Severe Accident Management Strategies

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Nuclear Power Plant Design Safety – Updated IAEA Safety Standards
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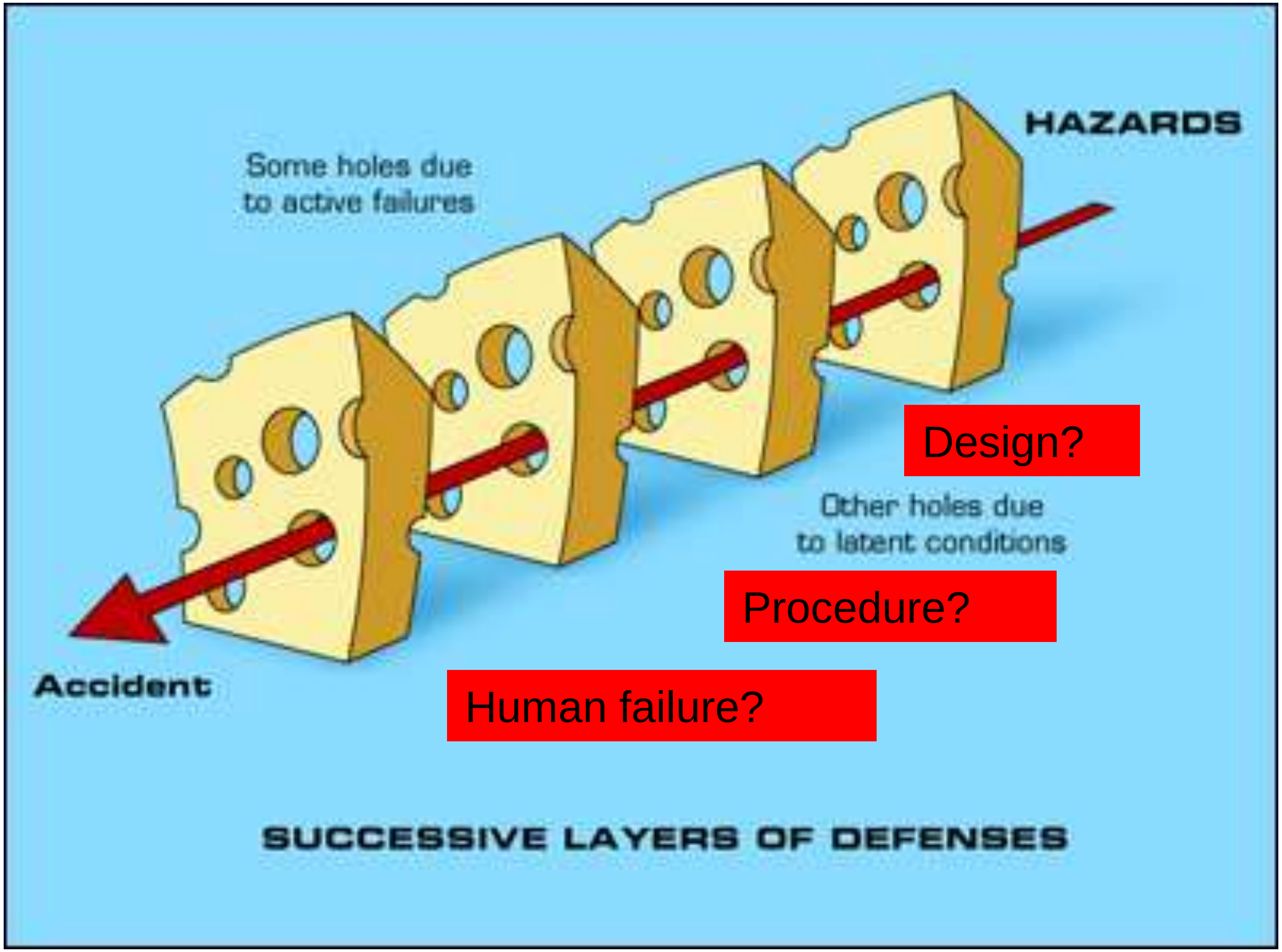
Presented by
Ivica Basic
APoSS d.o.o.

Vulnerabilities?



Fission Product Barriers

- For AM development, it is important to understand the challenges to Fission Product (FP) barriers

- Mitigating strategies may compete for resources, therefore, it is important to establish priorities

An understanding of severe accident phenomena is critical to AM

Strategies

- Our tasks at the initiation of an accident (AM):
  - Try to prevent further escalation of the accident
  - Mitigate the consequences of a severe accident (=SAM)
  - Achieve a final stable and safe state
- SAM: terminate progress of accident, protect FP boundaries, minimise releases
- We lost cooling of the core/SFP,must now focus on fisison product boundaries (FP boundaries)
  - while trying to restore cooling of fuel/ debris
- This lecture talks on possible and available strategies to protect the FP boundaries
- Major reference: EPRI Technical Basis Report (TBR)
  - Now publicly available; talks on ´Plant Damage Descriptors (Stages)`and strategies ´Candidate High Level Actions`, CHLAs

Core Damage States

OX

- Degraded fuel conditions
- Cladding oxidation significant
- Fuel degradation sufficient to lead to appreciable fuel debris relocation
- Potential for critical fuel configurations

OX = **Ox**idized Fuel

BD

- Degraded fuel conditions with RCS/RPV challenged
- Significant fuel relocation
- Coolability of the fuel geometry degraded

BD = **B**adly **D**amaged core

EX

- Degraded fuel conditions with RCS/RPV lower head breached
- Core debris relocation into containment occurred
- Direct attack of the concrete containment can occur

EX = core **Ex**-vessel

Ref: EPRI Technical Basis Report, 2012, courtesy J. Gabor, ERIN Engineering

Spent Fuel Pool Damage States

SFP-OX

- Degraded conditions
- Cladding oxidation significant
- Fuel degradation sufficient to lead to appreciable fuel debris relocation
- Potential for critical fuel configurations

SFP-BD

- Degraded conditions with challenge to SFP structure
- Significant material relocation
- Coolability of the fuel assembly geometry degraded

Ref: EPRI Technical Basis Report, 2012,
courtesy J. Gabor, ERIN Engineering

Containment Damage States

APoS

CC

- Containment intact and cooled

CC = **c**losed and **c**ooled

CH

- Containment challenged
- Appreciable buildup of energy
- Presence of flammable gases in containment

CH = **ch**allenged

B

- Containment bypass
- Direct pathway from RCS/RPV out of containment (e.g. SGTR, ISLOCA)

B = **B**ypassed

I

- Containment impaired
- Containment isolation failure or some other breach
- Direct pathway out of containment exists

