NTEC Module: Water Reactor Performance and Safety

Lecture 18: Severe Accidents I
Severe Accident Phenomena

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Reactor operating states

Operating states for which the system is designed to cope:

Normal operation	Continuous (apart from shutdowns for maintenance)
Operational transients	~ 10 per reactor year
Upsets	~ 1 per reactor year
Emergencies	1 in 100 reactor years
Limiting fault conditions (including design basis accident, DBA)	1 in 10,000 reactor years
Unprotected or beyond design basis accidents	1 in 1 million reactor years

Problem: Possible grave consequences of highly impossible events!

Circumstances leading to severe accidents

Design base accident: ECCS prevents loss of core coolability

Severe accident: ECCS itself fails

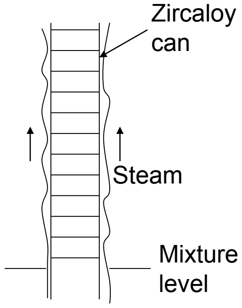
- Failure of ECCS system in itself
- Loss of off-site power over long period and inability to actuate alternative power sources
- Unpredicted operator faults

Core heat-up phenomena

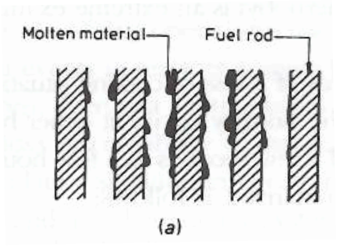
Temperature (°C)	Phenomenon
350	Approximate cladding temperature during power operation.
800 – 1450	Cladding is perforated or swells as a result of rod internal gas pressure in the postaccident environment; some fission gases are released; solid reactions between stainless steels and Zircaloy begin; clad swelling may block some flow channels.
1450 – 1500	Zircaloy steam reaction may produce energy in excess of decay heat; gas absorption embrittles Zircaloy, hydrogen formed. Steel alloy melts.
1550 – 1650	Zircaloy-steam reaction may be autocatalytic unless Zircaloy is quenched by immersion.
1900	Zircaloy melts, fission product release from UO_2 becomes increasingly significant above 2150 K.
2700	UO_2 and ZrO_2 melt.

Stages in beyond design basis accident I
Zircaloy/steam reaction

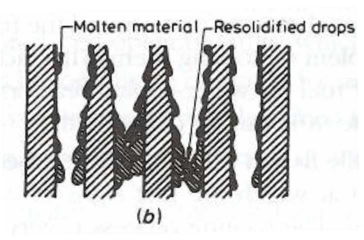
- When fuel reaches 1450 – 1500 Zircaloy reacts with steam
- Exothermic reaction gives “sparkler” effect. Reaction propagates along can.



