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Reflood following PWR loss of coolant accidents: The physical processes

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OUTLINE

- **Design basis accident; large break loss of coolant**
- **Physical processes during reflood**
- **Our main projects underway investigating these**

‘Design basis’ accident:

The worst credible accident:
A double ended break of a main coolant pipe

Must show plant can suffer this without too severe consequences

Imposes constraints on eg burn-up, fuel power ratings

Complexity of processes means great conservatism in analysis is required

Systems to provide post-LOCA cooling are expensive

True for both ‘conventional’ plant (eg Sizewell), and modern ‘passive’ designs.

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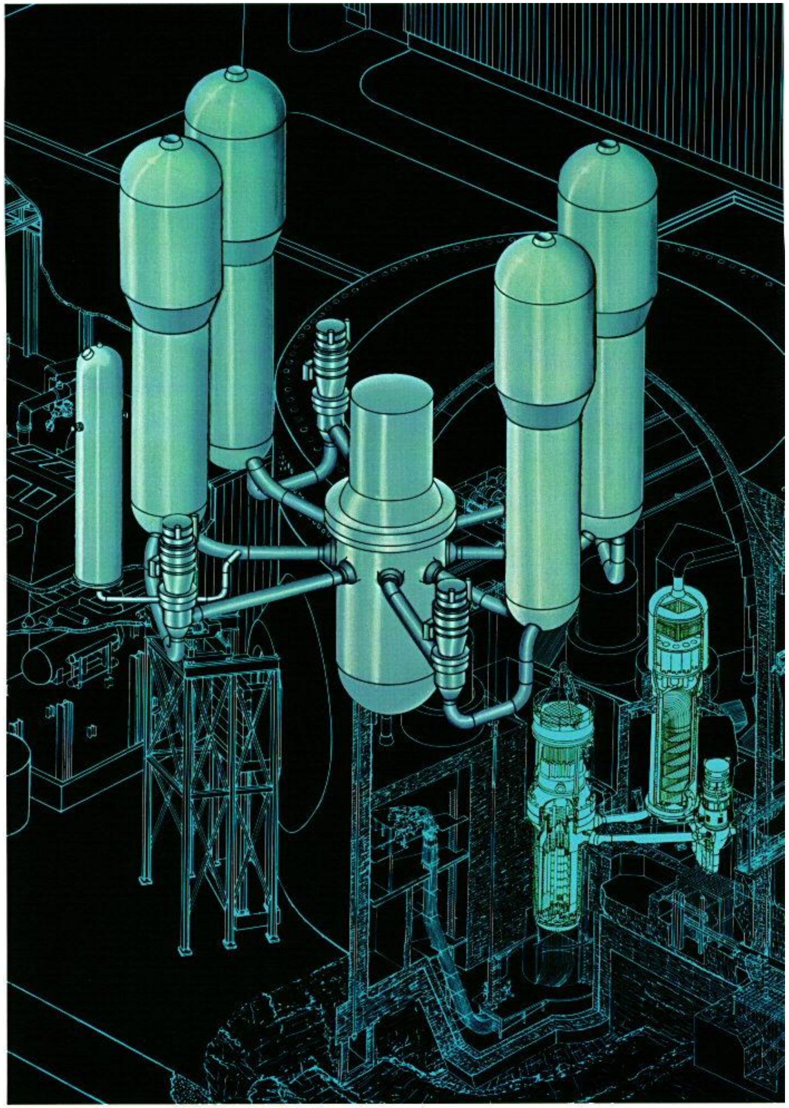
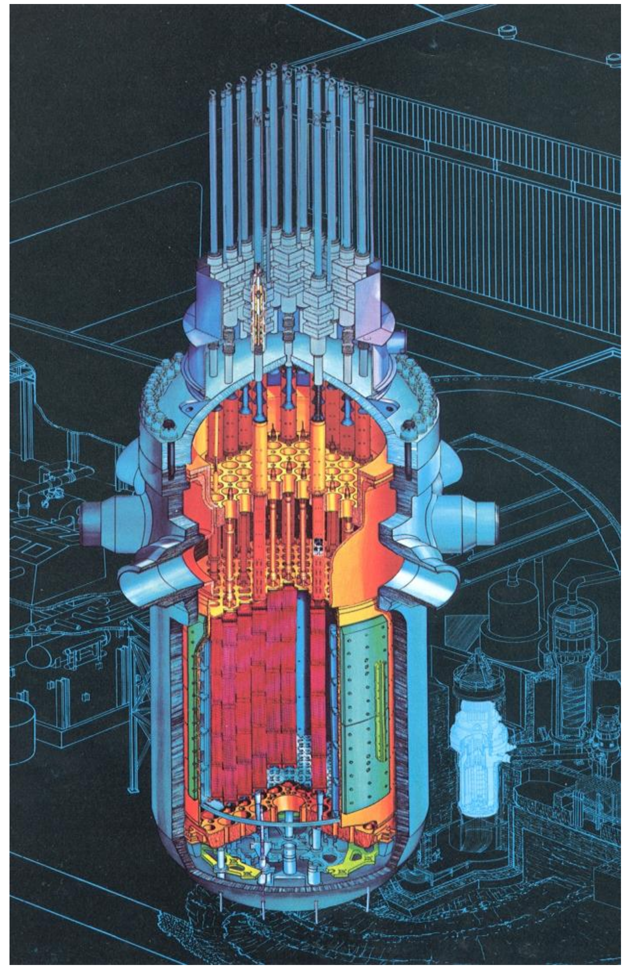
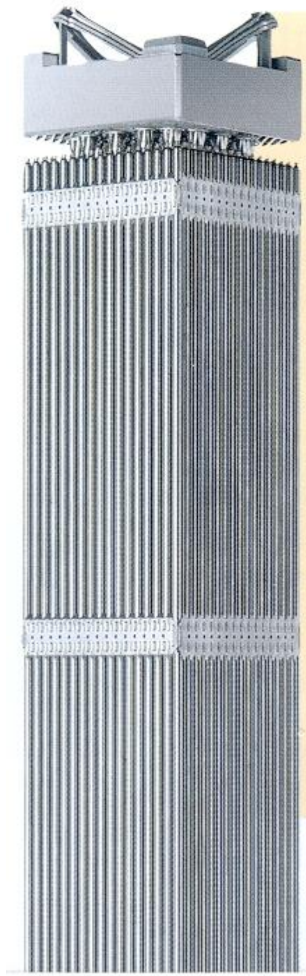
'Conventional' PWR



