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UK Gas Reactors Operational Feedback

Richard Stainsby

Export Control Rating: Not Controlled – No License Required

UK Gas-cooled Reactors

- Due to the UK's pioneering position in reactor technology the licensing standards had to evolve to match the evolution of reactor technology.
- In the earliest days a regulator did not exist.
- The Windscale Pile 1 fire in 1957 led to the creation of first an internal regulator (the Safeguards Group) and then to a truly independent regulatory body.

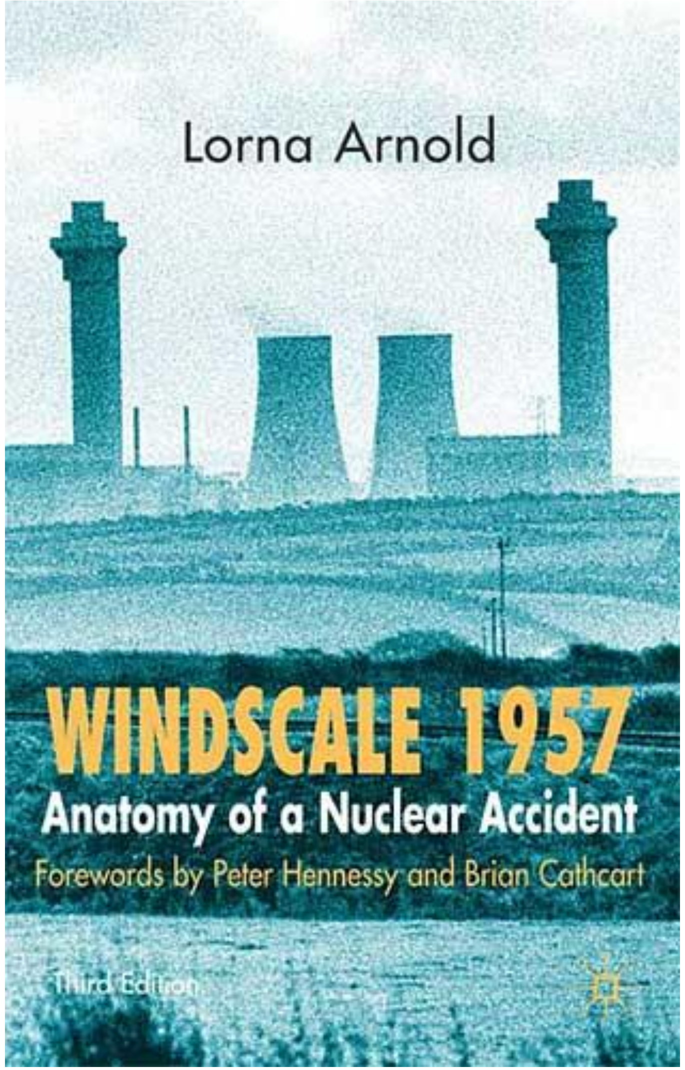
- There have been two previous generations of gas cooled reactors:
  - Windscale Piles – air-cooled (plus small experimental air-cooled reactors at Harwell)
  - Magnox Reactors – CO_2 cooled
  - Advanced Gas-cooled Reactors (AGR) - CO_2 cooled

- Plus one He-cooled experimental High Temperature Reactor (HTR) - Dragon

A Brief and Inconcise History of UK Gas Cooled Reactor Families

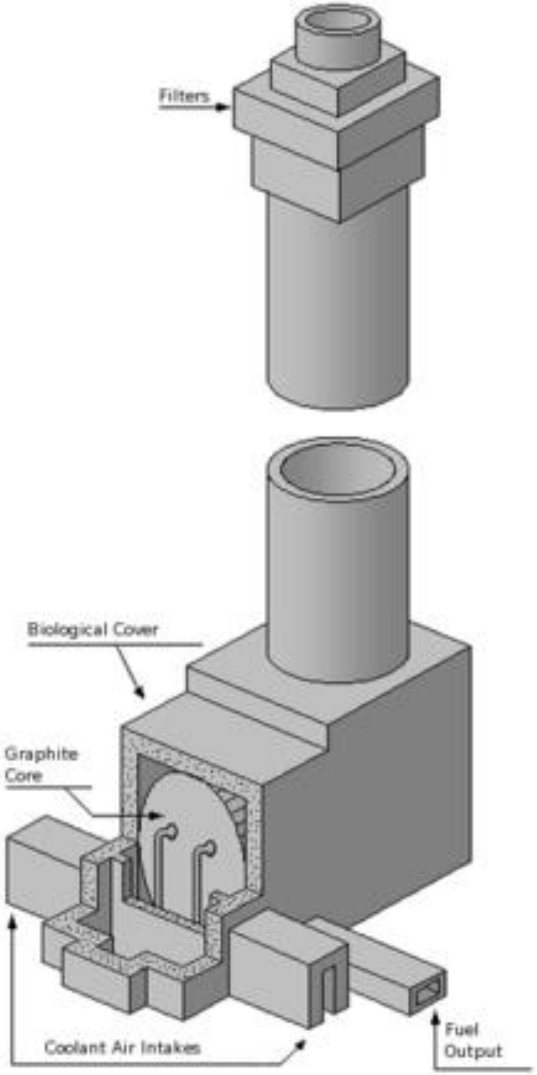
- 1947, Windscale Piles, UK - Military plutonium production
- Atmospheric air cooled, graphite moderated reactors
- Low temperature
- Open cycle
- Natural uranium metal fuel in aluminium cladding.

