NTEC Module: Water Reactor Performance and Safety

Lecture 13: Severe Accidents II
Examples of Severe Accidents

G. F. Hewitt
Imperial college London

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Summary

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LOCA incidents: Water cooled reactors

Light water cooled reactors

SL-I: Experimental reactor. Control rod withdrawn. Explosion. (Jan 3, 1961)

Millstone 1: BWR. Seawater ingress into core. (Sep 1,1972)

Browns Ferry Fire: BWR. Fire in cabling duct disabled safety systems. (March 22, 1975)

* Three Mile Island: Small break type LOCA. PWR. Serious core failure. (March 28, 1979)

Ginna incident: PWR. Steam generator tube. (Jan 25, 1982)

* Chernobyl: RBMK. Power excursion. (April 26, 1986)

Heavy water reactors

NRX: CANDU. Pressure tube failure. (Dec 12, 1952)

Lucens: CO_2 cooled, D_2O moderated. Fuel melt. (Jan 21, 1969)

** More detail later*

LOCA incidents: Gas and liquid metal cooled reactors

Gas cooled reactors

Windscale fire: Air cooled, graphite moderated. "Wigner" release. (Oct 7, 1957)

St. Laurent (Magnox): Flow restrctor loaded accidently into channel. Fuel melted. (Oct 17, 1969)

Hinkley Point B: AGR. Problems in fuel loading. Damage to graphite sleeve. (Nov 19, 1978)

Liquid metal cooled fast reactors

EBR-1 meltdown: Fuel element bowing and melting. (Nov 29, 1955)

Enrico Fermi 1: Broken zircalloy plate, blocked channel. Fuel melting. (Oct 5, 1966)

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Three-Mile island accident I: The initial cause

4 am on March 28th 1979 an <u>UPSET</u> occurred as follows:

- Condensate pump moving water from condensers stopped (designed-for UPSET)
- Main steam generator feedwater pumps tripped.
- Turbine tripped

Incident should have proceeded benignly to safety. Why not?

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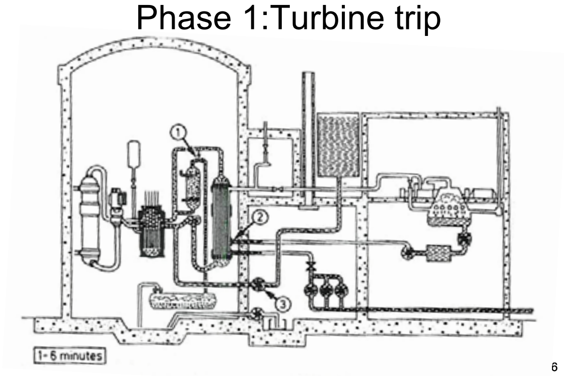
Three-Mile island accident II: Phase 1:Turbine trip



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Three-Mile island accident III: Events in Phase 1

Phase 1: 0-6 minutes (Turbine trip)

- Turbine tripped.
- Steam generators removing less heat.
- Water in circuit heats, expands and pressurises. Power-operated relief valve (PORV) opens
- Reactor trips after 8 seconds.
- At 13s, the pressure falls to closure point of PORV. ***THE VALVE STUCK OPEN***.
- Liquid level in pressuriser continued to rise. One HPIS pump ***SWITCHED OFF***.

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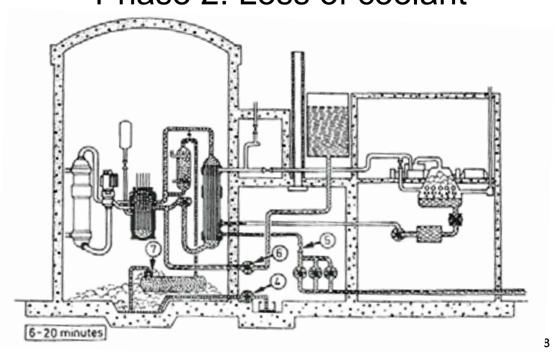
Three-Mile island accident IV: Phase 2: Loss of coolant



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Three-Mile island accident V: Events in Phase 2

Phase 2: 6-20 minutes (Loss of Coolant)

- 8 min: steam generators found to be dry. Valves inadvertently shut off before incident. Valves from auxiliary feed pumps opened. Steam generators refilled. ***NOT AS IMPORTANT*** as first thought.
- 10 min 24 s: second HPIS pump tripped. More water passing out of reactor than pumped in by HPIS. Core uncovered.
- 18 min: activity detected in ventilation. Indicated primary water loss – not understood.

