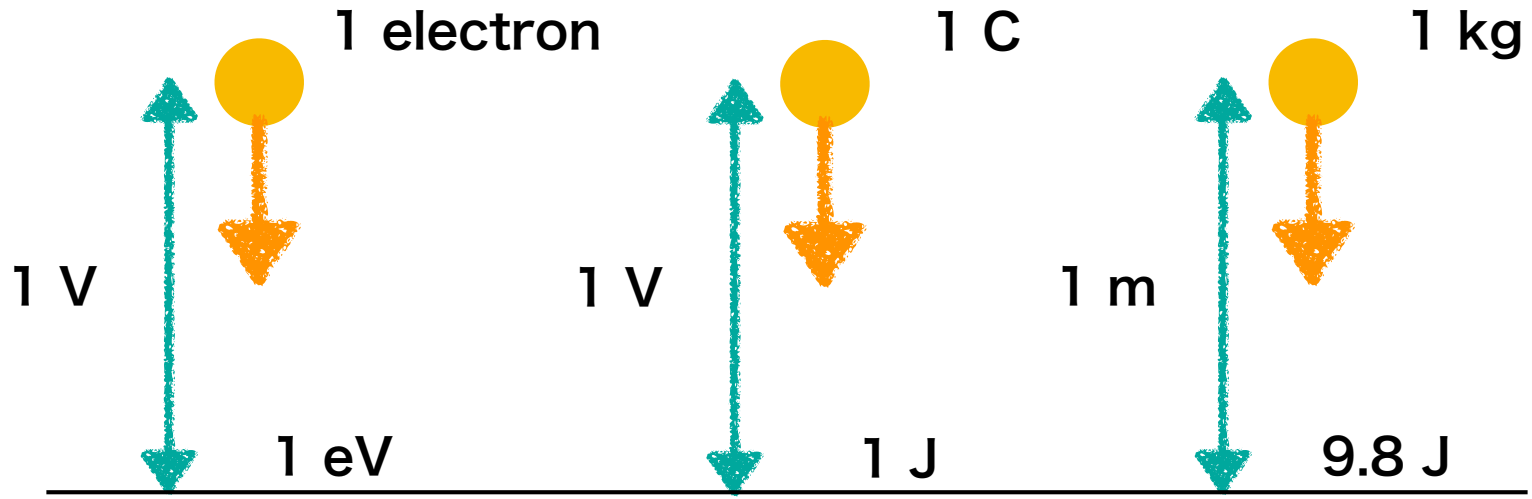
Radiation detector

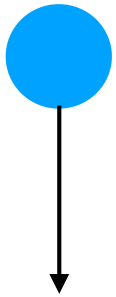


Energy scale



$1\ eV = 1.6 \times 10^{-19}\ J$

Gravitation



Free fall of 1 kg from 1m high

$mgh = \sim 10\ J = 6 \times 10^{19}\ eV = 6 \times 10^{7}\ TeV$

LHC = 13 TeV

It is large energy but it cannot causes high energy radiation.
Because each nucleon may get small energy.

$6 \times 10^{19}\ eV / (1000 \times 6 \times 10^{23}) = 1 \times 10^{-7}\ eV = 100\ neV$

Compare to other Energy,
it is several order magnitude smaller.

On the surface of neutron stars, “g” is 10^{11} larger

100 neV -> 10 keV !

chemical energy

Battery voltage is related to the chemical interactions.



Alkaline manganese battery (1.5V)

$$MnO_2 + H_2O + Zn \rightarrow Mn(OH)_2 + ZnO$$

Ni-Cd battery (1.2V)

$$2NiOOH + Cd + 2H_2O \rightleftharpoons 2Ni(OH)_2 + Cd(OH)_2$$

It is the same order of ionizing energy

Thermal Energy

Energy of gas molecular is proportional to the temperature.

