RADIATION: FACTS AND APPLICATIONS

Introduction on Nuclear Radiation

Patrick Le Du

Objectives

This introduction is intend edto be a simple overview of so called ‘radiation’ and its use. Its main purpose is just for information and education.

First OUR WORLD IS BATHED IN RADIATION

Human has been exposed to radiation since his first appearance on Earth. For example, we are exposed to visible radiation coming from the Sun and from space.This is known as cosmic radiation or cosmic rays.

As well as visible light, this includes invisible radiation known as ultraviolet and infrared. Both kinds of radiation are electromagnetic waves, as are radio waves, X-rays and gamma

Historical Context and Discover

The discovery of nuclear radiation dates back to the late 19th century. Short history will be presented from the radioactivity to many technologies (Tracer principle, Invention of the Cyclotron, artificial radioactivity to vision and first graphite miller)

Importance of Nuclear Radiation in Modern Society with applications spanning various fields will be presented.

Basics types of Radiation :

an Introduction

- 2.2 Measuring and Detecting Radiation Radiation Units is the way to measure and quantify the degree of radiation a short description of Curie, Becquerel, Gray, Seivert
- 2.3 Example of Sources of Radiation over the world

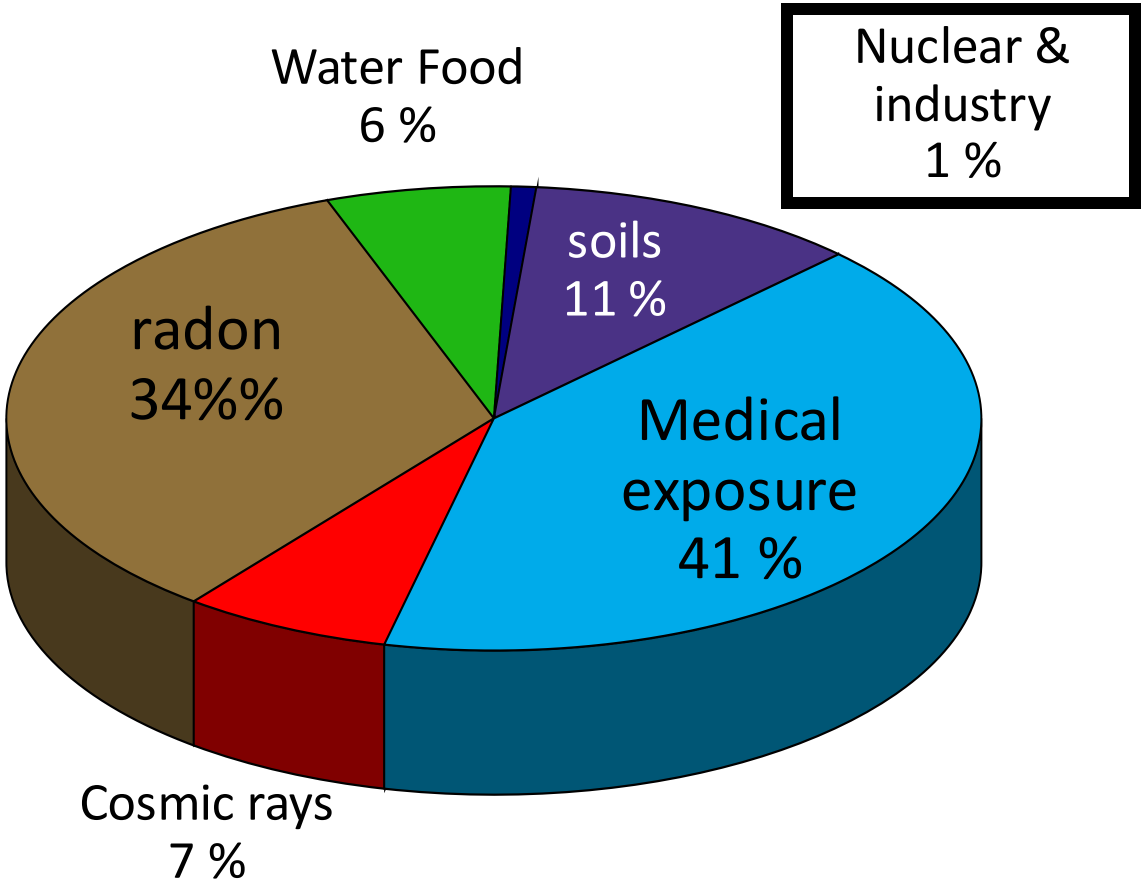
2.3.1 Example of Natural Sources -

Cosmic rays variation of natural radioactivity

2.4 .Exposure for radiological X ray exposure examples

- Finally I will describe the application of the most common exam: the radiography

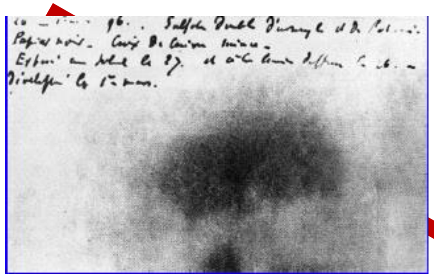
OUR WORLD IS BATHED IN RADIATION



- Earth has been radioactive ever since its formation into a solid mass over 4½ billion years ago. However, we have only known about radiation and radioactivity for just over one hundred years...

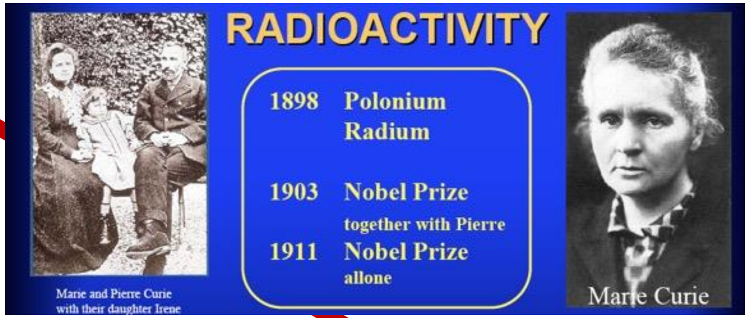
How physics discoveries have impacted our life (1)

1895
W.C. Rontgen
Discovery of X Ray



First image of
potassium uranyl disulfide

1896 - Discovery of natural radioactivity by H. Becquerel
1897 – J.J. Thomson – electron
1899 – E. Rutherford : Alpha & Beta
1900 – U. Vilars – the Gamma



RADIOACTIVITY

1898 Polonium Radium

1903 Nobel Prize together with Pierre

1911 Nobel Prize allone

Marie and Pierre Curie with their daughter Irene

Marie Curie

1898
Pierre and Marie Curie
the Radioactivity
Polonium,Radium

1910

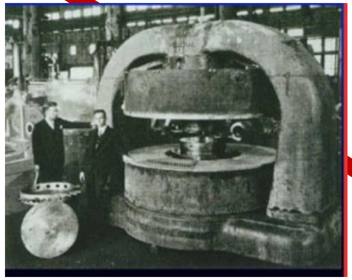
X Ray Radiography

1923 - The Tracer principle
`G.V.Hevesy- the father of nuclear medicine

How physics discoveries impact our life (2)

1932 - The Invention of the cyclotron
Production of radioisotopes

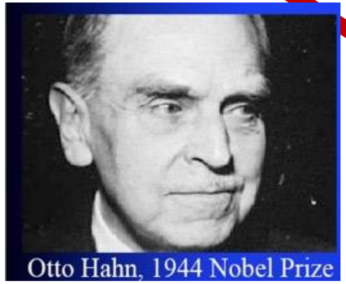
Ernest O. Lawrence and his
First cyclotron 1932



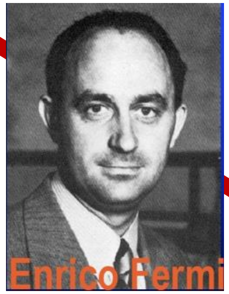
1934 - Artificial radioactivity
Irène and Fréderic Jolio Curie
in combination with the cyclotron open the door to the production of useful radio indicators.

1938-1942 Fission of Uranium

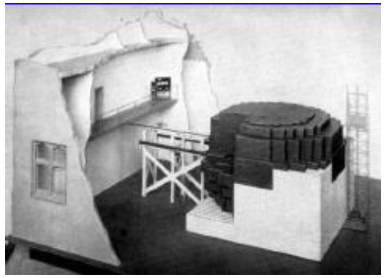
From discovery to first
graphite miler in Chicago
To the Production of long lived
radio-isotopes and nuclear energy
production



Otto Hahn, 1944 Nobel Prize

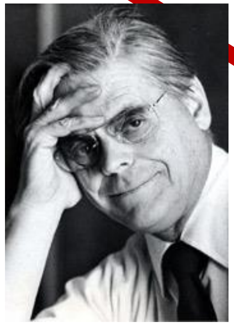


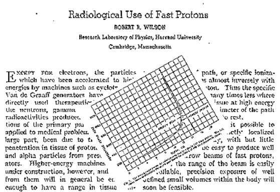
Enrico Fermi



O.Hahn
E. Fermi

1946 – R.R.Wilson The origin of
particle therapy
Using the Bragg peak discovery
(1903)



