Nuclear Power Safety and Radiological Protection

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Onagawa
Fukushima Daiichi
Tokai
Tokyo
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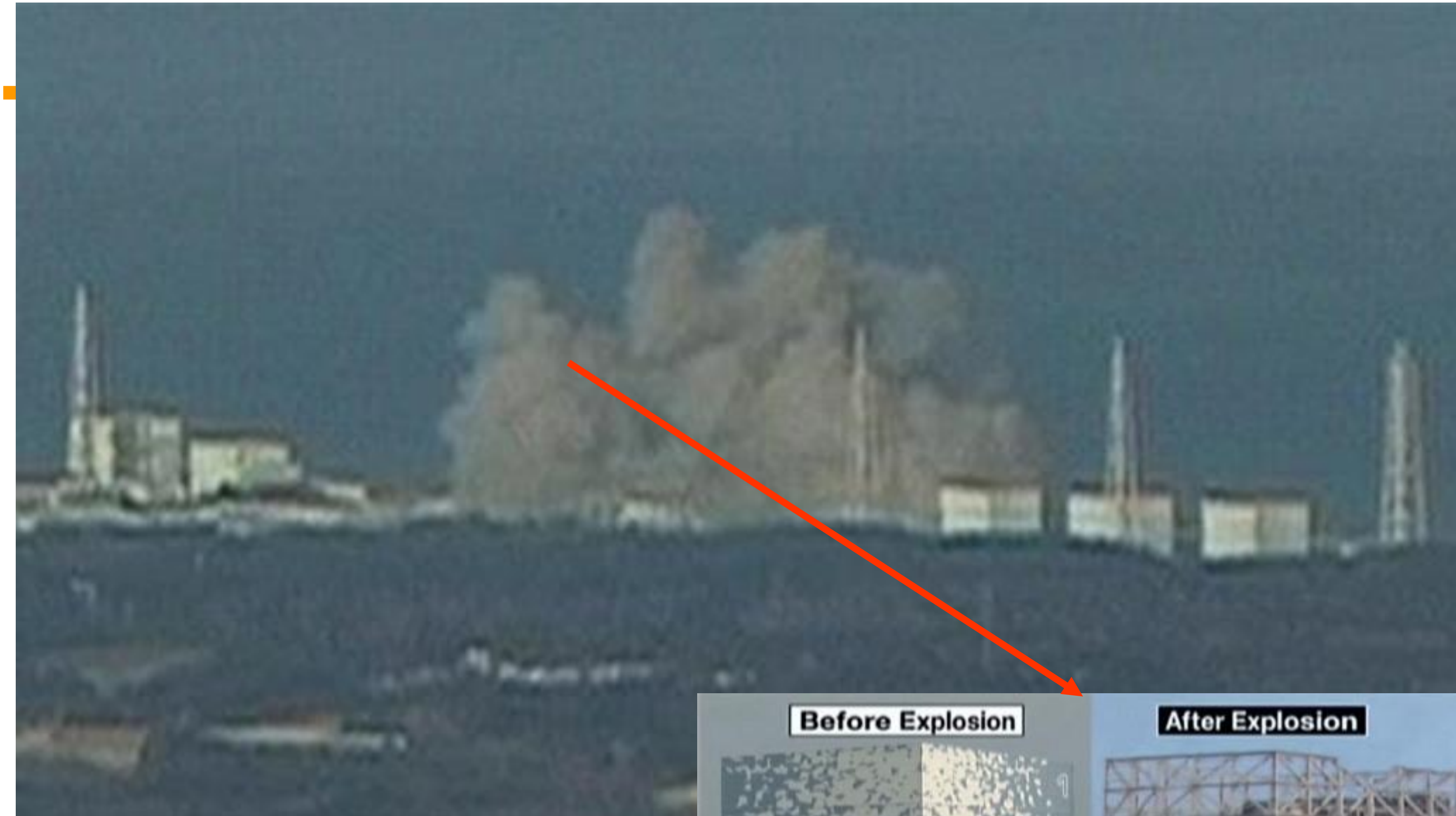
By Janet Loehrke, USA TODAY

Fukushima Daiichi Nuclear Power Plant



Explosion at Unit 1 on 13th March 2011

What has happened to Japan?

- A 9.0 Mm earthquake following by a 14m high tsunami hit the east coast of Japan at 2:46 p.m. on 11th March 2011
- Three of six operating nuclear reactors at Fukushima Daiichi Power Plant were automatically shut down, causing internal power blackout.
- External power grid was damaged by the disaster
- Backup diesel generators were damaged and fuel tanks washed away by the tsunami
- Backup batteries lasted only for 8 hours and no more power thereafter
- Residual heat at 2% an hour later to 0.2% one week later of the full power from the cores boiled off the water, causing the water level in the vessel to recede and expose part of the cores to steam.

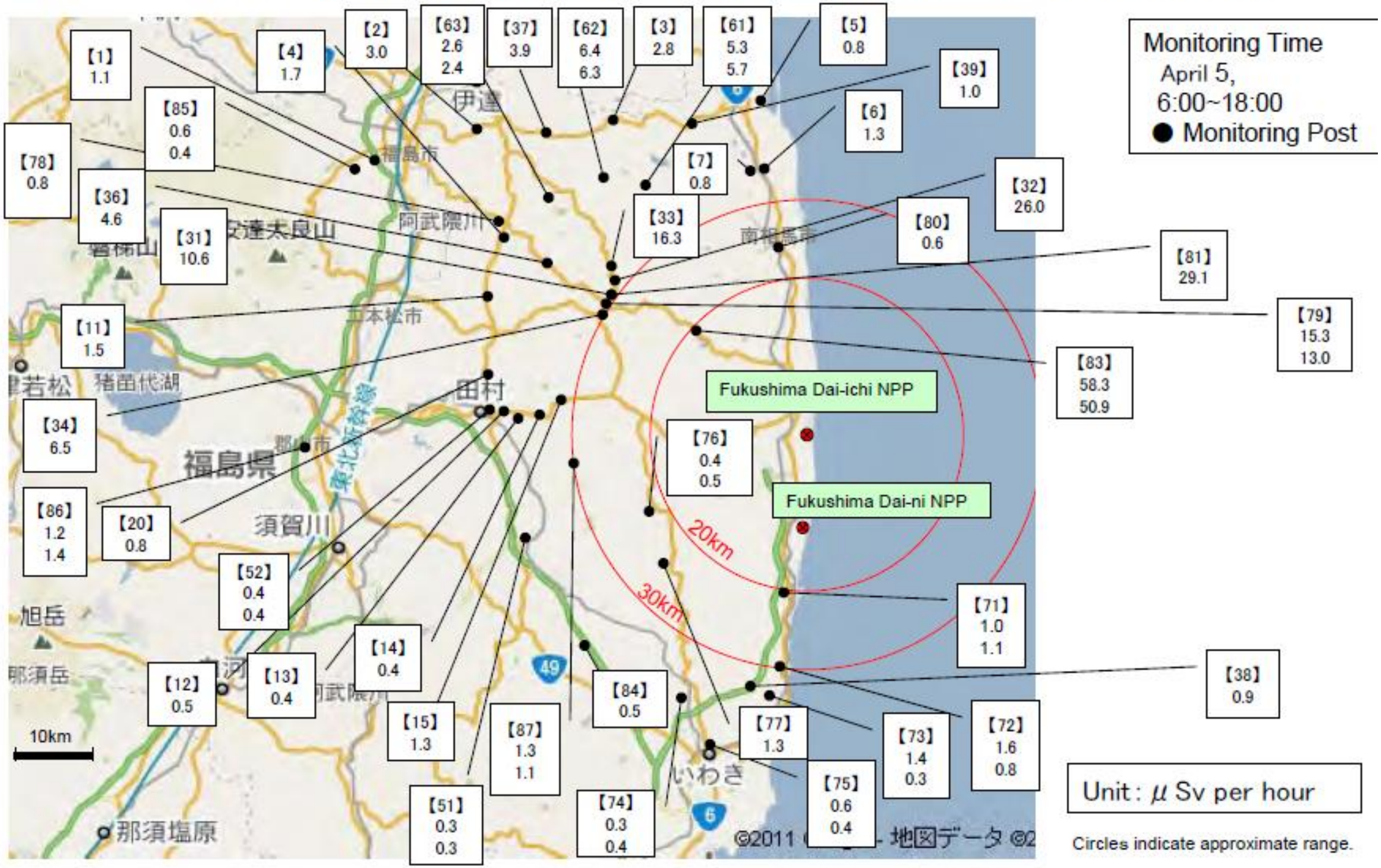
What has happened to Japan?