Lorna Arnold OBE, 1915 - 2014



Windscale Air-Cooled Plutonium Production Piles

Windscale Air Cooled Piles



Windscale Piles

Description:

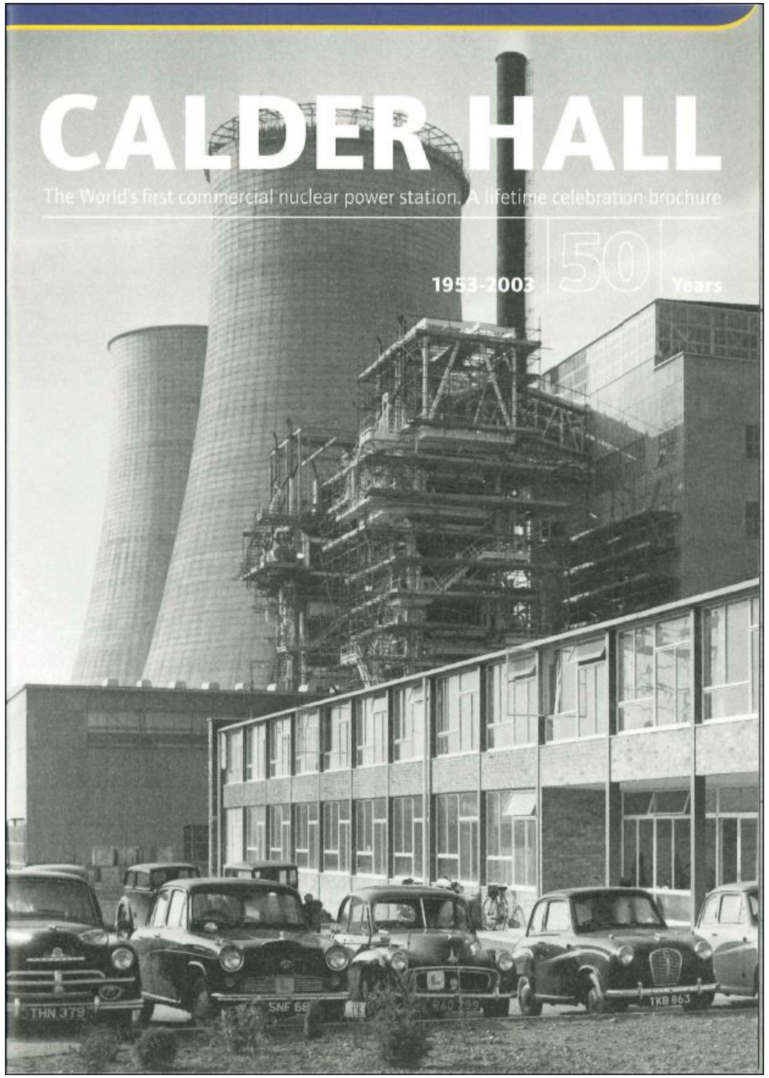
- Air cooled core – the atmosphere is the primary circuit
- Containment:
  - 1st barrier (incomplete), natural uranium metal fuel rod
  - 2nd barrier, aluminium cladding of the fuel elements
  - 3rd barrier (incomplete), filters in the chimney stacks
- Reactivity Control (two systems)
  - Control rods inserted and driven from the sides of the core
  - Shutdown rods, inserted from the top of the core and gravity-driven
- Cooling:
  - Massive electrically driven blowers assisted by chimneys
  - Natural convection driven by the chimneys for long-term decay heat removal

Windscale Piles – Lessons Learned

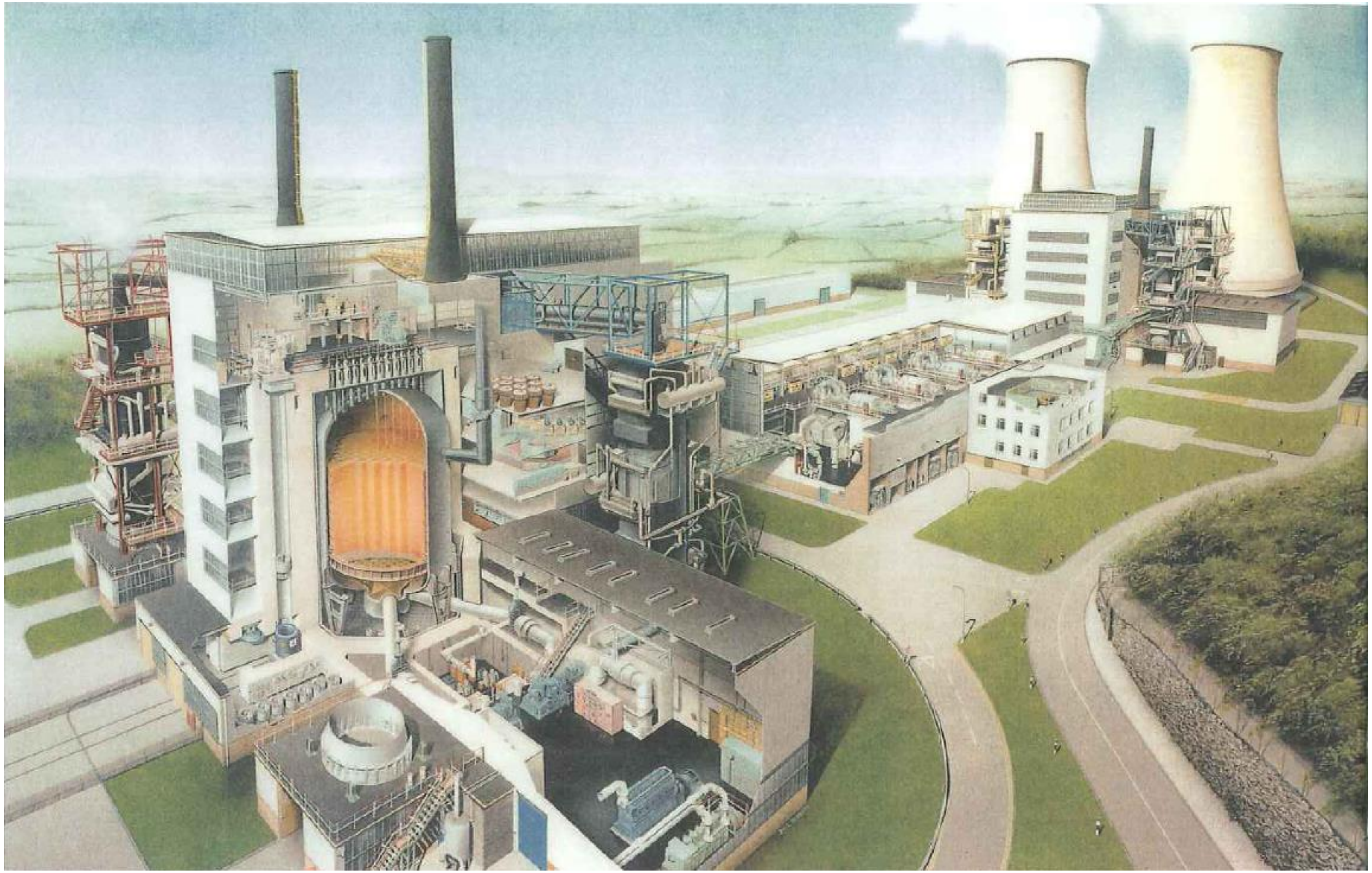
- Wigner Growth in graphite was known about at the time of the Windscal piles but Wigner Energy was not:
  - Wigner Energy was discovered when energy spontaneously released itself during operation in an uncontrolled manner.
  - Regular periodic anneals of the core were carried out thereafter to allow controlled release of the Wigner Energy.
    - Annealing was carried out by deliberately overheating the core to trigger the release.
    - Initiating temperature needed to release energy was increasing with time.
    - Rate of graphite oxidation at any temperature was increasing with time – sodium contamination from salt-laden sea air.
    - The too curves crossed in 1957 ….
- Don’t cool reactor cores with atmospheric air.
- Operate at high enough temperatures so that neutron induced damage in the graphite is self-annealing.

