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The Fukushima Tragedy – Is Koeberg Next?

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Background

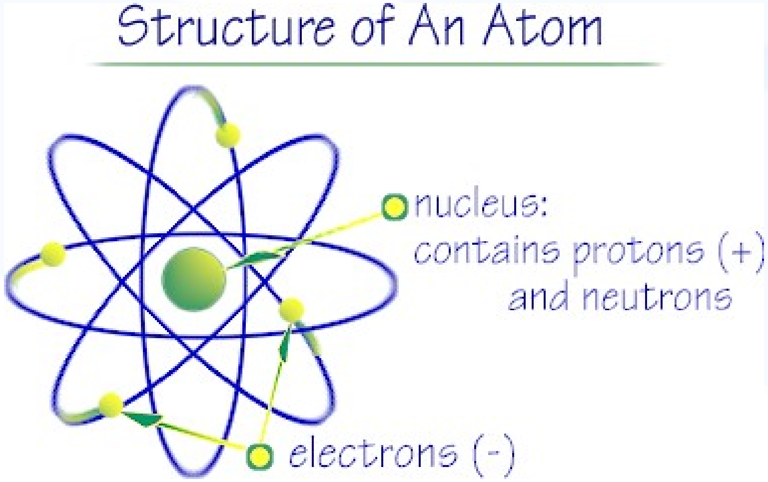
To understand radiation and its source, one needs to have an understanding :

- Of the fundamental particles of matter in terms of the:
  - Atomic Structure and
  - Isotopes
- Of the interactions of the four forces with these fundamental particles

Model of the Atom

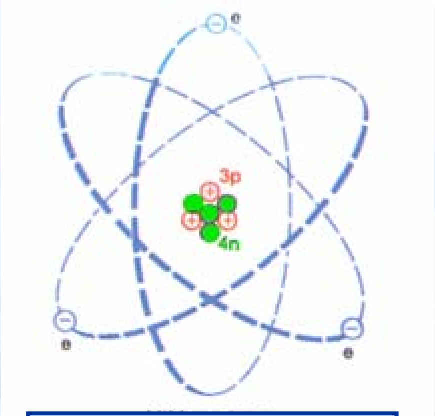
- Standard Model of the atom:
  - Central nucleus contains
    - Protons
    - Neutrons

- Surrounded by electrons



Model of the Atom

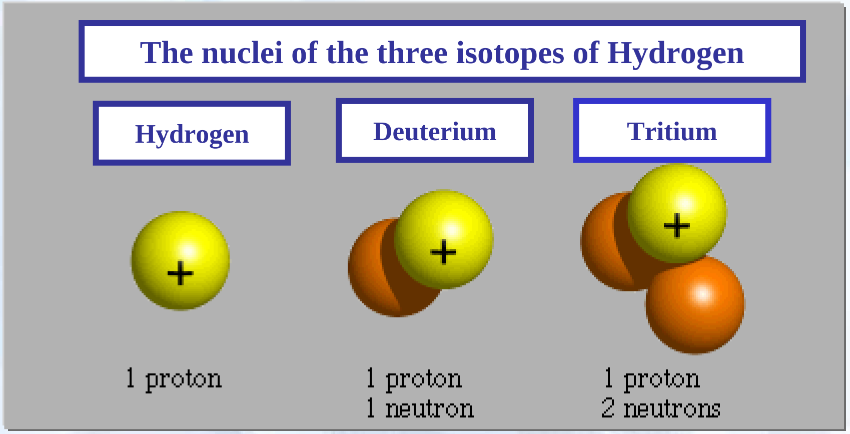
- The simplest nucleus (hydrogen) consists of a single proton
- Other elements have more protons held together by a similar or larger number of neutrons (strong force)
- The number of protons determines the chemical element
- Electrons surround the nucleus (same number as protons in a neutral atom)



Lithium Atom

Isotopes

- Atoms of the same element can have different numbers of neutrons
- The different possible versions of each element are called isotopes



Neutron/Proton Ratio

- There are ‘Preferred’ combinations of neutrons and protons in the nucleus of an atom
  - light elements tend to have about as many neutrons as protons
  - heavy elements need more neutrons than protons
- Atoms with too many (or not enough) neutrons are *unstable*

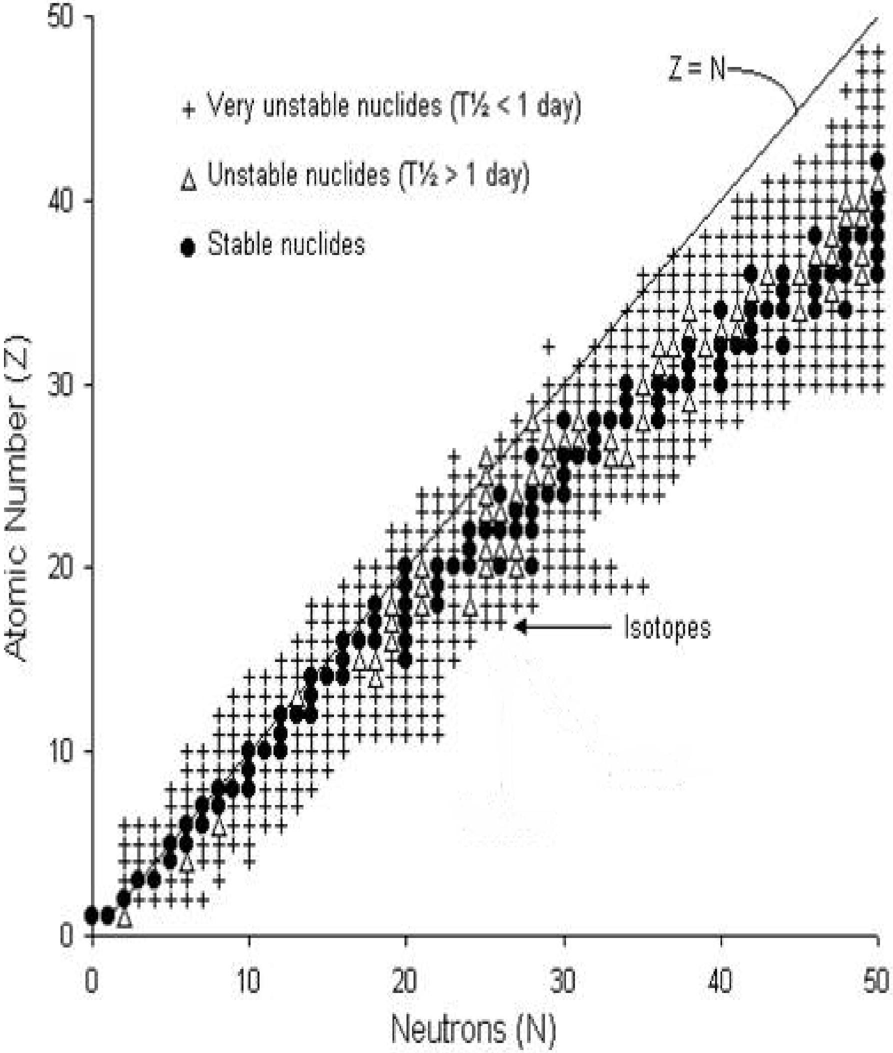
Chart of the Nuclides

Plots elements and their Isotopes

- X axis the number of neutrons
- Y axis the number of protons (elements)

Shows stable isotopes of each Element

- preferred nucleus energy levels



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Radioactivity

- Nucleus needs balance
  - protons repel each other by electrostatic force
  - neutrons and protons held together by strong nuclear force
  - nucleus has desired energy level
- Nuclei with excess energy or imbalanced neutron/proton ratio
  - achieve balance by radioactive decay
- Unstable atoms become stable, or decay, by emitting radiation
- Radiation is in the form of:
  - Particles
  - Electromagnetic waves
  - Therefore radiation is in its most generic sense simply energy traveling through space

Types of Radioactive Decay

Beta Particle

- Electron (-1 electrical charge)
- Positron (+1 electrical charge)
- From the nucleus
- Very small size

Alpha Particle

- Helium nucleus
- Positive charge of two
- Relatively large particle
- From large nucleus