Westinghouse NUCLEAR STEAM SUPPLY SYSTEM





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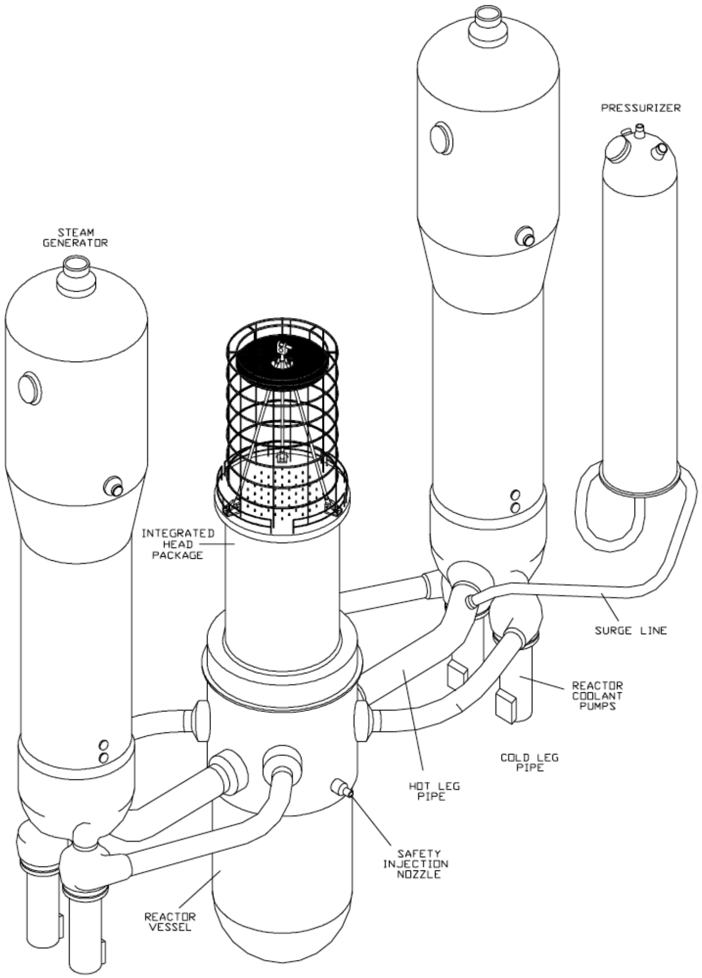
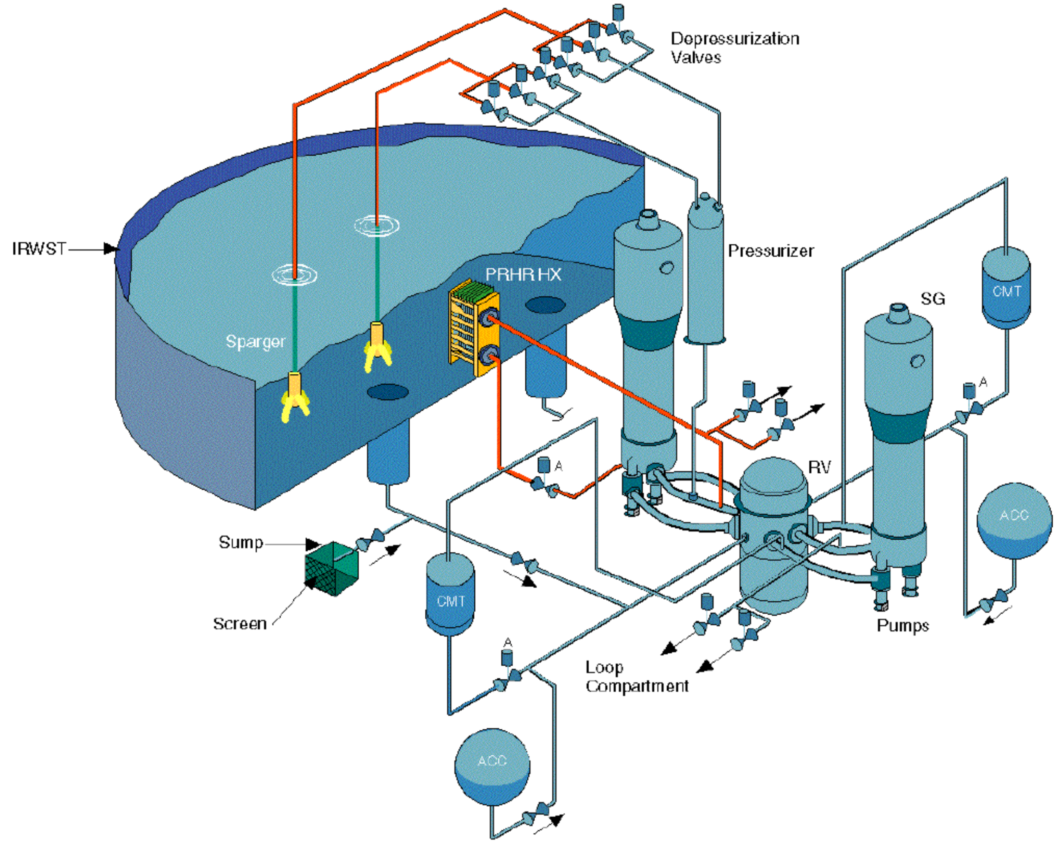
AP1000


STEAM GENERATOR
PRESSURIZER
INTEGRATED HEAD PACKAGE
SURGE LINE
REACTOR COOLANT PUMPS
COLD LEG PIPE
HOT LEG PIPE
SAFETY INJECTION NOZZLE
REACTOR VESSEL


Depressurization Valves
IRWST
Pressurizer
PRHR HX
SG
CMT
Sparger
RV
A
Sump
ACC
Screen
CMT
Pumps
Loop Compartment
ACC