Carbon dioxide cooled – Magnox reactors, 1953 - 2014

- Closed cycle with carbon dioxide gas
- Pressurised coolant to reduce pumping power
- Natural uranium metal fuel
- Magnesium alloy low-absorption cladding
- Higher temperatures with lower oxidation rate than for air
- Temperature high enough for commercial electricity generation
- Steel pressure vessel
- No recognisable containment building (for early plants)
- World's first commercial nuclear power station to export power to a distribution grid
- Generation-I technology



Calder Hall Nuclear Power Station (Magnox) (2 of 4 reactors shown)



Early MAGNOX reactors

Description:

- Pressurised CO_2 cooled core in a closed primary circuit
- Containment:
  - 1st barrier (incomplete), natural uranium metal fuel rod
  - 2nd barrier, Magnox cladding of the fuel elements
  - 3rd barrier, carbon steel primary circuit boundary
- Reactivity Control (two systems)
  - Control rods inserted from the top of the core
  - Shutdown rods, inserted from the top of the core and gravity-driven
- Cooling:
  - Electrically driven gas circulators
  - Boilers used for normal and decay heat removal
  - Back up electrical supplies, low voltage systems and feedwater systems
- The containment system of later Magnox reactors resembles that of the AGR

Magnox Reactors – Lessons Learned

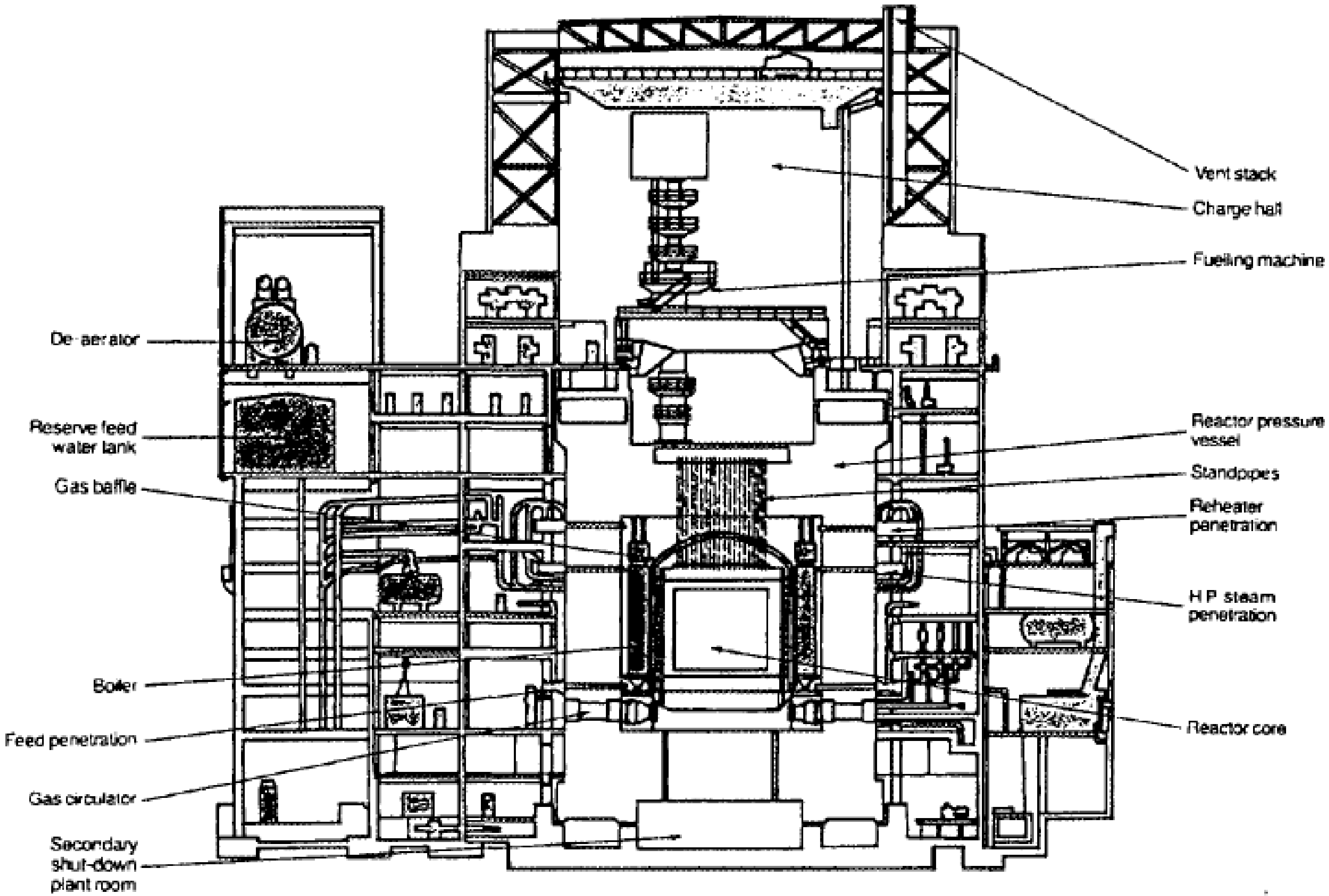