- Seawater was pumped into reactor vessels 1, 2 and 3 to maintain the water levels around the cores after the normal feed water supplies were exhausted.
- The cores at reactors 1, 2 and 3 were partially melt-down
- Hydrogen gas formed by reaction of the exposed Zircaloy alloy with steam/water at about 2700^{o}C.
- Release of steam to safeguard the integrity of the pressure vessel (normally maintained at ~75 atm.)
- Reactor buildings at Reactors 1, 3 and 4 exploded due to the release of hydrogen into the buildings. Multiple fires broke out at reactor 4
- Emissions of radioactive substances and subsequent fallout to other places
- Cooing systems for spent fuel pools in reactors 1- 4 reportedly also malfunctioned. Estimated to be emitting at around 2 million kcal/hr from each pool

What has happened to Japan?

- Spraying of seawater and fresh water in an attempt to cool the vessels and spent fuel holding tanks.
- Air, soil, water and sea at even 70 km from the stricken plant were contaminated with radioactive substances. For example, radiation levels were 100,000 times above the normal level in water inside reactor no.2, and radiation above 1,000 mSv/hr was detected in surface water in channels outside the reactor.
- People living within 20 km were evacuated and those between 20km and 30km were told to stay indoor.
- Over 27,000 people dead or missing from natural disaster, but probably only 1 person died so far from the radiation, while 3 workers in the turbine building were exposed to radiation in the order of 100-250 mSv and 2 of which suffered from skin burn in a water pool with radioactive substances.

Readings at Monitoring Post out of Fukushima Dai-ichi NPP



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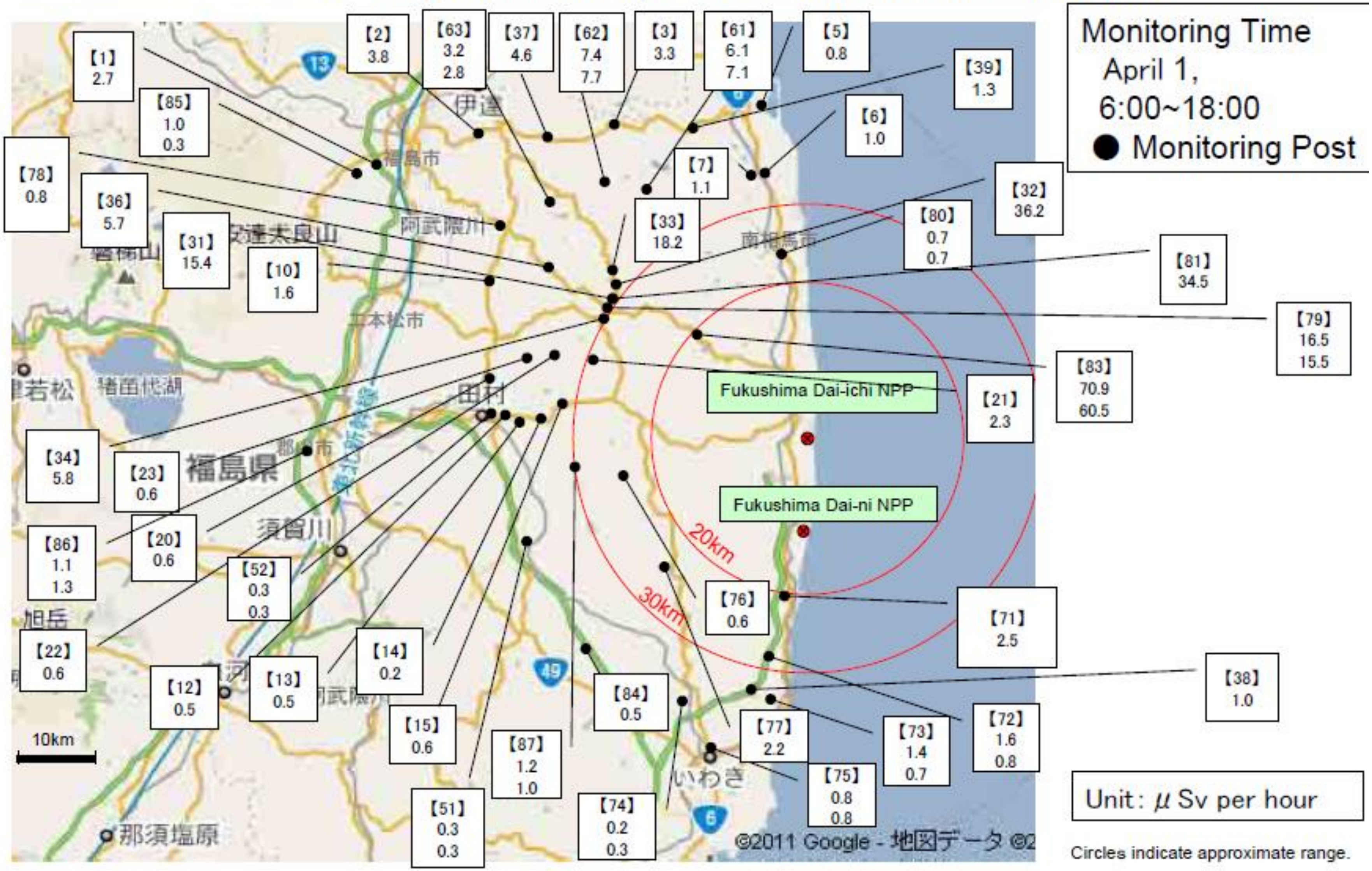
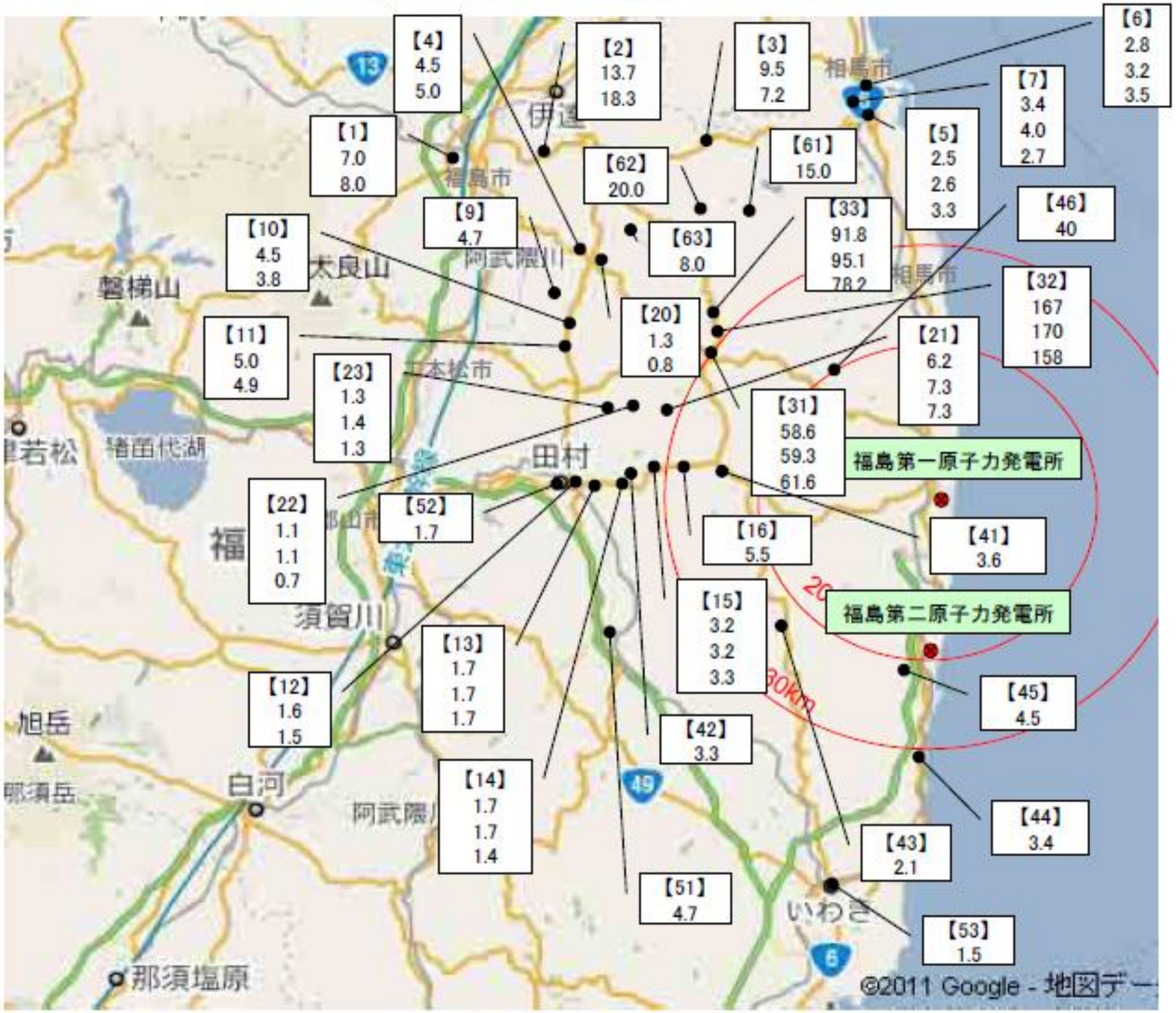