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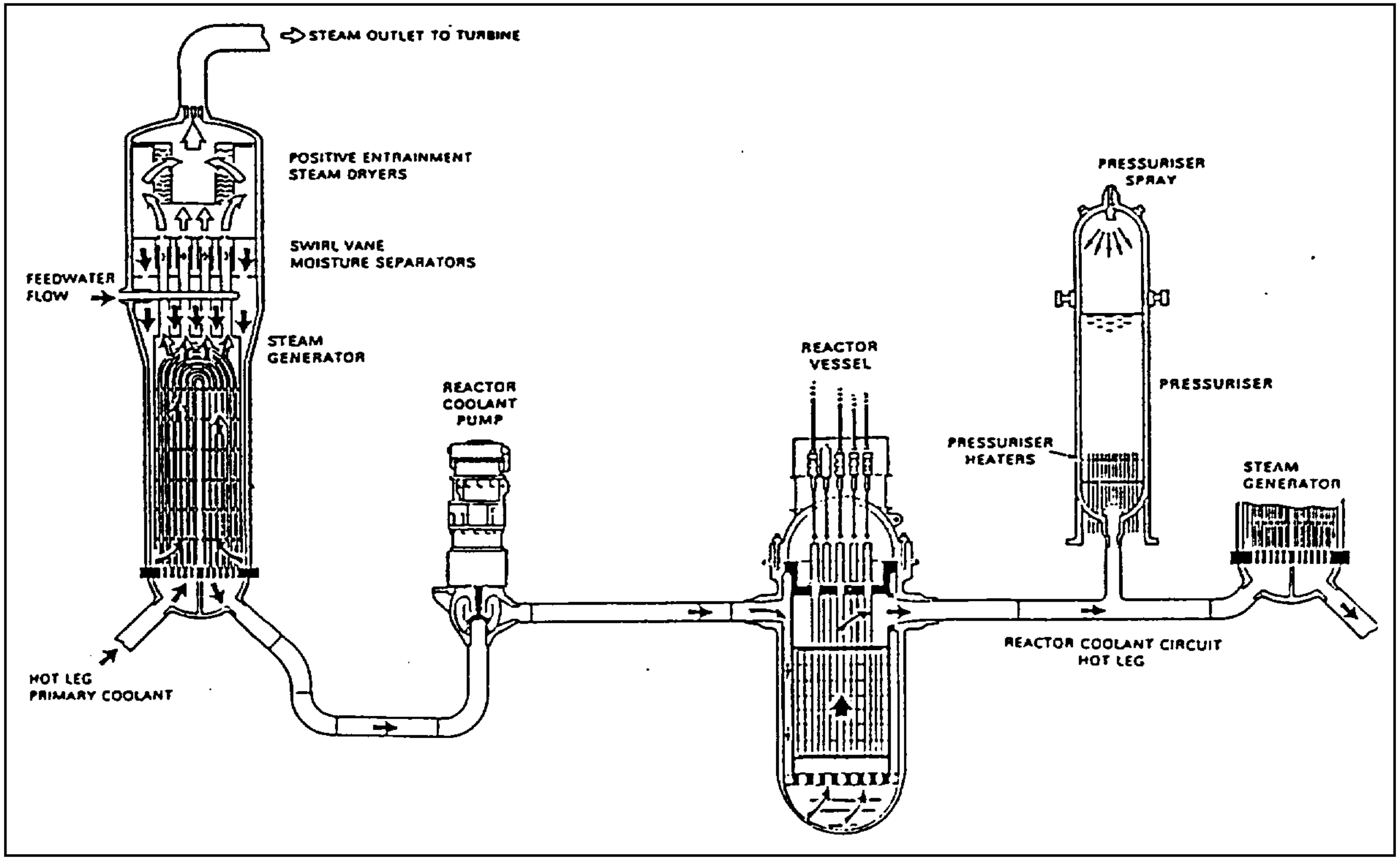
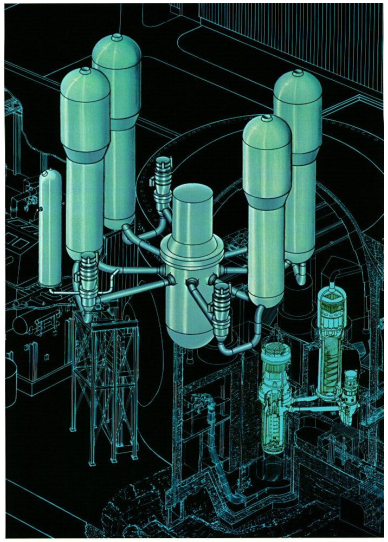
Large-break LOCA