$$E = kT$$

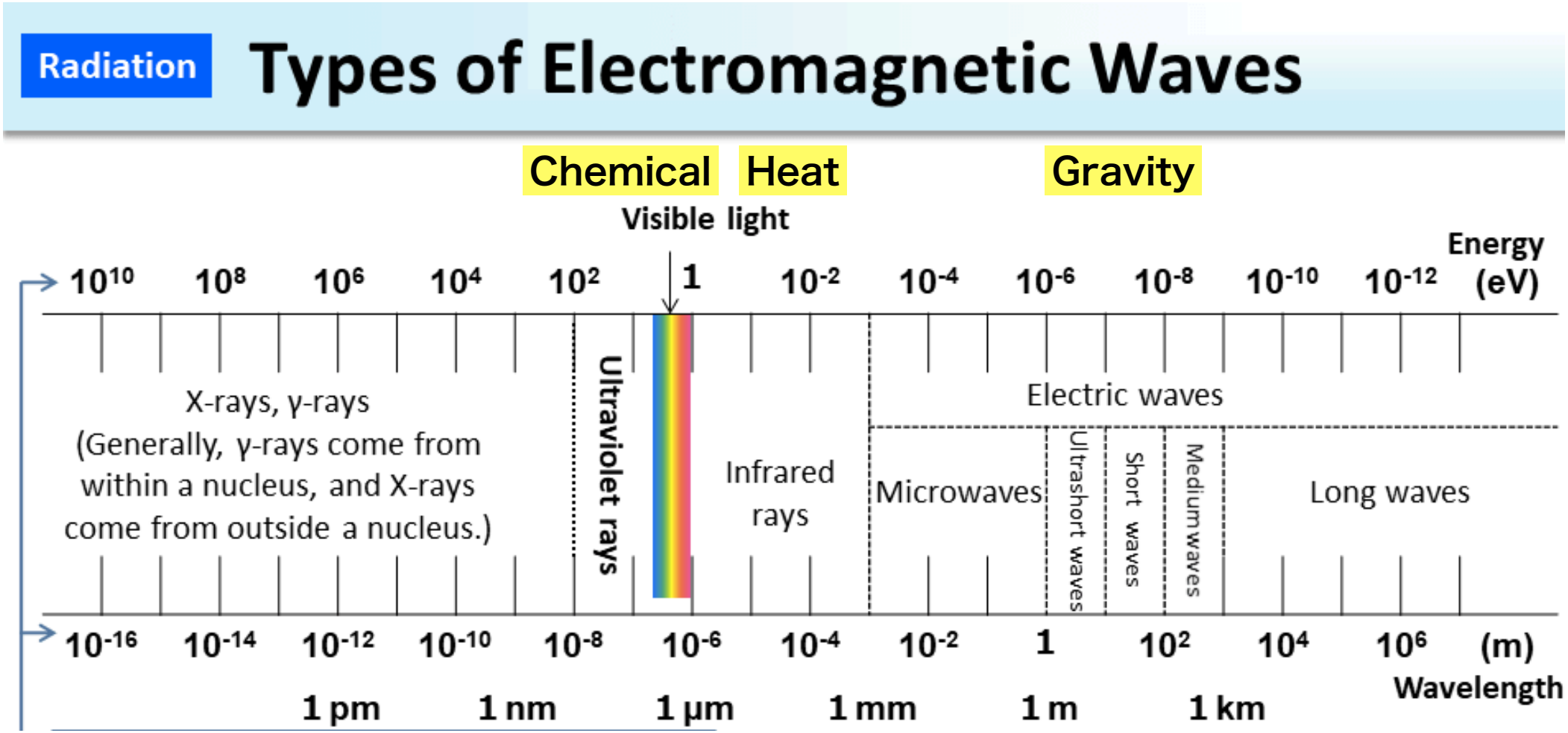
k is Boltzmann constant $8.6171E^{-5}$ eV/K

at room temperature, it is about 25 meV = 0.025 eV

Thermal neutron energy

It is much lower than the ionization energy

Ionizing radiation



ionizing radiation

Low-energy quanta cannot ionize an atom.
The total amount of thermal or chemical energy can be very large, but the energy carried by each quantum is too small to cause ionization.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Radiation detection

Radiations causes some effects in matter. The amount of those effects may indicate the energy of the radiation.