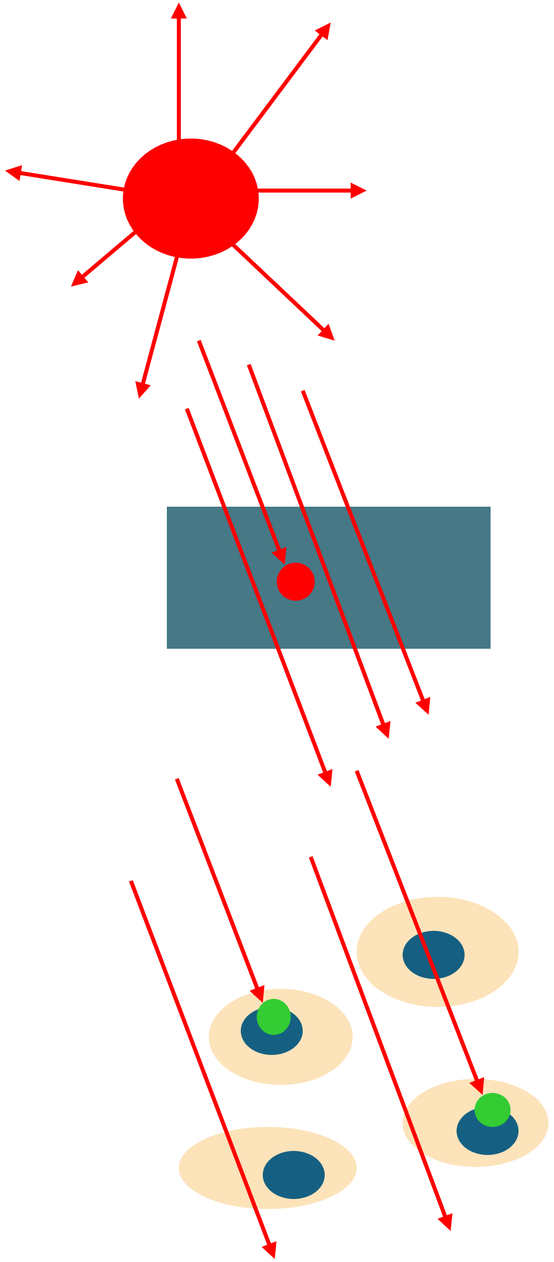


Radiological Use of Fast Protons

ROBERT R. WILSON

Research Laboratory of Physics, Harvard University
Cambridge, Massachusetts

The Units – basic definitions!



- Activity = Number of decays per second
  - Becquerel Bq : 1 decay / second
  - Curie Ci : 37 x 10^9 Bq (37 GBq)
- Dose : GRAY = amount of radiation absorbed in any material = absorbed energy / mass unit
  - Gy : 1 joule / kilogram = 100 Rad
- Effective dose : SEIVERT Sv = estimates biological effect from the absorbed radiation

→ indication of global risk

= absorbed dose x WR* x WT**

- Particle → WR*= 1 pour RX, beta and gamma, p=5, α=20
- Organ → WT** = 0.05 for thyroïd, 0.01 for skin

Effective dose values

- 10.000 mSv : high irradiation / rapid death
- 1.000 mSv : moderate irradiation / clinical visible signs (burn…)
- 5 mSv : annual irradiation in Clermont-Ferrand (volcanic soil)
- 2,5 mSv : annual irradiation in Paris
- 1 mSv : legal limit irradiation in France
- 1 mSv : average annual medical irradiation in France

1 Sv = 1 J/kg equivalent   1 Sv = 100 rem

Few simple exemples

a ‘standard’ Scintigraphy exam

		W_R	W_T	%
RX : 100 mGy / 50 cm^2 skin	1	0,01	30 %	
^{131}I : 10 mGy / thyroïde		1	0,05	100 %

Effective dose = (100 x 1 x 0,01 x 0,30) + (10 x 1 x 0,05 x 1)= 0,8 mSv

- Mammogram : 2 view x 2 breasts
- X ray with Q factor WR = 1
- Tissue weighting factor = 0,12
- Absorbed dose: 4 x 1 = 4 mSv
- Effective dose: 4 x 0.12 ≈ 0.5 mSv

- Mammogram exposure equivalent to whole-body dose of 0.5 mSv

Variation of natural radioactivity

- Cosmic rays
  - sea level 0,25 mSv / year
  - Mexico (2240 m) 0,80 mSv / year
  - La Paz (3900 m) 2,00 mSv / year
- External exposure due to earth exposure
  - average 0,9 mSv / year
  - Espirito Santo (Bresil) 35 mSv / year
  - Maximum (Iran) 100 mSv / year
  - Marseille (France) 0,20 mSv / year
  - Limousin (France) 1,20 mSv / year
- Internal exposure due to water
  - Evian water 0,03 mSv / year
  - St Alban water 1,25 mSv / year

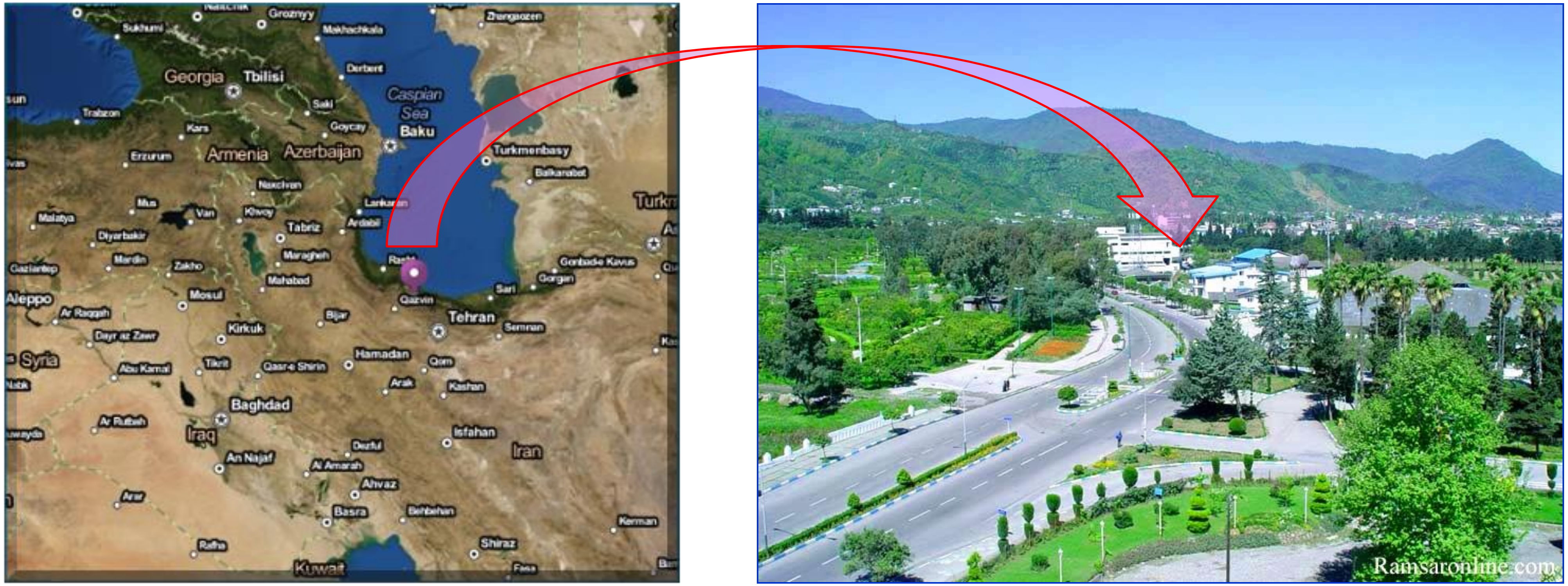
Exposure for radiological exams

- Some examples

organ	dose skin mGy	effective dose mSv
Thorax, face	0,2 - 0,5	0,015 - 0,15
Lumbar region	4 - 28	1,5
Urography	40 - 60	3
Brain scan	7 - 78	1
Whole Body scan	30 - 60	4 - 10
Mammography	7 - 25	0,5 - 1

Most radioactive place in the world: Ramsar, Iran

- Background radiation: 100- mSv / year due to ^{226}Radium
- No epidemiological evidence of adverse affects
- Residents demonstrate a marked increase in DNA repair capacity



Proposal: to relocate the inhabitants (2000) to a lower radioactive area!

