Introduction to Radiation Safety for Engineers

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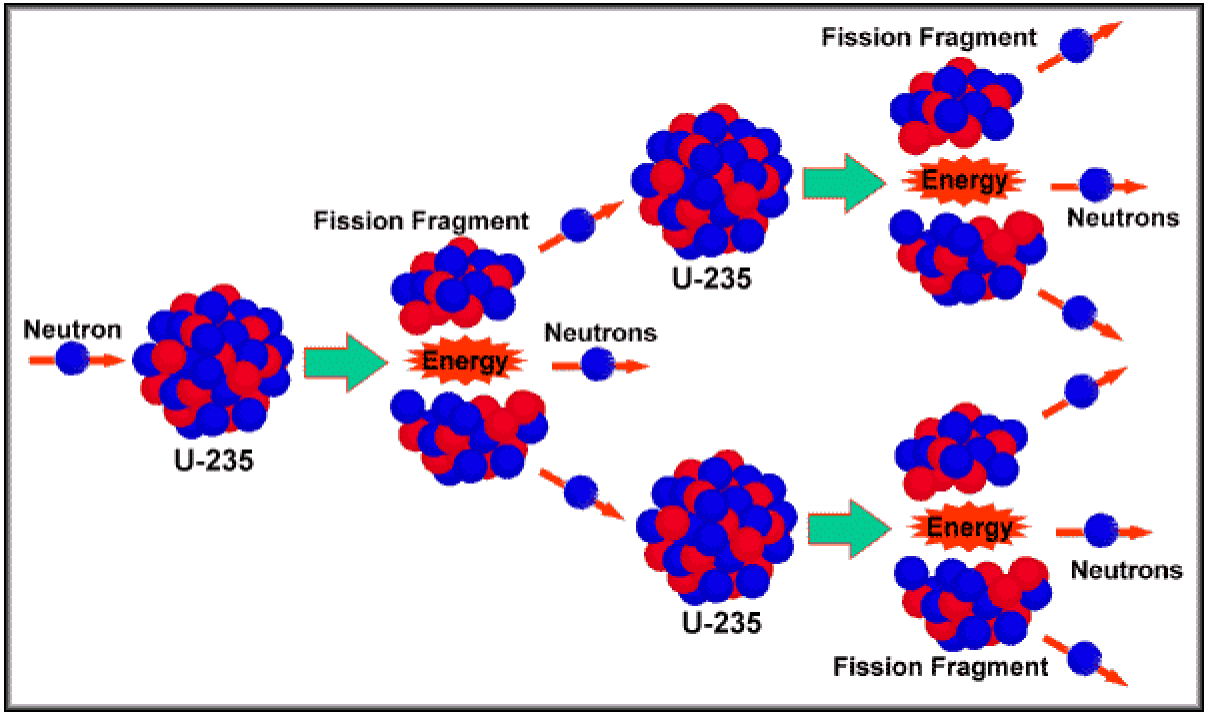
Outline

- **Background – nuclear reactor accidents**
- **Background radiation exposure**
- **Radioactivity**
- **Electromagnetic radiation (ionizing)**
- **Interaction of radiation with matter**
- **Principles of radiation safety**
- **Regulations and Limits**
- **Radiation Biology**

Nuclear Reactor Operations

- **Heat water**
- **Produce steam**
- **Drive turbines**
- **Drive generators**
- **Produce electicity**

Nuclear Fission



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1979

Three Mile Island Unit 2

Loss of coolant accident

Overheating of core – fuel cladding rupture

Release of radioactive gases

No deaths

No demonstrable long term health effects

Ohiocitizen.org

1984

Chernobyl Unit 4 (atomic pile)

Excessive heat ignited carbon blocks

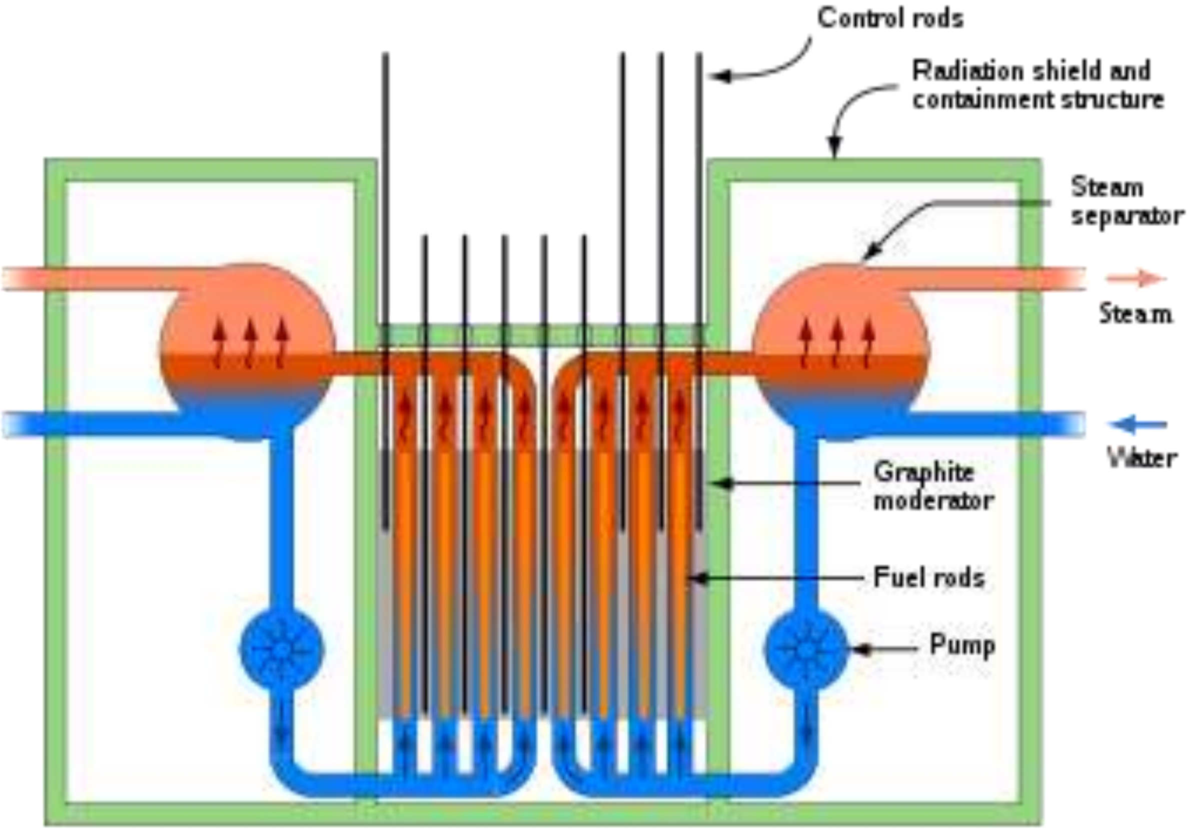
Release of radioactive gases

Evacuation/relocation 336,000 people

237 workers suffered acute health effects from radiation exposure, 31 died within three months

litzblog.com

Graphite Moderated Reactor



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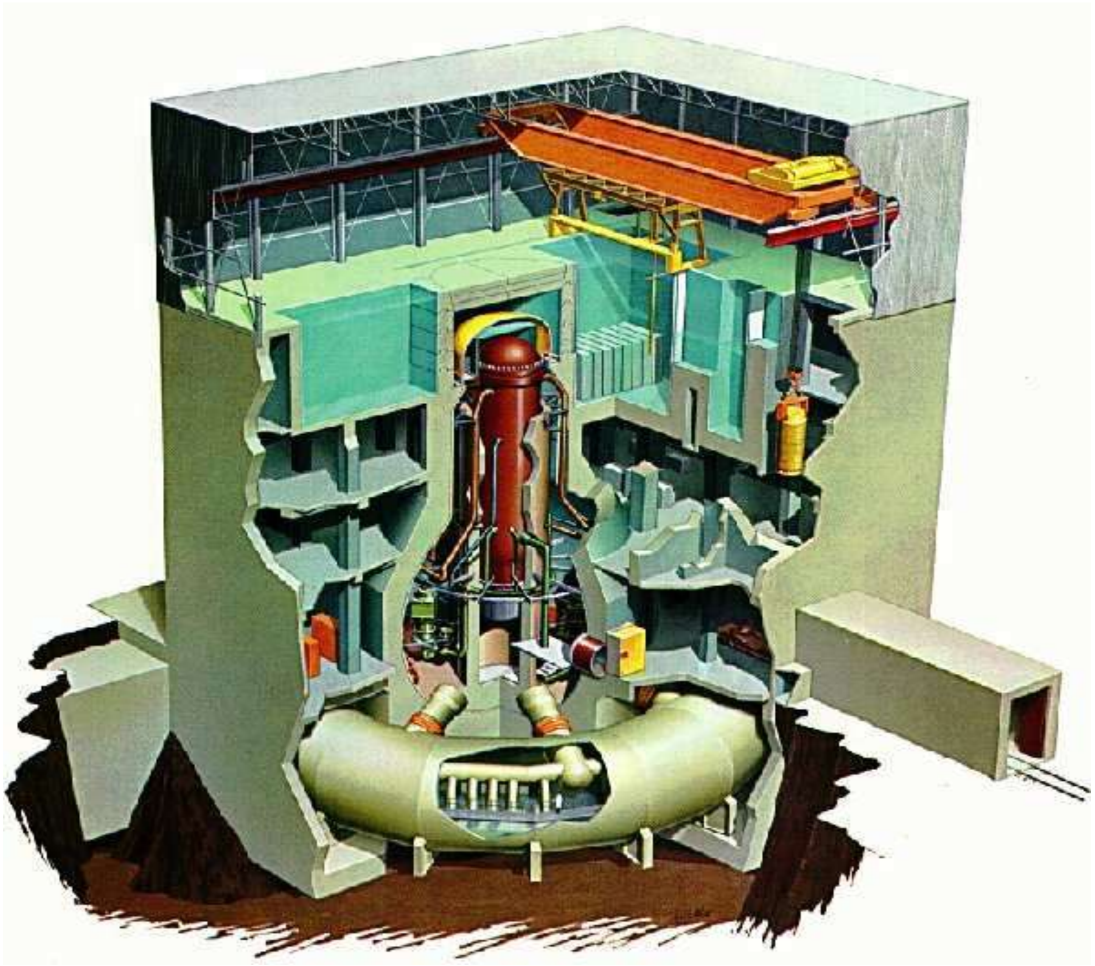
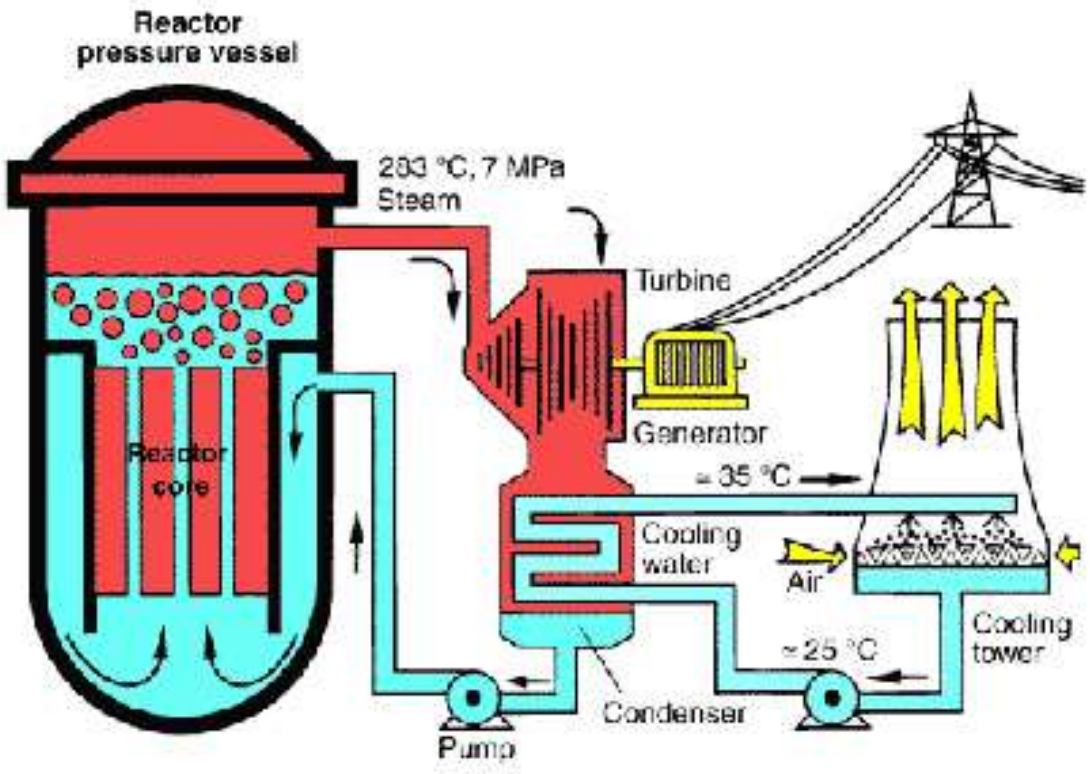
1986 reactor accident in the Ukraine was caused by human error

Fukushima Daiichi before the accident

GE BWR MARK 3 Design



Boiling Water Reactor



euronuclear.org

Major components of the reactor design are displayed below

Reactor Service Floor (Steel Construction)

