The Impact of Radiation and Radioactive Isotopes on the Earth and its Life Forms

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Outline of Presentation

1. Background
2. Discovery of Nuclear Energy
3. Observed Impacts of radiation on life forms
4. Impact of natural radiation on the earth’s internal structure and magnetic fields
5. (TIME PERMITTING) An engineering/nuclear safety story (Fukushima related)

1. Background – My Own

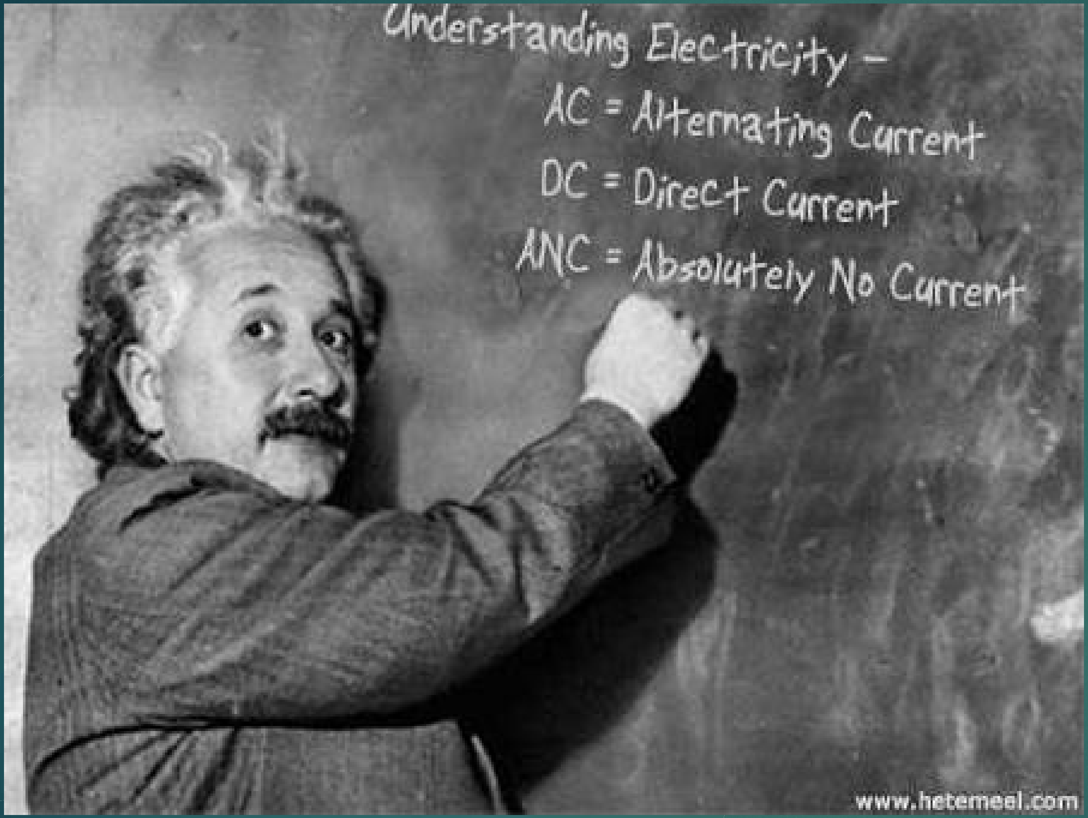
- Started working in Chalk River in 1985 after getting a PhD at the University of Toronto in Physical Chemistry
- Worked primarily on Laser Isotope Separation of Deuterium till 1997
- Moved to AECL's Engineering site in 1997 and worked on a variety of different product development projects
- Along the way became involved with SPEA and found myself in public debates with Greenpeace and many others regarding nuclear power

- About 10 years ago I gave a lecture in a graduate course on Environmental Engineering at U of T about the potential application of nuclear generated steam for extracting oil sands.
- This began a collaboration with Prof. Bryan Karney (Head of Interdisciplinary Sciences at U of T) and the Civil Engineering Department.
- A popular science course is taught there to 3rd and 4th year engineers called Terrestrial Energy Systems (CIV300) and I have taught that on a number of occasions.

- CIV300 seeks to explain “how the earth works” from an engineering perspective.
- It turns out that you can explain about 95% of all observable phenomena on earth if you understand the 1st Law of thermodynamics, the ideal gas law and concepts of convection, buoyancy and angular momentum coupling.
- But the course had nothing on nuclear energy, which is one of the most important forces in the universe and which plays a role in the evolution of our planet and our sun.

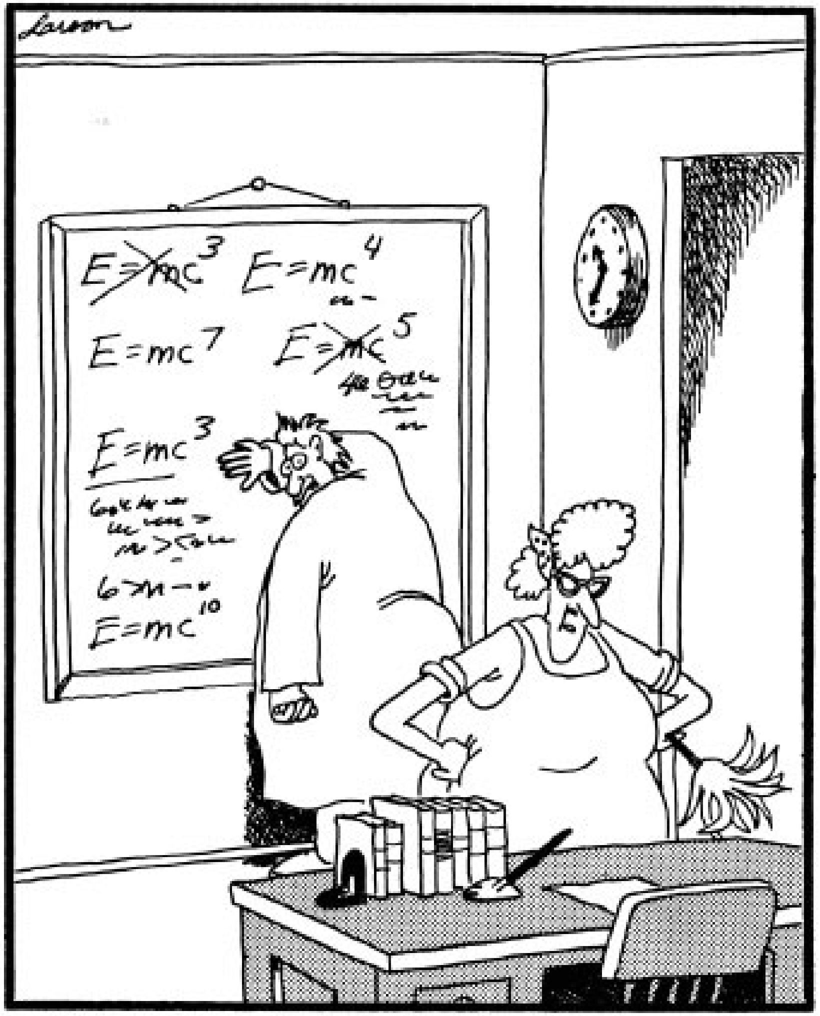
- This presentation is a summary of material that I added to the course on nuclear energy and radiation and why it is relevant.
- Students in most engineering schools, and U of T is no different, know very little about nuclear energy and radiation.
- So I had to start from basics
  - Some of this is old hat to many of you but there might be some things that are knew or that, at least, you haven't seen presented in this way.

2. Discovery of Nuclear Energy



- The notion of nuclear energy started with Albert Einstein.
- In a very famous paper written in 1905, on something called the Special Theory of Relativity, he came up with the idea that there was such a thing as nuclear energy.

The Eureka Moment!



"*Now* that desk looks better. Everything's squared away, yessir, squaaaaaared away."

From 'Valley of the Far Side' by Gary Larson
(Andrews and McMeel, Kansas City and New York)
ISBN 0-8362-2067-6

- Actually it didn't happen this way.
- The paper was about how time was relative but the speed of light was constant.
- Almost as an afterthought, in an appendix to the paper, he added something to the effect of: If you believe the rest of this paper then it follows that: $E = mc^2$

- IT IS REALLY AN ASTOUNDING STATEMENT. TO GIVE YOU AN IDEA OF WHAT IT MEANS CONSIDER HOW MUCH ENERGY THE AVERAGE HOUSE USES IN A YEAR (MY HOUSE FOR EXAMPLE).
- IN AN AVERAGE YEAR WE USE UP ABOUT 21,600 KILOWATT·HOURS OF ELECTRICITY = 7.8 X 10^{10} JOULES OF ENERGY
- WE ALSO HEAT OUR HOME WITH NATURAL GAS. IN AN AVERAGE YEAR WE USE ABOUT 5.0 X 10^{10} JOULES OF ENERGY.
- SO OUR TOTAL ENERGY USE IS ABOUT 1.28 X 10^{11} JOULES

What Does $e=mc^2$ Have to do With This?

IF I KNOW THE ENERGY OF SOMETHING AND I KNOW THE SPEED OF LIGHT, WHICH IS 3×10^8 METERS/SECOND THEN I CAN FIGURE OUT THE MASS.

SO $M = E/C^2$

IF YOU DO THE ARITHMETIC AND PLUG IN THE ENERGY I NEED TO RUN MY HOUSE FOR 12 MONTHS OF THE YEAR THEN I GET

0.0014 GRAMS

THIS IS ROUGHLY THE WEIGHT OF A FRAGMENT OF A FINGERNAIL CLIPPING.

SO EINSTEIN WAS SAYING THAT IF I COULD SOMEHOW EXTRACT ALL OF THE ENERGY FROM ATOMS THAT WEIGH ONLY AS MUCH AS A FINGERNAIL CLIPPING I CAN HEAT MY HOUSE AND PROVIDE ALL OF THE ELECTRICITY AND HEAT FOR IT IN A YEAR.

THIS WAS PRETTY HARD TO SWALLOW!

Could Einstein Really be Right?

WHAT EINSTEIN WAS PROPOSING SEEMED OUTRAGEOUS BUT HIS SPECIAL THEORY OF RELATIVITY HELD AND EVERYONE AGREED THAT $E=MC^2$ FOLLOWED FROM THE THEORY OF SPECIAL RELATIVITY AND NO ONE COULD FIND FAULT WITH HIS LOGIC.

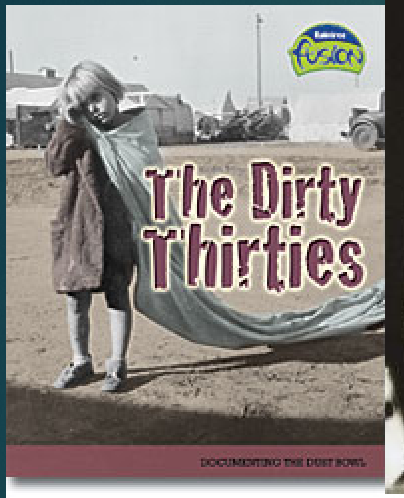
SO SCIENTISTS KEPT LOOKING FOR THIS MAGIC ENERGY ONLY TO DISCOVER THAT IT HAD ALREADY BEEN FOUND BEFORE EINSTEIN'S PAPER, JUST NEVER CONNECTED TO HIS FAMOUS EQUATION.

