Nuclear Power in the Age of New Threats
online webinar

Nuclear Power Plants in War Zones
Safety Considerations

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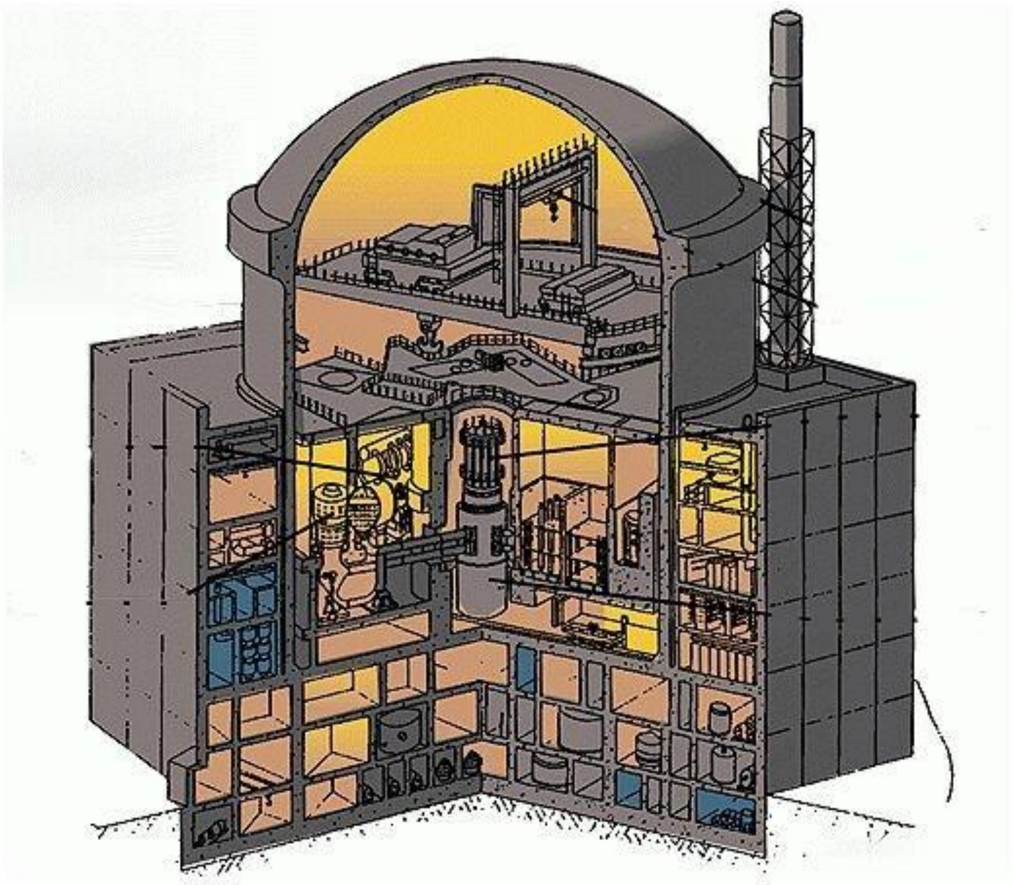
NPPs in operation in Ukraine

- **Rivne NPP**
  - Unit 1 VVER 440/213
  - Unit 2 VVER 440/213
  - Unit 3 VVER 1000/320
  - Unit 4 VVER 1000/320
- **Khmelnytskyi NPP**
  - Unit 1 VVER 1000/320
  - Unit 2 VVER 1000/320
- **South Ukraine NPP**
  - Unit 1 VVER 1000/302
  - Unit 2 VVER 1000/338
  - Unit 3 VVER 1000/320
- **Zaporizhzhia NPP**
  - All 6 Units VVER 1000/320

Introduction - VVER1000

- **VVER1000 –** Водо-водяной энергетический реактор



- **Water cooled**
- **Water moderated**
- **Electrical power 1000MW**
- **Thermal power 3000MW**

Introduction VVER1000 / Primary System

Power operated relief valve
(G = 50kg/s)

Emergency gas removal system
(G = 20-25 kg/s)

Steam Generator
(P=6.27 MPa, T=278°C, G=408kg/s)

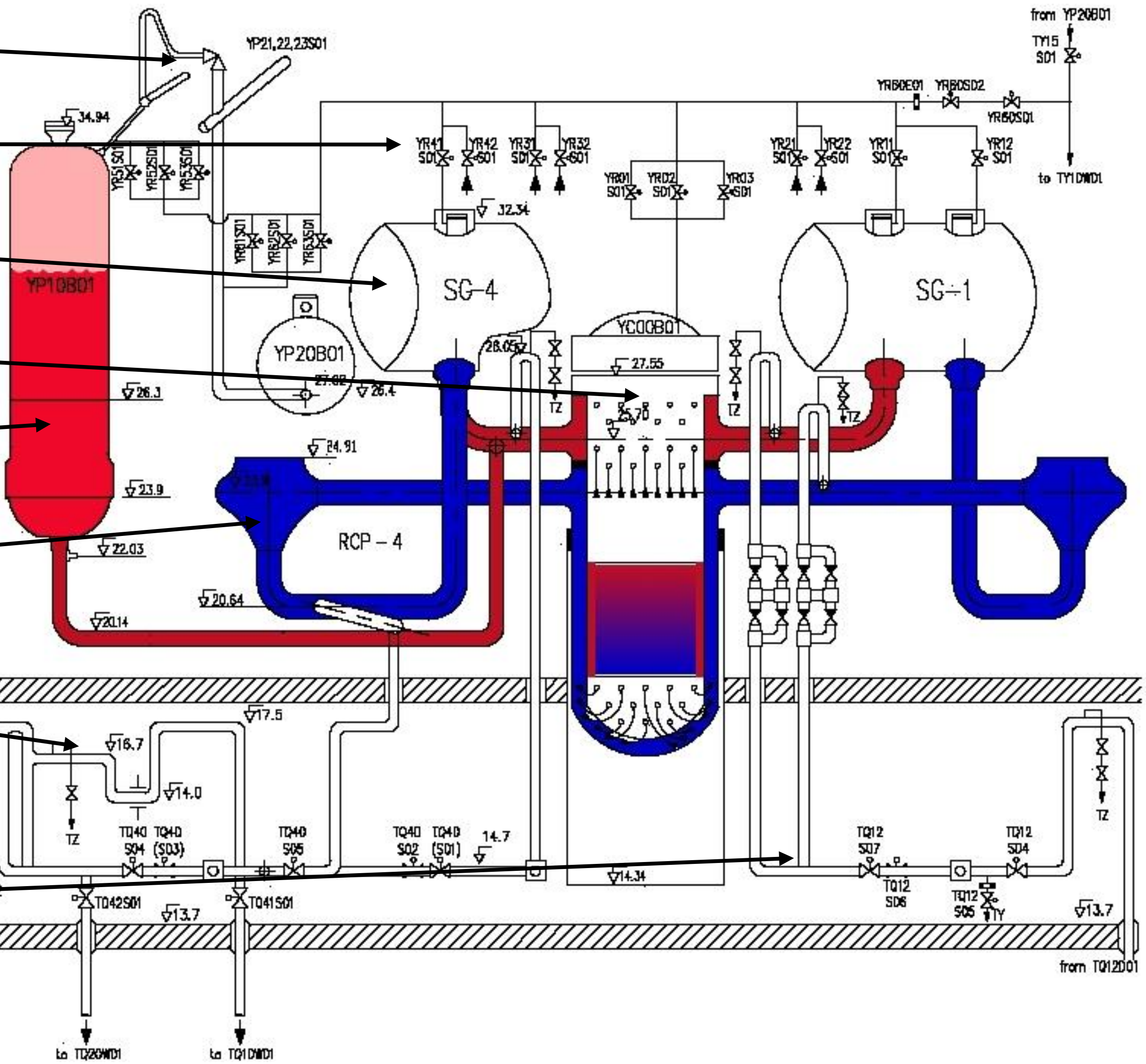
Reactor Pressure Vessel
(Ti=289.7°C, To=320°C)

Pressurizer
(P=15.7 MPa, T=344°C)

