ÚJV Řež, a. s.

Comparison of In-Vessel and Ex-Vessel Retention

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Outline

- Introduction
- IVR key phenomena
- ExVC key phenomena
- Evaluation of pos and cons
- Conclusion

Dept. of SA and Thermomechanics

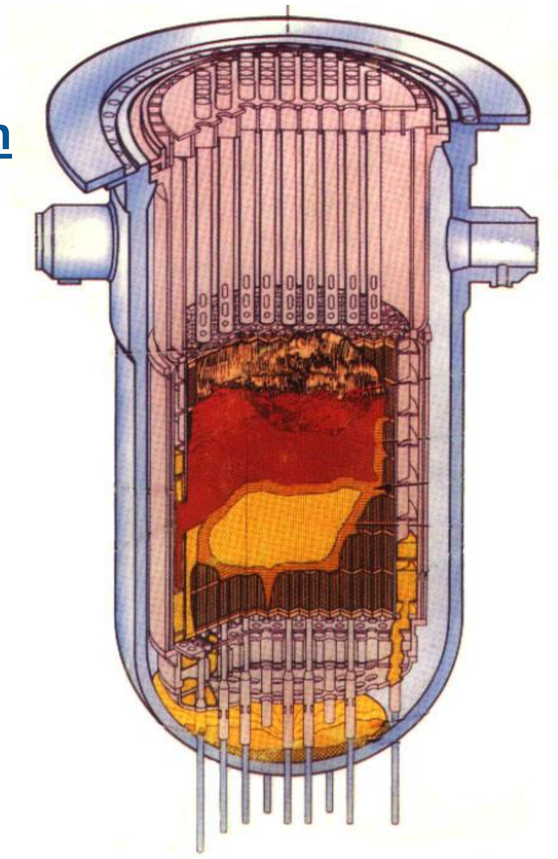
- **Three groups**
  - Severe accidents
  - Fuel behavior under operation and DBA/BDBA conditions
  - Gen IV – mainly GFR
- **Severe accident related activities**
  - Group established in 1988 as fully analytical
  - Implementation, validation, and application of system codes
    - Suggestions for development, improvement, and bug fixing
  - Tools available
    - MELCOR, ASTEC, ICARE/CATHARE, SCDAP/RELAP, CONTAIN, MAAP4/VVER, CORQUENCH, GOTHIC (and STCP-M)
    - Graphical tools – ATLAS (GRS), own tools (Linux platform)
  - International collaborations
    - IAEA
    - U.S. NRC – CSARP
    - EC FWP – many projects of 5th FWP, SARNET, SARNET2, NUGENIA
    - Bilateral cooperation – GRS, IRSN

Corium Retention Phase

Main objective – termination of SA progression leading to loss of last barrier in defence in depth

<u>Time evolution of possible strategies for corium retention</u>

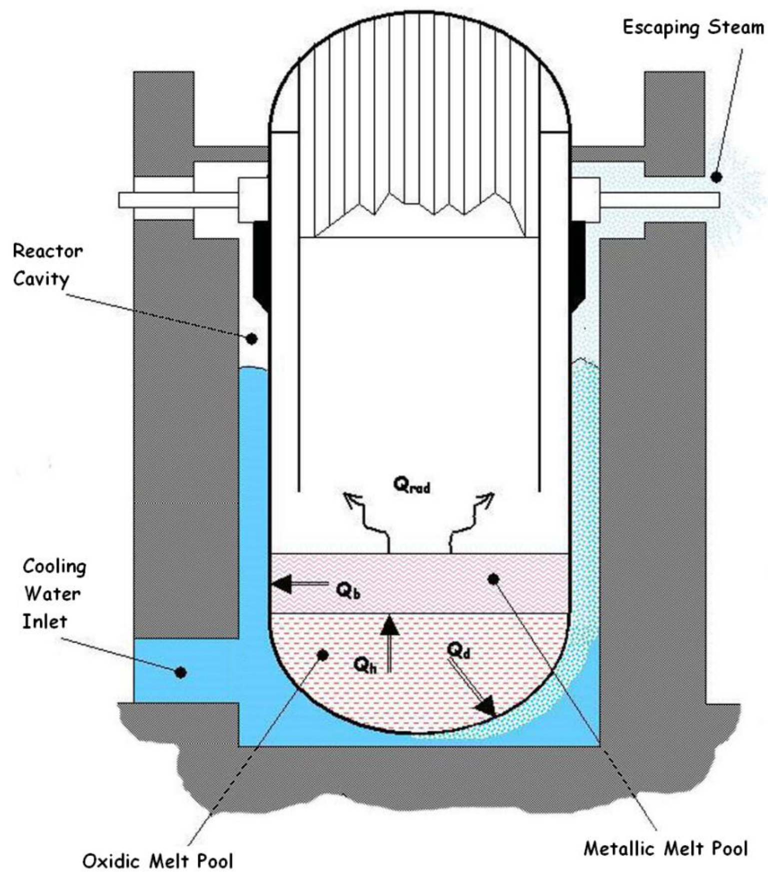
1. **Debris/melt retention inside of RPV with restoring of heat removal from reactor (TMI2 case); part of SAMG**
2. **In-vessel retention with external RPV cooling (IVR)**
3. **Retention and cooling of corium after lower head failure (ExVC)**



