

Reactor Safety

1. Void fraction

As bubbles of steam form:

- Liquid H₂O decreases
- Thermal neutrons decrease
- Persistence of fast neutrons
 - ⇒ more capture of fast neutrons by U-238
 - ⇒ more leakage of fast neutrons

"Void coefficient" =

$$\frac{\text{change in reactivity}}{\text{change in void fraction}}$$

Want a negative void coefficient,
i.e. want reactivity to decrease
as the void fraction increases.

However, H₂O also captures
thermal neutrons.

Thus, a competition is set up:
If increasing void fraction
 \Rightarrow less moderation,
then void coefficient is NEGATIVE.

However, if increasing void fraction \Rightarrow less capture,
then void coefficient is POSITIVE.

In LGR's, void coefficient can be either positive or negative, depending on design details. Chernobyl had a positive void coefficient.

2. Active and Passive Safety Features:

Active -- Proper operation of reactor equipment

Passive -- automatic -- e.g. gravity fall of control rods

3. Redundancy in safety design

4. "Defense-in-depth"

Series of improbable events must occur to cause an accident.

Types of Accidents

1. Criticality Accident

Runaway chain reaction.
Highly improbable in LWR of good design, because of negative feedbacks and shutdown mechanisms.

Less unlikely in other reactor types, especially if there are design flaws --

Chernobyl started as criticality accident, though much of energy release was from steam explosion.

Control of reactivity:

prompt criticality avoided.
delayed neutrons used to
reach criticality.

But control rods not perfect:

- Not instantaneous --
about 1 sec
- release mechanism could
fail
- path could be blocked

2. Loss-of-Coolant Accident

Coolant flow is disrupted.

Even if fission is stopped,
large amount of heat from
radioactive decay continues.

Unless heat is removed, core
may melt. If overheating
yields excess steam pressure,
radioactive materials can
escape. TMI was loss-of-
coolant accident, there was
core melting, but no large
escape of radioactive material.

Consider 1000 MW reactor:

200 MW from radioactive decay (during running)

16 MW after one day from shutdown of fission

9 MW after five days from shutdown of fission.

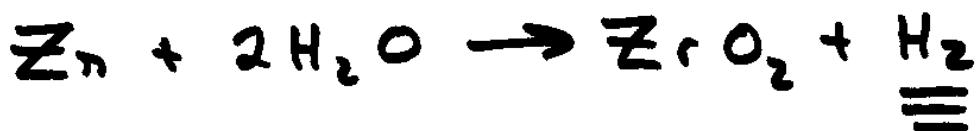
More than sufficient to melt fuel. Fuel melting at about 2800 °C.

Steam and Hydrogen Explosive

Normal LWR: water at 330-350 °C

Zircaloy cladding of fuel rods at only a slightly higher temperature.

If coolant flow is disrupted, if cladding reacts about 900 °C, following may happen:



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H_2 at $900^{\circ}C$, if it finds O_2 , will burn, will explode.

This happened during TMI accident, though explosion did not cause damage.

Steam: contact between water and very hot or molten fuel can result in a large amount of steam generation, and a high steam pressure, perhaps violent enough to damage the reactor pressure vessel.

It was once feared damaged core could fall into cooling water, with large steam generation

China syndrome:

molten reactor fuel settles
to bottom of reactor,
melts through vessel wall,
into concrete base,
releasing CO₂ and other
gases, which carry
radionuclides into atmosphere

3. Aftermath

Accidents can persist
because of radioactivity
-- different from other
types of accidents

Chernobyl caused 31 prompt
deaths, and 50,000
delayed cancers.

Three Mile Island

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906 MW_e PWR

Start up in 2/78

Full power operation by 12/78

Accident 3/28/79

Scenario:

1. Problem started in secondary water flow, i.e. water flow loop from heat exchanger to turbine to condenser back to heat exchanger.
Malfunction caused emergency pumps to start, but emergency valves were closed, and operators didn't notice this.
2. Thus, there was no secondary water flow to heat exchanger
3. Water flow from reactor to heat exchanger affected - had no place to dump its heat
4. Relief valve opened, and control rods were inserted, stopping fission.

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5. Water pressure in main loop dropped. Relief valve should have closed -- but it stayed open for 2.5 hours -- and operators didn't know the status of the relief valve.
 6. Within 2 minutes from start of accident, water in reactor boiled dry. Operators didn't recognize this.
 7. Three hours after start of accident, emergency declared, some radioactivity released
 8. Hydrogen formed, but apparently no explosion occurred, because of insufficient O₂.
 9. Four ^{days} later, H₂ removed
 10. Significant core damage, pressure vessel withstood molten fuel, small amount of radioactivity release
Loss-of-coolant accident.

Chernobyl

- Soviet RBMK-1000 reactor
- 1000 MWe, downsized to 952 MWe
- Graphite-moderated, water-cooled -- positive void coefficient
- Used for electricity generation and plutonium production
- At time of accident, 4/26/86, four reactors operating at Chernobyl, and two under construction.
- Accident occurred in unit #4
- Units #1 and #2 returned to operation in late 1986, #3 in 1987.
- Mid 1995 -- units #1 and 3 still operating, 11 other RBMK-1000 reactors operating in Russia.
- Poor control rod design: graphite spacer below control rod, to prevent water from filling space.

Scenario:

1. Special test underway.

Testing involved reducing steam flow to turbine. Operators wanted to determine if "coast-down" of turbine could provide sufficient power for pumping of water until emergency diesel generators kicked in.

2. Testing caused decrease in water flow through core -- some boiling occurred, increasing the fission because of the positive void coefficient.

3. Emergency shutdown attempted, control rods inserted -- but the design flaw (with the graphite spacer) caused the fission to further increase.

By the time the control rods were fully inserted, it was too late!

4. within 3 seconds, reactor went prompt critical.

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Within 20 seconds, two large explosions occurred.

First explosion: probably a steam explosion that exposed reactor fuel to air.

Second explosion: probably reaction of H₂ and CO (from burning graphite) with air.

5. Explosions breached the reactor building. There was no true containment structure (another design flaw).

6. Burning fragments injected into atmosphere. Fires on roof. Large release of radioactivity.

Conclusions

1. The Chernobyl reactor is of poor design. Not typical.
2. Humankind has gained much experience with nuclear power reactors.
3. If there is a future for nuclear fission power, newly designed reactors will probably be very good, very safe. Modular, standardized design should reduce costs.
4. The "weakest link" in the system is unlikely to be the reactor. It ^{"will"} probably be found elsewhere.

System (main elements) :

- Mining
- Processing and enrichment of fuel
- Reactor for power generation
- Spent fuel processing and relation to weapons
- Long term storage .