Nuclear Reactor Safety for Science Teachers: A Quick Overview

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Outline

- What is the Hazard?
- What is the Goal of Reactor Safety?
- Where is the Radioactivity?
- Stopping the Movement of Radioactivity
- Safety Functions:
  - Power Control
  - Decay Heat Removal
  - Containment of Radioactivity
  - Monitoring
- Severe Accidents
- Towards Safer Designs...

What Accident is This?

28 killed, 36 injured, 1821 homes and 167 buildings destroyed

(It did NOT occur in a nuclear reactor but in a chemical plant in Flixborough, England)

Nuclear Power is Dangerous

Nuclear Power is Safe

Dangerous	*Safe*
Radiation can kill you and cause cancer	**The radiation is contained in a series of physical barriers; it is difficult to get mobile; even in a severe accident, little will escape**
If the power is uncontrolled, it can rise exponentially	**The power rise is slow and can be stopped in <2sec. by any one of three independent systems; if these fail the reactor core will be damaged and the chain reaction will stop**
Power reactors can be used to make bombs.	**The fuel is highly radioactive and a "rogue" group would more likely kill themselves than anyone else. A government could do it but a small dedicated military reactor would be far more effective. An enriched uranium bomb does not require a reactor at all.**

The Chernobyl Disaster

- More than 12,500 of the 350,000 people who worked on the Chernobyl cleanup have since died

- For a population of the age and sex distribution of the “liquidators” in 1986, the normal mortality rate was 3 per 1000 per year. Thus the “expected” number of deaths would be:

  350,000 people x 12 years x 3/1000

  = 12,600

- The number should be larger (by 50%) because the normal rate of 0.3% increases as the group ages
- Is reporting inadequate? Does monitoring improve the life expectancy of the liquidators?

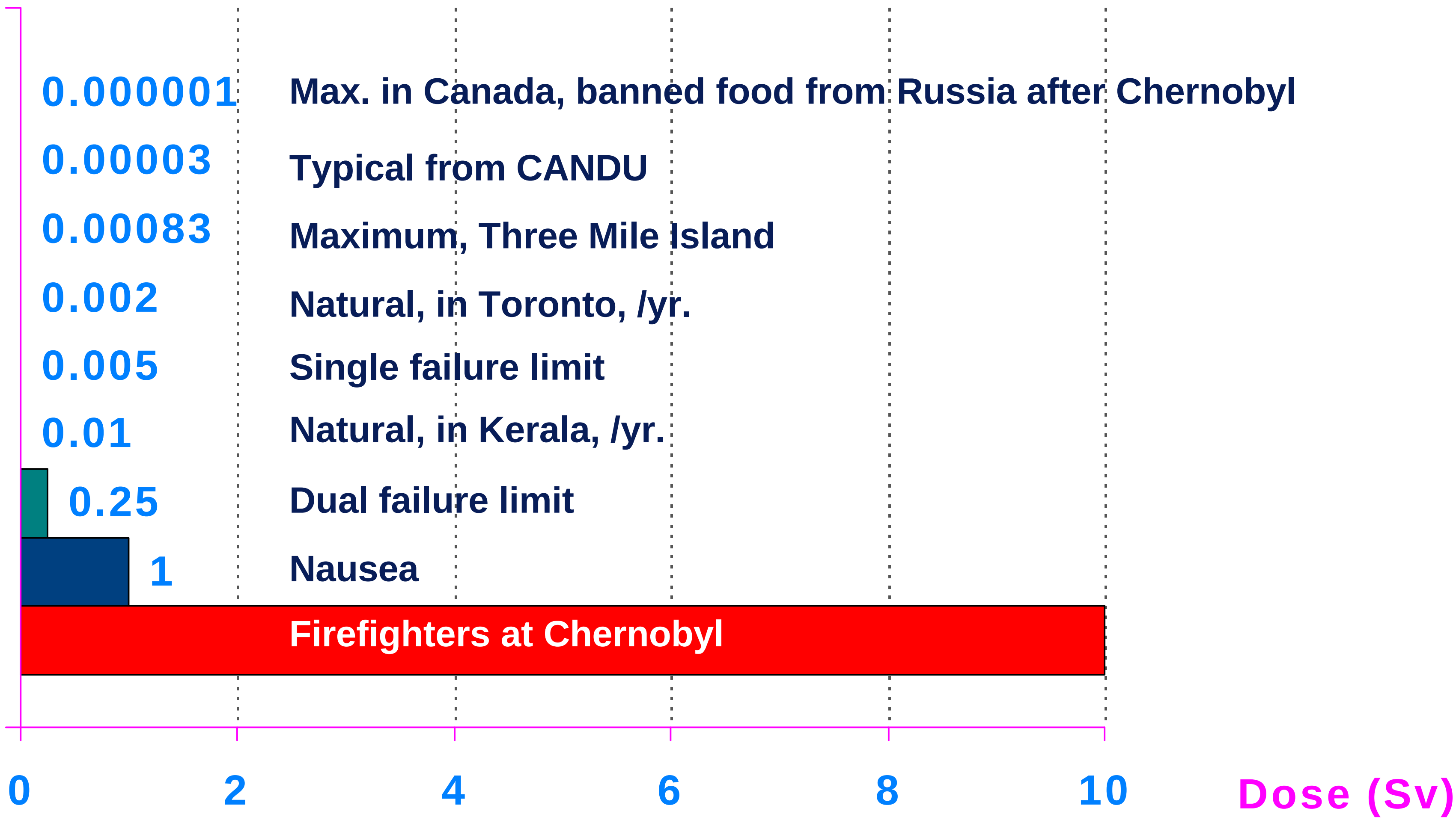
What is the Public Hazard?