- **Strategies 2 and 3 applied at advanced LWR (Gen III/III+)**
- **Units in operation (up to Gen II)**
  - Utilization of design reserves
  - Improvements, backfitting
    - Simpler solutions than at new units due to design limitations

In-Vessel Retention Phenomena

- **Necessary condition of successful IVR Strategy**
  - Reflooding of reactor cavity (initial and longterm)
  - Heat removal through RPV wall
    - Thermal-hydraulics conditions in cavity
  - Heat removal from containment



- **Heat fluxes from melt pools**
  - Q_d = from oxidic pool to vessel wall
  - Q_h = from oxidic pool to metallic layer
  - Q_{rad} = radiation losses from metallic pool surface
  - Q_b = from metallic to cylindrical vessel wall

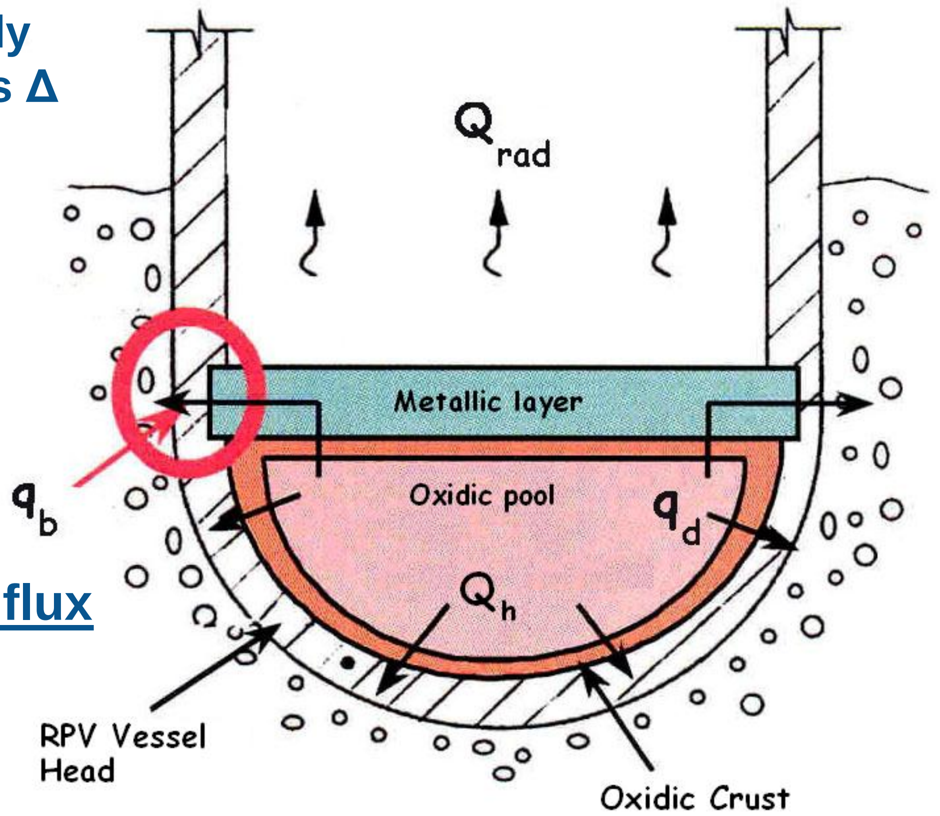
RPV Integrity during IVR

Focusing effect – location of vessel failure

- Contact of metallic pool with RPV wall
- Ratio of Q_h and Q_{rad} is not significantly influenced by metallic layer thickness Δ
- Heat flux density q_b is reciprocal proportion to Δ