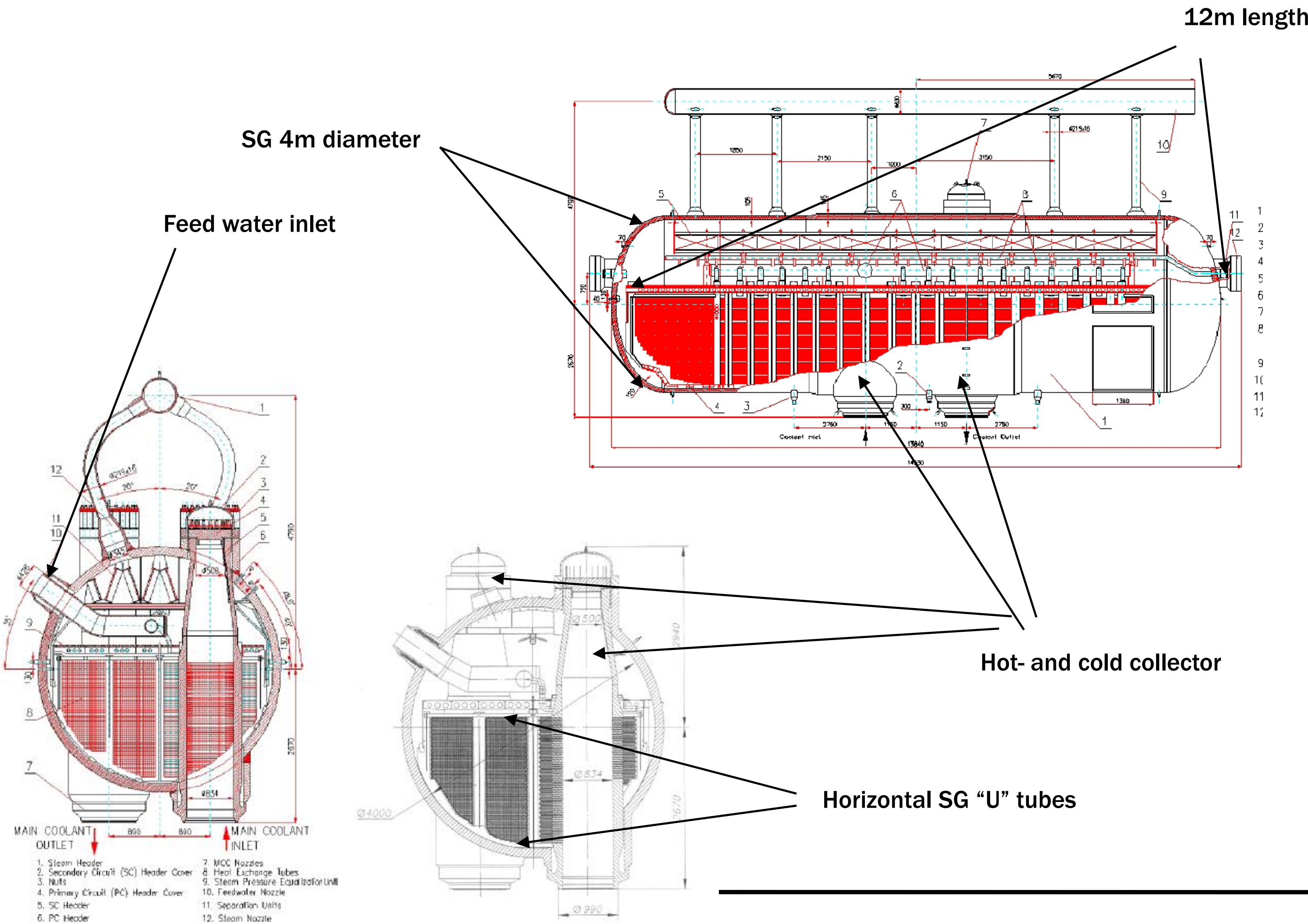
Main coolant pump
(G=21200m3/h, 4400kg/s)

Chemical and volume control system

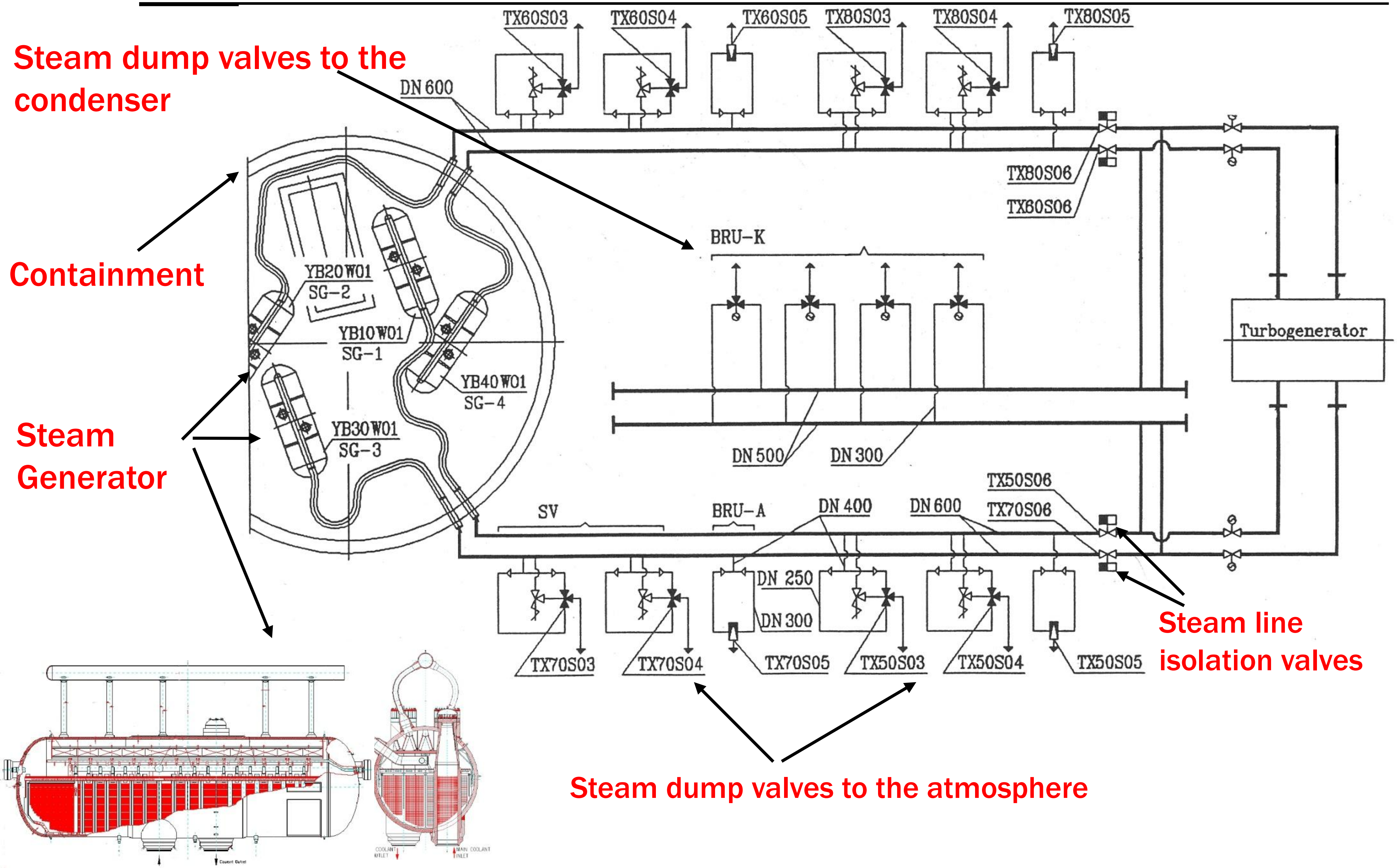
Low pressure injection system (one train)



Key design point – horizontal SG



Introduction – VVER1000/Steam Lines



Introduction – VVER1000/Feed Water Lines

- **Feed water system (from deaerator to SG)**
  - Two feed water (deaerator) tanks (5.8 bar, saturated steam/water, roughly 160 °C, Volume 185 m^3 each)
  - Two booster pumps and main feed water pumps, capacity 950 kg/s (3750 m^3 /h) each
  - Two auxiliary feed water pumps (for startup- and shutdown), capacity 40 kg/s (150 m^3 /h) each
  - Pipes, heat exchanger and valves (volume of pipes roughly 170 m^3)

- **Emergency feed water system**
  - Three independent trains (3x100%) consisting of:
    - Feed water tank (atmospheric pressure, temperature 50°C)
    - Pump capacity 40 kg/s (150 m^3 /h)
    - Pipes and valves
    - Supply from diesel generator in case of loss of offsite power

