Lecture 1 - Introduction

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UNENE Nuclear Reactor Safety Course

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Life is Risky

- Dams, coal plants, gas plants, solar energy, wind energy, nuclear energy
- Benefit / risk tradeoff
  - Individual basis
  - Societal basis
- Benefits of Nuclear Power

Hazards of Nuclear Energy

- Chemical? Biological? Physical?
- A nuclear reactor cannot explode like a nuclear weapon
  - Form a critical mass quickly
  - Ensure neutron source is located correctly & triggered at the right time
  - Pure fissile materials: k=1.7 on *fast* neutrons

Nuclear Time Scales

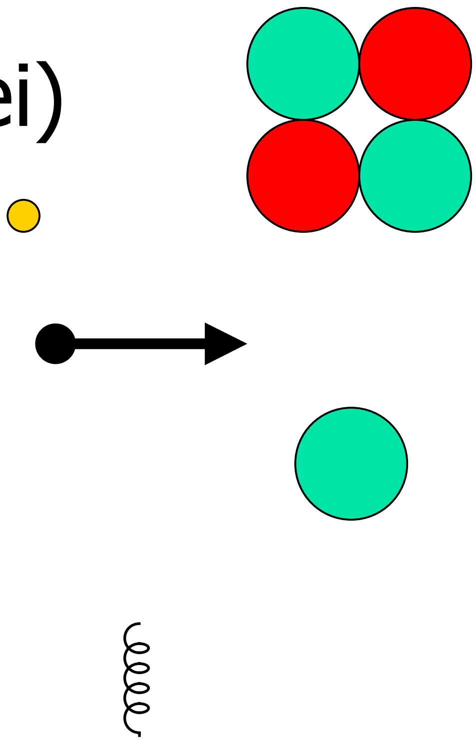
- Fast neutrons
  - A ‘shake’ is 10^{-8} seconds
  - A few shakes or ~50 generations of neutrons sufficient for a bomb
- Power reactors – thermal neutrons
  - Prompt neutron lifetime ~ 1 ms.
  - Still too fast for control …

Radiological Hazard

- Somatic, genetic
- Somatic
  - Acute, prompt, early, non-stochastic
  - Delayed, latent, stochastic
  - Teratogenic
- Genetic
  - Not observed in humans
- Non-human biota

Types of Radiation

- Alpha rays (helium nuclei)
- Beta rays (electrons)
- Gamma Rays (photons)
- Neutrons
- Neutrinos
  - but almost no interaction



Characteristics of 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 sense 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.**
- **Instruments 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.**

Units - Radiation

- 1 Becquerel = 1 nuclear disintegration / second
- 1 litre of milk = 40 Bq of naturally radioactive K^{40}
- 1 Bq = 2.7×10^{-11} Curies (Ci)
- TBq (10^{12} Bq) more useful