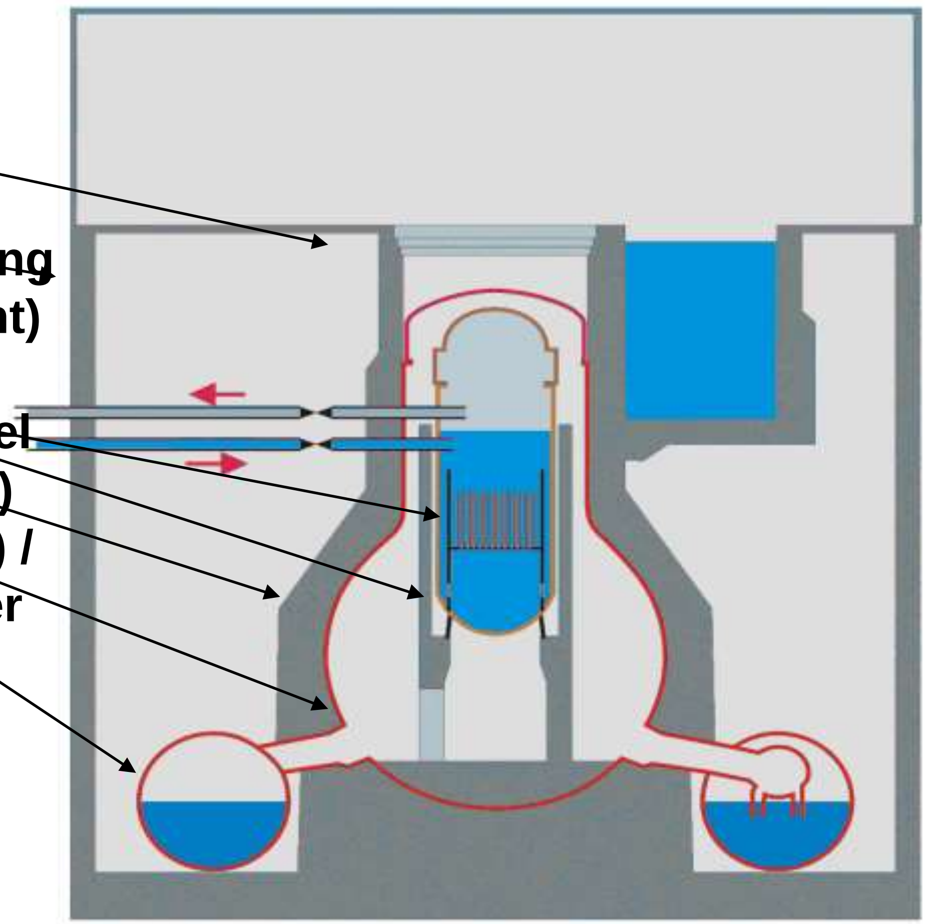
Concrete Reactor Building (secondary Containment)

Reactor Core

Reactor Pressure Vessel

Containment (Dry well)

Containment (Wet Well) / Condensation Chamber



Seawater enters the site

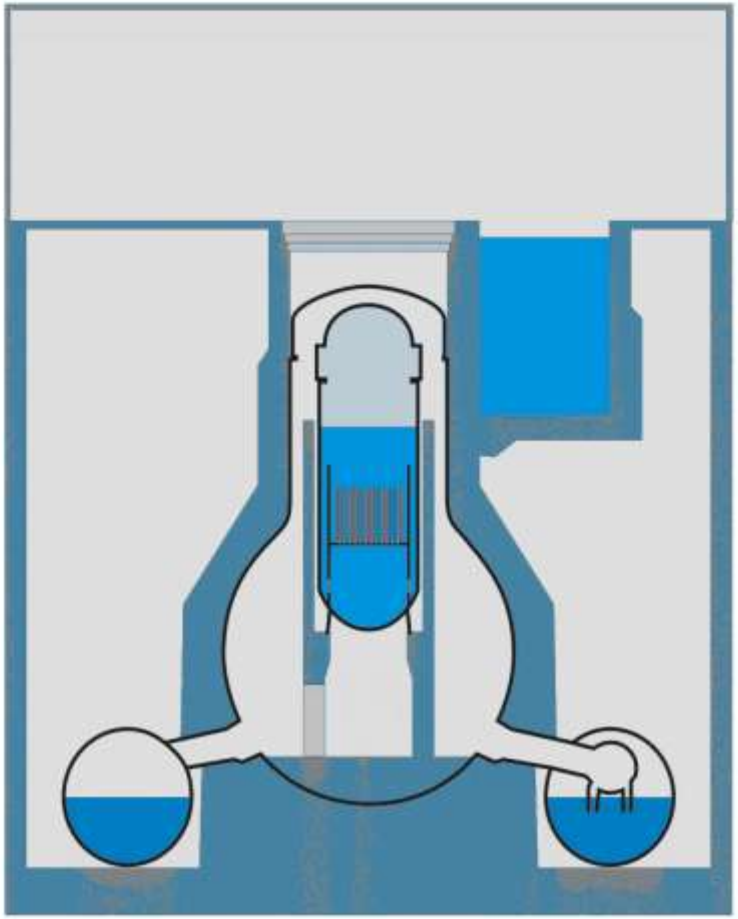
Key equipment is flooded

How did the Chernobyl releases compare to the first atomic bomb?

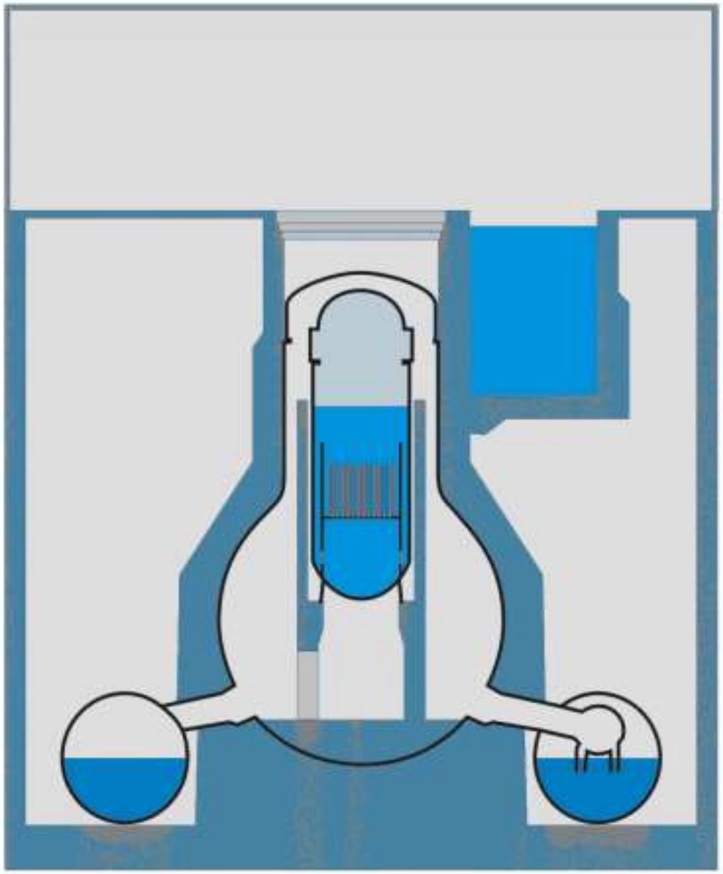
- **Isotope Ratio between the release due to the bomb and the Chernobyl accident**
- **90-Sr** 1:87
- **137-Cs** 1:890
- **131-I** 1:25
- **133-Xe** 1:31
- Fukushima is about 40% of the above values

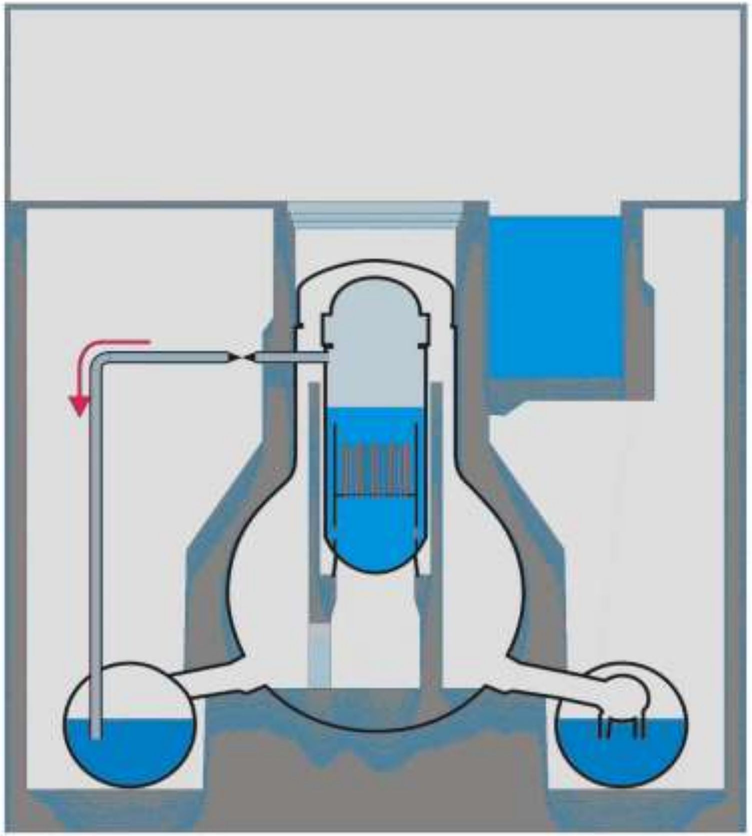
Impact of the Tsunami

March 11 @ 15:41 Tsunami hits the plant
Plant Design for Tsunami height of up to 21 feet (6.5 meters)
Actual Tsunami height > 24 feet (7m)
Flooding of the following:
· Diesel Generators and/or
· Essential SW building for cooling the generators
Station Blackout occurs.
Common cause failure of the power supply
Only Batteries are still available
Failure of all but one Emergency core cooling systems

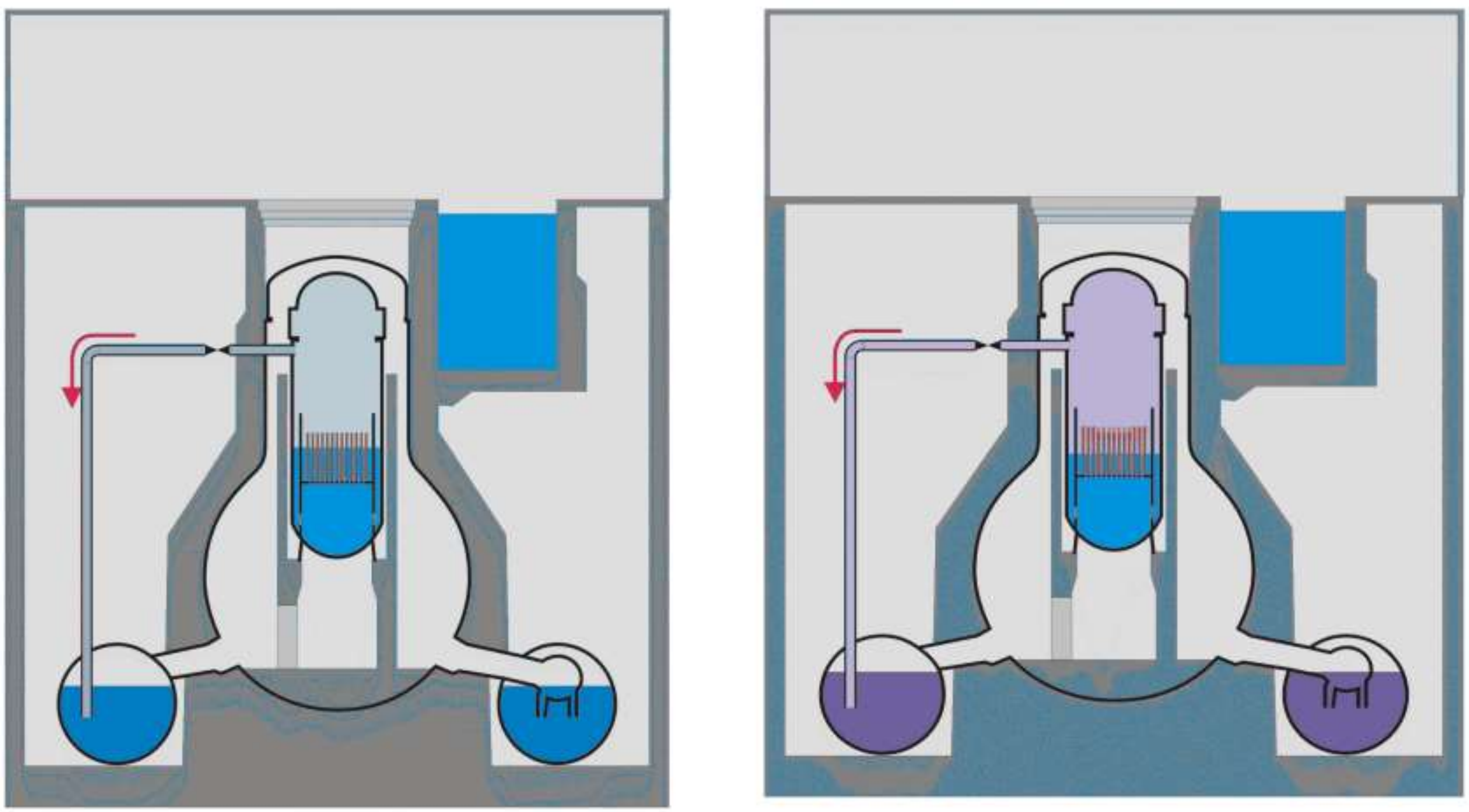


Water begins to be removed from the reactor vessel due to pressure build up





As water is removed, the temperature in the core increases, opening the steam relieve valves discharging steam into the Wet-Well



The core is exposed

At this time, it is thought that 3/4 of the core is exposed. Cladding exceeds ~1200° C. Zirconium in the cladding starts to burn under Steam atmosphere. The reaction is

$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$

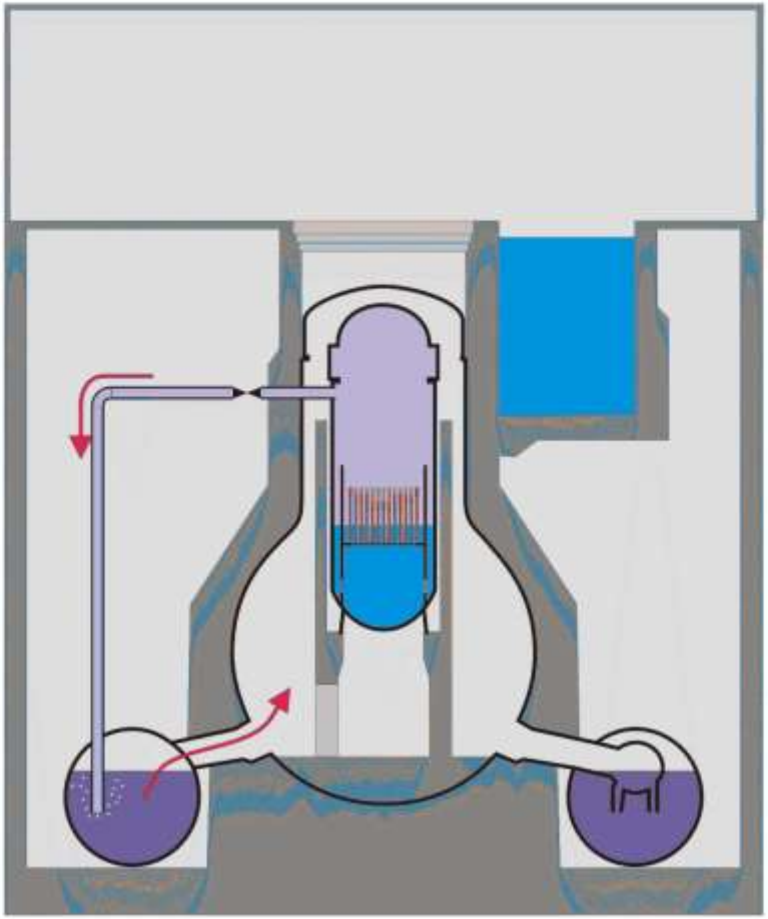
Exothermal reaction further heats the core.