Nuclear Radiation in Energy Production

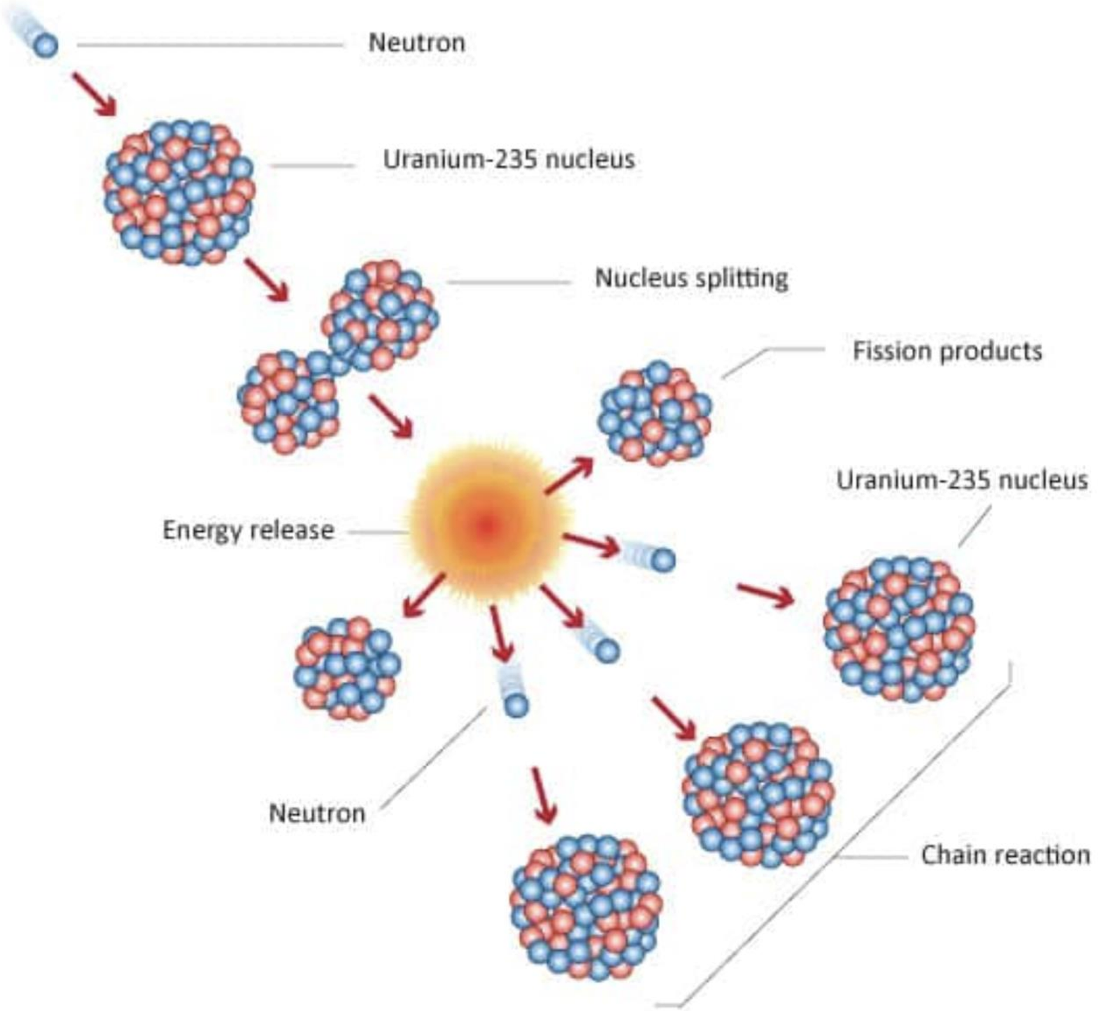
Richard Kouzes

Nuclear Power Plants

- The purpose of a nuclear reactor is to generate heat that can be used to create steam that drives a turbine to produce electricity.
- Nuclear power reactors use the uranium isotope uranium-235 (^{235}U), which is naturally occurring (0.72% of U on Earth).
- ^{235}U spontaneously fissions with a half-life of 700 million years.
- The fission reaction creates two lighter “daughter” nuclei plus some neutrons.
- The fission of a ^{235}U nucleus can be “induced” when struck by a slow (thermal) neutron.
- Thus, it is possible to create a “chain reaction” where the fission of one ^{235}U nucleus induces one or more other nuclei to fission.
- If controlled, this chain reaction can reach a steady state, releasing energy in a controlled manner that can be used to heat water into steam.

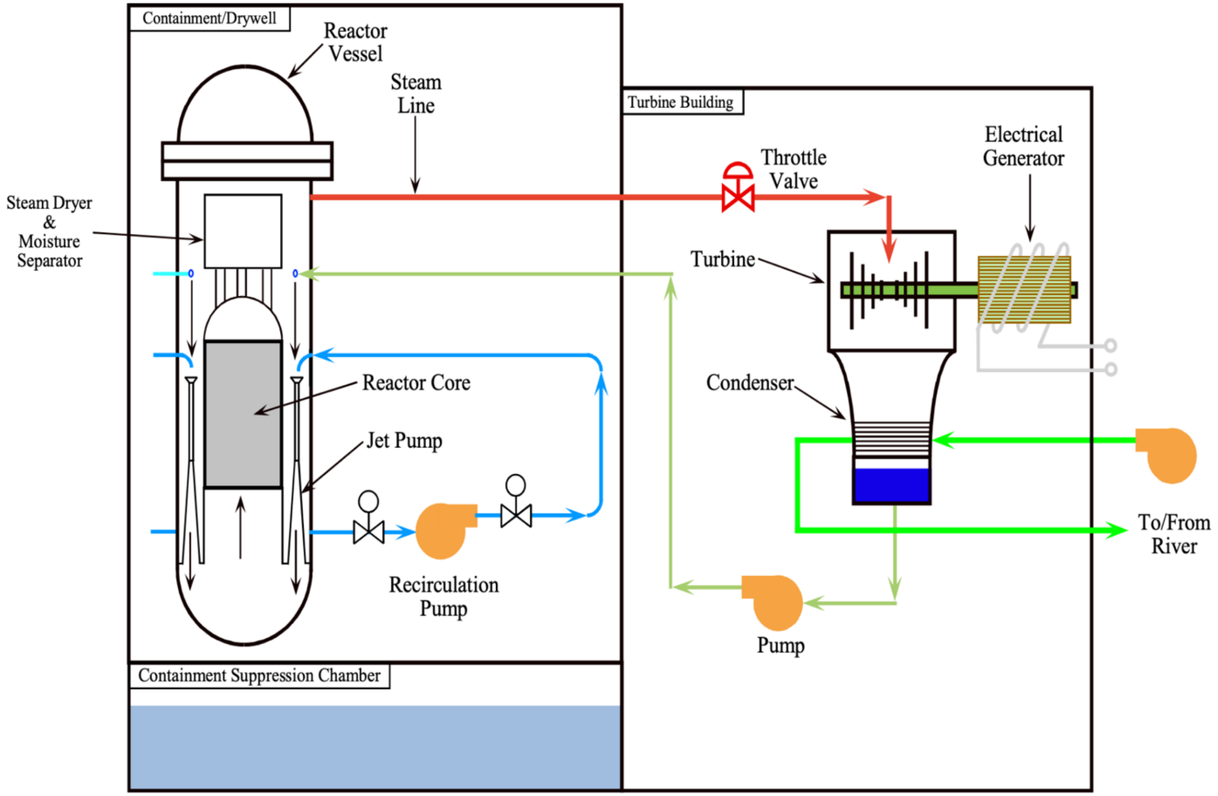
The Fission Reaction

- Fission of ^{235}U can be induced by thermal neutrons
- The resulting neutrons rom the fission can induce more fissions
- This produces a chain reaction that can be controlled
- A steady state is produced by absorbing excess neutrons



Nuclear Power Reactor

- The most common reactors are pressurized water reactors and boiling water reactors
- The neutrons in the reactor core are moderated by water to reduce them to thermal energies
- Heat generated by the steady state fission reaction is used to produce steam that drives a turbine



Benefits of Nuclear Energy

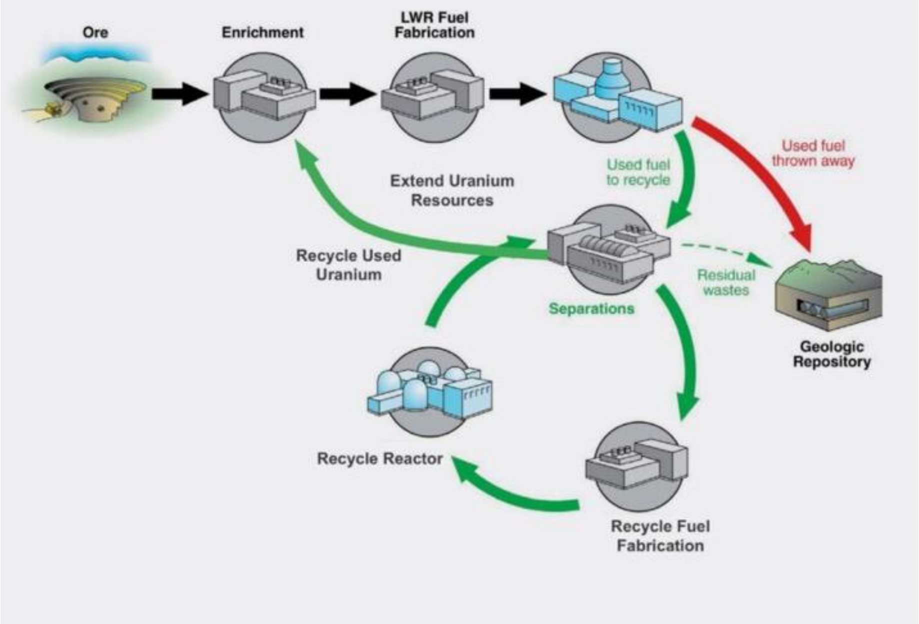
- Nuclear power reactors are highly efficient and reliable.
- A typical reactor generates about 1 GW of electricity and has an efficiency of 33-37%, comparable to fossil fueled power plants, powering about one million homes.
- The next Generation IV of nuclear power plants could have an efficiency above 45%.
- Nuclear reactors are typically refueled every 18-24 months where 1/3 of the fuel rods are replaced, requiring a shutdown of a few weeks.
- Nuclear power plant operation does not produce carbon dioxide or any other greenhouse gasses (such as methane), making nuclear power a "green" energy source.

Challenges and Risks

- Nuclear power produces waste.
- Used fuel elements removed from power plants during refueling are highly radioactive and still physically hot from the decay of daughter elements in the fuel.
- They are placed into water cooling ponds for about five years.
- After that time, they are put into concrete dry storage casks where they may remain permanently.
- The U.S. does not have a permanent storage site for spent fuel, so there are 85 sites in the U.S. where dry storage casks are located.

Reprocessing

- It is possible to reprocess spent nuclear fuel to separate out the remaining ^{235}U for reuse in new fuel elements.
- This has been done in some countries, but U.S. policy does not allow such reprocessing.
- Reprocessing has the advantage of using unburned ^{235}U and reducing the volume of the highly radioactive waste components in the spent fuel.
- The disadvantage of reprocessing is the possibility that some component materials in the waste could be used to make nuclear weapons, which is why the U.S. does not currently allow reprocessing.
- In the future, reprocessing of nuclear fuel may be implemented if the process can be adequately secured.
- Japan, for example, is investing in reprocessing technology to help reduce their nuclear waste problem.