$$q_b = \frac{Q_h - Q_{rad}}{\pi D \Delta}$$

- D is inner diameter of RPV



Moving of location with highest heat flux density

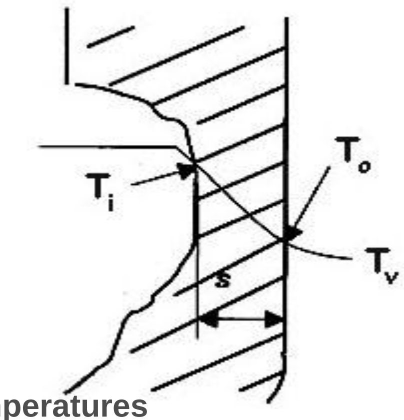
- For late phase it is predicted to move to upper part of oxidic pool

RPV Integrity Criterion

<u>Steady state of heat fluxes</u>

- Balance of heat fluxes from melt pool, conduction in vessel wall, and to cooling water – determination of remaining thickness of vessel wall

$$q_b = \lambda \frac{T_i - T_o}{s} \quad \Leftrightarrow \quad s = \lambda \frac{T_i - T_o}{q_b}$$

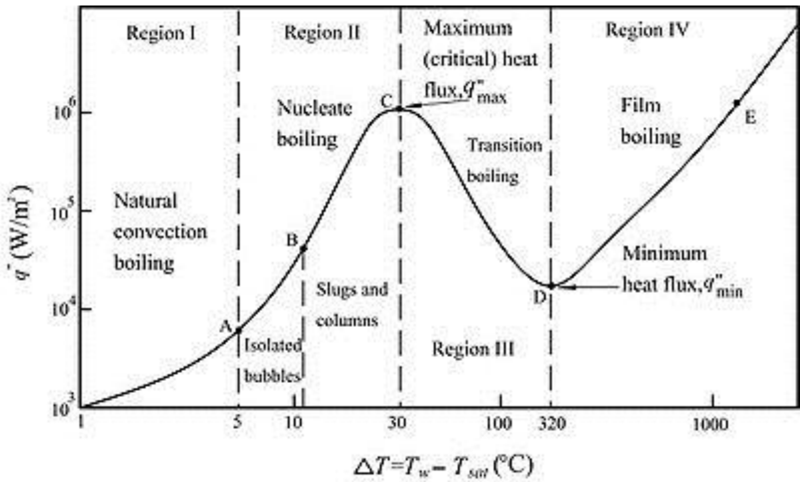


Temperatures
i – inner surface
o – outer surface
v – cooling water
s – thickness of vessel wall

Temperature of external RPV surface

$$T_o = T_v + \delta_T$$

- <u>Regimes of water boiling</u>
- **Nucleate boiling** - low δ_T (~ 10°C), s = 10-20 mm
- **Film boiling** - high δ_T (>100°C) ⇨ extremely thin remaining wall, overheating, failure



