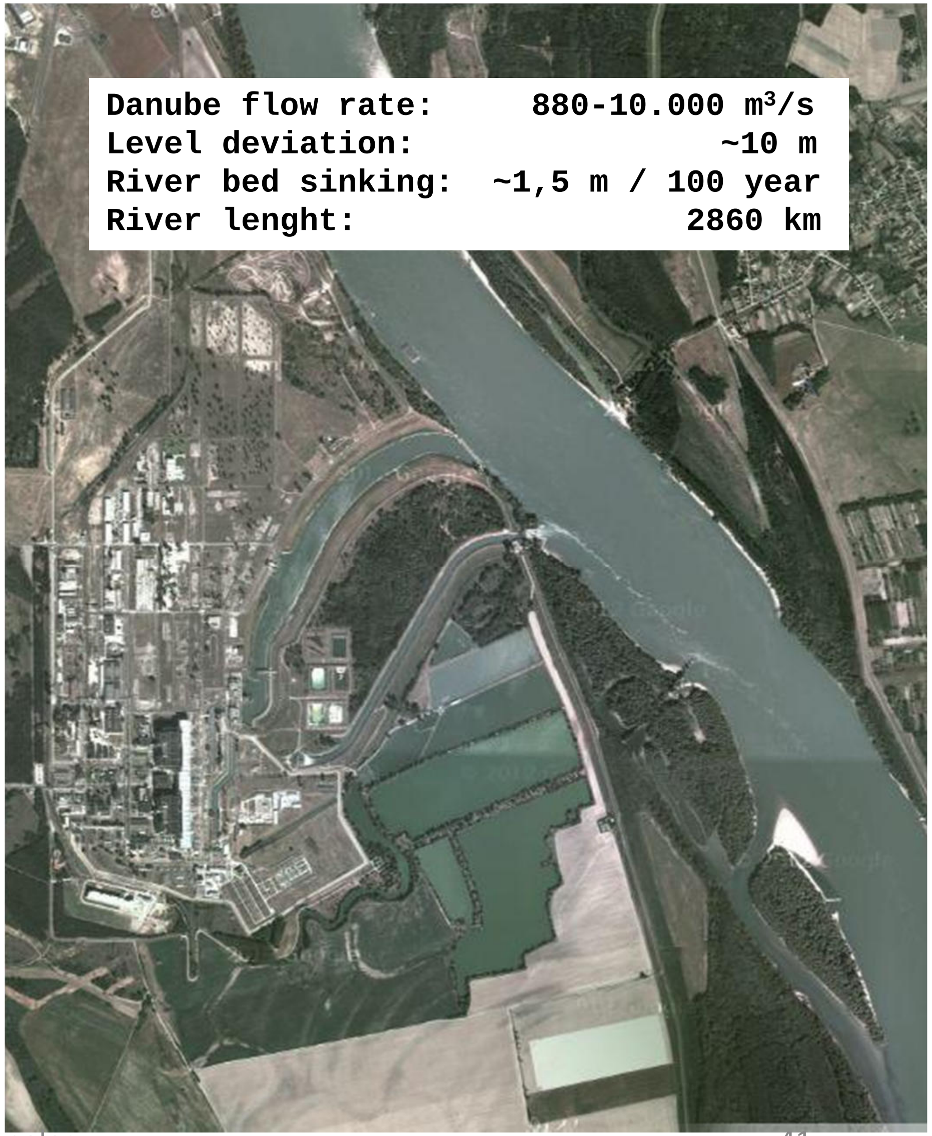
- Direct dry cooling, using air-cooled condenser (ACC)
- Or with condenser cooling circuit (water enclosed and cooled by a flow of air past finned tubes in a cooling tower)

- High energy demand
- Low efficiency
- Used where the amount of freshwater is not enough (uses less than 10% of the water required for a wet-cooled plant)
- In USA and UK ruled out from new NPP applications
- Safety concerns (LOOP)