Units - Dose

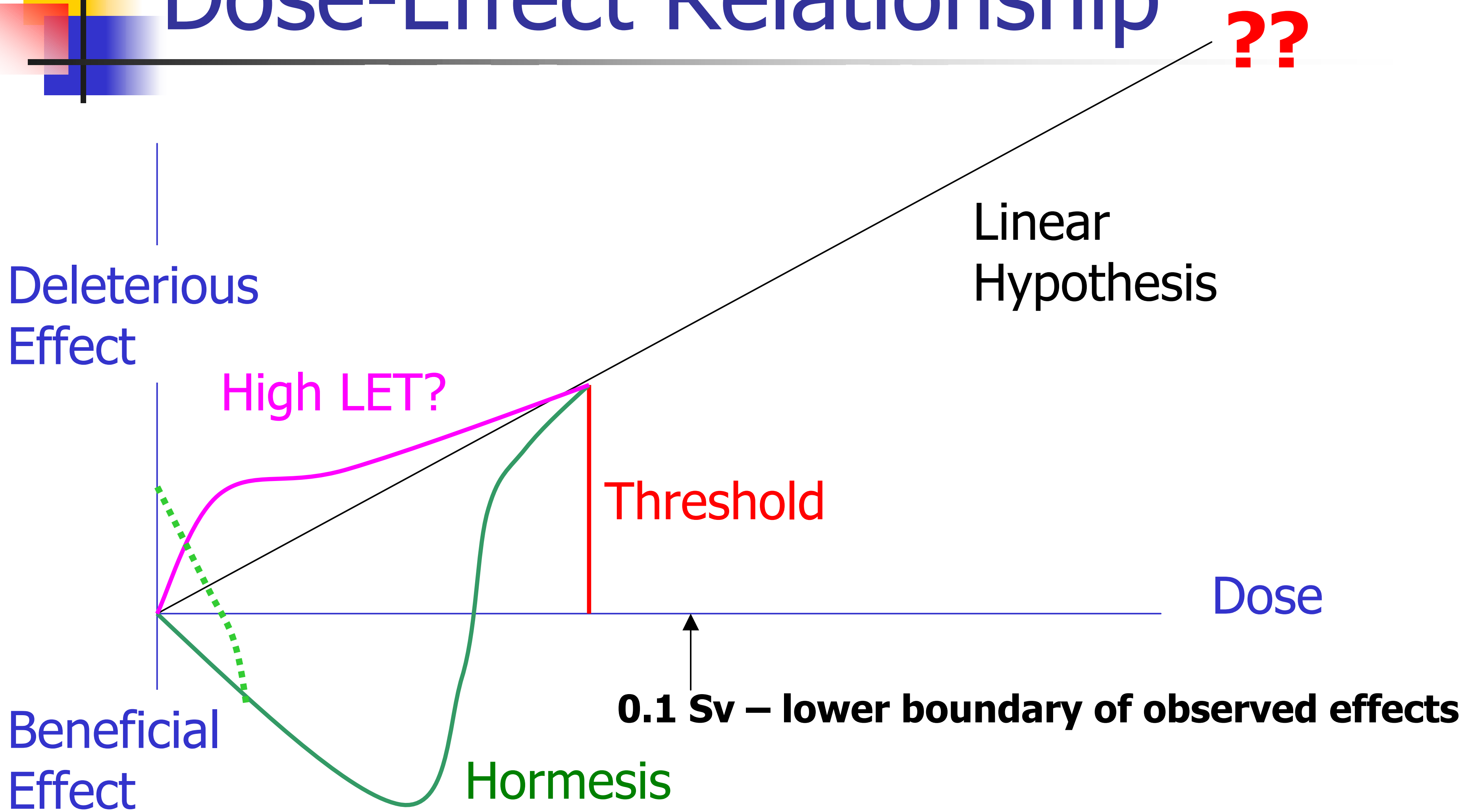
- 1 Roentgen = 87.7 ergs/g of air at STP
- 1 rad = 100 ergs/g absorbed energy
- 1 rem = 1 rad x RBE
- 1 Sv = 100 rem

Radiation	RBE
X-, γ-rays, β-particles	1
Thermal neutrons	3
α-particles, fast neutrons	10
Heavy recoil nuclei (fission fragments)	20