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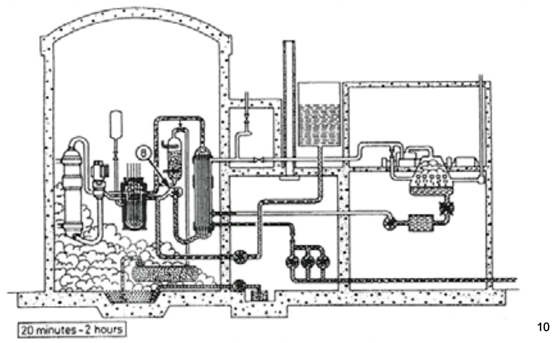
Three-Mile island accident VI: Phase 3: Continued depressurisation



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Three-Mile island accident VII: Events in Phase 3

Phase 3: 20min-2h. Continued depressurisation

- 1h 14min: Loop B pumps tripped due to vibration
- 1h 40min: Loop A pumps tripped due to vibration
- Core begins to be uncovered and heat up as decay heat evaporates remaining inventory

PORV is still stack open!

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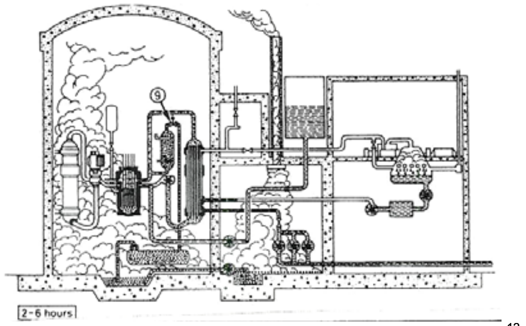
Three-Mile island accident VIII: Phase 4: The heat-up transient



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Three-Mile island accident IX: Events in Phase 4

Phase 4: 2-6 hrs. Heat up transient

- 2hrs 18min: block valve on PORV closed (at last!)
- 2hrs 55min: site emergency declared
- 3hrs 30min: general emergency declared
- 4hrs 30min - 7hrs: attempts to collapse steam voids to allow coolant loops to be operated. Unsuccessful.

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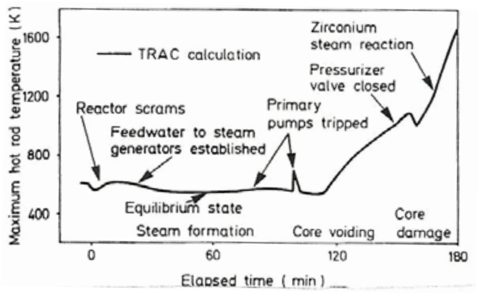
Three-Mile island accident X: Temperature history: TRAC calculation



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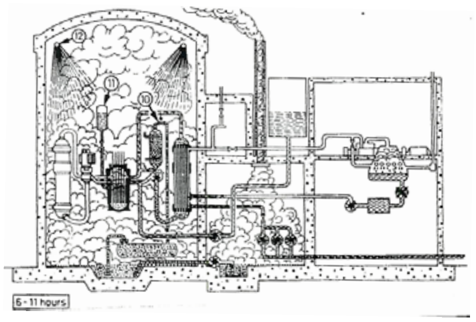
Three-Mile island accident XI: Phase 5: Extended depressurisation



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Three-Mile island accident XII: Events in Phase 5

Phase 5: 6-11hr. Extended depressurisation

- 7h 38min. PORV block valve opened with objective of depressurisation of circuit to allow ECCS.
- 8h 41min. Pressure 41 bar, therefore accumulations activated. Only small injection.
- 9h 50min. Pressure pulse recorded in reactor building. Hydrogen ignition (H_2 from zirconium/ water reaction). Sprays on.
- Minimum pressure achieved 28 bar. Not enough to activate LPIS.
- PORV block valve closed at 11h 8min.