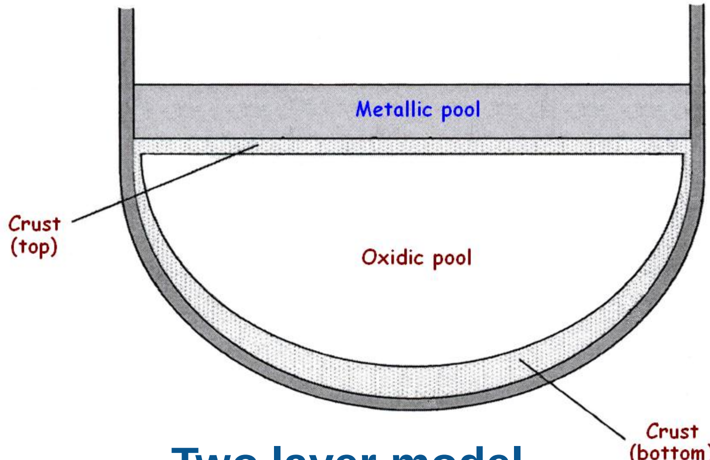
<u>RPV Integrity Criterion</u>

q_b is less than CHF

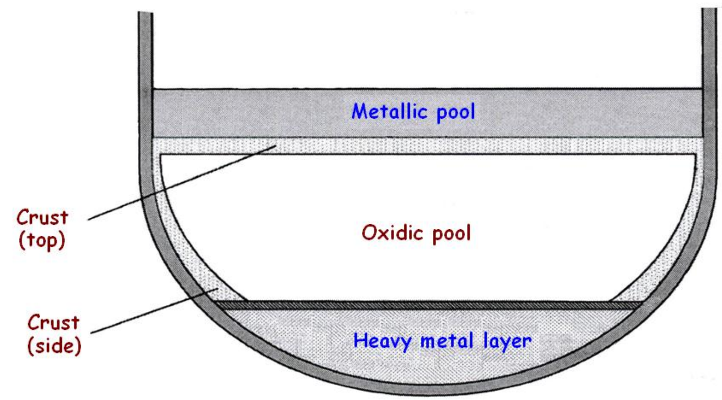
Open Issues of IVR

Chemical and physical processes

- Redistribution of metallic compound and decay power in layers
- Reduction of UO_2 and formation of heavy metal layer - indications from OECD MASCA2
  - Reduction of metallic pool thickness ⇨ intensification of focusing effect
  - Expected reduction of probability of successful application for AP-1000 from 95% to ~60%
- Corium material properties
  - Solidification of complex material composition of oxidic pool
- Heat flux profile to RPV wall



Two layer model



Three layer model (OECD MASCA2)

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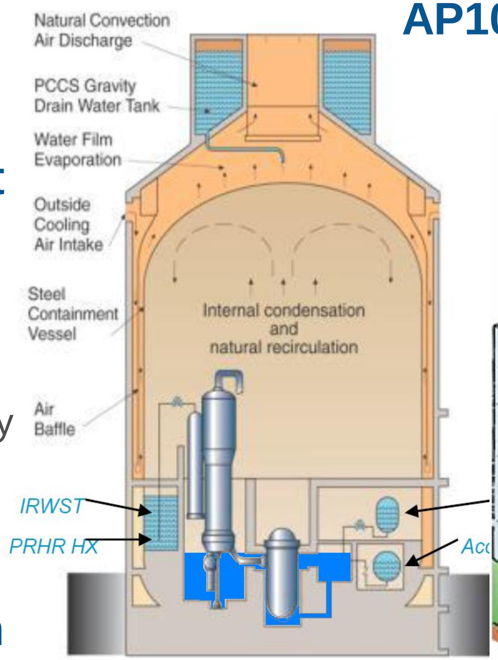
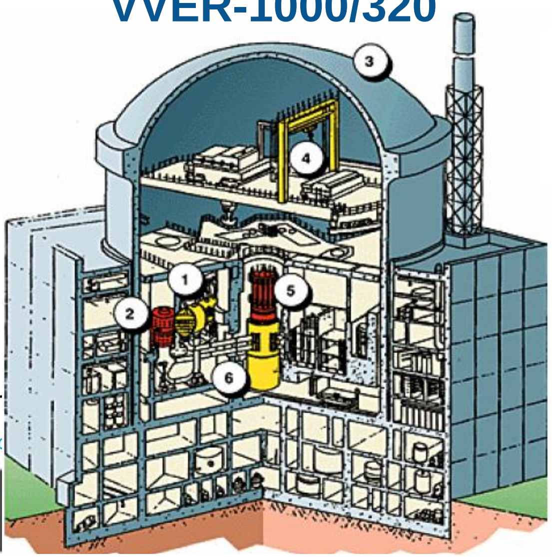
Open Issues of IVR



