Lecture 7 – Heat Removal & Containment

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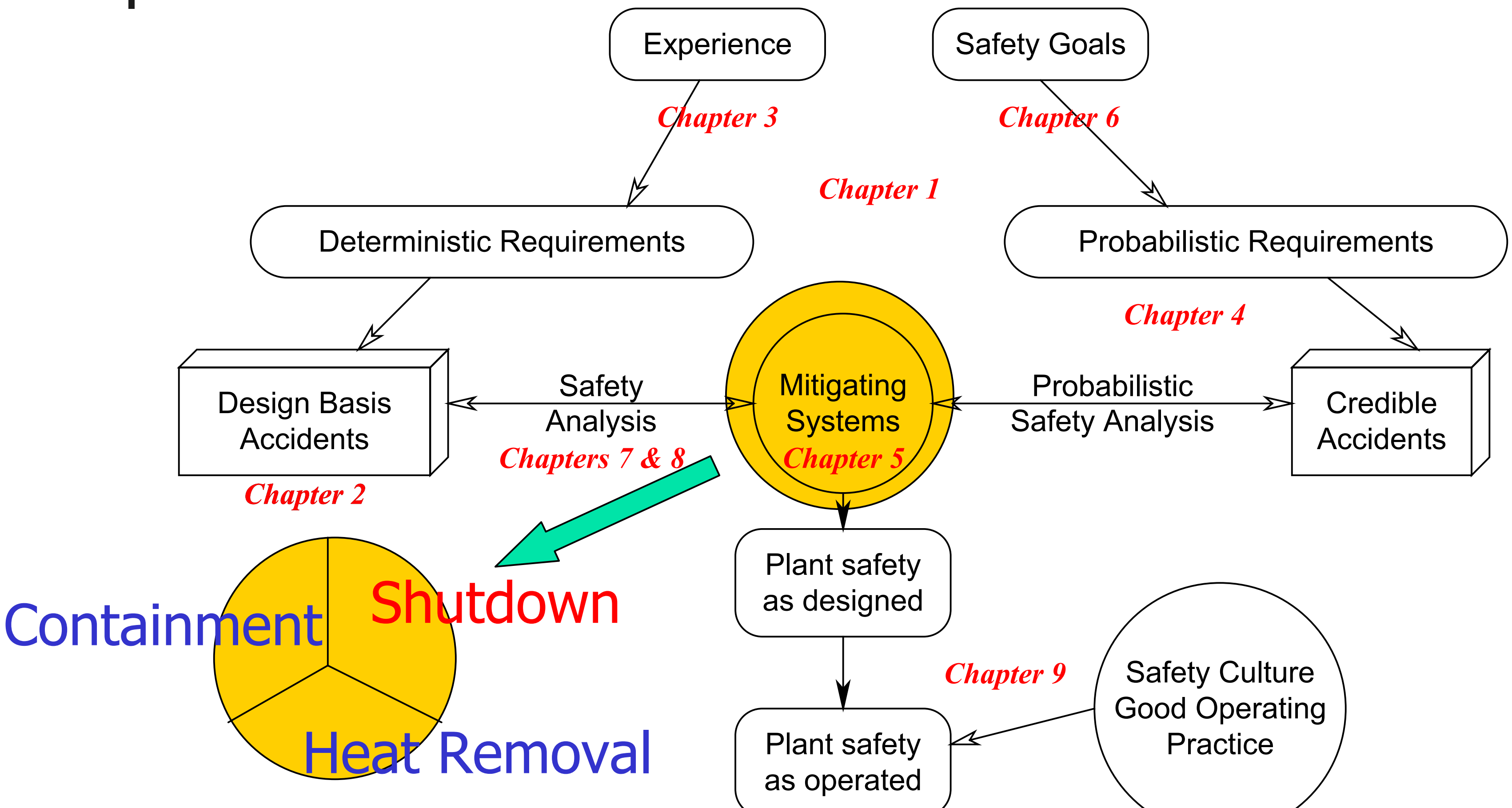
Nuclear Reactor Safety Course

McMaster University

Where We Are (still)…



Heat Removal – Issues

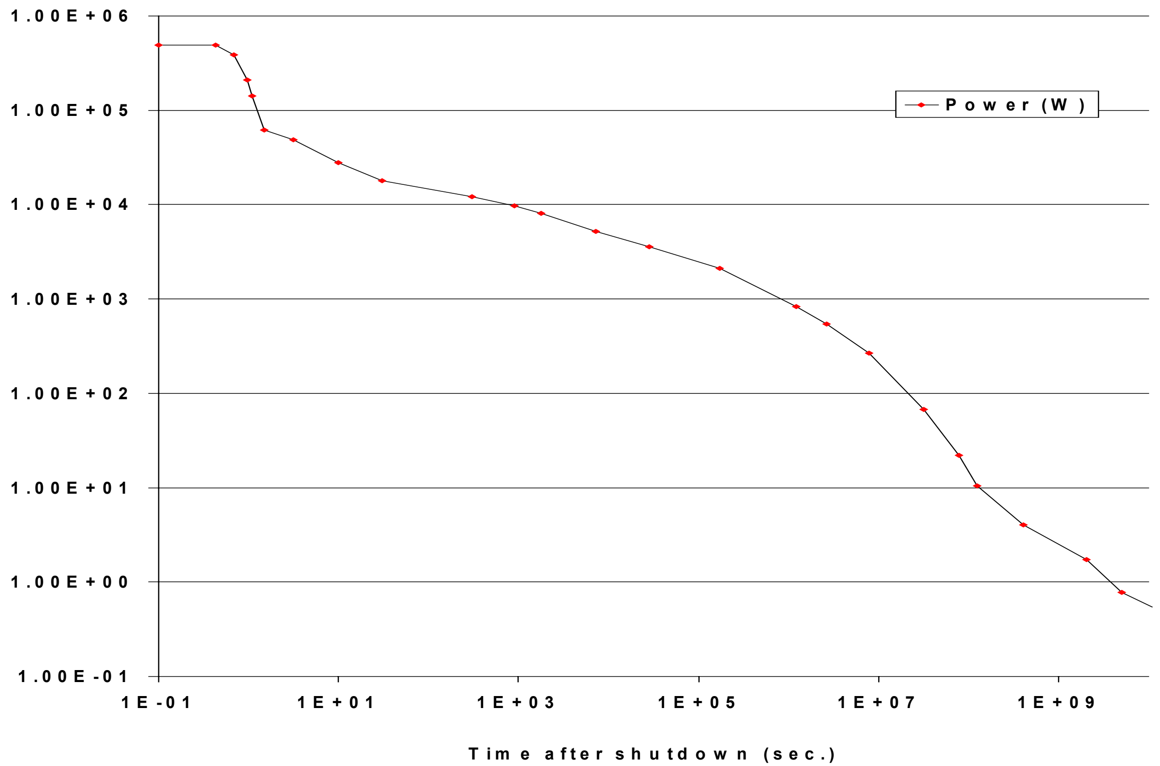
- How much heat?
  - Full power, decay power, decay power after *x* seconds?
- Where is it connected?
  - Primary side, secondary side, moderator
- How is it initiated?
- What conditions can it operate under?
  - Pressure, temperature
- What is its reliability?
- How long can it last?