- Gas-cooling is a viable means of generating electricity using nuclear reactors on a commercial basis.
- Magnox reactors were the first in the world to be connected to a natural grid providing reliable baseload generation.
- Extensive use of carbon steel in the construction of the pressure vessels and the garter core restraint system in early reactor lead to severe corrosion issues.
- Embrittlement of the RPVs was found to be an issue in some reactors.
- All Magnox reactors exceeded their design lives by considerable margins.
- Fuel generally performed well, but to low burn-up.
  - Produced very high quality plutonium that fuelled the UK fast reactor programme
- Spent fuel degraded quickly when stored in water – needed to be dismantled and reprocessed quickly.

Carbon dioxide cooled – Advanced gas cooled reactors (AGRs) (late 1960s onwards)

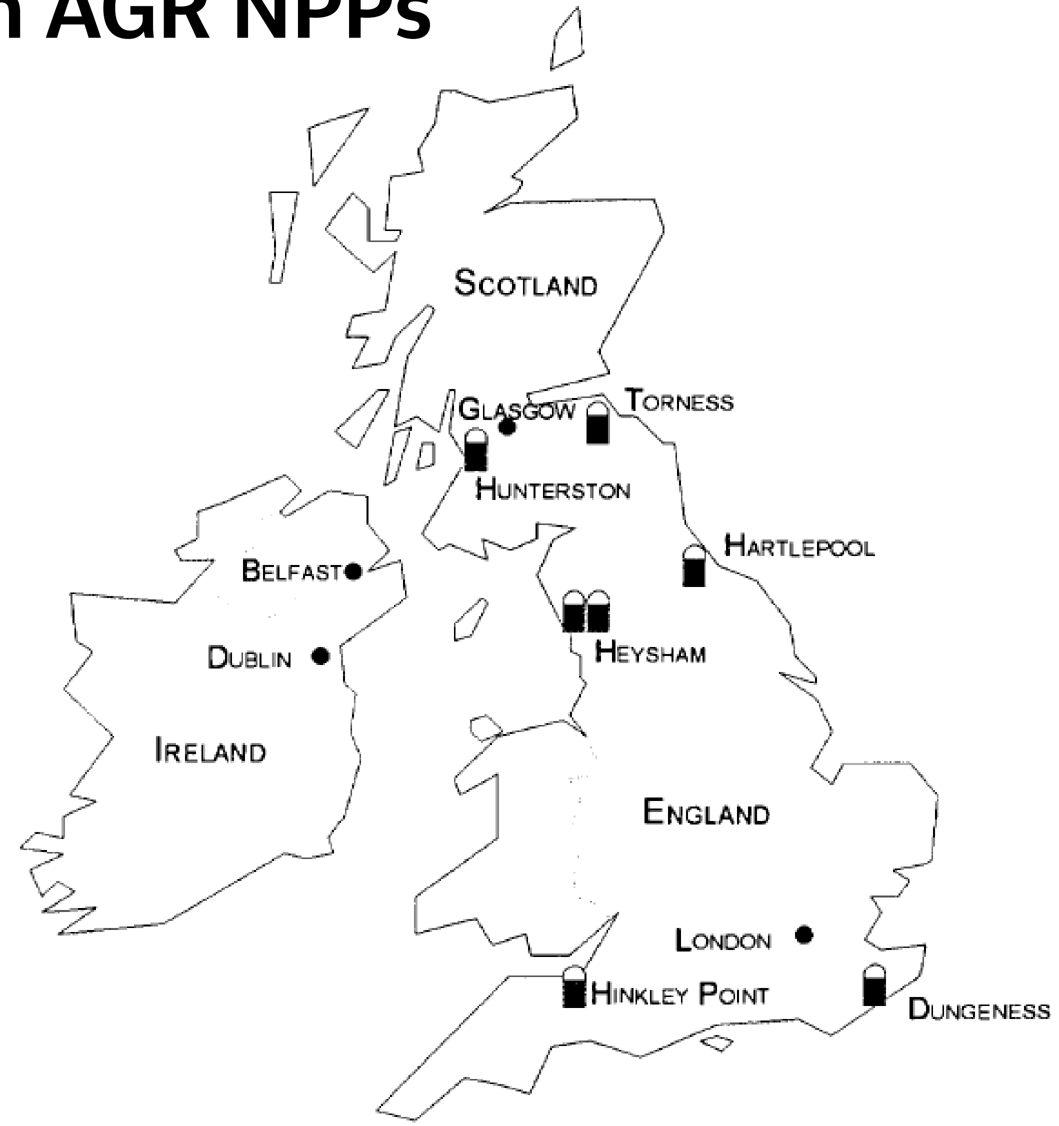
- Generation II technology
- Enriched uranium
- Stainless steel clad uranium-oxide ceramic fuel
- Pre- (and post) stressed concrete pressure vessel with integral gas circulators, boilers and decay heat removal boilers
- Gas-tight (but lightweight) upper reactor building
- Coolant outlet temperature up to 650^{o}C
- Good quality superheated (and reheated) steam (comparable to quality from a highly optimised coal plant)
- High thermal efficiency – 42%