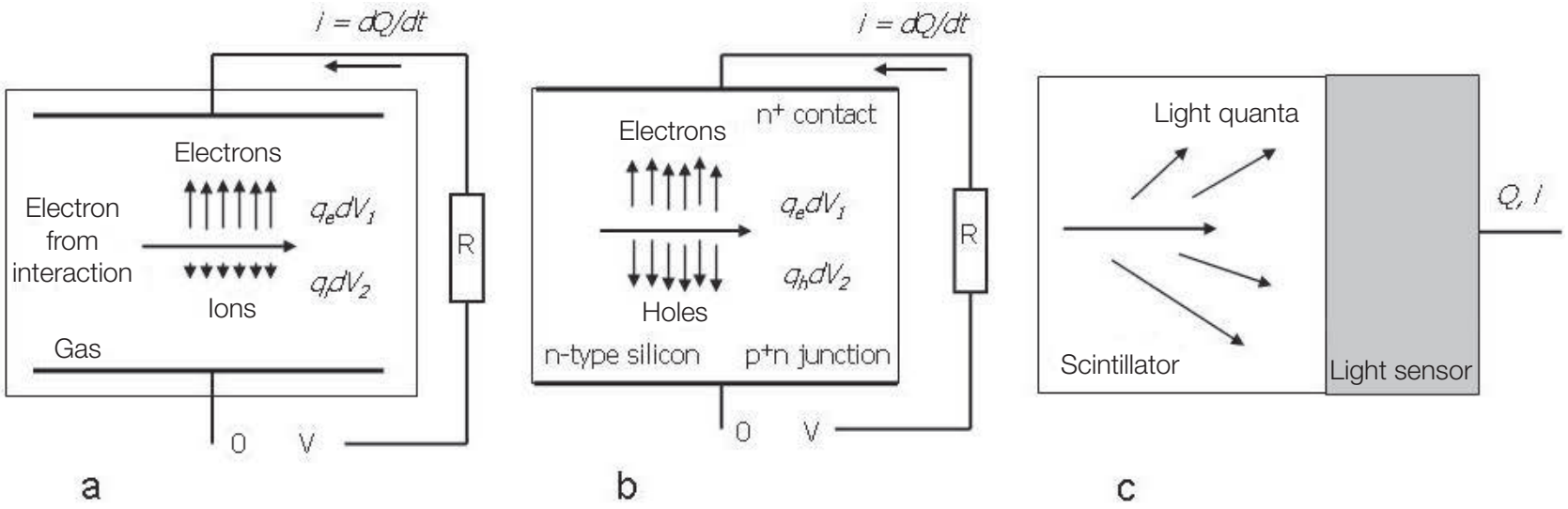


FIG. 6.1. Principle of operation of (a) a gas filled detector, i.e. an ionization chamber; (b) a semiconductor detector, i.e. a silicon detector; and (c) a scintillation detector. The former two detectors are capacitors. The motion of charge results in an observable signal. The light of a scintillation detector is usually detected by a photomultiplier tube.

TABLE 6.1. MEAN ENERGIES *W* TO PRODUCE INFORMATION CARRIERS

Detector type	*W* (eV)
Gas filled (electron–ion)	30
Semiconductor (electron–hole)	3
Inorganic scintillator (light quantum)	25
Inorganic scintillator + photomultiplier tube (electron)	100
Inorganic scintillator + silicon diode (electron–hole pair)	35

The number of electron

How much charge are we seeing?

Average energy to ionize ~10eV

662 keV / 10 eV = 66,200 electron

66,200 electron x 1.6 x 10^{-19} C/electron = 1.06 x 10^{-14} C

Can we measure 0.01 pC ?

Electron Counting

How many electron do we need to observe?



Ammeter can measure about 1 μA. How many electron?

$$1\mu\mathrm{A} = \frac{10^{-6}}{1.6 \times 10^{-19}}\ \mathrm{e/s}\ = 6 \times 10^{12}\ \mathrm{e/s}$$

We can see→ 0.1s

6 x 10^{11}electron is needed to “See”

7 x 10^{4} electron is not enough to “See”

66,200 electron pass in 10 ns.

Current = Charge/ Time

0.01 pC / (10 x 10^{-9}) = 1 uA

Cannot see in Ammeter but may be detected by electronics.

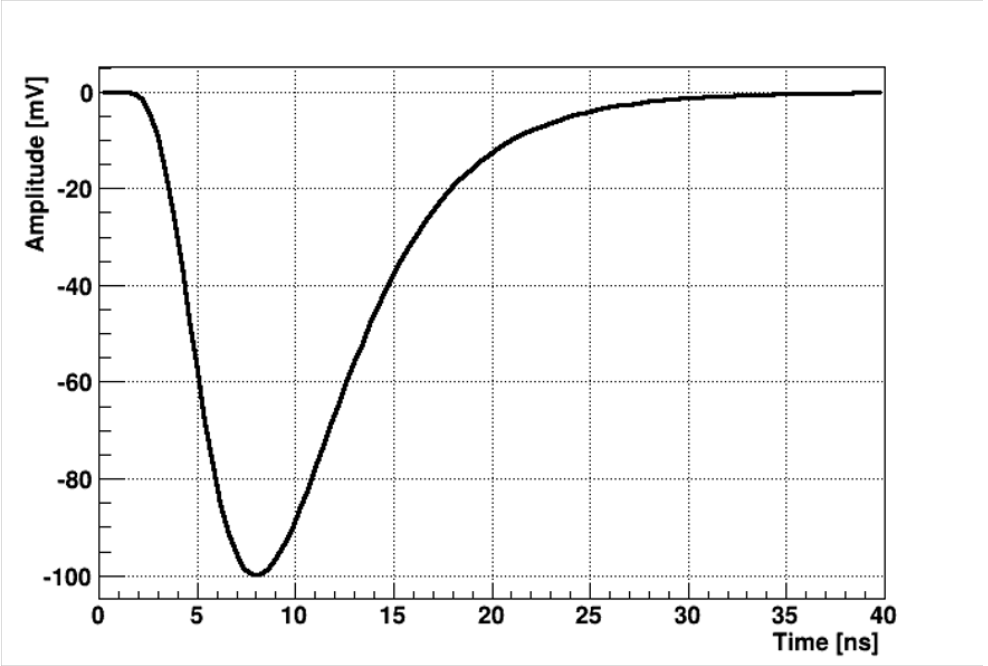
Electronics can measure voltage.

Current to Voltage

1 uA x 50Ω = 50 uV

Is it possible?