• chemical?	Chlorine for water treatment
• biological?	None
• physical?	Nuclear explosion impossible
• radiological?	Small risk of delayed effects, very small risk of prompt
• psychological?	Chernobyl, Indian nuclear tests

Effects of Radiation

- prompt (deterministic, non-stochastic)
  - 1 Sv + : illness
  - 3 Sv + : increasing risk of death (LD 50 is 3 to 10 Sv)
- delayed (random, stochastic)
  - risk of cancer
    - 0.25 Sv approx. 0.5% increase in individual risk
  - risk of damage to foetus
  - risk of genetic damage
    - not observed in humans

EXAMPLES OF RADIATION DOSE



What Is the Goal of Reactor Safety?

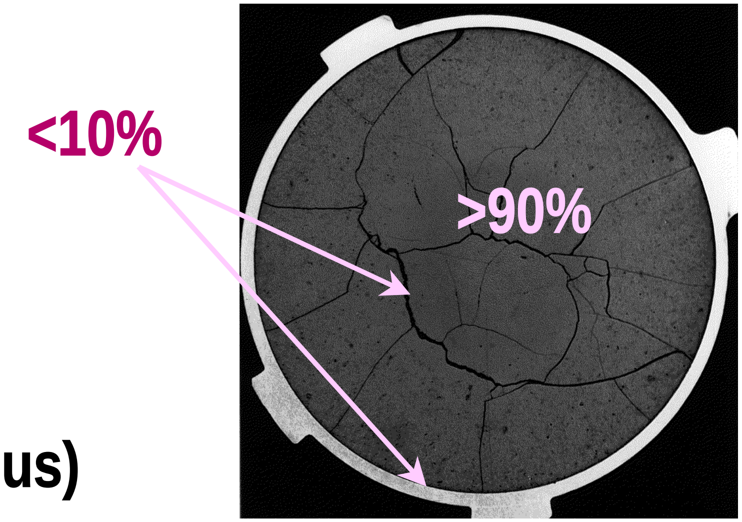
- **To prevent prompt effects with a high degree of assurance and minimize the risk of delayed effects**
- **Typically**
  - **frequency of a large release < 10^{-6} per reactor-year**
  - **frequency of a core melt (intact containment) < 10^{-5} per year**
- **We will cover in next lecture!**

Bad and Good Things About Radioactivity

- It's highly concentrated. A reactor contains only a few hundred grams of I^{131}; if it were all released to the air at once, the dose at the boundary could be several Sv.
- It can't be seen, smelled or felt. You can't tell if you're being irradiated (at low doses).
- It remains hazardous for a long time and must be guarded.

- Because the physical quantities are small, they can be easily contained. Iodine is chemically active & can be trapped (~99.99% effectiveness) in water. Accidents are wet.
- You can detect smaller quantities of radioactivity than almost any other hazardous material (~50x less than occupational limits).
- It's one of the few hazards which becomes less harmful with time.

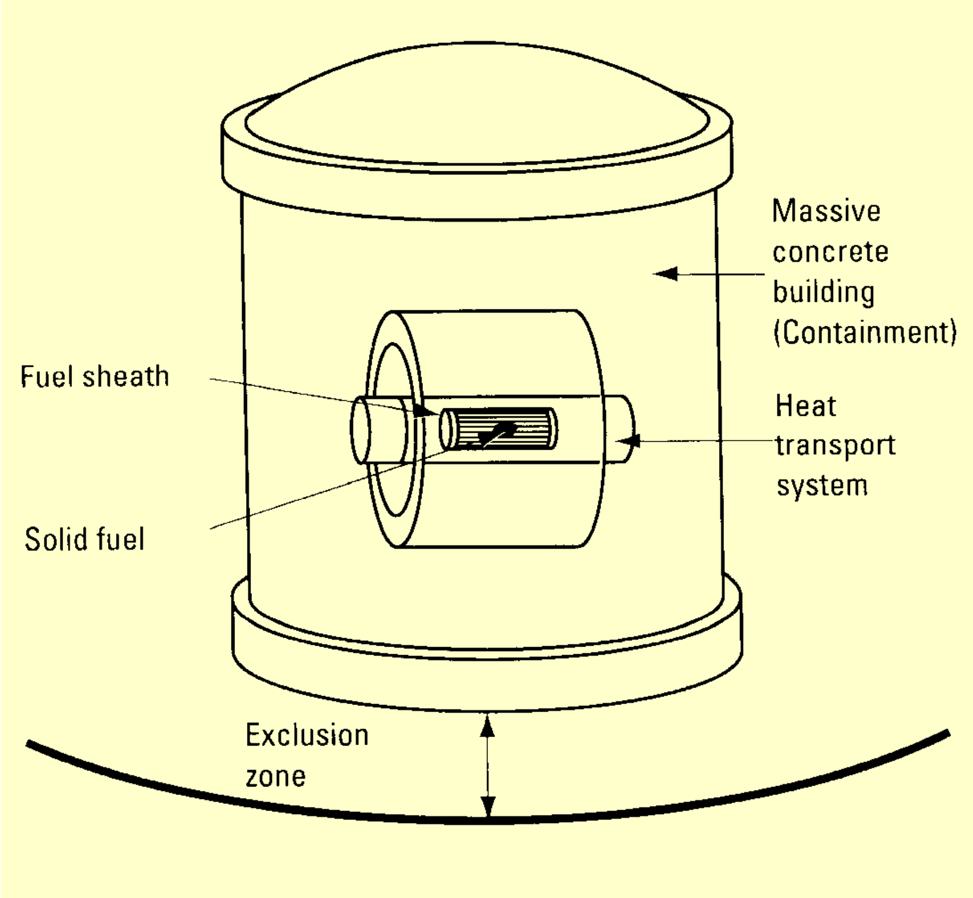
Where is the Radioactivity?