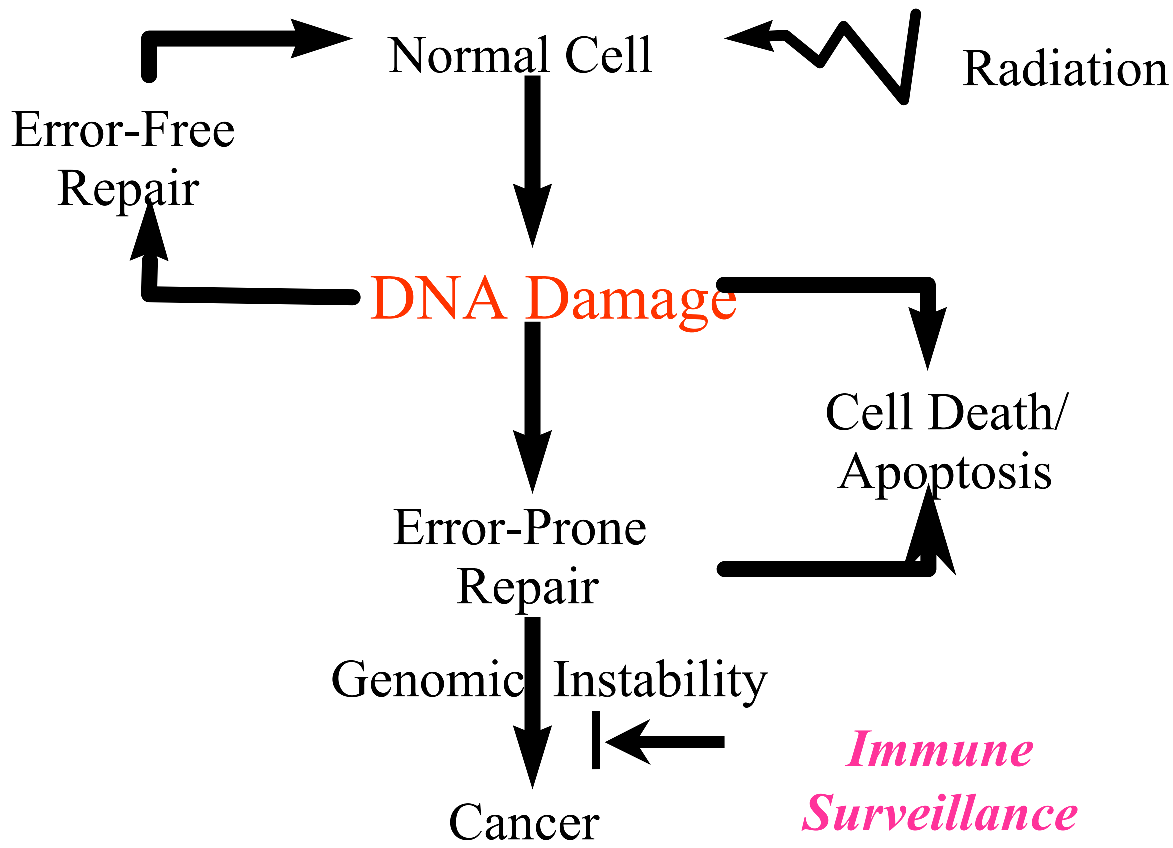
Effect of Radiation

- > 1 Sv – non-stochastic
- < 1 Sv – stochastic
  - 100 Sv = 5 fatal cancers in an exposed general population
  - Linear dose-effect hypothesis
    - Hormesis? Threshold?

Dose-Effect Relationship

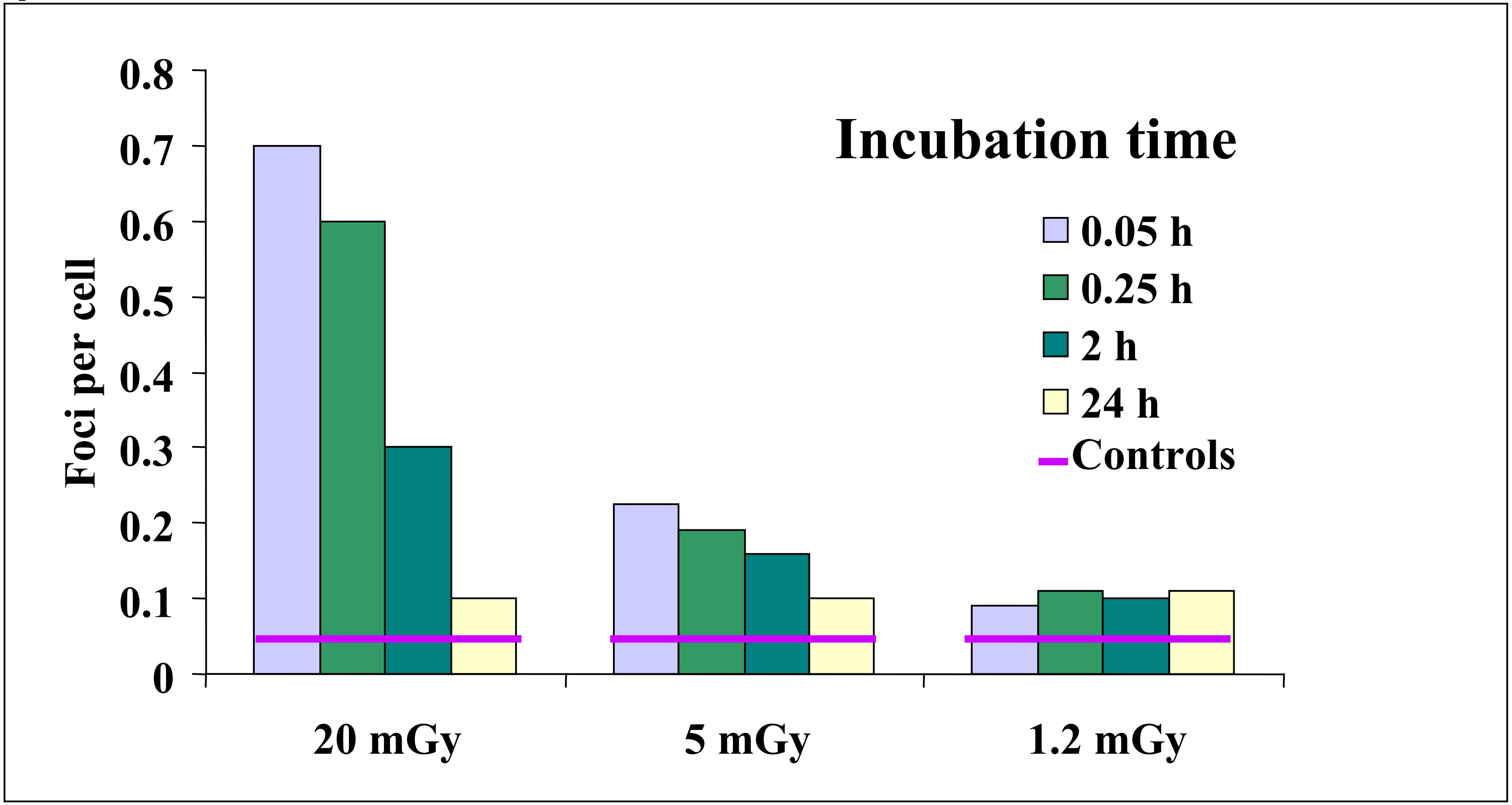


Possible Outcomes of DNA Damage



Ron Mitchel, 2004, modified 2007

DNA Repair



Rothkamm and Löbrich 2003

Chernobyl

- **More than 12,500 of the 350,000 people who worked on the Chernobyl cleanup have since died (to 1998)**