Generation of hydrogen for the units is thought to be;

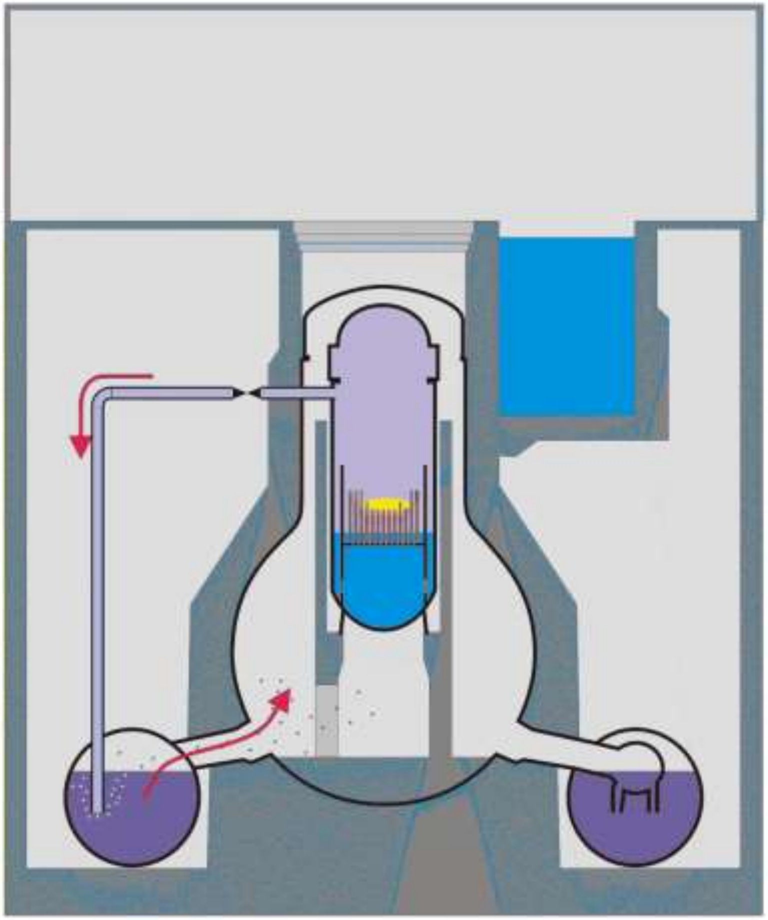
· Unit 1: 300-600kg

· Unit 2/3: 300-1000kg

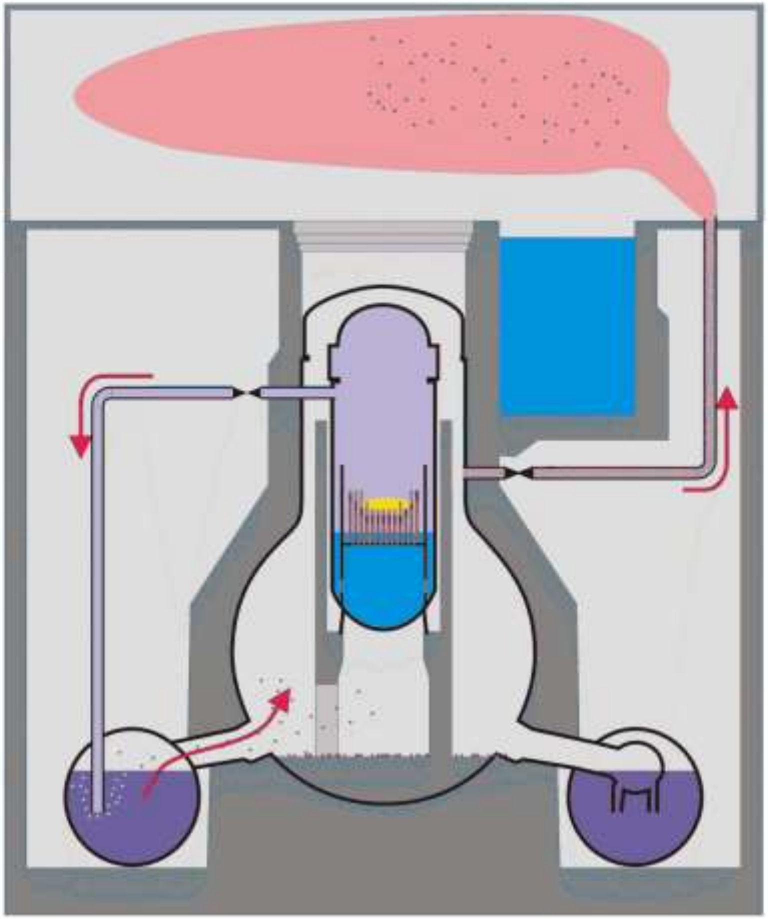
Hydrogen gets pushed from the wet-well, then the wet-well vacuum breakers into the dry-well.



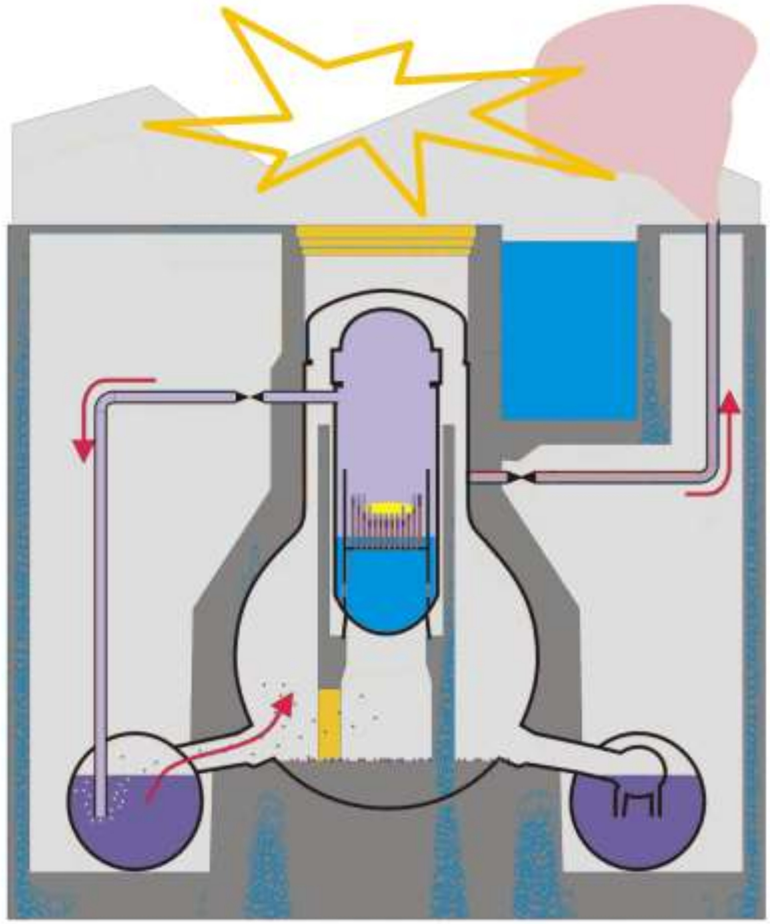
The release of fission products during melt down. This includes the Xenons, Cesium 134, 137, and the radio-Iodines, (~0.1%)



The release of activity begins, and hydrogen build up occurs in the reactor building. Hydrogen is flammable. There are no hydrogen recombining units at the Fukushima BWRs.

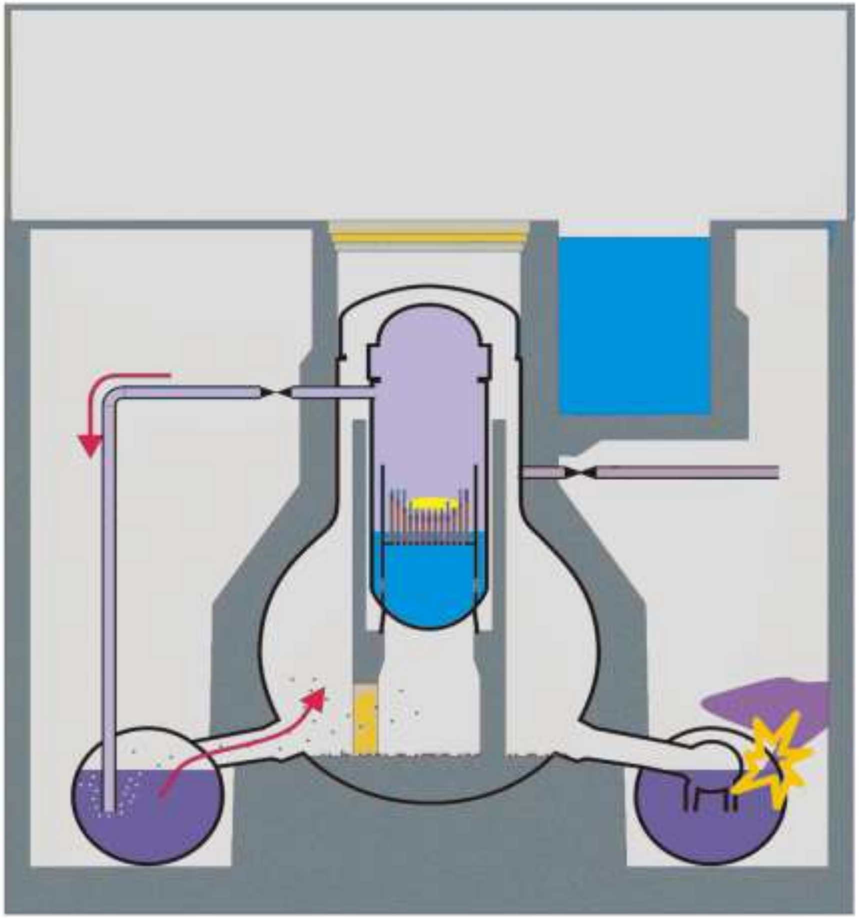


The hydrogen ignites, and no control mechanism for the release of fission products exists. Three out of four of the affected units suffer from a hydrogen explosion. One unit, which had a vent to the outside stuck open, does not explode. Unit 2 has an additional challenge.



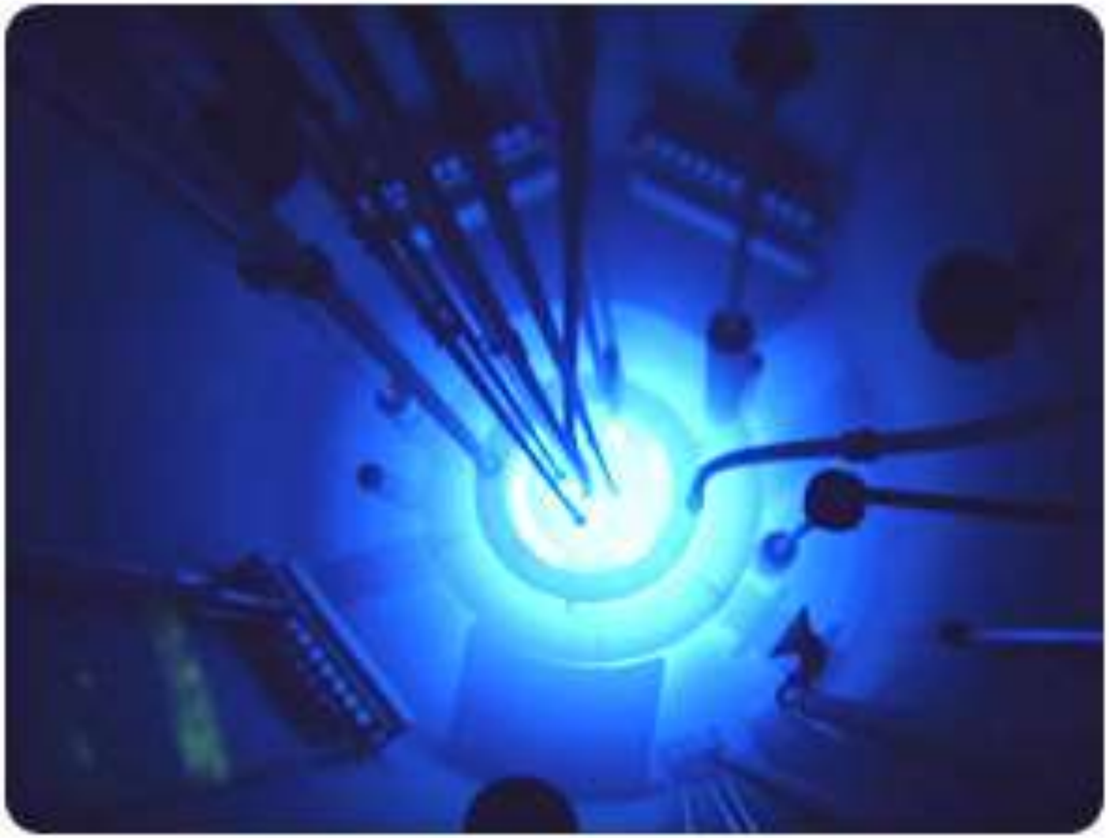
No clear information is available as to why Unit 2 behaved differently

- Hydrogen burn inside the reactor building
- Probably damage to the condensation chamber
- (highly contaminated water)
- Uncontrolled release of gas from the containment
- **Release of fission products**
- Temporary evacuation of the plant
- High local dose rates on the plant site due to wreckage hinder further recovery work