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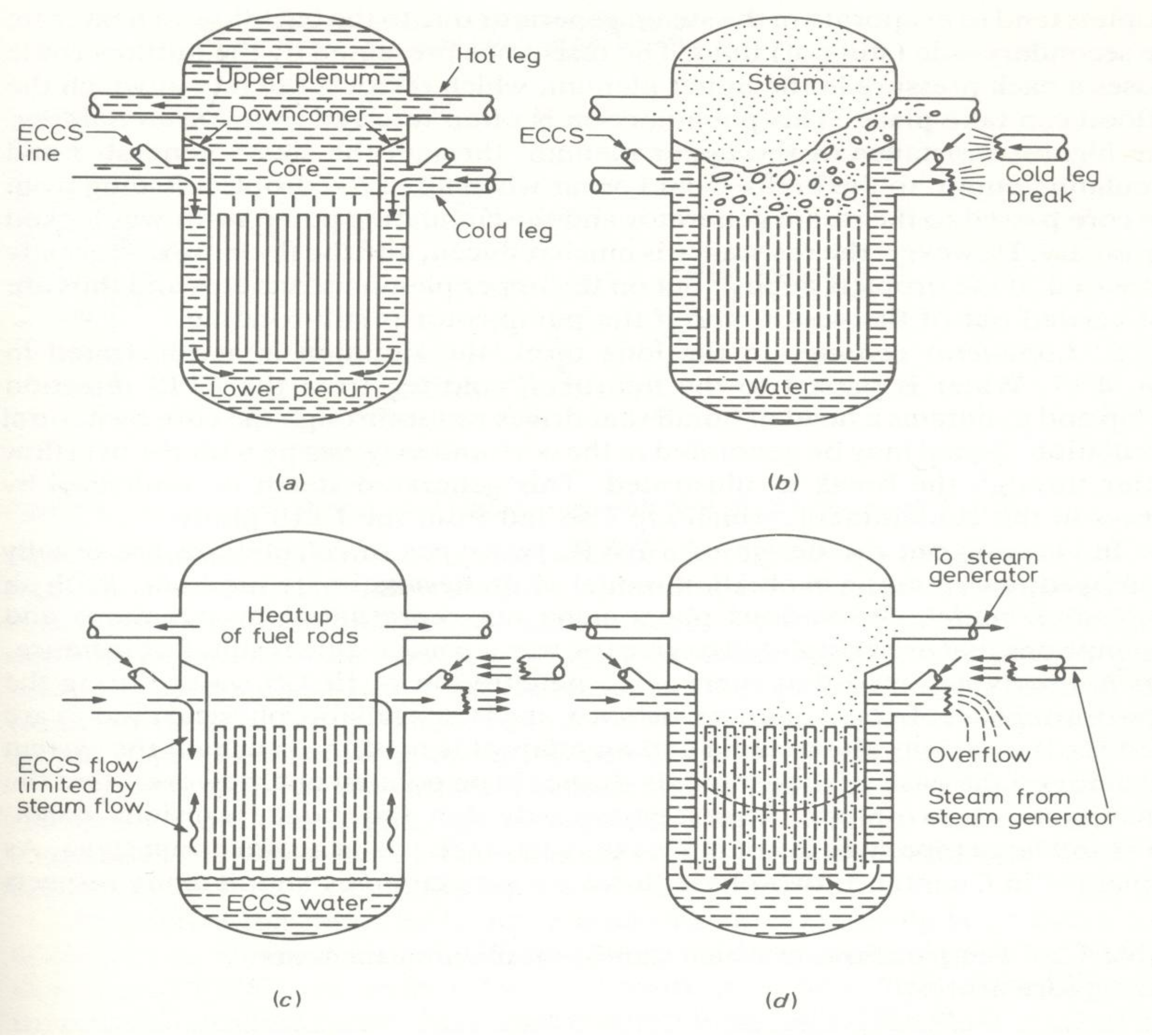
Events following a large break LOCA



(a) Normal operation

(b) Blowdown phase