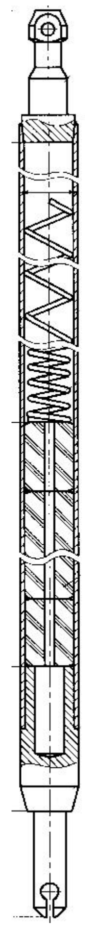
Introduction – VVER1000/Core

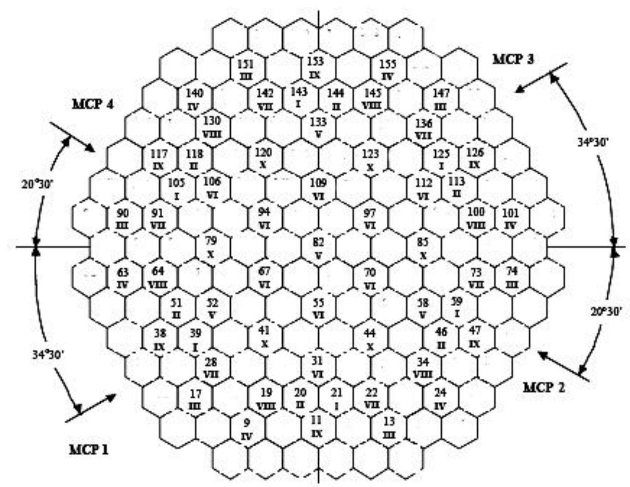
- **Pellets – cylindrical with central hole**
  - Outer diameter 7.57mm,
  - Diameter of central hole 1.5 mm
  - Height roughly 12 mm
  - Uranium dioxide

- **Fuel rods**
  - Height 4.57 m (active zone 3.55 m)
  - Alloy Zirconium + 1% Niobium
  - Outer diameter 9.91 mm,
  - Inner diameter 7.73 mm
  - Mass of fuel 1.57 kg
  - Helium filled, pressure 2 MPa

- **Fuel assemblies (311 fuel rods)**
  - Hexagonal
  - Pitch 12.75 mm

- **Core (161 fuel assemblies)**
  - Ten groups of control rods (61 fuel assemblies with control rods)
  - Four zones of enrichment 1.6%, 3%, 3.6%, 4.4%
  - Total mass UO_2 - 80 tons





Introduction – VVER1000/ECCS

- High pressure boron injection system HHPIS (TQ4)
  - Three independent trains 3x100%, each consisting of
  - Tank (15m^3 40g/kg of boric acid in water)
  - Pump (injection up to 20MPa, flow rate at nominal pressure 6.3 m^3/h, 2 kg/s)
  - Pipes and valves – injection into loop 1, 3 and 4 after MCP

- High pressure injection system HPIS (TQ3)
  - Three independent trains 3x100%, consisting of
  - Tank (15m^3 40g/kg of boric acid in water)
  - Pump (injection up to 10.9 MPa, flow rate at 8.8 MPa 130 m^3/h, 36 kg/s)
  - Pipes and valves
  - Once tanks are empty, pumps can take suction from the containment sump (500 m^3 water boric acid)
  - Common injection lines with TQ4

Introduction – VVER1000/ECCS

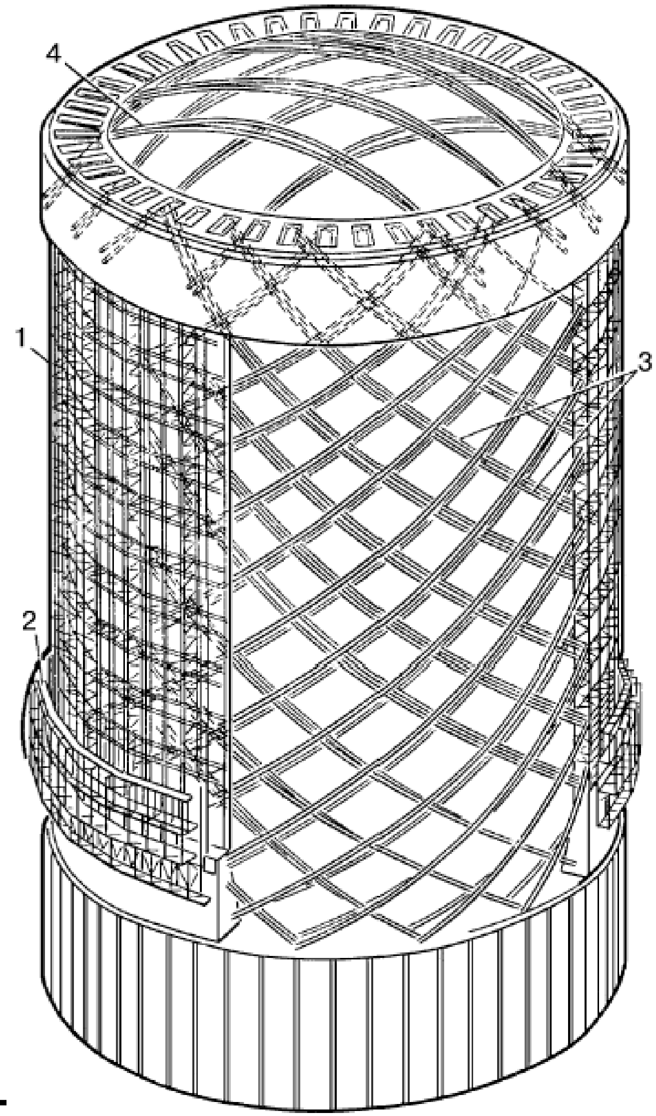
- **Hydro accumulators (YT)**
  - Four hydro accumulators (4x33%)
  - Boric acid concentration 16g/kg water
  - Activation pressure 5.9 MPa +/- 0.3 MPa
  - Pipes and Valves (four independent lines)
  - Injection point into upper plenum (2) and downcomer (2)
  - Water volume 50 m^3, Nitrogen volume 10 m^3

- **Low pressure injection system LPIS (TQ2)**
  - Three independent trains 3x100%, consistent of
  - Pump (injection up to 2.6 MPa, flow rate at 1 MPa 750 m^3/s, 210 kg/s)
  - Emergency cool-down heat exchanger
  - Pipes and valves
  - Suction from containment sump (500 m^3, 16g/kg of boric acid)
  - Two trains injection into UP and DC respectively, one into HL/CL of loop No 1