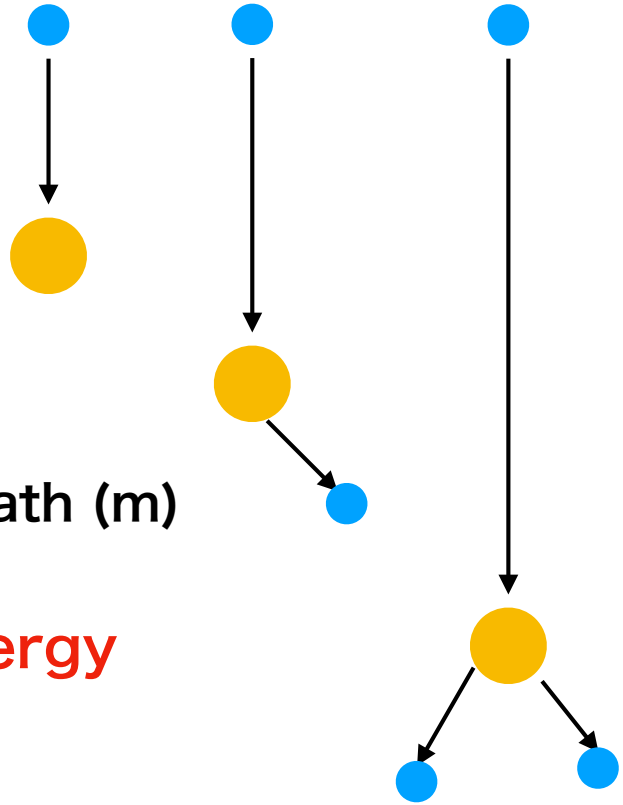
We need very good amplifier.



Electron multiplication

Accelerated electron hits an atom.

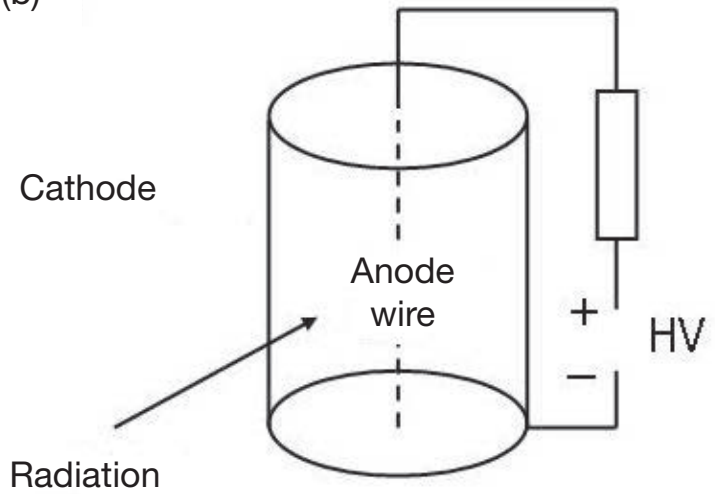
Secondary electrons may be emitted.



Accelerated electron :
Energy (eV) = Electric field (V/m) x mean free path (m)