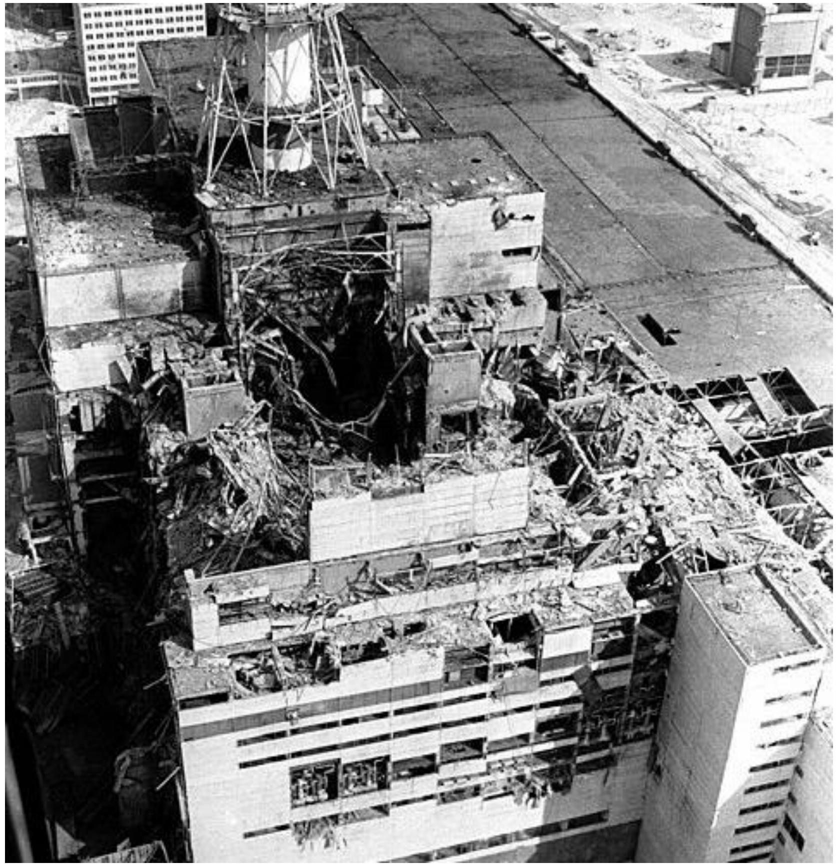


Nuclear Accidents 1

- There have been 3 notable nuclear power reactor accidents in all the years of reactor operation.
- The first was the Three Mile Island reactor accident in 1979 in Pennsylvania, USA.
  - In this accident, there were a series of malfunctions due largely to human error, resulting in a loss of coolant accident (LOCA) condition.
  - Poor response by the operators resulted in a meltdown in the core, destroying the usefulness of the reactor.
  - The only external consequence was a release of radioactive gas into the environment that were found to have no long-term impact on the surrounding population.
  - The cleanup after the accident cost about $1B.

Nuclear Accidents 2

- The second accident was the disastrous fire at the Chernobyl plant in the Ukraine in 1986.
  - This released large quantities of radioactivity into the environment impacting a large area in multiple countries.
  - The several rectors at Chernobyl are a water cooled and carbon moderated design from Russia.
  - The accident resulted from human error while performing a test to power the emergency pumps if there were simultaneous coolant pipe rupture and loss of external power.
  - A series of operator actions then resulted in a LOCA leading to a fire in the carbon moderator that destroyed the reactor and released huge quantities of radionuclides.
  - The cost of cleanup has been over $700B, the costliest disaster in human history.

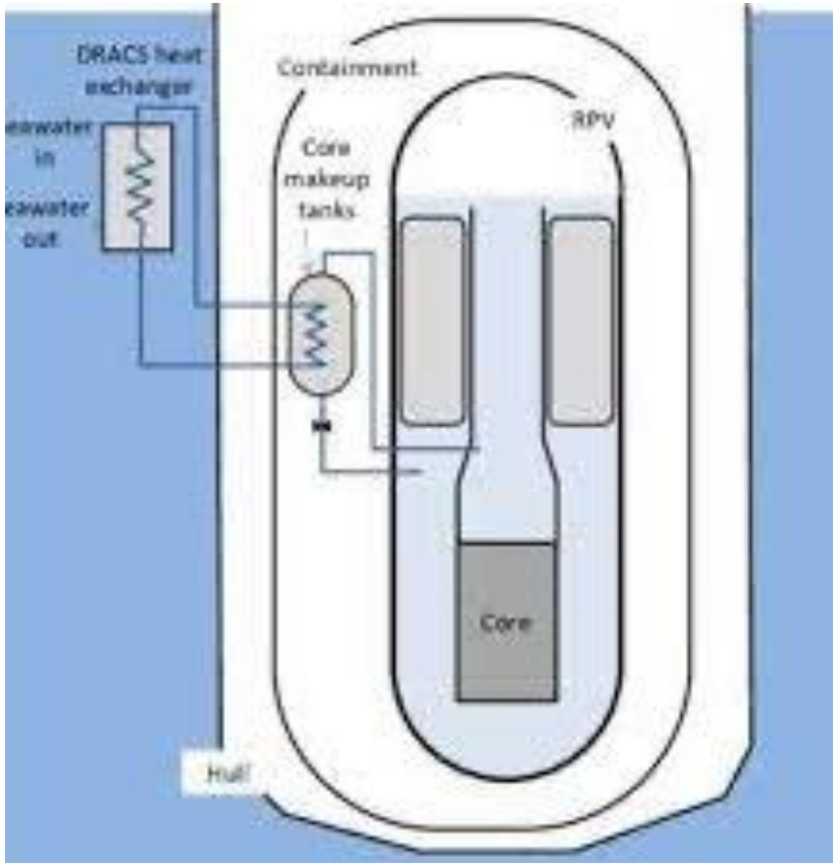


Nuclear Accidents 3

- The third accident was the Fukushima reactor meltdown in 2011 in Japan.
  - This accident occurred when a tsunami wave following an earthquake swamped critical backup power systems at the plant.
  - The resulting loss of external electrical power allowed the reactor to overheat, melting the core.
  - This was followed by an explosion of hydrogen gas in the reactor, thus releasing radionuclides into the area surrounding the plant.
  - The consequence of the accident has resulted in evacuation of the nearby population.
  - The cost to date has been well over $100B.

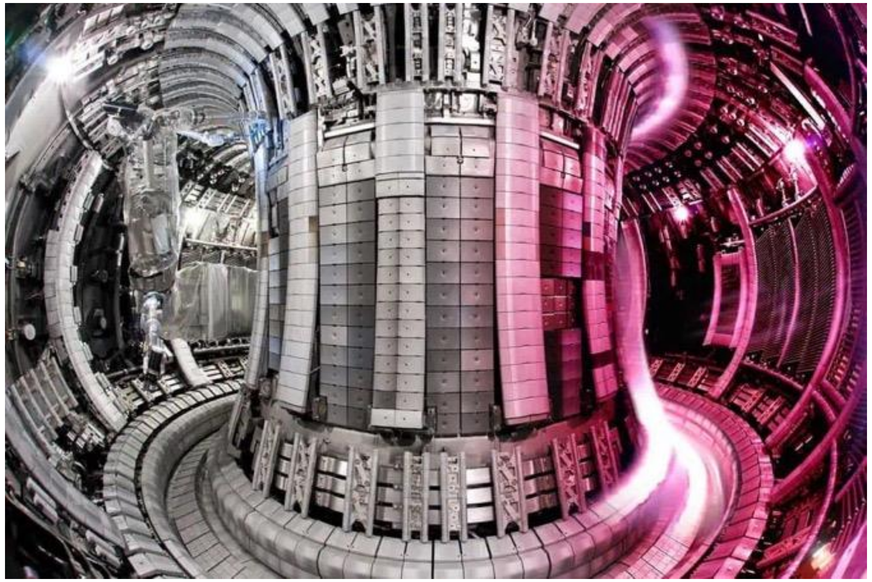
Advances in Nuclear Fission Technology

- Typical nuclear power reactors are of the scale of 3 GW thermal, resulting in 1 GW of electrical power.
- The latest trend in nuclear power reactor design is what is referred to as small modular reactors (SMRs), where a plant may contain multiple reactors that are on the scale of 300 MW electrical output, with a variety of designs.
- These new designs incorporate several passive safety features that prevent reactor accidents such as in the case of loss of external power.
- It should be possible to construct such reactors more quickly and at a lower cost than previous conventional designs.
- The SMRs should require less frequent refueling, every 3-7 years rather than the 1-2 years for conventional reactors.



Advances in Nuclear Fusion Technology

- Fusion is the process of merging certain light nuclei like deuterium with tritium, resulting in the release of energy.
- Fusion is the process that releases energy in the center of our Sun, and in thermonuclear weapons.
- If fusion can be produced in a controlled manner on Earth, it could lead to a safe and clean power source.
- Fusion is challenging since it requires very high temperatures and densities for it to occur.
- Once this reaction can be produced in a continuous manner, other reactions might become feasible with advantages in the power produced with less accompanying radiation.
- Fusion is the great hope for a clean nuclear power future.