I = **I**mpaired

Ref: EPRI Technical Basis Report, 2012, courtesy J. Gabor, ERIN Engineering

FP Boundary Threats - Overview

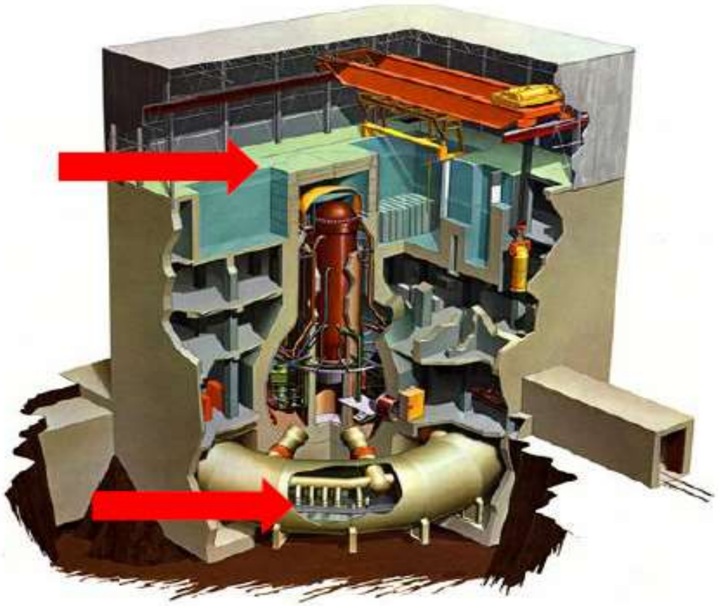
- Fission Product Boundary Challenges:
  - 2.1 Large release at onset of accident
  - 2.2 Bypass of the containment (SGTR, SGT creep-R, ISLOCA)
  - 2.3 High Pressure Melt Ejection (HPME)
  - 2.4 Core cooling, ultimate heat sink and RPV meltthrough
  - 2.5 Hydrogen production and combustion
  - 2.6 Molten Core Concrete Interaction (MCCI)
  - 2.7 Containment pressurisation
  - 2.8 Containment sub-atmospheric pressure
  - 2.9 Spent Fuel Pool damages
  - 2.10 Release of Fission Products to the environment
  - 2.11 Exit of SAMG, long term provisions

Large release at onset of accident

- May be caused by external event (e.g. seismic)
- Find leakage location
- Try to isolate leakage
  - Close any open valves
  - If in shutdown mode, close containment hatch
- Use sprays
  - Internal sprays: reduce containment pressure
  - External sprays: spray leakage location
- Controlled containment venting
- From secondary buildings, start ventilation
  - Exhaust is via filters
- SFP: flood pool, use sprays (if available)

Use of sprays – example
(R. Harter, DAEC, IAEA post-F-Daiichi, March 2014)

- **In the event of containment failure due to overpressurization, PRA insights indicate that the likely failure points would be the drywell head <u>or</u> torus above the waterline.**
  - If the torus room is accessible post-event, sprays could be deployed to support fission product scrubbing.
  - Sprays cannot be deployed to directly spray the drywell head. Instead, the refuel floor area above the drywell head shield blocks may need to be sprayed to mitigate releases from the drywell head.



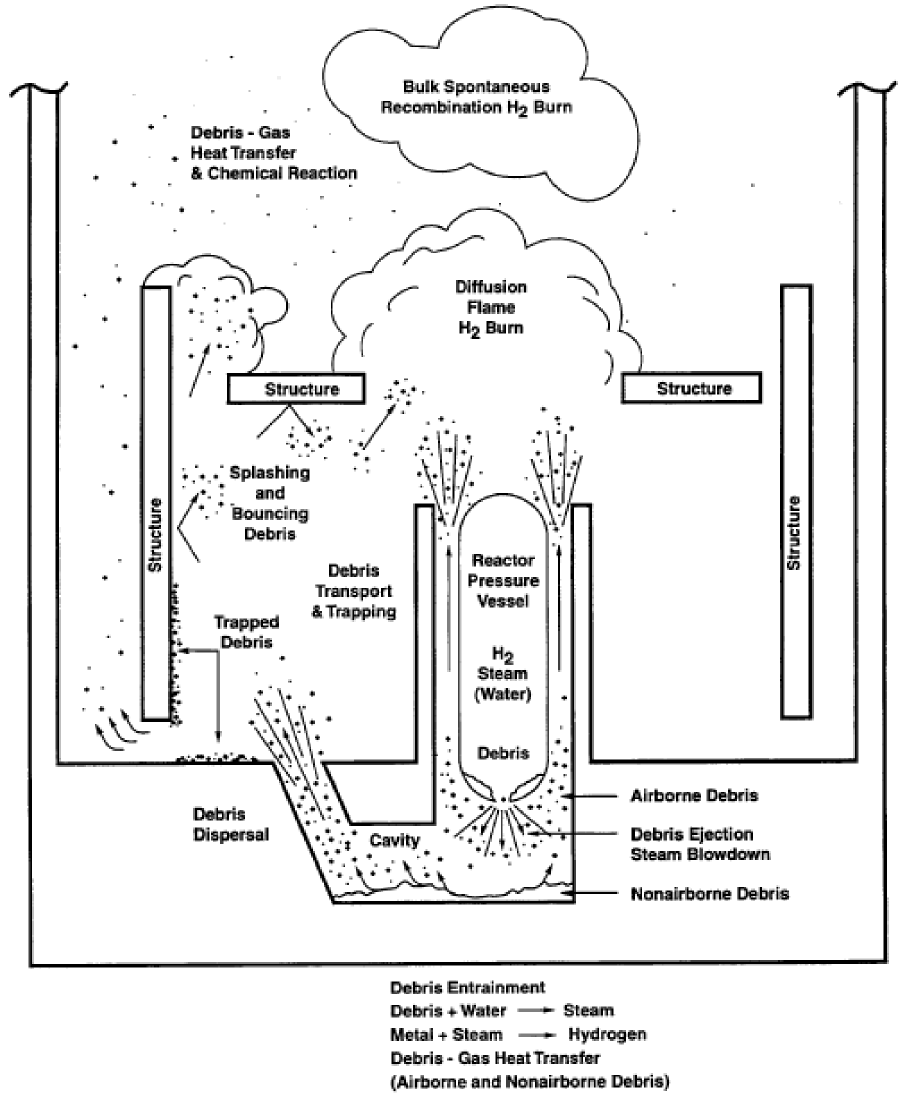
Bypass of the containment (SGTR, SGTR by creep, ISLOCA)

- High risk at PWR: SG tube creep rupture, mitigation by
  - flooding secondary side SG
  - depressuring RCS
    - but this will cause loss of RCIC / AFW
      - Some plant have therefore slow or partial depressurisation (will be in some SAMG updates)

- ISLOCA: isolate by closing valves
  - Depressurising RCS to prevent rupture of low pressure parts (if valves fail to close)

High Pressure Melt Ejection (HPME)

- Requires elevated RCS/RPV pressure (e.g. > 2 MPa)
- Spread of molten debris over large containment volume
- Debris stored heat transferred to containment atmosphere
- Short time scale