Torness AGR Nuclear Power Station

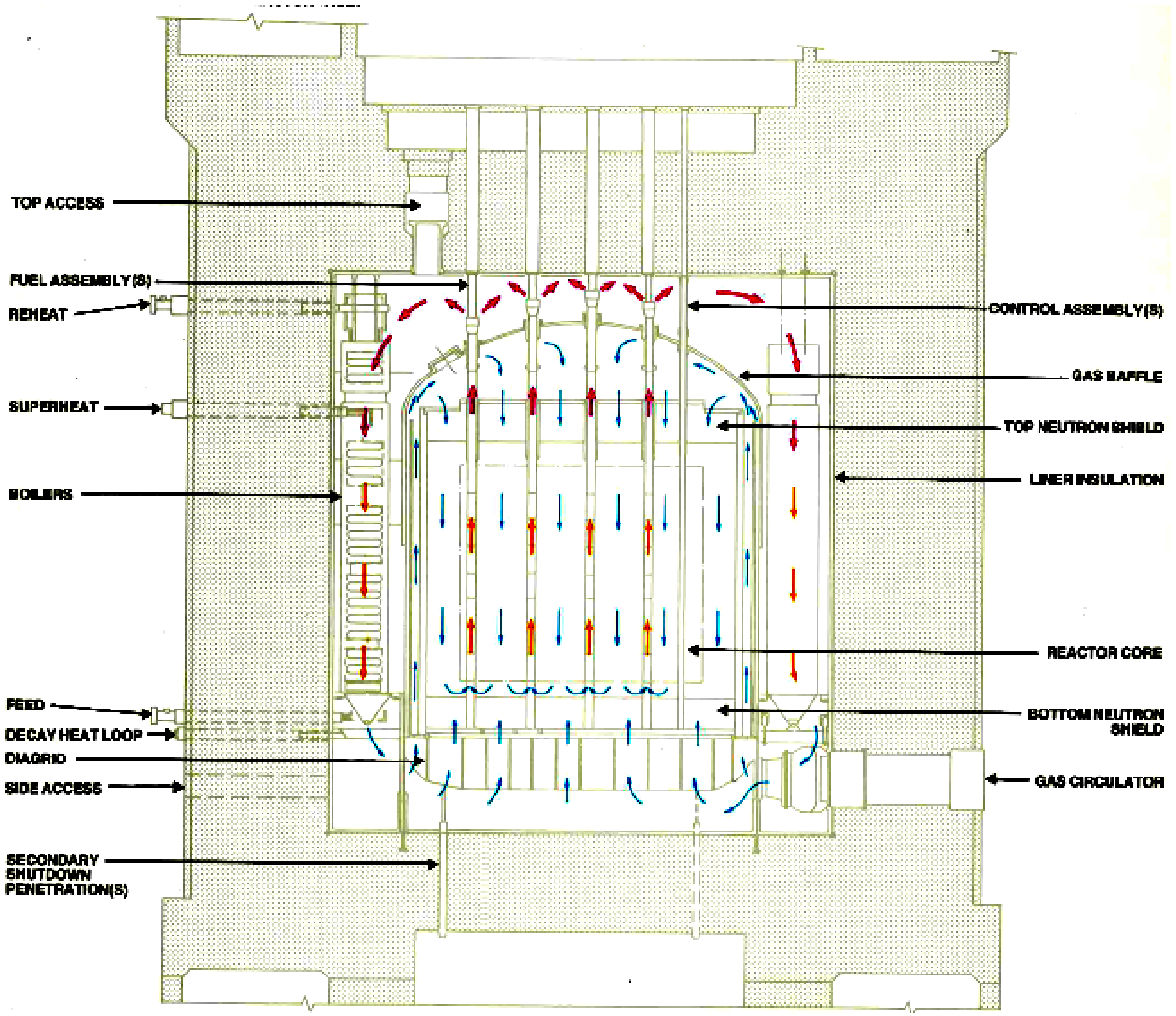
Cut-away view of an AGR reactor building