- **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?**

Range of Doses (Sv)

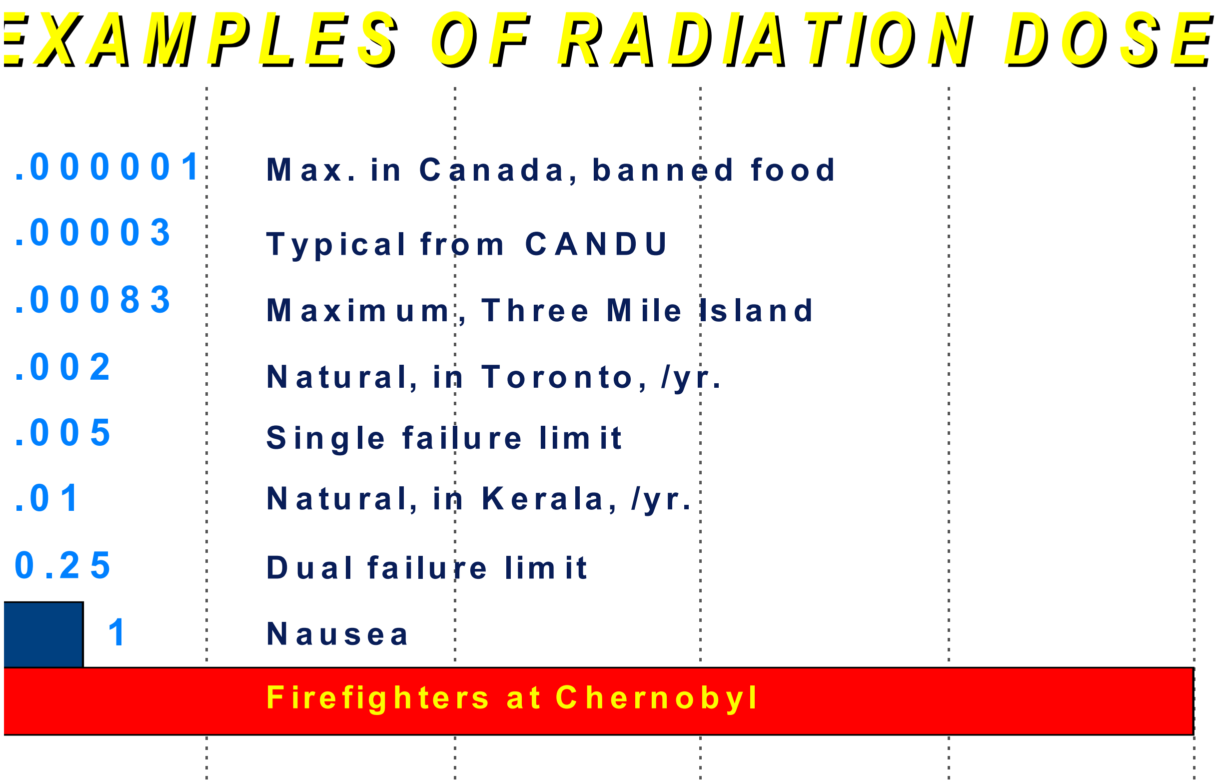


Figure 1-1

Global Dose vs. Time

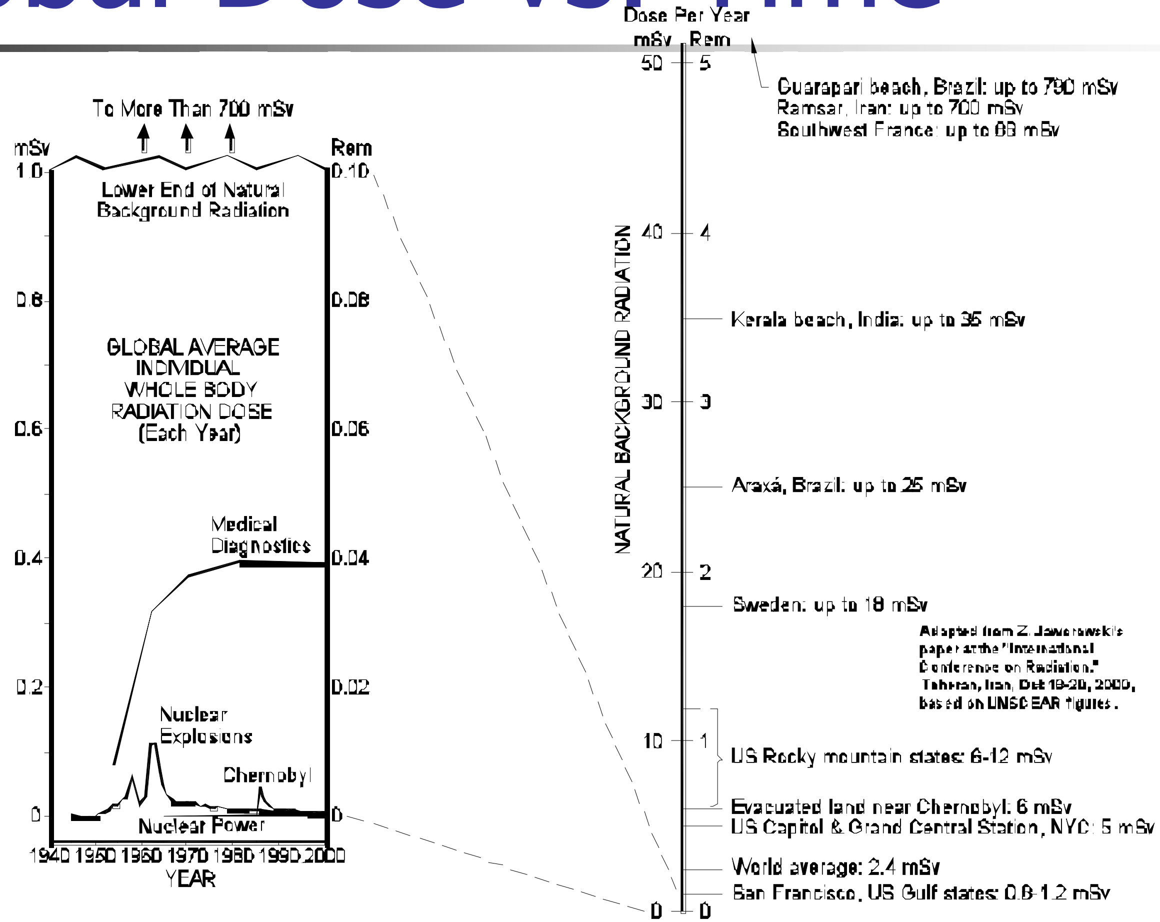


Figure 1-2 - Measures of Radiation Including Historical Weapons Fallout

Goal of Reactor Safety

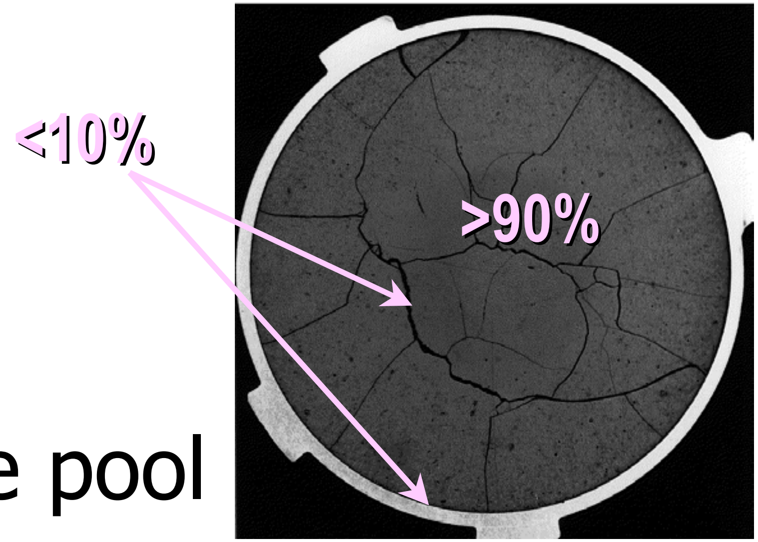
- To prevent prompt health effects with a high degree of assurance and minimize the risk of delayed effects

Sources of Radioactivity

- Fuel in core
  - Within fuel grains
  - In fuel-sheath gap
- Spent fuel in storage pool
- Tritium in coolant and moderator

$$D(n,p) + n \rightarrow T(2n,p) \xrightarrow{12\,years} D(n,p) + H(p) + e^{-}$$

- Carbon-14



Release of Radioactivity

- Fuel overheating
- Loss of coolant/moderator
- Mechanical damage
- Which category does Inadvertent Criticality fall into?

What Risk is Acceptable?

- Risk = Σ_i (frequency of event *i*) x (consequence of event *i*)^k
- *k* – Risk Aversion
- What is response to various levels of risk?