Nuclear Radiation in Medical Applications

Simon R Cherry

Radiation in Medicine

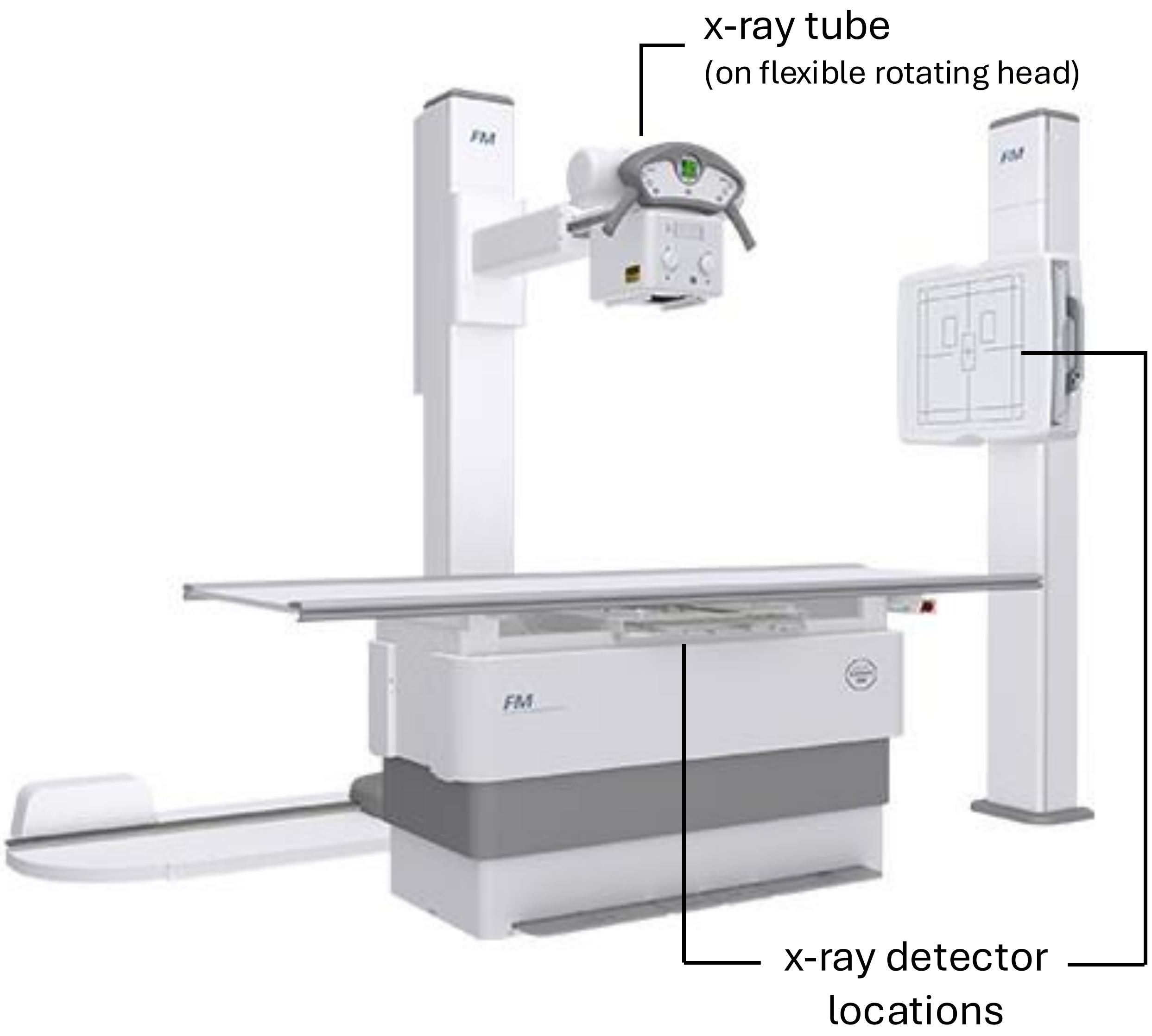
- X-rays and radioactivity discovered in late 1800s.

- **Diagnostic Medicine**
  - Imaging is a critical part of modern diagnostic medicine
  - Techniques involving radiation:
    - X-ray imaging
    - CT (computed tomography) scanning
    - Nuclear medicine imaging
  - ~1 billion procedures globally each year
- **Cancer Treatment**
  - Precise targeting of cancer with radiation for treatment
  - Techniques involving radiation:
    - External beam radiotherapy (photons, electrons, protons)
    - Radionuclide therapy
  - ~10 million patients treated globally each year

First x-ray image
Wilhelm Roentgen
Dec 21st , 1895

X-ray Imaging

- X-ray tube generates x-rays that are transmitted through the body onto an x-ray detector
- Clinical systems are very flexible, allowing many different parts of the body to be imaged.
- Specialized x-ray imaging systems for:
  - Breast imaging (mammography)
  - Imaging vessels (angiography)
  - Guided interventions (fluoroscopy)



Courtesy United Imaging Healthcare

X-ray Images

- Anatomical imaging
- Image contrast arises from differences in scattering and absorption of x-rays between different tissues
    - Lung
        - low scattering/absorption
    - Soft tissue
        - medium scattering/absorption
    - Bone
        - high scattering absorption

dark

bright

chest

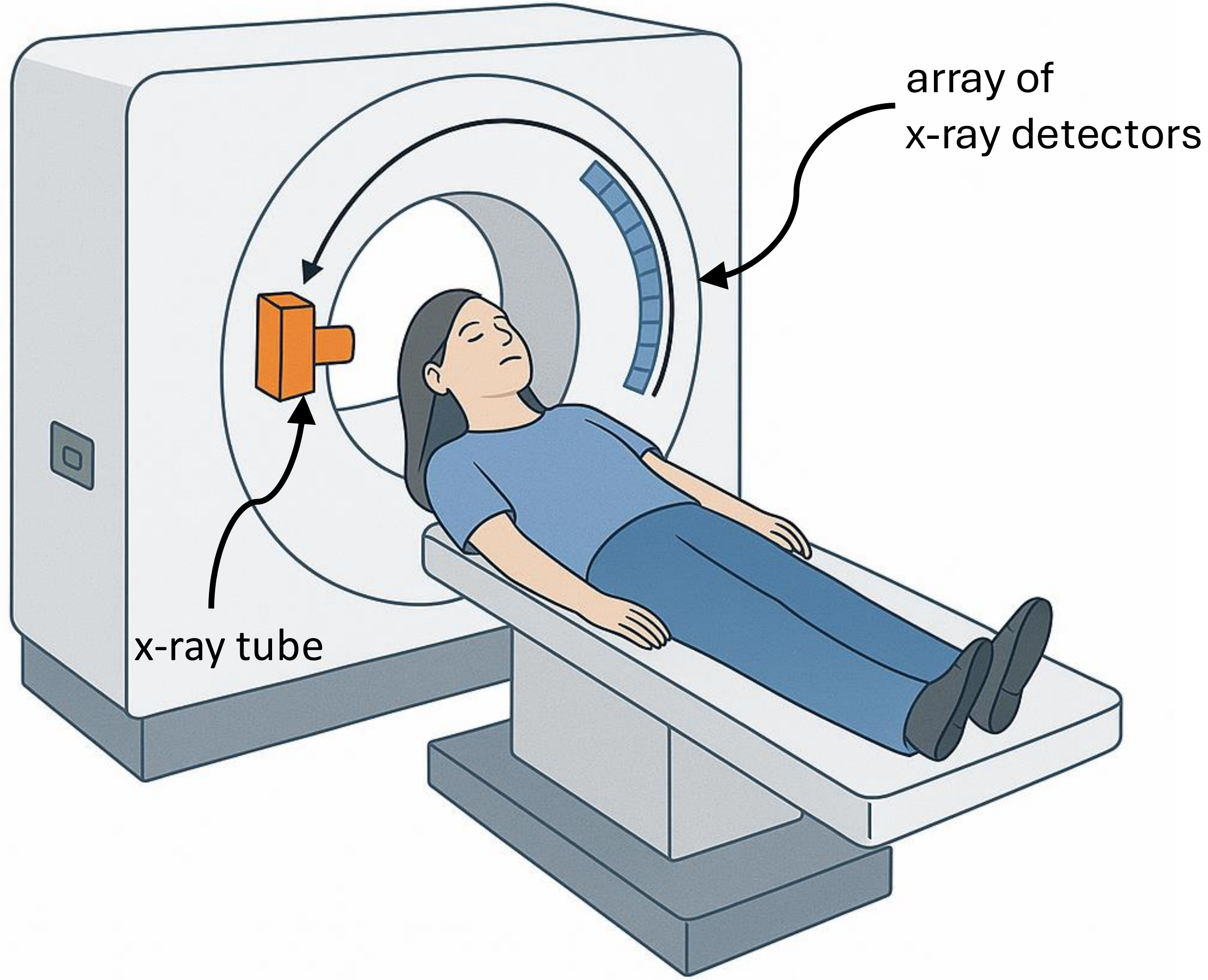
hand

knee

courtesy of Dr. B. Di Muzio,
Radiopaedia.org, rID: 37906, 38755, 48333.