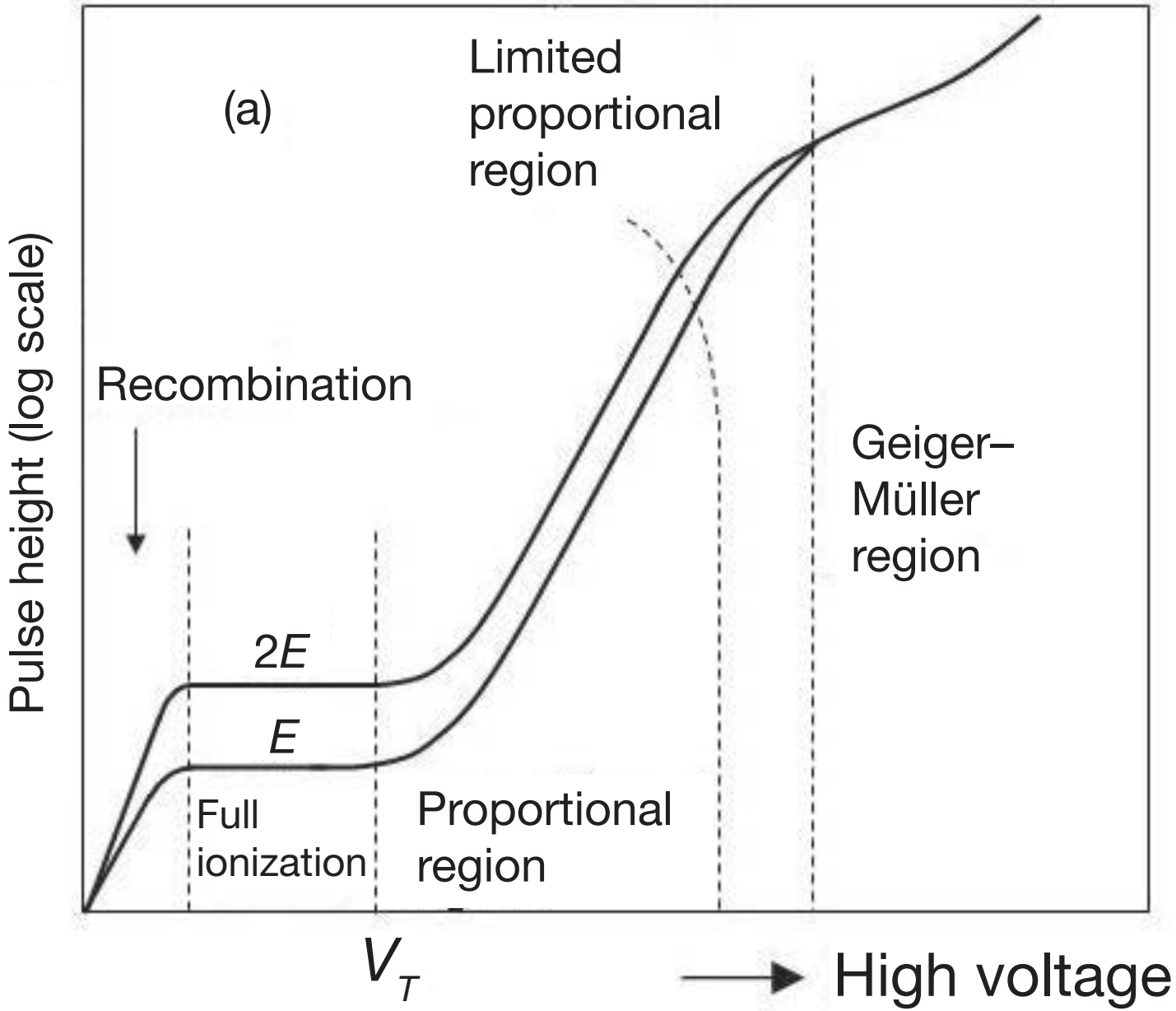
It must be bigger than ionizing energy

(b)



Cylinder geometry

Electric field is 1/r
Using a thin wire, strong electric field can be obtained near the wire.


(a)
Limited
proportional
region
Recombination
Geiger–
Müller
region
2E
E
Full
ionization
Proportional
region
Pulse height (log scale)
V_T
High voltage

Neutron detection

Charged particles directly ionize.

Photons cause photo-electric reactions. Secondary electrons ionize.

How about neutron.

Recoil reaction : Kicked charged particle may ionize.

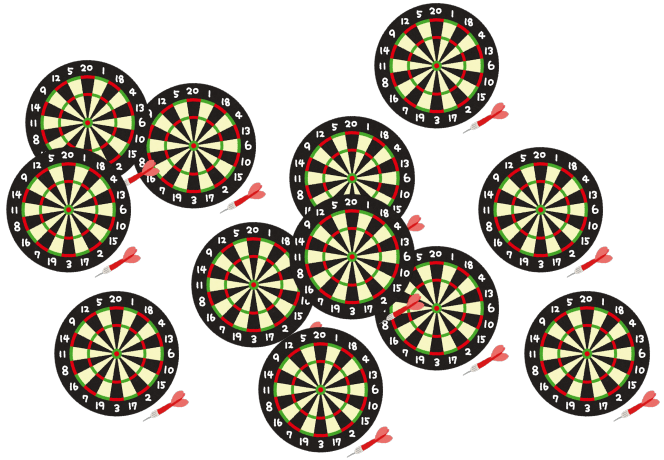
Nuclear reaction (Charge exchange reaction) (n,p) (n,α)

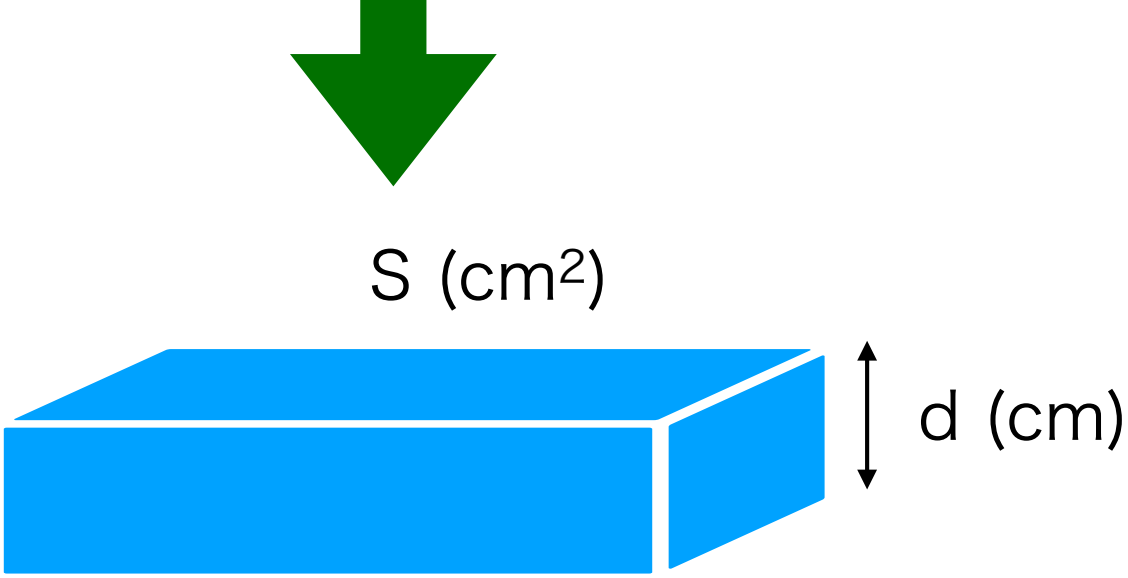
Fission reaction. Fission products ionize,.