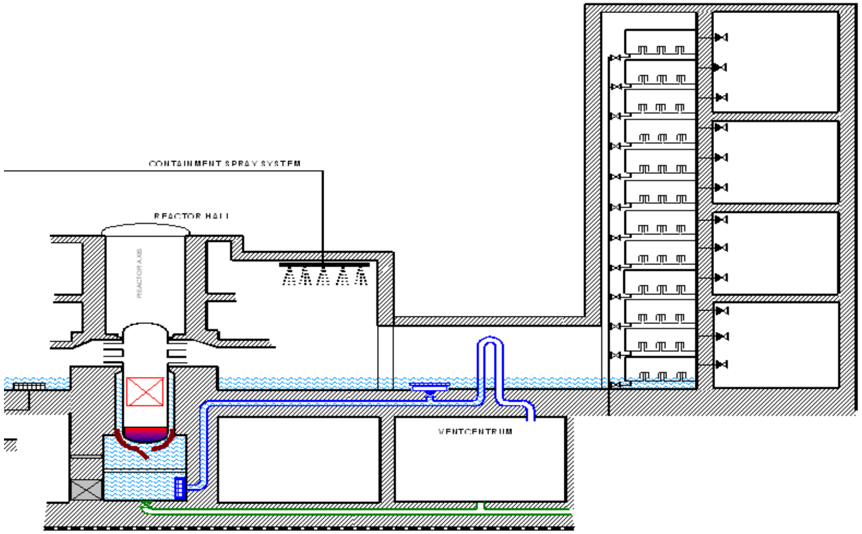
AP1000



VVER-1000/320

Coolability

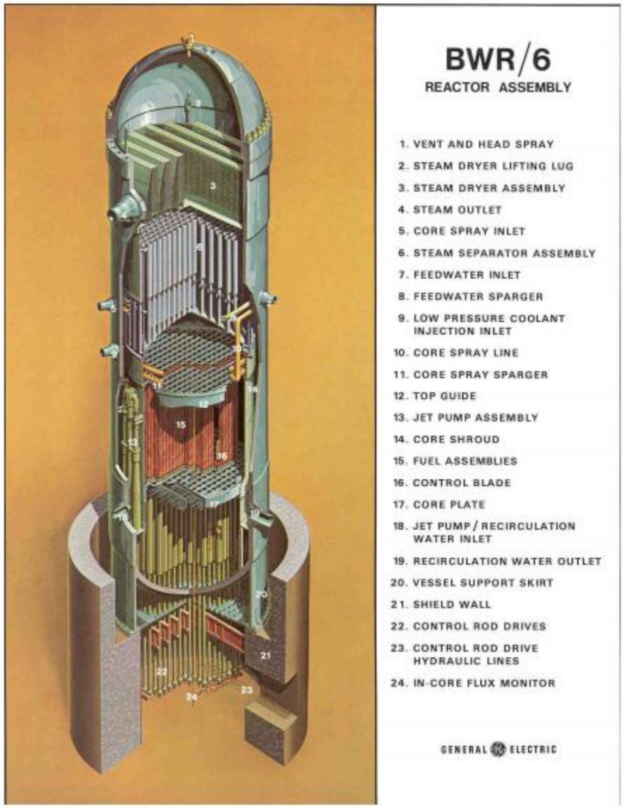
- New designs prepared with assumption of passive coolant circulation and heat removal from Cntn (AP1000)
- Existing units
  - Possibility of passive reflooding of cavity (VVER-440/213)
  - Only active systems for water injection into cavity (VVER-1000/320)
- Thermal-hydraulic condition in cavity
  - Overflow of water
  - Water level establishing
  - Circulation inside of cavity or through Cntn
- Consequences of failure of IVR



VVER-440/213

Limits of Application to Reactors in Operation

- **Designs of RPV or Containment**
  - BWR – skirt or penetrations
  - Containment configuration
    - Water inlet into cavity
    - Water circulation
      - Gravity flooding
  - Cavity configuration vs. decay heat generation
    - Heat transfer conditions – impact to CHF
    - Steam/water outlet
    - Intensification of heat transfer
      - Deflector
      - Surface improvement
        - Cold spray
        - Nano particles
      - Coolant properties
        - Boric acid vs. fresh water
        - Nano particles



