AN INTRODUCTION TO RADIATION, NUCLEAR ENERGY AND THE FUKUSHIMA DAI-ICHI ACCIDENT

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23 August 2011

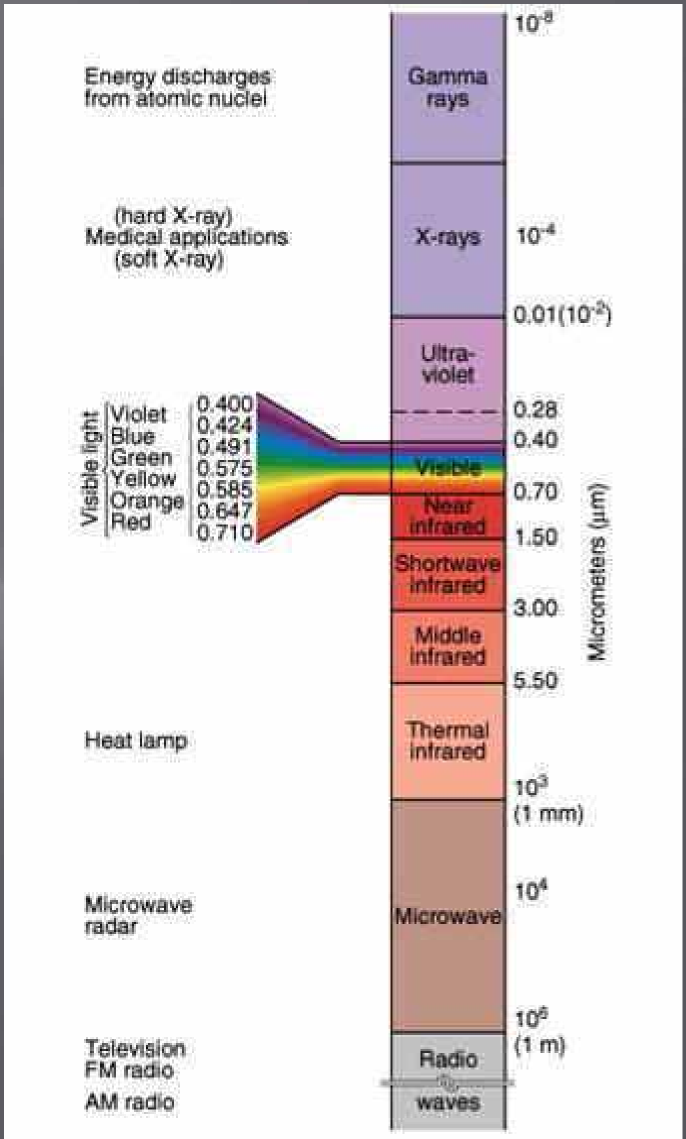
Fundamentals - Radiation

Part 1

Types of Radiation

- *Ionizing radiation* – types of radiation that are energetic enough to detach electrons from atoms
  - *Ionizing radiation causes damage to body tissues*

- *Non-ionizing radiation* – types of radiation that are not strong enough to remove electrons from atoms



Types of Ionizing Radiation

- Alpha Particle – a Helium nucleus, primarily emitted by heavy isotopes.
  - If ingested and retained in the body, an α-emitter can damage internal tissue since its radiation deposits its energy in a small volume.
- Beta Particle – an electron (β-) or a positron (β+) emitted from an unstable atom.
  - Easily shielded, but can cause damage if a β-emitter is ingested or inhaled, or by unshielded contact.
- Gamma and X-Rays – electromagnetic energy emitted from a nuclear transition.
  - Gamma and x-radiation is widespread and penetrating.

Radiation Protection

- There are three factors used to mitigate radiation exposure.
  - **Time** – reduce the time spent in a radiation field
  - **Distance** – increase the distance from radiation sources
  - **Shielding** – increase the amount of shielding between radiation sources and workers.

Shielding

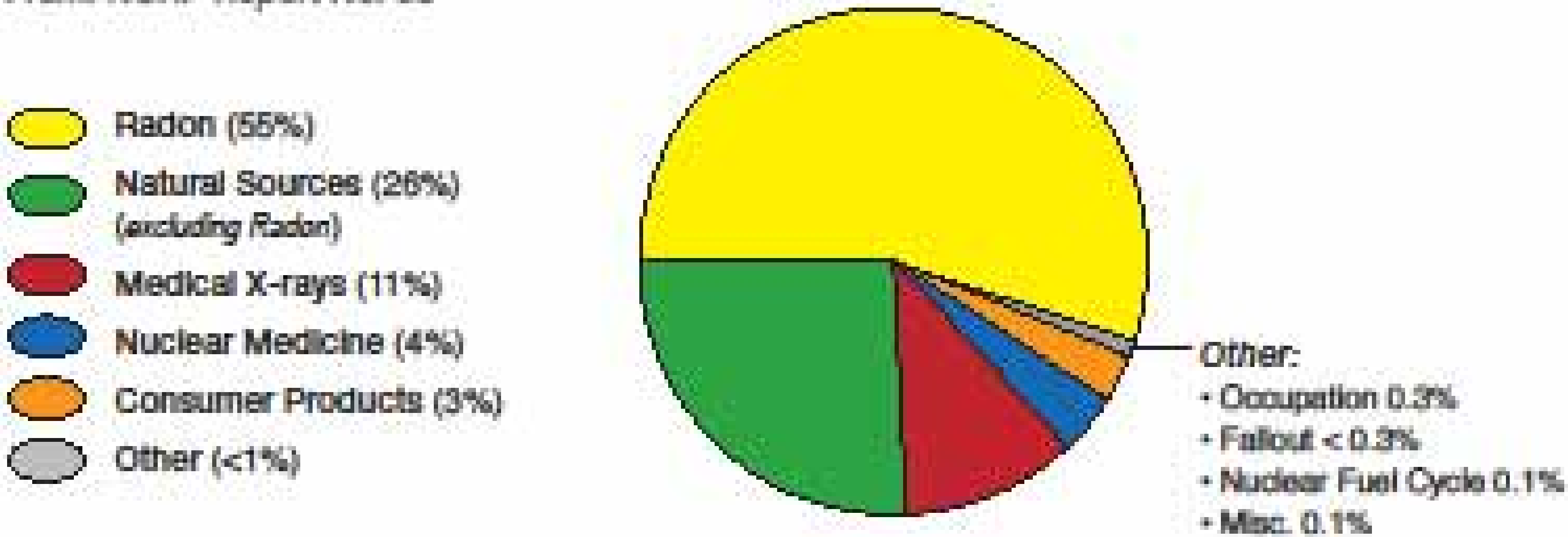
- Different types of shielding may be used to protect against various types of radiation.
- Alpha (α) and beta (β) radiation is easily shielded by thin materials such as paper, aluminum, and cloth.
- Gamma (γ) radiation can be stopped by heavy materials such as lead, iron or concrete, or several feet of water.