Heat Removal - Amount

- Obviously, only one system to remove full power - economics, not safety
- Sudden loss of heat removal:
  - Economics: Steam dump to condenser via CSDVs (poison prevent)
    - Good for loss of grid
  - Safety: Steam dump to atmosphere via MSSVs

Decay Heat

CANDU Bundle Power after Shutdown



Location - Secondary Side

- Water supply
- Motive force
  - Electrical power
  - Gravity
  - Steam turbine
  - Direct diesel drive
- With broken steam or feedwater pipes – refill SGs from top or bottom

Choices

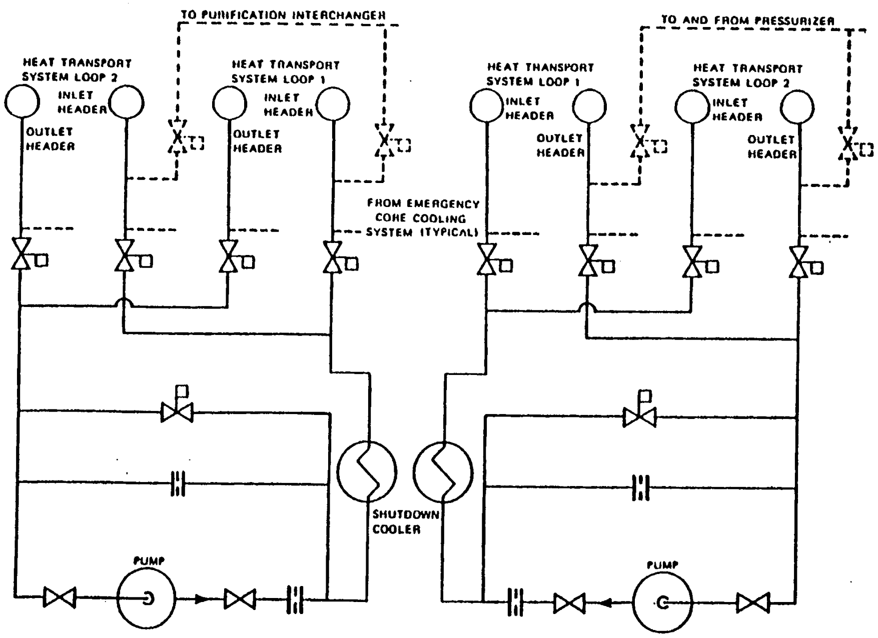
- Main steam and feedwater system
  - ~0-100% power
  - Water supply is continuous if condenser is available
- Auxiliary feedwater pumps (~4%)
  - Without Class IV electrical power
    - No condenser
    - Slow loss of inventory
    - Alternate heat sink needed eventually

More Choices

- Emergency Water System
  - Gravity feed from dousing tank to steam generators
  - Requires depressurization
  - Supplemented from pond, electrically pumped on Group 2 power
- Newer designs: four-train RWS/RCS
- Newer requirements: EHRS as a *safety* system

Location – Primary Side – Shutdown Cooling System

- Closed system
- Connected to reactor headers
- Dedicated pumps and HXs
- High pressure and temperature
- Variant: Maintenance cooling system (Bruce)

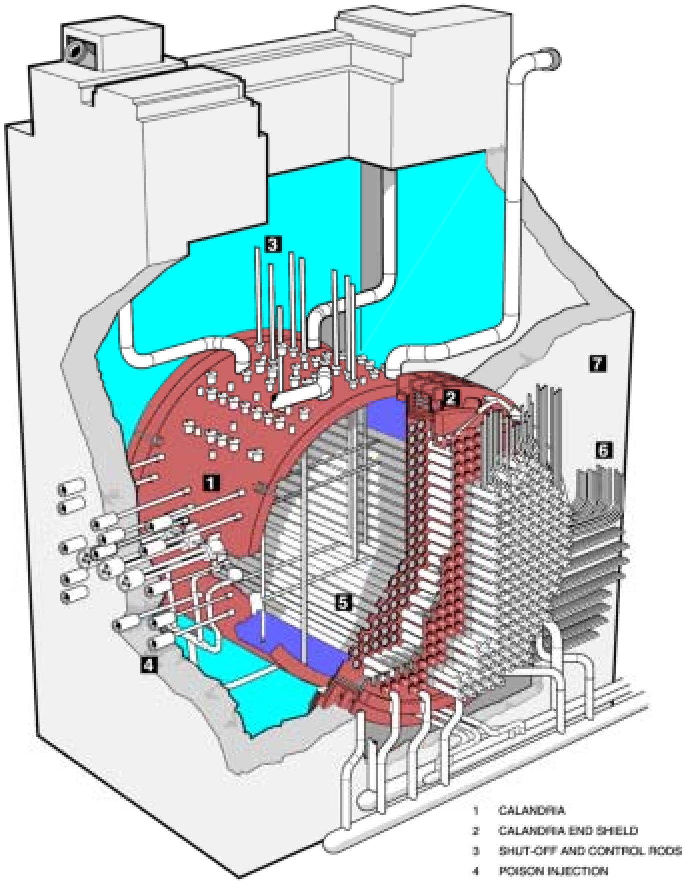


EWS and ECC

- Emergency water system…
  - Can also add water to primary side
  - Small LOCA, post-earthquake
  - Must be depressurized
- LWRs
  - Feed & bleed
  - RHR (low pressure)
- Emergency core cooling system
  - Decay heat removal for breaks

Moderator and Shield Tank

- Distributed sources of water around the core
- Moderator – can prevent fuel melting but not fuel damage
  - 5% steady heat removal
- Shield tank – delay melt-through of core
  - 0.3% steady heat removal
  - Cross-linked via service water
  - Could top up (ACR)