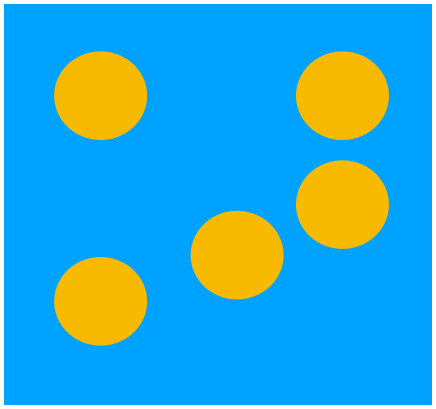




1 barn = 10^{-24} cm^2



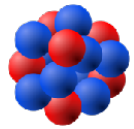




1 barn = 10^{-24} cm²

$\rho\, dS\ (g) \ /\ S\ (cm^2) = \rho\, d\ (g/cm^2)$

$\rho\, d\ (g/cm^2) \ /\ A\ (g/mol) = (mol/cm^2)$



Physical Cross section of nucleus :

U = 1.7 barn

B = 0.18 barn

Total Area of target in Unit area

$= N_A(1/mol)\,\rho\,(cm^2) \times \rho\, d/A(mol/cm^2)$

$= 0.6\ \rho\,(\mathbf{barn}) \times \rho\, d/A(mol/cm^2)$

Gas (~10^{-4} mol/cm²) has poor probability of hits for 1 barn cross section.

Helium-3 Neutron Proportional Counters

Helium-3 Proportional Counters utilize the He (n,p) H^3 reaction for the detection of thermal neutrons.

$$He^3 + n^1 \text{ (thermal)} \rightarrow H^1 + H^3 + Q$$ where Q = 764KeV.

He-3 Neutron Detectors provide an output pulse which is proportional to 764KeV for thermal neutrons. The cross section of He-3 for thermal neutrons is 5330 barns.
The cross section follows a 1/v relationship (v = neutron velocity) up to about 0.2 MeV.

https://web.mit.edu/8.13/www/JLExperiments/38/tgm-neutron-detectors.pdf

BF3 Neutron Proportional Counters

Boron Tri-fluoride (BF_3) Proportional Counters are largely sensitive to Thermal Neutrons.

$$B^{10} + n^1 \rightarrow Li^7 + \text{alpha} + Q$$

In 93% of the reactions Q=2.31 MeV, leaving the Lithium nuclide in the first excited state. The other 7% of the reactions have Q = 2.79 MeV, with the Lithium nuclide in the ground state.

BF_3 neutron detectors contain boron enriched to >90% B^{10}
The thermal neutron cross section for B^{10} is 3840 barns.
This is considerably less than the cross section of He-3 for thermal neutrons. The cross section drops off as 1/v up to about 0.1 MeV (v = neutron velocity).

https://web.mit.edu/8.13/www/JLExperiments/38/tgm-neutron-detectors.pdf

Fission Chambers

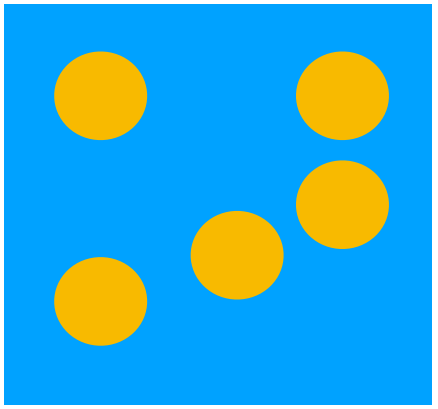
The coating-material form typically includes metallic uranium, UO_2, or U_3O_8 [28]. A very thin layer (0.02–2 mg/cm^2 surface thickness) is electroplated (sometimes evaporated or painted) on the inner walls. The thin layer is directly exposed to the detector gas. After a ssion event, the two ssion fragments travel in nearly opposite directions. The ionization caused by the ssion fragment that entered the gas is sensed by the detector; the fragment traveling in the opposite direction is absorbed in the detector wall.