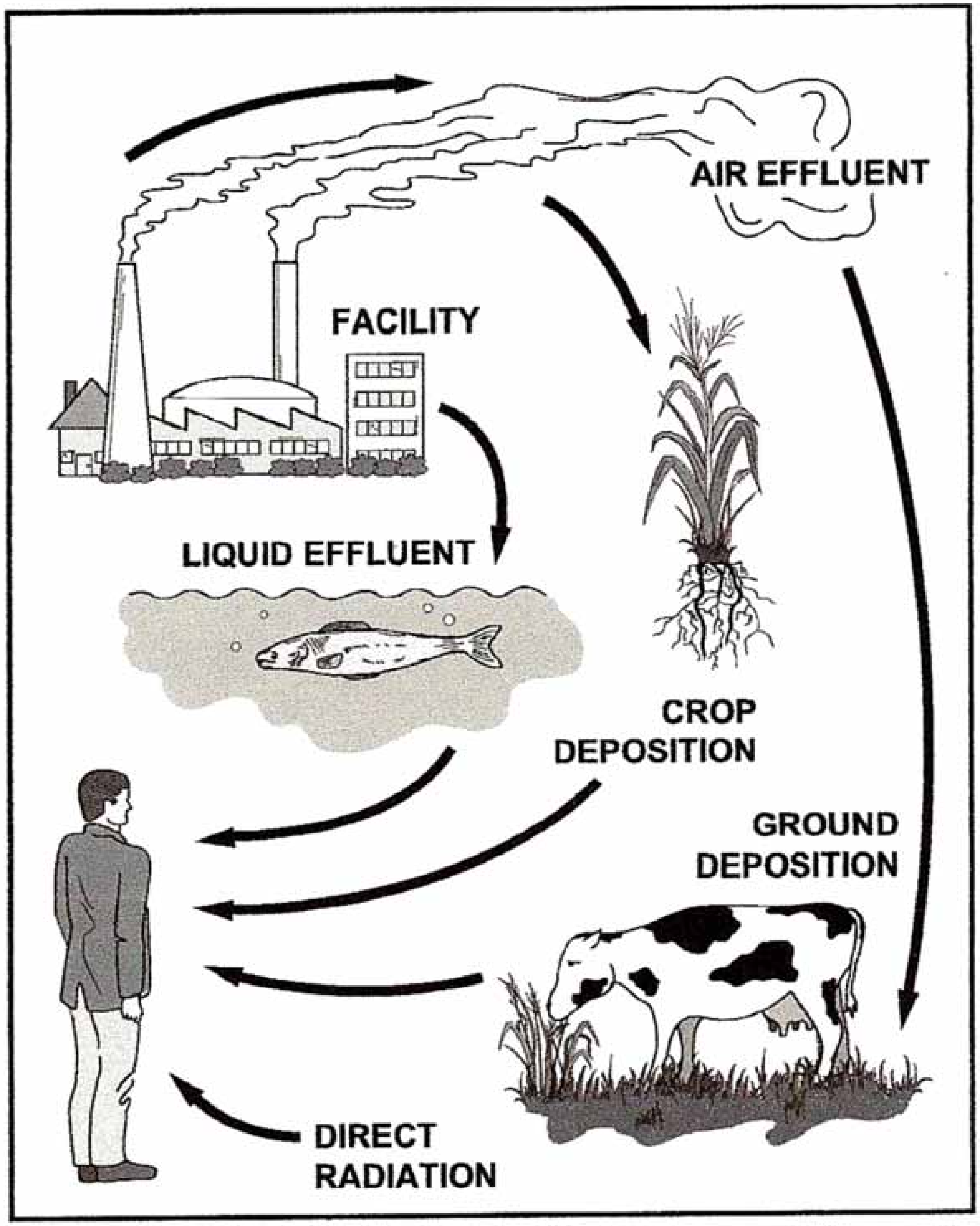
Some Dose Values

- Average annual background dose to persons in the Midwest: 500 mrem (5 mSv)
- US average annual background dose: 310 mrem
- US average annual dose: 630 mrem
- Allowable annual dose to a member of the public from NRC licensed activities: 100 mrem
- Allowable annual dose to a radiation worker in NRC licensed activities: 5000 mrem
- Onset of deterministic health effects: 50 000 to 100 000 mrem in a single dose.

Sources of Radiation Exposure

From: NCRP Report No. 93




AIR EFFLUENT
FACILITY
LIQUID EFFLUENT
CROP
DEPOSITION
GROUND
DEPOSITION
DIRECT
RADIATION

The Role of Nuclear Power in the US and World Energy Economy

Part 2

The Role of Nuclear Power

- As of the end of December 2010:
  - There were 444 operational nuclear power reactors, having a capacity of 378 GWe, located in 29 countries + Taiwan;
  - There were 109 nuclear power reactors either under construction or planned, having a capacity of 109 Gwe, in 18 countries + Taiwan. China alone has 26 units under construction and 16 planned, totaling 43 Gwe.

The Role of Nuclear Power

- Nuclear energy produces about 6% of total primary energy worldwide.
- Nuclear energy produces about 14% of electricity worldwide, and about 21% of the electricity in OECD countries.
- Nuclear and hydro are the only low-carbon sources presently providing significant amounts of energy.

Electricity Generation by Energy Source
(2007 NEA/IEA Data)

Energy Source	OECD (10 600 TWh)	World (19 800 TWh)
Coal	37.2%	41.6%
Natural Gas	21.7	20.9
Nuclear	21.4	13.8
Hydro	11.8	15.6
Oil	4.1	5.7
Biomass and Waste	2.0	1.3
Wind	1.4	0.9
Geothermal, Solar, Tidal and Wave Power	0.4	0.3

Fuel Requirements

- Fuel requirements for one day of operation of a 1000 MWe power plant at 33% efficiency (3000 Mwt):
  - 3.16 kg of U-235 fissioned;
  - 8000 tons of coal;
  - 2.4×10^8 standard cubic feet of natural gas;
  - 42 500 barrels of oil.
- The power generated is equivalent to the electricity consumed by about 800 000 average US households.

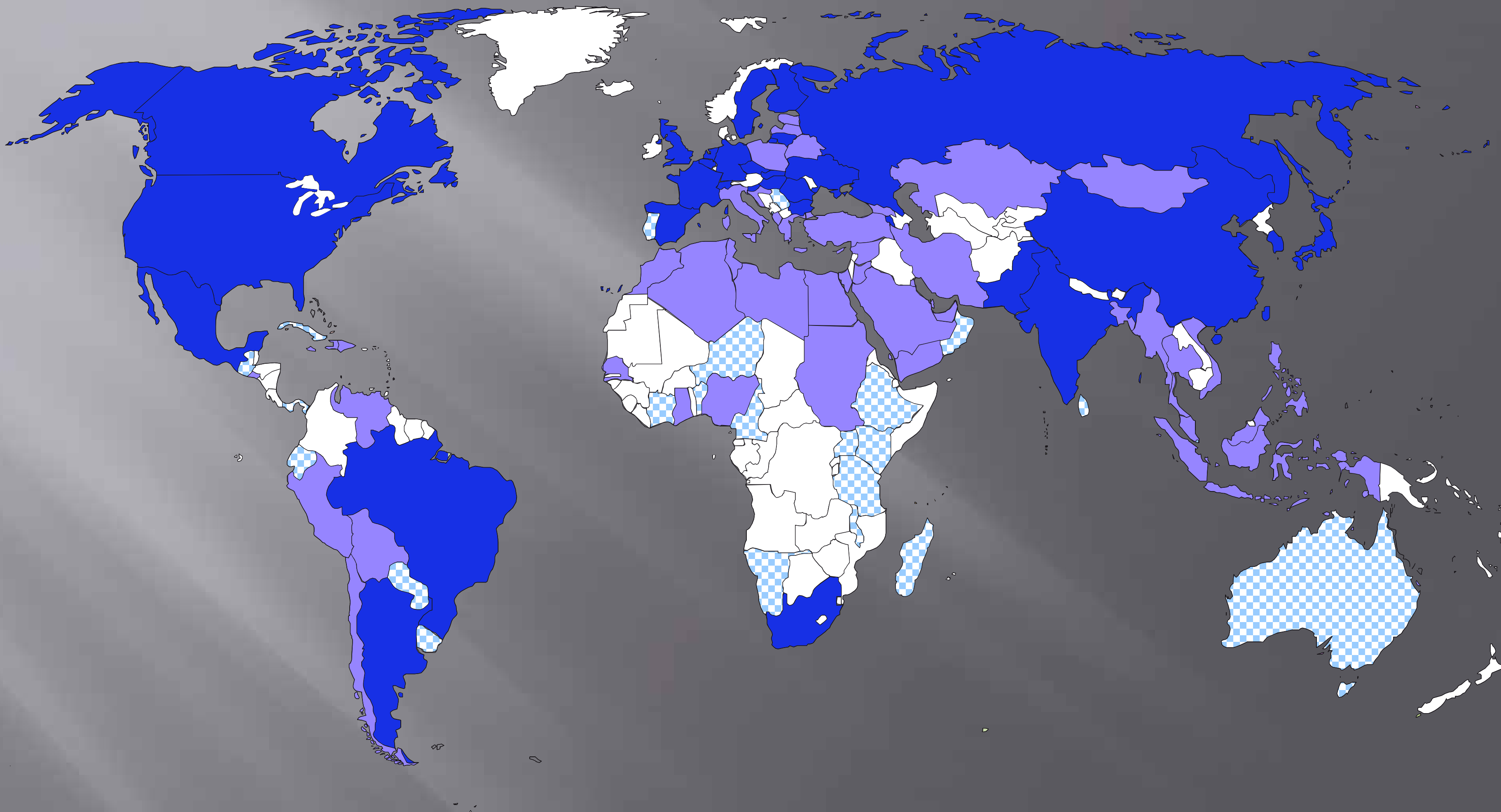
Nuclear Power Production
(2010 ANS, 2009 IAEA Data)