Ref: NUREG/CR-6533, Code Manual for CONTAIN 2.0, 1997

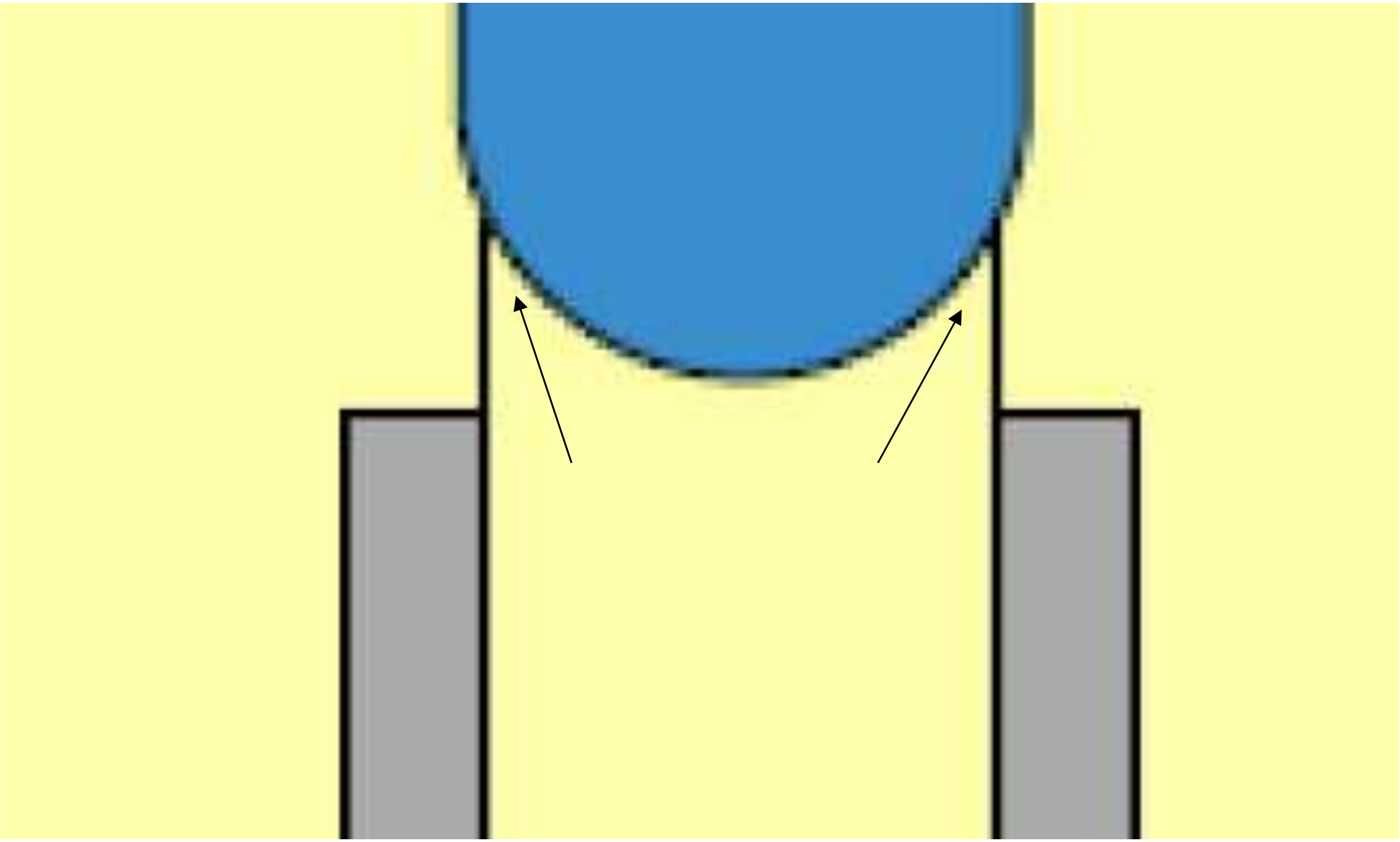
High Pressure Melt Ejection (HPME) – cont´d

- Prime strategy is depressurisation of RCS (to < ~2 MPa)
  - BWR: operate isolation condensor /RCIC
  - PWR: pressuriser sprays, depressurise the SGs
  - PWR: open letdown line of the chem. & volume control system
  - Open PORVs (SRVs) – and keep them open at low pressure!
    - Not all valves do so! Depends on working principle
  - Vent RPV
    - BWR: steam lines, if condensor is available; main steam drain lines
    - RPV head vent
  - Provoke creep failure of RPV-attached line
    - PWR: hot leg, SG tubes (but beware of cont. bypass)
    - Risk that the RPV will fail before the line will fail…

Core cooling, ultimate heat sink and RPV melt-through

- Core cooling: LP sources via RCS depressurisation
  - Sudden injection into RPV may create pressure spike
    - At PWR, restart of reactor coolant pump (RCP)
- Flooding RPV from outside (´In-Vessel Retention`- IVR - by external cooling)
  - BWR skirt may prevent water to fully reach the RPV lower head (next slide)
  - PWR: may not be able to reach lower head (plants with ´dry cavity`)
    - Some plants have built extra lines to flood the cavity
- Flooding debris: may cause pressure spike
- Provide UHS to prevent containment pressure build-up

IVR hindered by RPV skirt



Hydrogen Generation

- Steam oxidation of zirconium fuel cladding
- CO also generated ex-vessel due to core-concrete interactions
- Hydrogen flammable
  - Ignition at 4% (upward), 6% (downward)
  - Flame acceleration possible at > 8%
  - Detonation at > 14% (through DDT)
- Steam inerting at 55% steam

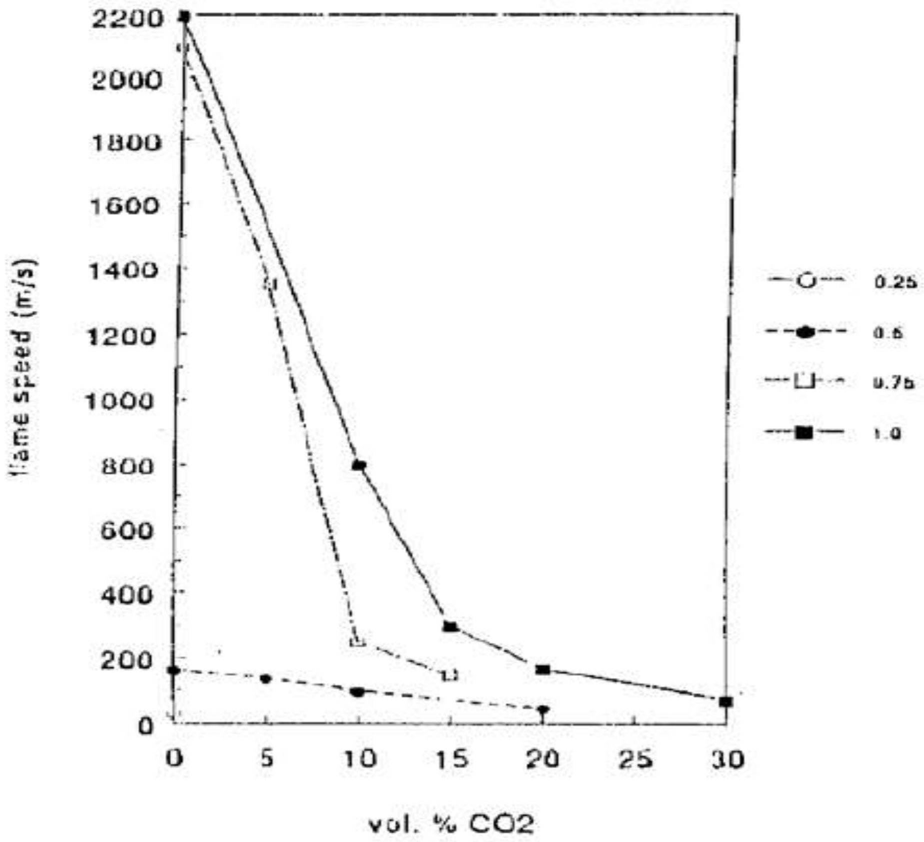
Ref. www.world-nucler.org

Mitigating hydrogen risk (1)

(Note: a part of the risk is combustion of CO from core-concrete interaction)

- Nothing needed for large dry containment
- Small BWR containments: inerted
  - GEH Mark I and II, Swedish BWRs
    - But inertisation does not remove hydrogen…!
- Mixing atmosphere to prevent local accumulation
  - Open SG tower blow-out panel (Areva PWR)
- Igniters
  - Objective: ignite H_2 at combustion limit (4-6 %), is fast, so no dangerous H_2 concentration build-up
    - May be dangerous if atmosphere initially is inert by steam and later steam condenses
- Post-inert containment with N_2, CO_2
  - Requires pressurisation to ~ 0,3 MPa, large quantity of gas required
  - Dilution may be enough – decreases flame speed and, hence, combustion pressure