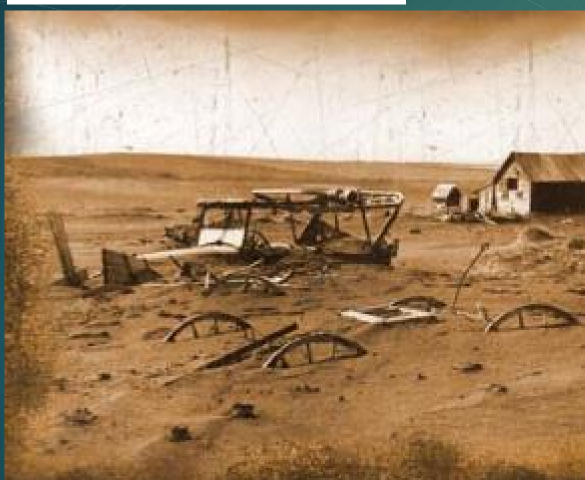
IT WAS DISCOVERED BY THESE TWO PEOPLE.

Marie and Pierre Curie

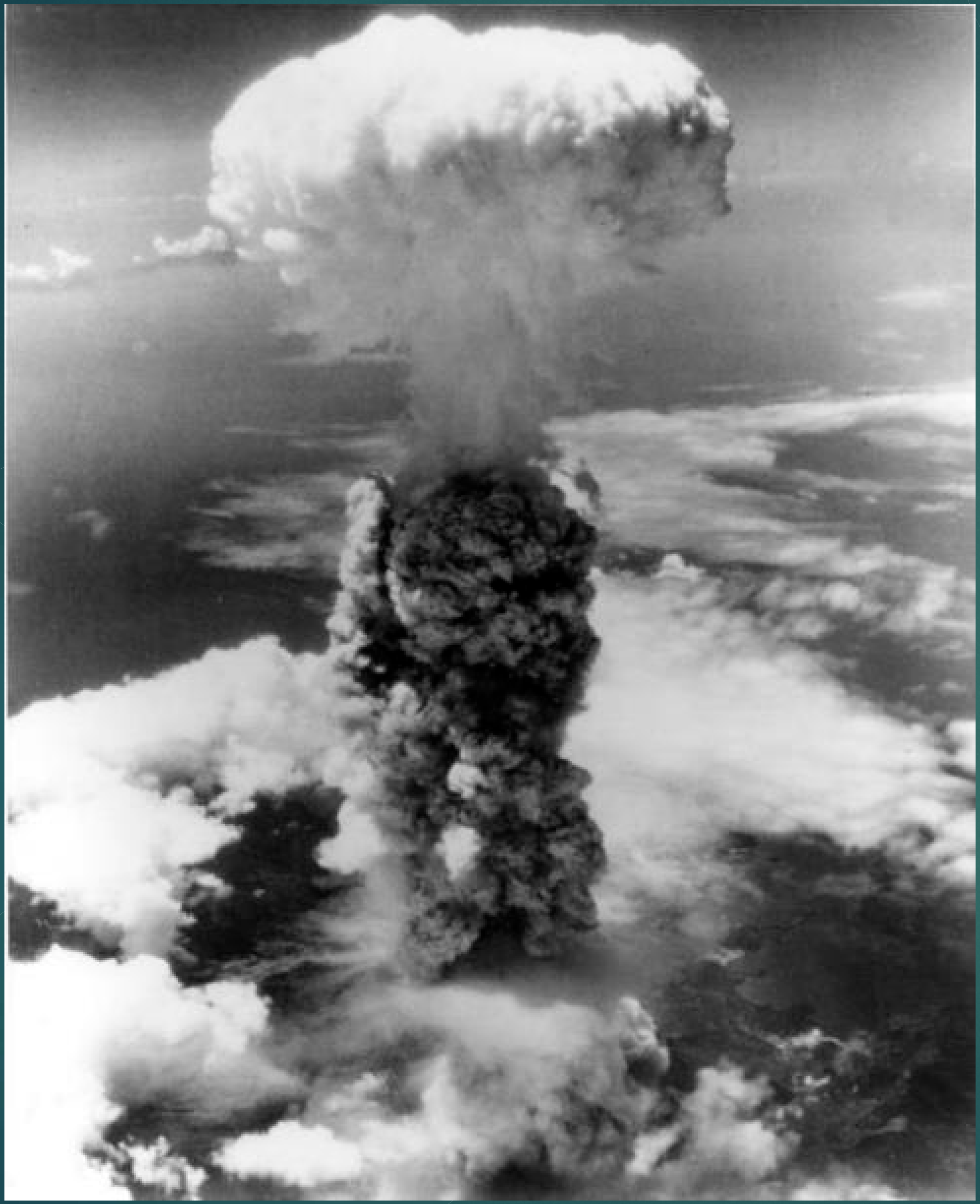
- They don’t look much like scientists in this picture (actually they are actors) but Marie Curie (inset) is arguably the greatest scientist who ever lived.
- To date she is the only scientist to win Nobel Prizes in both Physics (in 1903 with her husband) and in Chemistry in 1911.
- In particular they discovered Radium and observed that no matter now much light (hence energy) it gave off, they could not measure a decrease in its mass.

Exploitation of Nuclear Power





UNFORTUNATELY, WHEN SCIENTISTS STARTED TO TIE TOGETHER EINSTEIN'S THEORY WITH RADIOACTIVITY THE WORLD WAS FALLING APART. SOME PEOPLE SAW NUCLEAR ENERGY AS THE ULTIMATE WEAPON AND THERE WAS A RACE TO DEVELOP THE FIRST NUCLEAR WEAPON.



First exploitation of nuclear energy[1]

1 – I'm always told to never show a slide like this in talks about nuclear energy. But it was the first exploitation.

- Nuclear energy has had kind of a “bad rap” ever since.
- It should also be pointed out that pioneering scientist Marie Curie died of Aplastic Anemia, which is known to be associated with radiation.
- In any event, there were (and are) many reasons for people to be wary and fearful of radiation.

3. Observed Impacts of Radiation on Life Forms

- The radiation that we speak of here is ionizing radiation – i.e. radiation of an energy that can strip one or more electrons from an atom can be UV, x-rays, gamma rays, alpha particles or beta particles/rays.
- We are bathed in ionizing radiation from many, many sources. We get ionizing radiation from:
  - The sun (UV is the most common) – we are protected from the sun's more harmful ionizing radiation by the earth's magnetic fields and from UV by the ozone layer.
  - Long dead suns (cosmic rays)
  - Fossil fuel combustion
  - granite (which contains trace amounts of uranium) and, thus, radon gas
  - Foods rich in potassium and people who contain potassium (all people)
  - medical treatments, TV's, microwaves, watches , smoke detectors, and even, but not especially, nuclear power plants

- Needless to say, the life form that concerns us the most is Homo Sapiens but there are serious ethical problems associated with determining these impacts through experimental observation.
- To get good statistics it is necessary to expose a large population of humans to large amounts of radiation and then it is necessary to follow the offspring of those exposed for a number of generations.
- Radiation induced genetic damage, for example, can manifest itself in those exposed or to their offspring or their offsprings' offspring.

- The best statistical data for mammals consists of experiments carried out on mice but mice are not humans.
- Nonetheless data from mouse exposure is commonly used because it is considered conservative.
- Risks are also assessed using the assumption that zero risk only exists where there is no exposure (Linear No Threshold Model)
- Now although it is certainly unethical to carry out experiments on humans, of the sort carried out on mice (and some would argue that even those are not ethical), it turns out that there is a large body of data from survivors of the atomic weapons dropped on Hiroshima and Nagasaki.

What do we know from the Atomic Bomb exposures in Japan?

Quite a lot!

From a strictly scientific point of view, there are a number of things that are known.

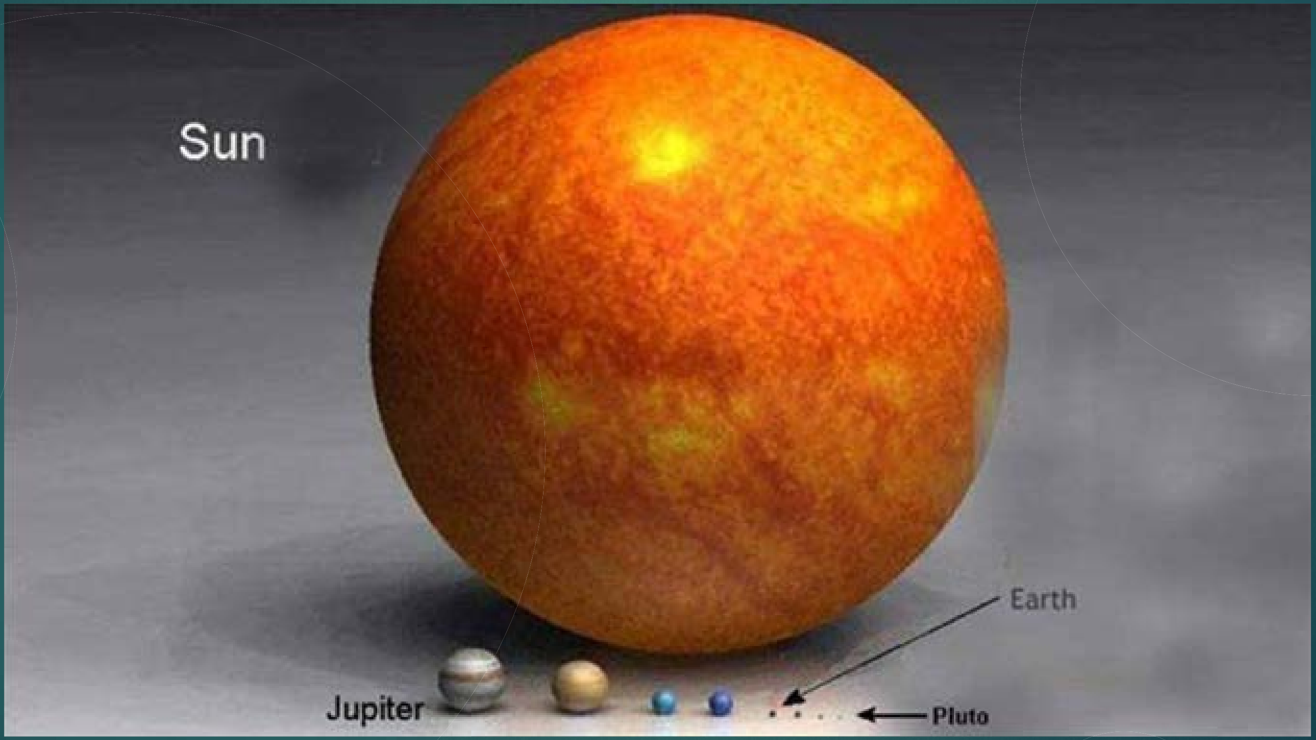
- The intensity of the explosions is known
- For survivors, their location at the time of the blast was known
- We know that the radiation exposure was proportional to the initial intensity at ground zero/(distance from ground zero)^2
- From these things we know the following:

- Exposure to 5,000 mSv means death will come in days
- Exposure to 3,500 mSv means death to 50% of people if left untreated
- Exposure to 2,000 mSv and you get radiation sickness (vomiting, diarrhea)
- Exposure to 1,000 mSv means a 5.5 % increase in death by cancer over a life time based on the LNT model
- Because 25% of all people will get cancer in their life time, this exposure will increase that chance from 25% to 30.5
- Actual data from survivors of the Hiroshima and Nagasaki bombs show approximately 2% increase in cancers for survivors
- Significantly no health effects have been observed in the offspring of survivors (Genetics Society of America)

What about Natural Radiation

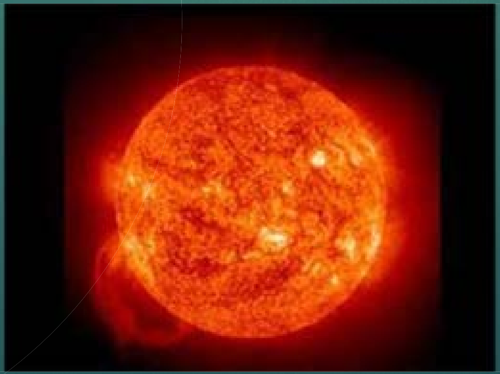
- Background radiation in Canada is approximately 2.7 mSv per year. Largest source of exposure is from Radon.
- Radiation paradox – we start to see slight effects in the blood at 200 mSv yet people in Ramsar, Iran are exposed to 260 mSv per year and they tend to be as healthy and have the same or lower cancer rates as world averages.
- Studies of people in the area have shown that there were no differences in laboratory tests of the immune systems, and no noted differences in hematological alterations between those in Ramsar and people in more normal low background areas. (Health Phys. 2002 Jan;82(1):87-93).
- This suggests that an adaptive response might be induced by chronic exposure to natural background radiation.

4. Impact of natural radiation on the earth's internal structure and magnetic fields



Let’s back up a little bit and look at the Sun

- As the temperature of a body increases, the radiation per second also increases, or, any body with temperature generates heat
- Stefan-Boltzmann law
- **$E = \sigma T^4$** – energy generated in Watts per m^2 of surface area where
- **$\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4} , T in KELVIN**
- This is approximate to ’black body radiation’



Quantifying the Sun

- **$E=\sigma T^4$** – energy generated per m^2 of surface area
- Temp. of the sun is 5,778K

$E = 5.67\times10^{-8} \times (5{,}778)^4$

$E = 63 \times 10^6\ Wm^{-2}$

- This is the energy output per second, or power, of the sun
- 63 MW per m^2

Quantifying the Sun…in Total

$E = 63x10^6\ Wm^{-2}$

- We need to multiply this by the sun's surface area, $4\pi r^2$ to calculate the total power / energy output per second

$E_{total} = 63x10^6 \times 4\pi(696x10^6)^2$

$= 3.8 \times 10^{26}$ W

What does Earth Get?

- That energy will be spread out as a sphere and the intensity will drop according to the inverse square law
- At our orbit we can therefore calculate what is received at the Earth's edge per m^2 i.e the energy or *solar intensity* at our orbit

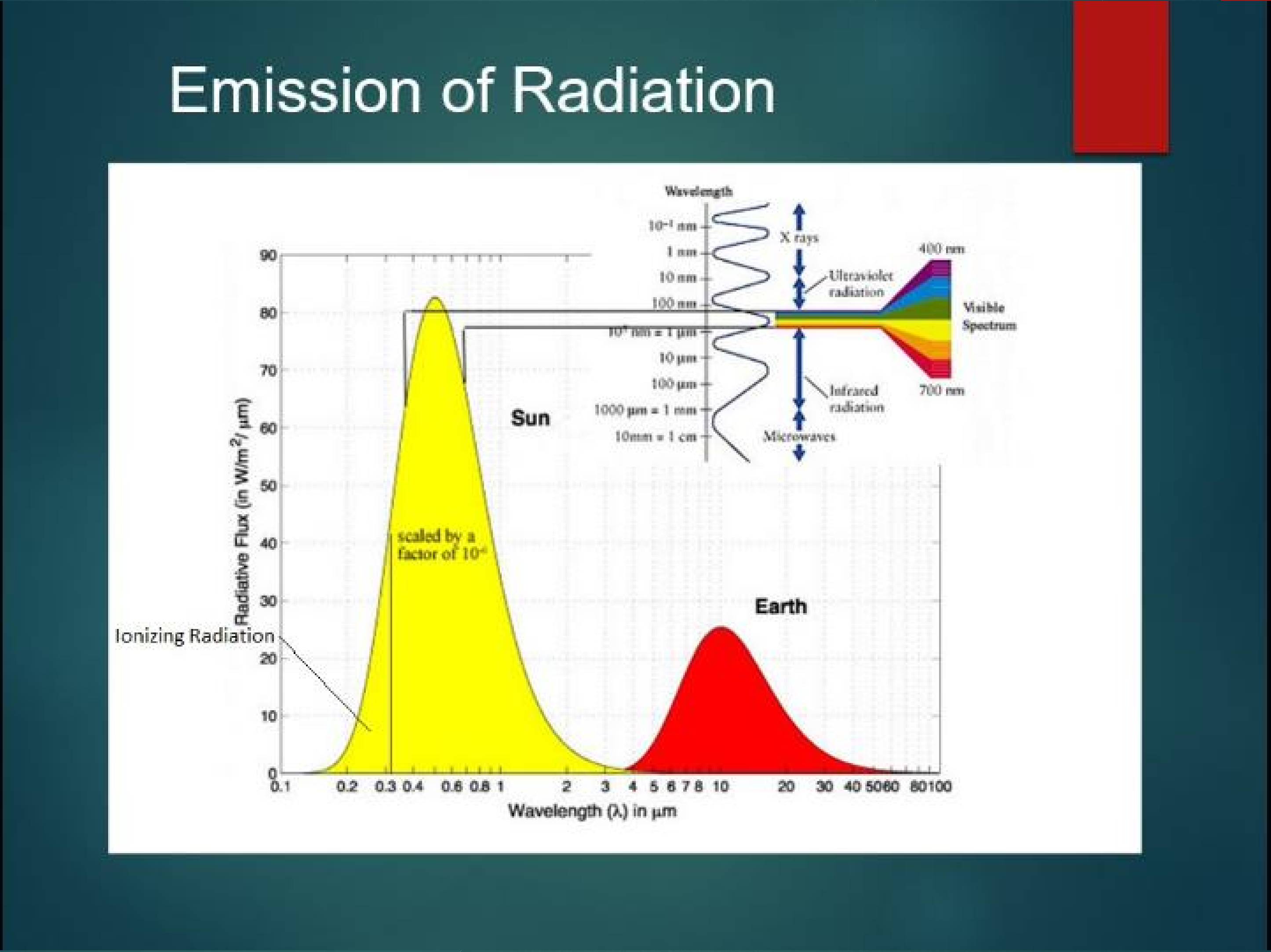
Solar intensity at Earth's orbit

= 3.8×10^{26} / $4\pi r^2$ where r is the distance from the sun to the Earth. (Recall from last slide that 3.8×10^{26} is the sun's total output)

= 3.8×10^{26} / $4\pi \times (149 \times 10^9)^2$

= 1,368 Wm^{-2}

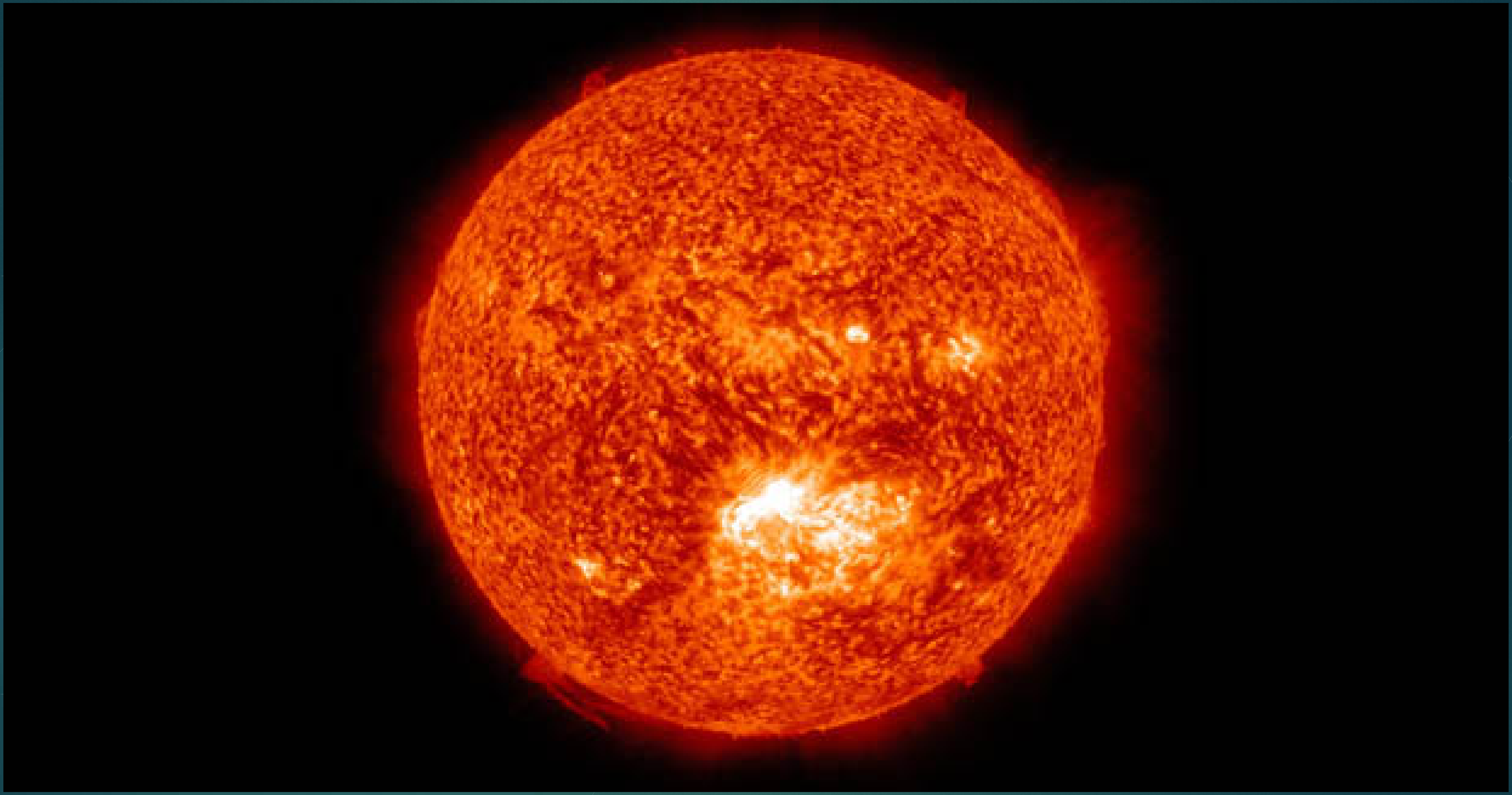
Emission of Radiation



- But the sun is not simply a “black body” that gives off radiation proportional to its surface temperature.
- It also has a Corona of highly charged particles consistent with a temperature of a million or more degrees. This corona consists of high energy electrons, protons, positrons and alpha particles.
- Some are energetic enough to escape the gravitational pull of the sun and represent a steady stream of charged particles that move outwards towards the planets.
- Occasionally (roughly every 11 years) the sun spits out large bursts of plasma known as coronal mass ejections (CMEs), or solar storms. More common during the active period of the cycle known as the solar maximum, CMEs have a stronger effect than the standard solar wind.