Readings at Monitoring Post out of Fukushima Dai-ichi NPP

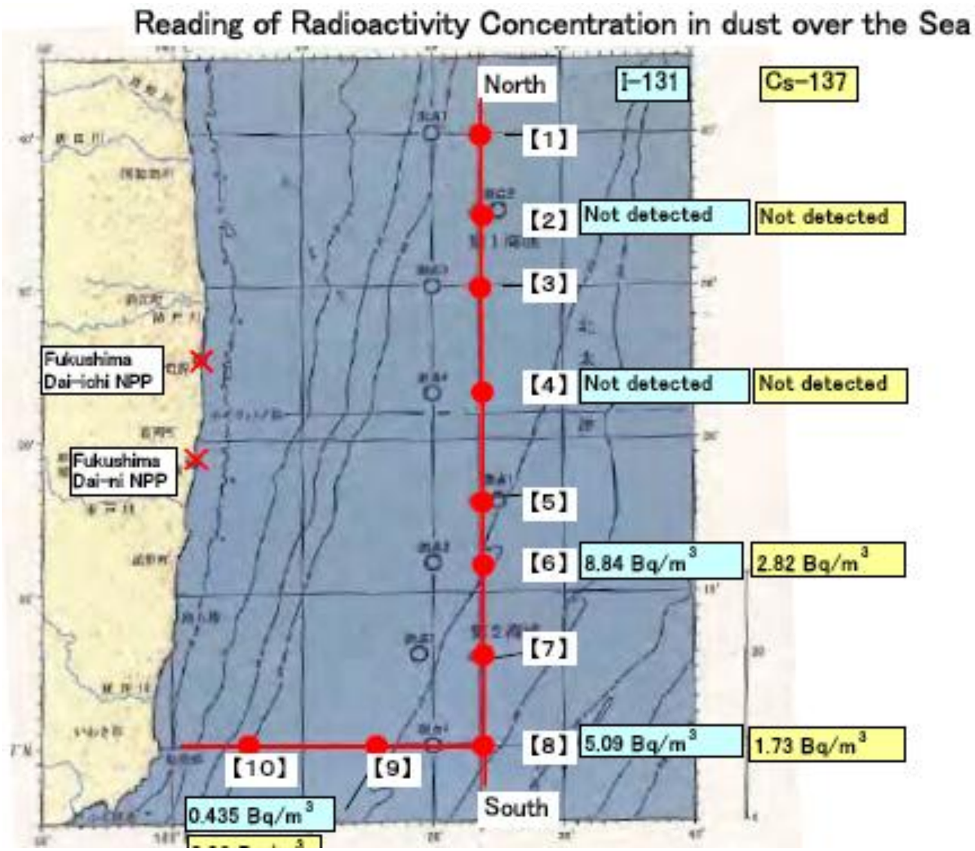


Monitoring Time
March 17,
9:20~17:43

●Monitoring Post

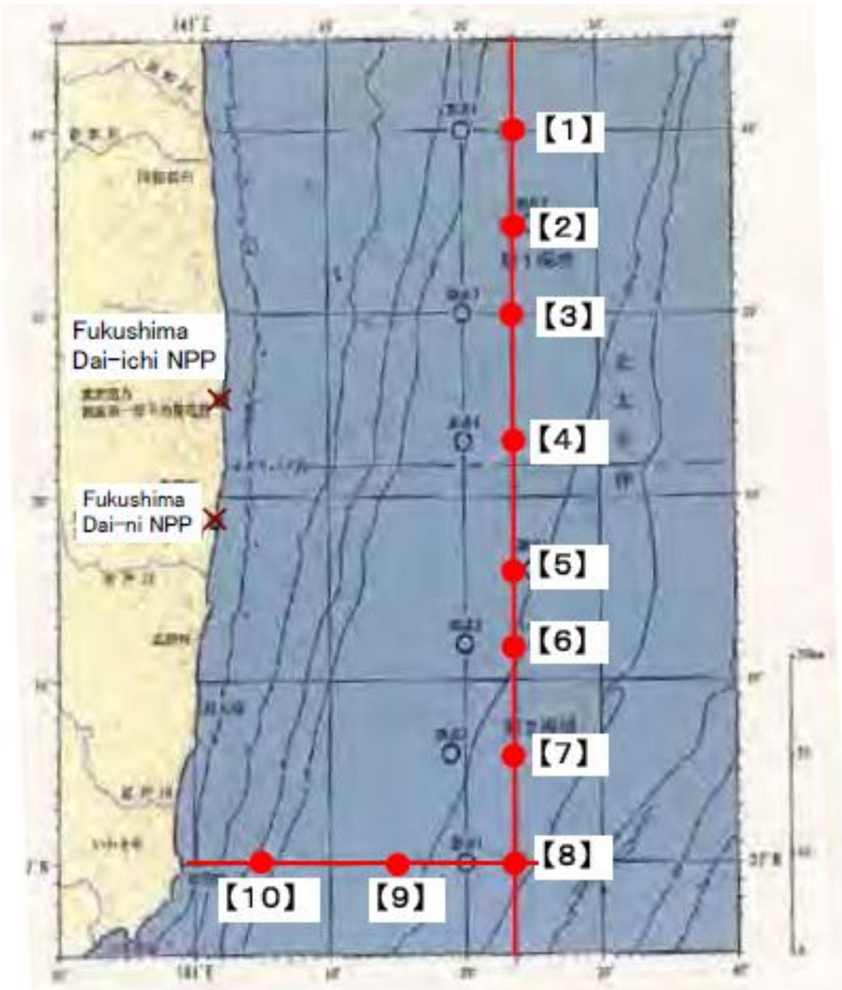
Unit : μ Sv per hour

Results of Radioactivity in Dust over the Sea

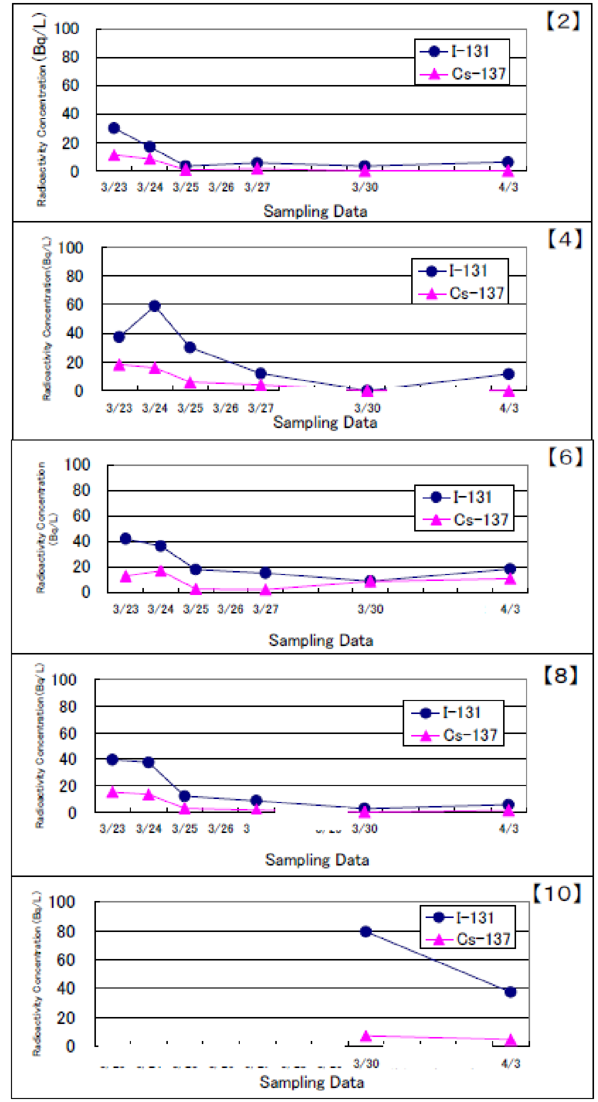


April 4th 2011

Results of Radioactivity in Sea



April 4th 2011

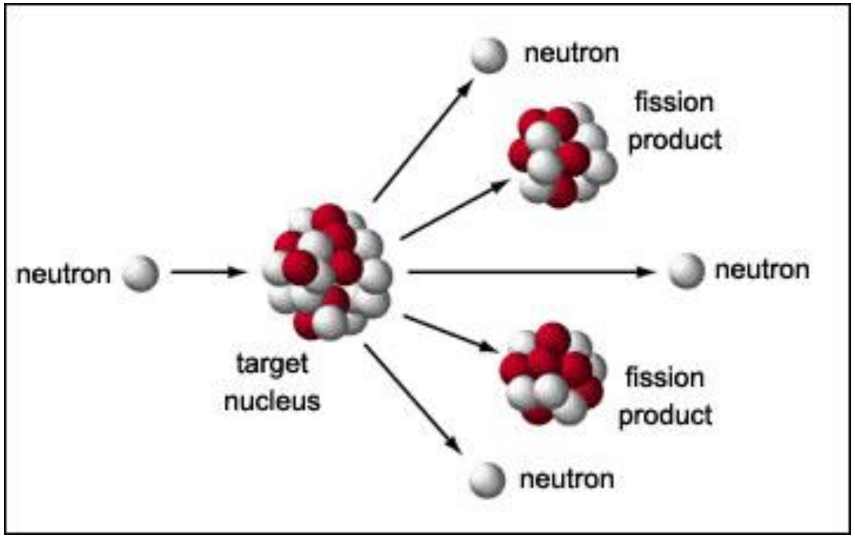


Note: "Not Detectable" is illustrated as 0Bq/L.

How do we generate Nuclear Power?

- Nuclear energy is generated by the fission of Uranium 235 by thermal neutrons
- A typical reaction (out of about 40) is:

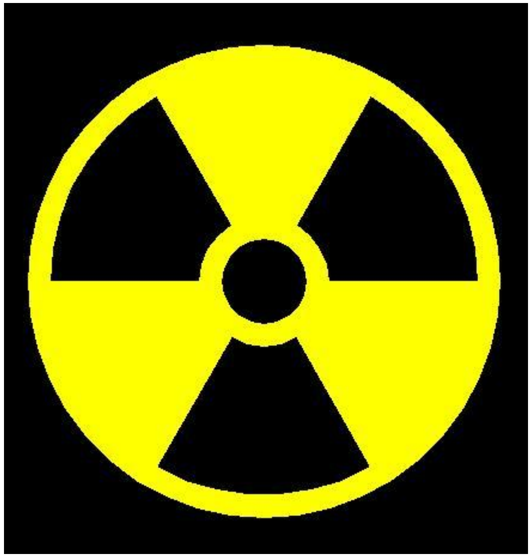
$$U^{235} + n^{1} \rightarrow La^{147} + Br^{87} + 2\,n^{1} + 195\text{ Mev}$$



- One kg of U^{235}, if totally fissioned, can release 8×10^{13} joule of energy. This is equivalent to the energy available from 3000 tons of coal.

What is radiation?

- Radiation can be ionizing and non-ionizing.
- Non-ionizing radiation includes light, radio wave, microwave, infrared, light, etc.
- Ionizing radiation includes high energy sub-atomic particles e.g. alpha particles, beta particles, protons, neutrons, or short wave, e.g. X-ray, gamma ray, cosmic ray, etc. that can detach electrons from atoms or molecules when irradiated



Principles of Radiological Protection?