10 B-Lined Detectors

Detectors lined with ^{10}B lie between ^{3}He and BF_3 proportional counters and fission chambers in terms of neutron-detection efficiency and gamma-ray insensitivity.
Structurally, ^{10}B-lined detectors are similar to fission chambers—with the neutron-sensitive material, boron (in form of enriched ^{10}B or $^{10}B_4C$), plated in a very thin layer (~0.2–0.5 mg/cm^2) on the walls of the detector

DOI:10.1007/978-3-031-58277-6_15

$$\frac{0.2\ \text{mg/cm}^2}{235\ \text{g/mol}} = 10^{-6}\ \text{mol/cm}^2 :\ 6\text{x}10^{17}\ \text{U/cm}^2$$



Total target area = 5000 b x $6\text{x}10^{17}$ /cm² = 3 x 10^{-3}

0.3% of neutron hits

A standard power reactor core has an average neutron flux of about 3 x 10^{13} n/cm²s

0.3% of 3 x 10^{13} n/cm²s is 10^{11} hit/cm²s

ion chamber : 10^{11} x 1.6 x 10^{-19} C/s/cm² =1.6 x 10^{-8} A/cm²

16 nA/cm²

Helium-4 and CH_4 Fast-Neutron Detectors

Helium-4 and CH4 fast-neutron detectors rely on the recoil of light nuclei to ionize the gas in the tube.

If the recoiling nucleus is only a hydrogen nucleus (proton), the maximum possible energy transfer is the total neutron kinetic energy E. For heavier elements, the maximum energy transfer is always less.
For a nucleus of atomic weight (A), the maximum energy transfer is

$$\mathrm{E(max)} = \frac{4\mathrm{AE}}{(\mathrm{A}+1)^2}$$

DOI:10.1007/978-3-031-58277-6_15

eV, barn and ···

You studied the definition and meaning in textbooks and lectures.

Please apply those units to real world. You will feel what are they.

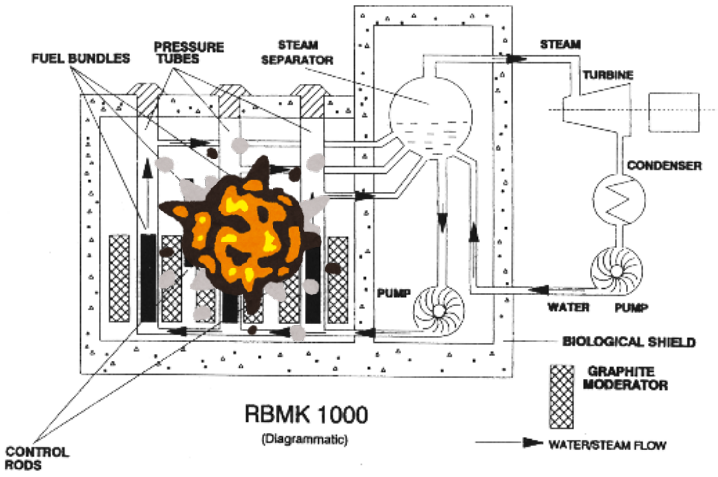
After the accident

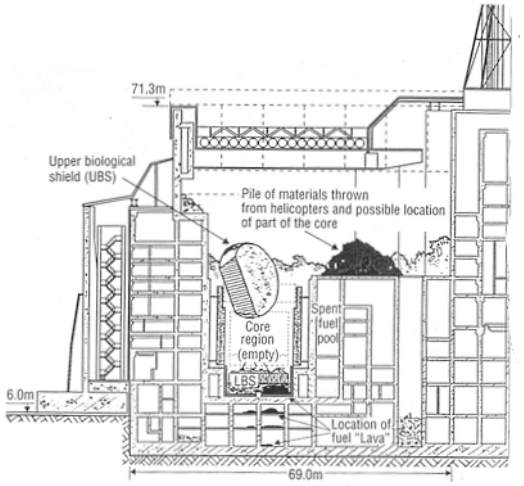


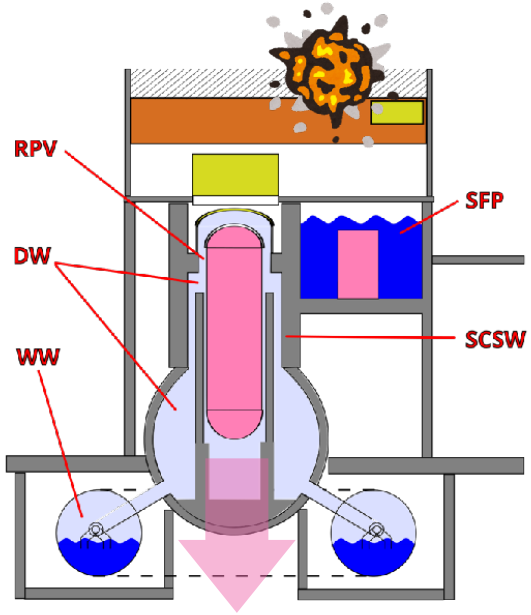


How was RI released?