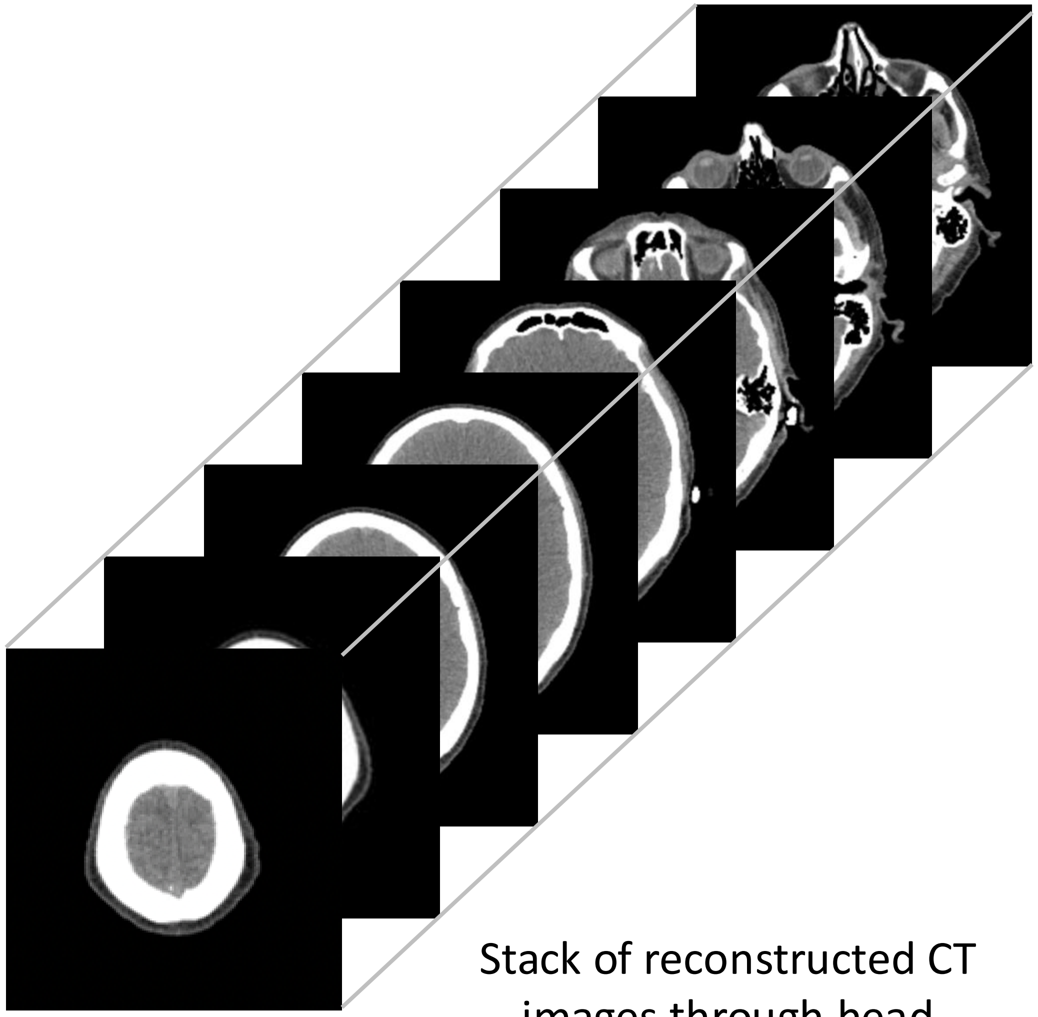
Computed Tomography (CT)

- Rotate x-ray tube and detector around body
- Acquire x-ray images from many different angles
- Scan takes only a few seconds



Computed Tomography (CT)

- Use mathematical algorithms to “reconstruct” a stack of cross-sectional images.
- Stack of images forms a 3-D image volume
- Image brightness related to tissue density



Stack of reconstructed CT images through head

Computed Tomography (CT)

CT scanner

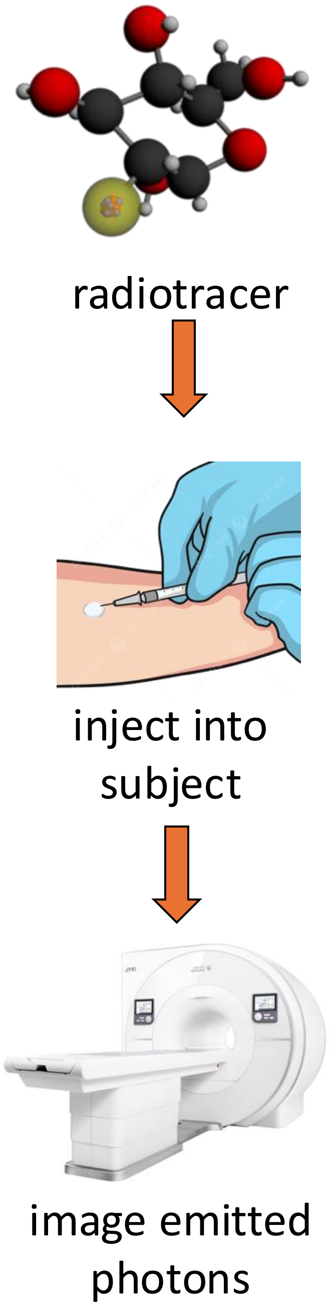
Courtesy Siemens Healthineers

CT image at level of liver showing multiple cancerous lesions (dark spots)

courtesy of Dr. A. BinNuhaid, Radiopaedia.org, rID-197788

Diagnostic Nuclear Medicine

- Injection of trace amounts of a compound labeled with a radionuclide ("radiotracer")
- Radiotracer distribution relates to how tissues/organs are functioning – functional imaging
- Image photons (often gamma rays) emitted from the body when radionuclide decays
- Three types of imaging:
  - scintigraphy (planar imaging)
  - single photon emission computed tomography (SPECT)
  - positron emission tomography (PET)



radiotracer

inject into subject

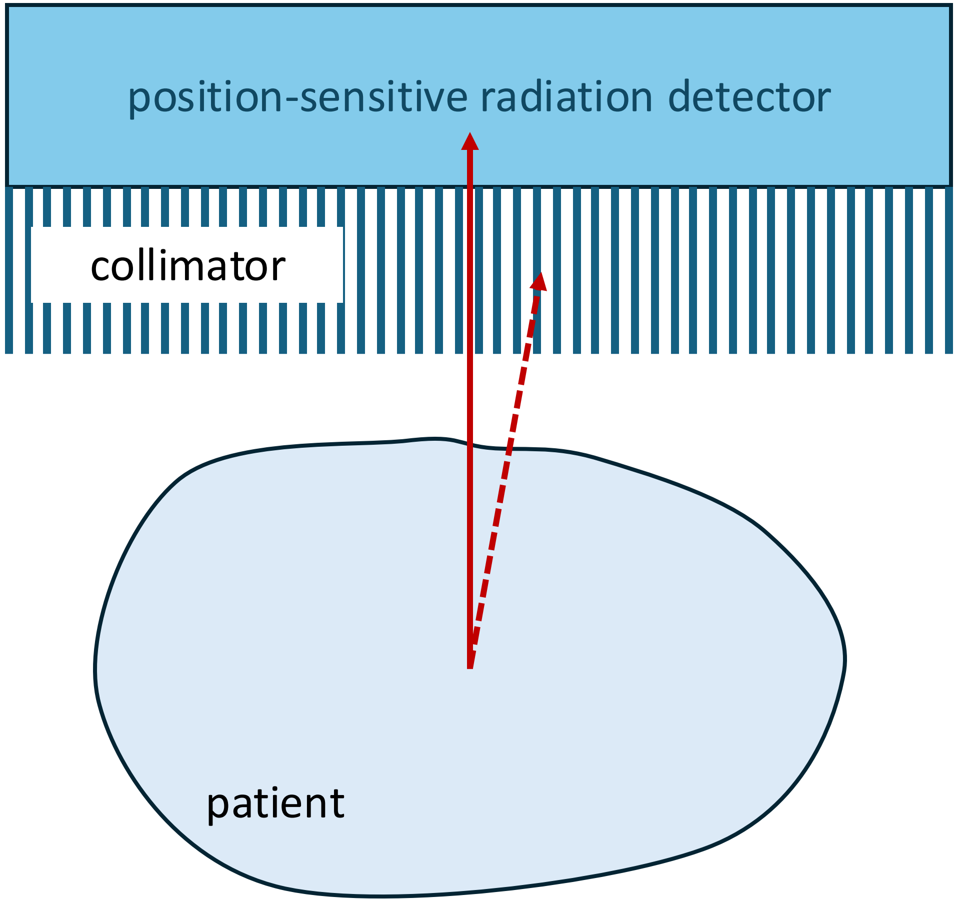
image emitted photons

Gamma Camera

- Use absorbing collimator to define direction of gamma rays reach detector

- Only gamma rays emitted parallel to the holes reach the detector (red solid line). Those emitted obliquely are absorbed by the collimator (dashed red line).

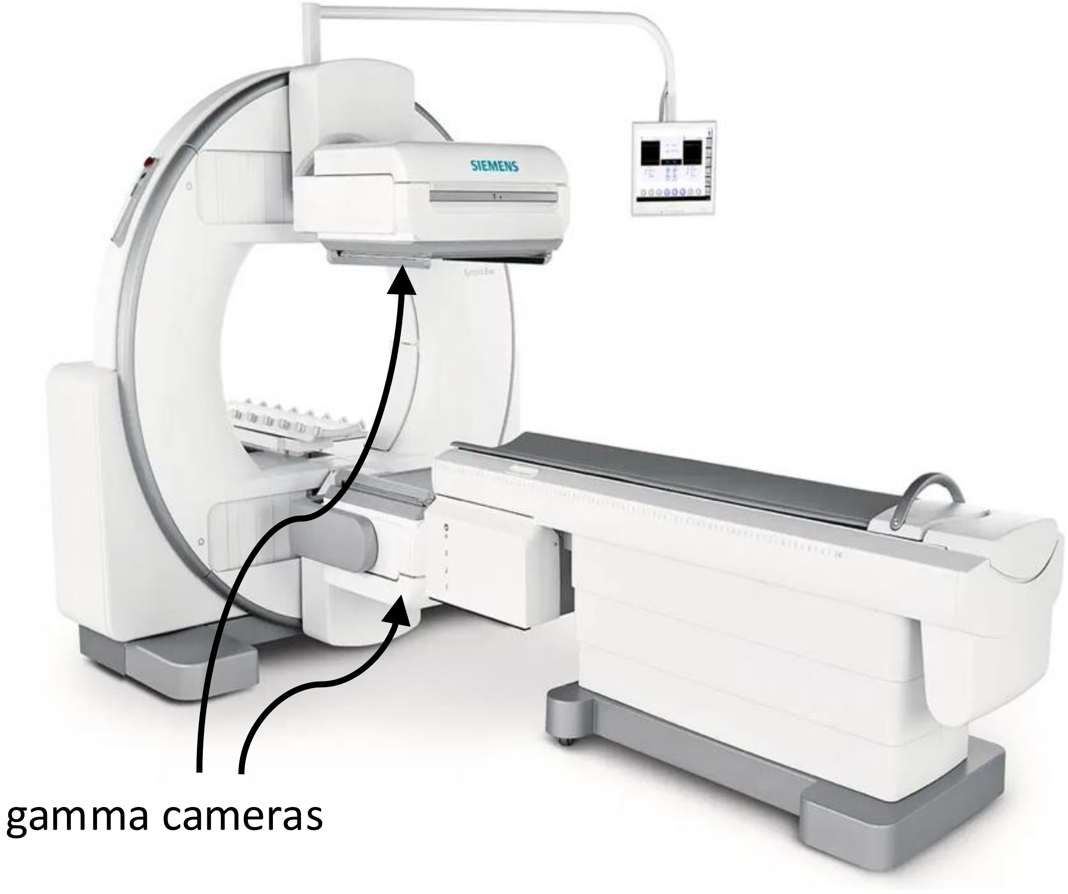
- This allows an image of the radiotracer distribution to be formed