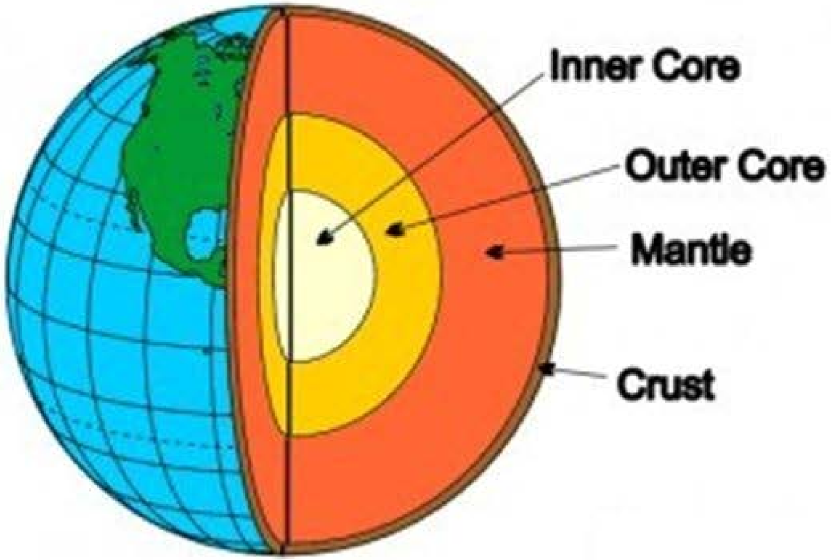
- If the material carried by the solar wind reached a planet's surface, its radiation would do severe damage to any life that might exist. Earth's magnetic field serves as a shield, redirecting the material around the planet so that it streams beyond it.
- So why do we have a magnetic field? The other terrestrial planets (Mercury, Venus, Mars and our moon) have either no magnetic field or a very weak one.
- The answer lies in the structure of the interior of the earth, combined with it rotational period.

Earth When First Formed



- It is believed that when the earth was formed, about 4.5 billion years ago, it was molten. Over time it has cooled through radiative emission.
- Estimates of the earth's age based on scientific principles have been made since the 19th century. Lord Kelvin estimated, based on thermodynamic principles, that since the earth was now solid, it could not be more than 100 million years old.
- His assumptions turned out to be spectacularly wrong but, to make a long story short, the internal temperature of the earth cannot be explained simply by the residual primordial heat of its formation.

Structure of the Earth

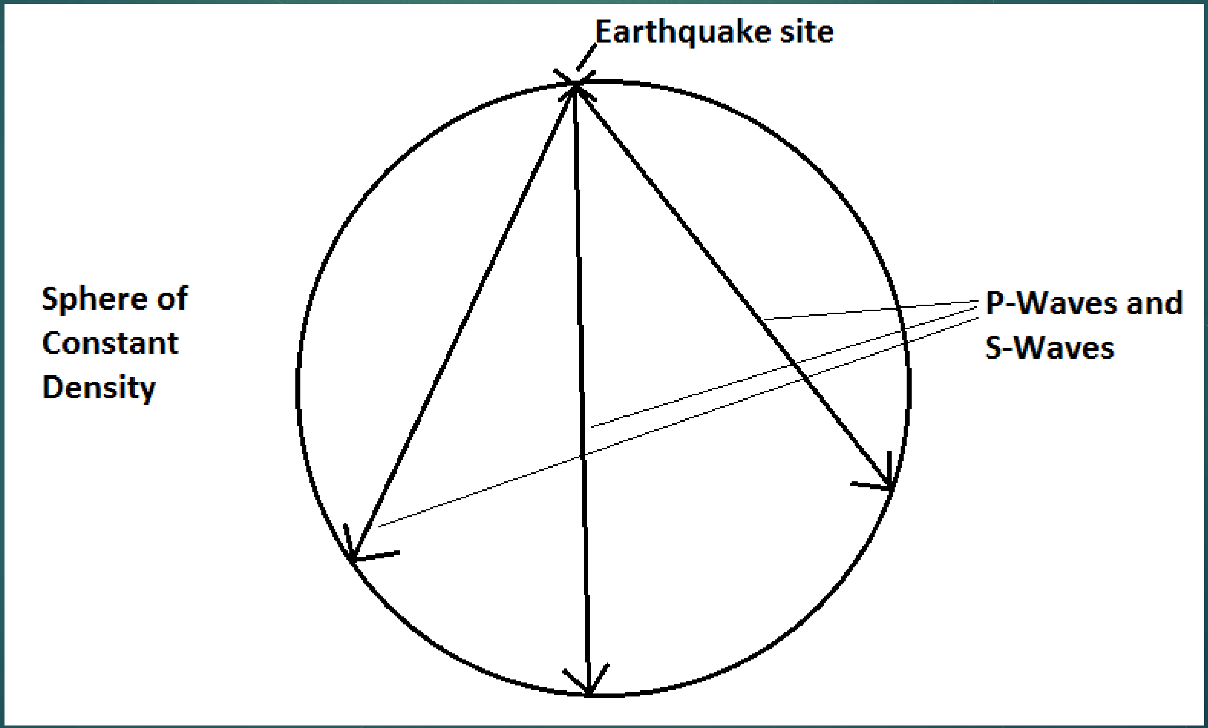


- **Crust** = thin, rocky outer layer
- **Mantle** = properties of solid but flows slowly
- **Outer core** = liquid nickel and iron
- **Inner core** = solid liquid and iron

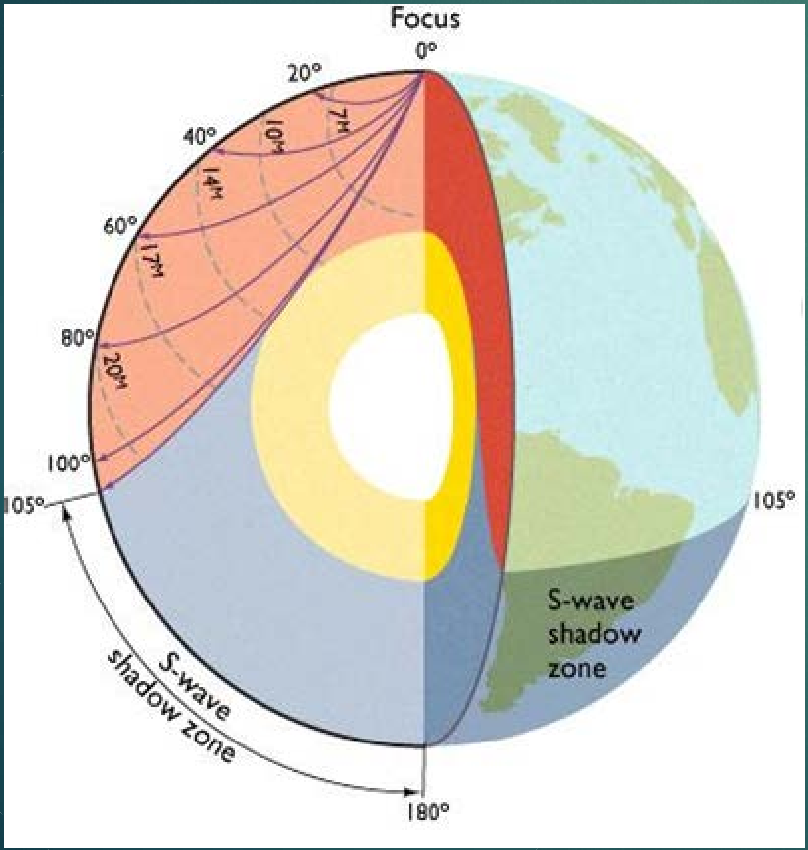
This is what we understand the structure of the earth to be today

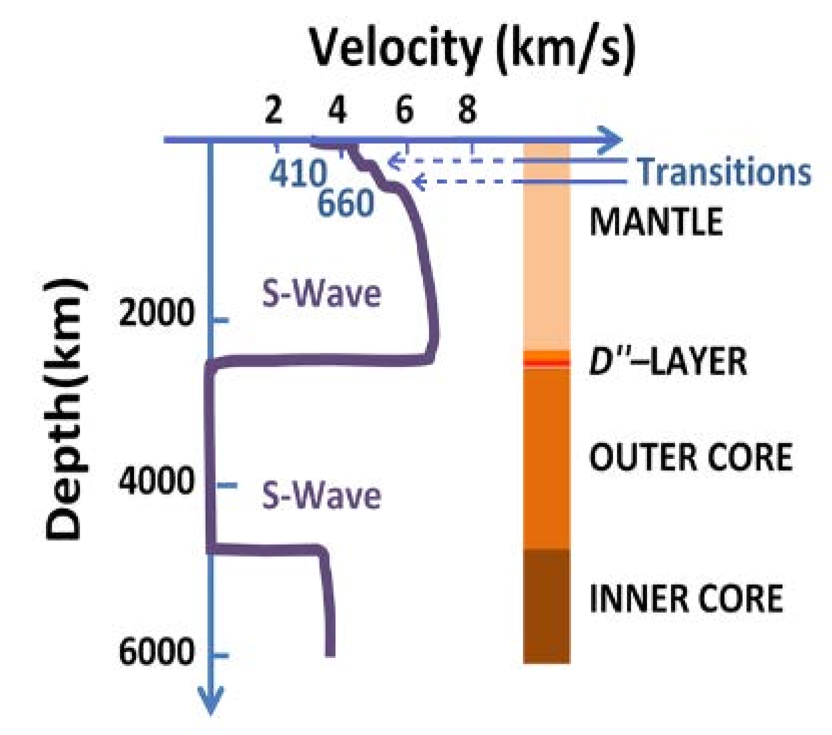
- As an aside, how do we know what the structure of the earth is? Since we haven't been able to drill down much more than 10s of km.
- Nobody has ever taken the mythical journey to the centre of the Earth, but by studying the way shockwaves from earthquakes travel through the planet, physicists have been able to work out its likely structure.