Electromagnetic Radiation

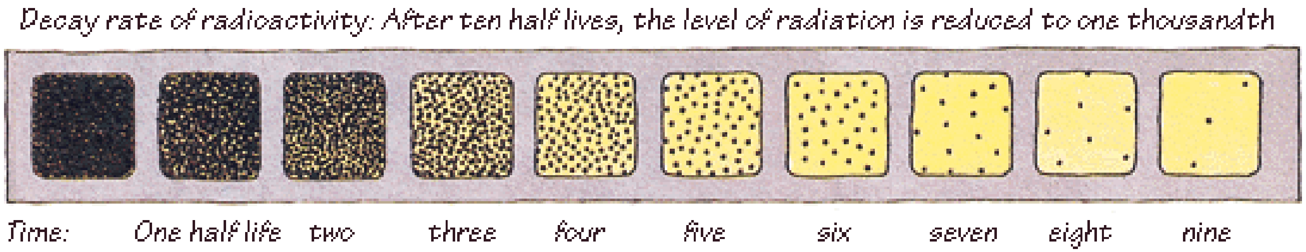
- Stabilizes energy level of nucleus
- Electromagnetic radiation
- Gamma ray
- X-ray (lower energy

Fission

- Large nucleus
- Two or more fission products (nuclei)
- Neutrons
- Gammas
- Large amounts of energy

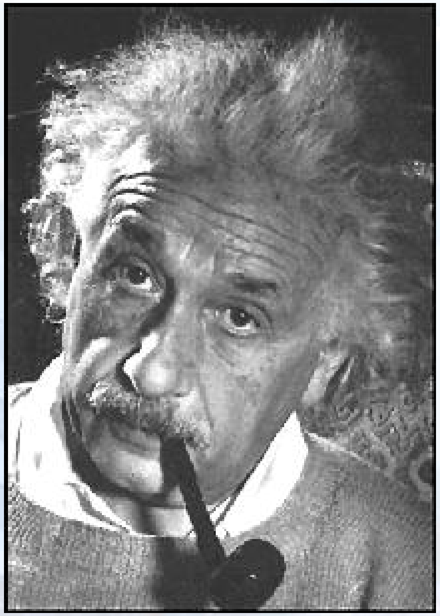
Half-Life

- *Time* it takes for *half* of the atoms in a sample to decay
- Half-life for a given isotope is always the same
- Not dependent upon:
  – number of atoms
  – how long they have been around

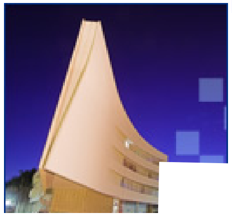


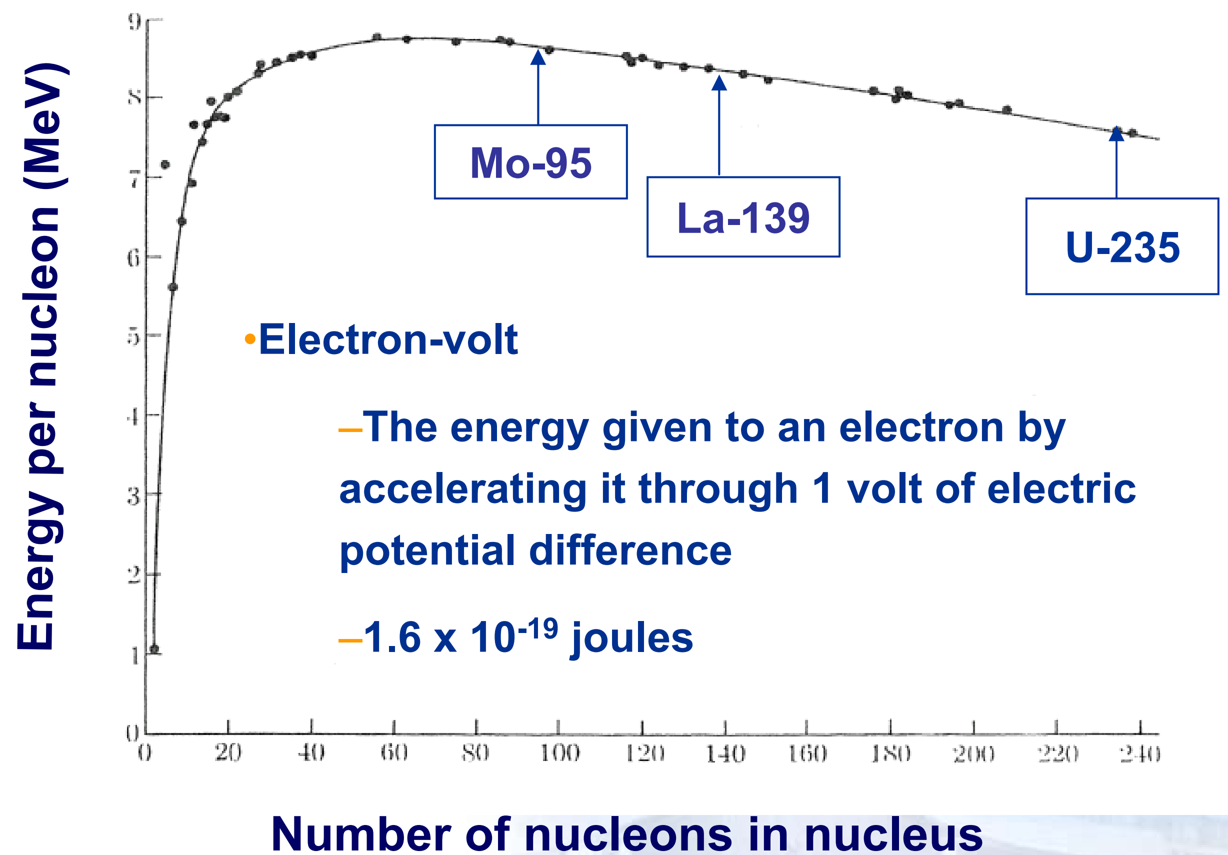
Binding Energy

- The atomic mass of a nuclide can be understood in terms of the masses of its constituent particles and,
- A quantity called the binding energy is used
- To account for the mass defect between the masses of the individual constituent particles and the atomic mass of the nuclide the principle of the equivalence of mass and energy, derived from the **special theory of relativity**, provides the explanation.