Table 1-1 - Acceptability of Risk

Annual individual fatality risk level	Conclusion
10^{-3}	This level is unacceptable to everyone. Accidents providing hazard at this level are difficult to find. When risk approaches this level, immediate action is taken to reduce the hazard.
10^{-4}	People are willing to spend public money to control a hazard (traffic signs/control and fire departments). Safety slogans popularized for accidents in this category show an element of fear, i.e., "the life you save may be your own".
10^{-5}	People still recognize these as of concern. People warn children about these hazards (drowning, firearms, poisoning). People accept inconvenience to avoid them, such as avoiding air travel. Safety slogans have a precautionary ring: "never swim alone", "never point a gun", "never leave medicine within a child's reach".
10^{-6}	Not of great concern to the average person. People are aware of these accidents but feel that they can't happen to them. Phrases associated with these hazards have an element of resignation: "lightning never strikes twice", "an act of G-d".

Optimized, not Minimized

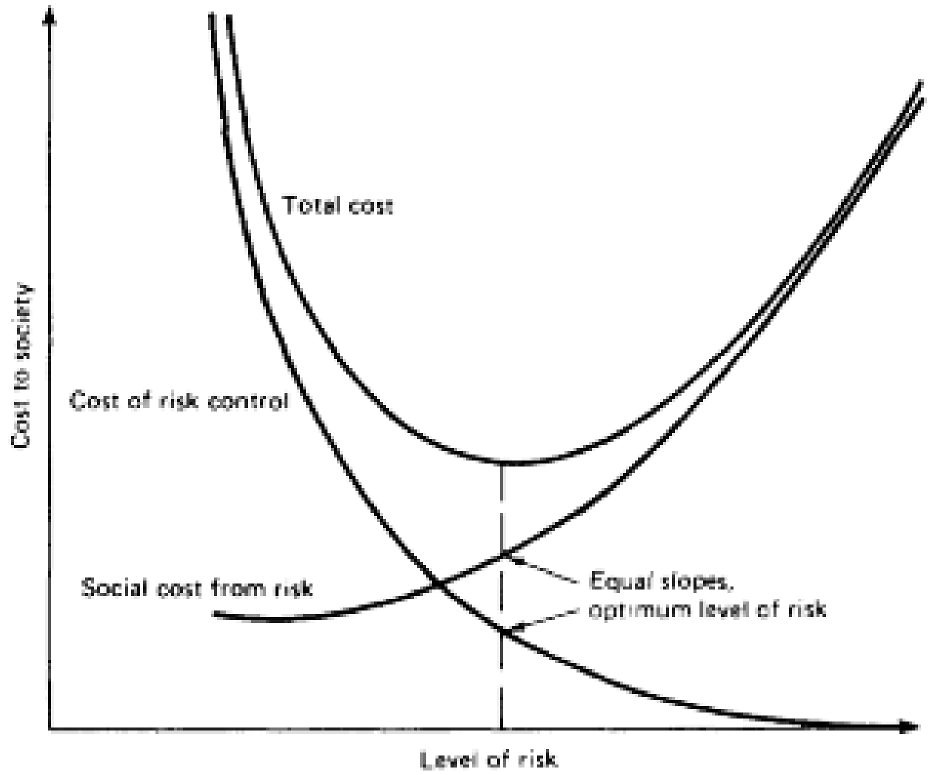


Figure 1-4 - Cost versus Risk

Treatment of Accidents

- Three approaches:
  - Eliminate accidents by **design rule**
    - E.g., Pressure vessel codes, earthquakes
  - Design safety systems from a **defined list** of accidents
    - Deterministic safety analysis
  - Design plant by selecting accidents of ‘**credible**’ frequency
    - Probabilistic Safety Analysis

Design Rule

- Pressure-retaining components
  - Rules based on experience of failures
  - Not much room for debate (or questioning)
  - Is Class III Nuclear really safer than Class 6?
- External Events
  - Design Basis earthquake, tornado, hostile event
  - What happens beyond that?