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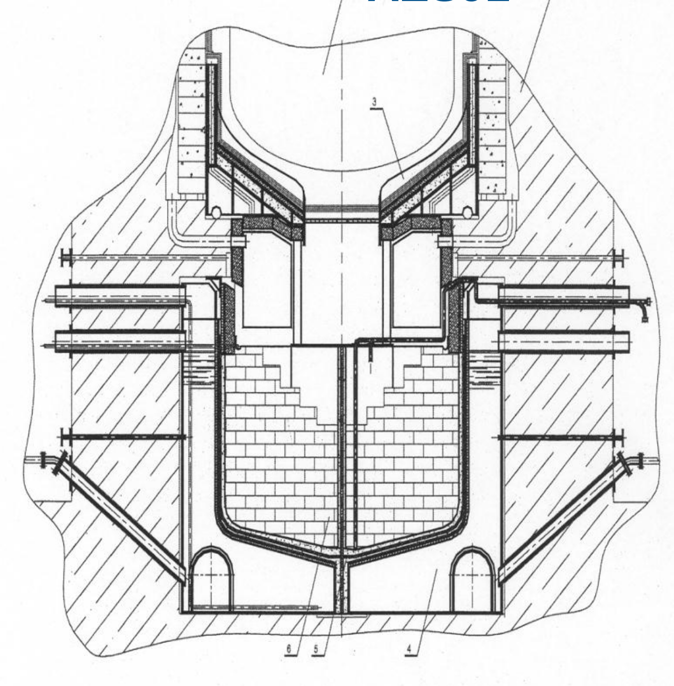
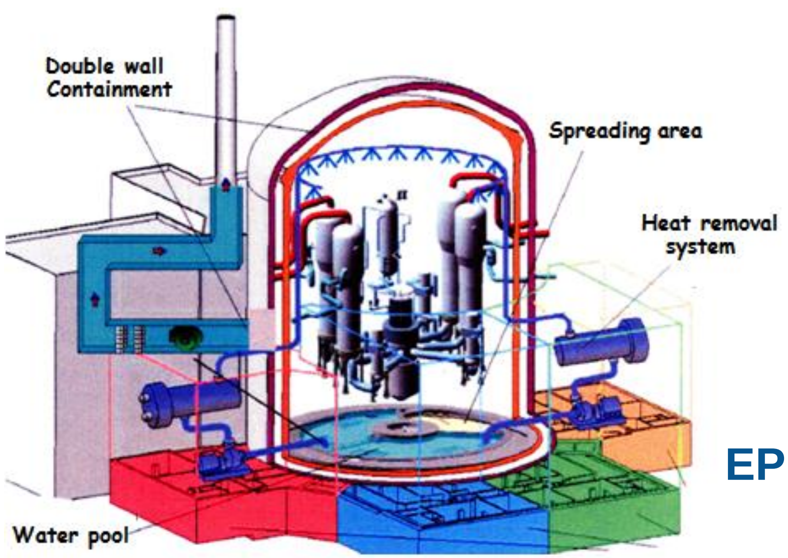
Ex-Vessel Coolability

- **Based on recent knowledge**
  - It is not possible to cool-down corium after initiation of molten corium concrete interaction (MCCI) inside of reactor cavity only
    - Standard cavities of LWR too small
  - Coolable thickness of corium < 25 cm
    - Mostly influenced by conductivity of corium
- **New designs**
  - Core catchers
    - MIR-1200 (VVER-1000 based)
    - EPR