(c) Refill phase

(d) Reflood phase

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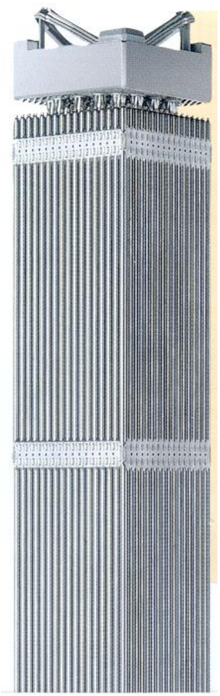
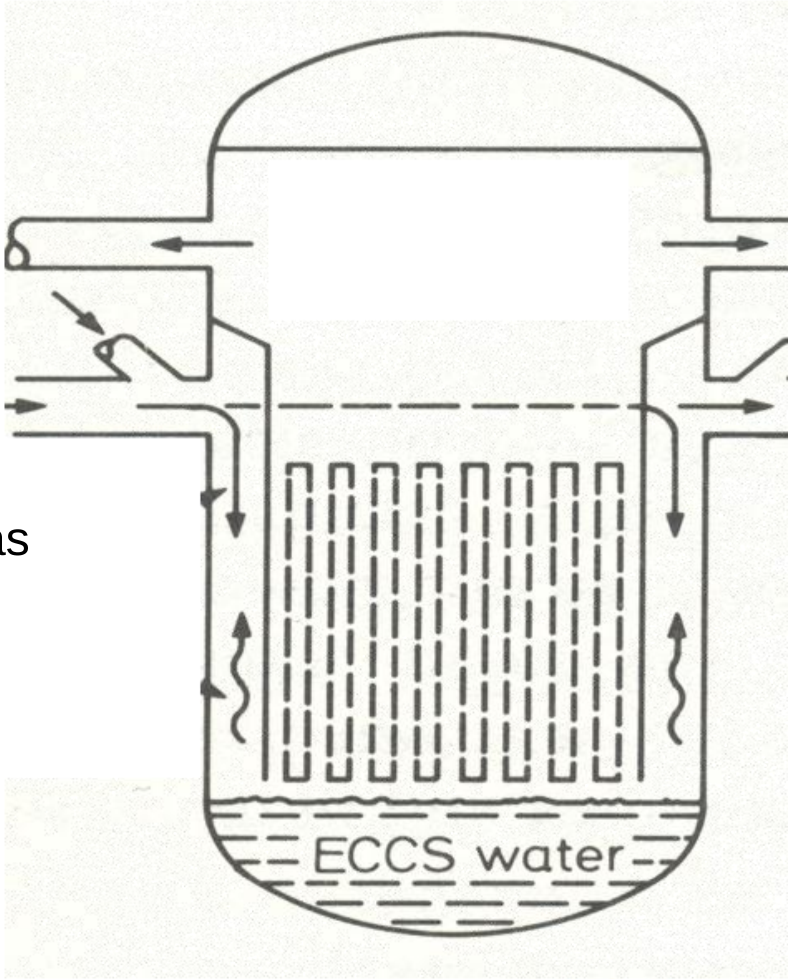
Reflood phase