- **Principle 1: (Principle of Justification)**
- Any decision that alters the radiation exposure situation should do more good than harm

- **Principle 2: (Principle of Optimization of Protection)**
- All radiation exposures should be kept As Low As Reasonably Achievable, (ALARA)

How dangerous is Ionizing Radiation?

- **Deterministic Effects:** caused by exposure to high level radiation, and become more severe as the exposure increases. Acute health effects include burns, radiation sickness, e.g. nausea, vomiting, weakness, hair loss or even death. For example, death results within hours or days if exposed to over 20 Sv.

How dangerous is Ionizing Radiation?

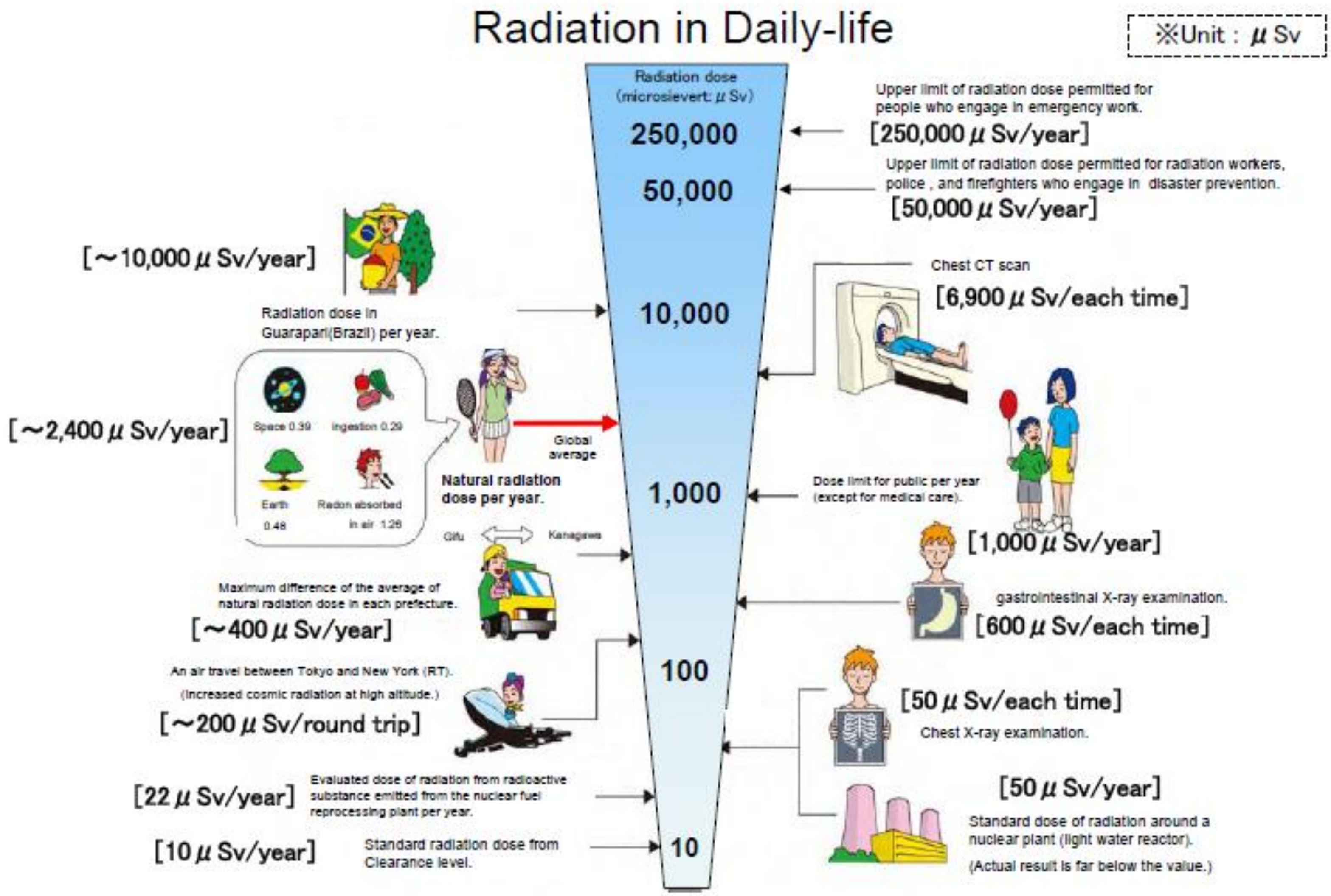
Symptoms and Health Effects for various radiation exposures

Exposure level (mSv)	Symptoms and Effects
50 - 100	Changes in blood chemistry
500	Nausea within hours
700	Vomiting
750	Hair loss within 2-3 weeks
900	Diarrhoea
1,000	Haemorrhage
4,000	Possible death within two months if no treatment
10,000	Destruction of intestinal lining, internal bleeding and death within 1-2 weeks
20,000	Damage to the central nervous system and loss of consciousness within minutes and deaths within hours or days

How dangerous is Ionizing Radiation?

- **Stochastic Effects:** caused by long-term, low level exposure to radiation. Increased levels of exposure makes the effects more likely to occur but do not influence the type or severity.
- Cancer is the primary health effect. Others include genetic mutation, circulatory diseases, leukemia in children, etc. No evidence of caner induction was found for acute dose below 100 mSv.
- However, the chance of getting cancer is low. The risk of one particle causing cancer is 1 in 30 $x10^{15}$, i.e. only about 1% of fatal human cancers are caused by the 30 trillion particles of radiation that hit us over a lifetime

Radiation Levels in Daily Life?



How dangerous is Ionizing Radiation?

- According to UNSCEAR Report 2006, based on studies of atomic bomb survivors, and other epidemiological studies, excess lifetime risk from all solid cancers of all ages following an acute dose of 1 Sv is estimated to be about 4.3-7.2 % and for leukemia is 0.6-1.0%, depending on the population and the model used.
- Natural background ranges from 2- 5 mSv per year.
- X-ray gives ~ 60μSv per dose
- CT scan gives 1-10 mSv per dose
- Radiotherapy gives over 100 mSv per dose

What are recommended Dose Limits?

- NCRP, ICRP & IAEA recommend dose limits
- Maximum exposure either acutely or in each year is 100 mSv
- Exposure > 100 mSv is only justifiable if life saving or prevention of serious disaster is required
- For continuous or prolonged exposure: 1 mSv/yr, maximum 5 mSv per year but on average 1 mSv/yr over 5 years.
- Annual maximum equivalent dose to lens of eyes: 15 mSv and skin, hands and feet 50 mSv
- For occupational exposure
  - ICRP: 20 mSv/yr
  - NCRP: 50 mSv/yr

What are the major Fission Products?

- Fission reactions generate at least 80 fission products, but major fission products emitted are:
  - Cs-137 (30 y), Cs-134 (2.1 y),
  - I-131 (8 d)
  - Kr-85 (10.8 y), Xe-133 (5.3 d)
  - Ru/Rh-106 (1 y)
  - Sr-90 (50.5 d)
  - Co-58 (71.3 d)
  - Co-60 (5.27 y)
- Half life is the time by which the radioactivity is reduced by half of it original amount

What is toxicity of radionuclides in human?