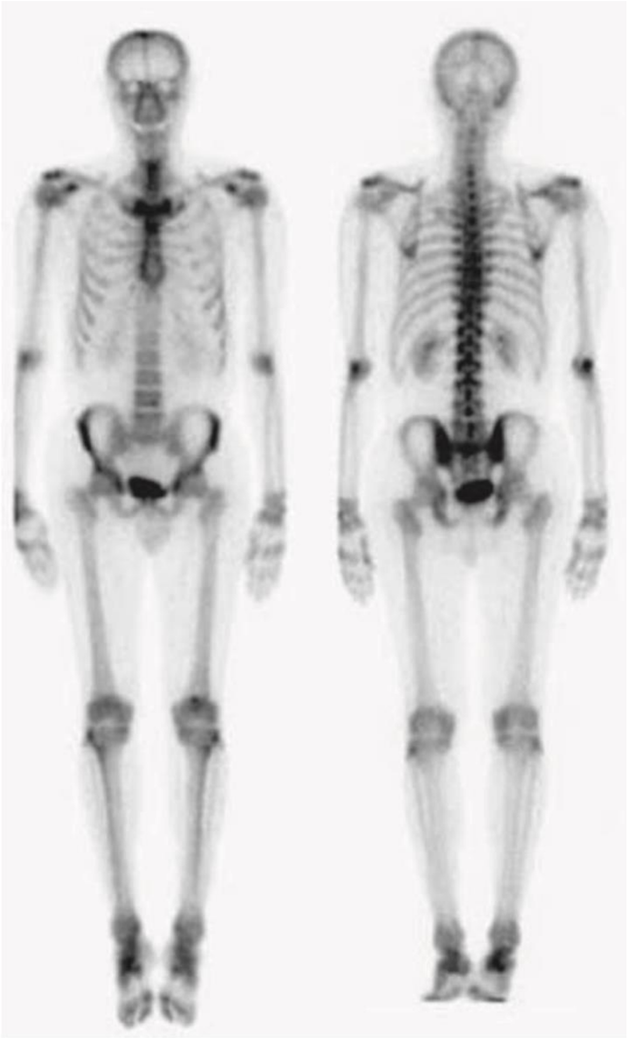
Principle of image formation by a gamma camera.

Gamma Camera

Dual-headed gamma camera



Courtesy Siemens Healthineers

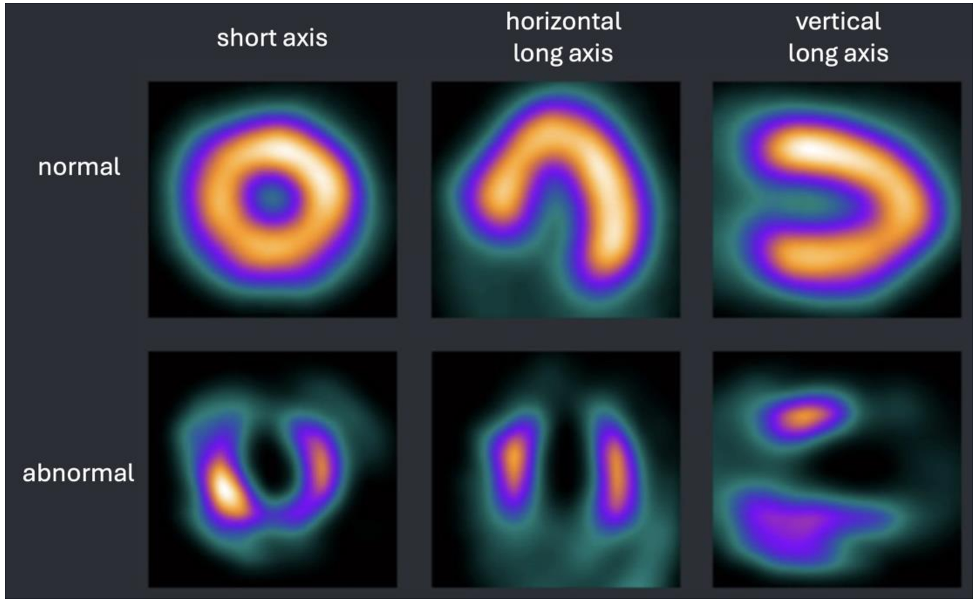


Planar nuclear medicine images of a radiotracer which selectively concentrates in bone

(front and back views corresponding to images from a dual-headed gamma camera are shown).

Single Photon Emission Computed Tomography (SPECT)

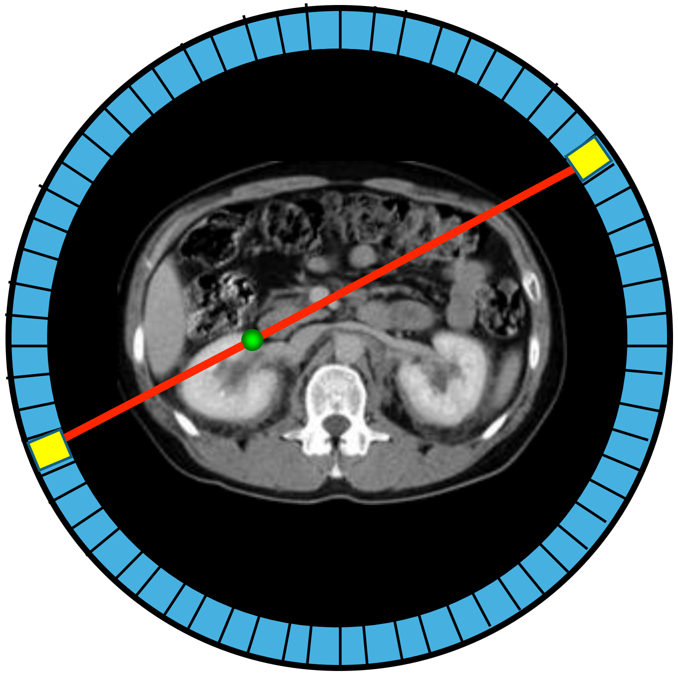
- Rotate gamma camera around patient and acquire multiple angular views.
- Reconstruct a stack of cross-sectional images (analogous to CT) to form a 3-D image volume
- Scans typically take 10-20 minutes



SPECT images of cardiac blood flow.
Three different views of the left ventricle of the heart in a healthy subject with uniform blood flow and a patient with abnormal blood flow (Images courtesy of Digirad Inc.).

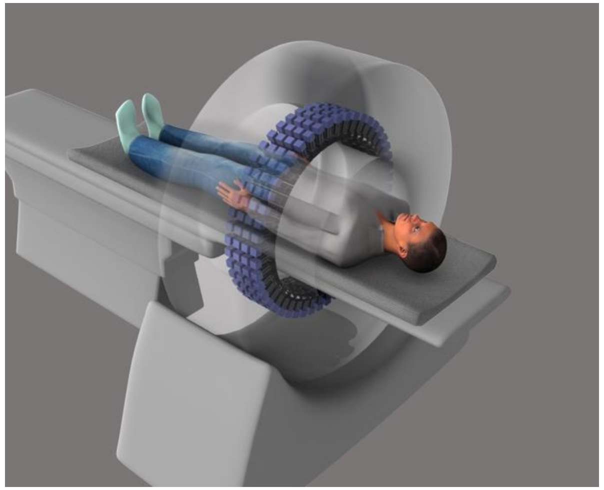
Positron Emission Tomography (PET)

- Uses radionuclides that decay by positron emission
- Positrons “annihilate” with an electron in tissue resulting in two back-to-back photons
- Photons detected in time coincidence by a ring of radiation detectors
- No collimator needed
- All angular views acquired at same time – no rotation



Annihilation of positron and electron (green dot) produces back-to-back annihilation photons that are detected