- P and S waves were first discovered by Richard Oldham in 1900.
- He used this discovery and some basic knowledge of physics to deduce that the earth had a solid and dense core.
- How, you might ask?
- Well, if the earth were perfectly homogeneous then the P and S waves generated by earthquakes would propagate in straight lines through the earth
- Note that "P" is a compression wave and "S" is a shear wave.

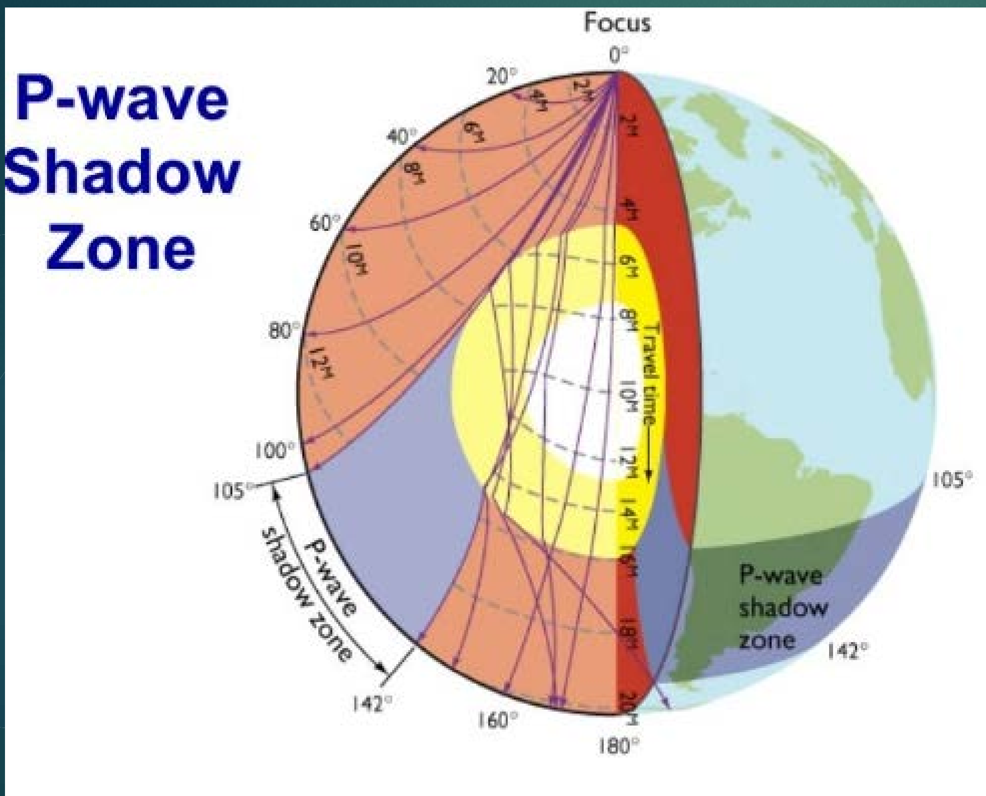


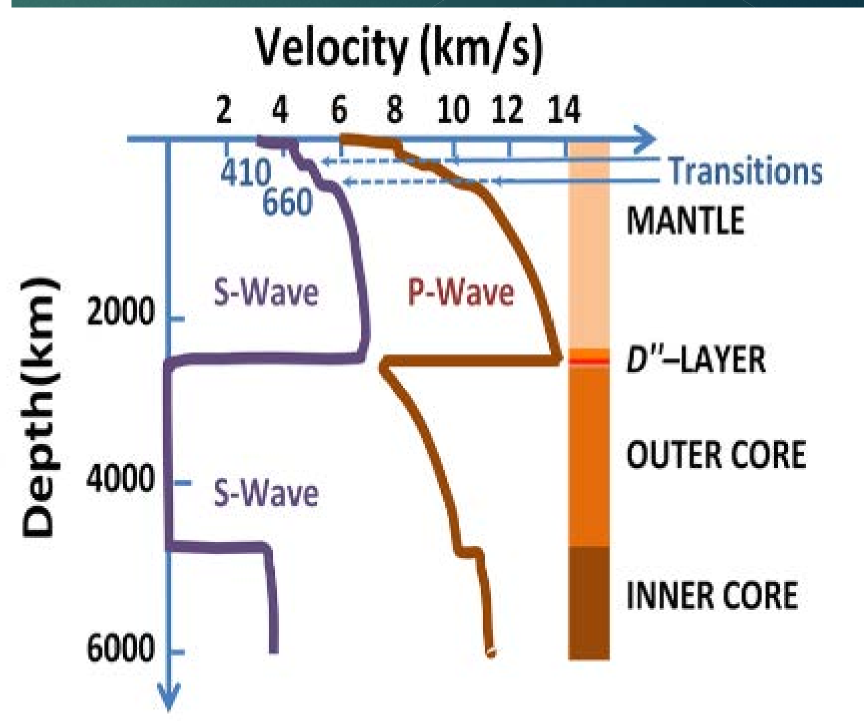
- Nothing is that simple of course
- What Oldham observed was that S-waves did not make it through the earth. Indeed, there was something called an S-wave shadow, from 105° to 180° if you divide the earth into a hemisphere.



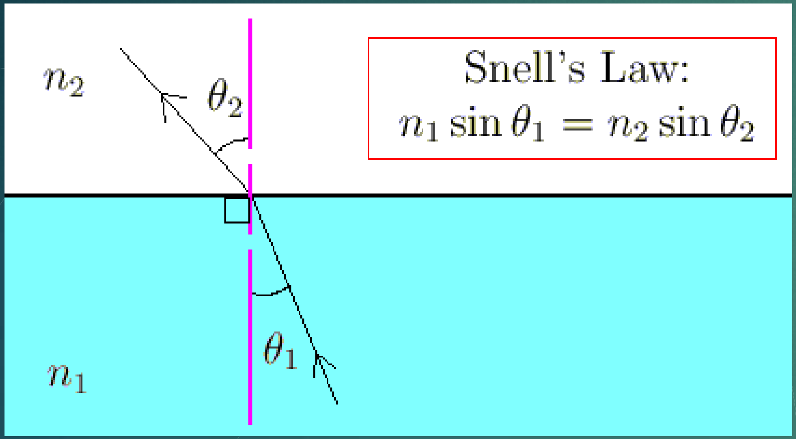


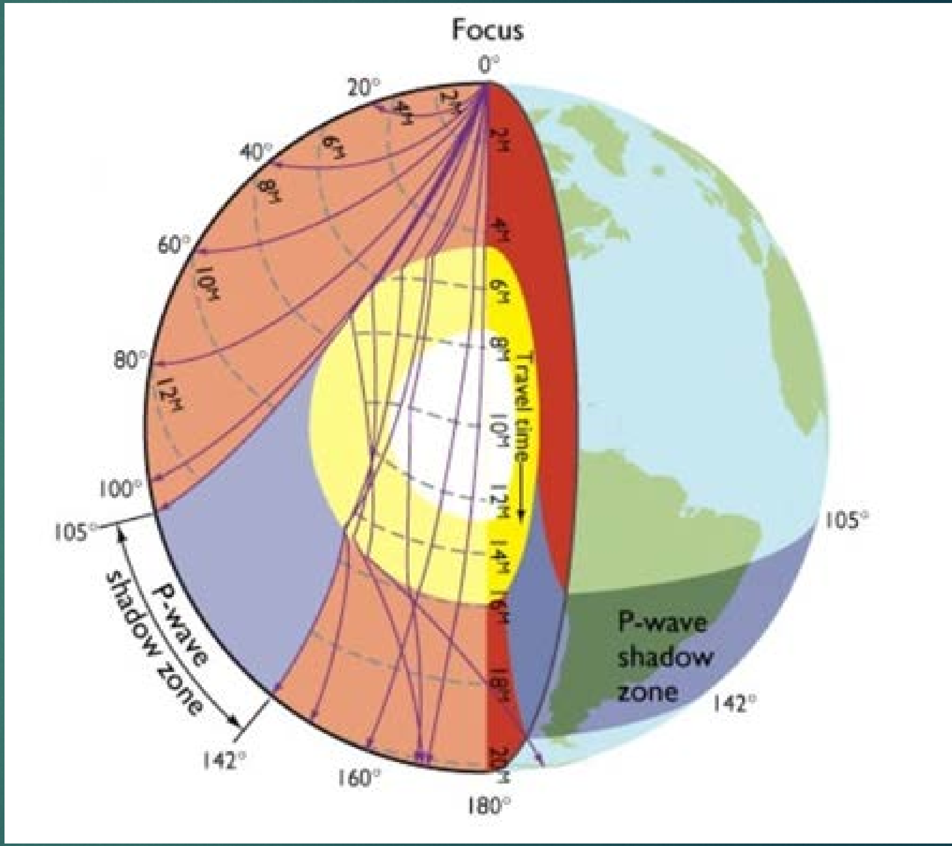
- So the S-wave shadow suggested that the centre of the earth was liquid, since shear waves can't travel through a liquid (liquids have no shear strength)
- P-waves by contrast can travel directly through the centre of the earth
- but there is also a region of the earth, where P-waves are not seen, something called a P-wave shadow
- This one is not as big, between about 105° and 142°
- Why is this?
- Well it turns out that it is completely consistent with the S-wave observation.