A more or less empty core; just ~atmospheric pressure water vapour, and some liquid down at the bottom



~60,000 pins
~10mm diameter
~5mm apart

Each still releasing up to ~2kW/m decay heat

(ie about the same heat release rate as an old fashioned electric fire element)

Can cooling be provided to the pins before they (or their clad) melt?

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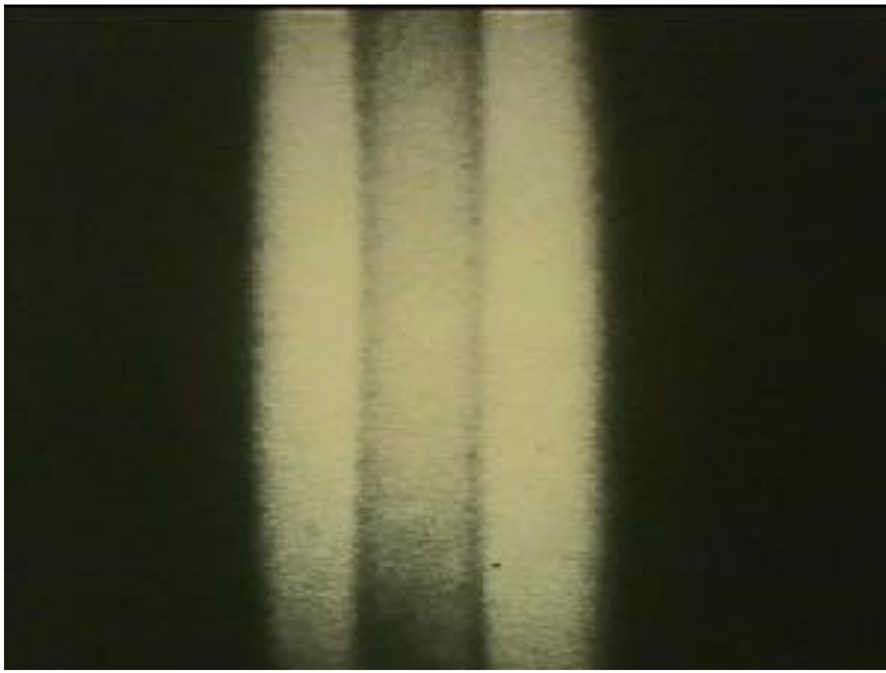
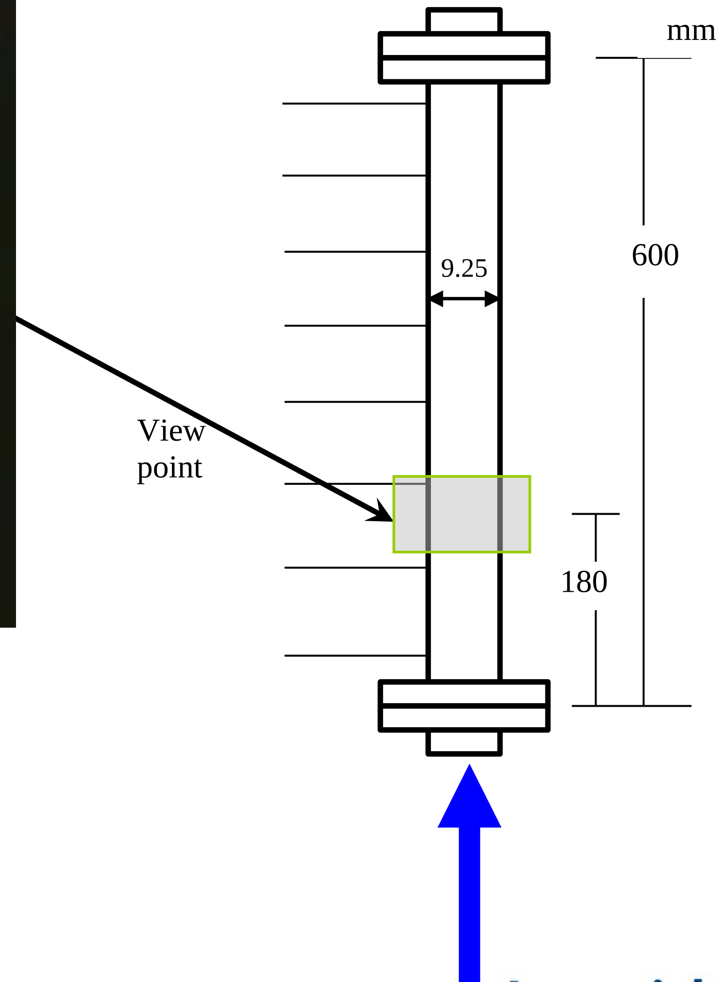
Complexity of rewetting process: Neutron radiography of rewetting of a hot tube