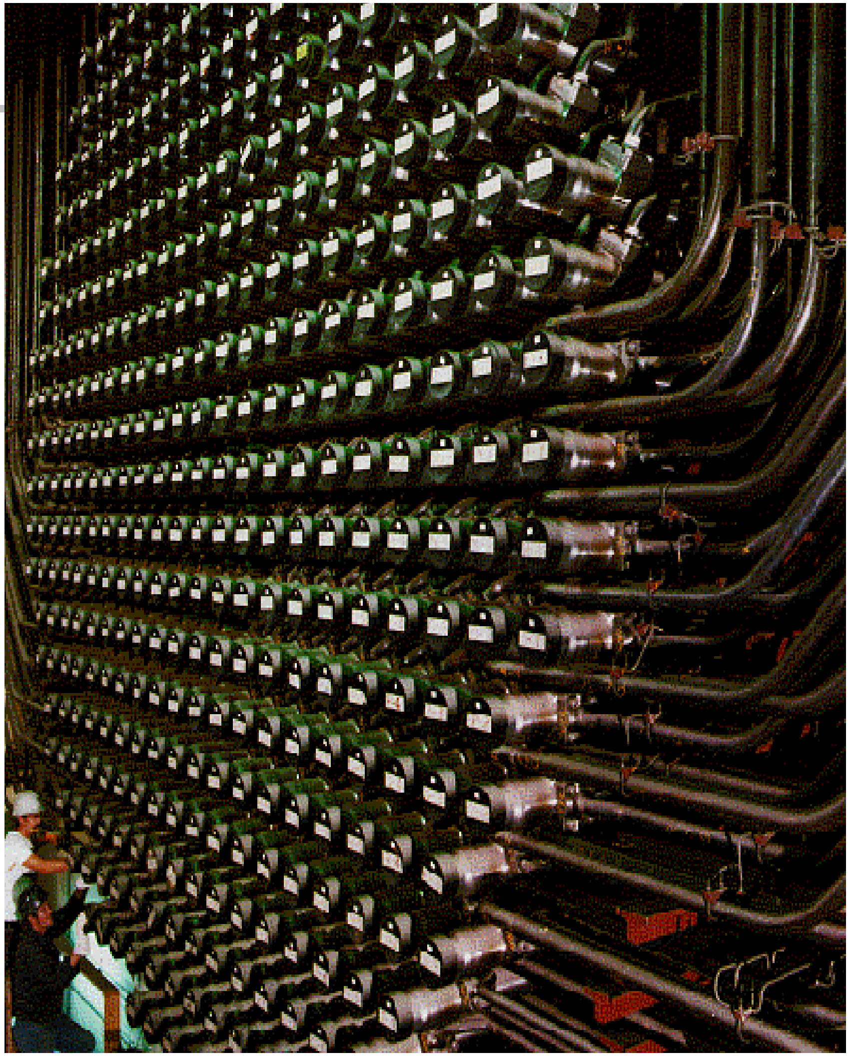


CANDU 6 Reactor Assembly

Figure 5-10 - Moderator and Shield Tank Surrounding Core

Feeder Pipes

- Reject reactor heat to air after a very long shutdown
- Only requirement is water in the channels
- Used at Point Lepreau after wood incident



Initiate Decay Heat Removal

- Mixture of manual and automatic, depends on
  - Time remaining - steam generators hold ~30 min. of water after shutdown (cf. Three Mile Island)
  - Likelihood
- Manual
  - SDCS, EWS
- Automatic
  - Auxiliary feedwater, ECC; Group 2 feedwater
  - Continuously running
  - Moderator, Shield tank

Operating Pressure

Operating Pressure	Advantages	Disadvantages
High	Can be brought in at any stage of an accident Components tend to be smaller due to more efficient heat removal (larger ΔT) More easily automated	More stringent requirements on code class of piping and components Need to ensure it is tolerant if bought in when system is at low pressure (e.g., risk of pump cavitation)
Low	Can be simpler/cheaper Can be made more passive	Requires prior depressurization of the system

Reliability

- Complex systems – pumps, valves
  - Require electrical power, water, control
  - Mission time can be days to months
- Typical unavailability ~10^{-2} to start, 10^{-1} over long mission time
  - ECC a factor of 10 better
  - EHRS 10^{-3} to start
- Passive systems?

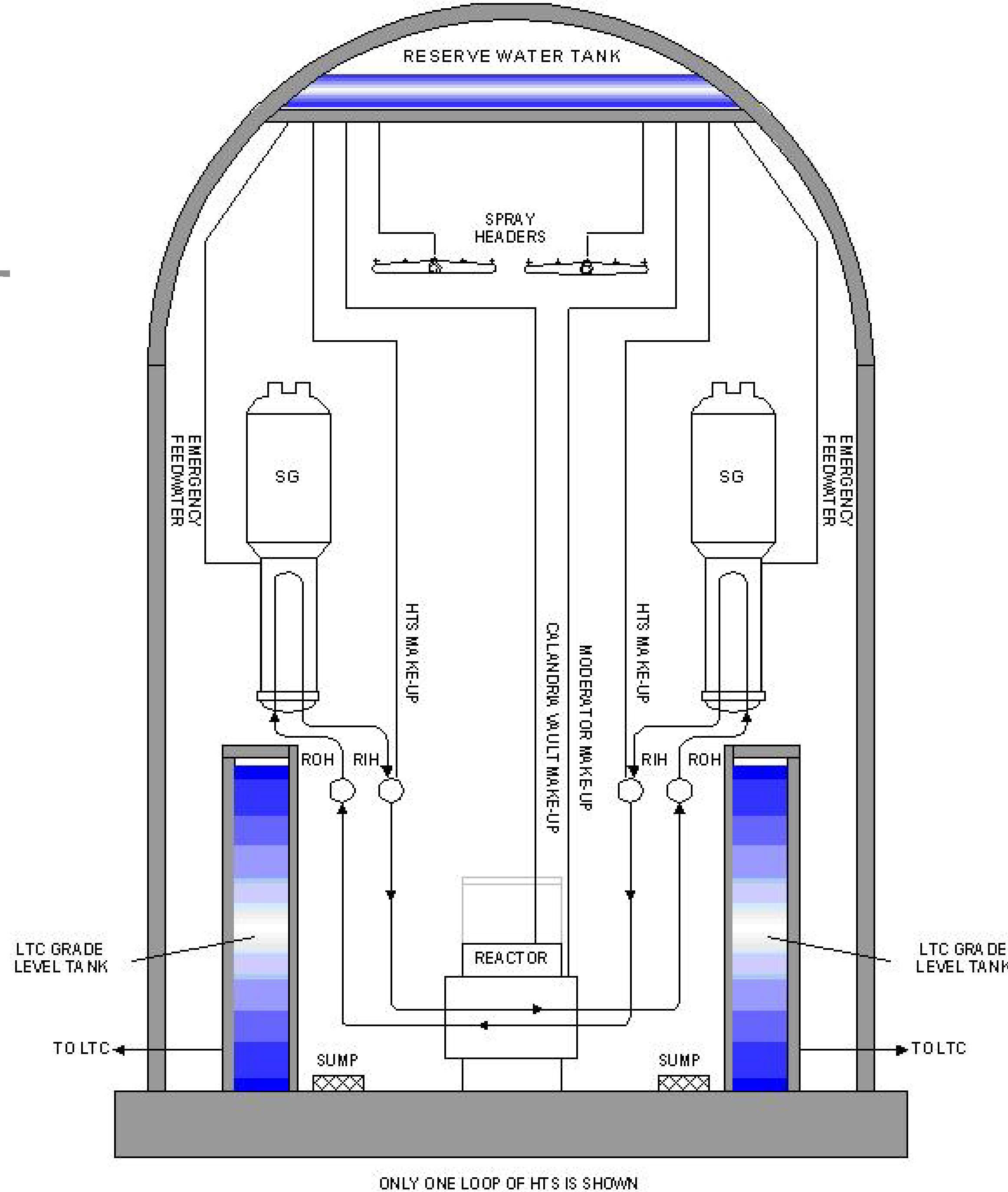
How Long?