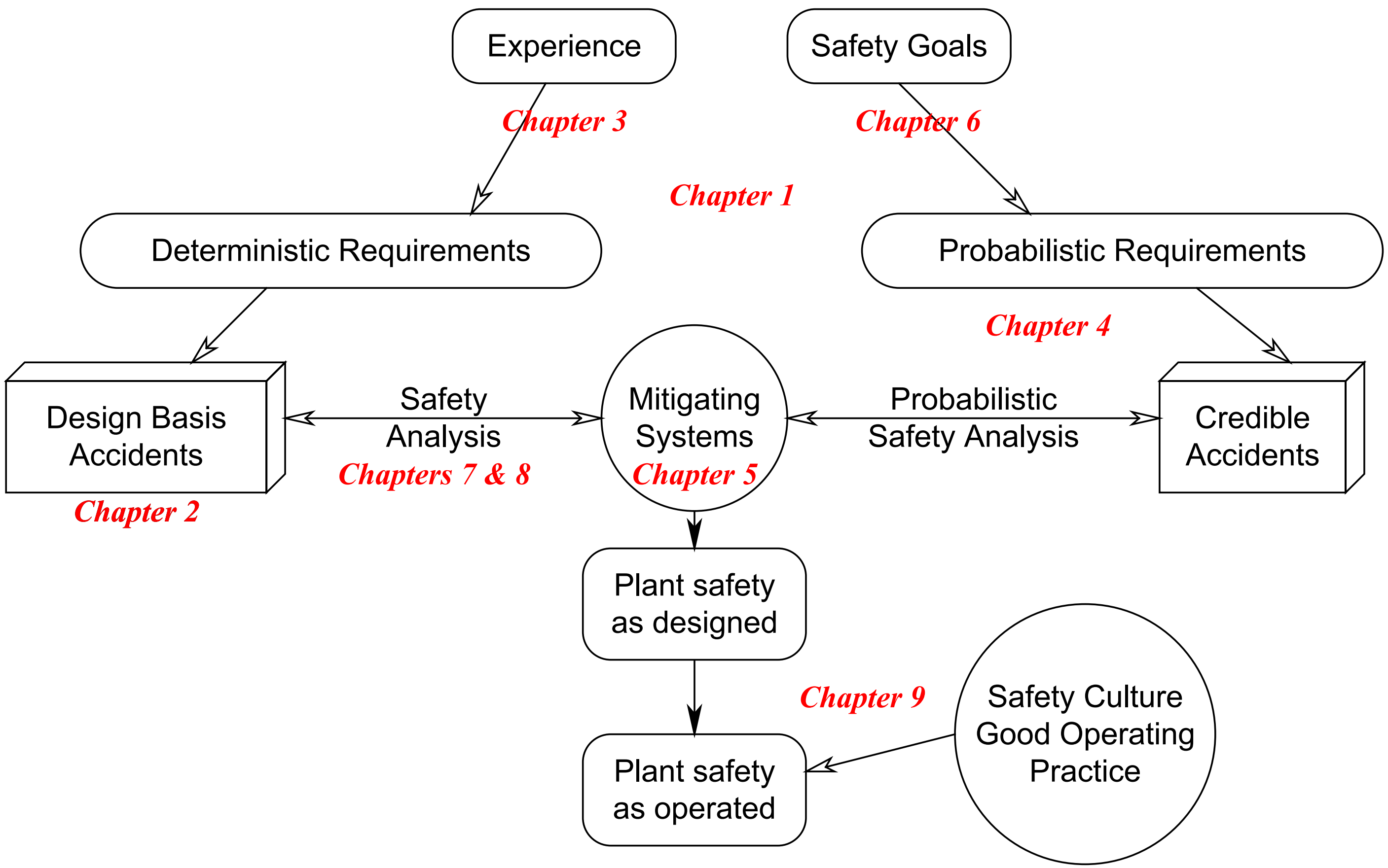
Design Basis

- List of events based on past experience and imagination
- Used for “design” of safety systems
- Rules for selection
- Rules for analysis
- Can something occur if it is not in the design basis?

Probabilistic Safety Analysis

- Define the acceptance criteria
- Generate a set of accidents to consider
- Predict the frequency of the event
- Show that the appropriate frequency-based criteria are met