P-wave
Shadow
Zone
Focus
0°
20°
40°
60°
80°
100°
105°
142°
160°
180°
105°
142°
Travel time
P-wave
shadow zone
P-wave
shadow
zone


Velocity (km/s)
2 4 6 8 10 12 14
Transitions
410
660
MANTLE
S-Wave
P-Wave
D″–LAYER
OUTER CORE
S-Wave
INNER CORE
Depth(km)
2000
4000
6000

- Remembering Snell's Law makes it easier to understand why there is a P-shadow

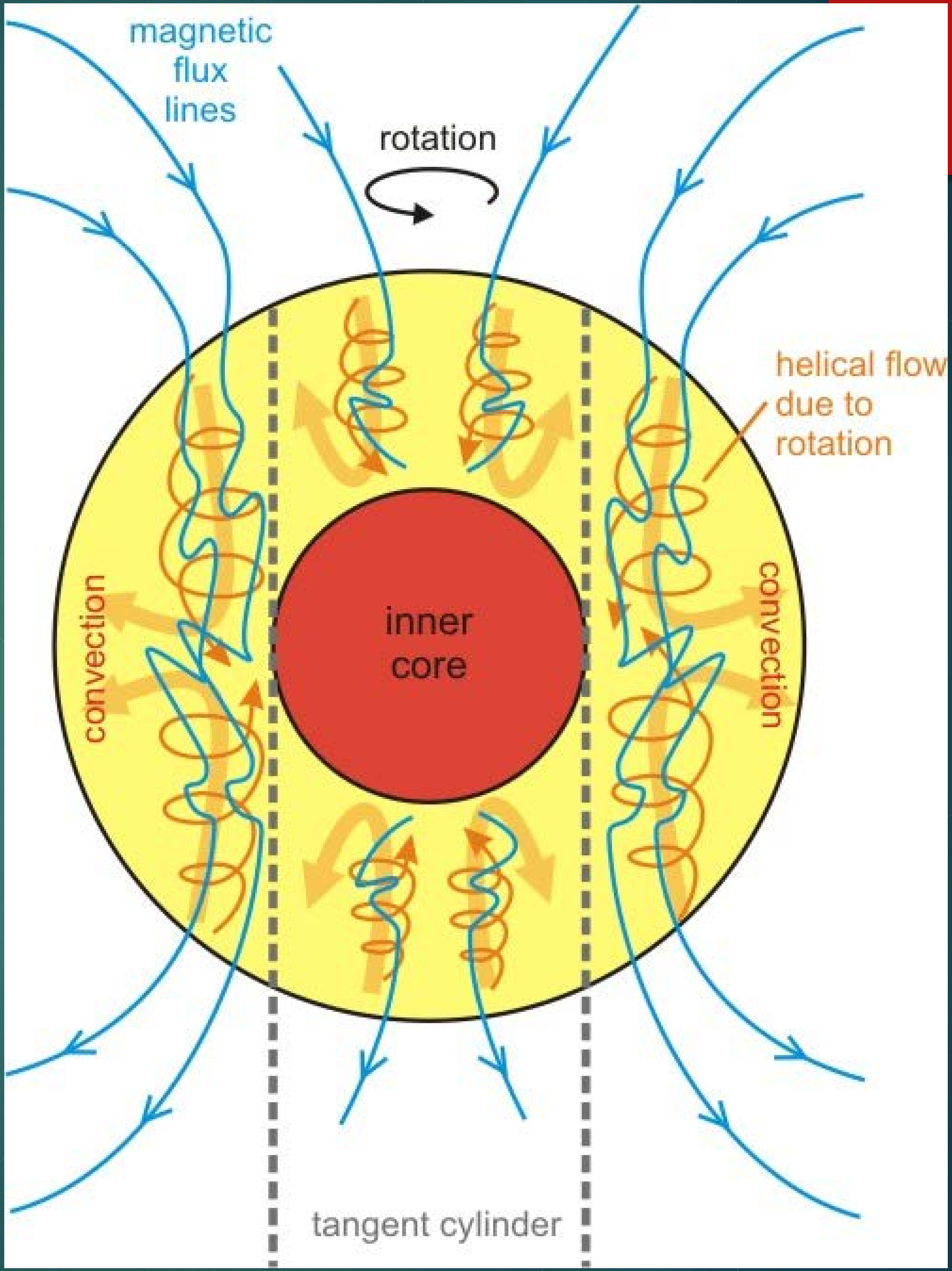




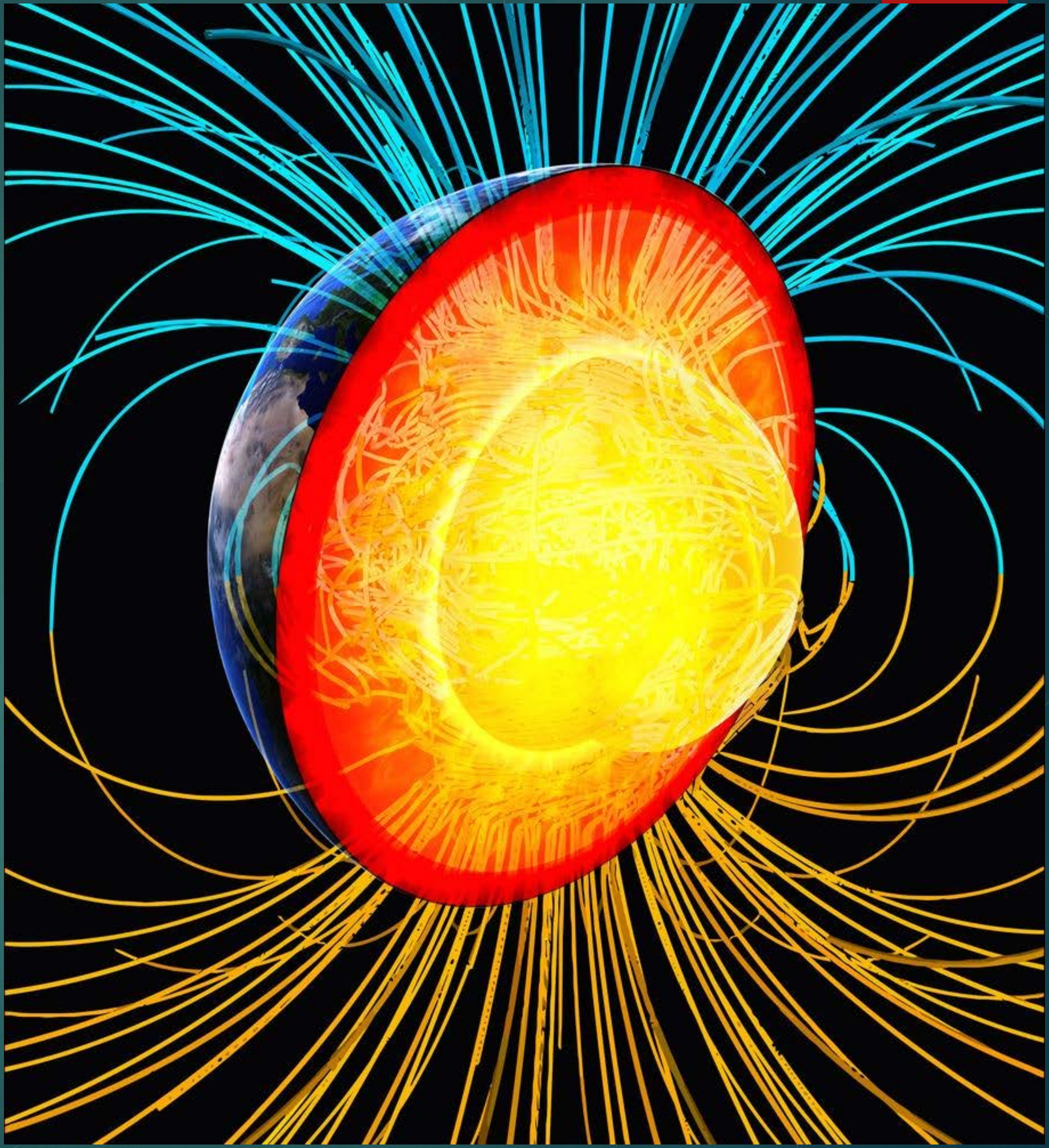
- Seismic waves bend inward towards the core, at the interface between the mantle, because the liquid is more dense than the mantle

- So we know from analysis of seismic waves not only the structure of the interior of the earth (i.e. that the outer core is liquid and the inner core is solid) but the size of the inner and outer core
- Knowing this helps us to understand why the earth has a magnetic field
- Right at the heart of the Earth is a solid inner core, two thirds of the size of the Moon and composed primarily of iron. At a hellish 5,700°C, this iron is as hot as the Sun's surface, but the crushing pressure caused by gravity prevents it from becoming liquid.
- Surrounding this is the outer core, a 2,000 km thick layer of iron, nickel, and small quantities of other metals. Lower pressure than the inner core means the metal here is fluid.

Differences in temperature, pressure and composition within the outer core cause convection currents in the molten metal as cool, dense matter sinks whilst warm, less dense matter rises. The Coriolis force, resulting from the Earth's spin, also causes swirling whirlpools.



This flow of liquid iron generates electric currents, which in turn produce magnetic fields. Charged metals passing through these fields go on to create electric currents of their own, and so the cycle continues. This self-sustaining loop is known as the geodynamo.



The fields create an impenetrable barrier in space that prevents the fastest, most energetic electrons from reaching Earth. The fields are known as the Van Allen belts, and they are what enables life to thrive on the surface of the Earth.

The earth's magnetic field extends several tens of thousands of kilometers into space, protecting the Earth from the charged particles of the solar wind and cosmic rays that would otherwise strip away the upper atmosphere, including the ozone layer that protects the Earth from harmful ultraviolet radiation.

But why is the earth so hot inside?

- Traditional thermodynamic heat loss calculations would predict that the earth should have solidified by now.
- To better understand the sources of the Earth's heat, scientists studied antineutrinos, elementary particles that, like their neutrino counterparts, only rarely interact with normal matter
- Using the Kamioka Liquid-scintillator Antineutrino Detector (KamLAND) located under a mountain in Japan, they analyzed geoneutrinos — ones emitted by decaying radioactive materials within the Earth — over the course of more than seven years.

- If one also knows how rarely such an antineutrino interacts with normal matter, one can then estimate how many antineutrinos are being emitted and how much energy they are carrying in total.
- These measurements have suggested that at least half of the earth’s internal heat is generated by radioactive decay.
- This would be decay of U-238, Th-232, K-40 and U-235
- The contribution of U-235 would have been more important in the past, because of its 700 million year half life.
- The heat generated is estimated to be on the order of 20 TW

So is natural radioactive decay responsible for the protective magnetic field that surrounds the earth?

- It would probably be fair to say that natural radioactive decay is responsible for there still being a protective magnetic field around the earth since it has greatly slowed down the cooling of the earth.
- Mercury, our moon and Mars have solidified.
- Although they are likely made of the same materials as the earth, they are smaller and since they cool through radiative emission from the surface, the ratios of surface area to mass are bigger for smaller objects than the earth

- The moon, Mars and Mercury have no (or very little) atmosphere, hence no greenhouse gases either. – Note that GHGs are actually a good thing in moderation.
- Venus has a very thick atmosphere and is believed to be much hotter inside than the earth but it is estimated to be so hot, that there is not as big a temperature gradient inside to drive convection. In addition the rotational period is very, very slow compared to earth so there is very little in the way of Coriolis forces to drive a geodynamo.
- So things have to be "just right" for a solid planet like ours to have a magnetic field and we likely have radioactive decay to thank for there still being one.

Summary

- In various presentations that I have made and debates that I have engaged in, it always surprises me that nuclear energy, and its corollary (radiation) is seen as an unnatural phenomenon.
- But the sun, that makes life on earth possible, is a nuclear fusion reactor.
- The very atoms that make up our earth, and our bodies come from the collapse of other giant fusion reactors (stars in our galaxy and others).
- We are, as I tell my students, made of "stardust" left over from the implosion of large natural fusion reactors.
- Nuclear energy and radiation are all around us all the time. That doesn't mean its harmless (far from it) but it is the most natural thing in the world.