Binding Energy Per Nucleon



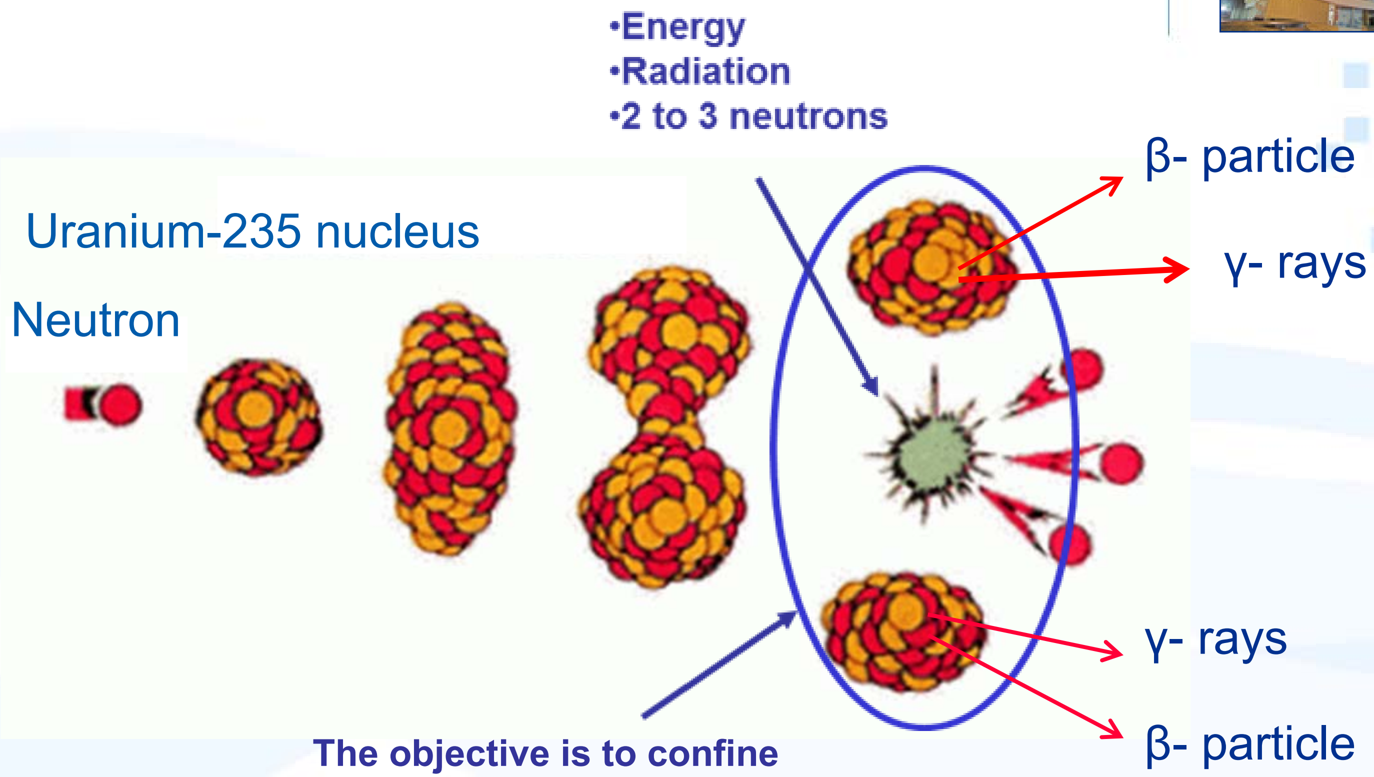


- Electron-volt
  - The energy given to an electron by accelerating it through 1 volt of electric potential difference
  - 1.6 x 10^{-19} joules

So What Is Now Produced In The Fission Reaction?

- Two to three neutrons which, in a reactor can sustain a chain reaction
- A lot of energy such that the consumption of 1.25 gram of Uranium will produce one million watts of heat energy for one day. This energy is equivalent to electrically power a 100 watt light bulb for 9 years and the Uranium consumed, if rolled in a ball will have a diameter of 5 mm.
- Two highly radioactive elements called fission products

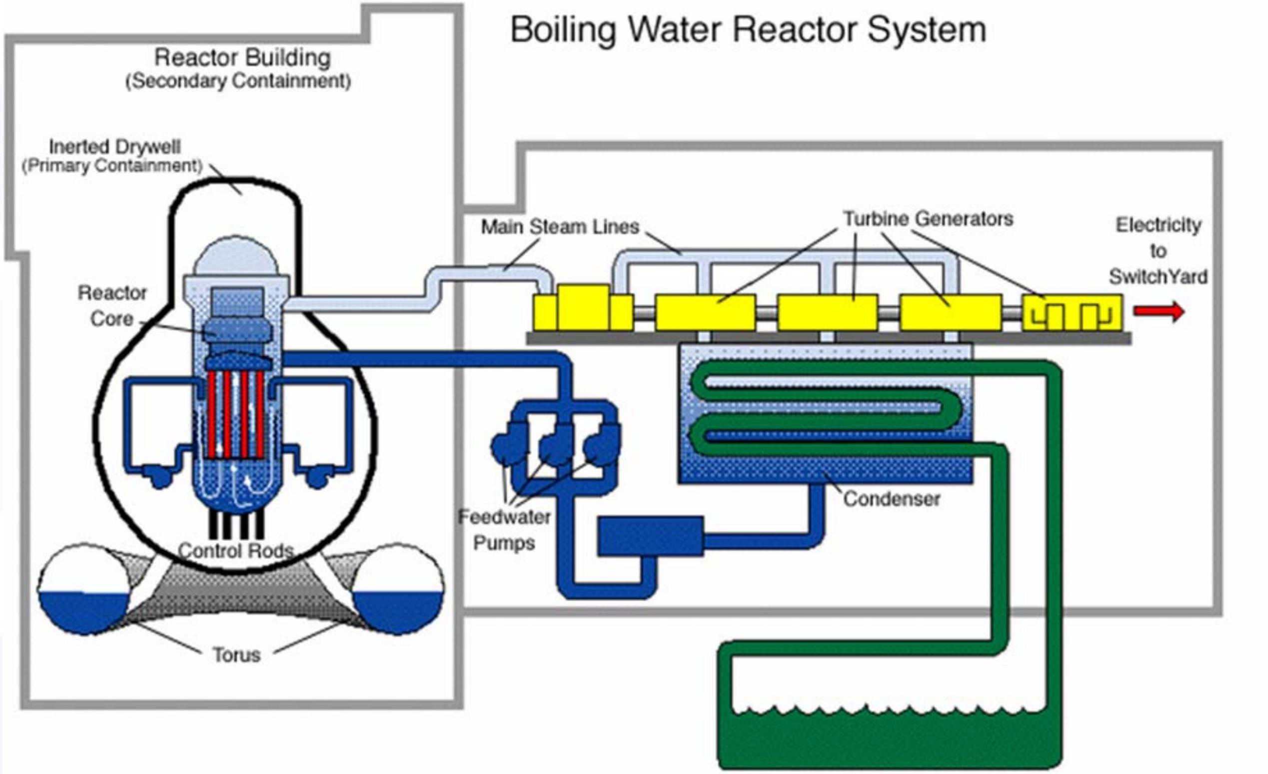
The Fission Process



The objective is to confine these fission products to the point of their creation