Rank	Country	Inst. Cap.-GWe	Number Reactors	TWH Generated (Avg. Cap. Factor)	% of Electricity
1	USA	103	104	797 (88%)	20.2
2	France	63.1	58	392 (71%)	75.2
3	Japan	46.8	54	263 (64%)	28.9
4	Russia	22.7	32	153 (77%)	17.8
5	Germany	20.5	17	128 (71%)	26.1
6	Korea	17.7	20	141 (91%)	34.8
7	Canada	15.1	22	85.1 (64%)	14.8
8	Ukraine	13.1	15	77.8 (68%)	48.6
	World Total	378	444	2558 (77%)	14

Existing NPPs – US Plant Performance

- 2007-2009 Capacity Factors
  - 13 reactors had capacity factor over 95%
  - 42 reactors had capacity factor between 90 and 95%
  - 43 reactors had capacity factor between 80 and 90%
  - 5 reactors had capacity factor between 70 and 80%
  - 1 reactor had capacity factor less than 70%
- US nuclear power plants produce about 20% of our electricity but are only about 10% of the installed capacity.

Interest in Nuclear Power is Worldwide



Operating   Considering   Expressed interest

New NPPs – Under Construction or Planned
(2010 ANS Data)

Rank	Country	New Cap.-MWe	Number Reactors
1	China	43430	43
2	Russia	10560	12
3	USA	10477	9
4	Korea	9600	8
5	U. A. E.	5600	4
6	India	5096	8
7	Turkey	4600	4
	Worldwide	108 867	109

Pros and Cons of Nuclear Power

- Pros:
  - Nuclear is the only large scale, emission-free, expandable energy technology available.
  - Nuclear energy is an efficient use of resources, since uranium is abundant and has few other uses. The amount of fuel needed is small compared to chemical fuel requirements.
  - Nuclear power plants operate efficiently and can achieve high availability and capacity factors.
  - Although the risk of an accident with radioactive release exists, nuclear power has an excellent safety record.

Pros and Cons of Nuclear Power

- Cons:
  - The capital cost of a nuclear power plant is very high. Economy-of-scale is necessary to compete economically in many markets.
  - A successful nuclear power program requires a long-term commitment, a high level of technical sophistication and a dedication to excellence.
  - The issue of ultimate disposal of high-level radioactive waste remains to be resolved.
  - However low the probability may be, the risk of an accident releasing radioactive material exists.

Fundamentals – Reactor Safety

Part 3

Fundamental Safety Functions

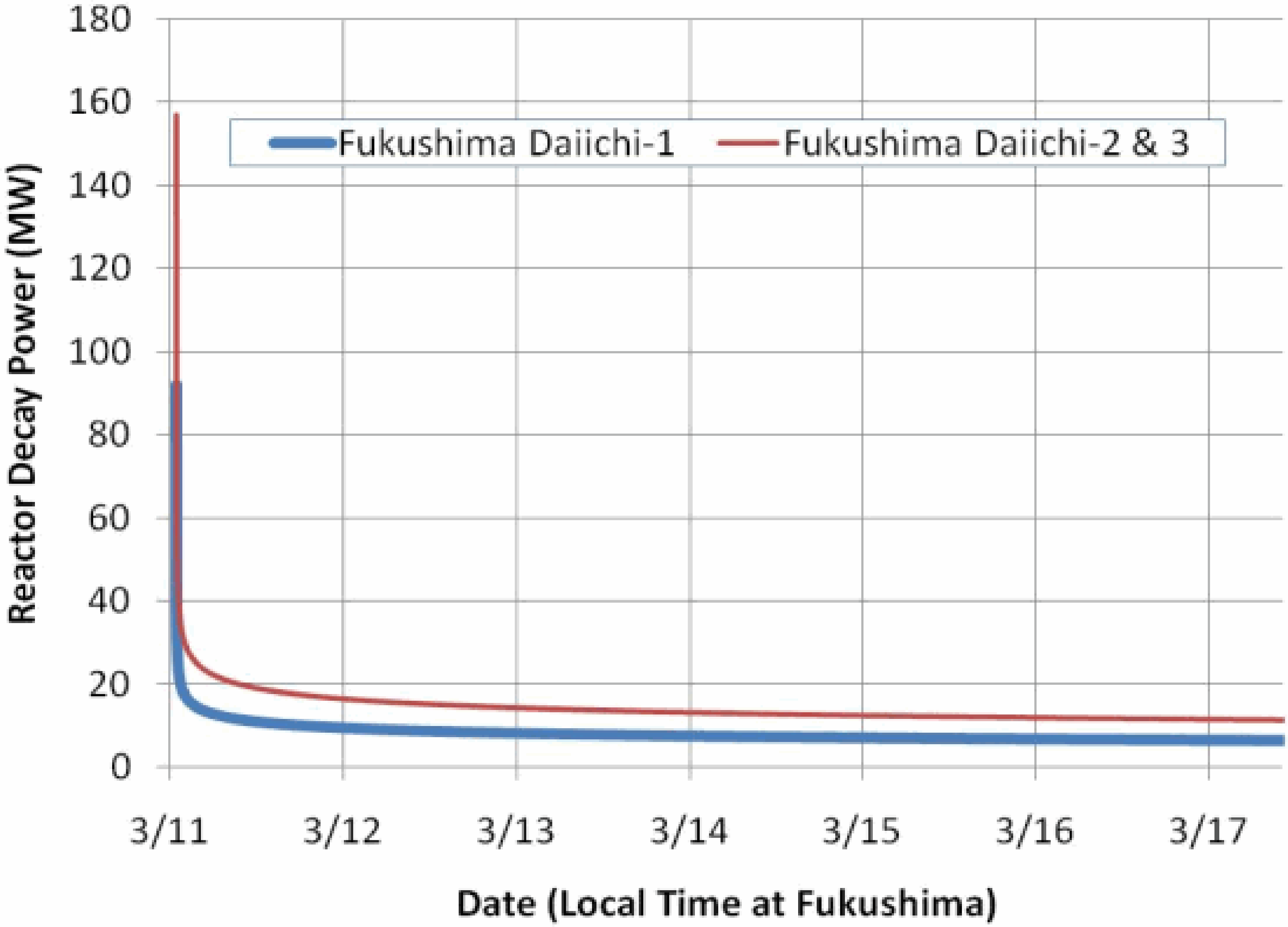
- Reactivity Control – Control the reactor power.
- Heat Removal – Remove heat during reactor operation and remove decay heat after shutdown, including from spent fuel.
- Containment of Radioactive Material – Control releases during normal and accident conditions and mitigate effects of severe accidents.

Decay Heat Removal

- Radioactive fission products release energy in decay to a stable state.
- Since fission products are retained within the cladding, adequate cooling must be maintained at all times to remove decay heat and prevent cladding failure in the reactor or in spent fuel storage.
- Decay heat is the thermal driving force in most accidents in light-water reactors.