Condenser cooling system of Paks NPP

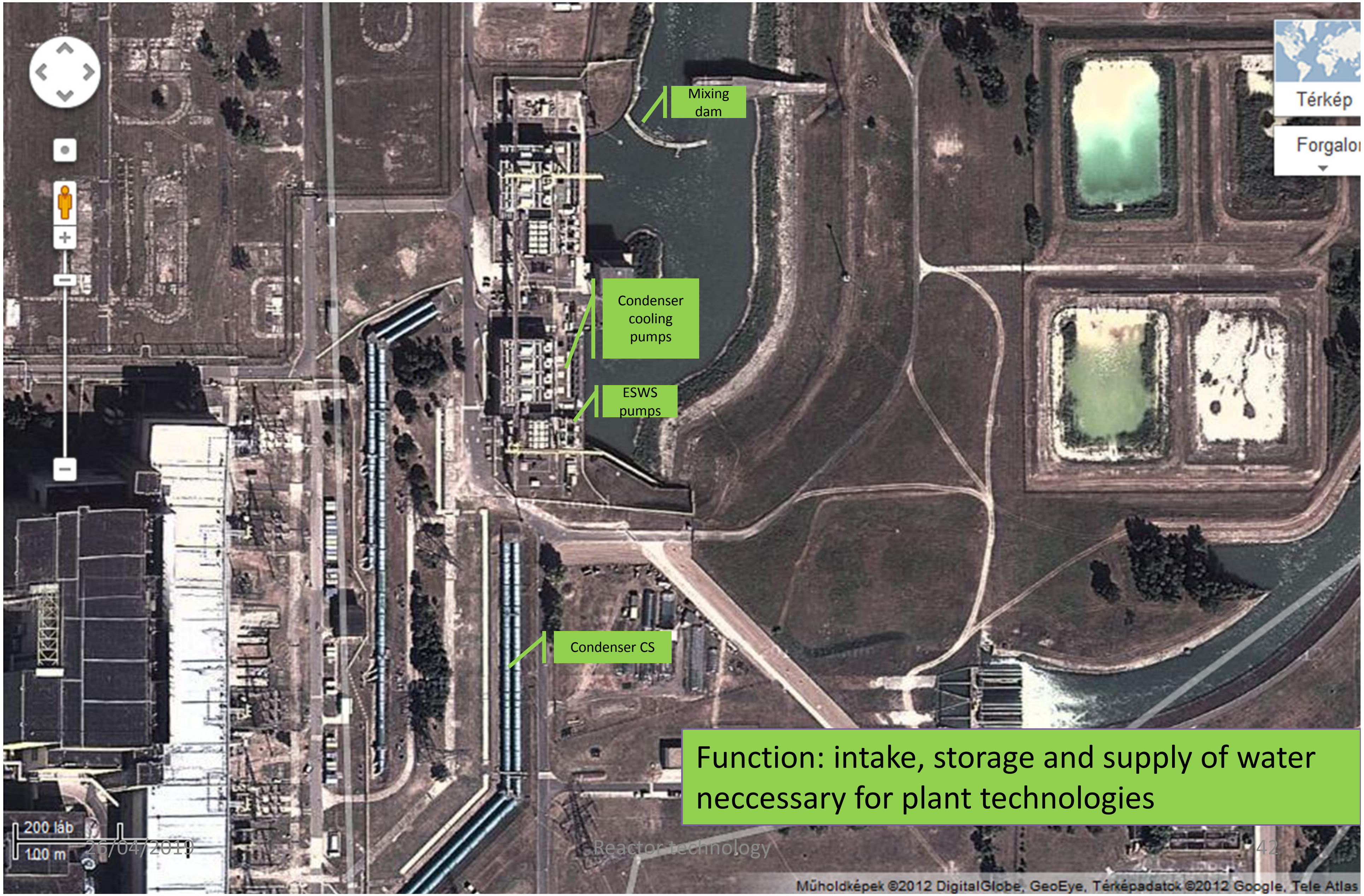
- 4*500 MW electric output, 4*1485 MW thermal power
- Condenser cooling: fresh water (once-through) cooling with the river Danube
- Water sources: river Danube, 30 m deep wells, 120 m deep stratum water
- Water usage of NPP:

Condenser coolant	105	m^3/s
Safety water system	3	m^3/s
Component cooling water	2	m^3/s
Fire water	0.21	m^3/s
Drinkwater	0.01	m^3/s