- Human Internal exposure to radiation
- Radionuclides can accumulate in bone, thyroid, organs, tissues and can intervene normal metabolism in body, with cancer or non-cancer effects
- Biological half life is the time needed for any particular radionuclides taken into the body to be reduced to half of its level of natural excretion.
  - Caesium-137 (70 d)
  - Strontium -90: (50 y because it is accumulated in bone structure
  - Plutonium-239 (200 y in bone structure and 500 d in lung)
- The longer the biological half-life, the greater the damage to the body

What are guidelines for foods and drinks?

- The Codex Alimentarius Commission was created in 1963 by FAO and WHO to develop food standards, guidelines and related texts such as codes of practice under the Joint FAO/WHO Food Standards Programme. The main purposes of this Programme are protecting health of the consumers and ensuring fair trade practices in the food trade, and promoting coordination of all food standards work undertaken by international governmental and non-governmental organizations.
- The food is considered safe for human consumption if the radionuclide levels in foods and drinks do not exceed the corresponding Guideline Levels
- These guidelines are based on an intervention level of 1 mSv/yr as recommended by ICRP, NCRP and IAEA

Guideline Levels of CODEX in Foods/Drinks

Product Name	Radionuclides	Level in Bq/kg
Infant foods	Pu-238, Pu-239, Pu-240, Am-241	1
	Sr-90, Ru-106, I-129, I-131, U235	100
	S-23, Co-60, Sr-89, Ru-103, Cs-134, Cs-137, Ce-144, Ir-192	1,000
	H-3, C-14, Tc-99	1,000
Foods other than infant foods	Pu-238, Pu-239, Pu-240, Am-241	10
	Sr-90, Ru-106, I-129, I-131, U235	100
	S-23, Co-60, Sr-89, Ru-103, Cs-134, Cs-137, Ce-144, Ir-192	1,000
	H-3, C-14, Tc-99	10,000

How about for multiple nuclides in food?

- If several radionucldies of the same group are present in a sample, the following summation criterion must be satisfied:

$$\Sigma (A_i / GL_i) \leq 1$$

where A_i = activity concentration of i^{th} type in food

GL_i = guideline level of the i^{th} type

- No need to add contribution from radionuclides in different groups
- No provision for summation of radionuclide activities in different food samples or food groups

How do we assess human internal exposure?

- The mean internal dose of the public, due to annual consumption of imported foods containing radionuclides can be estimated using the following formula:

$$E = GL(A) * M(A) * e_{ing}(A) * IPF$$

where $GL(A)$ = guideline level in Bq/kg

$M(A)$ = age-dependent mass of food consumed per year (kg)

$e_{ing}(A)$ = age-dependent ingestion dose coefficient (mSv/kg)

IPF = import/production factor (which is defined as the ratio of the amount of foodstuff imported per year from areas contaminated with radionuclides to the total amount produced and imported annually in the region or country under consideration)

Examples of assessment

1. If an adult ingested Cs-137 in food for the first year after the area is contaminated with this nuclide.

GL (Cs-137) = 1000 Bq/kg

M(Cs-137) = 550 kg

e_{ing}(A) = 1.3 x 10-5 mSv/kg

IPF = 0.1

This give E = 0.7 mSv < 1 mSv/year (safe)

Examples of assessment

2. If a sample of fresh milk contains 150 Bq/kg of Cs-137 and 40 Bq/kg of Sr-89, the food is considered safe for unrestricted commercial food supply because:

$$150/1{,}000 + 40/1{,}000 = 190/1{,}000 < 1 \text{ (safe)}$$

The Canadian Guidelines in Bq/kg or Bq/L for the restriction of radioactively contaminated food and water followings nuclear emergency are:

Radionuclide	Fresh Liquid Milk	Other Commercial Foods and Beverages	Public Drinking Water
Sr-89	300	1,000	300
Sr-90	30	100	30
Ru-103	1,000	1,000	1,000
I-131	100	300	100
Cs-134, Cs-137	300	1,000	100
Pu-238, Pu-239, Pu-240, Pu-242, Am-241	1	10	1

Note: the Canadian guidelines require summation of activity contribution from different groups

“Defense in Depth” in Typical Power Plant

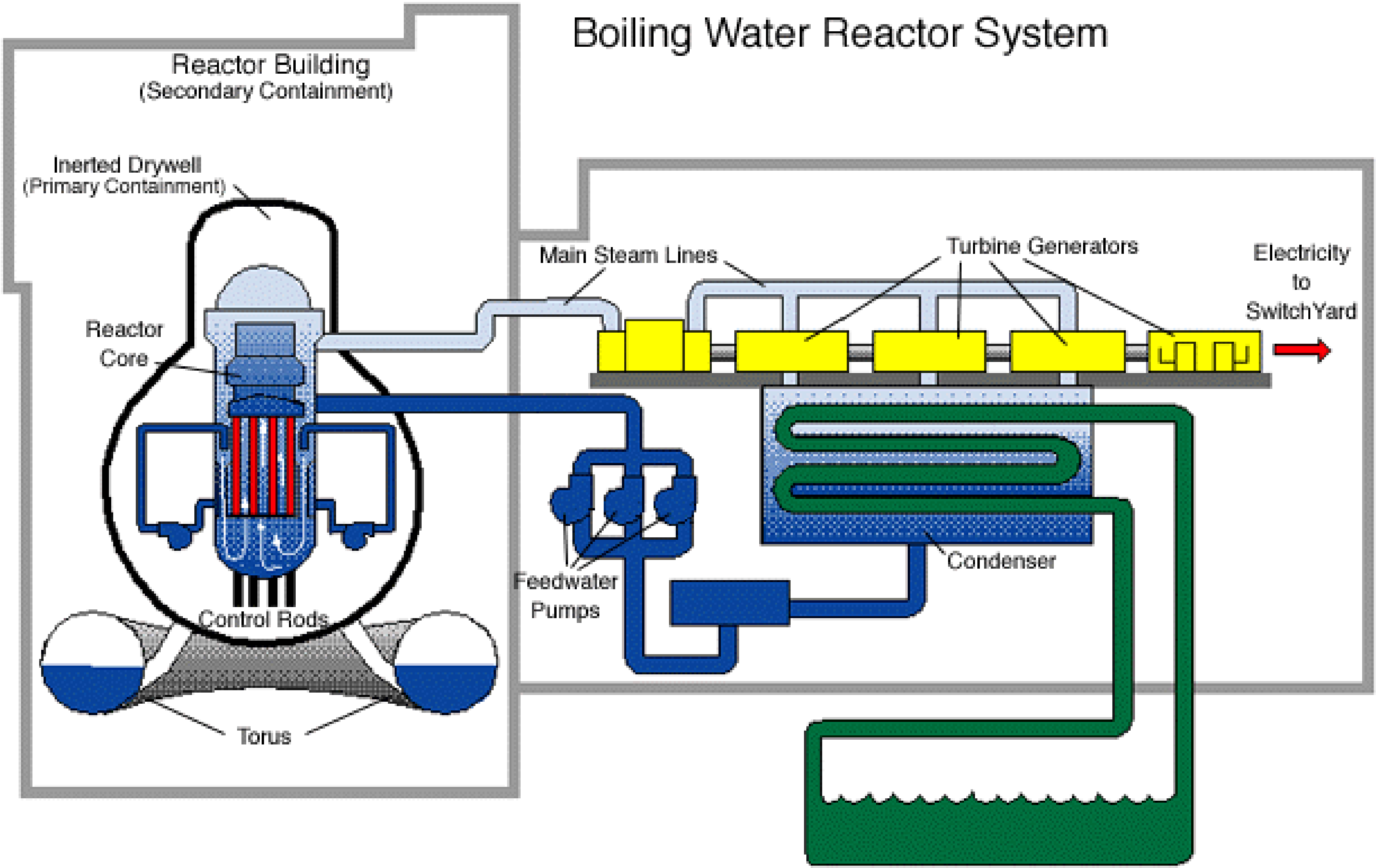
- No technology is absolutely safe and nuclear plant is no exception
- Nuclear power plants are designed to handle a variety of internal and external events including:
  - Human errors
  - Loss of coolant accidents (LOCA)
  - Failures in steam piping systems
  - Steam generator tube rupture
  - Leakage or failure of a system carrying radioactive fluid
  - Fuel handling accident
  - Loss of electric power
  - Fire
  - Internal flooding
  - Explosions
  - Aircraft crash
  - External explosion
  - Earthquake
  - Flood
  - Wind and tornados
  - Extreme temperature