VVER-1000. Containment

- ❑ **Concrete cylinder**
- ❑ **Reinforced by pre-stressed wire bundles**

1. Cage of reinforcement
2. Boxing for concrete formation
3, 4. Reinforcing wiring

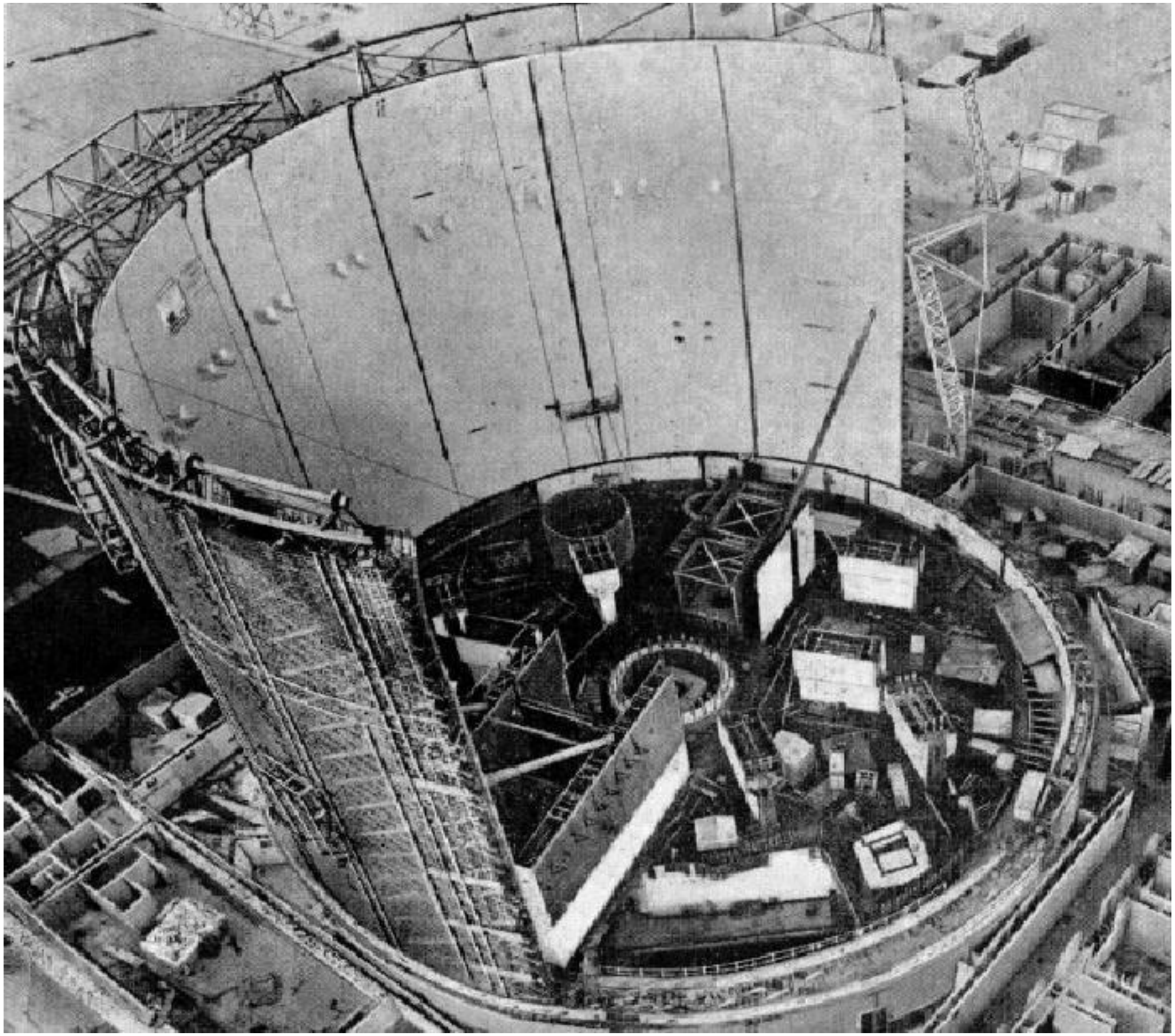


The reactor building construction is designed also to withstand effects of an external air blast with intensity 0.3 kgf/cm 2 for 1s. The containment structure must withstand the impact of a falling plane with speed of 750 km/h and mass 10 t.

Internal diameter	45 m
Height	66 m
Wall thickness	1.2 m
Base plate thickness	2.4 m

Data for Balakovo NPP (Russian Federation)

VVER-1000. Containment

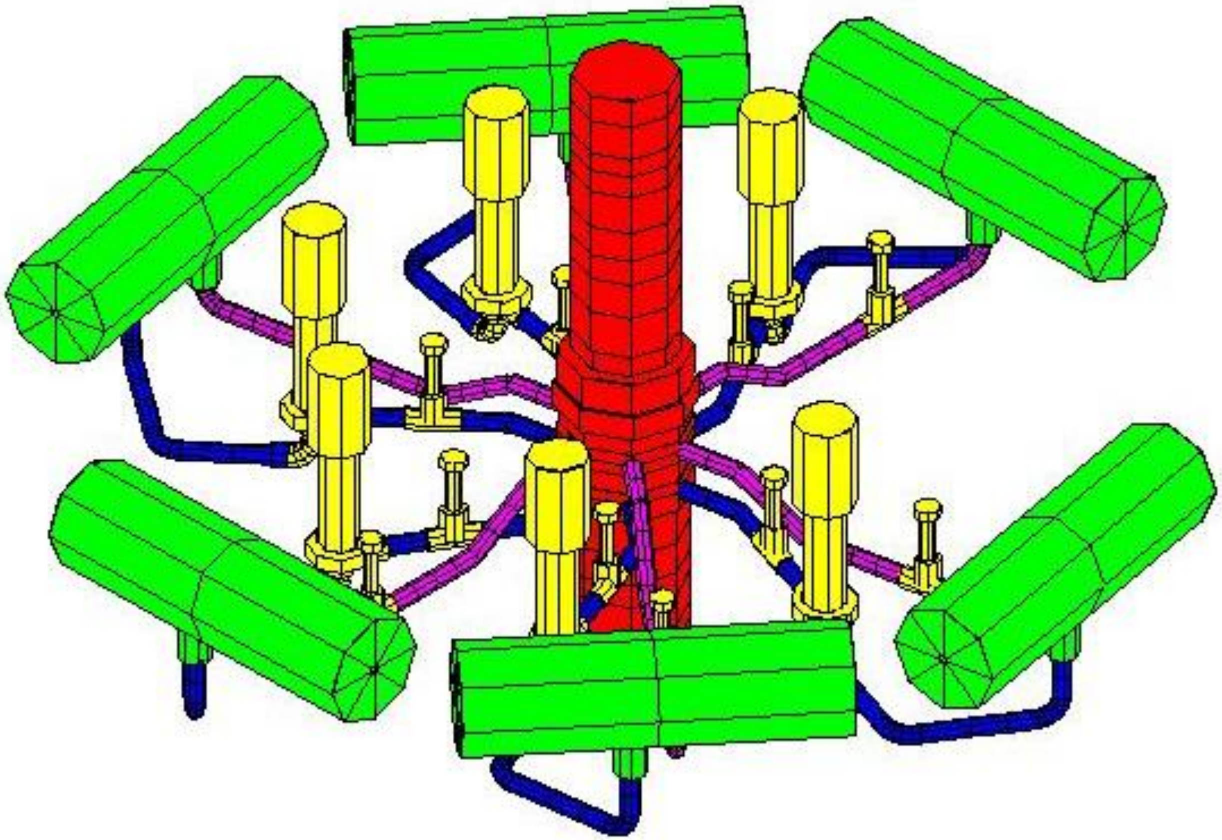


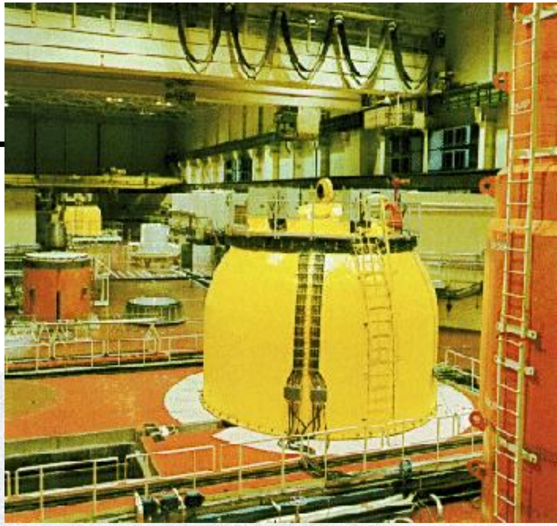
VVER-440. Main features

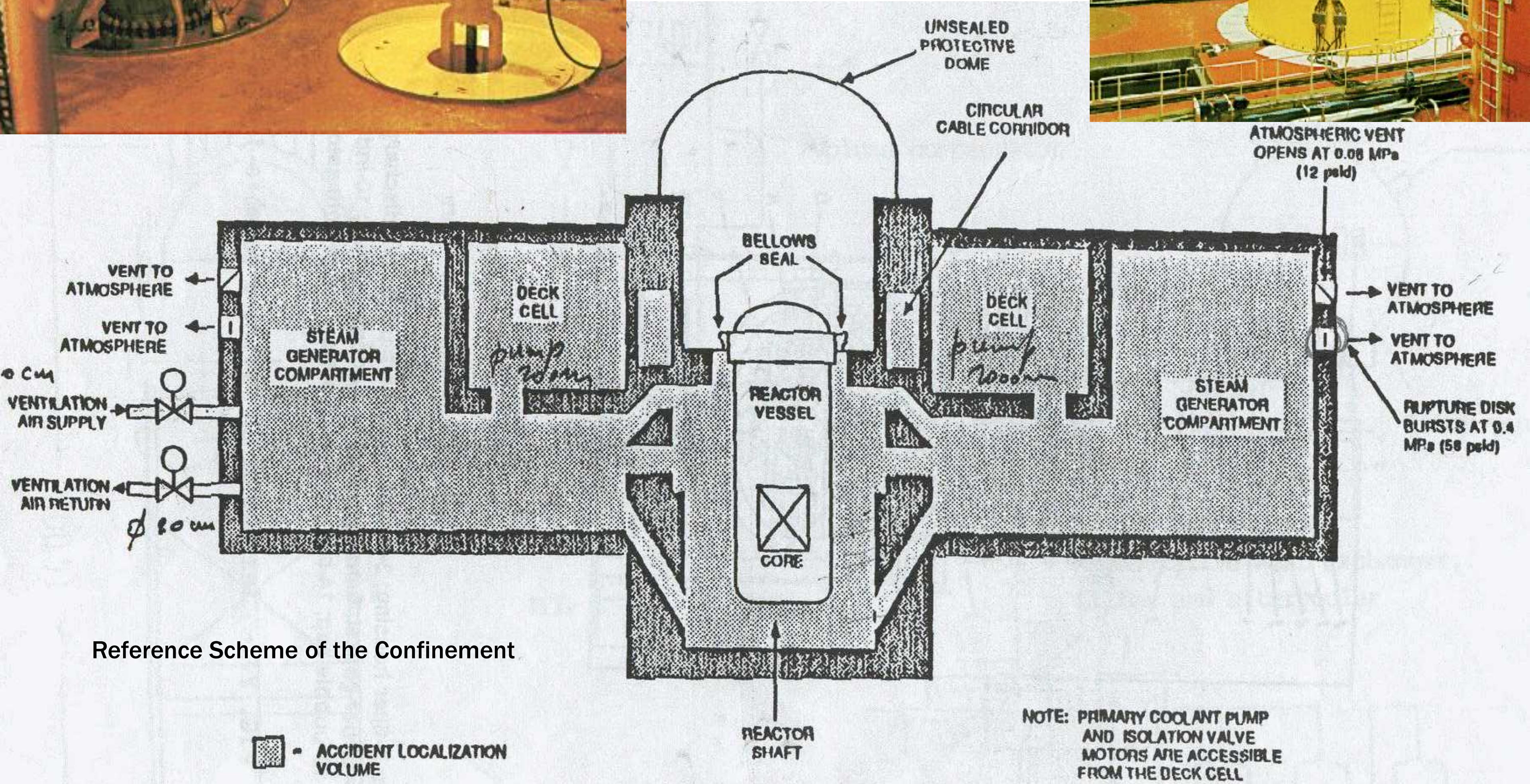
- Earlier design than VVER-1000 (1970-1980 years)
- Low power density in the fuel
  - provides more time for operator action before fuel failure
- Main isolation valves
  - allows service repair of one of 6 coolant loops during operation
- First VVER-440 RPV have problem with embrittlement
  - embrittlement (gradual weakening) due to lack of internal stainless-steel cladding and use of low-alloy steel with high levels of impurities
- Poor leak-tightness of confinement
  - A set of isolated compartments instead of leak-tight single-structure cylindrical containment