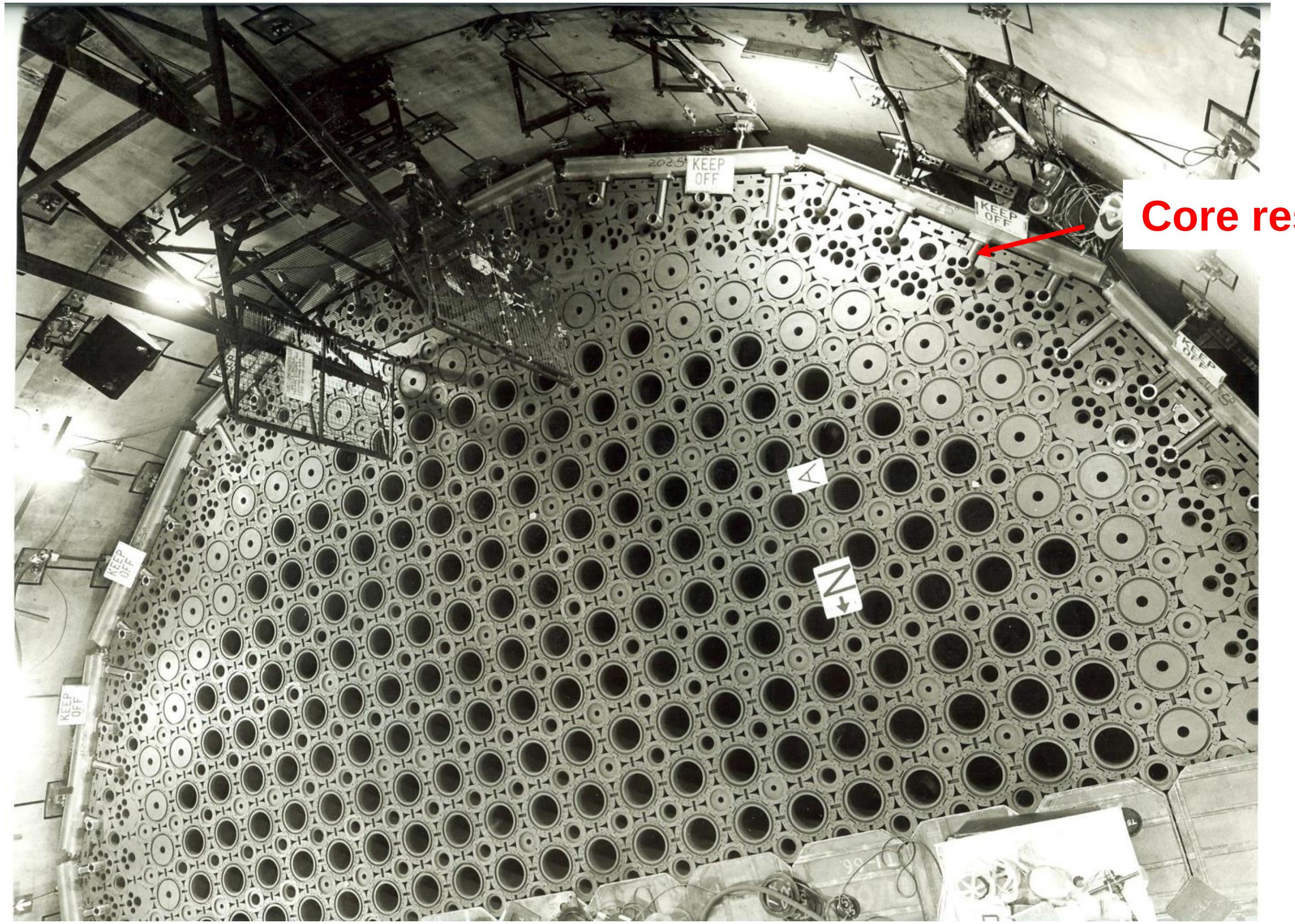
Location of the UK's 7 twin AGR NPPs



Architecture of a carbon dioxide cooled AGR

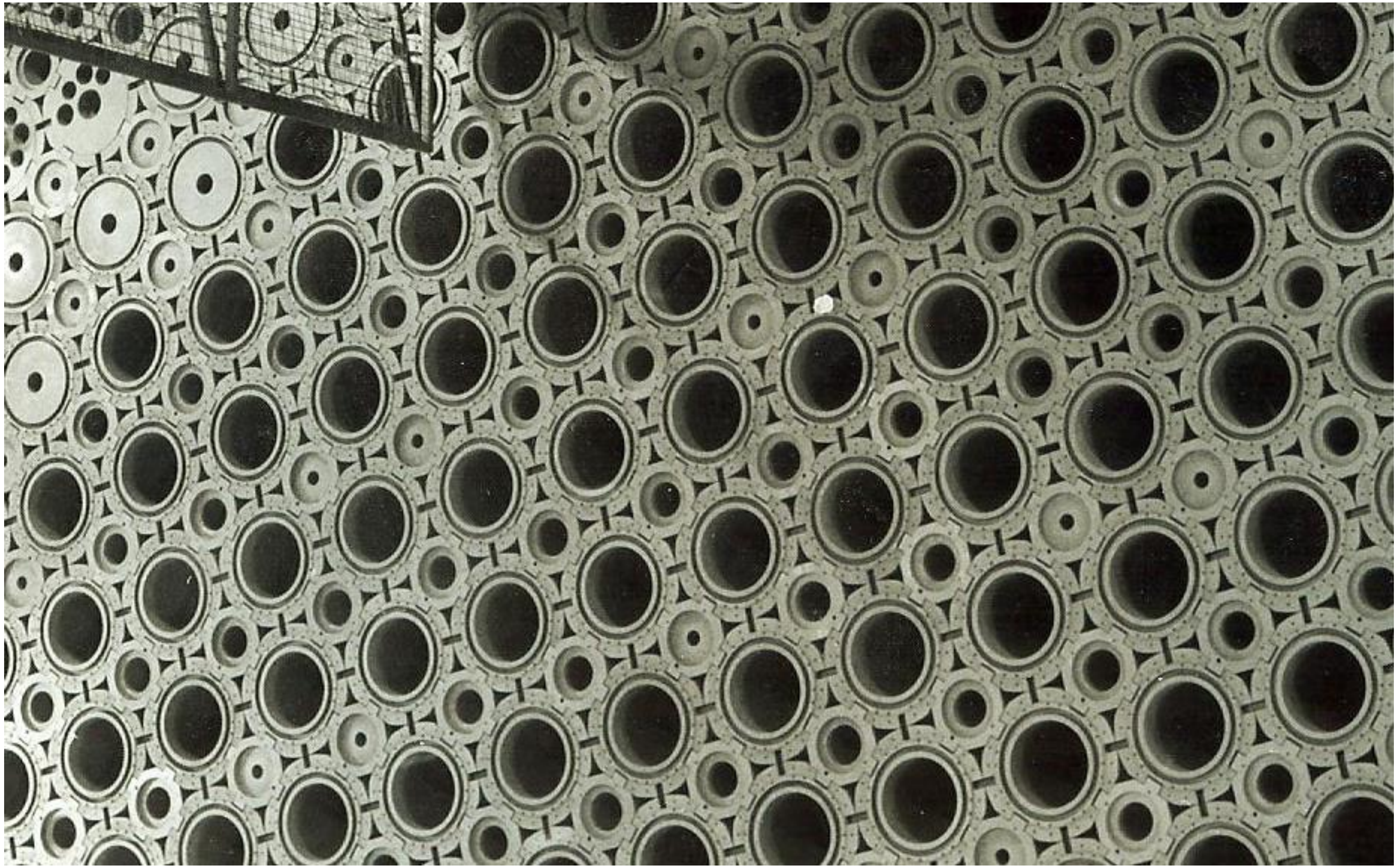


AGR Core Under Construction



Core restraint system

Accommodation of Dimensional Change – the Keying System



Advanced Gas-cooled Reactors (AGR)

Description:

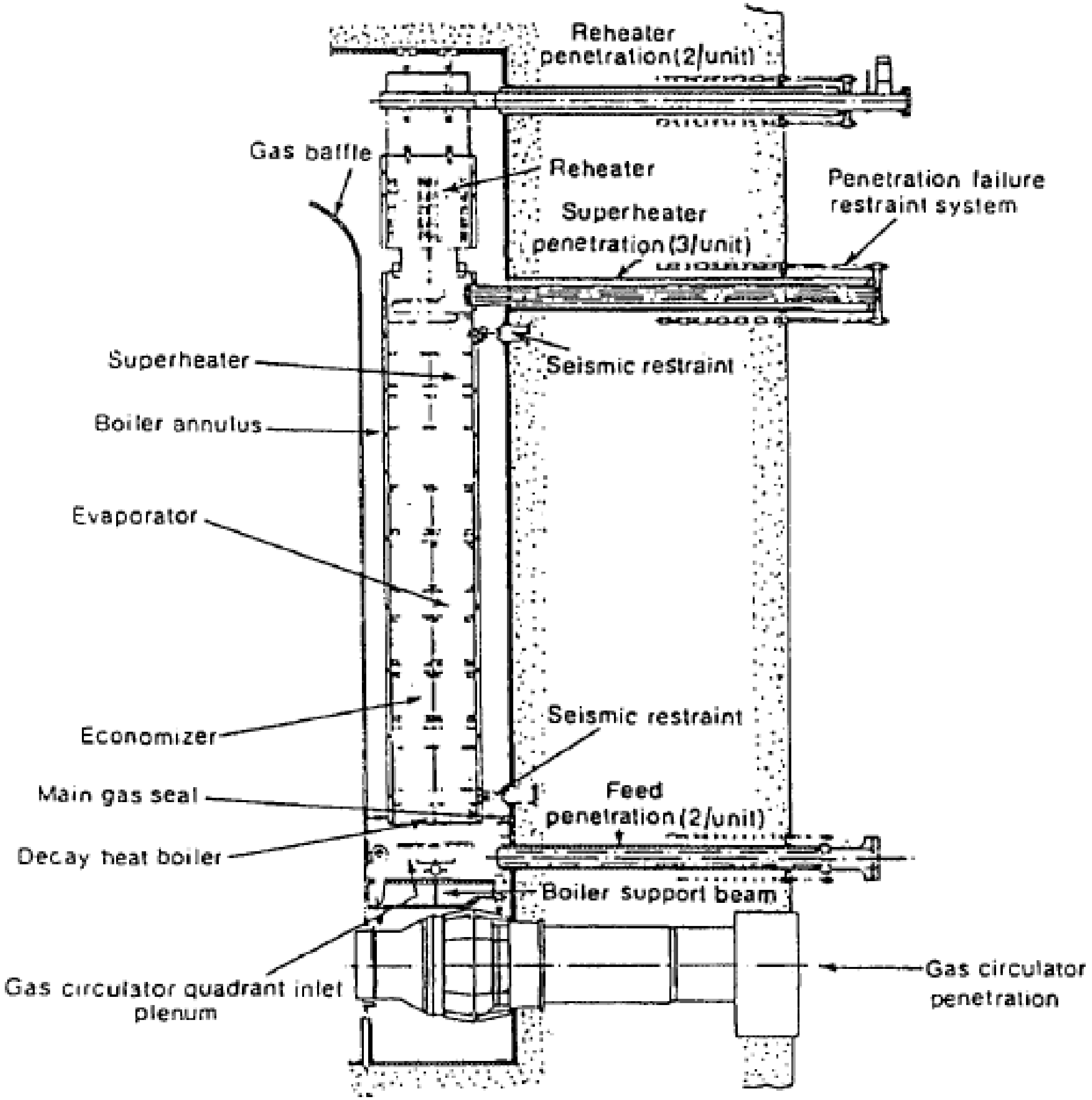
- Pressurised CO_2 cooled core in a closed primary circuit
- Containment:
  - 1st barrier (incomplete), uranium dioxide ceramic fuel pellets
  - 2nd barrier, Stainless steel cladding of the fuel elements
  - 3rd barrier, Primary circuit boundary fully enclosed in a steel-lined pre- (and post-) stressed concrete pressure vessel.
  - 4th barrier, gas-tight reactor building
- Reactivity Control (two systems)
  - Control rods and Shutdown rods inserted from the top of the core
  - Tertiary shutdown by either boron bead injection or nitrogen injection
- Cooling:
  - Electrically driven variable speed gas circulators
  - Boilers used for normal and post-trip heat removal
  - Decay heat boilers for long term decay heat removal
  - Back up electrical supplies, low voltage systems and feedwater systems