Heat Generation After Shutdown, Long Term Operation, PWR, Uranium Fuel

Time after reactor shutdown:	Fraction of operating power:
1 minute	5 %
1 hour	1.5 %
1 day	0.5%
1 week	0.3%
1 month	0.15%
1 year	0.03%
10 years	0.003%


Fukushima Daiichi-1
Fukushima Daiichi-2 & 3
Reactor Decay Power (MW)
180
160
140
120
100
80
60
40
20
0
3/11
3/12
3/13
3/14
3/15
3/16
3/17
Date (Local Time at Fukushima)

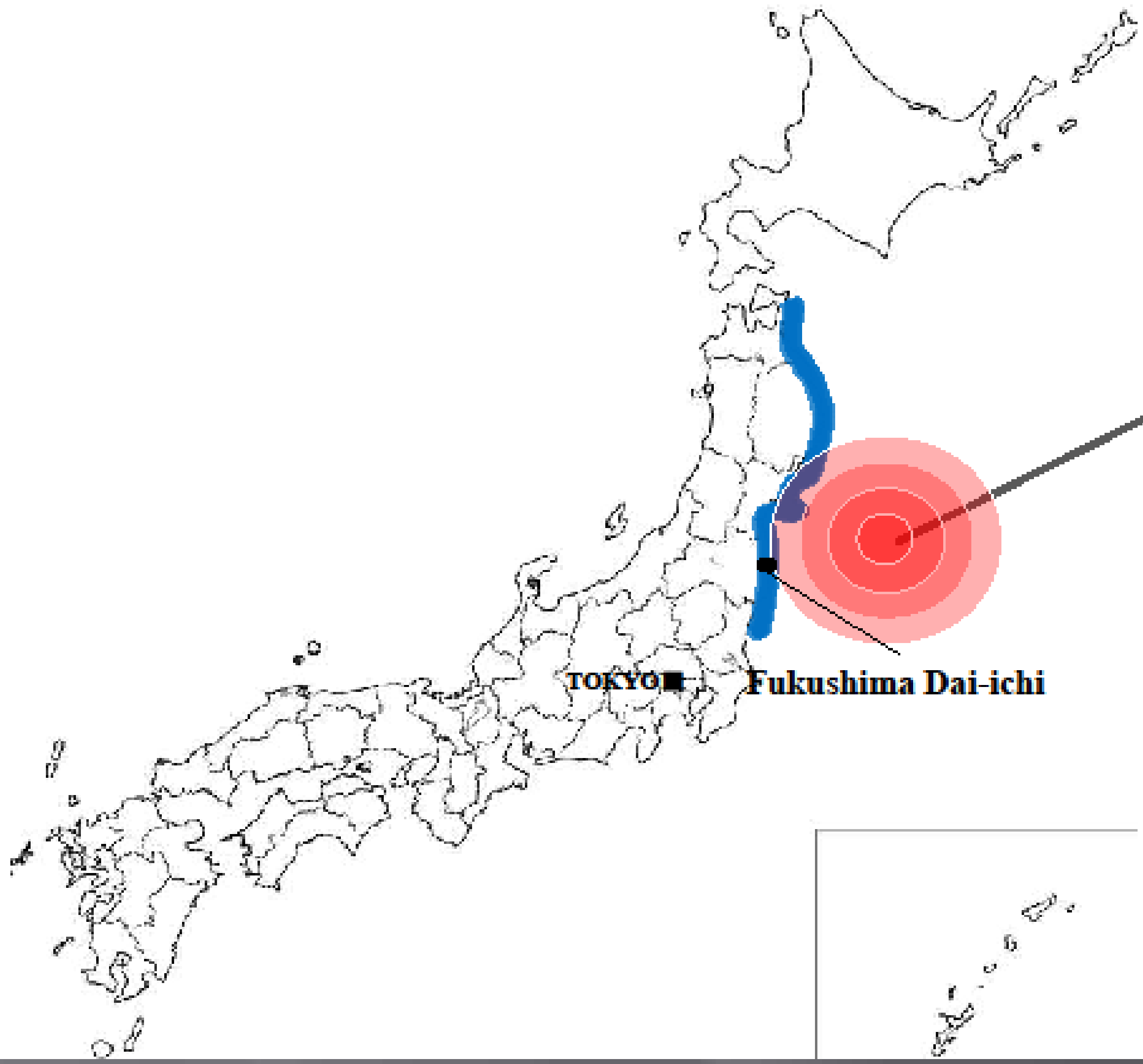
Defense-in-Depth

- Defense-in-depth is the key concept on which all of nuclear safety is based.
  - Defense-in-depth includes: prevention, detection and control of abnormal operation; safety systems to control accidents within the design basis; accident management measures to control of accidents beyond the design basis; and mitigation of radiological consequences.
  - Defense-in-depth includes multiple physical barriers (fuel pellet, cladding, reactor vessel, containment), and systems to protect these barriers.

The Fukushima Dai-ichi Accident

Part 4

A. Japan Faces an Unprecedented Challenge
(Enormous Earthquake, Tsunamis and Nuclear Accident)



Earthquakes:
- M - 9.0 quake (March 11)
- M - 7 class 5 times
- M - 6 class 71 times
- M - 5 class 380 times

(As of May 16th)

4

1. Damage

KYODO NEWS

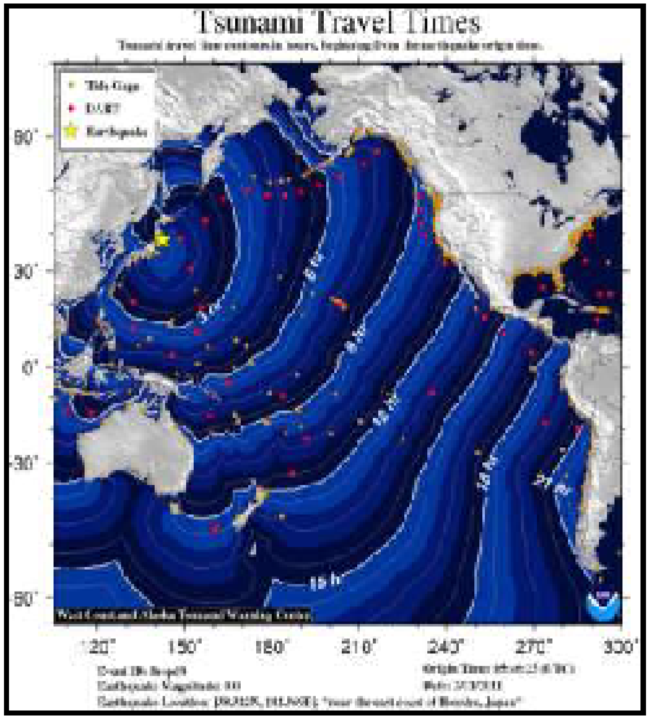
KYODO NEWS

<u>Casualties : over 28,000</u>

- Dead : over 15,400
- Missing : over 7,000
- Injured over 5,300

<u>Evacuees : over 124,000</u>

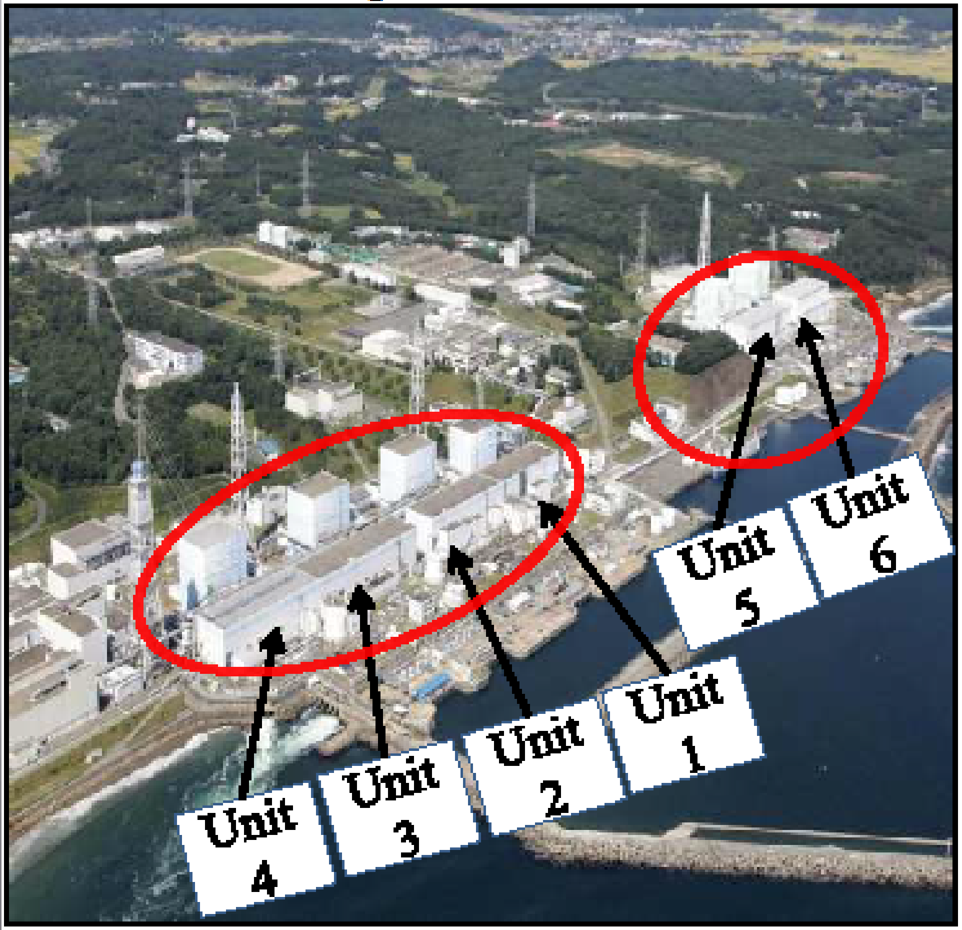
(As of June 20th)