"Defense in Depth" in Nuclear Power Plant?

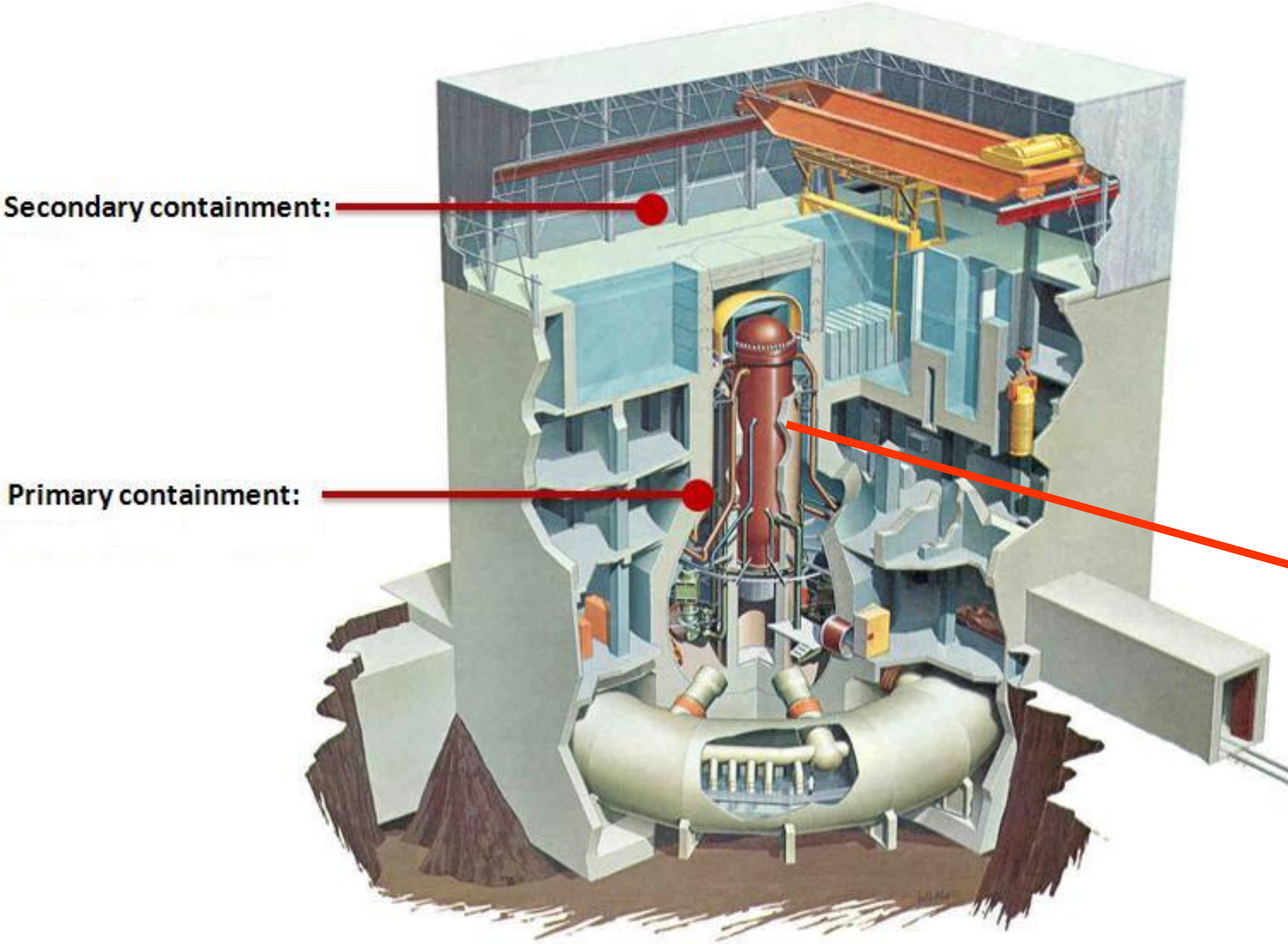
- The first containment: Enriched Uranium 235 oxide in the form of pellets is placed in fuel rods made of Zircaloy alloy with a melting point of 2200^{o}C and sealed off.
- The second containment: assembly of fuel rods (the core) is placed inside a pressure vessel made of at least 6 inches of steel with a melting point of about 1400^{o}C.
- Third containment: the pressure vessel with a large steel-lined concrete basin, i.e. pressure suppression wetwell (called "Torus" or "core catcher") and all associated piping, valves, pumps, and coolant reserves are placed within 1.2-2.4m thick prestressed concrete structure with an internal steel lining that can withstand the impact of even a 747 aircraft (internal pressure of at least 10 bars of atmospheric pressure).
- Fourth containment: the concrete structure is housed in a concrete reactor building.

“Defense in Depth” in Nuclear Power Plant?

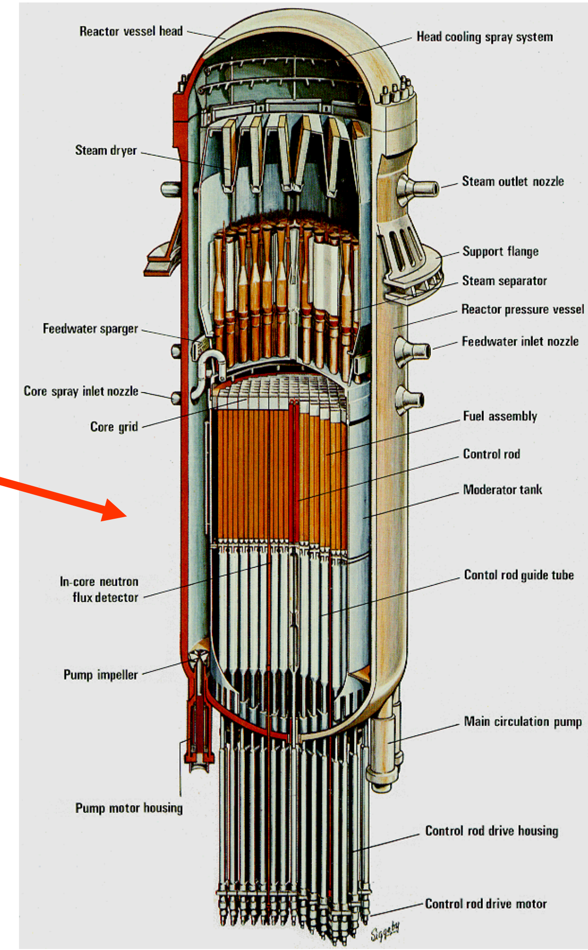
- Emergency core cooling system (ECCS), comprising high pressure corespray, low pressure corespray, automatic depressurization and low pressure injection systems to cool and remove residual heat
- Emergency shut down system to stop the fission chain reaction by automatically inserting the control rods.
- Within third containment, a ventilation system fitted with charcoal or sand filters to vent and scrub the air out and a water spraying system to wash out radioactive dust , except the most volatile fission products, e.g. Cs and I from the air inside the containment
- Others



Schematic Layout of Typical Boiling Water Reactor



Boiling Water Reactor Design



Pressure vessel and fuel rods/control rods

Biological Defense in Depth in Human?