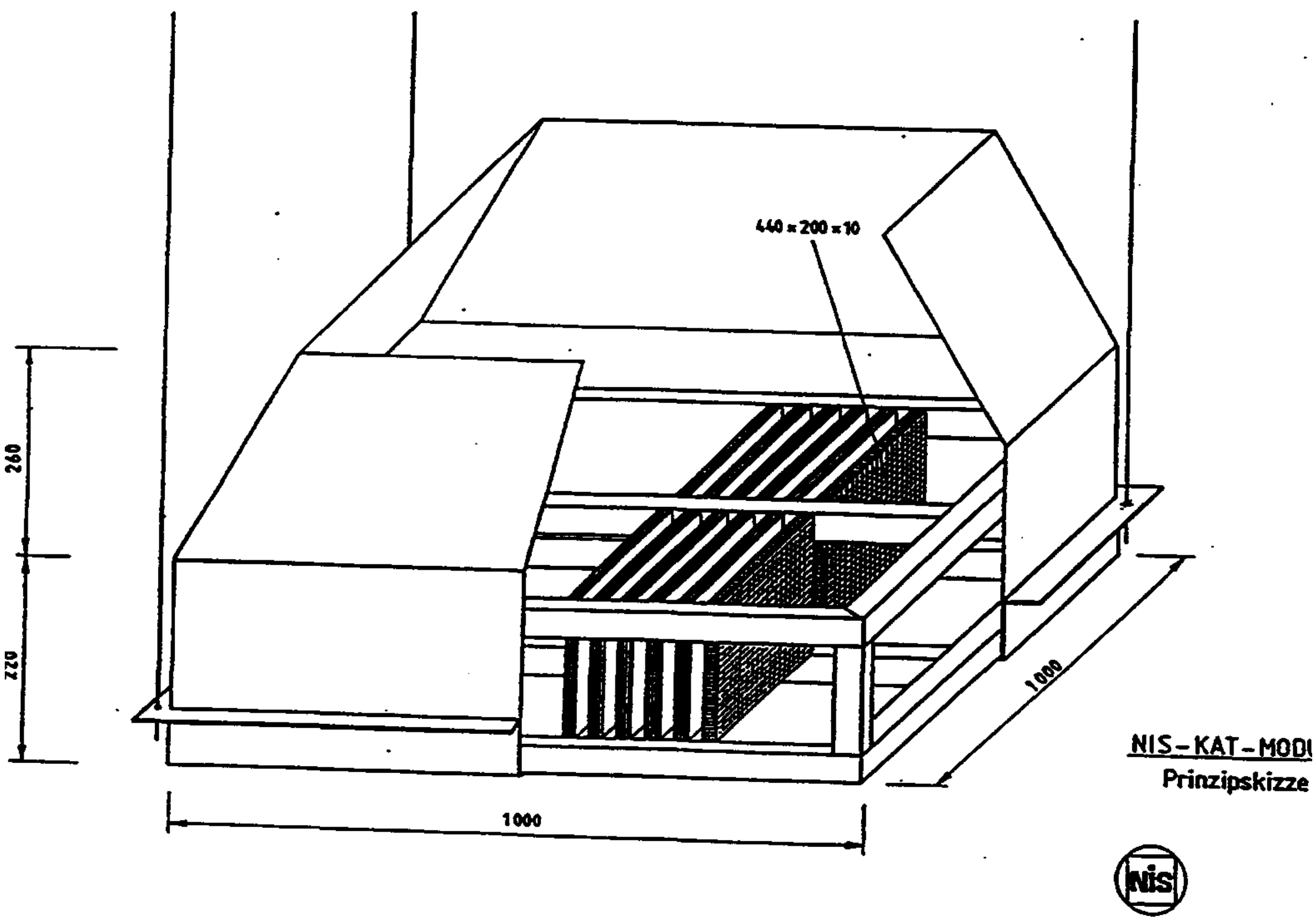
Mitigating hydrogen risk (2) – dilution by CO_2, reduces flame speed, large effect from ´blockage,ratio`



Mitigating hydrogen risk (3)

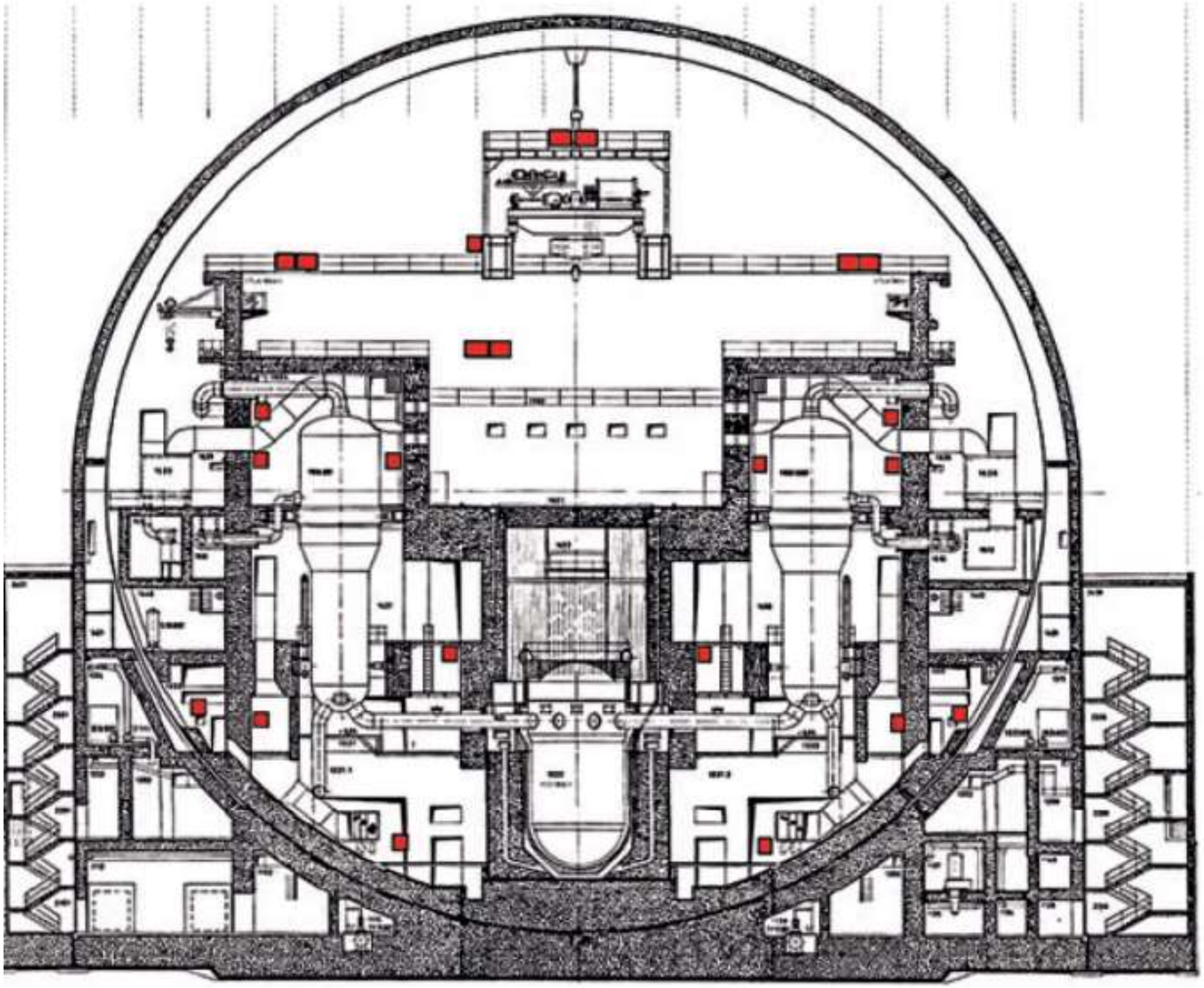
- Passive Autocatalytic Recombiners (PARs)
  - Do not ignite H_2, but recombine with O_2 by catalytic reaction
  - Widely used application for H_2 mitigation
  - Response is slow
    - Takes many hours to recombine H_2
  - Work as igniters > ~ 10% H_2
  - Before proposed: igniters + PARs (´dual concept`)
    - Igniters work fast, but not under inert conditon (with much steam)
    - PARs work slowly, but also during inert conditions (which never last forever – steam condensation will occur)