NOAA/US Dept of Commerce, http://wcatwc.arh.noaa.gov/

3. Nuclear Power Stations
Fukushima Dai-ichi Nuclear Power Station

Before the Earthquake and Tsunamis



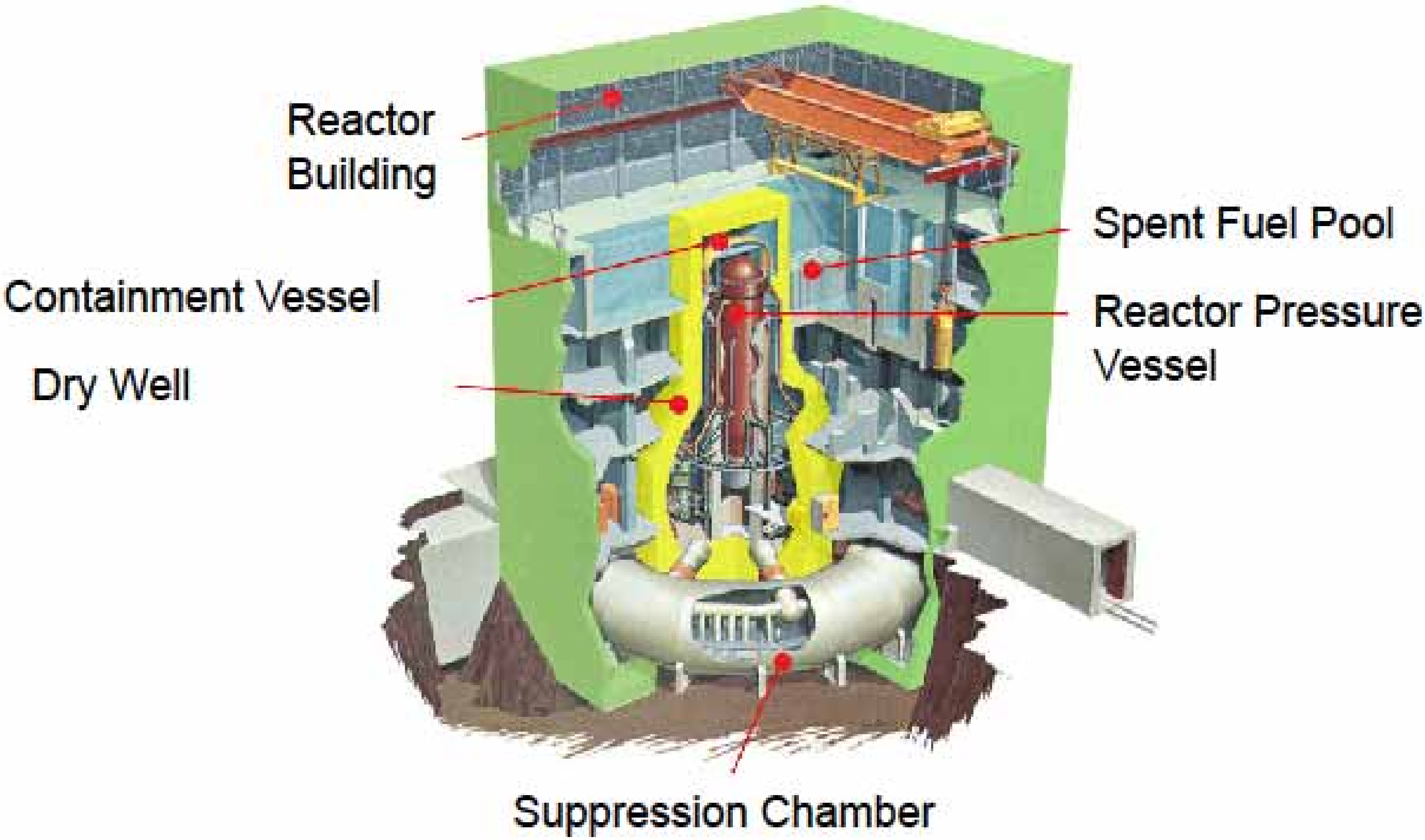
TEPCO

After the Earthquake and Tsunamis

Air Photo Service Inc (Myoko, Niigata Japan)