Fission is the process of dividing into two or more parts

Now Let Us Look At Fukushima



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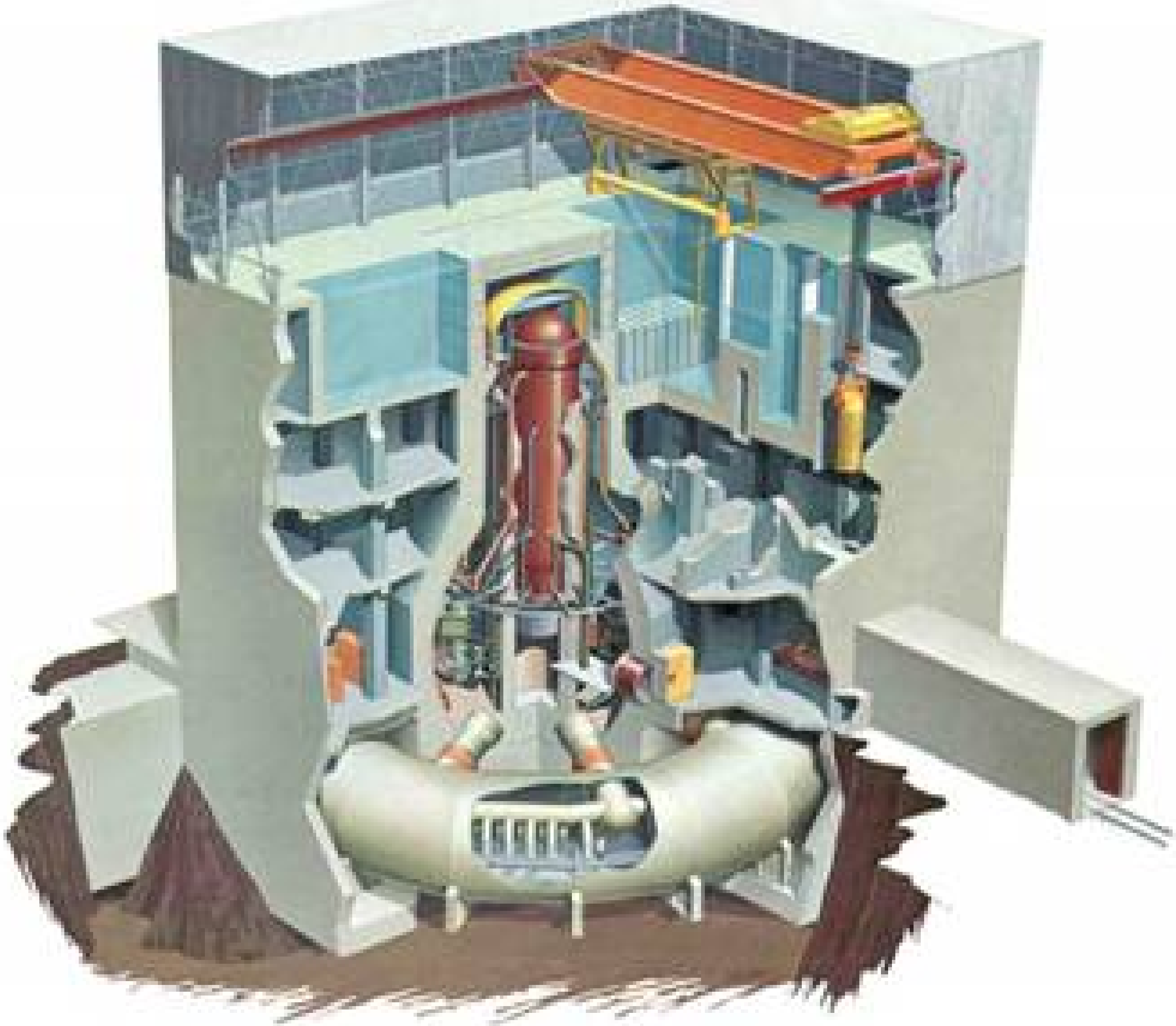
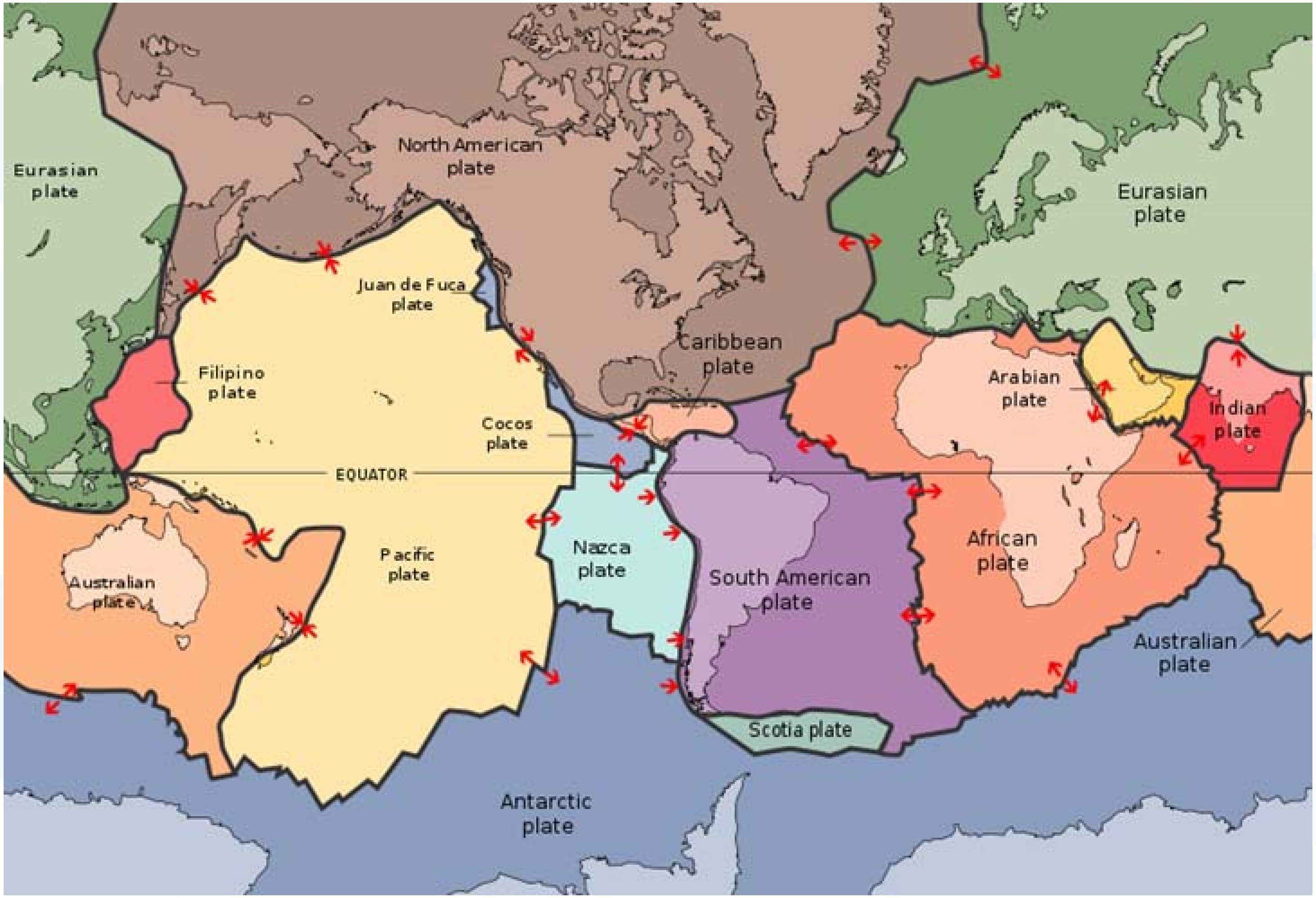
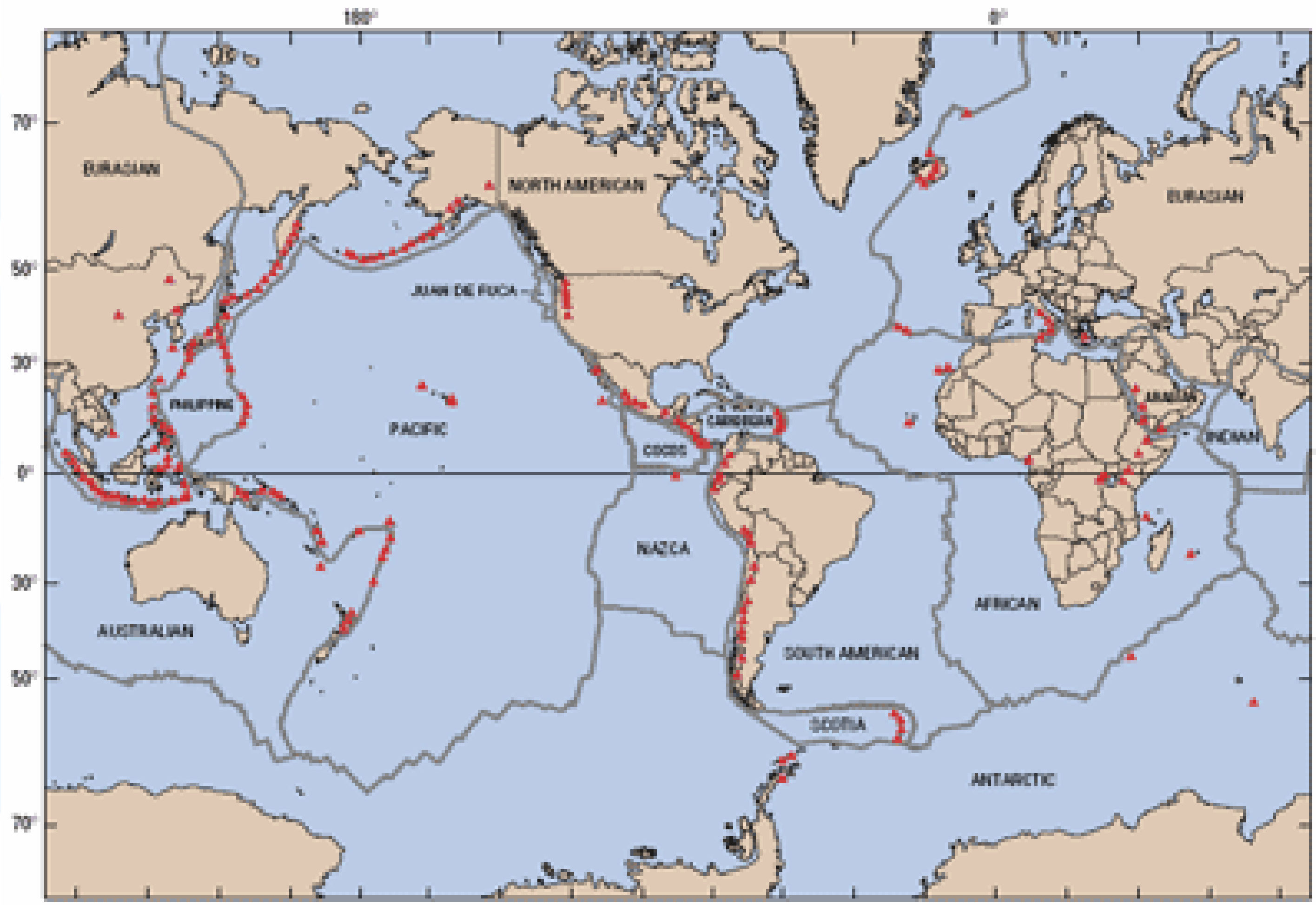
Boiling Water Reactor 3-D Image Typical of Fukushima