VVER-440. Primary side layout

- Reactor
- Hot legs
- Steam generators
- MCP and Main Gate Valves
- Cold legs

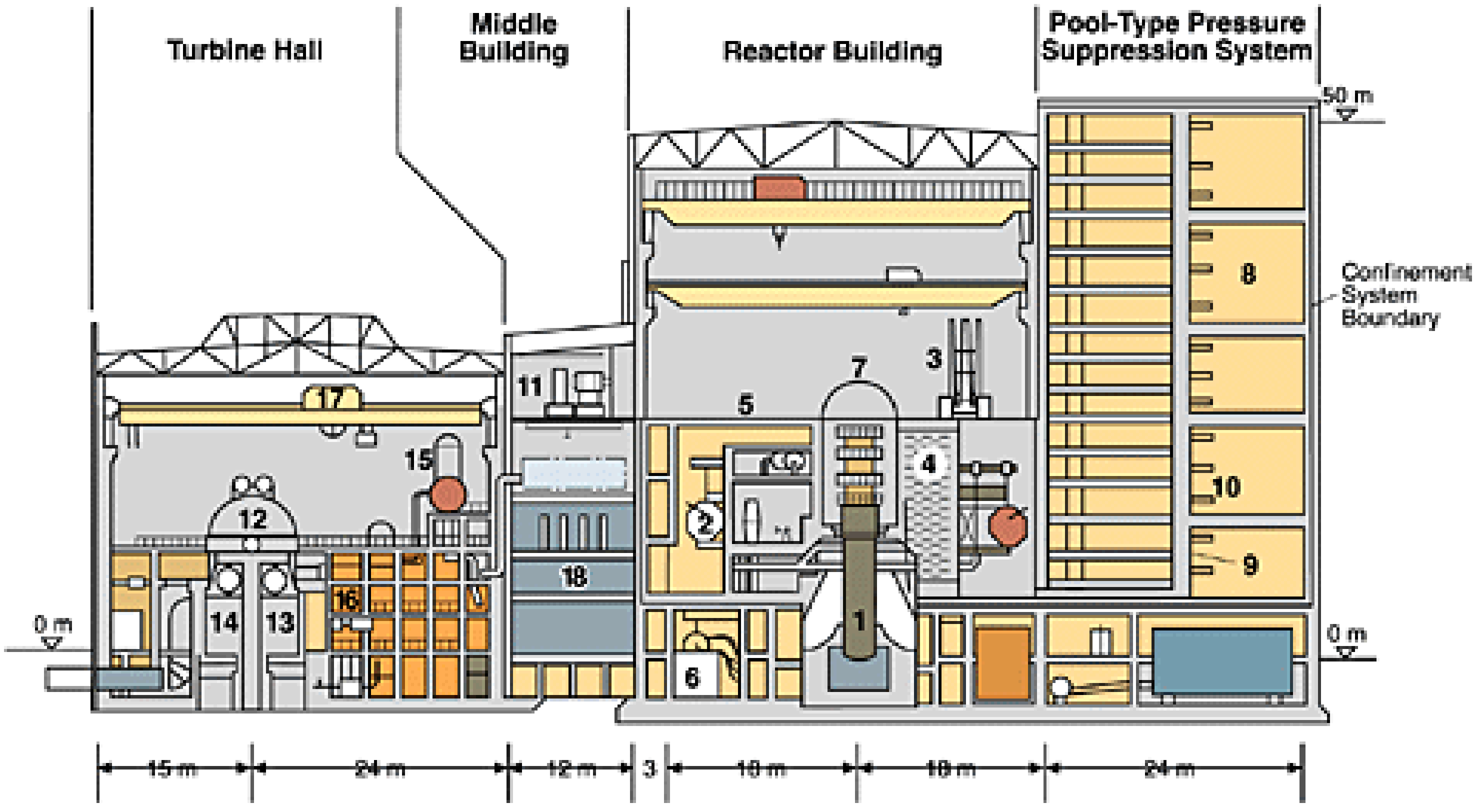






Reference Scheme of the Confinement

VVER-440/213 Plant Layout

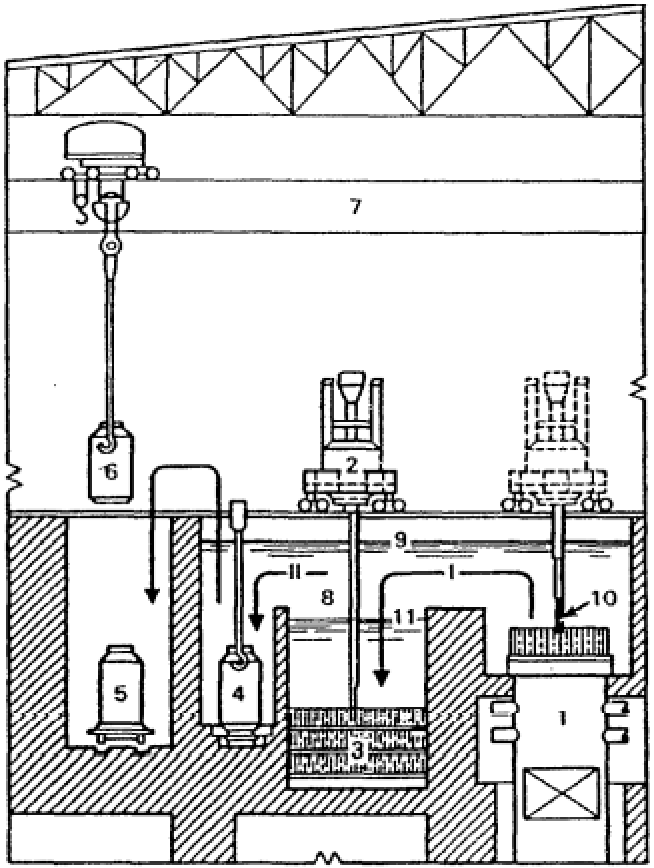


1. Reactor pressure vessel
2. Steam generator
3. Refueling machine
4. Spent fuel pit
5. Confinement system
6. Make-up feedwater system
7. Protective cover
8. Confinement system
9. Sparging system
10. Check valves
11. Intake air unit
12. Turbine
13. Condenser
14. Turbine block
15. Feedwater tank with degasifier
16. Preheater
17. Turbine hall crane
18. Electrical instrumentation and control compartments

This illustration shows a vertical "cut" through containment with bubble condenser tower.

VVER-440/213 – Risks in Conflict

- ❑ Spent fuel pool in Reactor hall, outside confinement
- ❑ Roof light metal construction
- ❑ Protection against accidental shelling likely not existent
- ❑ Dependence on Bubbler-Condenser for large loss-of-coolant accidents



1- reactor pressure vessel, 2 - refueling machine, 3 - racks for spent fuel, 4 - receiving container, 5 - railroad transport, 6 - transport cask, 7 - reactor building bridge crane, 8 - spent fuel storage pool (I - reloading of spent fuel from reactor to storage pool and II - reloading of "cooled" spent fuel to transport container), 9 - water level during refueling, 10 - spent fuel element, 11 - water level during storage.