Containment

- Incredibility of failure is declared for the bulk structure of the pressure vessel and for its penetrations to eliminate the rapid depressurisation case.
- Small breach loss of coolant is still possible and the large reactor building is capable of containing escaped gas.
- There is no phase change of coolant so the level of pressurisation of the reactor building is predictable.
- … As such, here is no heavy containment building as in the case of a PWR.
- Primary circuit and building can be blown-down through filters to protect the structures
- Design basis faults:
  - Hot gas release – leakage of coolant from the primary circuit – main hazard is loss of coolant pressure and impingement on structures and instrumentation systems
  - Steam release – leakage of steam from the secondary circuit – main hazards are blast loading and overpressure of the reactor building and impingement on sensitive equipment

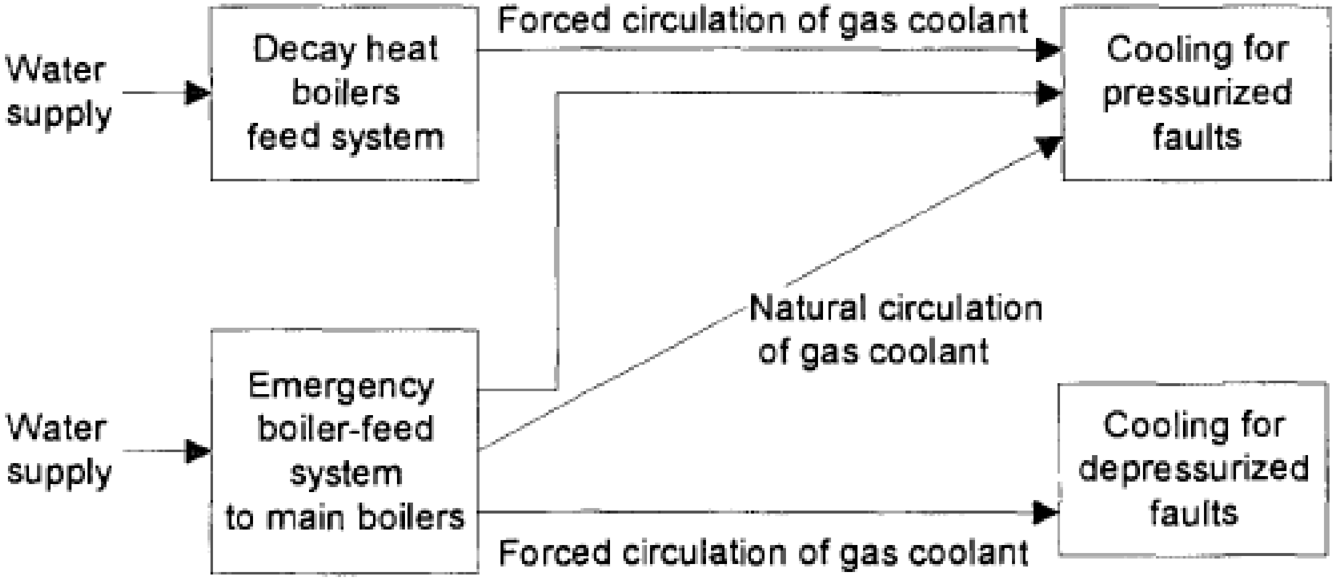
Heat removal

- Normal heat removal requires gas circulators, the feed system, turbine and condenser to be operational.
- Immediate post trip cooling can be by venting steam or by diverting steam to the condenser.



Decay Heat Removal

- Low power density and large thermal inertia of the graphite core provide long grace times.
- Pressurised decay heat removal can occur by either forced or natural convection of the primary coolant.
- Rate of depressurisation is limited by the reactor pressure vessel design.
- Depressurised decay heat removal requires the circulators to be operable (at 3000 rev/min)
- Back up water supplies, power supplies and feedwater pumping capacity are provided to cope with all of the loss of cooling faults within the design basis



Operational Experience

- Fuel Stringer problems
  - Oscillation of the fuel stringer during on-load refuelling
  - Refuelling at 30% power is permitted for some reactors
- Boiler tube failures leading to water/steam ingress into the graphite core
- Boiler closure unit restraint faults (reactors with “pod” boilers)
- Boiler spine cracking (reactors with pod boilers)
- Graphite weight loss leading to loss of moderation (and loss of strength)
- Graphite cracking
  - Key-way route cracking – result of turn-around phenomenon in irradiated graphite.
- No accidental depressurisation events
- Some circulator failures – mechanical and electrical (latter after boiler tube failure)
- All reactors have exceeded their design lives – oldest by almost a factor of 2.

In respect of safety, how does an AGR differ from GFR?

- Core power density
  - Low power density in an AGR ~ 5 MW/m^3
- Core thermal inertia much larger owing to graphite moderator
- Steel-lined pre-(and post-) stressed concrete pressure vessel with integral primary circuit makes depressurisation a rare event and rapid depressurisation impossible
- Higher density coolant
- Like GFR, natural convection is adequate to remove decay heat in pressurised conditions
- But, external power is required to remove decay heat to prevent fuel damage in depressurised conditions.

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