Tectonic Plates of the Earth



Earthquake Intensive Areas of the World



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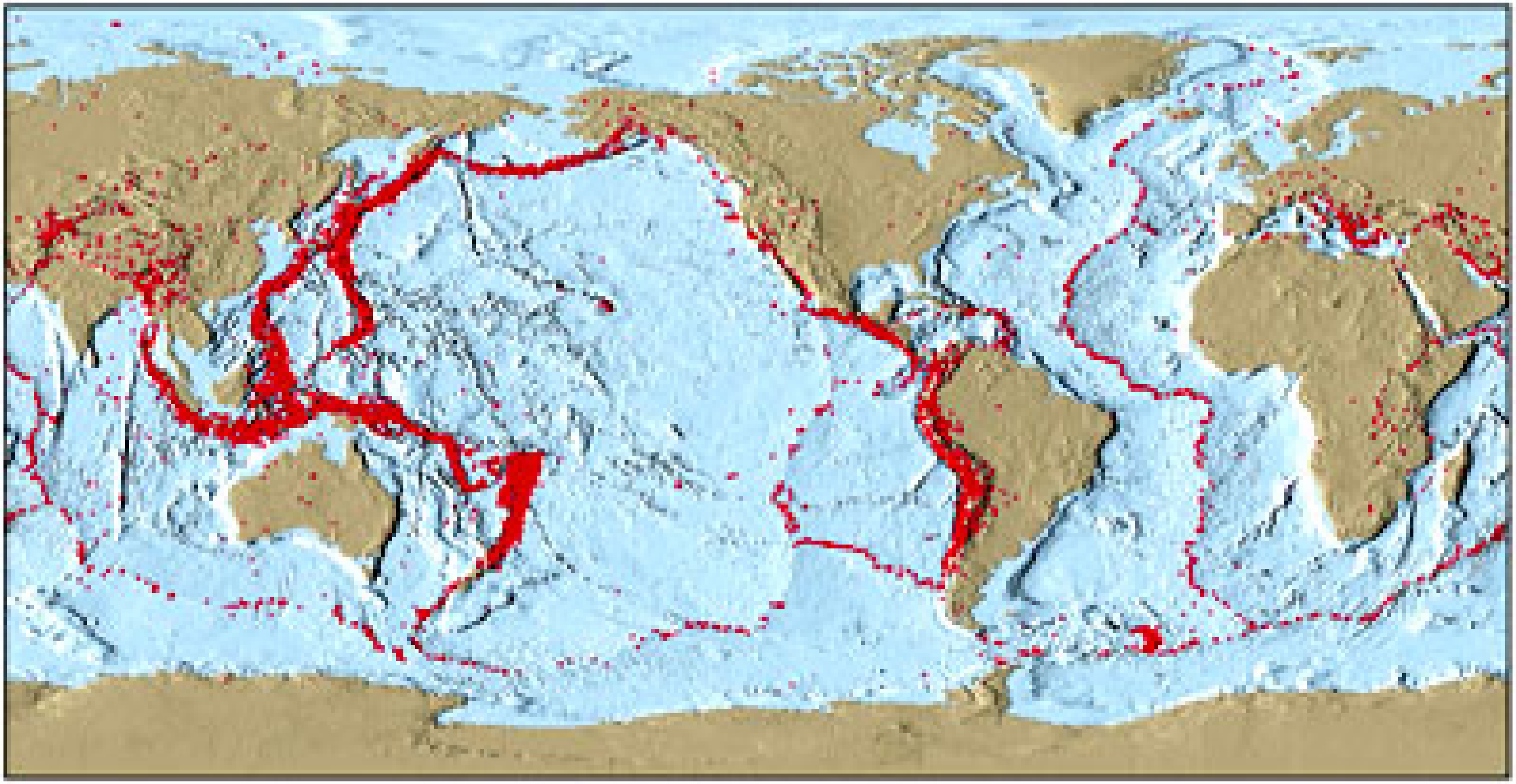

Fukushima Daiici Plant Before and After

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Now Who Are The Main Culprits?

CULPRIT No 1

Power Produced by the Fission Products After the Reactor is Shut Down

$$P_D = 0.06P_R t^{-0.2}$$

Where t in in seconds after shutdown
but is valid only for $t \geq 10$ seconds

or

$$P_D = 0.06P_E t^{-0.2}$$

Where t in in seconds after shutdown
but is valid only for $t \geq 10$ seconds

Where: P_D is the decay power
P_R is the reactor power at shut-down
P_E is the element power at shutdown

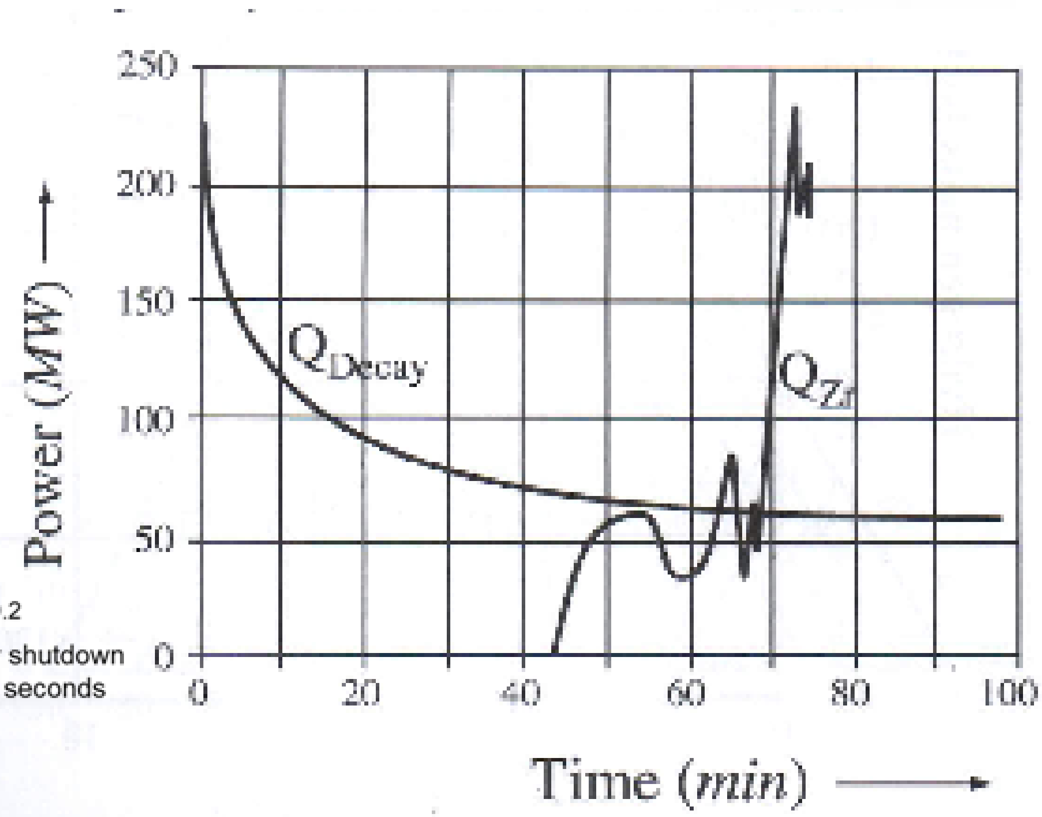
CULPRIT No 2

Energy from Zirconium/Water(Steam) Reaction

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

$\Delta H = 586$ kJ/mol (exothermic)

Heat Production from Decay of Fission Products Compared to the Heat Produced by the Zr/Steam Reaction (Typical for a 3800 MWt PWR)



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Where t in in seconds after shutdown but is valid only for t ≥ 10 seconds

Heat Generation Processes in Core

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Where t in in seconds after shutdown but is valid only for t ≥ 10 seconds