- uranium dioxide fuel
  - >90% in ceramic fuel
- fuel-sheath gap
  - <10% in normal operation (gaseous)
- spent fuel bay
  - large inventory of long-lived fission products
  - little driving force
- fuelling machine
  - up to one or two channels' worth (< 0.5% of bundles)
- tritiated heavy water (DTO) in coolant and moderator

Safety - Stopping the Movement of Radioactivity

- prevent radioactivity from going where it isn't supposed to
- use physical barriers
- mobility affected by:
  - temperature
  - physical form
  - chemistry
  - physical barriers
  - decay



Safety Design

- prevent fuel from overheating
- overheating mechanisms (power/cooling mismatch)
  - power rise
  - loss of coolant / cooling
- three safety functions
  - control power and, if needed, shut down reactor
  - remove decay heat
  - contain fission products

Safety Functions - Power Control

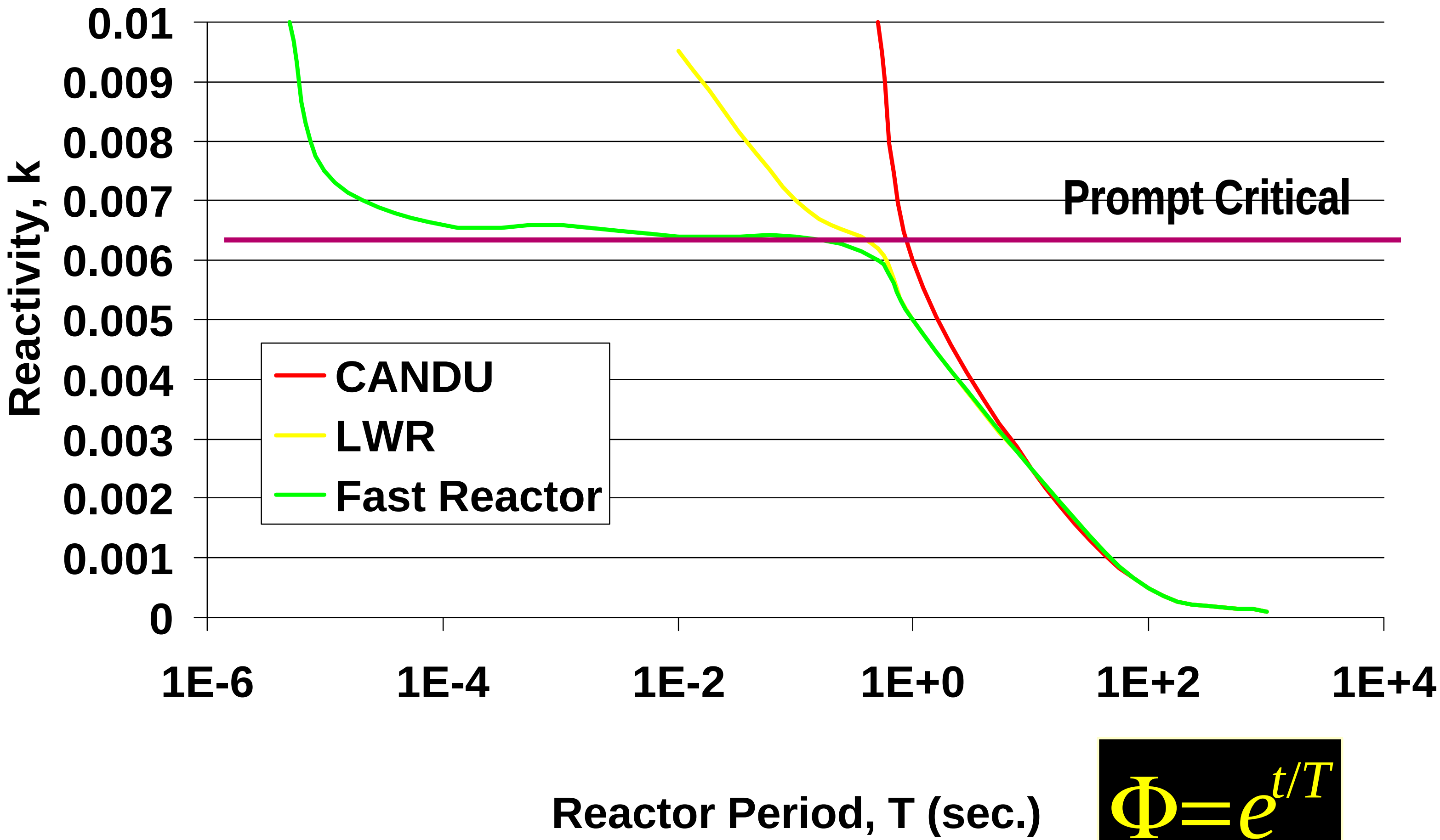
- at criticality, the number of neutrons produced in one generation (n_i) is the same as the number produced in the next generation (n_{i+1})
- or, production = losses (leakage + absorption)
- if $n_{i+1} > n_i$, the power increases; e.g., if $n_{i+1} = 1.002n_i$, then in each generation:
  - N, 1.002N, 1.002^2N, 1.002^3N, 1.002^4N... - a geometric series