7

BWR wih Mark I Containment



出典：http://[illegible].cachefly.net/static/images/BWR illustration.jpg

BWR Mark I Containment Structure

- Pear-shaped Dry-Well
- Torus-shaped Wet-Well

en.wikipedia.org/wiki/Browns_Ferry_Nuclear_Power_Plant

Service Floor of a BWR with Mk I Containment

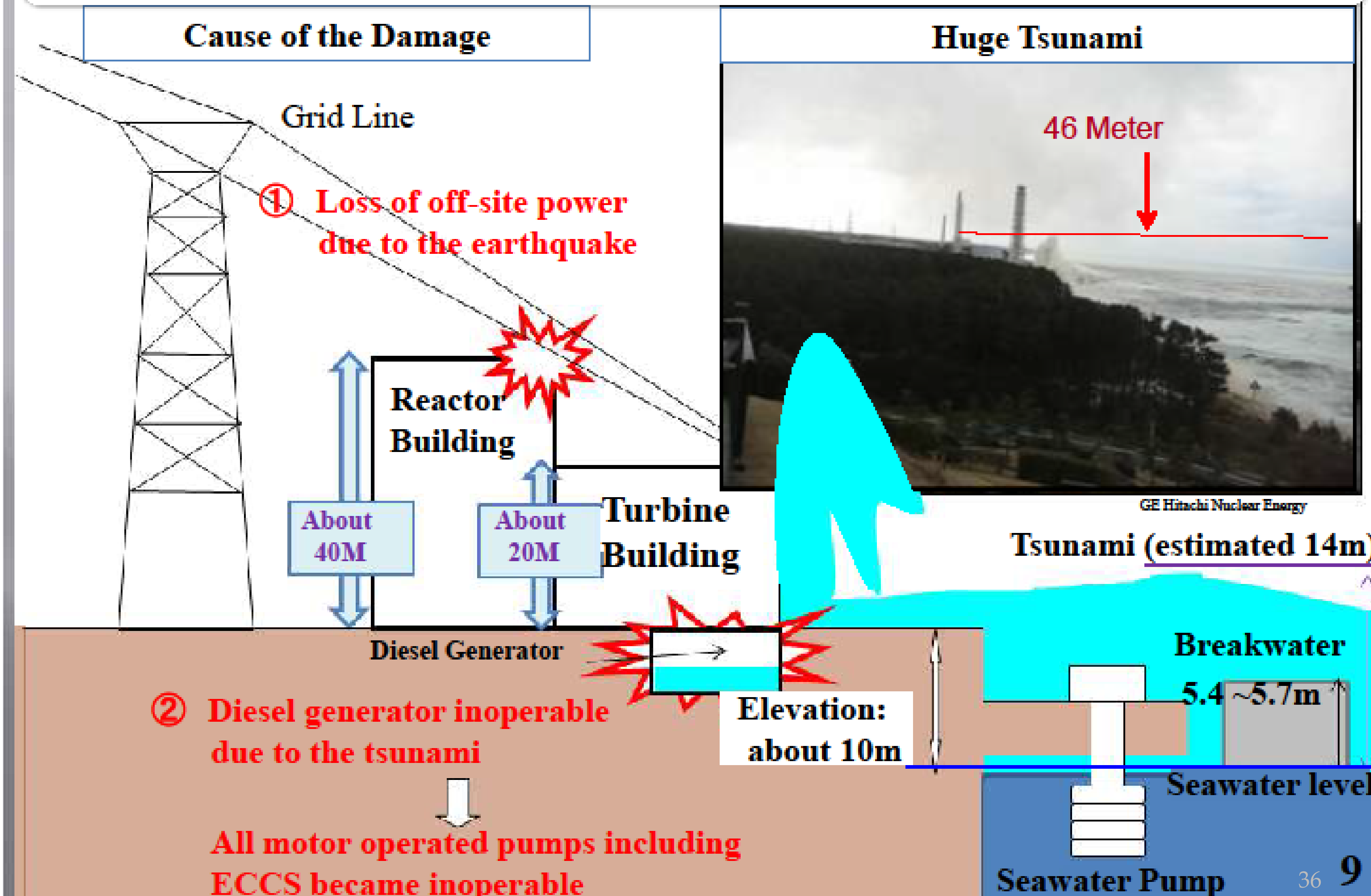
Fukushima Dai-ichi 1-4

	Unit 1	Unit 2	Unit 3	Unit 4
Reactor Model	BWR-3	BWR-4	BWR-4	BWR-4
Containment Model	Mark -1	Mark-1	Mark-1	Mark-1
Commercial Operation	3/1971	7/1974	3/1976	10/1978
Rating, MWe/MWt	460/1380	784/2381	784/2381	784/2381
Status Before/After 11 March Earthquake	Operation/ Shutdown	Operating/ Shutdown	Operating/ Shutdown	No Fuel in the Reactor
Fuel Assemblies in Core	400	584	584	0
Spent/Fresh Fuel Ass'ys in Spent Fuel Pool	292/100	587/28	514/52	1331/204
Spent Fuel Pool Capacity/Volume (m^3)	900/1020	1240/1425	1220/1425	1590/1425
Most Recent Shutdown	27 Sept 10	18 Nov 10	23 Sept 10	29 Nov 10

Effects of the Earthquake at Fukushima I

- Off-site power lost immediately as a result of the earthquake.
- Reactors were shut down and cooling established on emergency diesel-generator power as designed.
- First tsunami wave hit 41 minutes after the earthquake, followed by another 8 minutes later.
  - Height of tsunami experienced: more than 14 m;
  - Plant was flooded to a depth of 5 m before the water receded.
- All AC power lost; battery power lost; all heat removal to the ultimate heat sink (sea water) lost.

3. Nuclear Power Stations
Fukushima Dai-ichi Nuclear Power Station



Status of Fukushima-I 1-4 (July 2011)

- Core Damage: Fuel melting in each of Units 1, 2 and 3; extent unknown.
- Reactor Vessel Integrity: Some damage and leaks are apparent in each of Units 1, 2 and 3.
- Containment Vessel Integrity: Some damage and leaks are apparent in each of Units 1, 2 and 3.
- Building Condition: Badly damaged in Units 1, 3 and 4 due to hydrogen explosions; slightly damaged in Unit 2.

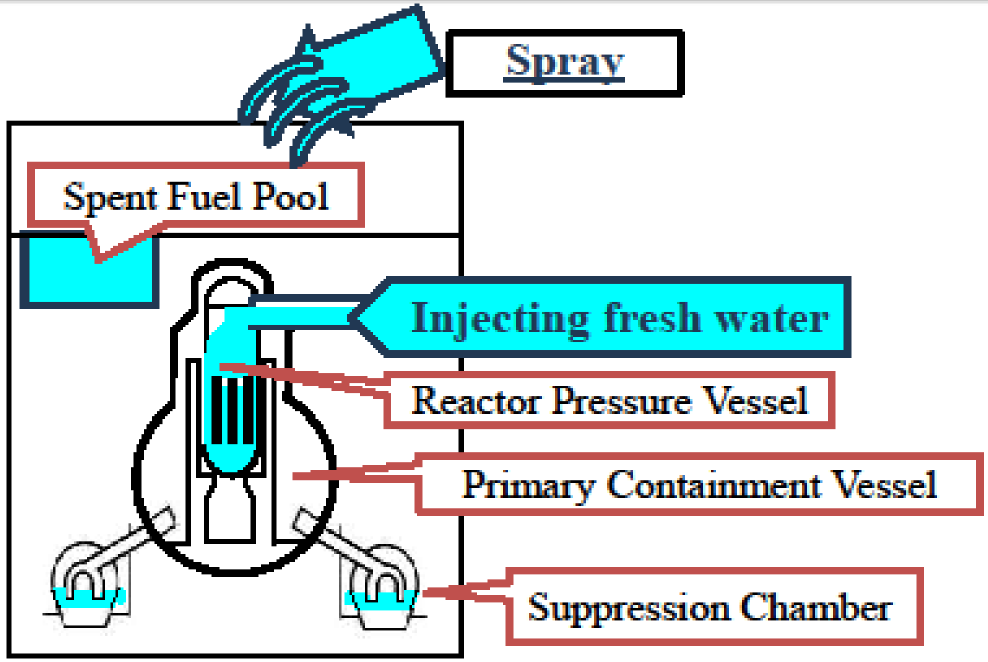
Status of Fukushima-I 1-4 (July 2011)

- Reactor Cooling: Fresh water injection to the reactor vessel is continuing. The reactors have not achieved cold shutdown (temperature <100 C), although temperatures and pressures are stable and close to 100 C.
- Spent Fuel: Condition unknown in Units 1 and 3; most spent fuel not damaged in Units 2 and 4. Spent fuel pool in Unit 4 has been reinforced to ensure structural integrity. Cooling by water injection in Unit 1; circulation through heat exchanger in Units 2, 3 and 4.

1.Cool Down the Reactors

Unit1

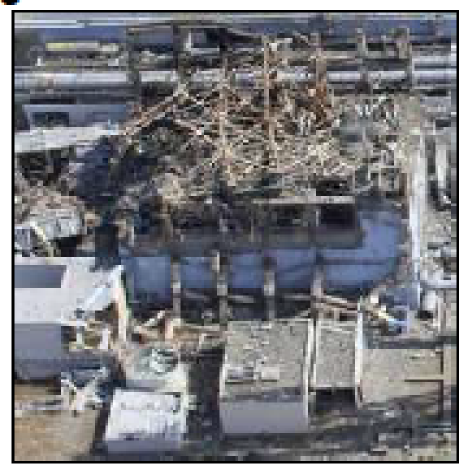
TEPCO



Unit2

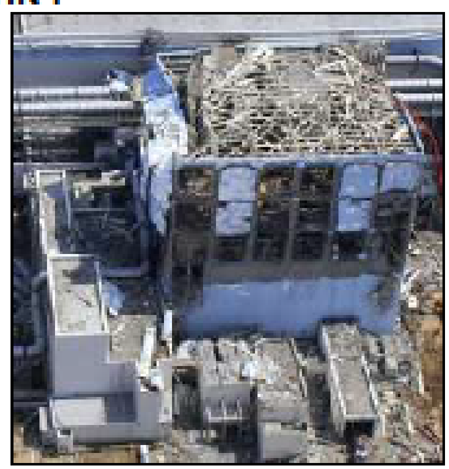
Ministry of Defense

Unit3



Air Photo Service Inc (Myoko, Niigata Japan)