Stages in beyond design basis accident II
Fuel melting I

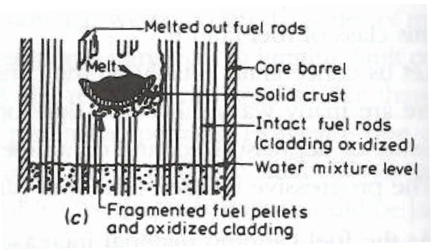


Melting of can, support and fuel

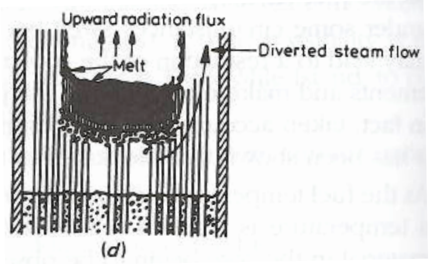


Formation of blockages

Stages in beyond design basis accident III
Fuel melting II

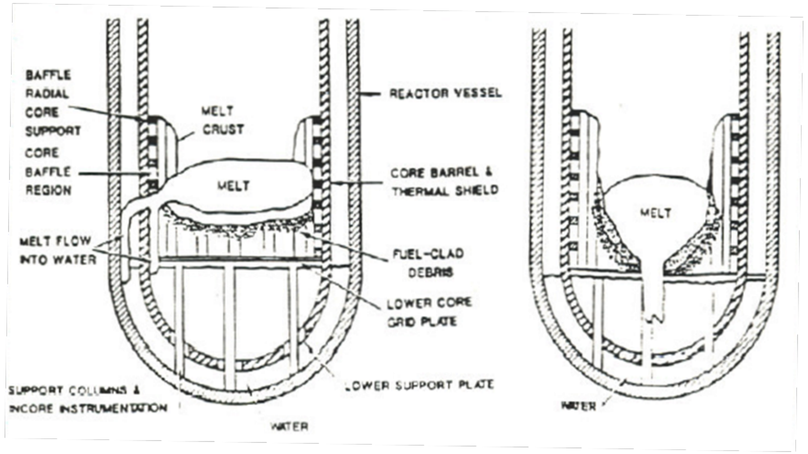


Formation of small molten pool



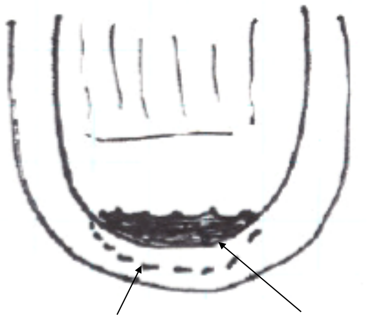
Radial and axial growth of pool

Stages in beyond design basis accident IV
Melt escape



Stages in beyond design basis accident V
Remelting of debris

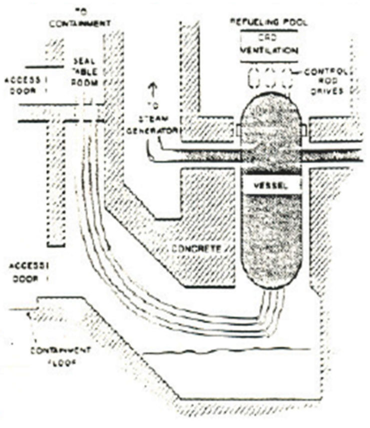
- Water in vessel disappears
- Debris continues to heat up and remelts
- Strainless steel vessel melts through
- Core material enters containment