After the accident

Other images of the impact of the event



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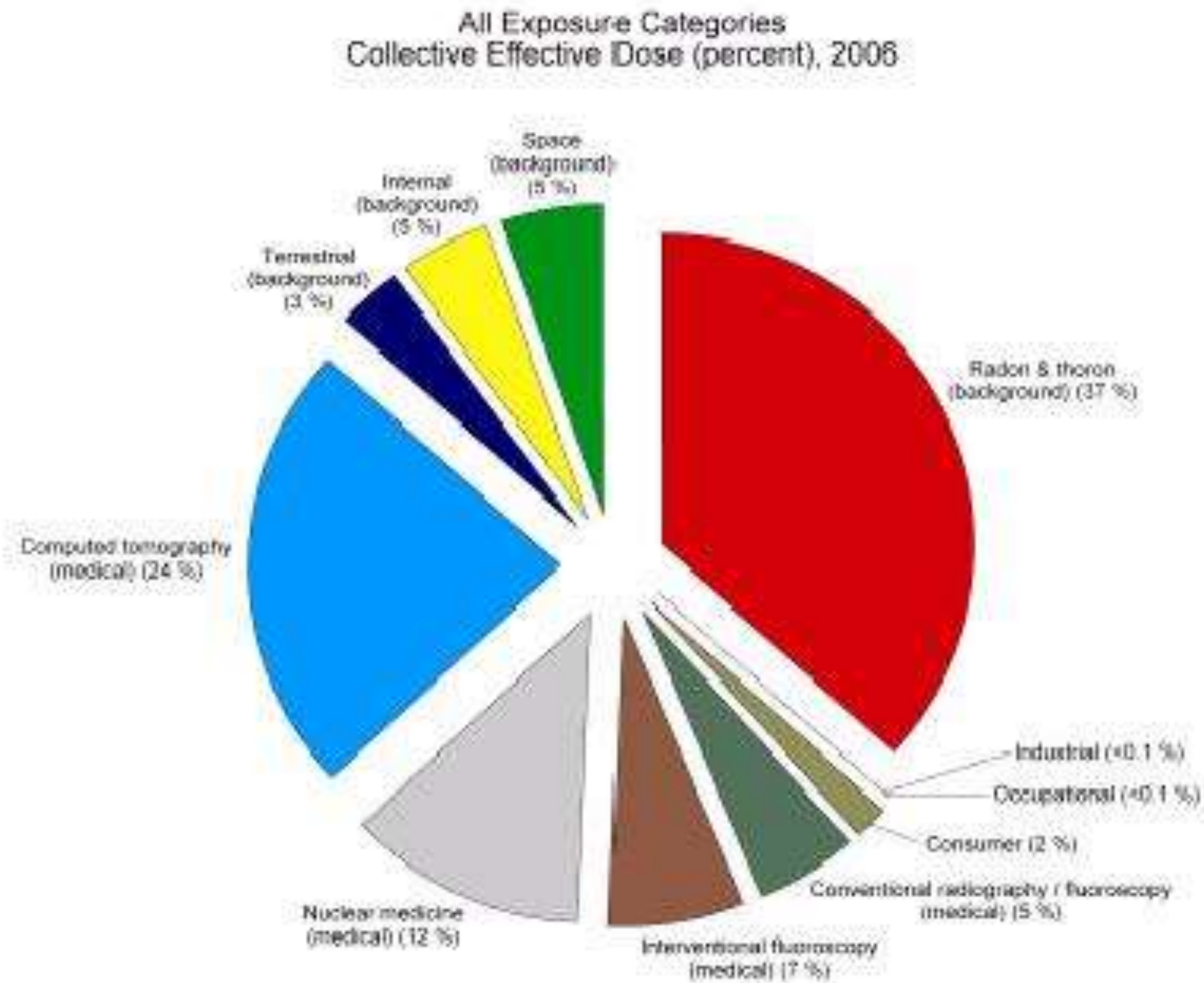
Radiation Safety

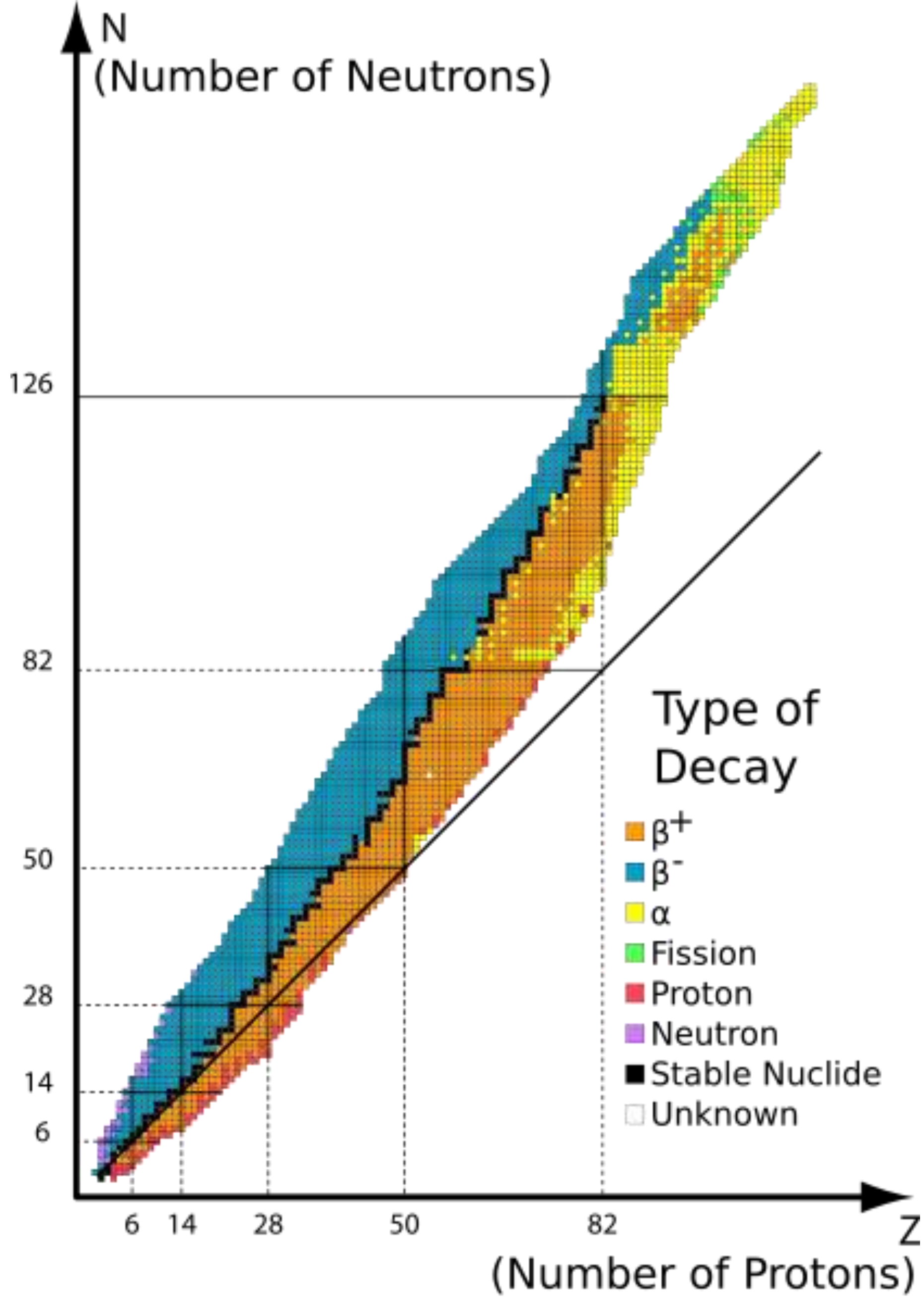
The discipline of protecting the public, employees and patients from excessive and/or unnecessary exposure to ionizing radiation by

- **Continuously assessing the risk**
- **Applying best practices to reduce risk**
- **Constantly monitoring processes to ensure risks are reduced as low as possible**


All Exposure Categories
Collective Effective Dose (percent), 2006
Space (background) (5 %)
Internal (background) (5 %)
Terrestrial (background) (3 %)
Radon & thoron (background) (37 %)
Computed tomography (medical) (24 %)
Industrial (<0.1 %)
Occupational (<0.1 %)
Consumer (2 %)
Conventional radiography / fluoroscopy (medical) (5 %)
Nuclear medicine (medical) (12 %)
Interventional fluoroscopy (medical) (7 %)

Radioactivity

- Isotope – combination of protons and neutrons. All the isotopes of an element contain the same number of protons
- Most are unstable – 256 stable, >1400 unstable
- Instability causes transformation (decay)
  - Neutron decays to proton and electron
  - Proton combines with electron to form neutron
  - Nucleus expels α particle (He nucleus)
  - Nucleus spontaneously fragments (fission)


N
(Number of Neutrons)
126
82
50
28
14
6
6
14
28
50
82
Z
(Number of Protons)
Type of Decay
β+
β-
α
Fission
Proton
Neutron
Stable Nuclide
Unknown

wikipedia

Particulate Radiation

- Electrons – positive or negative
- Neutrons
- Protons
- Alpha particles
- Nuclear fragments

Units

- Curie (Ci) – the amount of an isotope that has a decay rate of 37 billion decays per second (dps)
- Becquerel (Bq) – the amount of an isotope that has a decay rate of 1 decay/sec
- Use the "typical" modifiers (m, k, M, μ, etc)

Half-life measurement

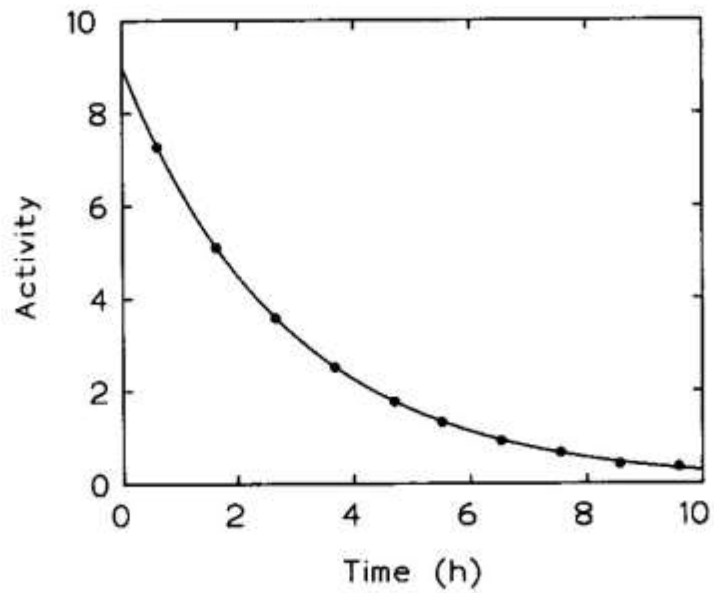


Figure 5.15. The activity of a radioactive sample with a half-life of two hours. At any time on the exponential curve, the activity is one-half of the activity two hours earlier.

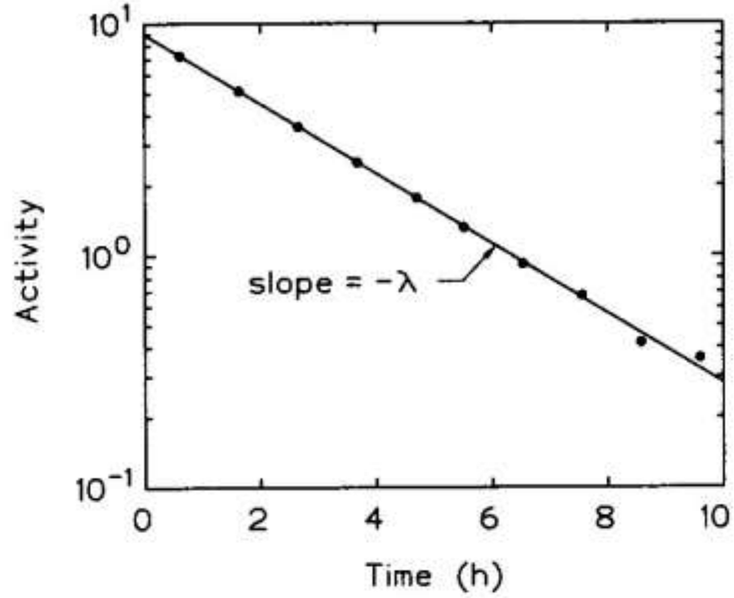
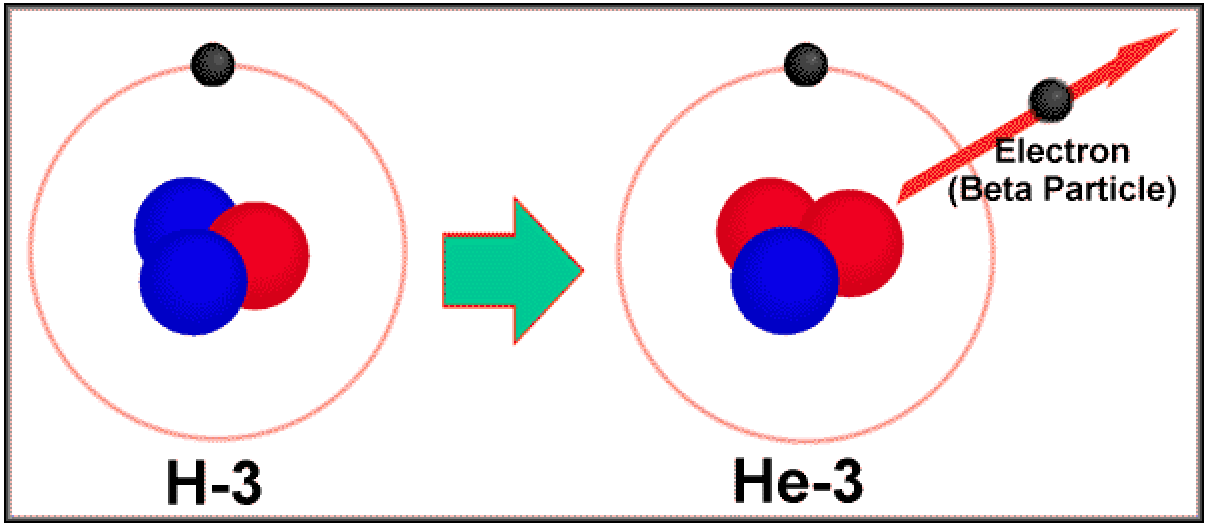


Figure 5.16. Semilog plot of the decay of the sample's activity. The decay curve is a straight line with a slope of $-\lambda$, from which the half-life $T_{1/2} = \ln 2/\lambda$ can be calculated.