Unit4



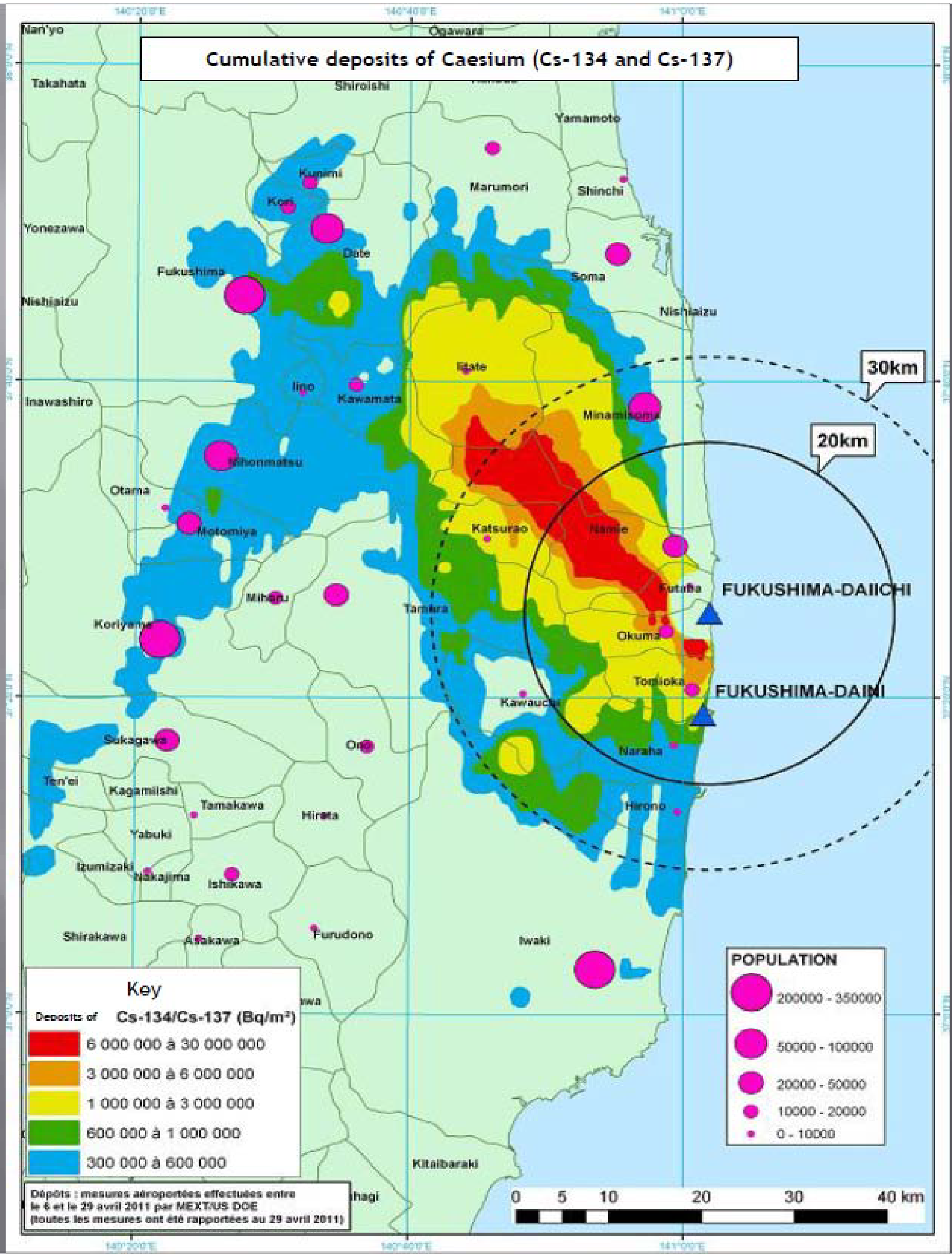
Air Photo Service Inc (Myoko, Niigata Japan)

Status of Fukushima-I 1-4 (July 2011)

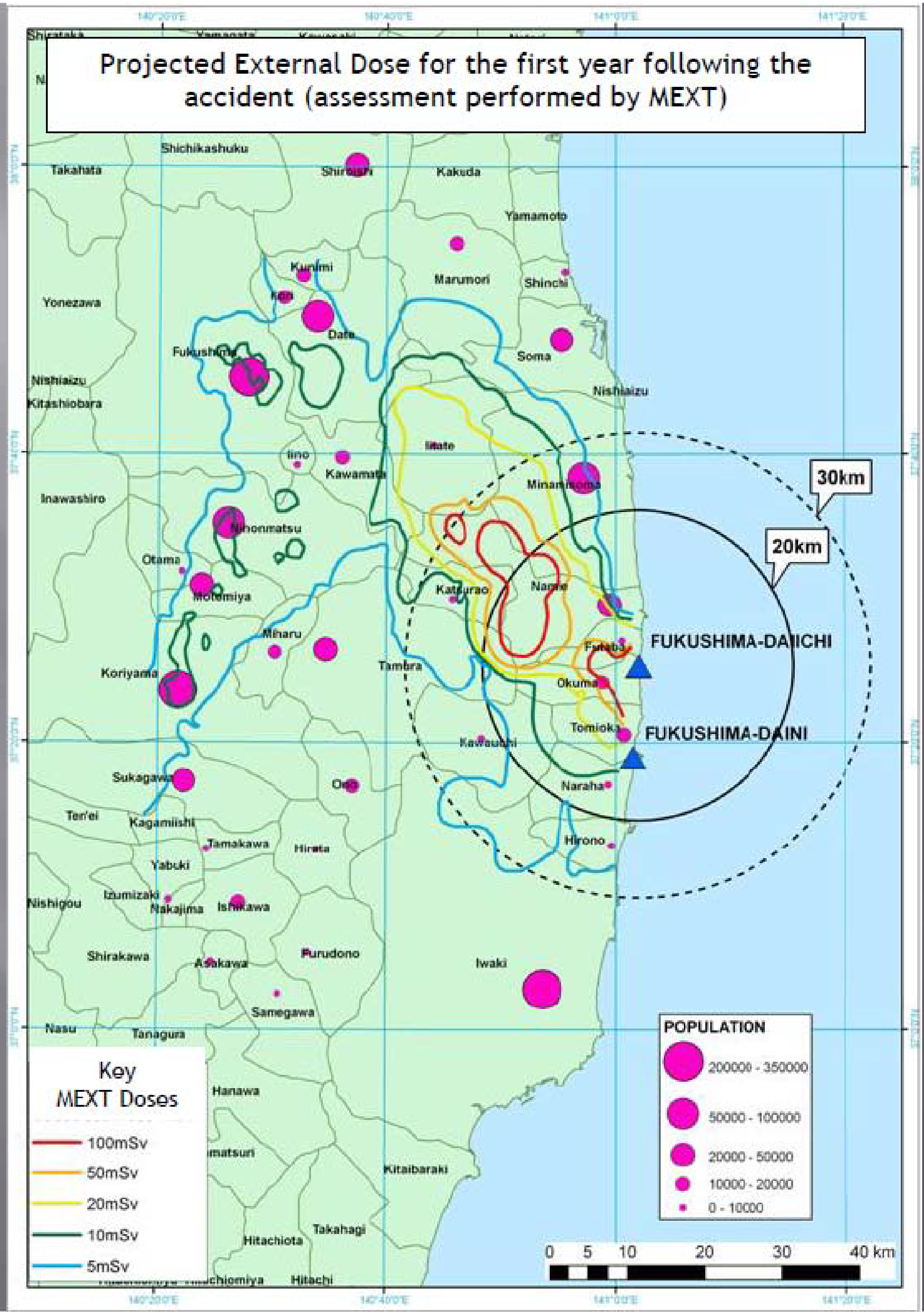
- All known leaks of radioactive water into the ocean have been stopped. Containment venting has stopped. Much debris has been removed from the site and spraying to prevent dust spreading has been completed.
- Large amounts of contaminated water remain a challenge. A high capacity clean-up system has started operation; decontaminated and desalinated water is now being recycled for cooling the damaged reactors.

Status of Fukushima-I 1-4 (June 2011)

- The evacuation order remains in effect for 20-km radius and has been extended to some areas beyond 20 km where annual exposure >20 mSv (2 rem) is expected.
- Environmental radiation levels have declined to normal or near-normal, except for some limited areas. Contamination in sea water and the sea floor remains above limits near the plant. Some food restrictions are in force.