Typical PET scanner geometry

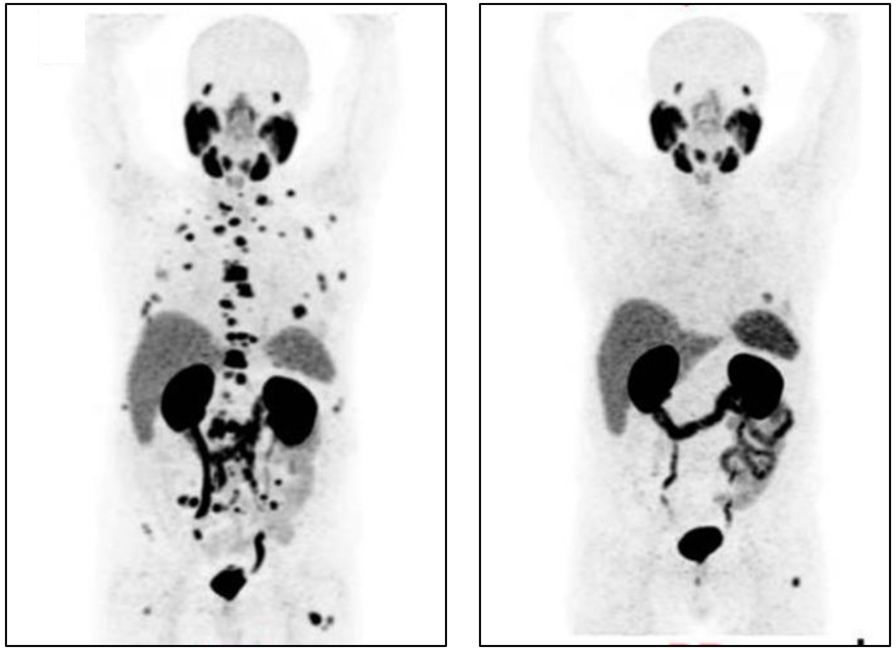


Positron Emission Tomography (PET)

- Patient often moved through scanner to acquire whole-body images.
- Scans take a few minutes

Courtesy United Imaging Healthcare

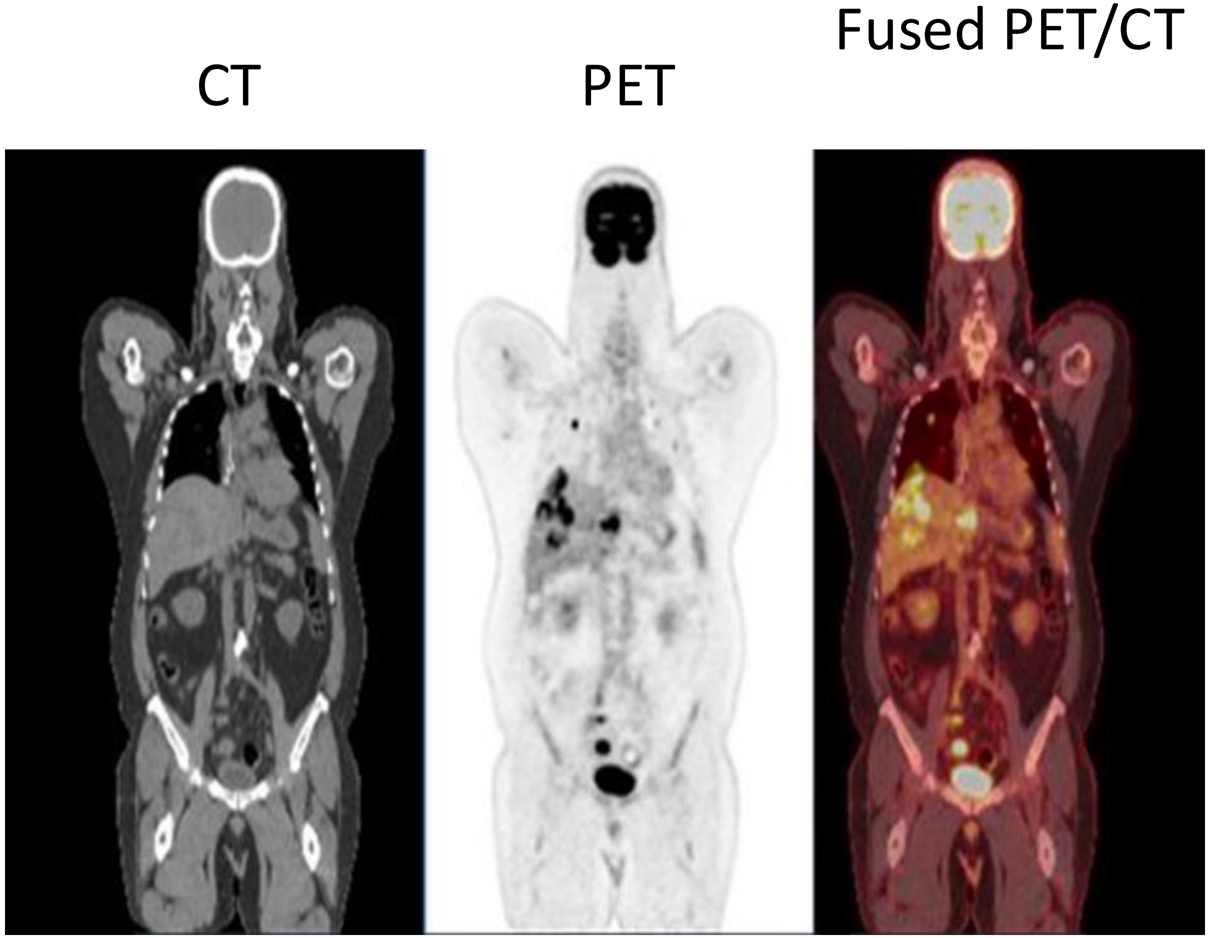
PET scans showing ^{68}Ga-PSMA distribution in a cancer patient before (left) and after (right) treatment



Shagera et al, J Nucl Med 63: 1191-98 (2022)

Hybrid Imaging

- SPECT and PET scanners often integrated with an anatomic imaging modality
  - SPECT/CT
  - PET/CT
  - PET/MRI
- Provides functional and anatomic imaging in same imaging session.



^{18}F-FDG PET/CT whole-body scan

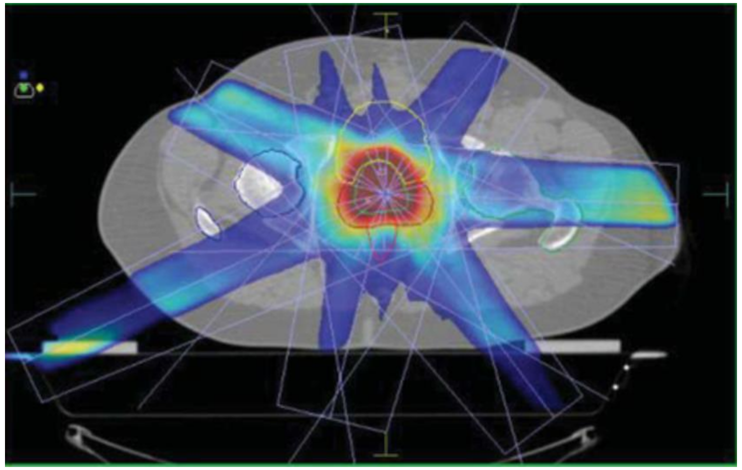
courtesy of ncpic.org

External Beam Radiation Therapy

- Widely used for cancer treatment
- Accelerator produces beams of high-energy photons, electrons or protons.
- Beam directions, intensity and energy carefully controlled to maximize dose to cancer while sparing other organs/tissues

Courtesy Varian

Typical photon/electron radiotherapy system (LINAC)

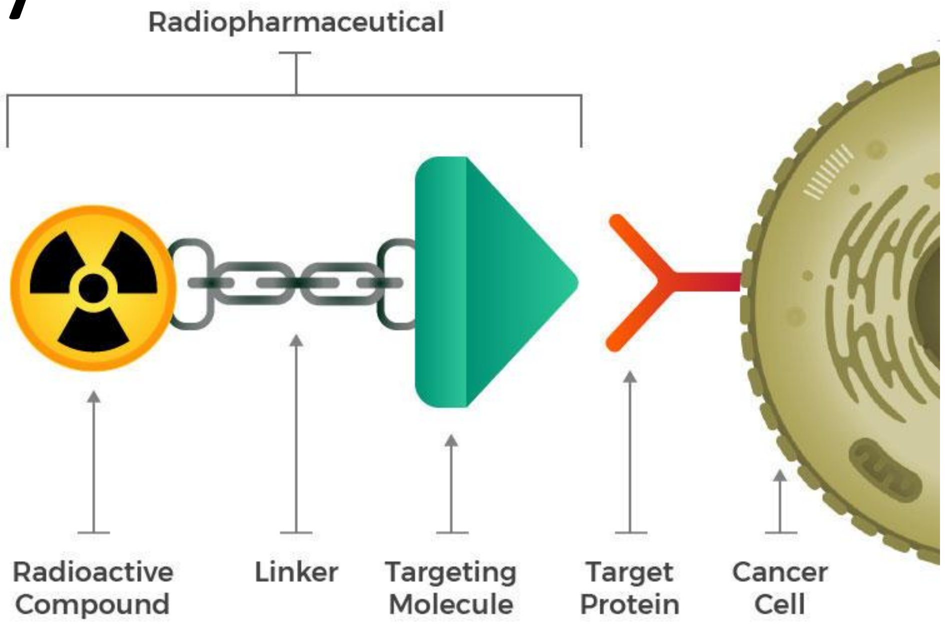


Treatment plan showing dose distribution for multiple intersecting beams delivering high dose to the prostate.

Sia et al, Cancers 2011, 3, 3419-3431

Internal Radionuclide Therapy

- Growing use for cancer treatment
- Injected radiopharmaceuticals that target tumors
- Labeled with radionuclides that emit energetic beta or alpha particles (e.g. ^{177}Lu) and can destroy tumor cells
- Useful for targeting some cancers that have spread



Radiopharmaceutical

Radioactive Compound

Linker

Targeting Molecule

Target Protein

Cancer Cell

Courtesy National Cancer Institute