Beta Decay



N -> P^+ + e^-

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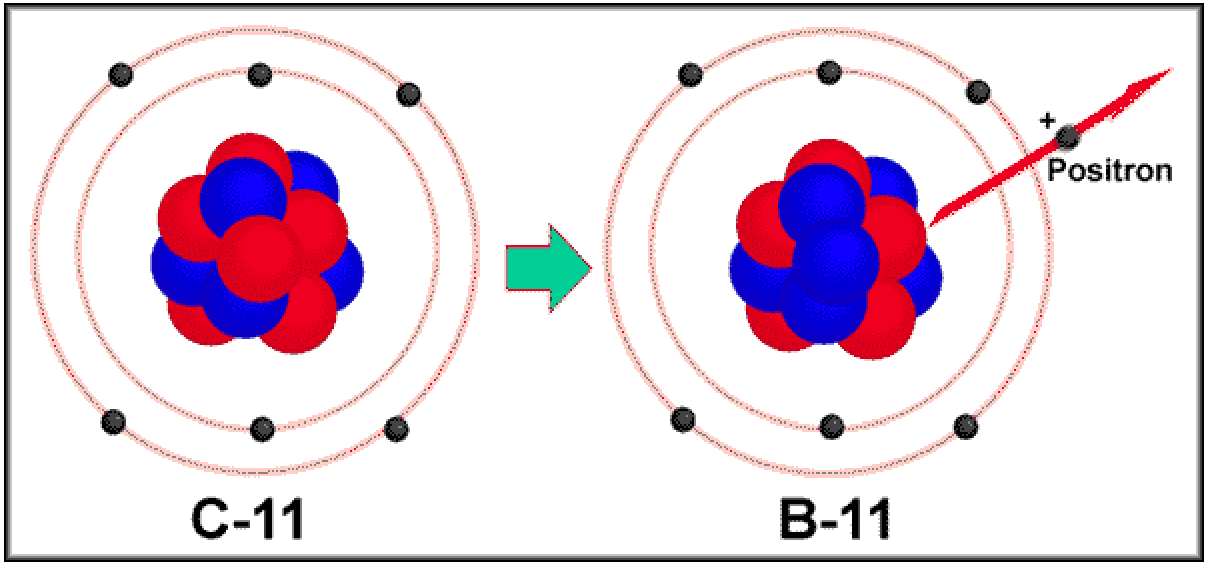
Positron (beta$^+$) Decay



$P^+ + e^- \rightarrow N + e^+$

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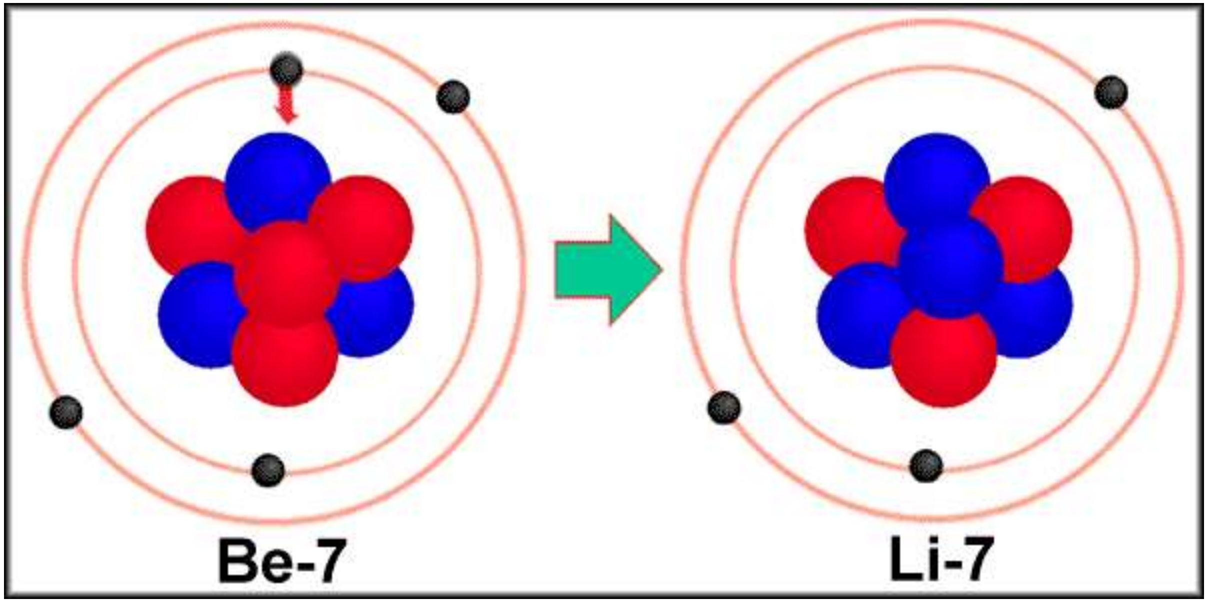
Electron Capture Decay



$P^+ + e^- \rightarrow N$

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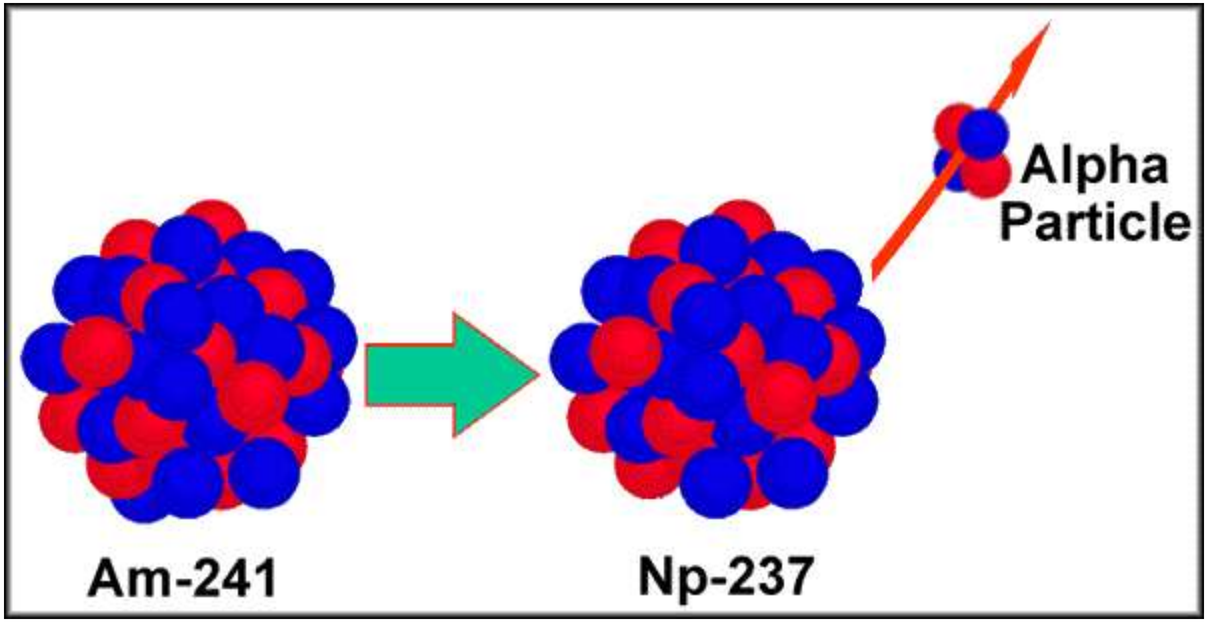
Alpha Decay



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Radioactive decay equation

$$-dN = \lambda N(t)dt$$

$$\frac{dN(t)}{dt} = -\lambda N(t).$$

$$\boxed{N(t) = N_o e^{-\lambda t},}$$

Other Necessary Constants

- $A = N\lambda$ (Activity equals the number of atoms x the decay constant).
- Specific Activity, (Curies per gram) is defined as:

$$\frac{1 \text{ gm} \times 6.0\text{E}{+}23 \text{ atoms/mole} \times \lambda \times 1 \text{ Ci}/3.7\text{E}{+}10}{\text{grams/mole}}$$

Examples

- 1 gram of Co-60 =

$$\frac{6.02E+23 \text{ atoms/mole}}{60 \text{ grams/mole}} = 1E+22 \text{ atoms}$$

A = Nλ

A = 1E+22 atoms x 0.693/(5.27 yrs x 7.6E+8 sec/yr) =

1.74E+12 dis/sec per gram

or

1.74 E+12 Bq, or

47 Curies

Typical references on photon energy and half life; Rad Health Handbook, 1970

MeV	Nuclide	Half-Life	Production cross section* (barns) or fission yield (%)	Yield† (%)	Daughter
0.658	Ag-110	24.4s	89b	4.5	Cd-110‡
0.662	Cs-137--	30y	5.9%	85	---
	Ba-137m	2.55m	---	---	Ba-137‡
1.173	Co- 60	5.26y	19b	100	Ni- 60‡
1.21	Y - 91	58.8d	5.9%	0.3%	Zr- 91‡
1.275	Na- 22	2.60y	---	100	Ne- 22‡
1.308	Ca- 47	4.53d	0.3b	74	Sc- 47
1.332	Co- 60	5.26y	19b	100	Ni- 60‡
1.35	Mg- 28	21h	---	70	Al- 28
1.369	Na- 24	15.0h	0.53b	100	Mg- 24‡

What is the impact of 1 gram of Co-60?

- To convert activity to dose, we use a simplified equation:
- Dose (rem/hr at one foot) =

  6 x Activity (in Curies) x total energy (in MeV)

  47 Ci x 2.5 MeV = 705 rem/hr @ one foot (7.05 Sv/hr).

  450 rem (4.5 Sv) is considered a lethal exposure.

Transient Equilibrium equation, necessary for nuclear medicine

$$N_1(t) = N_1(0)e^{-\lambda_1 t}.$$

$$N_2(t) = N_2(0)e^{-\lambda_2 t} + \frac{\lambda_1 N_1(0)}{\lambda_2 - \lambda_1}[e^{-\lambda_1 t} - e^{-\lambda_2 t}].$$

Solution

- Since $A = N\lambda$, we need to multiply both sides of the equation by $\lambda_{(2)}$ or 0.693/6 hrs = 0.116 hr^{-1}

- Let t = 12 hrs, and initial Mo-99 activity = 100 GBq

$$A_2 = \frac{\lambda_2 100\ \text{GBq}}{\lambda_2 - \lambda_1} \left(e^{-(\lambda_1 t)} - e^{-(\lambda_2 t)}\right)$$

A_2 = 70 GBq of Tc-99m

Application

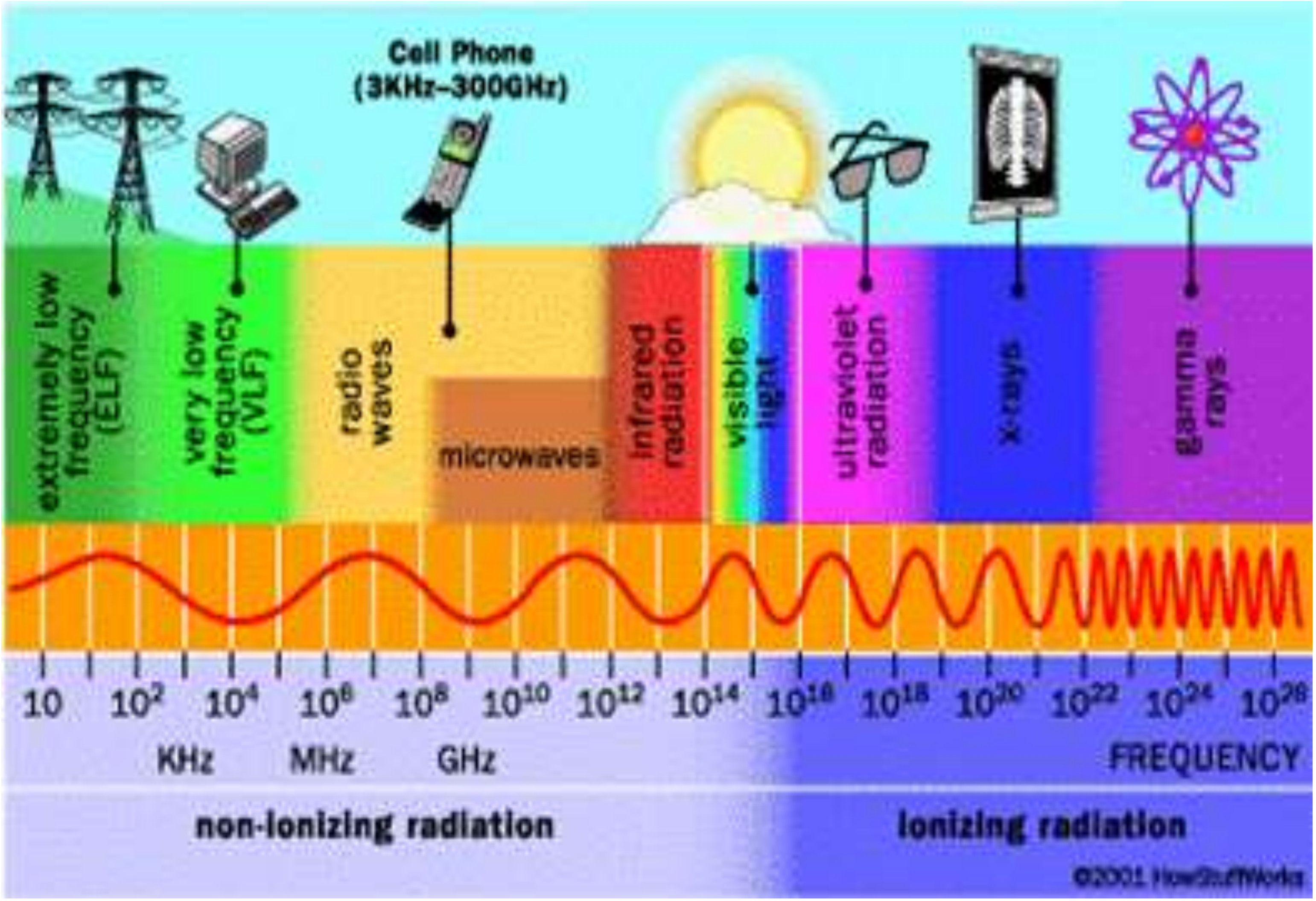
- Decaying a long-lived parent to a short-lived daughter as a generator
- Medical isotopes
- ^{99}Mo ($T_{1/2}$ = 65.6 h) / ^{99m}Tc($T_{1/2}$ = 6.01 h)
- Pass saline solution through aluminum oxide column containing ^{99}Mo

In nuclear power, (From the RHH, 1970 edition, pp: 309,310) Ce-144 an indicator of failed fuel