- First level: Production of anti-oxidants in cells to fight reactive oxygen species generated by ionizing radiation and by any oxidative stress,
- Second level: Elimination of injured cells (mutated or un stable) through two mechanisms (i) apoptosis (細胞自然死亡) which can be initiated by doses as low as a few mSv, thus eliminating cells from the genome of which has been damaged or mis-repaired, (ii) death of cells during mitosis (細胞有絲分裂) when lesions have not been repaired.
- Third level: Stimulation or activation of DNA repair systems following slightly higher doses of about ten mSv.
- Fourth level: Activation of the immune system to kill cells that are not sensed to be 'one of ours', possibly formed by the double strand breaks.
- Others: ??

What are the preliminary lessons learnt?

- Never build a nuclear power plant along an active fault line.
- Never install the backup diesel generators below the flood level
- Nature's power is huge: A 9.0 Mm earthquake on the moment magnitude scale is equivalent to 9 billion tons of TNT.
- Natural disasters are highly unpredictable. Even a 1: 10 million year return period of such earthquake can occur within the life time of a nuclear power plant (normally 40 yrs).
  - The Fukushima plant was designed to withstand only 8.2, but the Tōhoku earthquake is 8 times more powerful than what the plant was designed to withstand. The seawall was designed to stand a tsunami of 5.7m, but the one that struck the plant was 14m. The Unit 1 was supposed to retire in 2011.

What are the preliminary lessons learnt?

- Never allow the plant to lose power for more than 8 hours even though redundancies were built in the plant, e.g. the diesel generators, batteries, grid connection to outside.

How about the Daya Bay Nuclear Power Plant?

- Review the safety measures, i.e. “Defense in depth” in Daya Bay Power Plant
- Review the disaster management plan in Daya Bay Power Plant
- Retrofit, as necessary, the Daya Bay Nuclear Power Plant by adding more or enhancing existing backup and safety devices, e.g. (a) more backup power in the event of power blackout and loss of external power for the coolant system, (b) control of the hydrogen releases by pre-pressurizing the containment with nitrogen to prevent hydrogen from reaction with oxygen, (c) more training of qualified operators, (d) more passive safety measures, e.g. gravity-feed water reservoirs to feed the pressure vessel in the event of LOCA, (e) more safety drills for the operators, etc. to safeguard any release of radionuclides into the environment.

How about the Daya Bay Nuclear Power Plant?

- Establish an emergency plan for the Hong Kong citizens in the unlikely event of any radiation leakage from the plant. [Note: Hong Kong has no place to hide since an accident of the scale as that of Fukushima Daiichi plant requires at least 50 ~ 80 km.]
- Establish a close monitoring network of the operation at the plant including (a) air monitoring network, (b) radiation check of the water and food
- Educate the public on nuclear safety and health effects of radiation

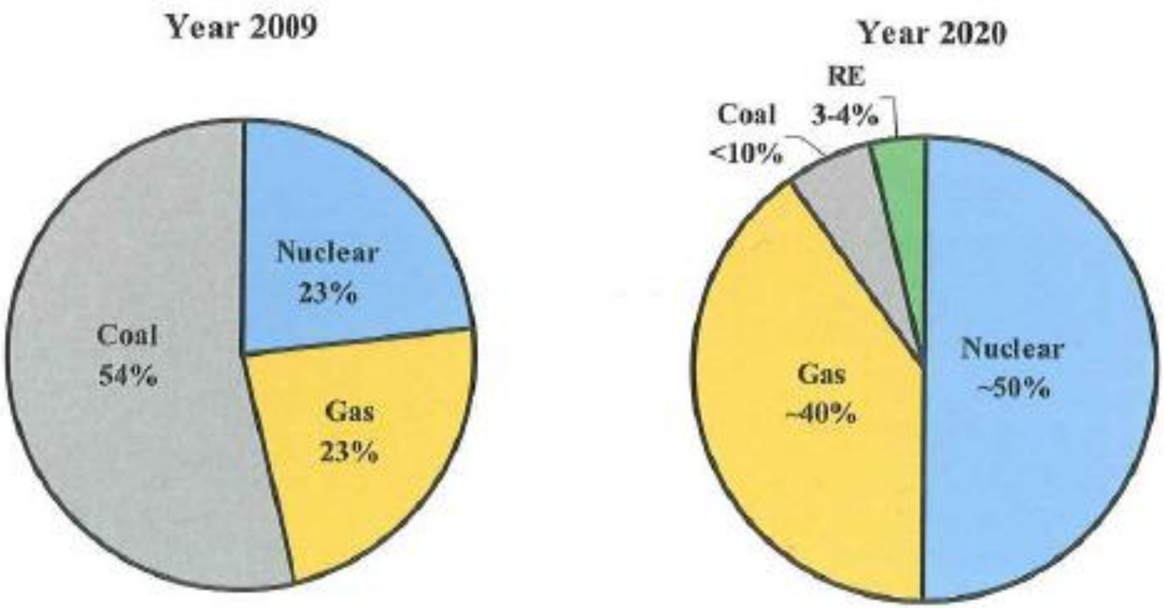
Concluding Remark

- **Is our quest for power sustainable?**
  - The continual and insatiable quest for power is likely to cause more pollution and more pre-mature death.

- **Is nuclear power safe and how safe is safe?**
  - Nuclear power is largely safe but minor accidents do occur from time to time. The question is: can we afford to have one fatal accident ? Germany has temporarily shut down 7 of its oldest reactors and ordered a review of the safety of all national nuclear power plants. China has ordered CNNC to review its nuclear program. Beijing may also have to scale back the 2020 target for nuclear from 5% to about 3% of total national power capacity.

Concluding Remark

- **Have we explored other power options?**
  - Rethink about future fuel mix: coal-fired, gas fired, wind-driven, solar power, biomass, etc. The consultation Paper "Hong Kong's Climate Change Strategy and Action Agenda" has proposed a fuel mix for 2020 as below:



Concluding Remark

- **Are our renewable energy sources really very limited?**
  - Can we install solar panels on all slopes, mountain ridge, bare rock, public facilities to generate power for the future generations since we have 40% of the land as country parks. The excess power in the daytime can be used to pump seawater up the mountains as potential energy and use this energy where needed in the nighttime or under cloudy days as hydropower

Thank you