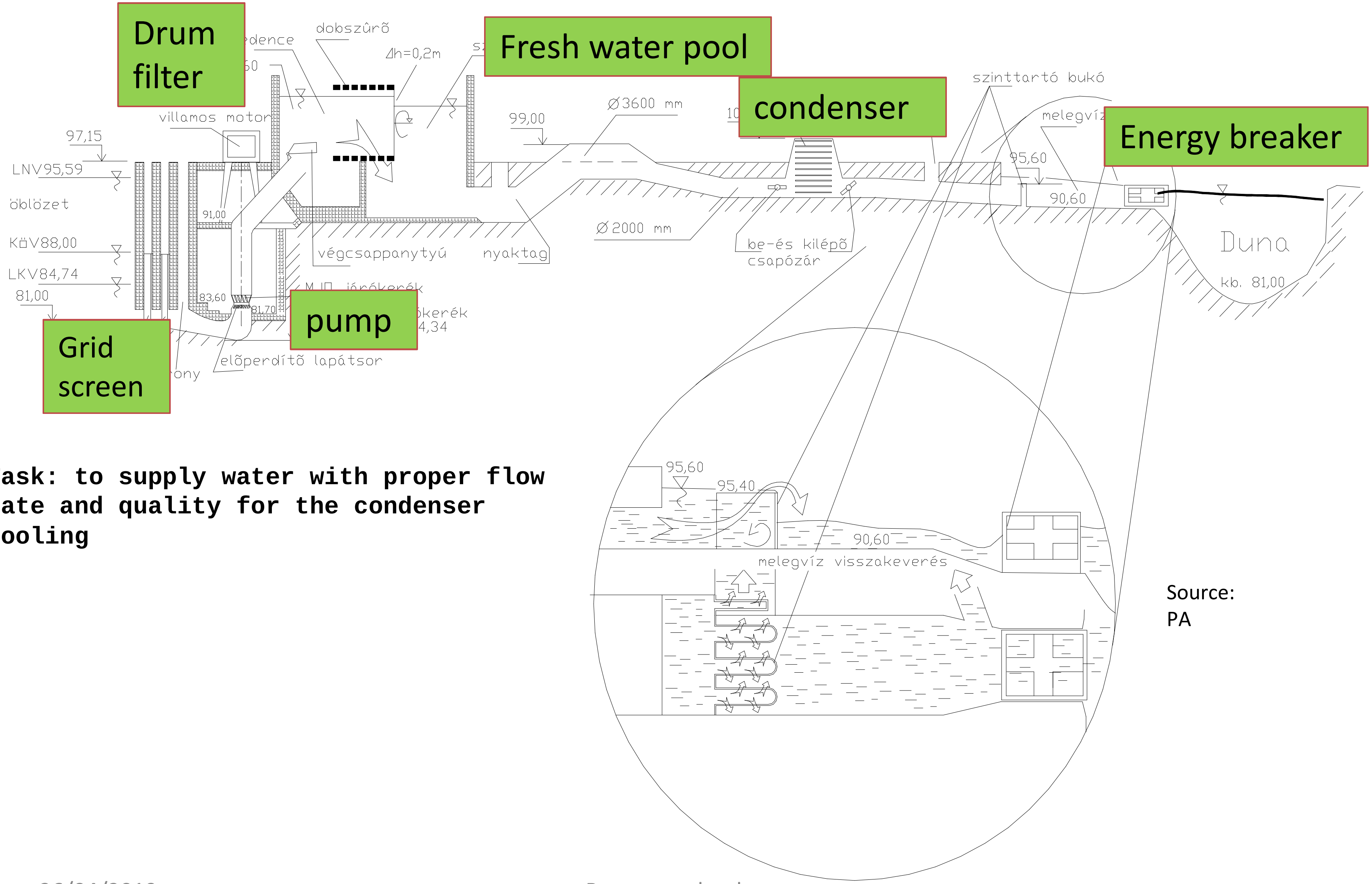
Danube flow rate: 880-10.000 m^3/s
Level deviation: ~10 m
River bed sinking: ~1,5 m / 100 year
River lenght: 2860 km