Ce^{144}	284 d (FlyK65a) 285 d (SchumR56, MerW57) 277 d (EasH60) others (BurgW51a, JoliF44)	♈ β^- (HahO40c) Δ −80.49 (MTW) σ_c 1.0 (GoldmDT64)	A chem (HahO40c) chem, mass spect (HaydR48) parent Pr^{144} (HahO43a, NewA51a) descendant Xe^{144} (DilC51)	β^- 0.31 max e^- 0.038, 0.092 γ Pr X-rays, 0.080 (2%), 0.134 (11%) daughter radiations from Pr^{144}	fission (HahO40c, BornH43a, DilC51a, NewA51a, BurgW51a, GrumW48, FinB51c)
Pr^{143}	13.59 d (PepD57) 13.76 d (WriH57) 13.6 d (HoffD63) others (FelL49, BallN51f, RoyL56, PoolM48, MartiDW56)	♈ β^- (BallN51e, JoliF44) Δ −83.11 (MTW) σ_c 89 (GoldmDT64)	A chem (BallN51e, JoliF44) mass spect (HaydR46a) daughter Ce^{143} (PoolM43, BotW46a, BallN51d) others (HahO43a, FinB51c)	β^- 0.933 max average β^- energy: 0.31 calorimetric (HovV64) γ no γ	$Ce^{142}(n,\gamma)Ce^{143}(\beta^-)$ (PoolM43, BotW46a, BallN51d) fission (HahO43a, JoliF44, BallN51e, FinB51c)
Pr^{144}	17.27 m (PepD57) 17.30 m (HoffD63) others (NewA51a, SeiJ51b, HahO43a, GrumW46)	♈ β^- (NewA51a) Δ −80.81 (MTW)	A chem, genet (NewA51a, HahO43a) daughter Ce^{144} (HahO43a, NewA51a)	β^- 2.99 max γ 0.695 (1.5%), 1.487 (0.29%), 2.186 (0.7%)	daughter Ce^{144} (HahO43a, NewA51a)

Electromagnetic Radiation (Ionizing)

- **Photons of sufficient energy to ionize atoms**
- **Gamma rays – from the nucleus**
- **X rays – from the atom**
- **Energy unit – electron volt (eV) – kinetic energy acquired by an electron upon acceleration through a potential difference of 1 volt**
  - **1 eV = 1.6021 x 10^{-19} j**


Cell Phone
(3KHz–300GHz)
extremely low frequency (ELF)
very low frequency (VLF)
radio waves
microwaves
infrared radiation
visible light
ultraviolet radiation
X-rays
gamma rays
10 10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16} 10^{18} 10^{20} 10^{22} 10^{24} 10^{26}
KHz MHz GHz
FREQUENCY
non-ionizing radiation
ionizing radiation
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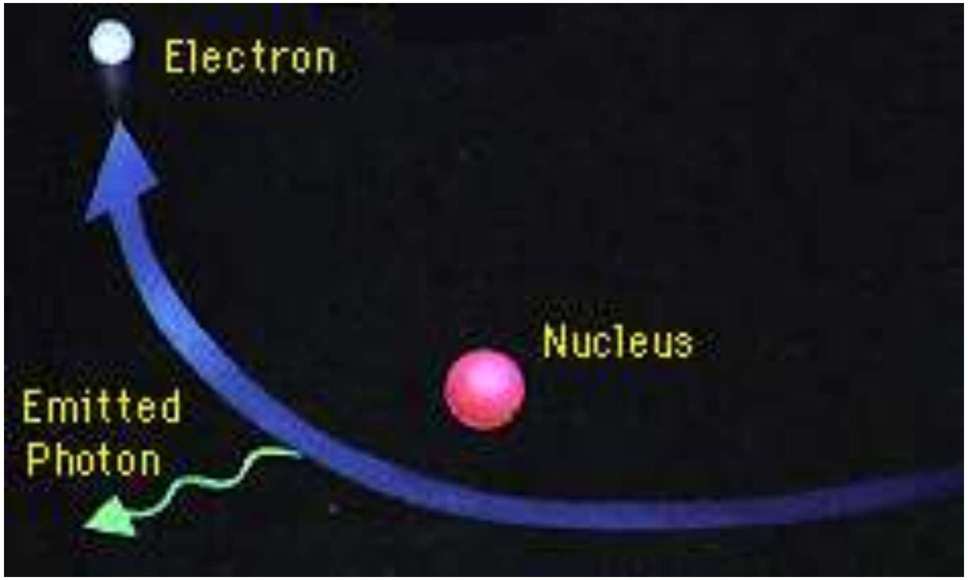
kmvtech.com

Electromagnetic Radiation

- Gamma rays – energy transitions in nucleus during decay
- X rays



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Interaction of Radiation with Matter

- **Collisions with atomic electrons**
- **Interaction with nuclear field**
- **Absorption by nucleus**

Photoelectric Effect

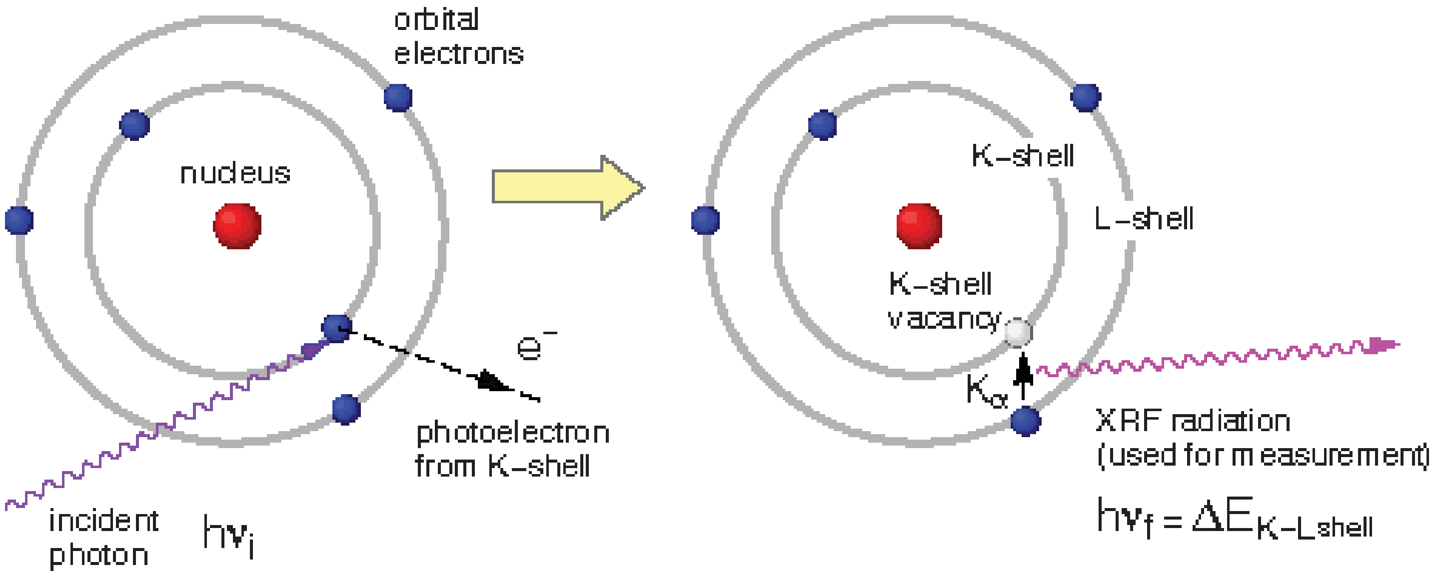
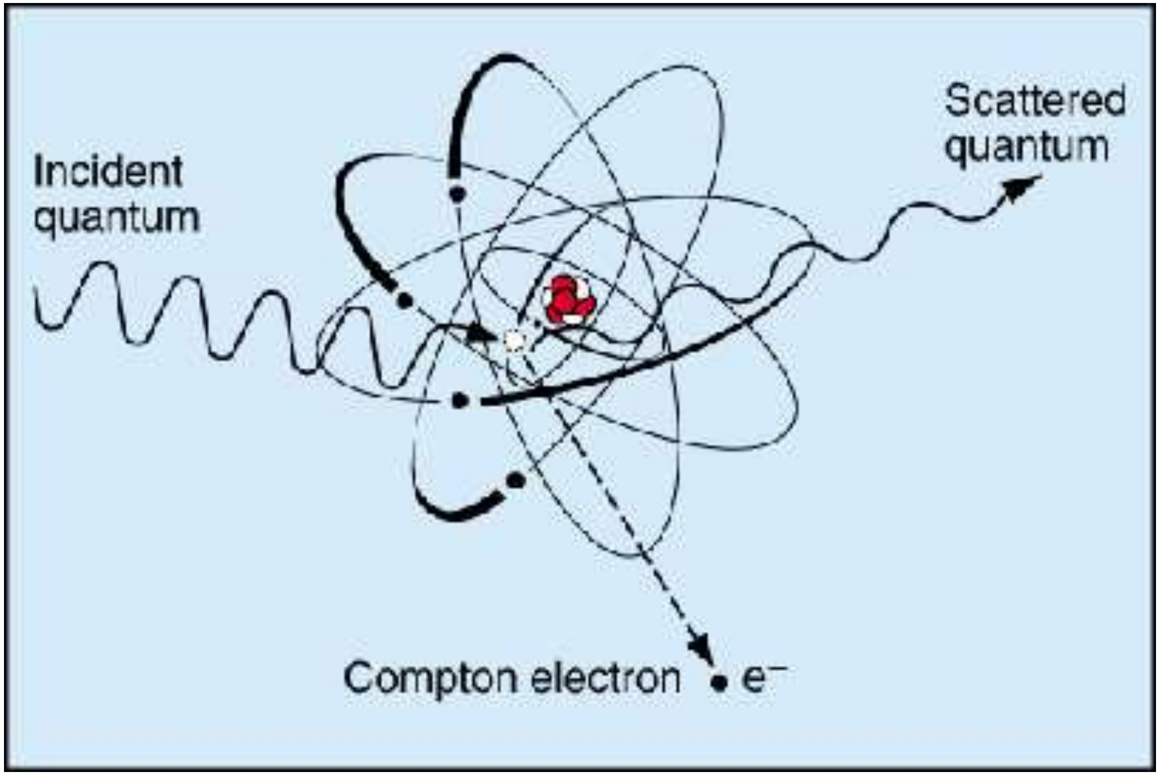


Fig. 1: Generation of XRF radiation by photoelectric effect

Thermo.com

Compton Effect



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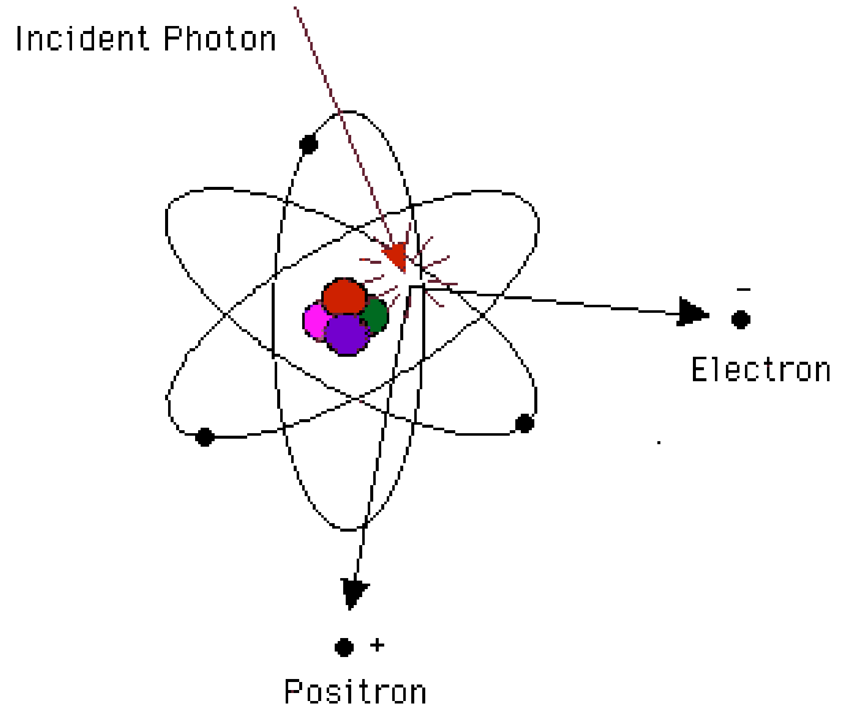
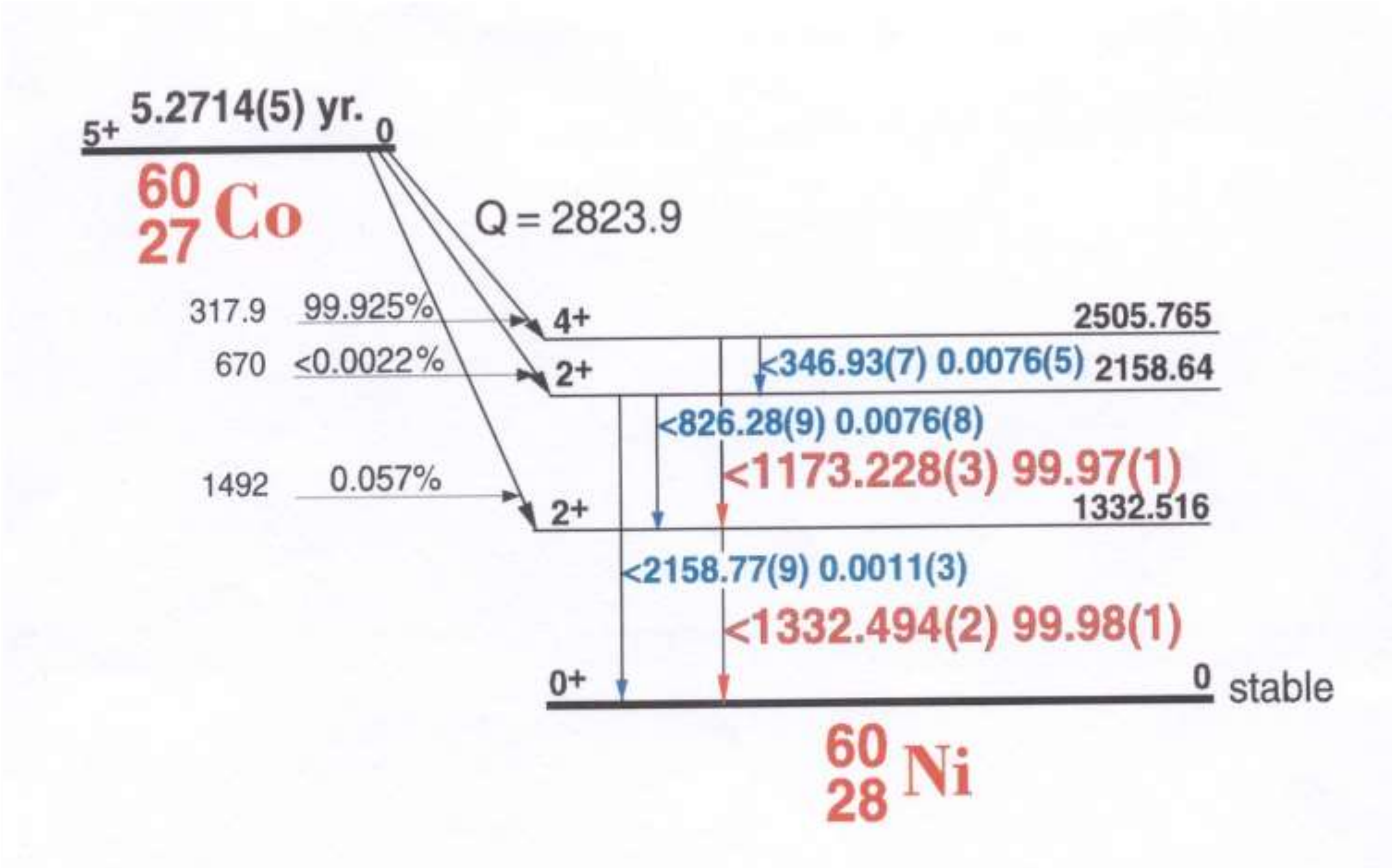
Pair Production