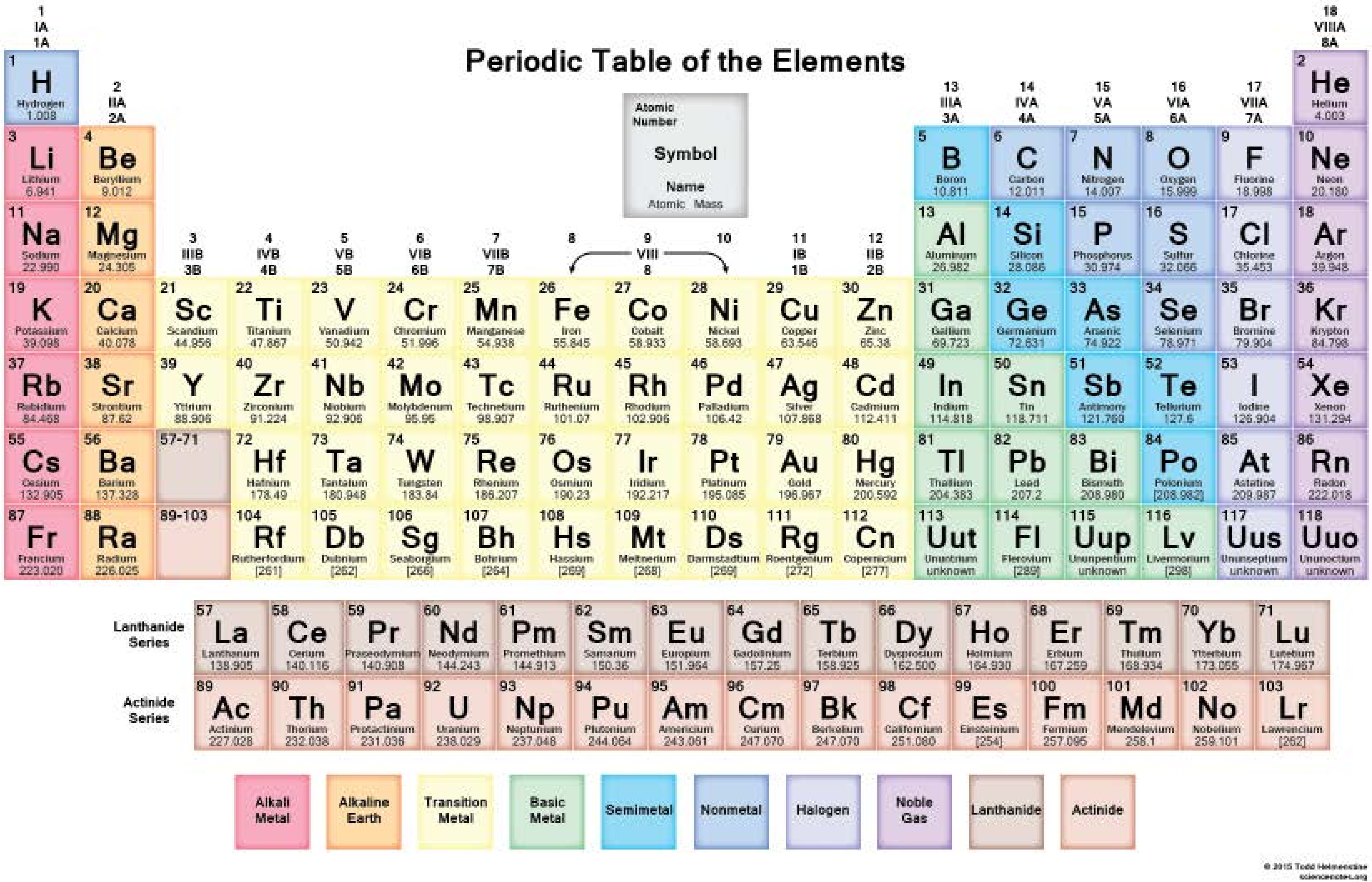
An Engineering/Safety Story
What happened at Fukushima – in a Nutshell

When it comes to the Tsunami in March 2011 in Japan the first thing that most people remember is what happened at Fukushima Daichi, a 4-unit nuclear station that was destroyed as a result of the Tsunami

It is an interesting engineering story because the plant was designed to withstand a tsunami, but clearly it did not.

To understand how this happened you first have to go back to some basics - the periodic table

You may have noticed that as elements in the periodic table get heavier the ratio of neutrons to protons increases



Periodic Table of the Elements
1 IA 1A
2 IIA 2A
3 IIIB 3B
4 IVB 4B
5 VB 5B
6 VIB 6B
7 VIIB 7B
8
9 VIII 8
10
11 IB 1B
12 IIB 2B
13 IIIA 3A
14 IVA 4A
15 VA 5A
16 VIA 6A
17 VIIA 7A
18 VIIIA 8A
Atomic Number
Symbol
Name
Atomic Mass
1 H Hydrogen 1.008
2 He Helium 4.003
3 Li Lithium 6.941
4 Be Beryllium 9.012
5 B Boron 10.811
6 C Carbon 12.011
7 N Nitrogen 14.007
8 O Oxygen 15.999
9 F Fluorine 18.998
10 Ne Neon 20.180
11 Na Sodium 22.990
12 Mg Magnesium 24.305
13 Al Aluminum 26.982
14 Si Silicon 28.086
15 P Phosphorus 30.974
16 S Sulfur 32.066
17 Cl Chlorine 35.453
18 Ar Argon 39.948
19 K Potassium 39.098
20 Ca Calcium 40.078
21 Sc Scandium 44.956
22 Ti Titanium 47.867
23 V Vanadium 50.942
24 Cr Chromium 51.996
25 Mn Manganese 54.938
26 Fe Iron 55.845
27 Co Cobalt 58.933
28 Ni Nickel 58.693
29 Cu Copper 63.546
30 Zn Zinc 65.38
31 Ga Gallium 69.723
32 Ge Germanium 72.631
33 As Arsenic 74.922
34 Se Selenium 78.971
35 Br Bromine 79.904
36 Kr Krypton 84.798
37 Rb Rubidium 84.468
38 Sr Strontium 87.62
39 Y Yttrium 88.906
40 Zr Zirconium 91.224
41 Nb Niobium 92.906
42 Mo Molybdenum 95.95
43 Tc Technetium 98.907
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.906
46 Pd Palladium 106.42
47 Ag Silver 107.868
48 Cd Cadmium 112.411
49 In Indium 114.818
50 Sn Tin 118.711
51 Sb Antimony 121.760
52 Te Tellurium 127.6
53 I Iodine 126.904
54 Xe Xenon 131.294
55 Cs Cesium 132.905
56 Ba Barium 137.328
57-71
72 Hf Hafnium 178.49
73 Ta Tantalum 180.948
74 W Tungsten 183.84
75 Re Rhenium 186.207
76 Os Osmium 190.23
77 Ir Iridium 192.217
78 Pt Platinum 195.085
79 Au Gold 196.967
80 Hg Mercury 200.592
81 Tl Thallium 204.383
82 Pb Lead 207.2
83 Bi Bismuth 208.980
84 Po Polonium [208.982]
85 At Astatine 209.987
86 Rn Radon 222.018
87 Fr Francium 223.020
88 Ra Radium 226.025
89-103
104 Rf Rutherfordium [261]
105 Db Dubnium [262]
106 Sg Seaborgium [266]
107 Bh Bohrium [264]
108 Hs Hassium [269]
109 Mt Meitnerium [268]
110 Ds Darmstadtium [269]
111 Rg Roentgenium [272]
112 Cn Copernicium [277]
113 Uut Ununtrium unknown
114 Fl Flerovium [289]
115 Uup Ununpentium unknown
116 Lv Livermorium [298]
117 Uus Ununseptium unknown
118 Uuo Ununoctium unknown
Lanthanide Series
57 La Lanthanum 138.905
58 Ce Cerium 140.116
59 Pr Praseodymium 140.908
60 Nd Neodymium 144.243
61 Pm Promethium 144.913
62 Sm Samarium 150.36
63 Eu Europium 151.964
64 Gd Gadolinium 157.25
65 Tb Terbium 158.925
66 Dy Dysprosium 162.500
67 Ho Holmium 164.930
68 Er Erbium 167.259
69 Tm Thulium 168.934
70 Yb Ytterbium 173.055
71 Lu Lutetium 174.967
Actinide Series
89 Ac Actinium 227.028
90 Th Thorium 232.038
91 Pa Protactinium 231.036
92 U Uranium 238.029
93 Np Neptunium 237.048
94 Pu Plutonium 244.064
95 Am Americium 243.061
96 Cm Curium 247.070
97 Bk Berkelium 247.070
98 Cf Californium 251.080
99 Es Einsteinium [254]
100 Fm Fermium 257.095
101 Md Mendelevium 258.1
102 No Nobelium 259.101
103 Lr Lawrencium [262]
Alkali Metal
Alkaline Earth
Transition Metal
Basic Metal
Semimetal
Nonmetal
Halogen
Noble Gas
Lanthanide
Actinide
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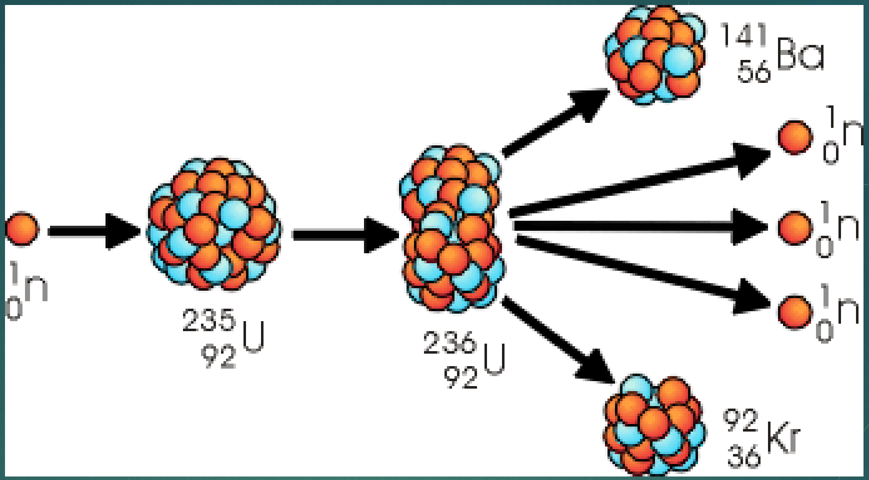
- By the time you get to Uranium, which is the heaviest naturally occurring element, the atomic number is 92 but the average weight is about 238, so on average there are 54 more neutrons than protons
- That is about what you need to keep the nucleus stable – sort of
- Strictly speaking there is also U-235, which is a quasi stable isotope that has 51 more neutrons than protons
- The isotopes of uranium are quasi stable.
- U-238 has a half life of 4.47 Billion years – pretty stable
- U-235 has a half life of 704 million years – still pretty stable
- e.g. half life of Hg-202, the most abundant mercury isotope, = ∞

U-235 has one really important property – namely that it is the only naturally occurring fissile isotope



Now this (above) is not the only fission reaction – there are many leading to atoms that span the entire periodic table but it is one of those with the largest branching ratio

What this picture shows is that after U-235 absorbs a neutron it becomes unstable and splits into two smaller elements with the release of 3 prompt neutrons – that is the essence of the chain reaction that can occur if engineered properly.