PAR (NIS – Germany)

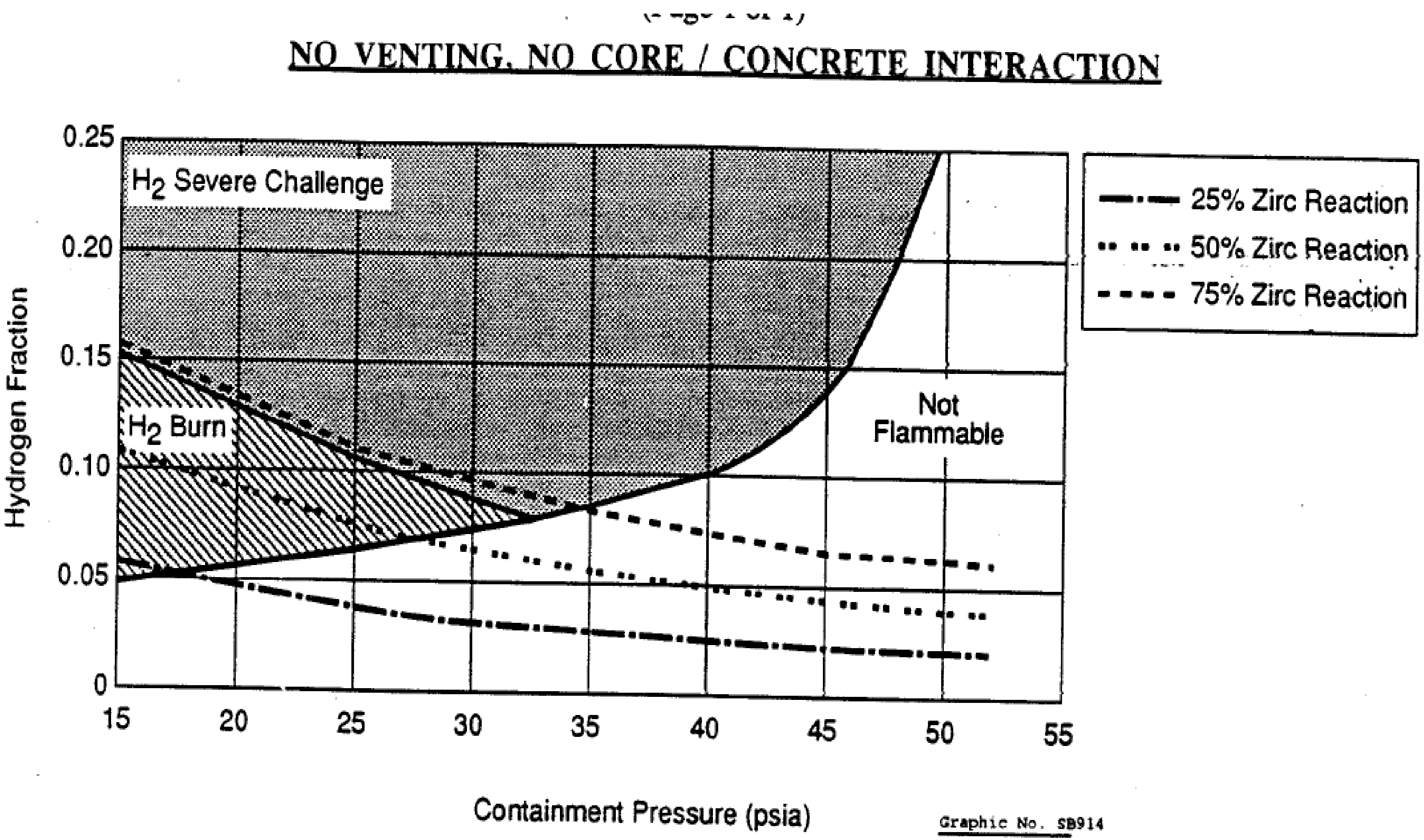


NIS recombiner installed

PARs in Areva PWR

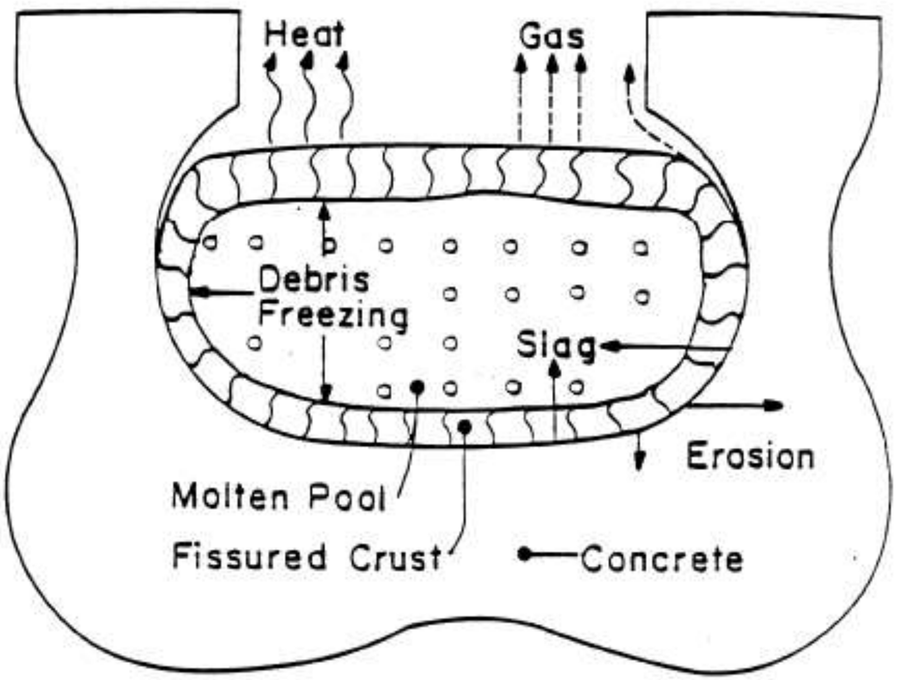


How dangerous is H_2?
Use Computational Aid (W)



Molten Core Concrete Interaction (MCCI)

- Ex-vessel challenge
  - Basemat erosion
  - Sidewall erosion
  - H_2, CO, CO_2
- Occurs in dry cavity conditions
  - No debris cooling
- Wet cavity
  - May still occur for deep core debris pools (e.g. > 10 cm)