- Some systems have limited capability:
  - Steam generator via MSSVs – 30 min
  - Moderator – hours (unless topped up)
  - Shield tank - ~day (unless topped up)
  - EWS pond, Reserve Water Tank – days
- Systems which can run continuously usually require external power and/or an ultimate heat sink

Passive Systems - Pros & Cons

- Pros
  - More reliable
  - Natural forces
  - Simpler
  - Less reliance on external power
  - 'Transparent' – easy to explain
  - Less dependence on operator
- Cons
  - Failure modes subtle
  - Small forces
  - Large volumes, $
  - Most need control power
  - Modeling can be difficult
  - Hard to test & operate manually

Example: ACR-1000 Reserve Water System



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Summary

System	HTS Operating Pressure Range	Heat Removal Capacity	Support Systems	Comments
Main steam and feedwater system	Atmospheric to operating (10MPa)	0-115%	Class IV power Water from condenser	Normal power operation Cooldown to 177C after a shutdown
Auxiliary feedwater system	Atmospheric to operating	Decay power	Class III power Water from condenser	Used for loss of Class IV power
Shutdown Cooling system	Operating to atmospheric	Decay power	Class III power (+ Group 2 Emergency Power System on some new designs) Recirculating Cooling Water (RCW)	Used for cooldown from 177C after a shutdown Can be brought in at full system temperature in an emergency

Summary - 2

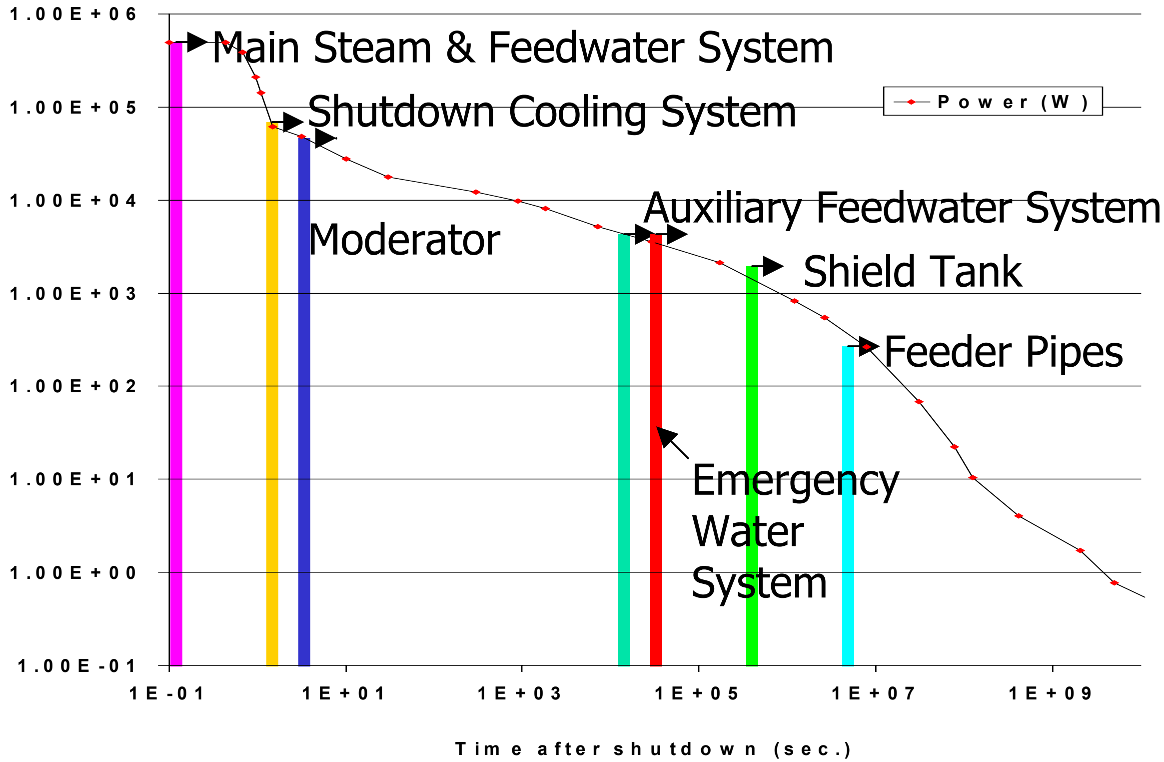
System	Operating Pressure Range	Heat Removal Capacity	Support Systems	Comments
Emergency Water System	Near-atmospheric (up to secondary side operating pressure on some new designs); can remove heat with HTS at high pressure	Decay power	Group 2 Emergency Power System. Some form of water reservoir (dousing tank, external pond)	Used after an earthquake and as a backup to Group 1 heat removal systems. Requires depressurization of primary or secondary side to be effective.
Moderator	Atmospheric (can remove heat from Heat Transport System up to about 6 MPa)	Decay power a few minutes after shutdown (5%)	Class III power RCW	Used in severe accidents where there is no primary-side heat sink. In ACR, water can be added to the moderator.