Delayed Neutrons

Subcritical	*Critical*	*Supercritical*
$r < 0$	$r = 0$	$r > 0$

- **99.4% of neutrons are "prompt"**
  - **can cause next fission in 1 ms. in CANDU, 0.02 ms in LWR**
- **0.6% are "delayed" from seconds to tens of seconds**
- **basics of safe reactor control:**
  - **negative or small prompt feedback (fuel temperature - Doppler)**
  - **limit excess reactivity (require delayed neutrons to keep reactor critical, or r < 0.0064 or 6.4 milli-k)**

Reactor Period vs. Reactivity



$$\Phi = e^{t/T}$$

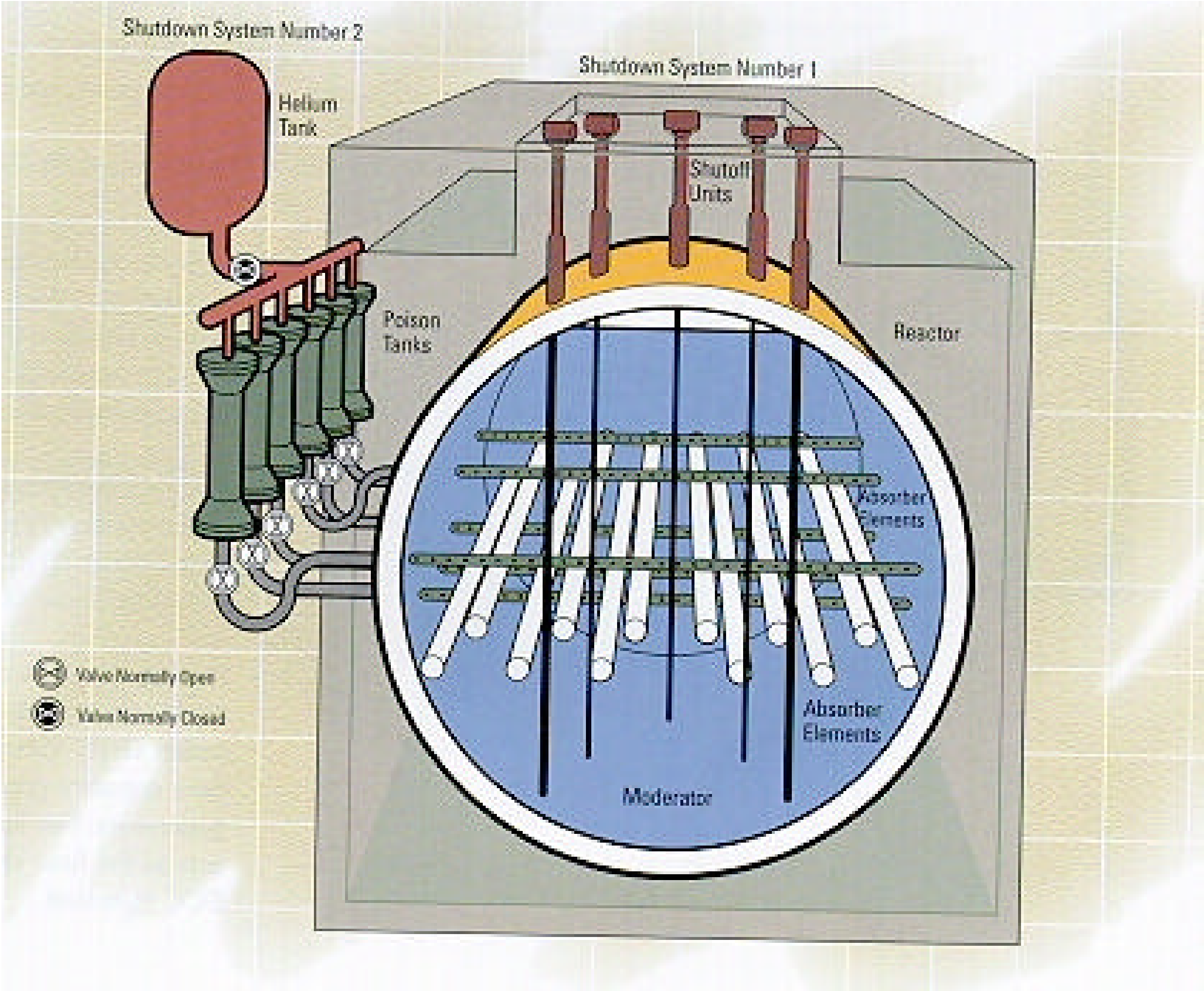
Sources of Positive Reactivity

- **all reactors: withdrawal of control rods**
- **CANDU: boiling of the coolant**
- **BWRs: collapse of boiling of the coolant**
- **PWRs: drop in coolant temperature**
- **positive reactivity insertion in CANDU:**
  - **loss of reactivity control - up to 1 mk/sec**
  - **large loss of coolant - up to 8 mk/sec**