Ref: EPRI Technical Basis Report, 2012

Molten Core Concrete Interaction (MCCI) – cont´d

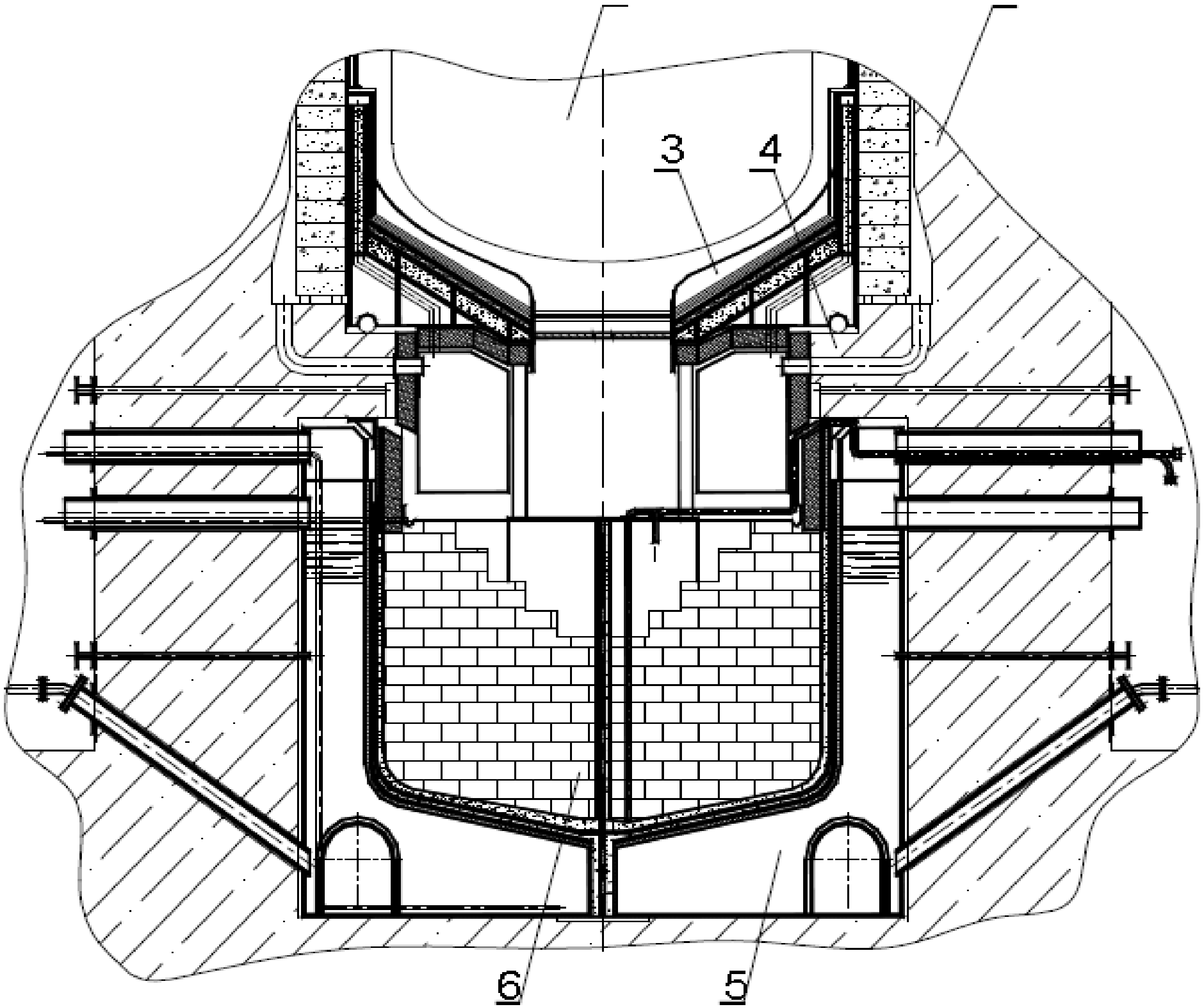
- Recall: corium debris in the cavity /drywell floor often not coolable
  - thick layer, lack of porosity
- MCCI creates large quantity of CO_2, also CO and H_2
  - pressurises the containment (mostly: days)
  - Sprays do not really work: non-condensables
    - But still cool, as do room coolers
- Try to prevent: by IVR, but may work only as delay of RPV meltthrough, may not prevent

Molten Core Concrete Interaction (MCCI) – cont´d

- IVR works only for moderate NPP power
  - Say up to 1000 MWe (or even lower)
    - For > 1000 MWe various vendors have developed core catchers
  - Claims exist it works up to 1400 MWe (e.g. nano fluids)
- Cavity/drywell ´wet`(i.e. water on the floor)
  - To mitigate initiating of MCCI
  - But some fear ex-vessel steam explosion
- Top flooding NOT effective to stop MCCI, but washes FPs
  - Many experiments done: MACE (US)
  - Small layers (~ 10 cm.) debris should be coolable
- New designs: core catcher

EPR Speading Area

Russian core catcher



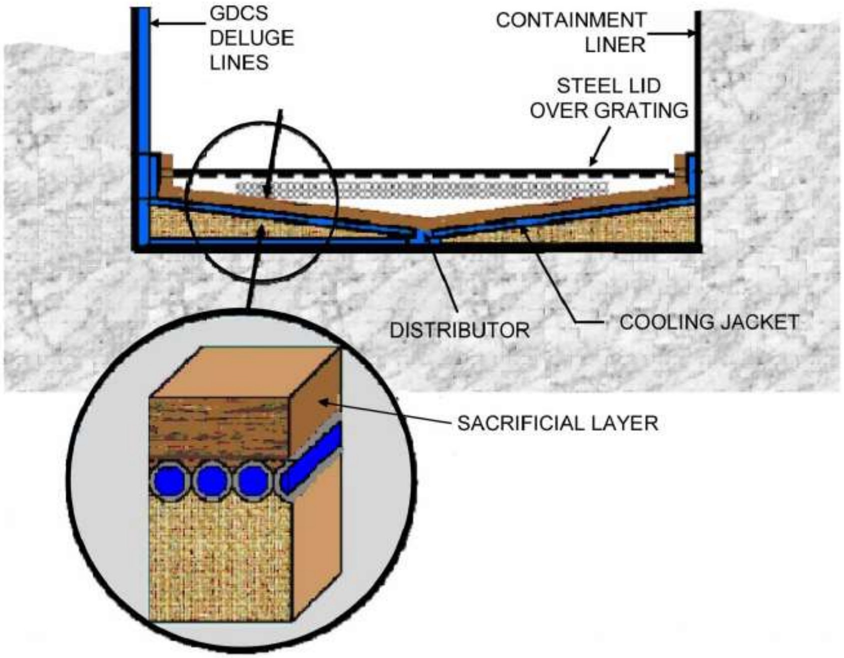
GE HITACHI Ex-vessel Core Cooling

BiMAC concept

BiMAC - Basemat internal Melt Arrest and Coolability

BiMAC designed to:

- Passively quench high temperature corium
- Mitigate core-concrete reactions
- Controlled by an independent logic platform



HITACHI

Containment Pressurisation

Increase of pressure by various sources:

- Release of mass and energy to containment
  - Mass: steam, H_2, CO, CO_2 (from MCCI)
  - Energy: decay heat, H_2 burn/recombination
- And through SAMG actions
  - Flooding cavity
    - May result in pressure spike at RPV meltthrough
  - Flooding debris
    - May result in pressure spike
      - Throttle flooding may be necessary
  - Filling up containment (to TAF) from outside sources
    - Pressurises the containment + static load on the containment floor

Strategies against containment overpressure

- Using fan coolers or other heat sinks
- Using sprays
  - Caution: may de-inert containment atmosphere
- Using ventilation systems
- Using dedicated containment coolers
  - Sometimes by new design feature (AP600/1000)
    - Picture in next slide
- Using containment vent systems
  - May lead to large release, even with filter
    - Filter does not stop noble gases, neither organic iodine