Risk Analysis - Scenarios

- Distinguish two different warlike impacts on the plant:
  - Military attack to destroy the nuclear power plant.
  - Military attack to control the nuclear power plant site.

- In the first case, suitable munitions would be selected to reach the target - bunker-busting weapons, suitable bombs or guided missiles.

- Both warring parties have suitable weapons and neither has the capability to repel an attack aimed at destroying the plant.

- In this case, destruction of the facility and substantial releases must be assumed. However, this scenario is not very likely, since no advantage for warring parties is apparent.

Risk Analysis

- More likely scenario -> Combat operations to control power plant or fight to combat units at the power plant site.
- Weapons used are therefore not aimed at destroying civil structures of the plant, but at fighting troops. Depending on the accuracy of the hits, however, damage to the plant may still occur.
- It can be assumed that such hits will not destroy plant components that are bunkered for "civilian" reasons or designed to withstand aircraft crashes (e.g. containment). Penetration of the containment might occur without destroying the whole structure
- However, other plant components (e.g. power lines, buildings not specially reinforced) could be destroyed.

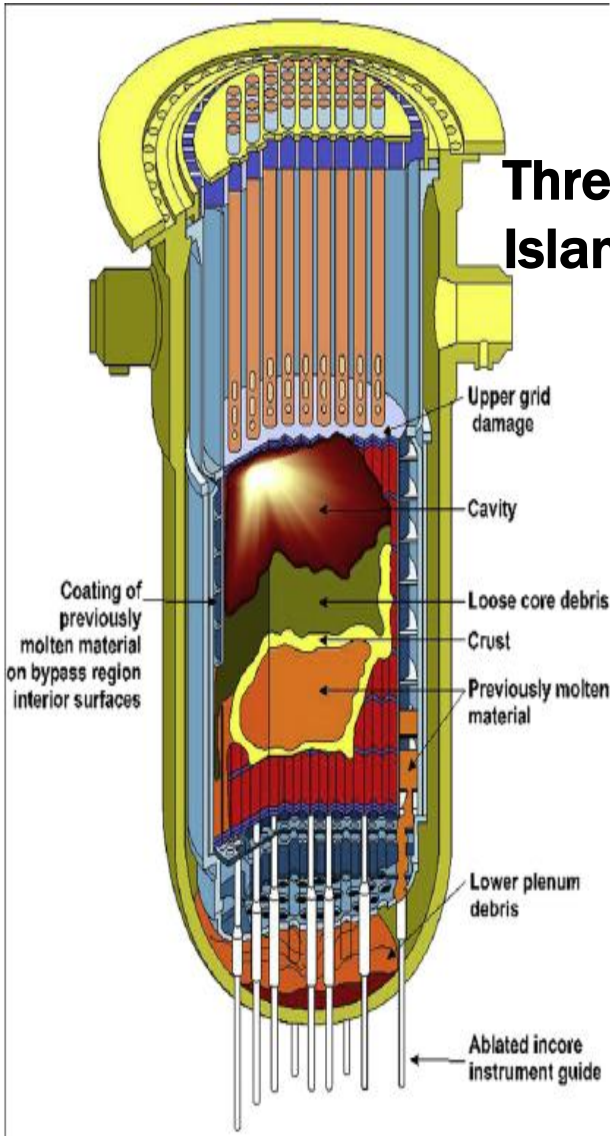
Scenarios

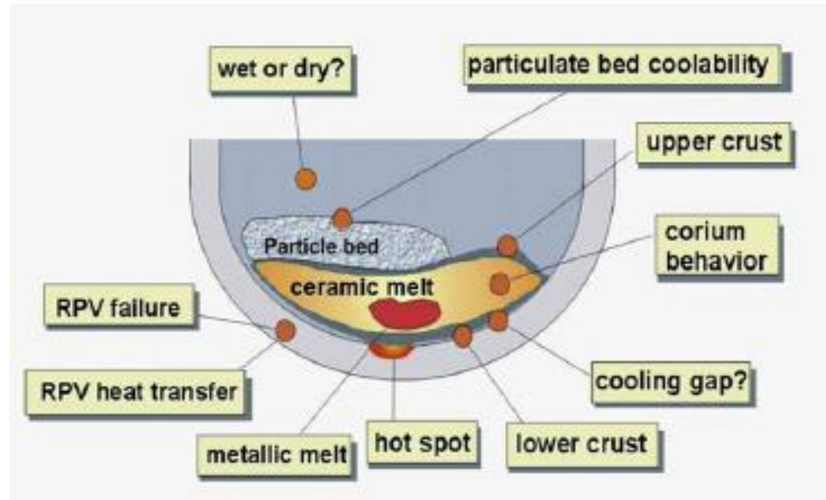
- VVER–1000/320 Scenarios – SBO
  - Station Blackout without operator actions
  - Station Blackout with operator actions
  - Station Blackout without operator actions, open containment 10cm
  - Station Blackout with operator actions, open containment 10cm

- VVER-1000/320 Scenarios – MSLB 4x
  - 4x Main Steam Line Break without operator actions
  - 4x Main Steam Line Break with operator actions
  - 4x Main Steam Line Break and consequential Steam Generator Tube Rupture without operator actions

Severe Accident

Three Mile Island RPV





"Severe Accident"

Next Barrier: "Failure Reactor Pressure Vessel"

FOREVER Experiment

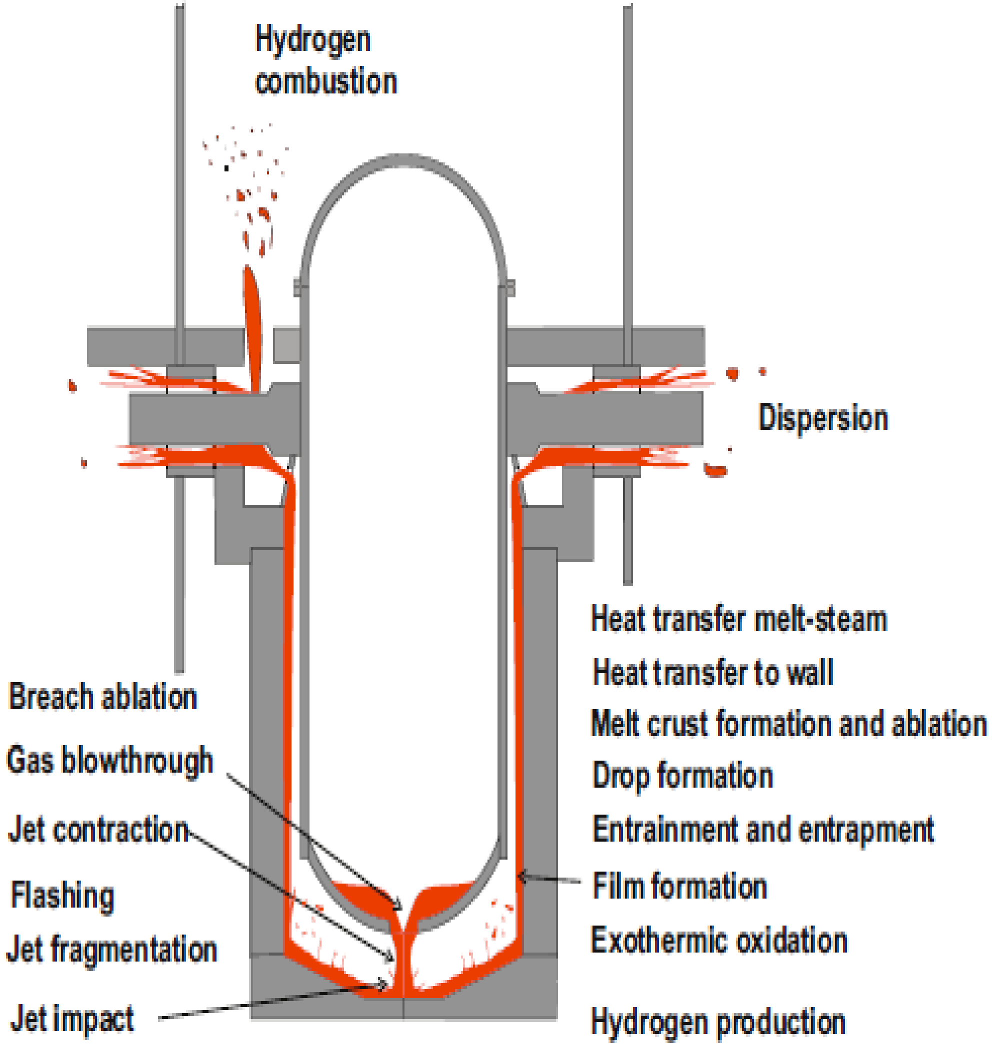
Direct containment heating / early containment failure

Wesentlich:

Findet Versagen des Reaktordruckbehälters bei hohem (>2 MPa) primärseitigen Druck statt?