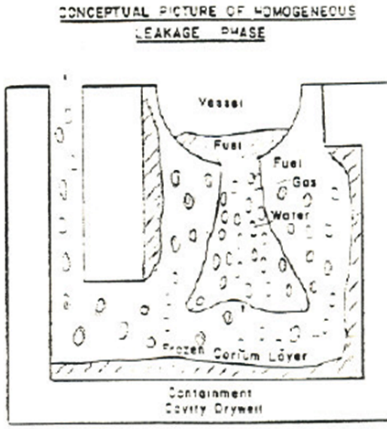


Melting of stainless steel vessel

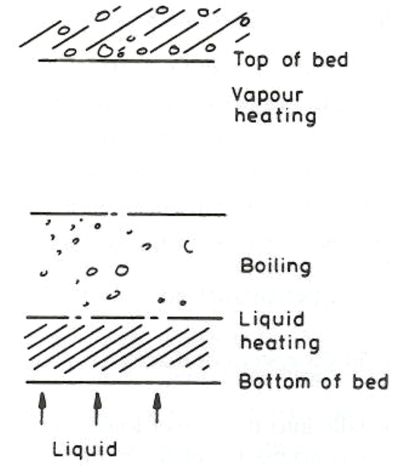
Pool of molten material

Stages in beyond design basis accident VI
Fuel in containment



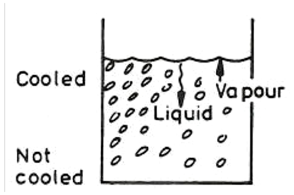


Phenomena associated with severe accidents I
Debris bed cooling I

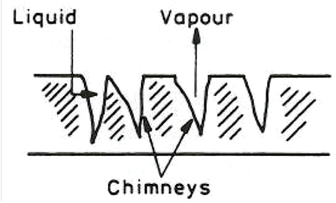


Once-through cooling of debris bed

Phenomena associated with severe accidents II
Debris bed cooling II



Countercurrent flow



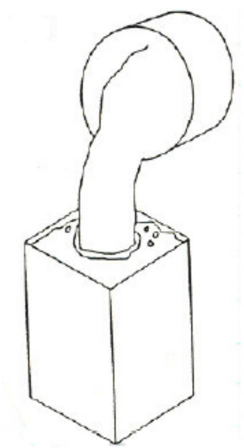
Chimney formation

Cooling in countercurrent flow

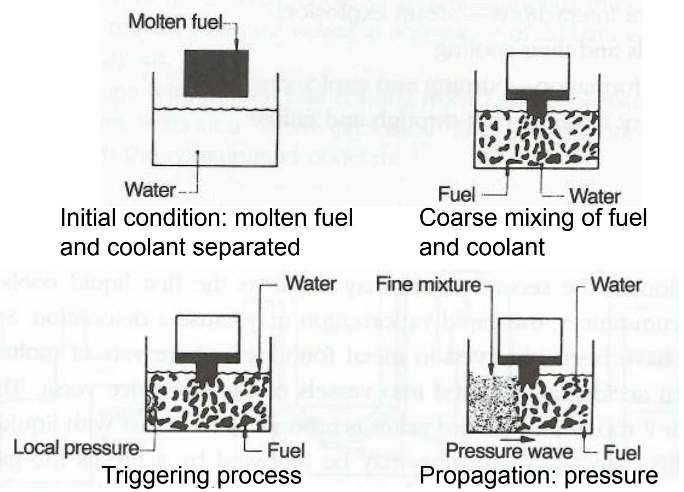
Phenomena associated with severe accidents III
Steam explosions I

Vapour explosions occur in many industrial applications

- Transport of LNG
- Aluminium Casting
- Steel Foundries
- Paper-Pulping Mills
- Postulated accident in nuclear power plants



Phenomena associated with severe accidents IV
Steam explosions II: Stages in explosion



Initial condition: molten fuel and coolant separated

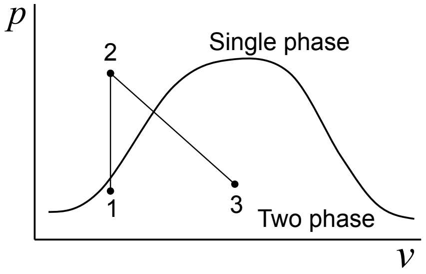
Coarse mixing of fuel and coolant

Triggering process

Propagation: pressure wave fragments fuel

Phenomena associated with severe accidents V
Steam explosions III: Hicks/Menzies model

- Fuel and coolant mix and reach equilibrium at constant volume $(1 \rightarrow 2)$
- Isentropic expansion of fuel-coolant mixture $(2 \rightarrow 3)$

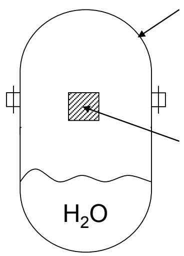


Maximum work

$$= \int p\,dv$$

Phenomena associated with severe accidents VI
Steam explosions IV: Typical experiment

If all work converted to energy in shock wave, explosion equivalent to 4 – 5 tonnes TNT!
How efficient? Many experiments.
Typical experiment: Bird (1984) - Winfrith



Pressure vessel

24 kg thermite UO_2 / molybdenum mixture represents fuel

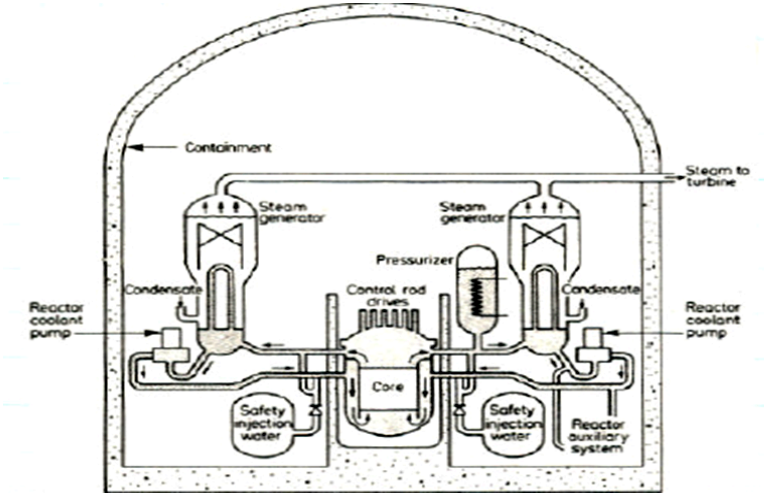
Explosive yield extimated from pressure transient