Summary - 3

System	Operating Pressure Range	Heat Removal Capacity	Support Systems	Comments
Shield Tank	Atmospheric	0.3% power	Class III power RCW	Will delay progression of core melt due to large amount of water. In ACR, water can be added to the shield tank.
Feeder pipes	Full pressure to atmospheric	Very low (weeks after shutdown)	Channels should be full of water Heat must be removed from containment	Used at Point Lepreau during the long shutdown to remove debris from the HTS

Decay Heat – Various Systems

CANDU Bundle Power after Shutdown



Emergency Core Cooling

- Safety performance requirements?
- Where is it connected? (where is the best place to put the water?)
- What is the injection pressure?
- What other functions besides water injection must ECC perform?
- How is it initiated?
- What is its reliability?

Safety Performance

- Safety
  - Meet public dose limits
  - Prevent pressure tube failure
  - Ensure coolable fuel geometry
- Economics
  - Prevent fuel failures for small breaks

Where to Put the Water

- Light water into 8 headers
- Pros and cons?

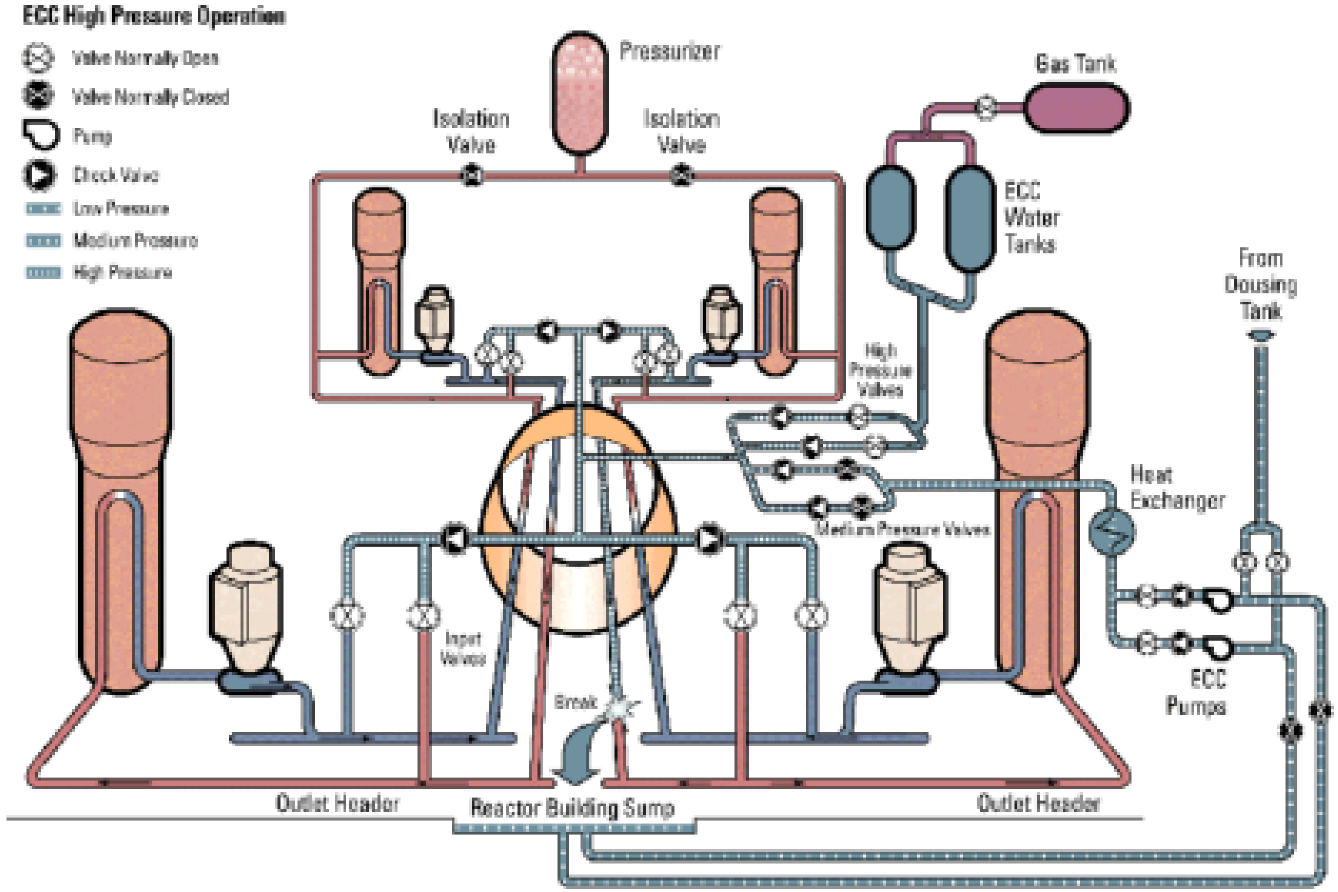
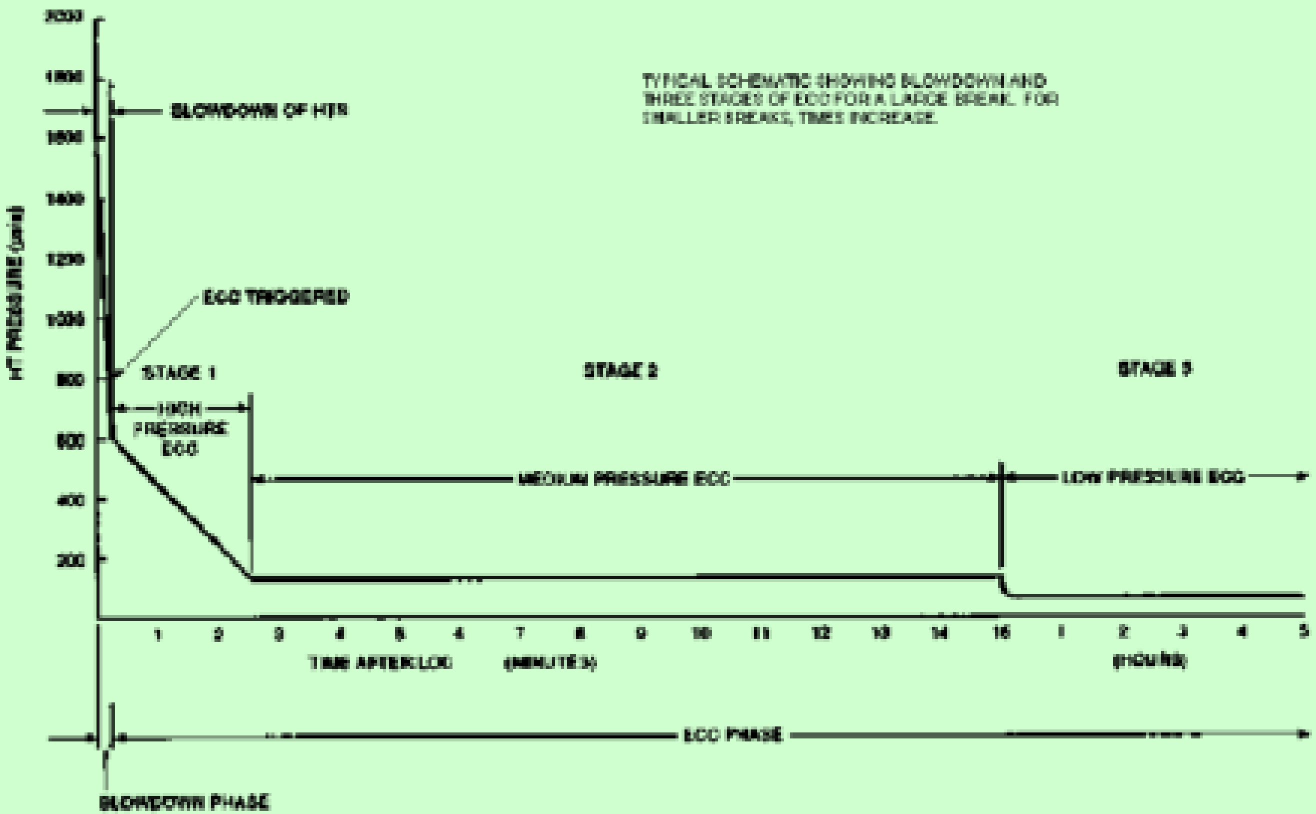