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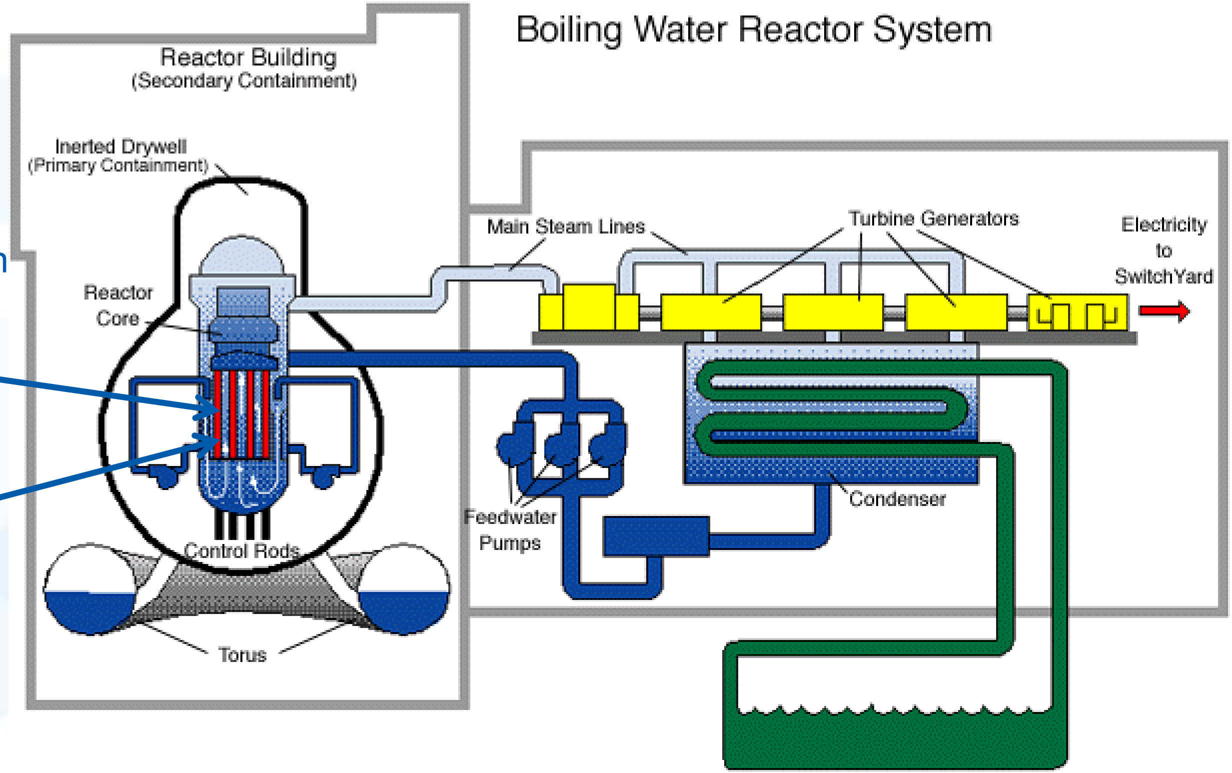
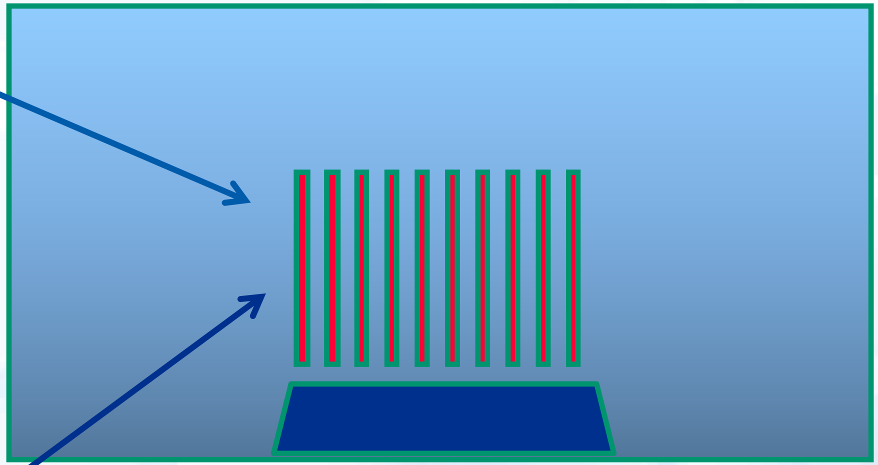


Reactor Fuel Elements Storage Pool

$$P_D = 0.06 P_E \, t^{-0.2}$$

Where t in in seconds after shutdown but is valid only for t ≥ 10 seconds



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

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Evaporation of Water in Reactor Vessel
or
Spent Fuel Pool

$$\int_{t_1}^{t_2} P_D \mathrm{dt} = \mathrm{m_w} . \mathrm{h_{fg}}$$

(where h_{fg} = heat of evaporation of water)

m_w = mass of water in reactor vessel or spent fuel pool

Zirconium/Water(Steam) Reaction Possible in Core and Spent Fuel Pool

$$E_{Zr\ /water\ \ reaction} = m_{Zr}\ .\ \Delta H_{Zr/water\ reaction}$$

Melting of Core and Support Structures

$$\int_{t_1}^{t_2} P_D dt = m_{UO2}[C_{p\,UO2}(T_{mUO2} - T_{oUO2}) + \Delta h_{UO2}]$$
$$+ m_{St}[C_{p,St}(T_{m,St} - T_{o,St}) + \Delta h_{St}]$$
$$+ m_{Zr}[C_{p\,Zr}(T_{m,Zr} - T_{o,Zr}) + \Delta h_{Zr}]$$

Where: m is the mass in kg of components

C_p is the specific heat of component material kJ/kg.K

T is the temperature in °C

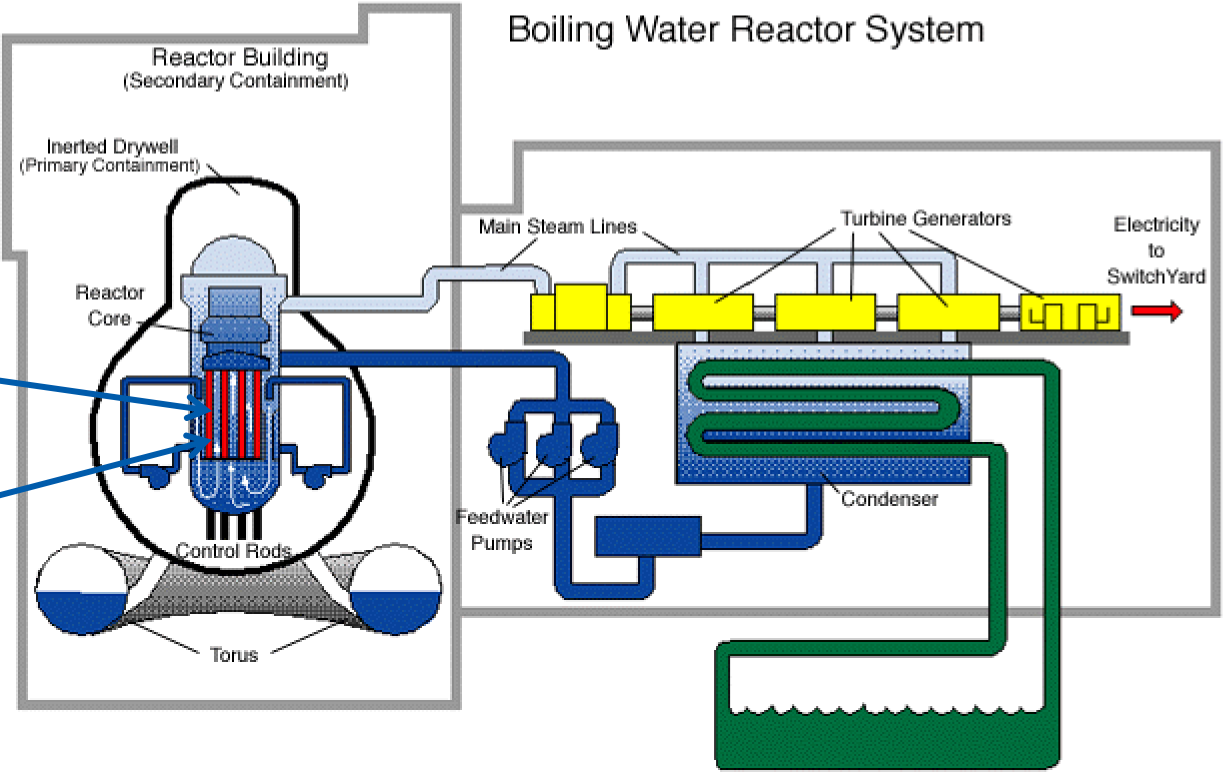
Δh is the heat of melting of component material

Subscripts to temperature:

o: operating temperature

m: melting temperature

Heat Generation Processes in Core



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Where t in in seconds after shutdown but is valid only for t ≥ 10 seconds