Accident Analysis and Design



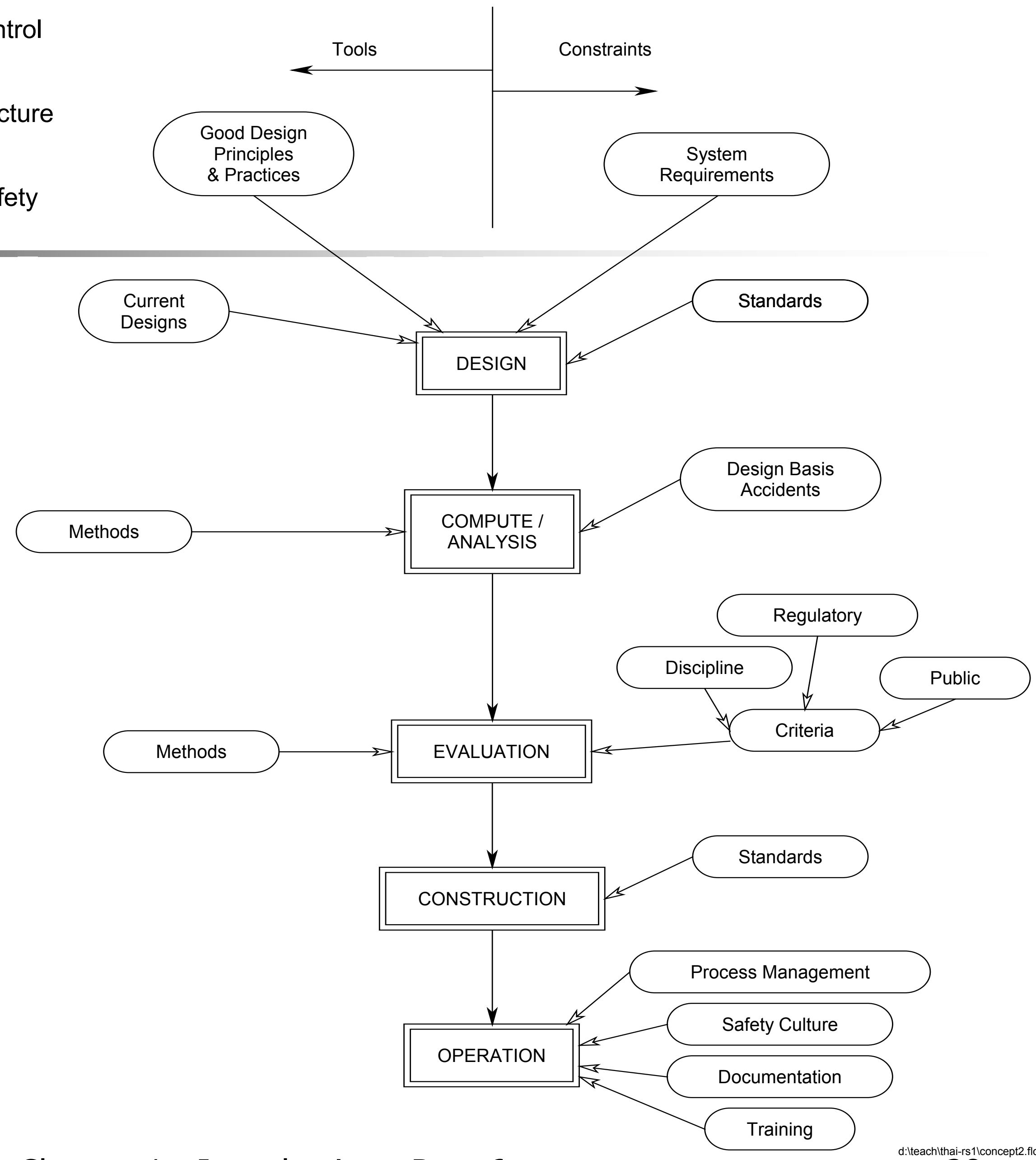
Design

process

control

structure

safety



Summary

- Hazard from nuclear plant is *radiological*
- Health Effects to people of release of radioactivity in most accidents are *random*
- Release of radioactivity caused by power-cooling mismatch
- Protection by rule, by list, or by credible frequency

Problem 1

A nuclear regulator is considering a high-level safety goal for new nuclear power plants in Canada. He proposes two requirements:

a. The risk to an individual close to the nuclear power plant of dying immediately from an accident must be less than 10^{-6} per year

b. The risk to an individual close to the nuclear power plant of getting cancer from an accident must be less than 10^{-5} per year.

Two nuclear power plants apply for a licence. They have done an accident analysis and the results are as follows:

For plant 1, there are no significant releases for any accident above a frequency of 10^{-7} per year. However there is an uncontained core melt at that frequency which gives a dose of 10 Sv to each individual in the nearby population.

For plant 2, two accidents are the major contributors to risk. One causes severe fuel damage but prevents core melt. It occurs at a frequency of 10^{-4} per year and gives a dose of 0.25Sv to each individual in the nearby population. The other is a core melt but it is contained - it occurs at a frequency of 10^{-6} per year and gives a dose of 1 Sv to each individual in the nearby population.

Determine numerically whether these plants meet either, both, or neither safety goal.

Hint: consider converting average dose to risk.

Problem 2

A nuclear designer is trying to optimize his design. He knows of an accident with a frequency of 10^{-7} per year which leads to a contained core melt and causes the following effects:

a. Permanent damage to the plant (i.e. cannot be recovered)
b. Evacuation of nearby people (5,000) for three days
c. No prompt fatalities
d. A collective dose to the closest population of 100 Sv

He can reduce the frequency (but not the consequences) of this accident by a factor of 10, by putting in an extra heat removal system, costing M$10 in capital costs and an extra $100,000 per year in maintenance and operating costs. How would you make this decision in an quantitative way?

Assignment

- Do questions 1,2,3,4,6

and

- Do question 15 *or* 17