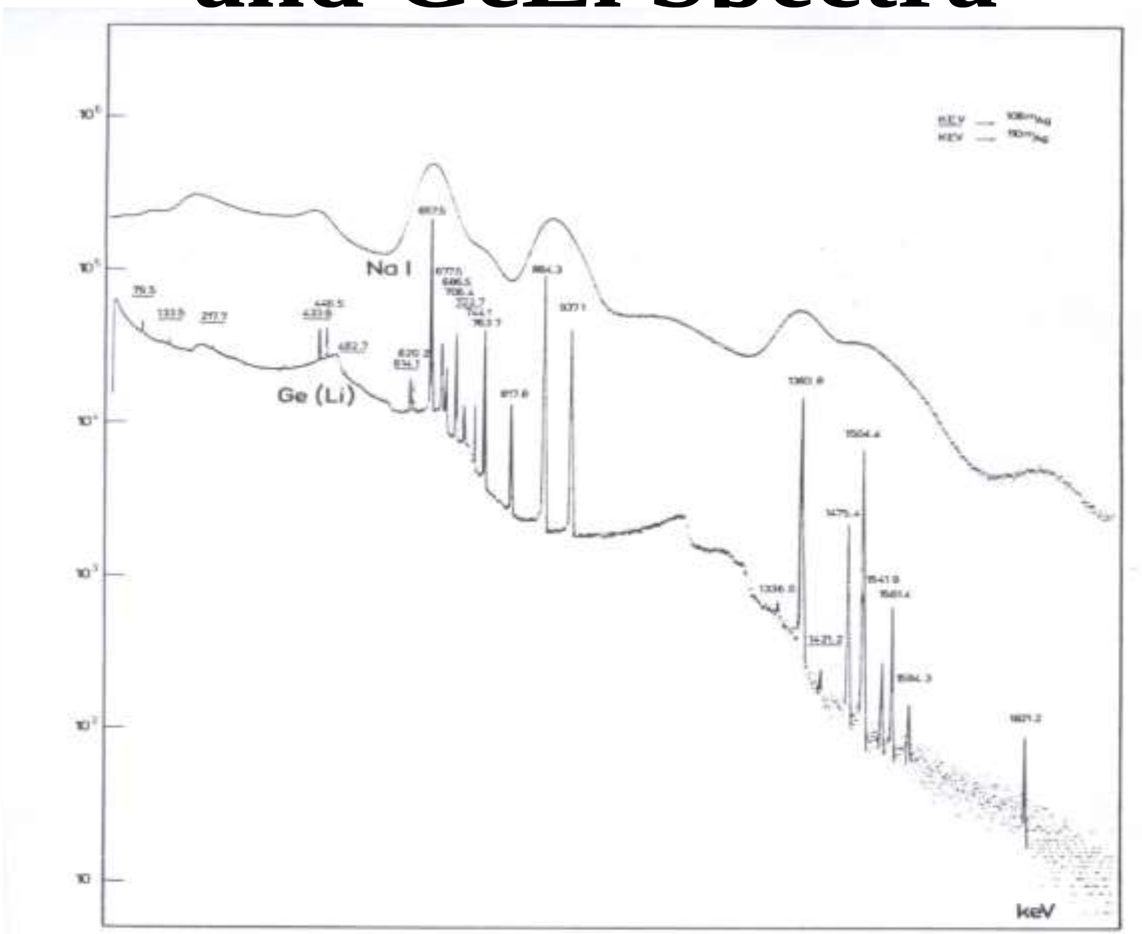


Internaldosimetry.com

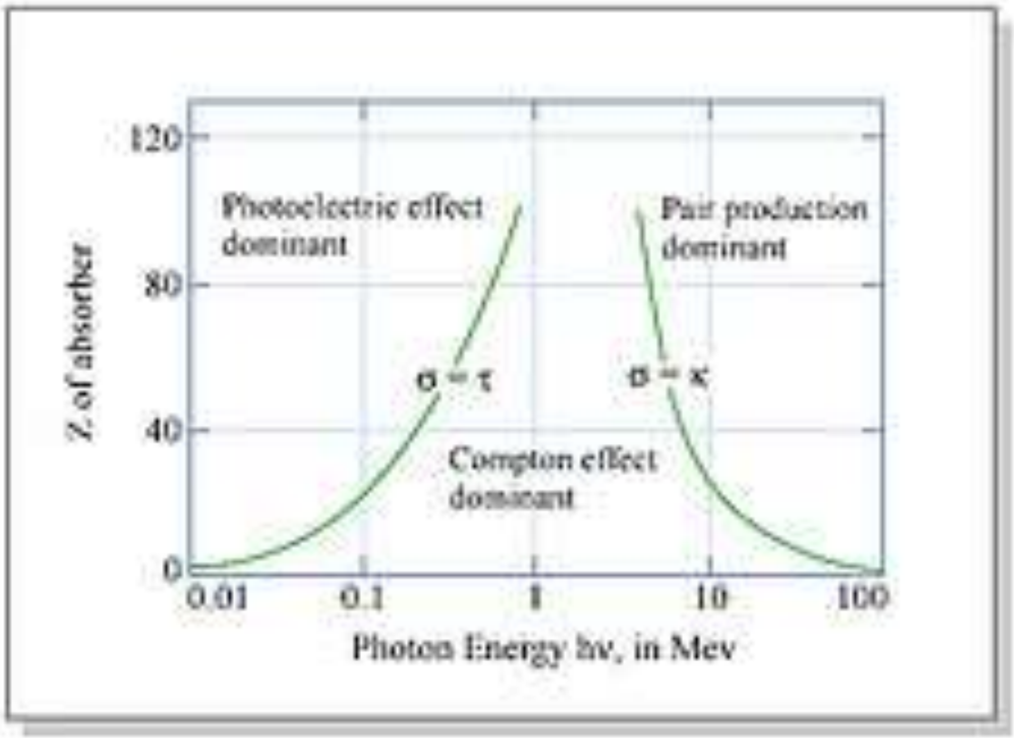
Co-60 Decay Scheme



Comparison of NaI(Tl) and GeLi Spectra



Energy Transfer Mechanisms



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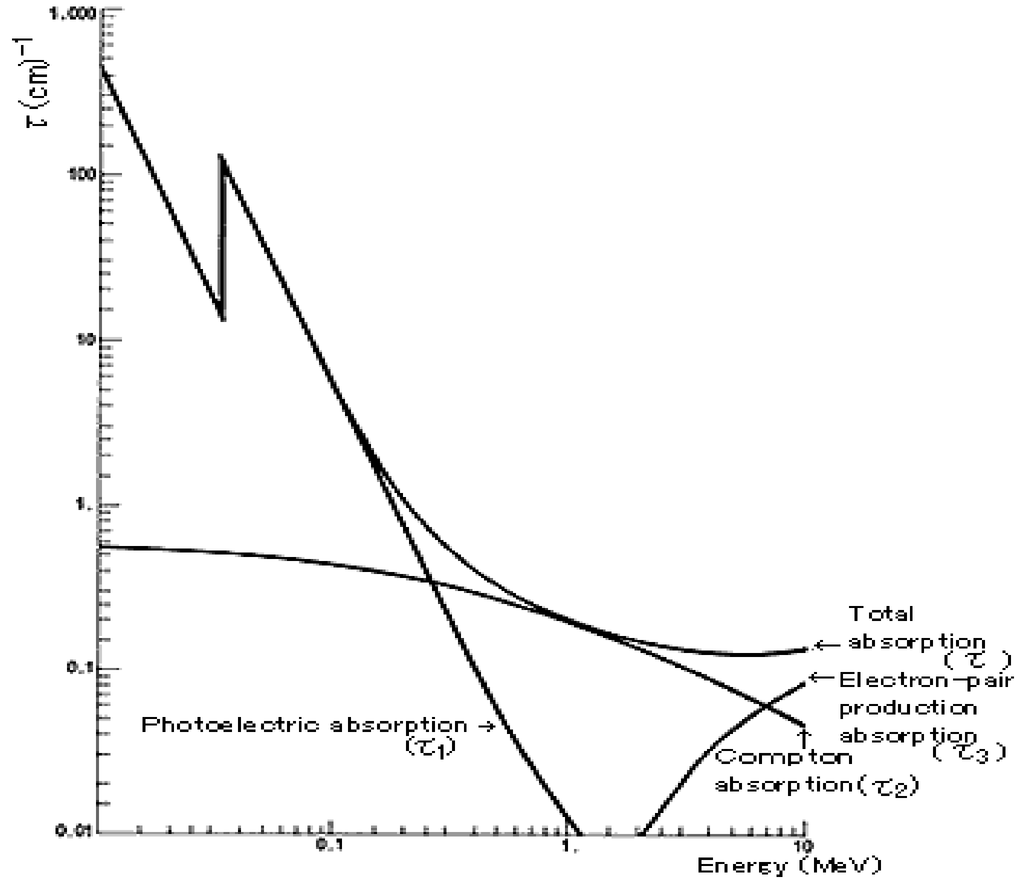

τ (cm)$^{-1}$
1,000
100
10
1.
0.1
0.01
0.1
1.
10
Energy (MeV)
Total absorption (τ)
Electron-pair production absorption (τ3)
Photoelectric absorption (τ1)
Compton absorption (τ2)

Okcen.co.jp

X-ray, Gamma-ray Divergence

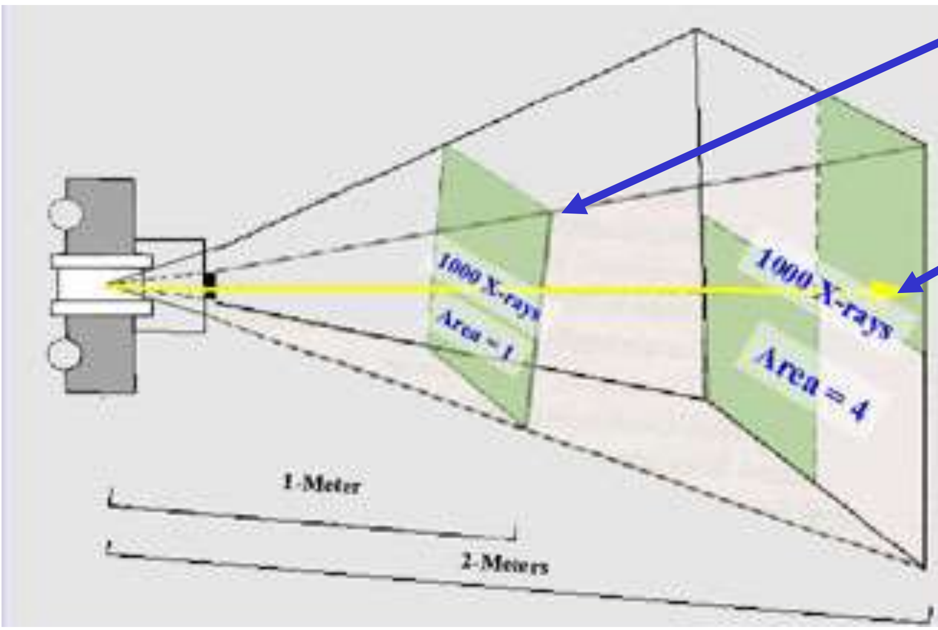
- Photons travel in straight but divergent directions when they exit the tube
- Divergence increases with distance
- The number of photons through a given area decrease with distance and thus radiation exposure also decreases
  - ***Inverse-Square Law***

Inverse-Square Law

$$X_A \propto X_B \bullet \left(\frac{D_B}{D_A}\right)^2$$

Doubling the distance from the source decreases exposure by a fourth. Conversely, halving the distance increases exposure 4 times.

Example



1 Meter Distance:1,000 X-rays pass through a unit area.

2 Meter Distance: The beam diverges to an area 4 times the original. The same 1,000 X-rays are evenly distributed over the new area (4 times the original). Thus the amount of X-rays per unit area is 250 or 1/4 the original. The resulting radiation exposure is 1/4 less.