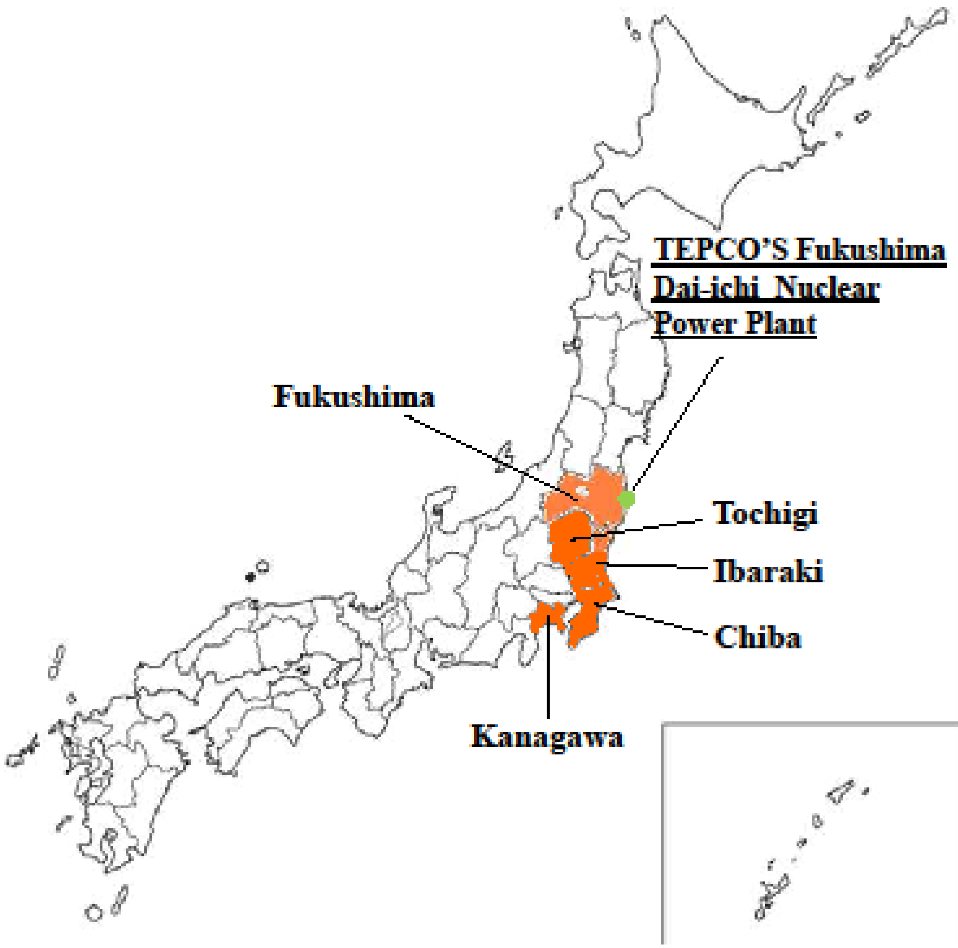


Cumulative deposits of Caesium (Cs-134 and Cs-137)
30km
20km
FUKUSHIMA-DAIICHI
FUKUSHIMA-DAINI
Key
Deposits of Cs-134/Cs-137 (Bq/m²)
6 000 000 à 30 000 000
3 000 000 à 6 000 000
1 000 000 à 3 000 000
600 000 à 1 000 000
300 000 à 600 000
POPULATION
200000 - 350000
50000 - 100000
20000 - 50000
10000 - 20000
0 - 10000
Dépôts : mesures aéroportées effectuées entre le 6 et le 29 avril 2011 par MEXT/US DOE (toutes les mesures ont été rapportées au 29 avril 2011)
0 5 10 20 30 40 km
Fukushima
Koriyama
Iwaki
Minamisoma
Namie
Futaba
Okuma
Tomioka
Naraha
Iitate
Katsurao
Nihonmatsu
Date
Soma


Projected External Dose for the first year following the accident (assessment performed by MEXT)
30km
20km
FUKUSHIMA-DAIICHI
FUKUSHIMA-DAINI
Key
MEXT Doses
100mSv
50mSv
20mSv
10mSv
5mSv
POPULATION
200000 - 350000
50000 - 100000
20000 - 50000
10000 - 20000
0 - 10000
0 5 10 20 30 40 km
Shichikashuku
Takahata
Shiroishi
Kakuda
Yamamoto
Kunimi
Marumori
Shinchi
Yonezawa
Date
Soma
Nishiaizu
Kitashiobara
Iitate
Iino
Kawamata
Minamisoma
Inawashiro
Nihonmatsu
Otama
Motomiya
Katsurao
Namie
Miharu
Tamura
Futaba
Koriyama
Okuma
Tomioka
Kawauchi
Sukagawa
Ono
Naraha
Ten'ei
Kagamiishi
Tamakawa
Hirata
Hirono
Yabuki
Izumizaki
Nakajima
Ishikawa
Nishigou
Shirakawa
Asakawa
Furudono
Iwaki
Samegawa
Nasu
Tanagura
Hanawa
Kitaibaraki
Hitachiota
Takahagi
Hitachi

Safety of Food

Japan inspects radioactivity in food every day, and restricts distribution of food that fails to meet provisional regulation values taking into consideration the spread of contamination.



Instructions (as of 23 June 2011)

… Not to Distribute

- **Fukushima Prefecture**
  - Raw milk
  - Non-head type leafy vegetables (e.g. spinach)
  - Head type leafy vegetables (e.g. cabbage)
  - Flowerhead brassicas (e.g. broccoli, cauliflower)
  - Turnip
  - Log grown shiitake (grown outdoor)
  - Bamboo shoot
  - Ostrich fern
  - Ume
  - Juvenile (baby) fish of Japanese sand lance
  - Cherry salmon (excluding farmed fish)
  - Japanese dace
- **Ibaraki, Tochigi, Chiba and Kanagawa Prefecture**
  - Tea leaf

Please refer to the following URL for the details of Instructions.
http://www.mhlw.go.jp/english/topics/2011eq/index.html 21

Impact of Earthquake, Tsunami and Radiation Exposure

- About 23 000 – 25 000 dead and missing from the earthquake and tsunami.
- Zero deaths or serious injuries to the public from direct radiation exposure.
- Primary negative effect on health and well-being is prolonged displacement of about 100 000 people.
- Based on estimated collective dose levels, the projected increase in cancer mortality is on the order of 0.001% above the natural rate. Remediation or further evacuation may be necessary to avoid larger risk to a sub-population.

INES-7 Accidents - Comparison of Fukushima I and Chernobyl

Isotope	Estimated Release from Fukushima I (PBq)	Estimated Release from Chernobyl (PBq)
I-131	160	1800
Cs-137	15	81
I-131 equivalent of Cs-137	600	3400
Total I-131 equivalent	760	5200
NSC Estimate of Current Release as of 24 April	.024/day (about a factor of 1000 less by mid-July)	

The Path Forward

- TEPCO has issued a plan for stabilizing the situation and remediation so that evacuees can return as soon as possible.
  - Restore stable cooling in 1-2 months (done); restore normal shutdown cooling in 6-9 months.
  - Restore stable spent fuel pool cooling (done in Units 2,3,4); shore up structures under Unit 4 spent fuel pool (done).
  - Manage contaminated water, including new storage and treatment facilities. Clean up and recycle cooling water (done).
  - Minimize additional radioactive release by covering reactor buildings; decontaminate off-site areas to allow evacuation to be lifted.

The Path Forward

- There will be extensive and thorough study of the accident to ensure that lessons to be learned are identified and acted upon. Some thoughts:
  - Improved emergency planning, management, training and exercises, staging and protection of emergency equipment and communications links;
  - Possible modifications to deal with low probability events that can cause multiple failures;
  - Possible modifications to deal with extended station blackout events.

Sources

- Japan Atomic Industrial Forum (JAIF)
- Japanese Government:
  - Nuclear and Industrial Safety Agency (NISA)
  - Ministry of Education, Culture, Sports, Science and Technology (MEXT)
  - Ministry of Economy, Trade and Industry (METI)
- Japan Nuclear Energy Safety Organization (JNES)
- Tokyo Electric Power Company (TEPCO)
- American Nuclear Society (ANS)
- World Nuclear Association (WNA)