What Does that Mean for Design?

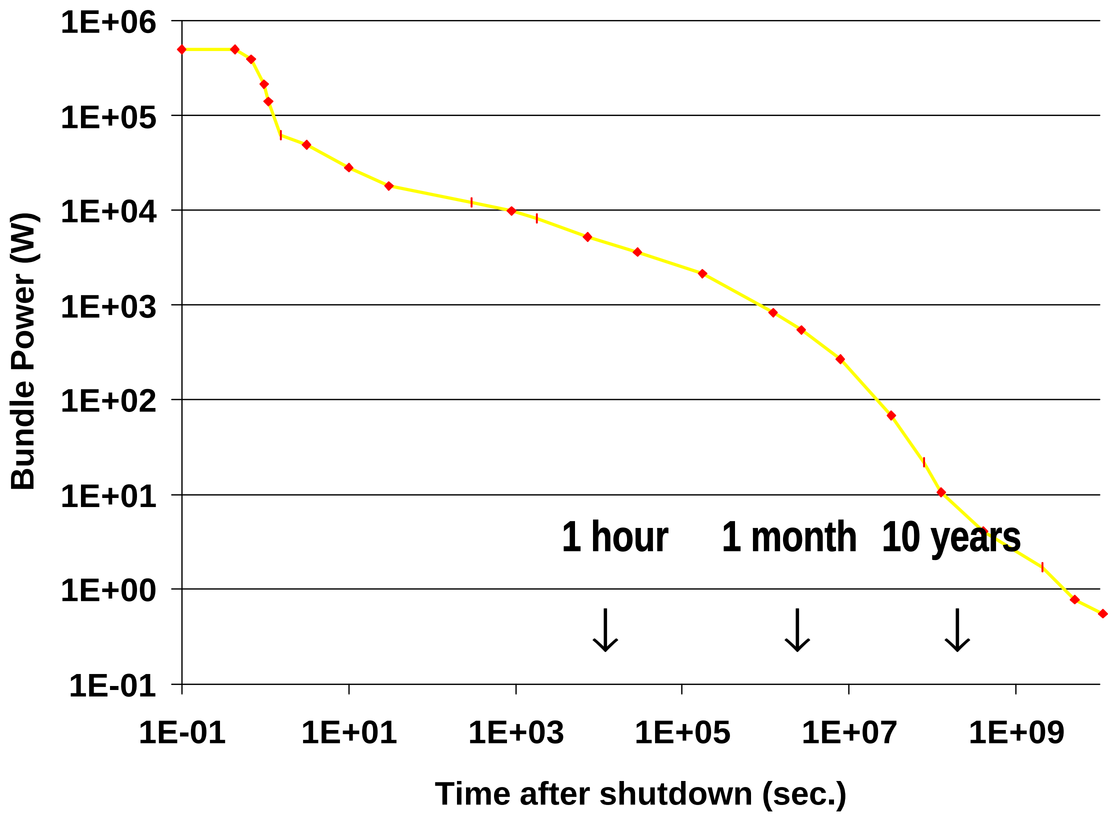
- **in CANDU: shutdown time needed is about 1.5 seconds - achievable with mechanical (shutoff rods) or hydraulic (“poison” injection) devices**
- **in LWRs: prompt neutron lifetime is about 10 times shorter**
  - **rod ejection accident: prompt critical in << 1 sec.**
  - ***need* (and fortunately *have*) an inherent fast feedback**
    - **Doppler effect, shift of UO_2 resonance absorption**
- **are there any disadvantages to a fast, prompt negative reactivity feedback due to temperature**
  - **in the fuel?**
  - **in the coolant?**

Shutdown Systems in CANDU



Safety Functions - Decay Heat Removal

- each isotope decays with characteristic half-life
- sum total is what matters
- after about 4 months, can remove heat from channels, even if empty, without fuel damage
- sets mission time of systems for decay heat removal