File:- Reflood movie.avi



- Initial temperature 600 °C;
- Water temperature 27 °C;
- Reflood velocity 2.5 cm/s;
- Atmospheric pressure.

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During reflood:-

-Slow rise of liquid level, so

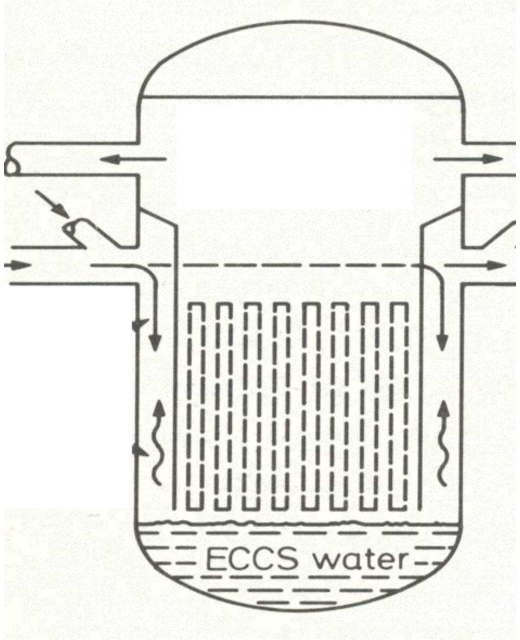
-Precursory cooling, before liquid arrives, is vital

-('Single phase') cooling by the vapour flow; vapour becomes superheated

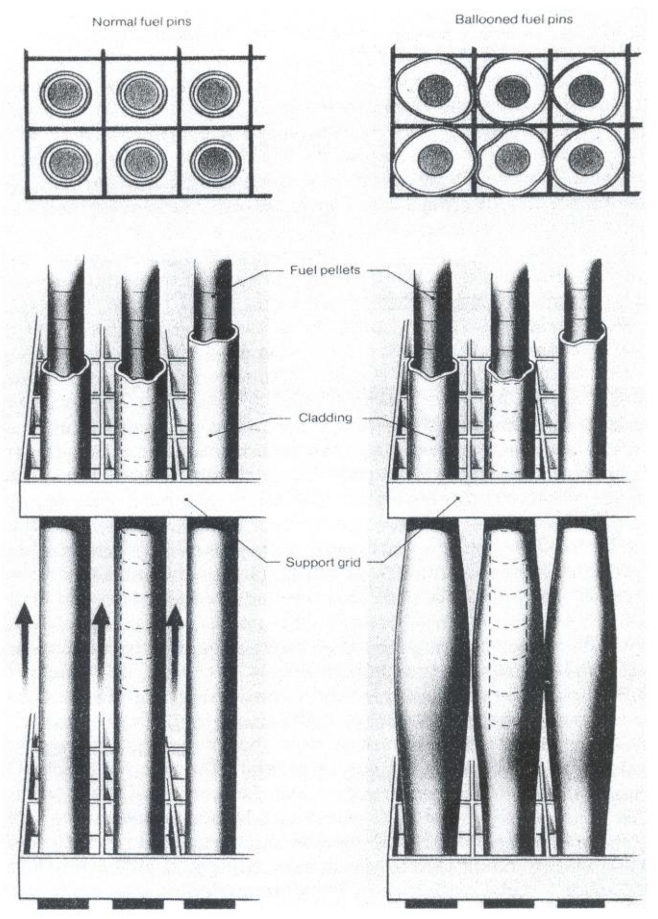
-Entrained droplets stay at saturation temperature (~100C)

-Pins are too hot for the entrained droplets to touch

-Droplets evaporate into the superheated vapour; their latent heat causes them to act as a very important heat sink in keeping vapour temperatures down.