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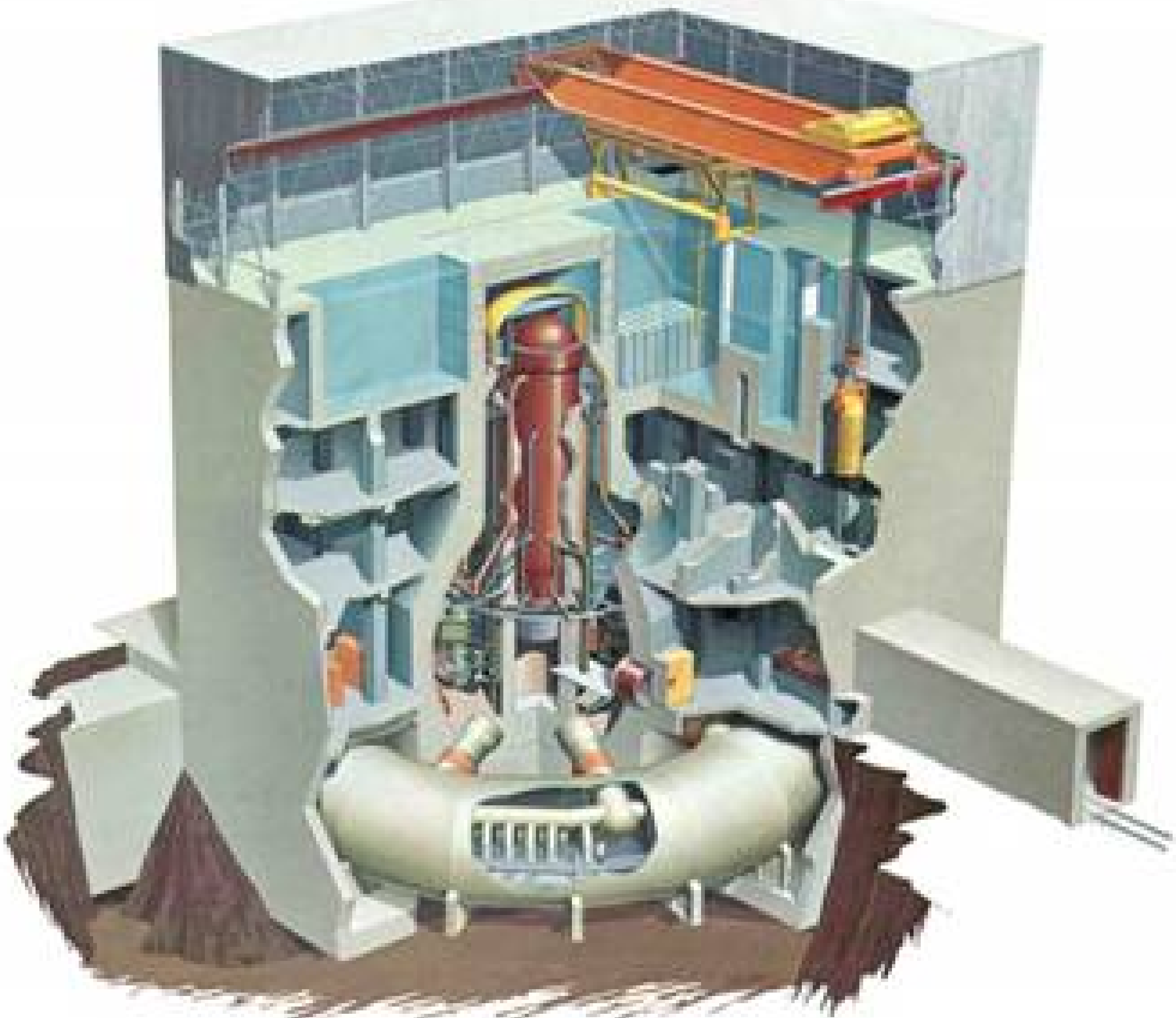
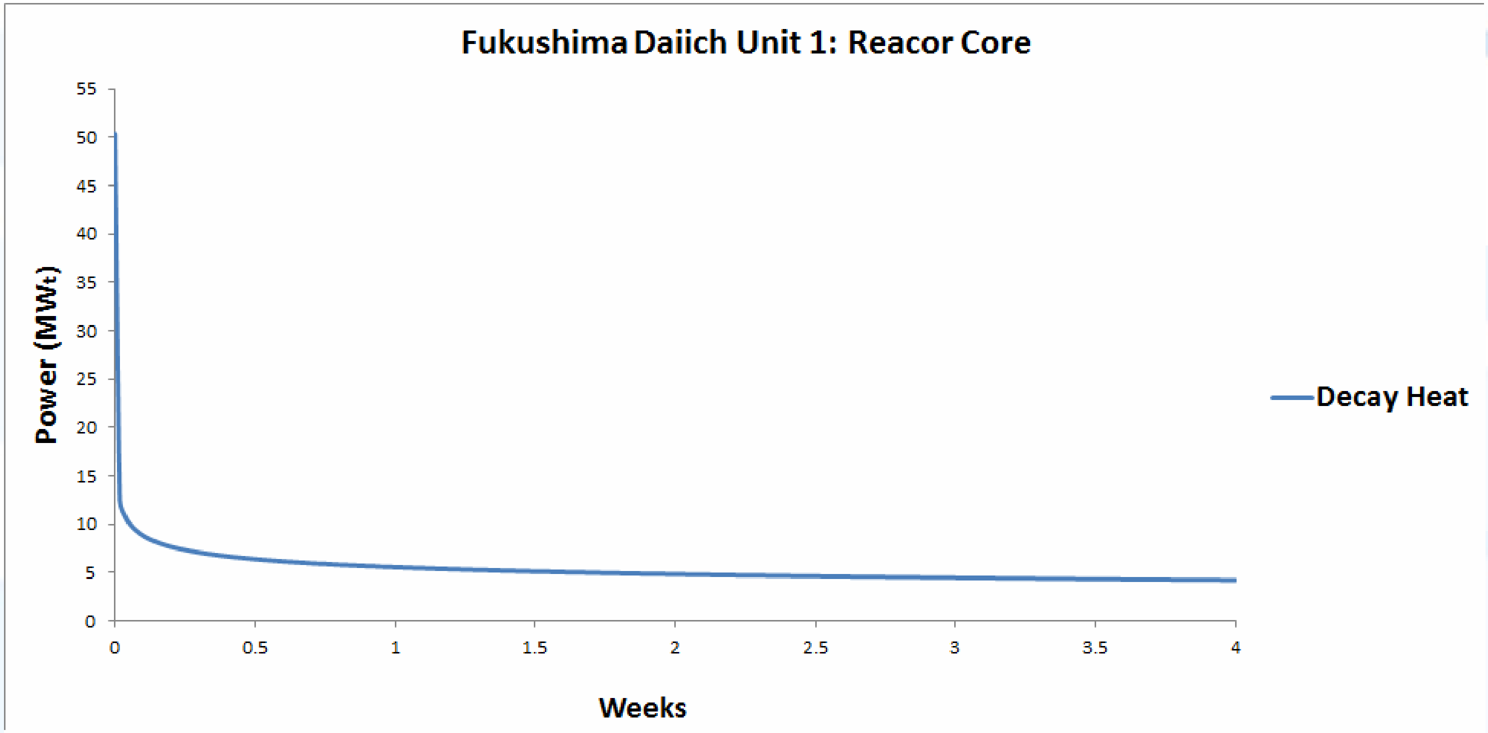
Typical of Fukushima



Decay Heat Curve for Fukushima Daiichi Unit 1 Core



Time zero starts when reactor is shut down

Basic Formula and Input for Those That Want to Calculate the Time Various "Grace" Times

Core and Reactor Pressure Vessel

$$\int_{ti}^{t2} 0.06P_R\, t^{-0.2}\, dt = \{m[C_p(T_m-T_o) + \Delta h]\}_{uo2} + \{m[C_p(T_m-T_o) + \Delta h]\}_{zr} + \{m[C_p(T_m-T_o) + \Delta h]\}_{st}$$