VVER-1000/428

AES91

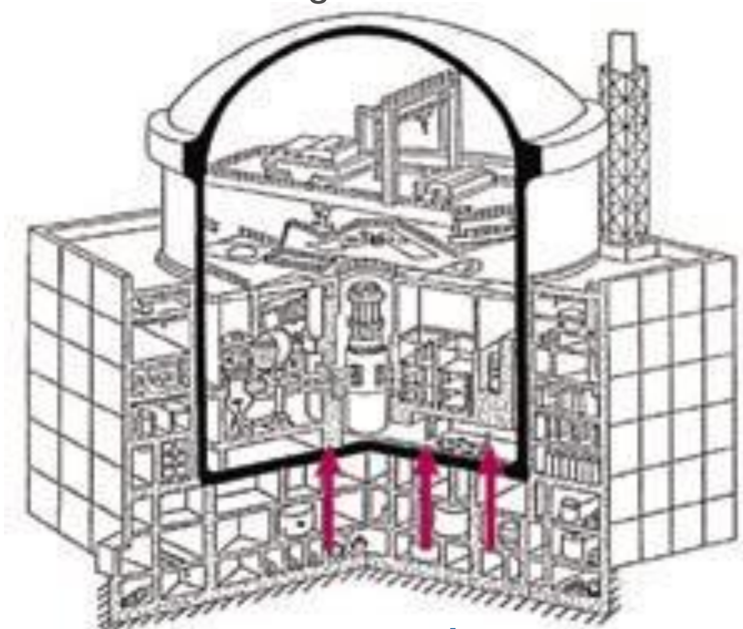




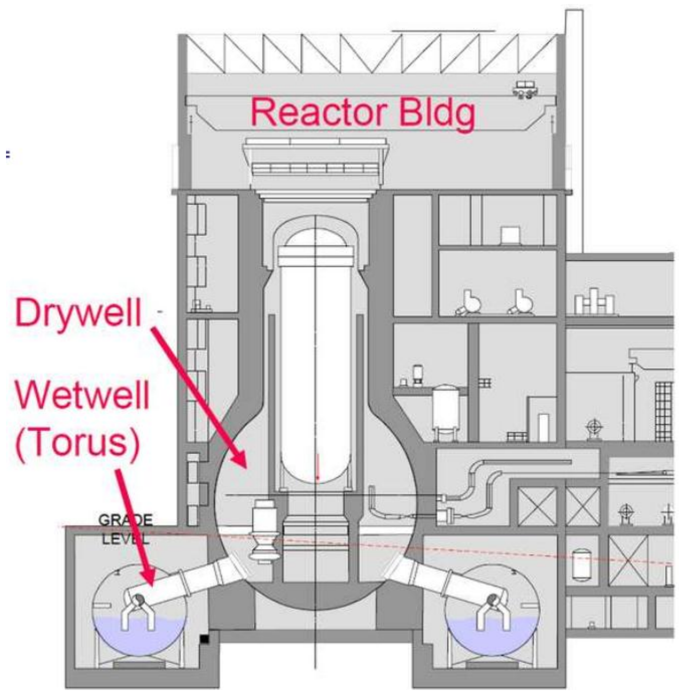
EPR

Ex-Vessel Coolability

- **Units in operation**
  - Studies of possibility to cooldown corium during MCCI
    - Design of cavity and possibility to spread corium
    - Cooling with water on corium – intensification of heat removal
    - Concrete composition
  - Design of containment strongly influences possible solutions
    - Location of cavity
    - Water drainage



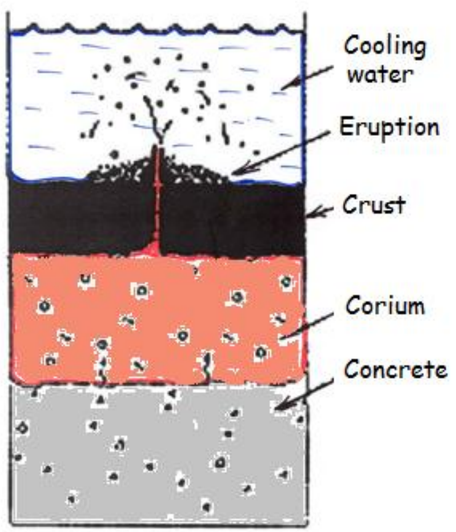
VVER-1000/320



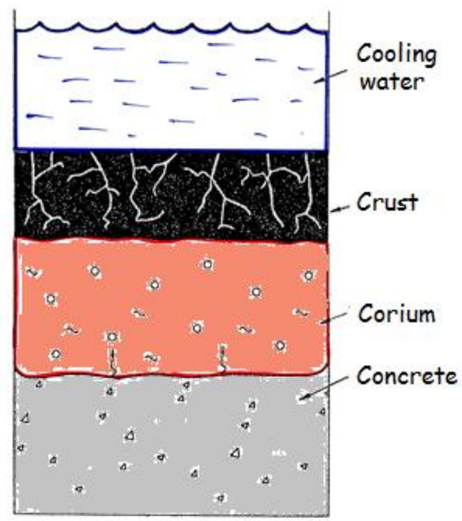
BWR Mark I

Open Issues of ExVC

- **Core catchers**
  - Impact of chemistry to corium/sacrificial material/wall interactions
- **Spreading and cooling during MCCI**
  - Possibility to terminate MCCI for common sands concrete
    - Melt eruption and water ingression processes intensify het removal
    - Experimental investigation still on-going
  - Impossible for siliceous concrete
    - Intensification processes insufficient