Small particles (Participated)

Large particles (Non-participated)

Conversion for those participating = 4.3%. Fraction participating = 13% at 1bar, 75% at 10 bar

Containment failure I
PWR containment

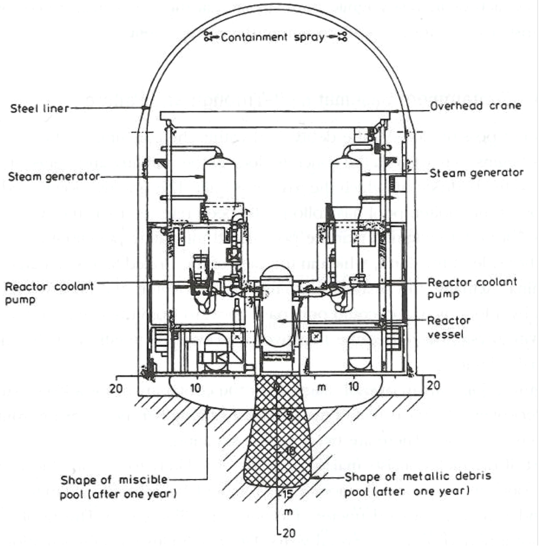


Containment failure II
Mechanisms of failure

Typical containment can withstand 3-4 bar pressure. Failure modes:

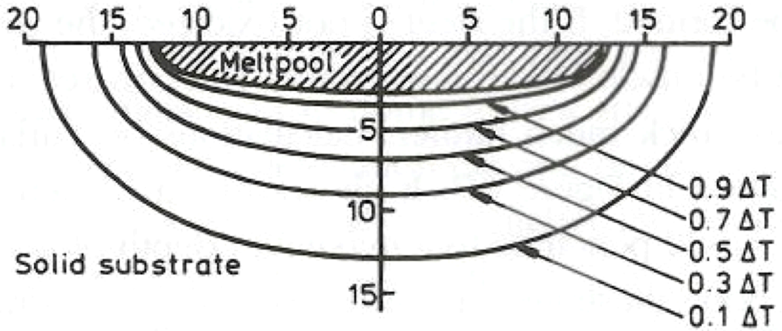
- Melt-through (see slides 19-20). Not likely to give large scale releases
- Missile damage: External (747's!), Internal (steam explosions)
- Failure to isolate after accident
- Over pressurisation due to:
  - Steam release (sprays for condensation)
  - Hydrogen (actual, explosion)
  - Fuel/concrete interaction

Containment failure III
Melt-through: THE CHINA SYNDROME

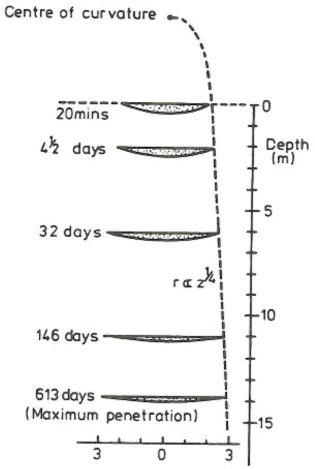


Shape of melt pool depends on whether melt in mixed (including oxide) or metal (e.g. stainless steel).

Containment failure IV
Temperature profiles in melt



Containment failure IV
Descent of a 3 cubic metre melt



Calculations by Turland & Peckover (1978).

Steel arising from reactor penetrates further than concrete / fuel mix.

Conclusion

- Severe accidents may be the limiting factor in acceptability of nuclear power.
- Can we deign reactors which are free of them?
- Is the reliance on engineered safety acceptable?