Figure 5-12 - ECC Schematic

Pressure and Flowrate



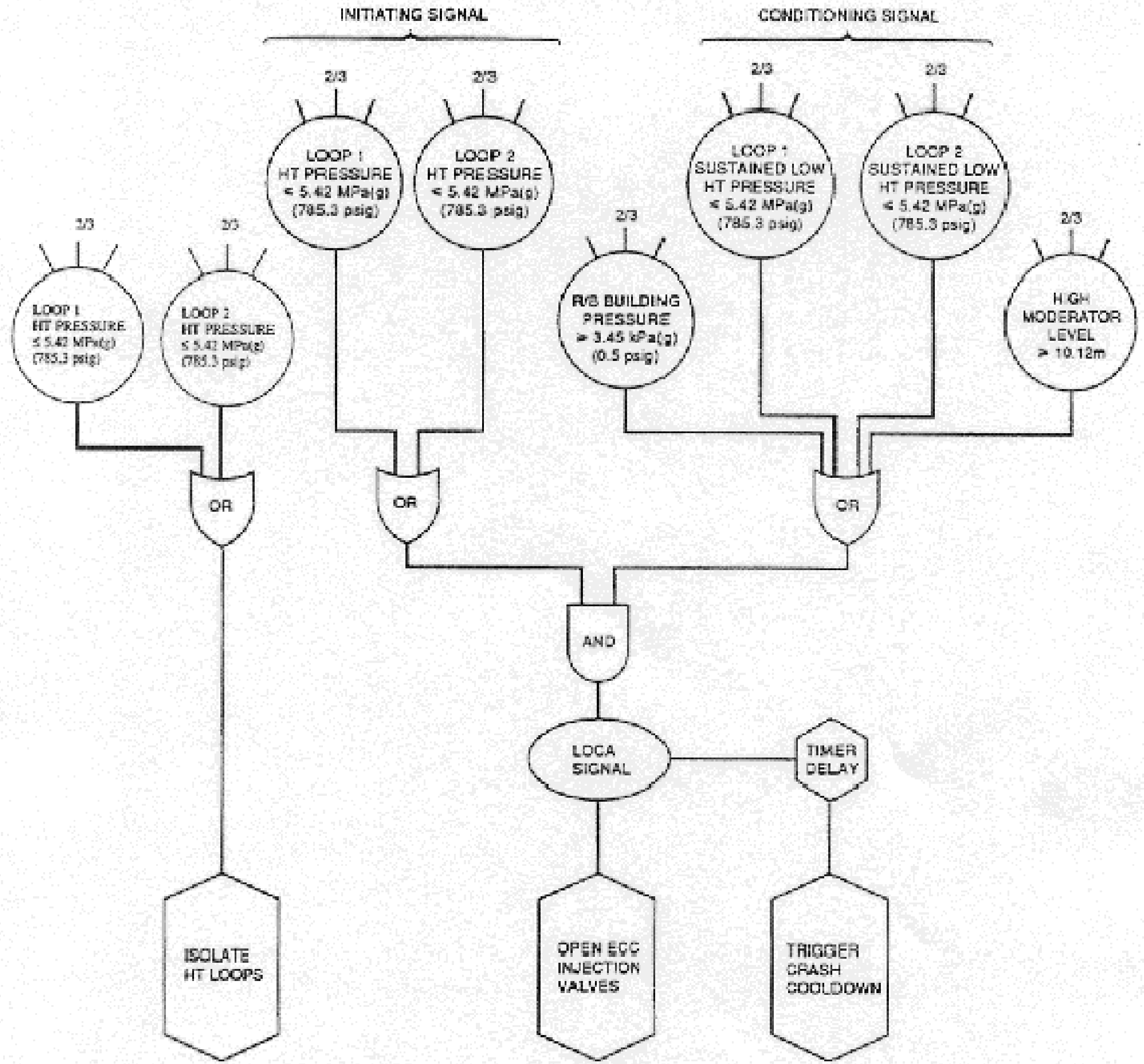
Blowdown and ECC Pressure Curve Schematic