An operator positioned 3 feet from the X-ray beam entrance area will receive 0.1% of the patient's ESE

Application of inverse square law principles can yield significant reductions in exposure

- Example
  - **An operator normally stands 1 meter away from the patient during cineangiography. The exposure rate at this point is 15 mrem/min and total cineangiography time is 2 min. What is the reduction should the operator stand 1.2 meters away? (8 inches farther away)**
- Solution
  - **The original exposure was 30 mrem (15 mrem/min for 2 min). The new exposure would be:**

$$X_1 \propto 15 \bullet \left(\frac{1.0}{1.2}\right)^2 \bullet 2 \propto 20.8\, mrem$$

  - ***A 31% percent reduction in radiation exposure is achieved in this example.***

Basic Principles of Radiation Safety

- **ALARA**
- **Engineering controls**
- **Personal protective equipment**
- **Policies and procedures**
- **Training**
- **Surveillance**

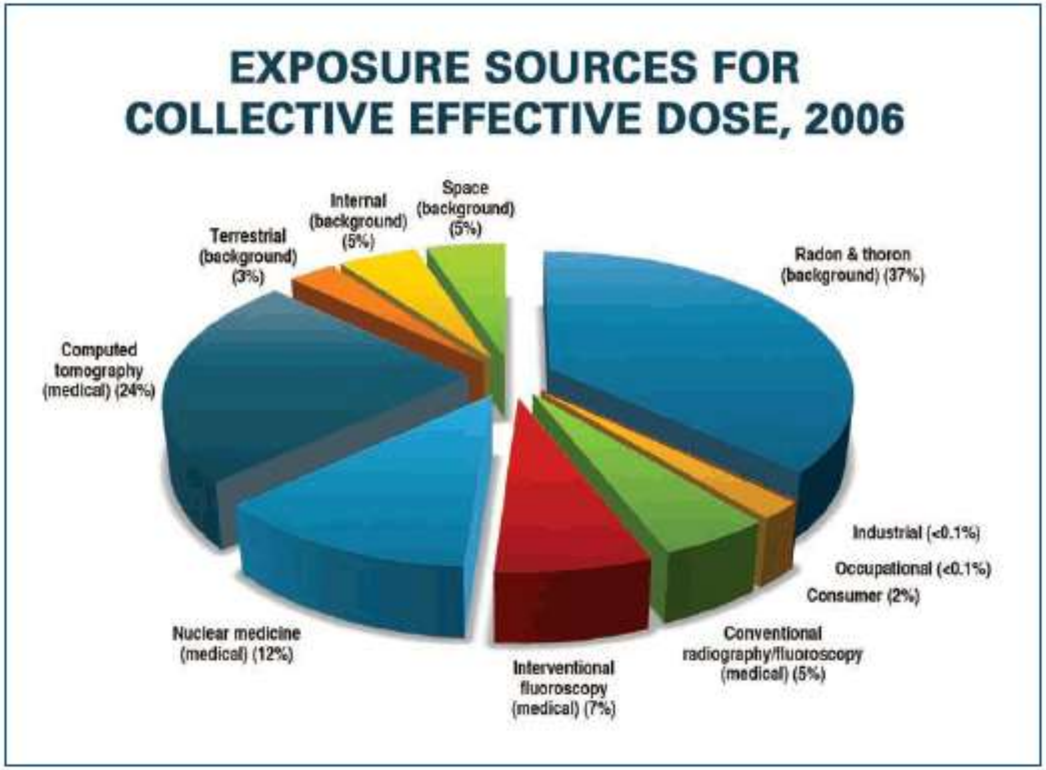
ALARA

- **As Low As Reasonably Achievable**
  - **Minimize radiation dose to employees, pubic, and visitors as low as *practical* by using all *reasonable* means**
  - **Background radiation levels**
    - **Prior to 2007 - ~360 mrem/yr (~ 1 mrem/day)**
    - **In 2007, NCRP report 160 increased to 600 mrem**

Description of Radiation Exposure Units

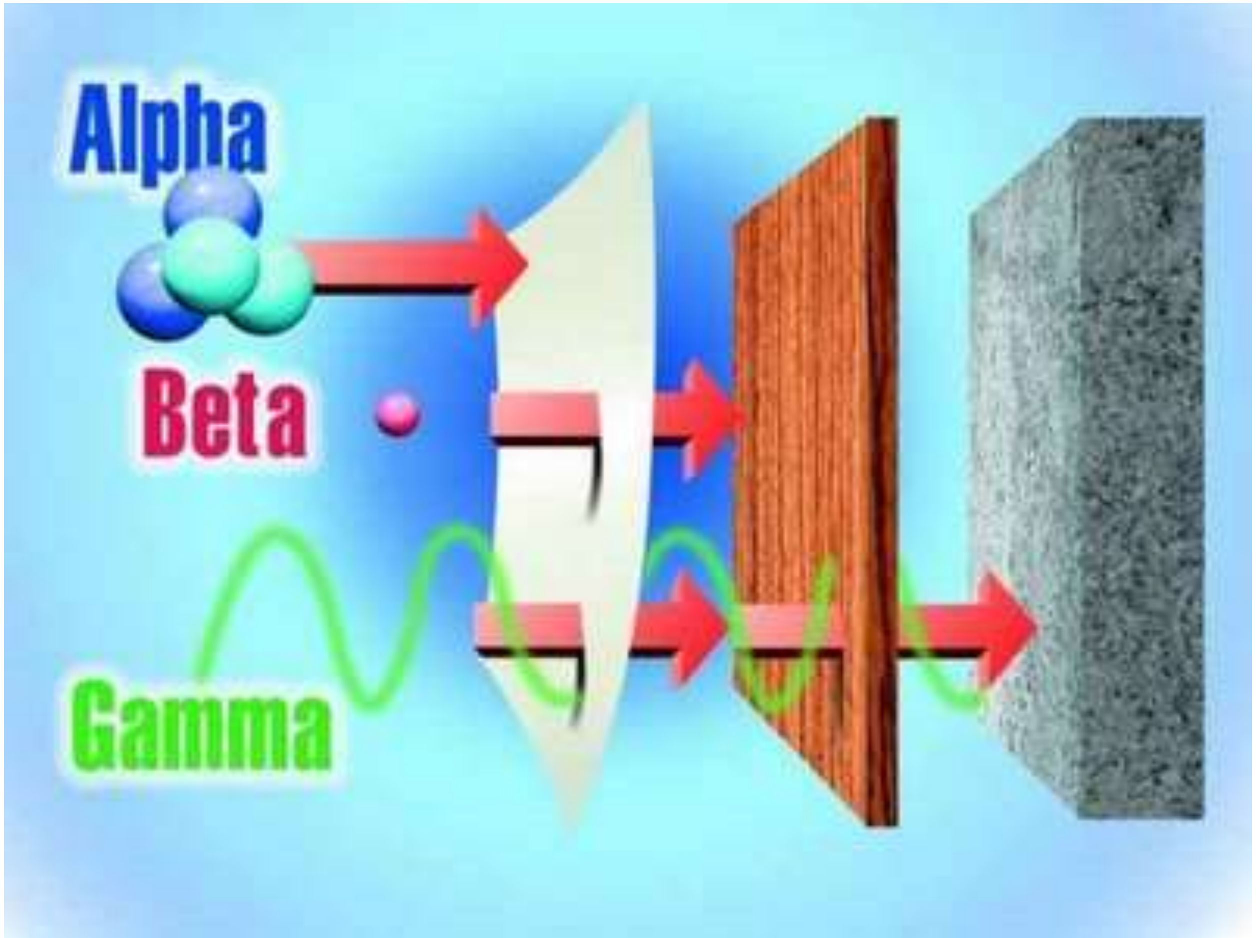
- X-ray machine radiation output
  - Defined in Entrance Skin Exposure (ESE)
  - ESE units: Roentgens/min (R/min)
  - Federal Maximum Limit = 10R/min
- Patient radiation exposure : dose absorbed
  - Radiation dose is the energy imparted/mass of tissue w/ units: Rad or Gray (Gy)
  - Immediate biologic effects described in Rads
- Personal radiation risk or dose equivalent
  - Occupational exposure units: Rem or Sievert (Sv)
  - RBE for X-Rays and Gamma rays is 1, thus 1 Rad = 1 Rem

Background – NCRP 160



Diagnosticimaging.com

Shielding



4.bp.blogspot.com

Shielding

Graymontinc.com

Effective Shielding Calculation

Calculate the Half Value Layer (HVL) using the equation:

$$I = I_0 Be^{-\mu x}$$

where:

I = exposure reading with added filtration
I_0 = exposure reading with no added filtration
μ = linear attenuation coefficient of the material of interest (cm-1)
This is different for all materials and energies.
B = the build up factor, and may be expressed as $(1 + \mu x)$
Build up must be calculated for broad beam, poor geometry conditions as well as for materials in excess of 1 cm thick.

Shielding example

- I = ?
- Io = 100 mSv/hr
- x = 5 cm
- u/p (lead at @ 1.5 MeV = 0.05 cm2/gm)
- p = 11.86 gm/cm3
- Solve for I (8.3 mSv/hr)

Containment – Hot Cell

sckcen.be

Glove box

Warning Signs

uic.edu

Dose Monitoring, Traditional

Live time monitoring accomplished by electronic dosimetry and a display board.

Personal Protective Equipment

dd.anl.gov

Personal Protective Equipment

rci-pulsemed.com

Policies and Procedures

Regulators

Governance	
Federal	Governing Laws
NRC	10 CFR 19,20,61
DOT	49 CFR 173
FDA	
NY State	ICR-16
U of R	Radioactive Material License

Dose Limits as of 2011

▪ Rad workers	5000 mrem/yr
▪ Public	100 mrem/yr
▪ Lens of eye	15 rem/yr
▪ Any organ	50 rem/yr
▪ Extremities	50 rem/yr
▪ Pregnant workers (dose to fetus)	500 mrem/pregnancy 50 mrem/month

Note: 1 rem = 1,000 mrem

Proposed dose limits already adopted by the University of Rochester

▪ Rad workers	2000 mrem/yr
▪ Public	100 mrem/yr
▪ Lens of eye	2 rem/yr
▪ Any organ	50 rem/yr
▪ Extremities	50 rem/yr
▪ Pregnant workers (dose to fetus)	500 mrem/pregnancy 50 mrem/month

Dose limits under new units

Type of limit	Occupational	Public
Effective dose	**20 mSv per year**, averaged over defined periods of 5 years	1 mSv in a year
Annual equivalent dose limits to the:		
Lens of the eye	20 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	

Biological Effects
Acute vs Chronic

- Acute health effects – Prompt radiation effects (Those that are observable within a short period of time) in which the severity of the effect varies with the dose. These are threshold based.

- Chronic Exposure – The absorption or intake of radioactive materials over a long period of time (i.e. over a lifetime). These effects are stochastic.

Biological Effects - Acute

- ~1 rad chromosomal changes
- 25 rad blood cell count changes
- 100 rad radiation sickness
- 450 rad LD_{50} (without treatment)
- 1000 rad LD_{100}

- These refer to whole-body exposure

Sources of Acute Exposure

- Medical equipment - fluoroscopes, radiation therapy irradiators, medical accelerators
- X-ray diffraction equipment
- Research irradiators
- Laboratory for Laser Energetics
- All require added training and have safety devices installed

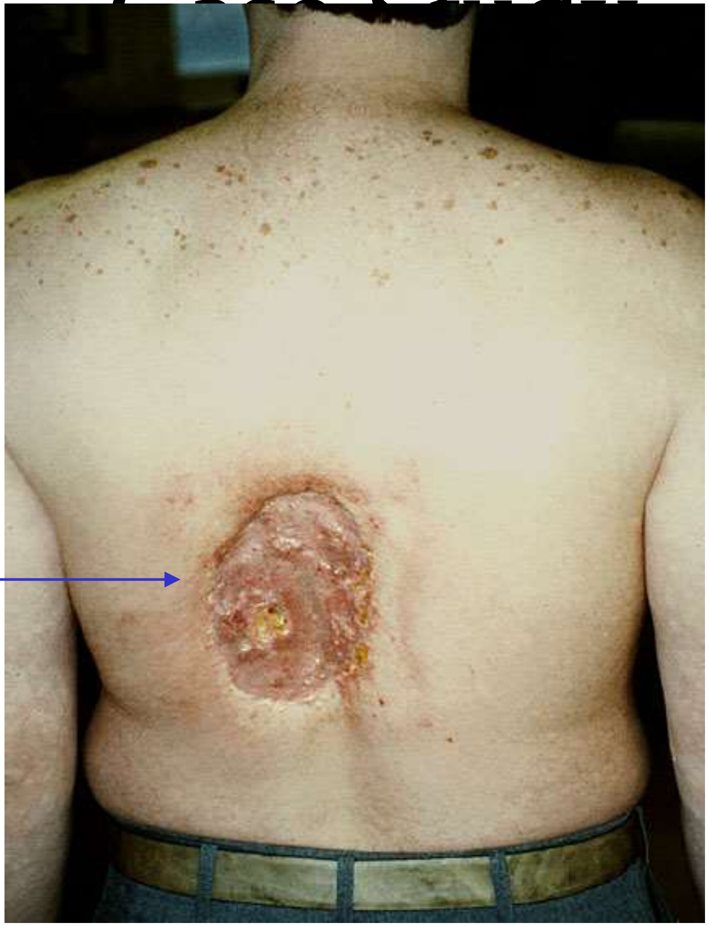
Case Study

40 year old male: coronary angiogram, percutaneous Coronary Intervention, 2nd angiogram for complications, then coronary angio bypass graft. Total fluoro time >120 mins.

6-8 weeks post

Case Study

Tissue Necrosis



18-21 months post

Case Study

Post skin grafting

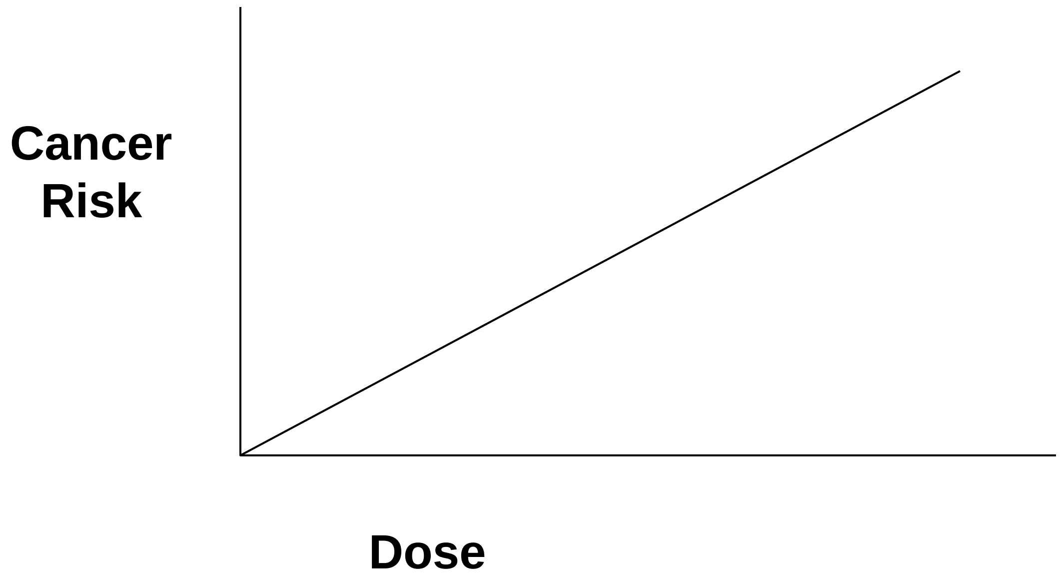
Chronic Exposure

- Greatest risk is chance of cancer probably caused by mutations in DNA
- With an exposure of 100-200 mrem/yr, risk is about the same as any other occupational hazard (NRC:$4x10^{-4}$ increased risk of death per 1 rem exposure)
- The shape of the dose-response curve at low levels of exposure is not known in detail

Linear, No-Threshold Dose Response Curve

- Forms basis for all regulations in the world
- Claims that all exposure to radiation is harmful
- Risk of getting cancer is directly proportional to dose
- Probably not scientifically accurate, but likely over-estimates risk (so actual risk is lower)

LNT model



Questions, Comments