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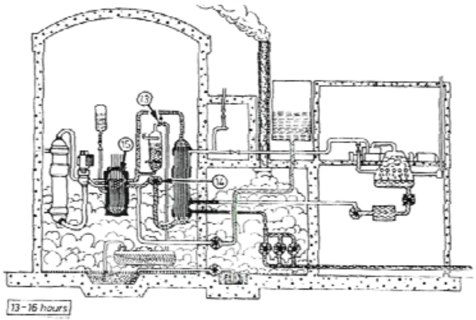
Three-Mile island accident XIII: Phase 6: Re-pressurisation and stable cooling



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Three-Mile island accident XIV: Events in Phase 6

Phase 6: 13-16h. Repressurisation and establishment of stable cooling

- 13h 30min. HPIS started to repressurise circuit and fill with water.
- 15h 51min. Loop A coolant pumps restarted and flow through steam generators reestablished giving stable cooling.

[**Phase 7: 1-8 days**: Removal of "hydrogen bubble" from vessel by dissolution. April 28th (1 month later), pumps switched off – natural circulation cooling]

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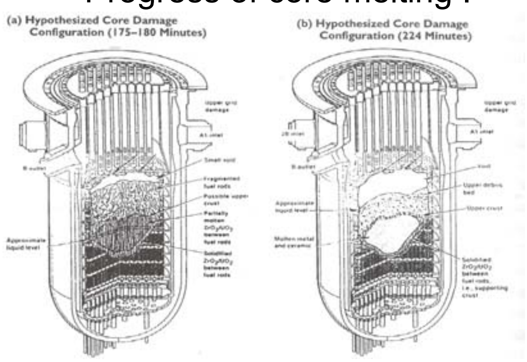
Three-Mile island accident XV: Progress of core melting I



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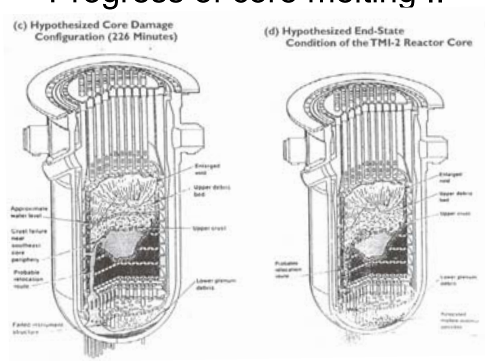
Three-Mile island accident XVI: Progress of core melting II



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Three-Mile island accident XVII: Post-mortem

- Core uncovered partly or wholly during various phases of accident
- Temperatures enough to cause Zirconium-steam reaction (→ H_2)
- Fuel meltdown ***did*** occur. No steam explosion.
- Krypton and xenon main releases.
- Consequences <1 additional cancer death (out of 200000) in 30 years.
- Engineered safety systems should easily have prevented accident ***BUT WERE SPECIFICALLY PREVENTED BY OPERATORS***.

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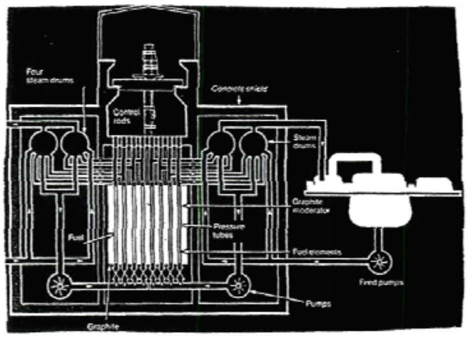
The serious accident at Chernobyl I: The RBMK reactor



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The serious accident at Chernobyl II: The planned experiment

- Objective: Could the turbine, disconnected from steam supply and isolated from grid, continue to supply power (e.g. for circulating pumps) for station due to mechanical inertia for 40-50 seconds.
- Problems: Reactor has positive void coefficient. Reactivity has to be controlled by control rods.
- Experiment initiated at 1am on April 26th 1986.

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The serious accident at Chernobyl III: Before the experiment

- Experiment setup April 25-26th.
- Many violation of operating rules e.g.
  - ECCS system disengaged
  - Coolant flow higher than allowed
  - Control rods not in safe operating condition: Control rods “dipping” into core less than ½ “safe” minimum.
- Control rod situation particularly dangerous since rods take 10 seconds to reinsert if in near fully withdrawn position.