Clad ballooning



Following LOCA, fuel pin surface temperature increases and cladding becomes ductile and weakens.

With the coolant pressure now ~zero, there is a large net internal pressure in the pin

The clad expands (balloons) under this internal pressure

Consequences of clad ballooning:

•Restriction of passage reducing heat transfer.

•Diversion of flow to adjacent sub-channels

Studies of the reflood processes

Overall objectives:-

•Improved understanding of some of the fundamental aspects

-rewetting physics
-droplet heat transfer

•Coupling of multi-pin structural mechanics and three-dimensional transient two phase thermal hydraulic analysis

-develop models to incorporate the systematic and stochastic heterogeneity of pin ballooning under reflood conditions
-reduction of conservatism implicit in single-pin models would relax operating envelope constraints
-particularly important in context of drive for higher burnups
-better understanding is crucial to permit use of advanced, high ductility clad

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Reflood-related projects

- CFD studies of droplets entrained in flows in clusters of ballooned fuel elements
- Experimental and modelling studies of reflood processes; measurement and modelling of droplet diversion around balloons
- Analysis of the detailed physics of the rewetting process
- Modelling critical heat flux & dryout: ‘Systems Codes’, and more physically-based modelling
- Coupled thermal-hydraulic (TRACE) and structural mechanics (Mabel) modelling of reflood
- CFD (two-phase Level Set) and experimental studies of the cooling of hot surfaces by droplets

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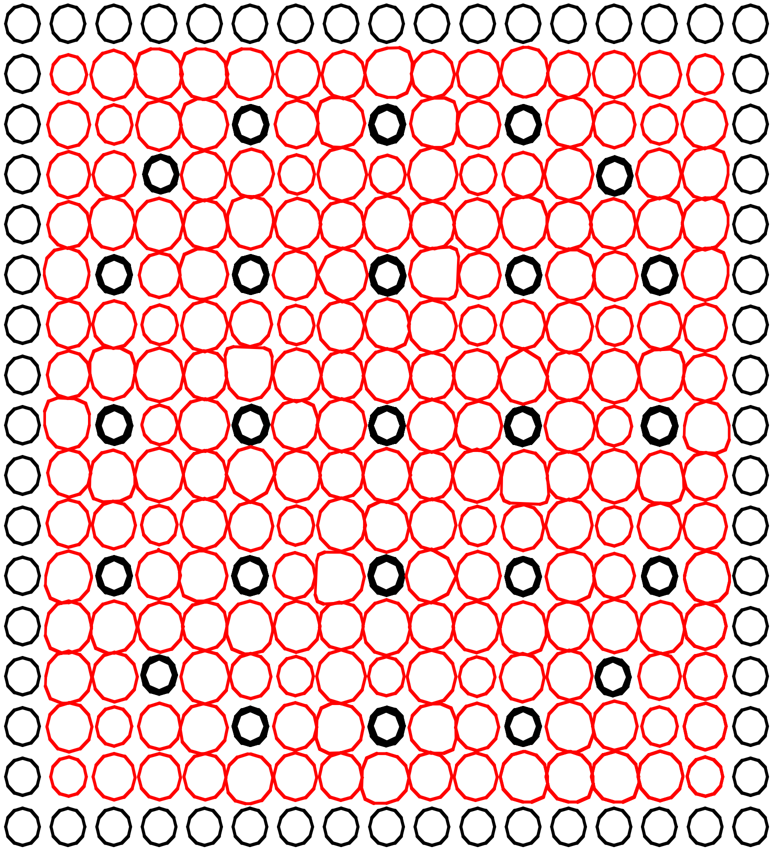
Coupled multi-pin modelling



Ballooning computed for a PWR subassembly undergoing a loss of coolant accident. Systematic and stochastic differences between pins have been incorporated. Distinct differences in the ballooning behaviour of pins is clear, as is the absence of large regions of coherent ballooning.

Droplet heat transfer