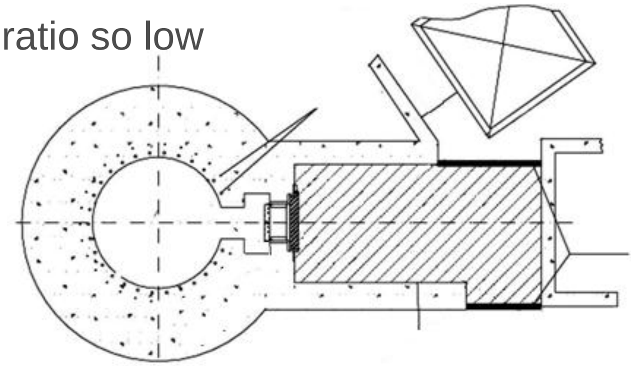
Melt eruptions



Water ingression

Open Issues of ExVC

- **Spreading and cooling during MCCI**
  - Application of sacrificial material to modify corium properties
    - Impact on $T_{solidus}$ and $T_{liquidus}$
    - Influence of effective conductivity of corium
- **Modifications at existing units**
  - Initiation of coolant injection
    - Risk of stratified steam explosion
      - Indicated in KTH (Sweden) - relatively low conversion ratio so low possibility of loss of containment integrity
  - Opening of doors or fast passing of barriers
    - Cavity can be isolated for efficiency of venting system
  - Application of heat resistant (isolating) liners



- **Formation of coolable debris bed**
  - For some BWR is expected to reflood deep cavity and to let escape corium into water to form debris bed
  - Need to solve issue of steam explosion
    - Coolant subcooling, metal content in corium, triggering etc.

Comparison pos and cons (1)

IVR	ExVC

IVR

- **Less release of fission products to Cntn**
- **Less production of hydrogen**
- **Risk of steam explosion**
  - In case of loss of RPV integrity with reflooded cavity
  - Study of SE consequences required

ExVC

- **Higher release of fission products to Cntn**
  - Important for non-mitigated MCCI
  - Slightly in case of successful termination of MCCI with cooling
- **Important production of hydrogen from MCCI**
  - Successfully cooldown corium does not produce H2 – same for core catchers
  - Robust hydrogen removal system solves H2 issue (excluding phase of decommissioning)
- **No SE in case of dry cavity**
  - Risk of shallow water pool

Comparison pos and cons (2)

IVR

- Depressurization conditions – fast and deep
  - Remaining pressure difference below 0.2 MPa – otherwise RPV integrity not guaranteed
  - Duration is determined by times
    - Entry to SAMG
    - Relocation of corium into lower plenum
    - HA injection results in pressure rise
- Cavity reflooding – has to be done before corium relocation to LP
  - Fastest scenario requires < 1 h
- Failure of IVR results in ExVC

ExVC

- Depressurization conditions – slower and to higher remaining pressure
  - As low as possible remaining pressure is needed, but below 0.5 MPa (prevention of DCH)
- Melt cooling can be initiated after LHF
  - As soon as possible preferred
- Failure of ExVC results in loss of Cntn integrity

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Conclusions

- **New units (GenIII and III+) – SAM is part of design**
  - Including corium retention
- **Application of any strategy for corium retention to existing units in operation (GenII) is technically complicated**
  - Only few units already solved this issue (VVER-440)
  - Many plant specific issues to be solved
    - Material, design assumptions
  - Solution of residual risks needed
    - Consequences of non-successful IVR
    - Loss of Cntn integrity
  - Proposal of strategy
    - Step definitions (depressurization, coolant injection, other measures)
    - Timing of steps
- **General question**
  - Is it possible to improve GenII units to level of GenIII?
  - Answer: Generally **NOT**, but to be at least as close as possible.
    - Active instead of passive; to keep Cntn integrity, but not to prevent MCCI, etc.

References

- **Within a preparation of contribution following sources were used**

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Thank you for your attention

? Questions ?

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