Water in Reactor Pressure Vessel or Fuel Pool

$$\int_{t1}^{t2} 0.06P_R\, t^{-0.2}\, dt = m_{water}\, h_{fg}$$

Material	Mass m (Ton)	Specific Heat C_p (kJ/kg.K)	Melting Temp. T_m(°C)	Operation Temp T_o (°C)	Heat of Melting Δh(kJ/kg)	Heat of Evaporation h_{fg} (kJ/kg)
UO_2	40	0.33	2800	1000	250	
Zircalloy	24	0.25	1850	500	260	
Steel(CSS)	20	0.45	1500	300	260	
Steel (RPV)	20	0.45	1500	300	260	
Water RPV/Pool	60/1000					1400

Results of Grace Time Calculations

- Time to boil off water in reactor pressure vessel

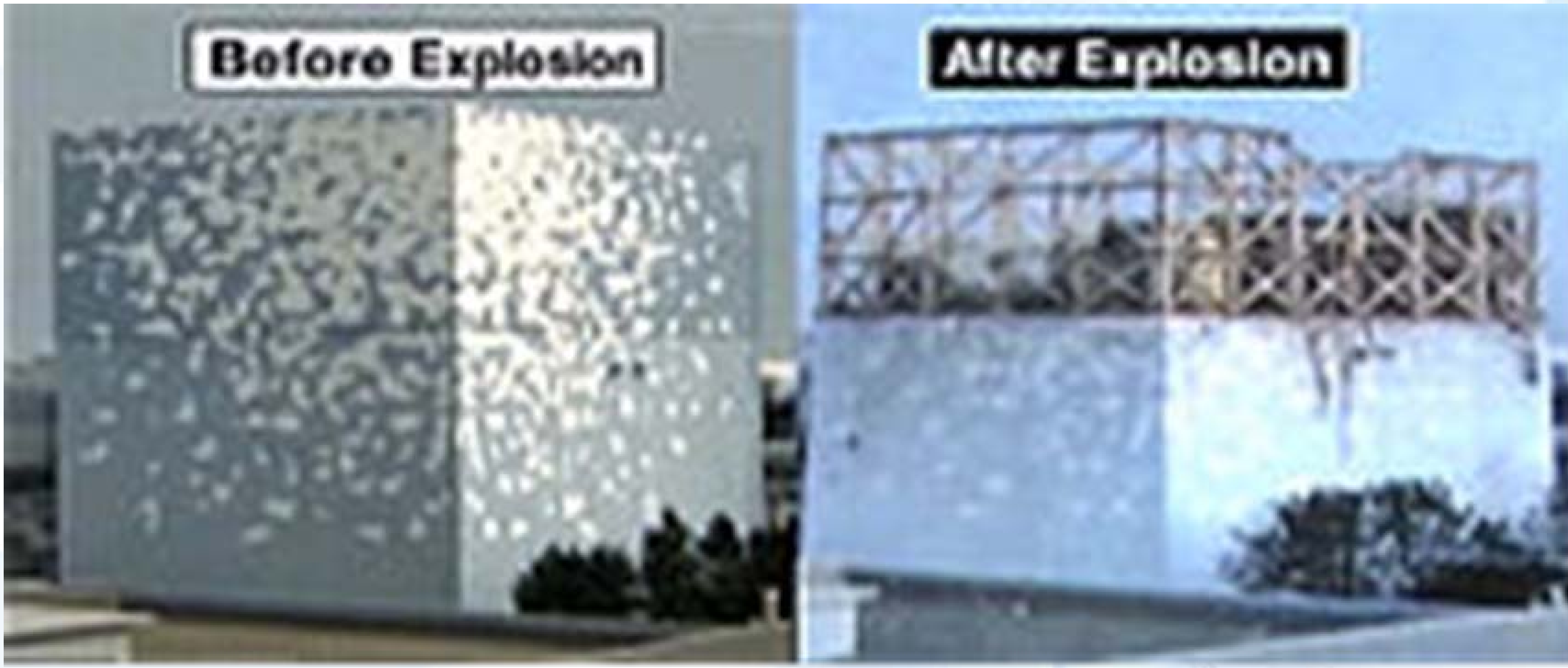
1.27 h after reactor shutdown

- Time to melt core and core structures

2.5 h after reactor shutdown

- Fukushima Daiici Unit 4 and assuming the same power as Unit 1: The fuel in the spent fuel pool has been unloaded from the core to allow maintenance. Assuming the same reactor power as Unit 1. The time to evaporate 50% of the water in the pool thereby exposing the fuel:

17.86 h after reactor shutdown


Before Explosion
After Explosion

So What Can We Deduct? (1)

- It is clear that the cooling of the fuel was insufficient to prevent overheating and dry-out of at least some part of the core and fuel storage pools;
- Overheating caused the water/zirconium reaction to take place with resultant generation of hydrogen;
- Hydrogen vented and collected in some volume until an explosive mixture with surrounding air was reached;
- We all have seen the dramatic results.

So What Can We Deduct? (2)

- The heat source is still heating and unless sufficient cooling is restored and guaranteed the fuel will melt into a mixture known as “corium”;
- The fission products will escape and cause off-site radiation levels;
- If at all achievable and rather sooner than later as much fuel will have to be removed from the facilities;
- The reactors will most probably have to be sealed into a safe storage state with later bunkering into sarcophagus state.

What Can We Say About the Koeberg Design Against Earthquakes ?(1)

- Koeberg was designed for a peak ground acceleration (PGA) of 0.3g (Richter magnitude 7, Mercalli intensity VIII) at 7 km offshore;
- The “formula” used was to locate the nearest active fault to the site (Milnerton) and use the earthquake with the highest intensity (Ceres 1969) on the fault at a point closest to the site.
- The seismic accelerations were calculated and with extra conservatism the design value was chosen as 0.3g.

What Can We Say About the Koeberg Design Against Earthquakes? (2)

- The Licensing Authority requested proof that for a 0.36g earthquake event not more than 10% of the core Iodine fission products will be released
- A standard French design was used which was designed for 0.2g PGA, and uncoupling the reactor and fuel building, which is mounted on an upper raft, 6.1m thick in the centre under the reactors, and 3.3m thick elsewhere, from the 2m thick concrete lower raft by approximately 2000 ‘aseismic’ bearings mounted on ~500 concrete pedestals.

What Can We Say About the Koeberg Design Against Tsunamis? (1)

- The maximum height above mean sea level taking into consideration tides, storm surge, wave combinations were determined. These maximum values were added together as if they will occur all at the same time and place;
- This resulted in 4 meter above mean sea level;
- Tsunamis associated with events at the Mid-Atlantic ridge and a maximum tsunami height was calculated to be 3 meter.

What Can We Say About the Koeberg Design Against Tsunamis? (2)

- These two values were added thereby assuming that all phenomena coincided and a safe terrace level of 7 meter above mean sea level was specified
- The contractor then chose 8 meter above mean sea level as the terrace height.

Conclusions (1)

- The reactors at the Fukushima Daiichi site shut down as designed on receiving an earthquake warning;
- The structures survived the earthquake which was as quoted as magnitude 9;
- The emergency back-up power systems functioned as designed to keep the essential cooling going;
- Then 55 minutes later the tsunami (now estimated as 14 m high) arrived, and took out the diesel generators for at least the first four of the 6 units and consequently the core cooling and spent fuel cooling were lost;

Conclusions (2)

- The four reactors that have lost cooling suffered damage due to overheating and the hydrogen explosions;
- Some radioactivity has been released into the surrounding environment;
- The foundations of the Koeberg plant has been designed to handle an earthquake with a PGA of 0.3g;
- The terrace level is 8m above mean sea level with a predicted tsunami of 7m which assumed very conservative combinations of conditions;
- The earthquake activity around the South African coastline is extremely low

Conclusions (3)

- Since all events impacting on nuclear facilities has a probability of occurrence one can never make a statement that a specific event will never occur, however,
- The probability of an event occurring which challenges the design basis of the Koeberg plant from an earthquake or accompanying tsunami point of view is extremely low.
- Therefore we can say with good confidence:

“KOEBERG WILL NOT BE NEXT TO SUFFER THIS FATE”

So what lies in the future?

- Reactors will have to evolve towards designs which have more passive safety features;
- Fuel cladding material should be developed to withstand the high temperatures generated during loss of cooling events and to eliminate the high-temperature exothermic reaction with the water/steam mixture. Ceramic materials seem to be the obvious choice;
- Maybe reactors will become smaller and more modular so that inland siting could be considered.

To quote Marie Curie: "Nothing in life is to be feared. It is only to be understood"

THANK YOU