Systems for Decay Heat Removal

- **If there is *no* hole in the cooling system:**
  - **backup supplies of water to the boiler secondary side**
  - **separate decay heat removal system (shutdown cooling)**
  - **make a small hole and keep up with it**
    - **in LWRs, feed & bleed**
    - **in CANDU - not desired but will occur if you do nothing**
- **If there *is* a hole in the cooling system:**
  - **pour water in as fast as it is being lost (ECC)**
  - **cool it and recirculate it from the floor**
  - **contain radioactivity in the building**
    - **fuel may be damaged if break is large**

Chemistry

- one of most significant isotopes in an accident is I^{131}
  - volatile, short half-life [8 days]
- Caesium also released, and combines almost instantaneously with iodine:
  - $Cs + I \rightarrow CsI$
- in the presence of water, CsI dissociates:
  - $CsI \rightarrow Cs^{+} + I^{-}$
- hard to get the iodine out of the water (like getting chlorine out of the sea)
- moral of TMI vs. Chernobyl - <u>wetter is better</u>

Some Fundamental Principles of Safety Design

- ***redundancy*: ensure that safety does not depend on any single system functioning correctly**
- ***reliability:* design to numerical reliability targets (999/1000)**
- ***testability:* ensure systems are testable to demonstrate their reliability**
- ***independence:* ensure systems which perform the same safety function are independent**
- ***separation:* ensure systems which perform the same safety function are spatially separated**
- ***diversity:* ensure where possible that systems which perform the same safety functions are of dissimilar design**
- ***fail safe:* ensure system/component fails safe if practical**

Containment of Radioactivity

- leaktight concrete building around major sources of potentially mobile radioactivity
- lined, prestressed
- why are the walls so thick (0.7 to 1.5m)?
  - shielding of gamma rays
  - withstand interior pressure (»200 kPa)
- leaktightness: typically from 0.5% to 0.1% per day at design pressure
- water spray to control pressure / vacuum building

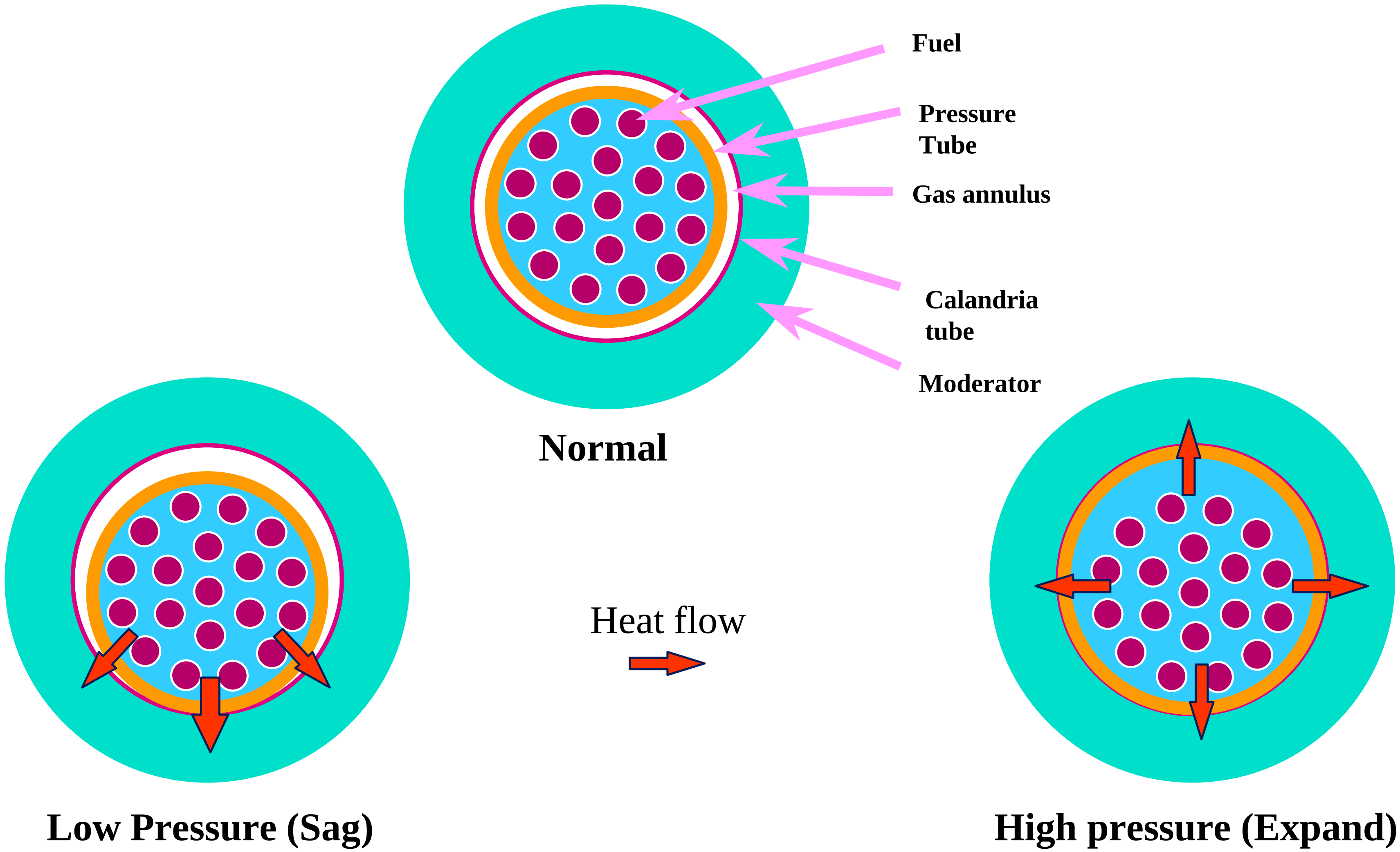
Monitoring

- **provide two control rooms from either of which:**
  - **the plant can be shut down**
  - **decay heat can be removed**
  - **barriers to release of radioactivity can be maintained**
  - **the plant state is known**