AP 600 /1000 containment

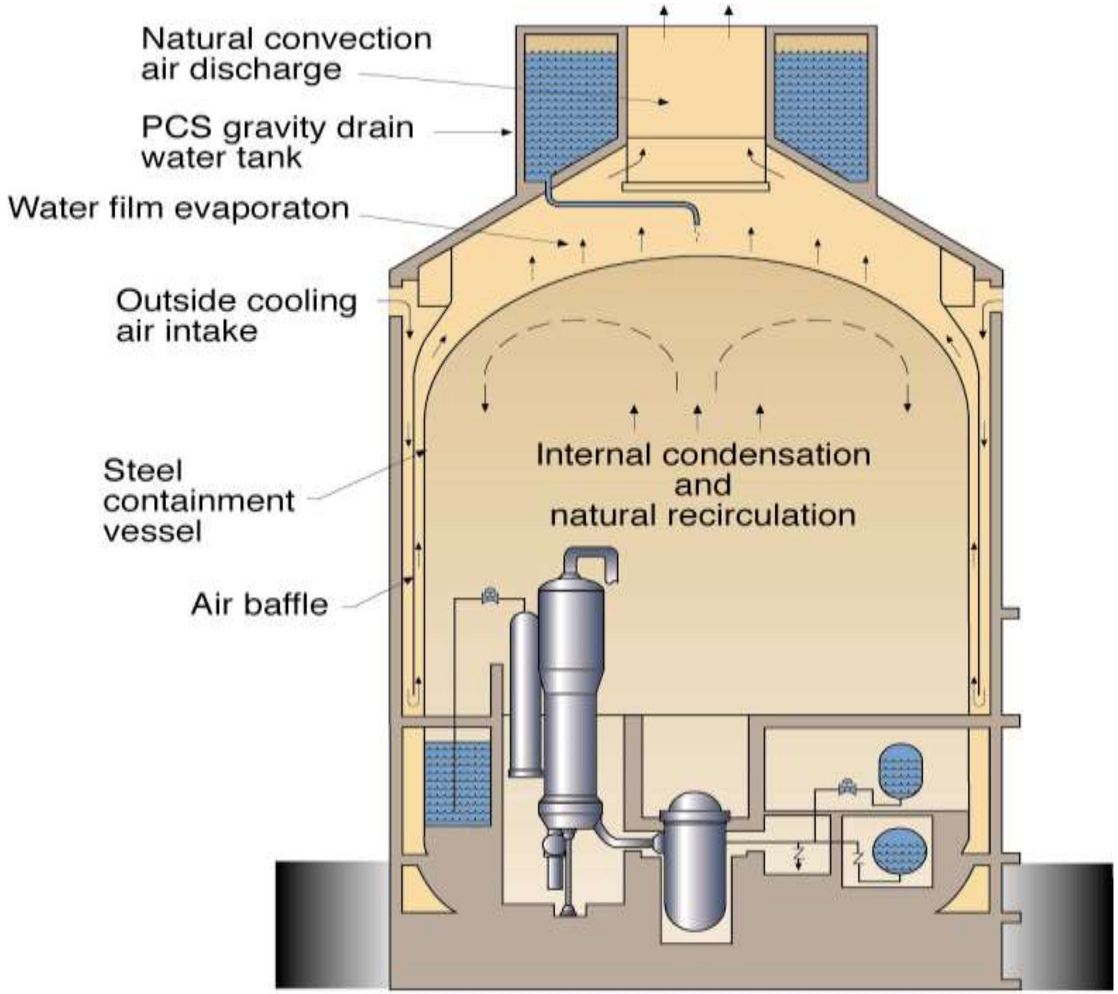
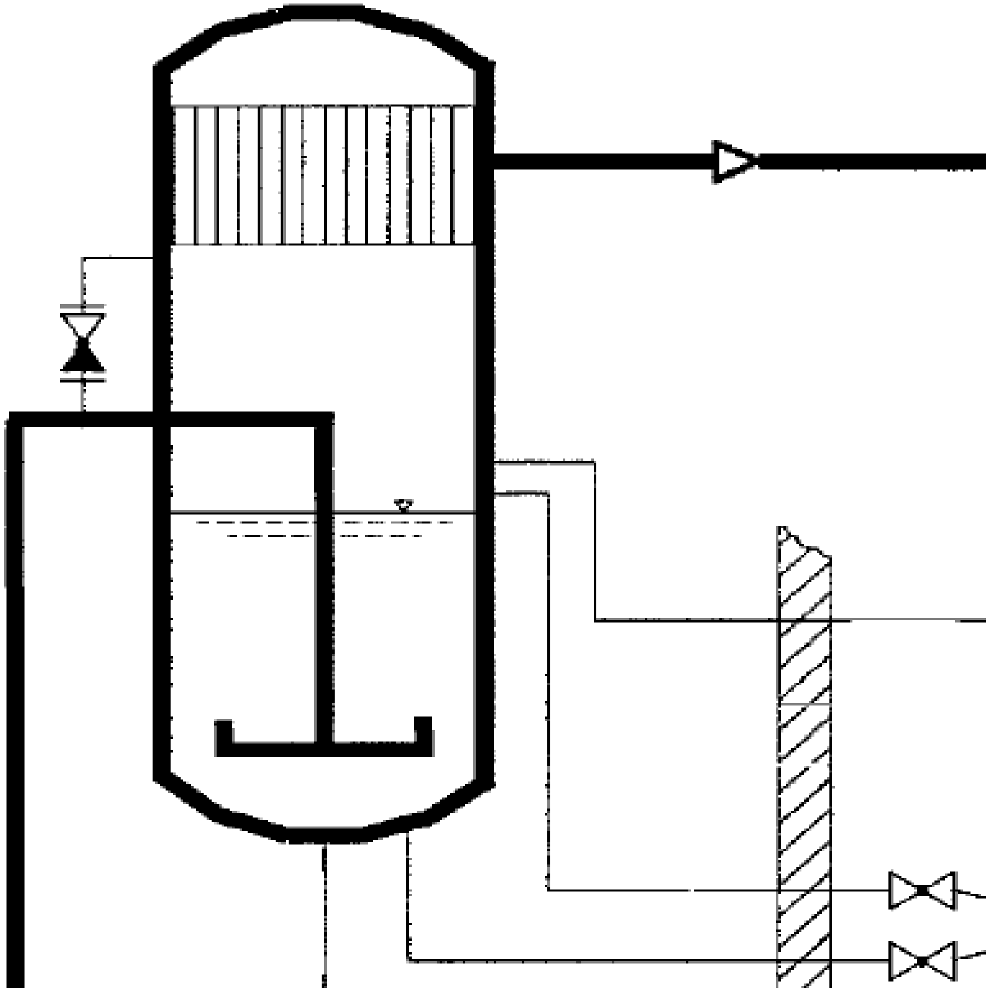
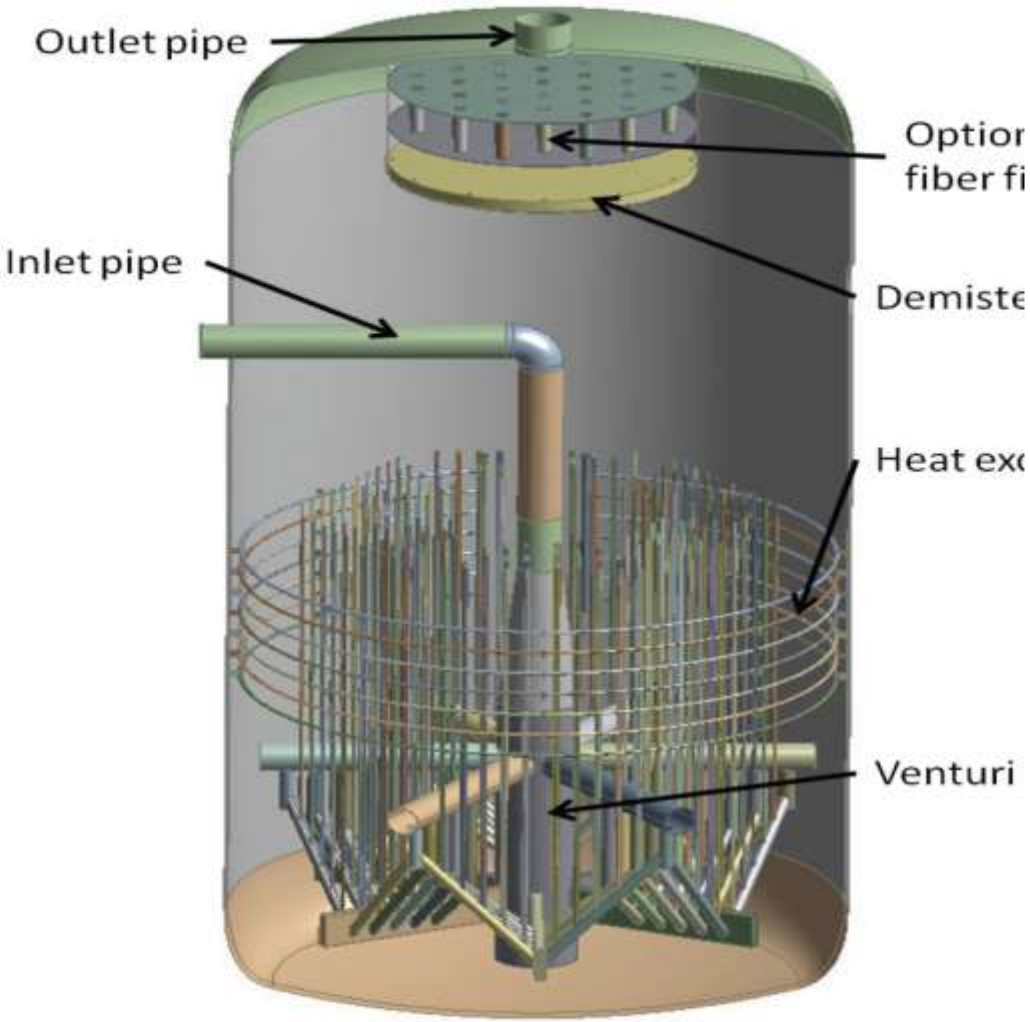