But look at how neutron rich the fragments are even after the prompt neutrons are released

For example, Barium with an atomic number of 56 has an atomic weight of 141 so that is 85 neutrons

But Naturally occurring barium, i.e. barium not made in the core of a nuclear reactor, has an atomic weight of 137

Similarly, naturally occurring krypton has an atomic weight of 84.8, not 92

So the process of nuclear fission generates fragment atoms that are, in almost all cases, neutron rich and therefore generally unstable and radioactive

Some have radioactive half lives of a few seconds or minutes. Some hours and some days, weeks, months, years, hundreds to many thousands of years.

Because of this, all reactors, when the fission is shut down (that is easy to do), still generate heat for many months because of those neutron rich fragments with half lives of the order of days, weeks and months.

This is called <u>decay heat</u> and this caused a big problem at Fukushim

So after a reactor is shut down, the reactor still generates about 6% as much heat as it does when it is running because of decay heat.

This is dealt with by circulating water through the fuel even when the reactor is shut down

Because this is a safety related system, engineers put in multiple levels of redundancy to make sure it does not fail

E.g. there are cooling pumps run in parallel but each with enough capacity to cool the fuel on their own and then there are spare pumps available to replace any that fail

The pumps are electrically powered but the electricity is provided by the plant itself.

If the plant shuts down the electricity is provided by the grid.

If the grid is down, the electricity is provided by back up diesel generators and there are redundant diesel generators as well.

Enter the Tsunami of 2011, although it could just as well be an extra, extra large storm surge following a typhoon

Reactors tend to be located on the coast of large bodies of water because they need a large heat sink and like any large thermal station, be it nuclear, coal or combined cycle natural gas, you need a lot of cooling water for the condensers, primarily.

For nuclear reactors you also need cooling water for systems, such as the one that cools fuel even after the reactor is shut down – called the shutdown cooling system. But these are relatively minor compared to what is required to re-condense steam used to drive the turbine generators.
The nuclear plant at Fukushima Daichi had a sea wall that was designed for a tsunami based on historical records but not the one that hit in March of 2011

The sea walls were only about 5 m high whereas the tsunami was well over 10 m, as high as 38 m in some locations

When the site was swamped with water the plant had to be shut down, which it was. **All 4 units shut down safely**

But the grid was unavailable because that was also knocked out by the tsunami
The tsunami went over the sea wall, which flooded the diesel generators and made them inoperable.

This caused a situation called "**station blackout**" and this is a very grave situation.

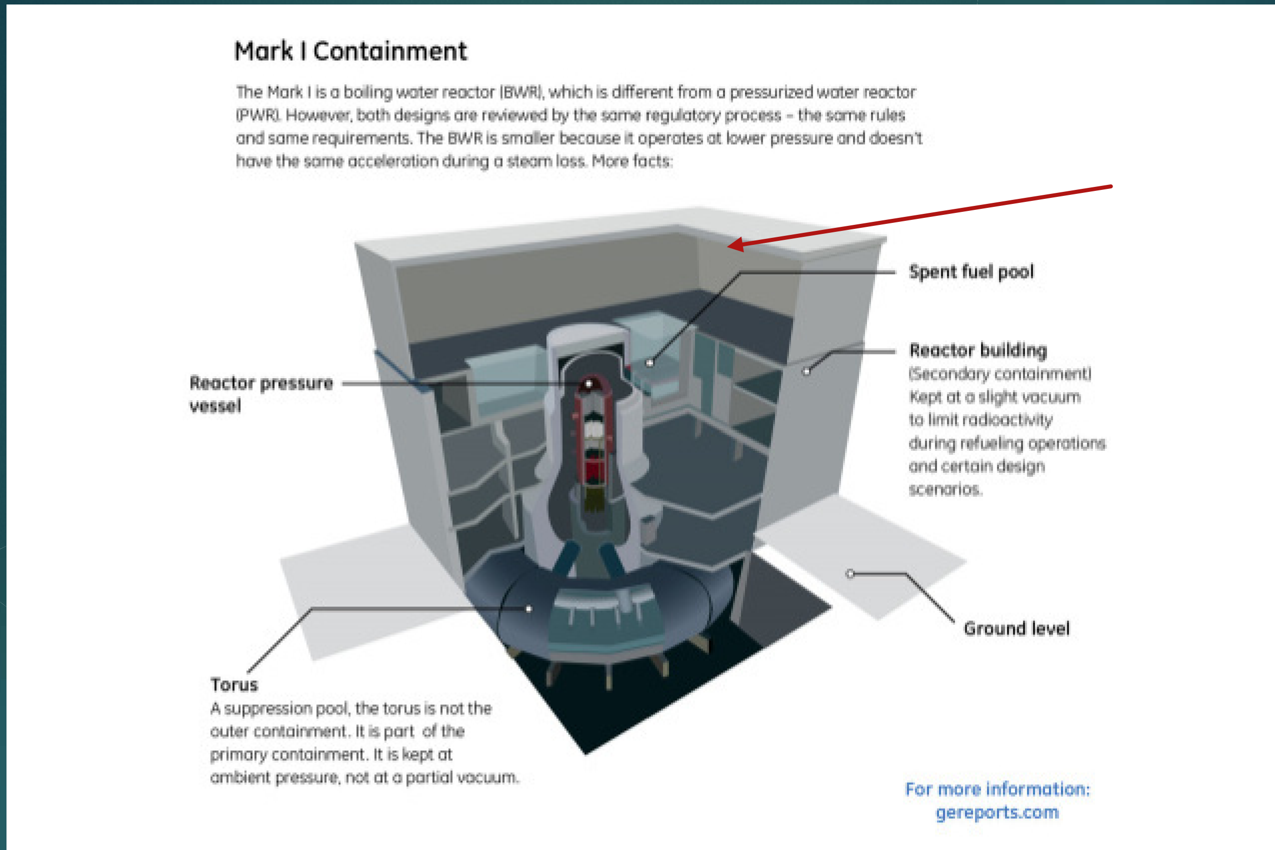
For the boiling water reactor design of the Fukushima station this meant that within about 12 hours the decay heat could start to soften and melt the reactor fuel

And this caused the ironic situation that there was water everywhere but no ability to get it to cool the fuel

Note that since Fukushima it has become a requirement that all back up diesel generators must the located at higher elevations

Anyway, after station blackout occurred and the fuel started to melt, all kinds of operational mistakes were made leading to things like this.

https://www.youtube.com/watch?v=ff9SzEO0bUY



So what blew up in these videos was not the reactor containment buildings but these rectangular "secondary containment" buildings.

So what is supposed to happen is that if there is fuel melting, or a “meltdown” the fuel gets really, really hot – approx. 3400 C

Fuel is clad with zirconium metal to contain the fuel pellets but at this high temperature there is a reaction between zirconium metal and water that generates H_2 gas as well as oxygen.

This represents an explosion hazard so whatever gases exist in the reactor core after a meltdown are vented into secondary containment to keep the public from exposure

In secondary containment there are igniters that burn hydrogen gas and this keeps its partial pressure below levels where it would otherwise detonate – typically above 10% H_2 partial pressure

The H_2 gas is burned rather than release it to the environment because there are other gases like radioactive iodine that would be released with it

Now reactor operators, are not quite like Homer Simpson. They are highly trained and it is drilled into them that they must follow procedures

So venting hydrogen into secondary containment following a meltdown is one of those procedures. They did it because that is what they were trained to do.

The only problem was that the igniters were resistive ones powered by electricity and there was no electricity*

So naturally, the hydrogen concentration just built up until you got detonation

And all of those radioactive gases were released into the environment anyway

They should have vented the secondary containment buildings. It would have released radiation into the environment but at least it would have been in a controlled way, not because the secondary containment buildings blew up

But they did not vent the buildings and two more of them blew up

Also, and this was very peculiar, in the Fukushima reactors their spent fuel pools were elevated at the secondary containment levels and these explosions damaged the pools

Spent fuel is not that thermally hot but when you have a lot of it and you can't get water to it for over a week it can start to become a big problem, which it did in this case as well

But that is a whole other story and I promised you Fukushima in a nutshell

Today, most of the areas near the reactor are uninhabited. Although they are habitable

There is just so much fear of radiation out there, largely fear from ignorance, that people are afraid to move back.

Today radiation levels are slightly above background, but lower than they are in Ontario – because of the Canadian Shield we have exposure from Uranium daughters like radon. Background here is typically 2500 μSv per year

Is that a lot? Not really. There are places in the world where the natural background is as high as 260,000 μSv per year yet the cancer rates are about the world average. An abdominal CT scan is about 10,000 μSv by comparison

In the end the death toll from the March, 2011 Tsunami was over 20,000

The death toll due to radiation at Fukushima was zero, though 4 workers were drowned

44 people died as a result of the evacuation, and there is a sad irony in that.

An example of how a single engineer can make a difference

There is another nuclear plant closer to the epicenter of the earthquake than Fukushima called Onagawa (a 3-unit station).

Although the town of Onagawa was completely destroyed by the tsunami the reactors suffered almost no damage and shutdown safely.

Indeed many of the towns' residents lived for sometime after the disaster in the nuclear facility's gymnasium

But the reason the reactor was not damaged had nothing to do with the reactor design –these were BWRs like in Fukushima Daichi

It was because of the persistence of one engineer involved in the construction of the plant

Hirai Yanosuke

Hirai Yanosuke, who died in 1986, was the only engineer in the entire power station construction project to push for a 14.8-meter high sea wall for the plant

All of his colleagues regarded 12 meters of height as sufficient.

Hirai's authority eventually prevailed, and Tōhoku Electric spent the extra money to build the 14.8m tsunami wall.

The March 2011 tsunami was 13 m high in the Onagawa region

Another of Hirai's proposals also helped ensure the safety of the plant during the tsunami

Before a major tsunami, you would expect the sea to draw back at first

So he also made sure the plant's water intake cooling system pipes were far enough out to sea so it could still draw water for cooling the reactors in case of a very large tsunami.

The message here is that for a technology that can be dangerous you need good engineers

There was nothing inherent in nuclear technology that made it vulnerable to the tsunami, rather it was the trade off between construction costs and safety and the wrong engineering decisions that were made.

The sea walls at the TEPCO owned and operated Fukushima reactors were much lower than at Onagawa – mostly because of an argument with the regulator prior to construction, in which TEPCO prevailed

Note that I have referred to the Fukushima reactors as the Fukshima-Daichi reactors

This is because there is another set of reactors at Fukushima, the Fukushima-Daina reactors. They too were swamped and most systems knocked out but operators managed to string 9 km of high current cables to back up power sources in less than 24 hours to avert disaster.