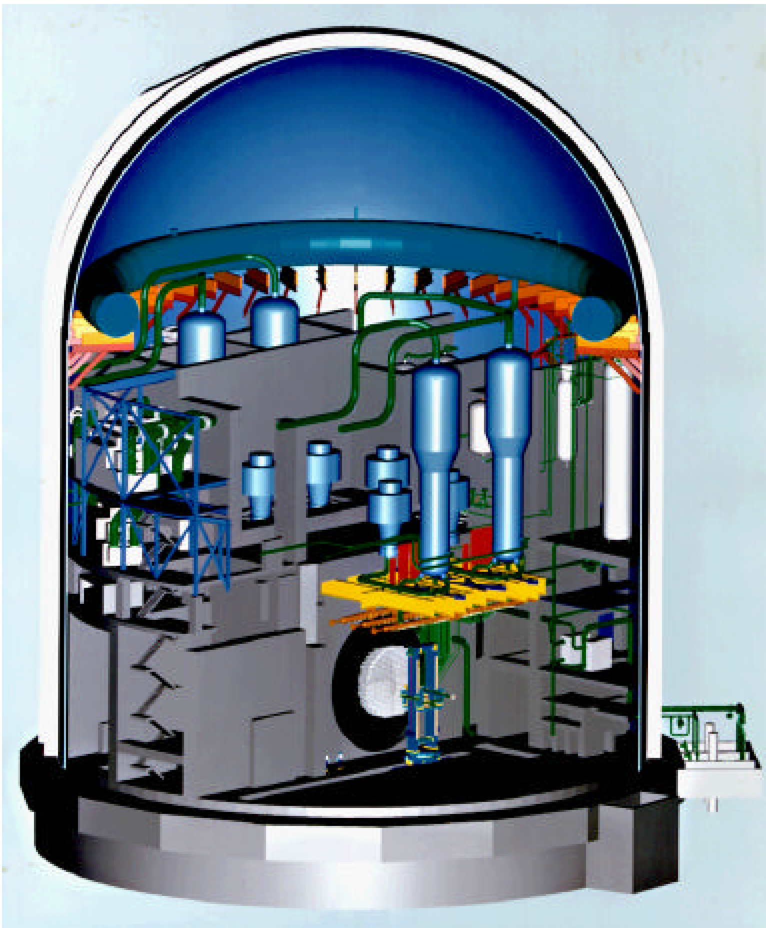
Severe Accidents

- "if the defences you have put in ***all*** fail, what happens?"
- in LWRs: leads to
  - melting of reactor fuel (TMI)
  - penetration of reactor pressure vessel
  - eventual penetration of containment basemat or overpressure of containment building
- the most likely outcome:
  - no prompt deaths
  - inferred delayed cancer cases which cannot be detected due to "natural" cancers

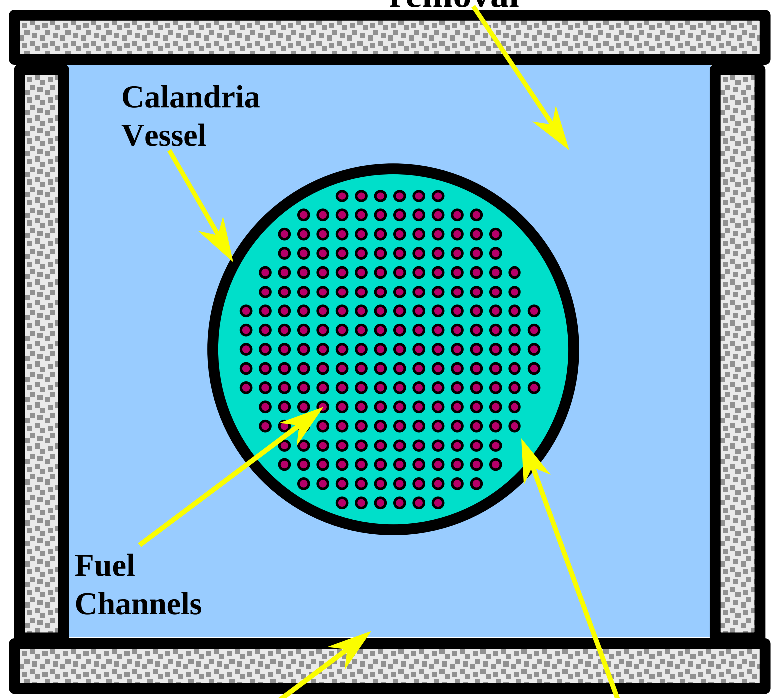
CANDU - Moderator as Heat Sink



Shield Tank as Heat Sink



Shield Tank
Can remove 0.4% decay power. Takes >20 hours to heat up and boil off with no heat removal