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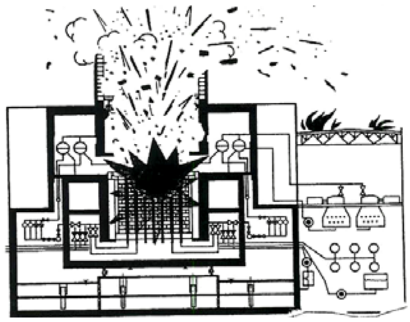
The serious accident at Chernobyl IV: The experiment

- At 01:23:04 on April 26th, experiment initiated by shutting down steam line to a turbine generator. Feed water pumps, turbine ***AND FOUR MAIN CICULATING PUMPS BEGAN TO RUN DOWN***.
- Steam generation occurred giving higher voids; therefore, higher power.
- At 01:23:31 power increase noted.
- At 01:23:40 operator attempted manual “scram” of reactor. Not possible.
- Prompt critical power excursion. Energy into fuel.
- Steam explosion then hydrogen/CO explosion.

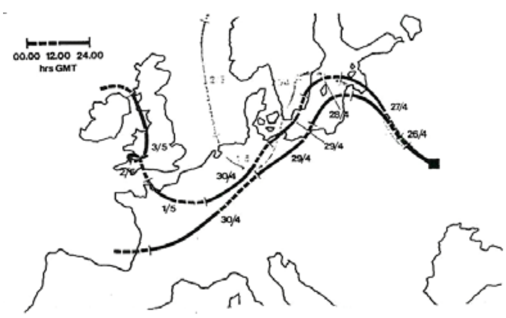
The serious accident at Chernobyl V: Explosion



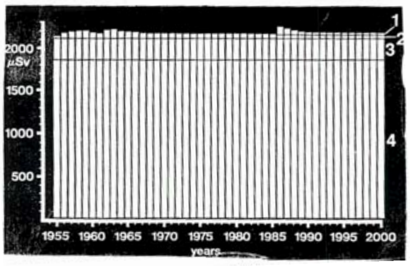
The serious accident at Chernobyl VI: Actions taken

- Graphite fire – initial attempt to cool using auxiliary feed water pumps. Not successful.
- Solid material dropped on core
  - Boron compounds to stop recriticality
  - Dolomite → CO_2 to quench fire
  - Lead to absorb heat and provide shielding
- April 27th – 10th May: 5000 tonnes of material dropped.
- Entombment: 1m thick concrete shell built around turbine and reactor blocks

The serious accident at Chernobyl VII: Spread of plume



The serious accident at Chernobyl VIII: Effect on environmental radiation



Annual average radiation dose in the United Kingdom.
1.Chernobyl
2.Miscellaneous (including weapons testing)
3.Medical
4.Natural background

Unprecedented challenge for Japan since 3・11

The Great East Earthquakes

Earthquakes

Main shock
- Magnitude : 9.0 (Mar. 11th)

Aftershocks
- Magnitude 7 or greater : 6 times
- Magnitude 6 or greater : 93 times
- Magnitude 5 or greater : 559 times

(As of Aug. 31st)

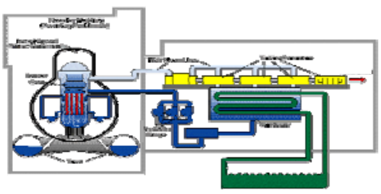
Casualties
- **Dead : over 15,700**
- **Missing: over 4,500**
- **Injured: over 5,700** (As of August 24th)

Evacuees
- **Over 124,000**

Enormous earthquake, tsunami and nuclear accident

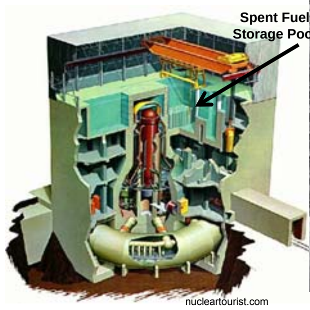
Source: Ministry of Economy, Trade and Industry

Fukushima III: The BWR's at Fukushima



Fukushima IV: The Mark 1 BWR-31

- Reactor Building Structure :
  - Concrete building (bottom)
  - Handling Hall (Beams)
- Containment
  - Drywell (pear shaped)
  - Pressure Suppression Torus



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ukushima Accident : the Facts
B. Barré NLT 29-09-11
Slide 33