Ja: "Direct Containment Heating"

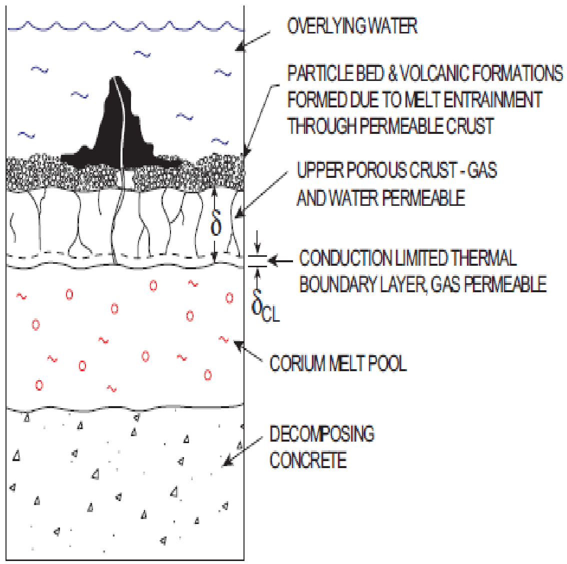
Containmentversagen als Folge wahrscheinlich!

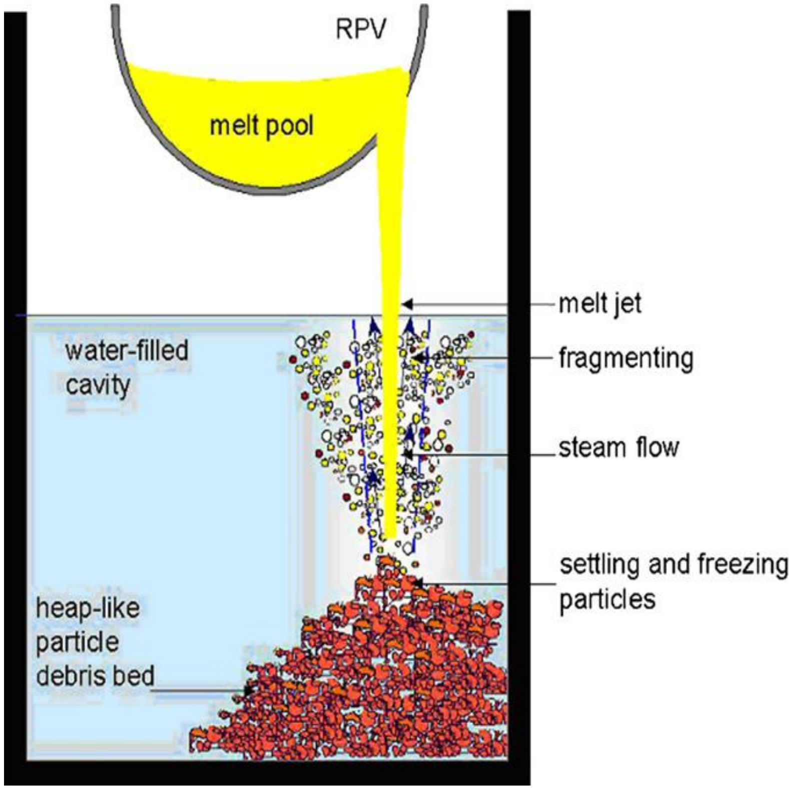


Molten core concrete interaction / late containment failure

In case RPV fails at less than 2-3 MPa:

Attack on reactor cavity bottom concrete

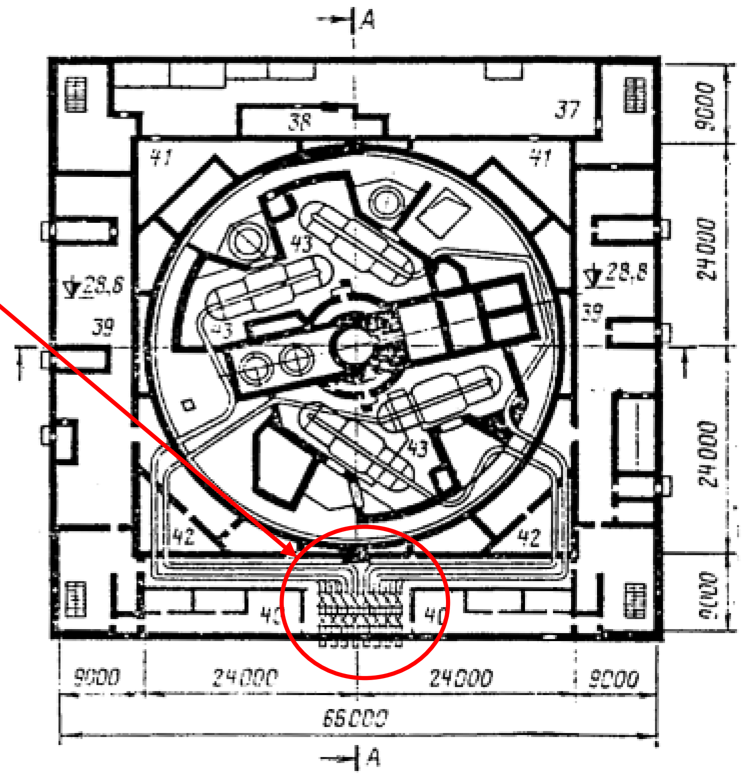




VVER-1000/320 – Risks in Conflict

- **Direct hit artillery/rockets containment**
  - Air blast of 0.3 kgf/cm2 (0.29 bar) for 1s.
  - Falling plane with speed of 750 km/h and mass 10 t.

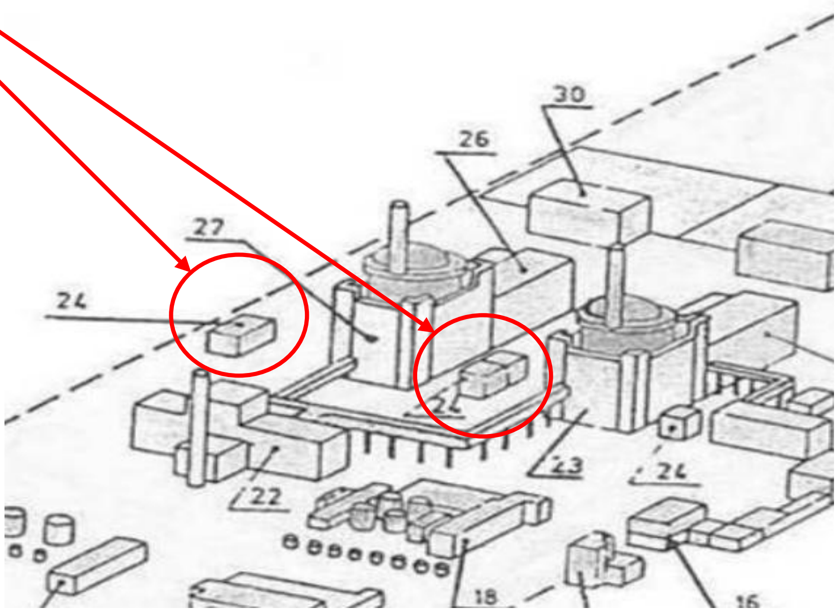
- **Direct hit artillery/rockets steamlines at MSIV location**
  - Outside containment
  - Close to the roof
  - Non isolable
  - Multiple steam line break
  - Possible consequential SGTR/SG header lift-off



VVER-1000/320 – Risks in Conflict

❑ Loss of all AC Power (Station Blackout SBO)

- Line to the power grid
- 3 x 100% Emergency Diesel Generator
- DGs situated in one building
- Houseload operation mode limited reliablity



❑ In case of SBO

- Original design VVER1000 battery requirement (for valves) – only 30min, in practice, a view hours
- Without operator interventions: ~3h to core uncovery
- With operator interventions: ~10h to core uncovery
- Core meltdown and reactor pressure vessel RPV failure – another 3-5h

VVER-1000/320 – Risks in Conflict

- In case of SBO
  - Bifurcation point – RPV failure at high or low pressure
    - High pressure – direct containment heating that could lead to containment overpressure
    - Low pressure – start of molten core concrete attack in the reactor cavity
  - Reactor cavity issues
    - Penetrations for instrumentation lines
    - Plugged at NPP Temelin & Kozloduy
    - With Penetrations, melt-through in matter of hours
    - Without Penetrations, melt-through within day