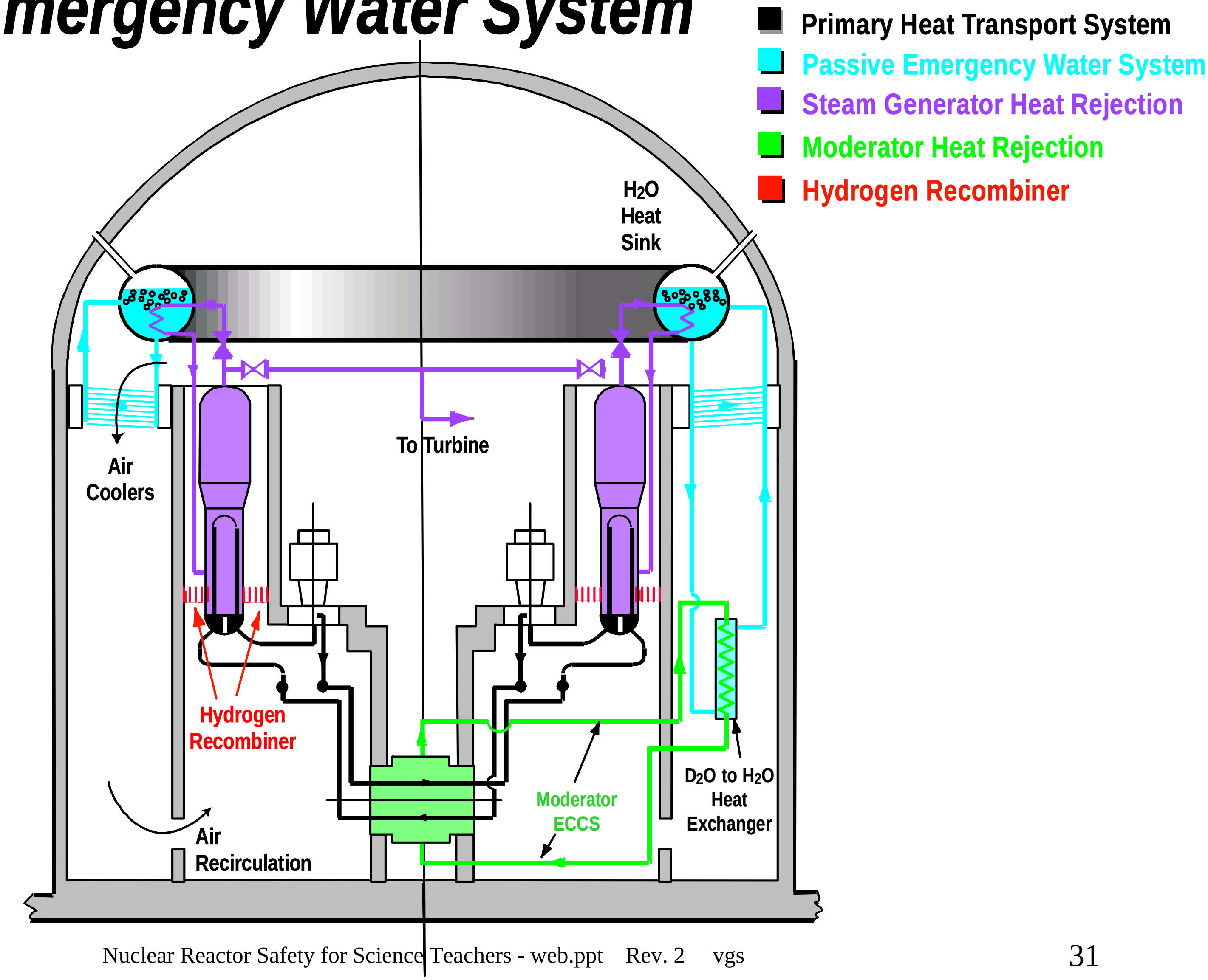
Debris spreading & cooling area

Moderator
Can remove 4.4% decay power
Takes >5 hours to heat up and boil off with no heat removal

Toward Safer Designs...

- current evolutionary designs
  - ensure a water covering over the damaged “core on the floor” & remove heat from containment
- passive designs:
  - passive: a component or system which does not need any external input to operate (e.g., electrical power)
  - usually uses gravitational forces to supply water, natural convection to transport heat, capability to store heat
  - sometimes requires active valves, signals
- passive designs allow more time to arrest an accident before core damage and are believed to be simpler

Passive Emergency Water System



Failure Modes of A Household Fuse

- **Is a passive fuse better than an active circuit breaker?**
  - **wrong material used in wire**
  - **wrong size wire used**
  - **internal short in fuse**
  - **wrong size fuse used in socket**
  - **fuse defeated by putting in penny instead**
  - **electrician cross-connects two circuits**
- **how many of these are detectable by test?**

Conclusions

- **are reactors safe?**
- **are reactors acceptably safe?**
- **is reactor safety amenable to scientific discipline: well-posed questions and objective answers?**