Water intake structure at Paks NPP



Function: intake, storage and supply of water neccessary for plant technologies

Condenser cooling at Paks NPP

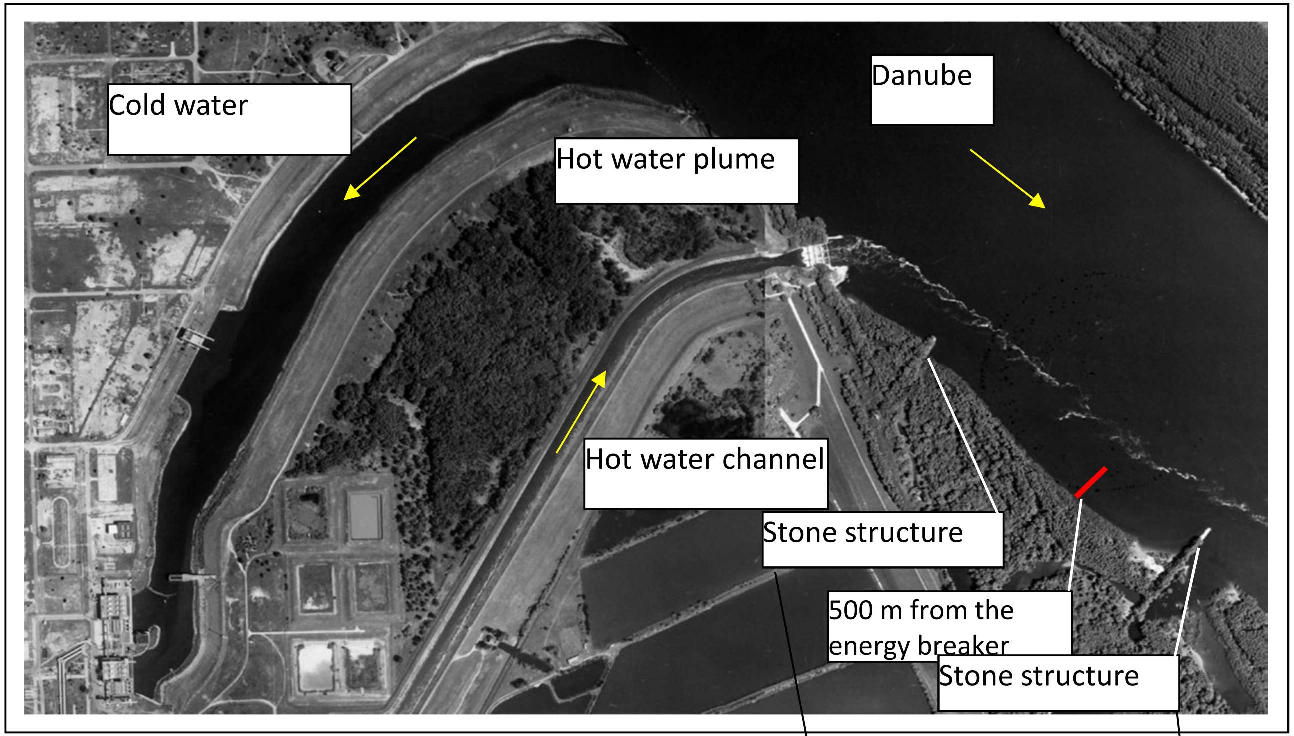


Task: to supply water with proper flow rate and quality for the condenser cooling

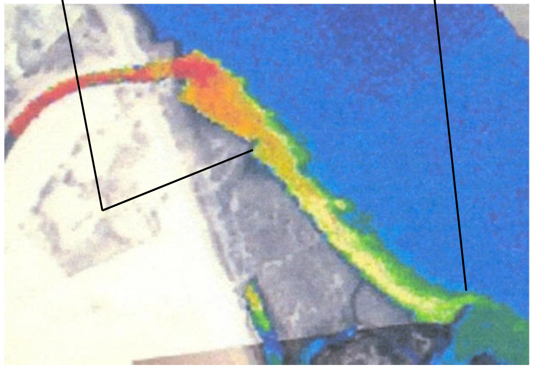
Source:
PA

Paks NPP – regulatory limits

- The temperature difference between the discharged water to the Danube and the temperature of the Danube water shall be below 14 °C (under 4 °C Danube water temperature) or below 11 °C (above 4 °C Danube water temperature),
- The temperature of the Danube water shall not exceed 30 °C at any point of the cross section in a distance of 500 m from the discharge (energy break structure)



The hot water plume



Source: PA

Essential service water system (ESWS)

- Function: supplying coolant for consumers that are necessary for maintaining the fundamental safety functions (cooling the reactor and keeping it in subcritical state)
- <u>Main consumers of ESWS</u>
  - Heat exchangers of emergency coolant systems
  - Cooling of MCP, CRDM (control rod driving mechanism) intermediate cooling circuits
  - Cooling of spent fuel pool heat exchanger
  - Cooling of emergency diesel generators
  - Cooling of containment recirculation air cooling system
- The system has different tasks in normal operation and in accidental conditions:
  - In normal operation it serves the consumers of technology system and the shutdown and cool-down systems of the reactor
  - In accidental conditions: it supplies the consumers of decay heat removal systems