Figure 5-13 - ECC Phases

Other functions

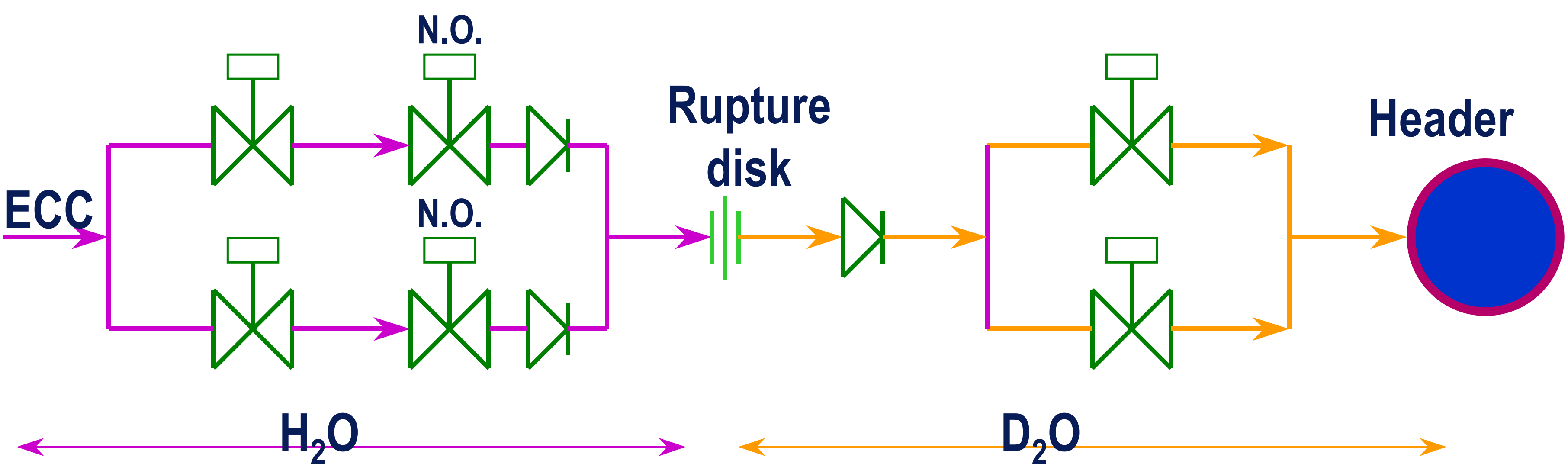
- Loop isolation
  - Limit hydrogen source term for LOCA + LOECC
  - Tradeoff: slow refill of unfailed loop
- Crash Cooldown
  - Force secondary pressure down so HTS pressure stays below accumulator pressure
  - Less important if HP pumps are used
- Run HTS pumps until forced to trip

Initiation Signals



Unavailability

- <10^-3^ to start; ~10^-2^ for 3 month mission
- Difficult due to large numbers of valves
- Recent designs: ball valve and rupture disk



Containment

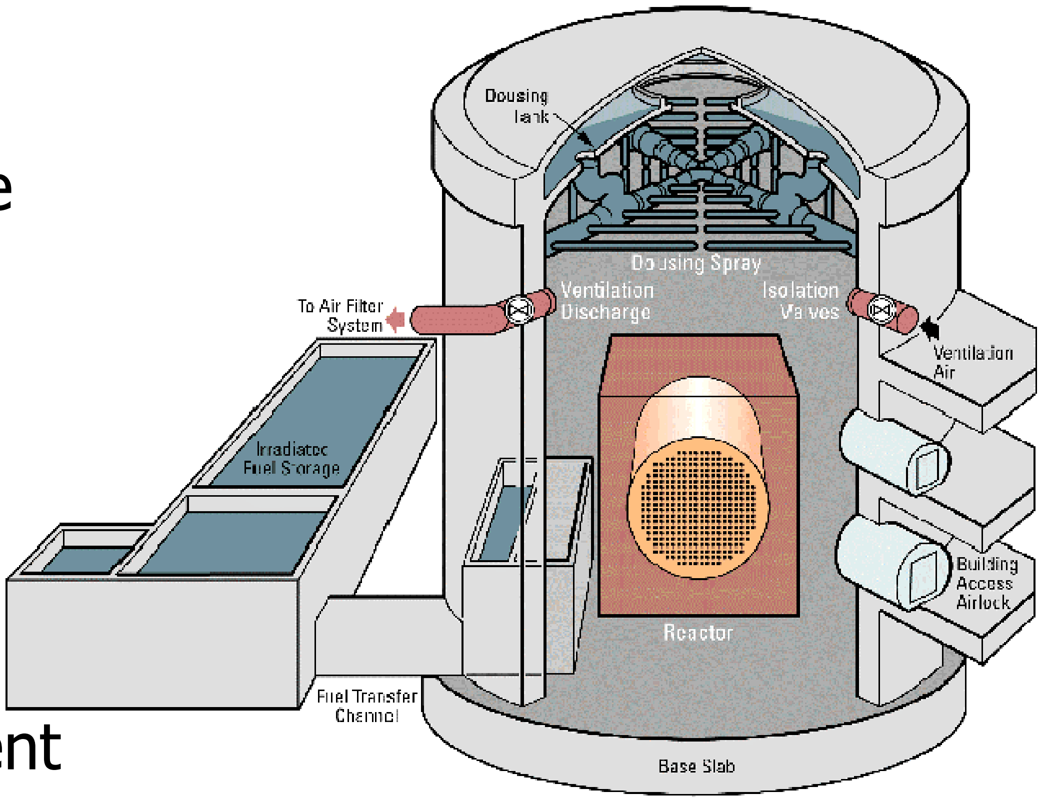
- What is the design pressure?
- What is the leakrate at design pressure?
- How is pressure controlled? How is heat removed?
- How is containment isolated?
- What is the containment reliability?
- Other functions?

Design Pressure & Leakrate

- Design pressure
  - Set by maximum pressure from accident
  - *Leakrate at design pressure is known*
  - CANDU 6 – 0.5% / day at 124 kPa (g)
  - Vacuum containments – lower design pressure and higher leakrate yet more effective – why?
- Steam main failure vs. design pressure
  - Bruce/Darlington steam main location
- Safety margin to catastrophic failure ~ x3
  - Leakrate not guaranteed (depends on liner)
  - Must examine penetrations
- ACR – lower leakage rate (0.2%/day), higher pressure (350 kPa)
  - Include steam main failure