15h42
15h43
15h44
15h57
Fukushima Accident : the Facts
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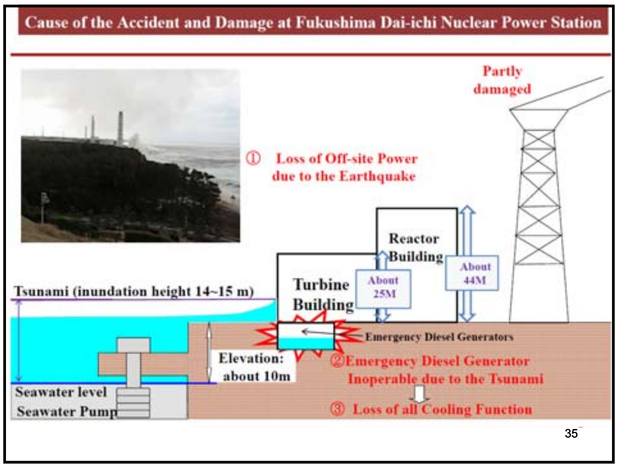
Slide 34



Cause of the Accident and Damage at Fukushima Dai-ichi Nuclear Power Station
Partly damaged
① Loss of Off-site Power due to the Earthquake
Reactor Building
About 44M
Turbine Building
About 25M
Tsunami (inundation height 14~15 m)
Emergency Diesel Generators
Elevation: about 10m
②Emergency Diesel Generator Inoperable due to the Tsunami
Seawater level
Seawater Pump
③ Loss of all Cooling Function
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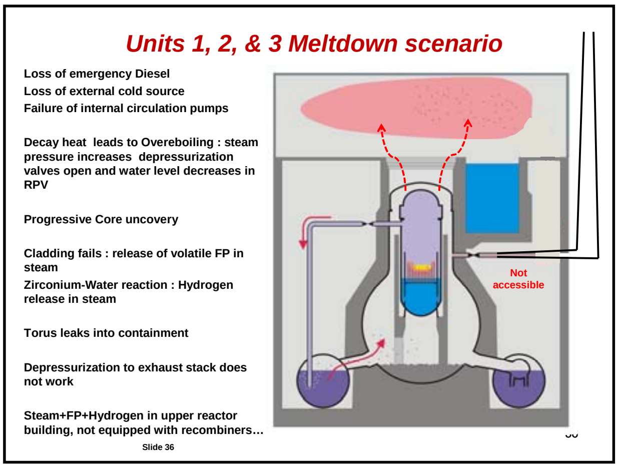

Units 1, 2, & 3 Meltdown scenario
Loss of emergency Diesel
Loss of external cold source
Failure of internal circulation pumps
Decay heat leads to Overeboiling : steam pressure increases depressurization valves open and water level decreases in RPV
Progressive Core uncovery
Cladding fails : release of volatile FP in steam
Zirconium-Water reaction : Hydrogen release in steam
Torus leaks into containment
Depressurization to exhaust stack does not work
Steam+FP+Hydrogen in upper reactor building, not equipped with recombiners…
Not accessible
Slide 36

Fukushima IX: Fate of Reactors

Earthquake caused successful shutdown.
Loss of offsite power.
Diesel generators activated.
Diesel generators swamped by Tsunami
Batteries ran down.
No power therefore no cooling!

Consequences:
Reactor 4: Defuelled at time of accident. OK
Reactors 5 and 6 in cold shutdown mode. OK
Reactors 1, 2 and 3. Experienced full meltdown

2400 Curies radioactivity released (c.f. 7000 Curies at Chernobyl)

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Solutions to severe accident problem

1. Keep PWR concept but improve design
   Increase safety features whilst keeping conventional design (EPR)
   Modify design to reduce reliance on active safety systems (AP1000)

2. Design so that fission product heat is removed by natural convection.
   Fused salt High temperature Reactor (FHR)

3. Avoid large fission product inventory in core. Fission products processed out of fuelled continuously - low fission product inventory. Fluid fuelled reactors. (FFR). Molten salt reactor (MSR)

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Conclusions

- Many minor and two major incidents have occurred.
- Such incidents will continue to occur periodically. They are typical of incidents in all major industrial projects.
- We must learn the absolute maximum possible from such incident and develop our engineered safety systems.
- Nuclear power is essential for the future and accidents must be seen in proper perspective.

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