Figure 3. AP600 Passive Containment Cooling System

Siemens containment filter

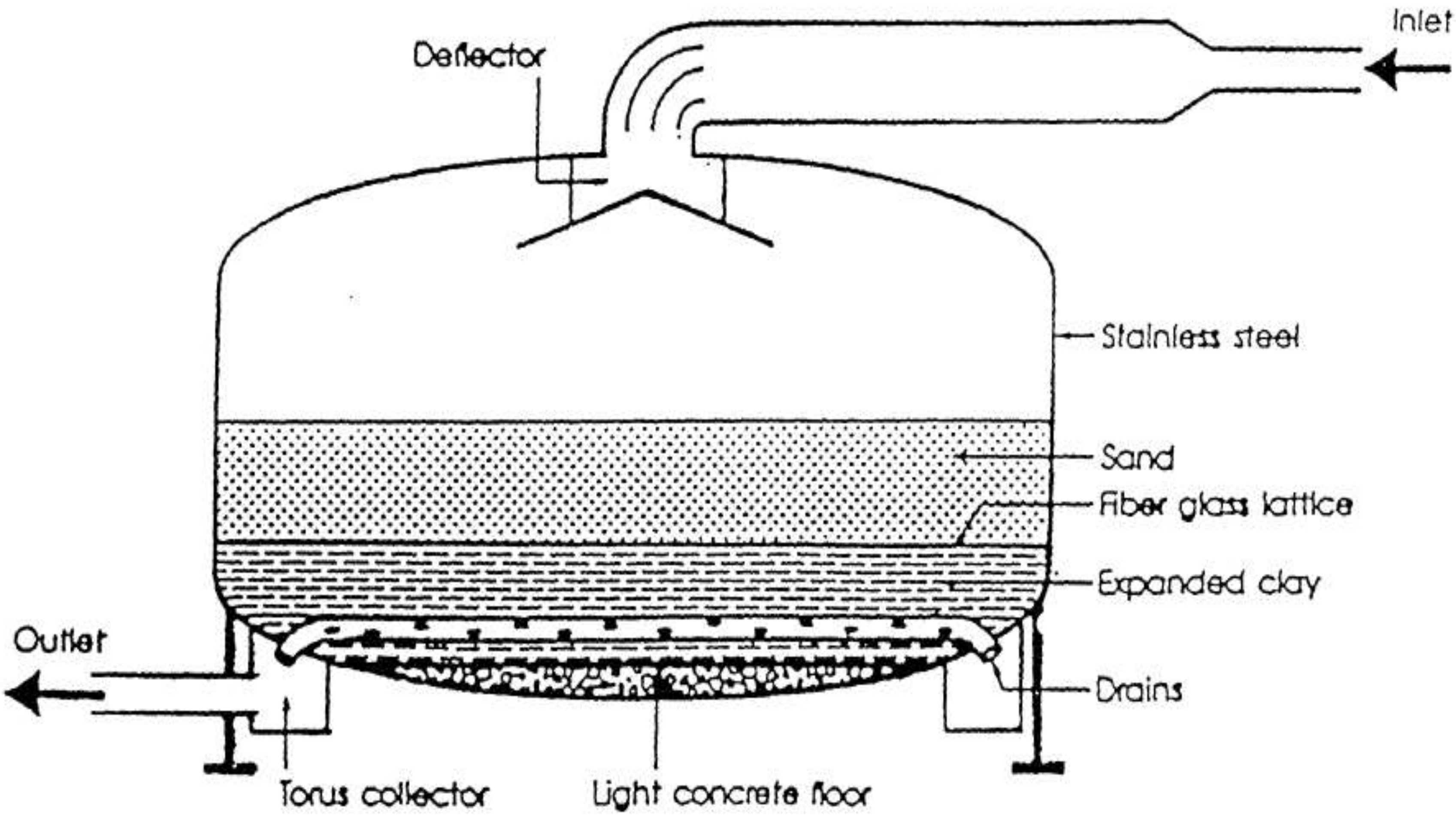


Swedish containment filter



FILTRA-MVSS system design

French sand-bed filter



Containment sub-atmospheric pressure

- Venting releases steam AND non-condensables (air, CO_2), absoption of O_2 by PARs or by H_2-burns
- After condensation of steam: sub-atmospheric pressure
- Containments have limited resistance against negative pressure difference
- Strategies:
  - Have vacuum breakers
  - Stop containment heat sinks
  - Open pressuriser PORVs
  - Add instrument air to containment
  - Establish nitrogen flow to accumulators

Mitigate releases

- From containment:
  - depressurise containment by fan coolers
  - sprays (prefer from internal sources)
    - Prevent sump dry-out (caused by FPs scrubbed by spray to sump) – control pH of sump water
- From SG:
  - isolate SG
  - dump steam from affected SG to condenser
  - fill affected SG
- From auxiliary building:
  - isolate leaking containmant penetration
  - reduce RCS injection
  - keep containment pressure low
- Capture and store contaminated run-off water

Exit from SAMGs

SAMG are used until a longer term stable and safe condition has been achieved and the transition to long term provisions can be made; example:

- Site releases under control and small or decreasing
- Core debris covered and subcooled (e.g. core exit temperature < 100 ° C and stable or decreasing)
- RCS pressure low and stable
- Containment pressure low (near or equal ambient pressure) and stable or decreasing
- Hydrogen content in the containment clearly and permanently below flammability limits
- Containment sump flooded and being kept flooded (to prevent revolatilisation of FPs)

Conclusions

- Various strategies are defined to mitigate a severe accident
- Plant equipment can be used, or portable equipment
  - portable equipment requires time to hook on
- Next step is development from strategies to A/M guidelines, i.e. detailed instructions to operators and TSC to implement the strategies
- Not yet treated: SFP and shutdown modes

Questions?

Comments?

Thanks for your attention!