VVER-1000 Reference Data Base

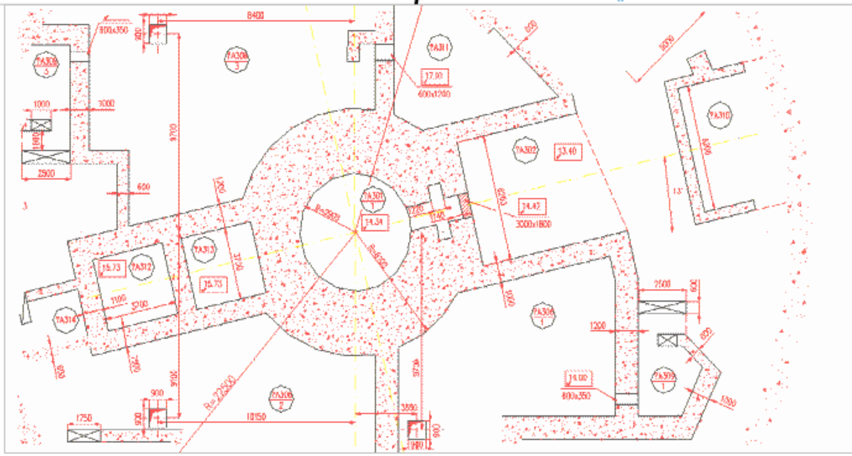


Figure 2.20 Containment - layout

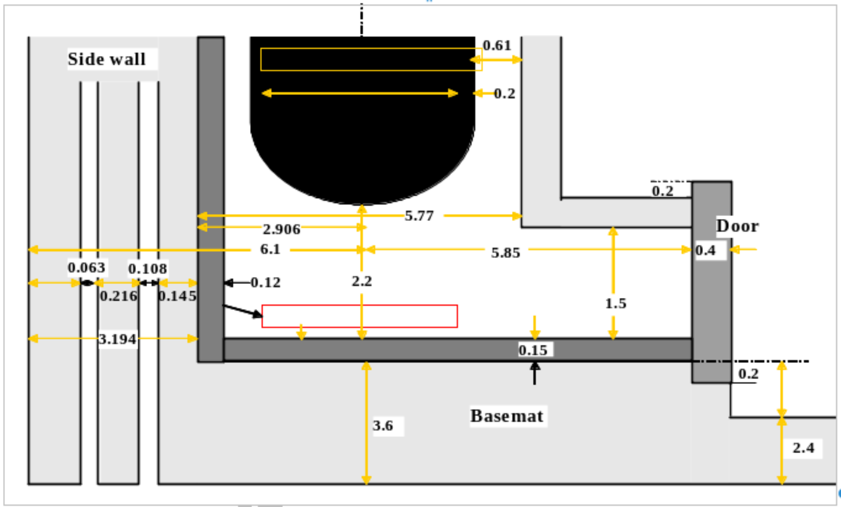
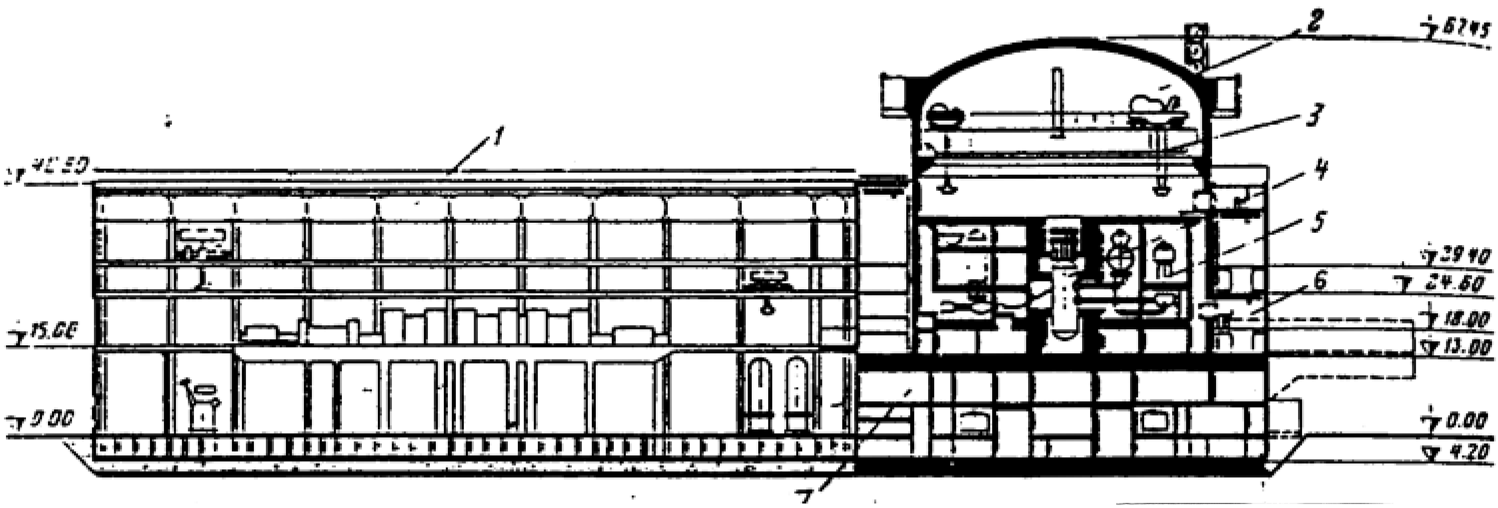


Figure 2.21 Reactor cavity, pedestal and basemat

VVER-1000/320 – Risks in Conflict

- ❑ **Basemat melt-through issue**



- ❑ **Spent fuel pool**
  - ➢ Inside Containment
  - ➢ Storage capacity of the VVER-1000 SFP ~690 FA
  - ➢ Water level during normal operation seems low

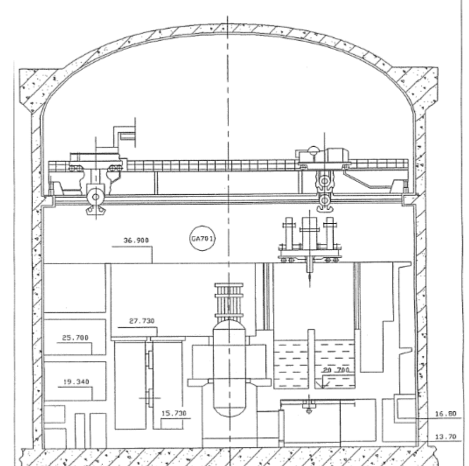


Fig. 14.1. Containment main longitudinal section through the refueling pool and wet refueling shaft

Results

Scenario	Time until core damage	Time until rupture of RPV	Time until releases to environment
SBO unm.	4.7 h	6.6 h	6.6 h
SBO mit.	3.8 h	8.1 h	8.1 h
SBO pen. unm.	4.7 h	6.4 h	6.4 h
SBO pen. mit.	3.8 h	7.9 h	7.9 h
MSLB unm.	3.9 h	7.8 h	7.8 h
MSLB mit.	3.1 h	5.5 h	5.5 h
MSLB+SGTR mit.	4.1 h	16.6 h	> 160h

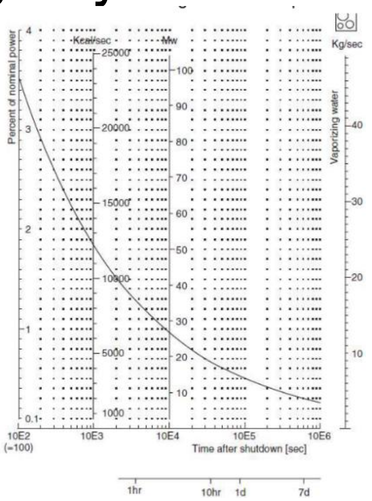
Release Fractions (in %) Key Nuclides

	SBO	SBOm	SBOp	SBOpm	MSLB	MSLBm	SGTR
Noble Gases	100	100	100	100	100	99	
Iodine species	45	30	49	37	61	38	
Cesium species	22	15	25	19	34	35	
Strontium species	9	12	6	13	14	13	

Conclusions

- Relatively fast accident sequence, failure of RPV/containment already possible between 5.5 and 8 hours.

- MSLB: Few possibilities for reactor operators in the AM area, since pressure on PS is too high for feeding the Emergency Core Cooling System (ECCS) (110 bar max for HPIS).



- Assumed manual measures for 4xMSLB not effective in achieving goals.

- Risk Mitigation:
  - shut down reactors – time in shut down state prolongs the "Grace Period".
  - Feed & Bleed with PORV by design not sufficient -> could be replaced by blowdown valve with higher flow rate.
  - Instrumentation feed throughs containment -> extends time to release in case of LPME sequence
- Systematic comprehensive Analysis would be highly beneficial