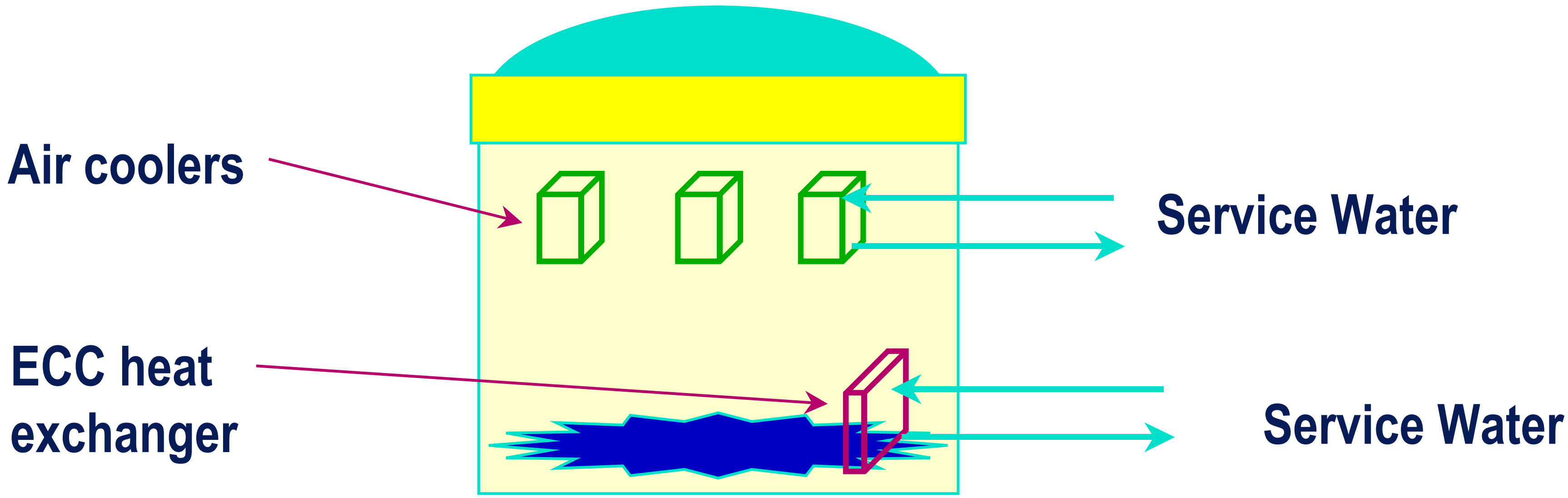
Control Pressure

- Short & long term heat removal
- 'Dry' high pressure containment
- Dousing sprays
- Vacuum containment
- Ice condenser
- Suppression pool
- Passive containment
- Pressure relief

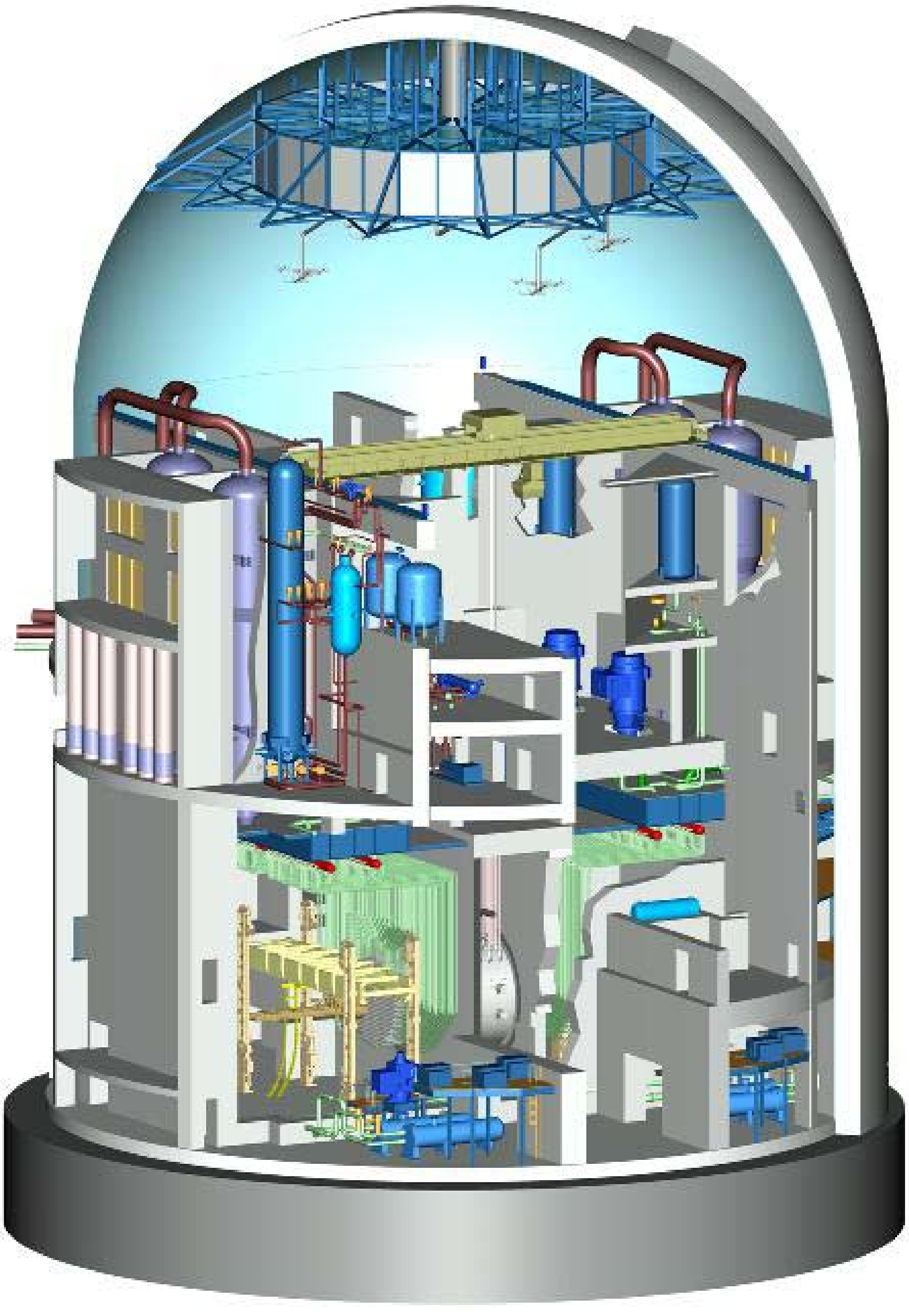


CANDU Heat Removal

- Conventional heat exchangers, pumps, fans
- Severe accident heat removal
  - Sprays, venting



ACR-1000 Containment



Unavailability

- <10^{-3} unavailability per demand
- How to test leak-tightness
  - Test to design pressure invasive, expensive
  - Monitor in/out flows and pressures to find holes
- Subsystems for isolation, dousing

Other Functions

- Barrier for external events including malevolent acts
- Shielding
- Hydrogen control – mixing and removal

Monitoring

- Two control rooms to maintain safety functions
- SCA for seismic, loss of Group 1
- MCR must be evacuated in current designs for earthquake
  - ACR MCR seismically qualified
- Impact of terrorism and sabotage