	Chernobyl	Fukushima
Explosion	steam explosions at the core	Hydrogen explosion outside of the core
Ejection of RI	By explosion and fire.	Evapolation







Source: OECD NEA

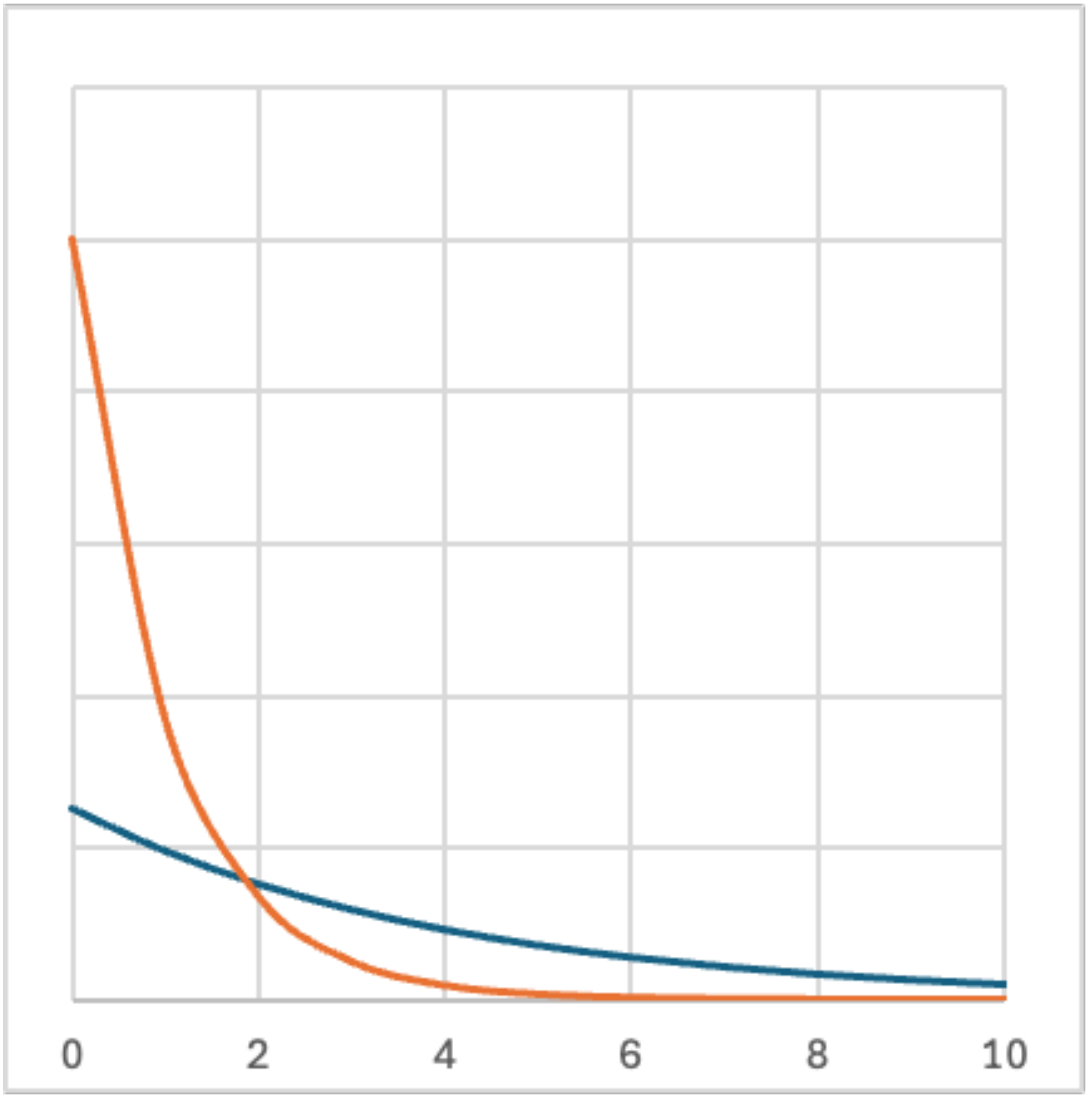
Exposed activities

Table 5. Characteristics and total inventories of radionuclides for Units 1–3 at FNPS1 (Nishihara et al., 2012).

Radionuclide	State in atmosphere	Half-life	Boiling point (°C)	Total inventory (PBq)
^{131}I	Gas/aerosol	8.0 days	180	6.02×10^6
^{132}I	Gas/aerosol	2.3 hours	180	8.85×10^6
^{132}Te	Aerosol	3.2 days	1400	8.68×10^6
^{133}I	Gas/aerosol	21.0 hours	180	1.26×10^7
^{137}Cs	Aerosol	30.0 years	670	6.98×10^5
^{134}Cs	Aerosol	2.1 years	670	7.18×10^5

Atmos. Chem. Phys., 15, 1029–1070, 2015
www.atmos-chem-phys.net/15/1029/2015/

Activities



Same amount of radioactivities.
Decay rates (Bq) are different.

Decay rates (Bq) · life (s) is the number of atom.

Decay rate of ^{133}Xe and ^{131}I are high but those amounts are less than ^{137}Cs.

$^{90}Sr/^{137}Cs$

^{90}Sr and ^{137}Cs are fission products. Yields are almost the same.

The amount of those nuclei in the core should be the same.

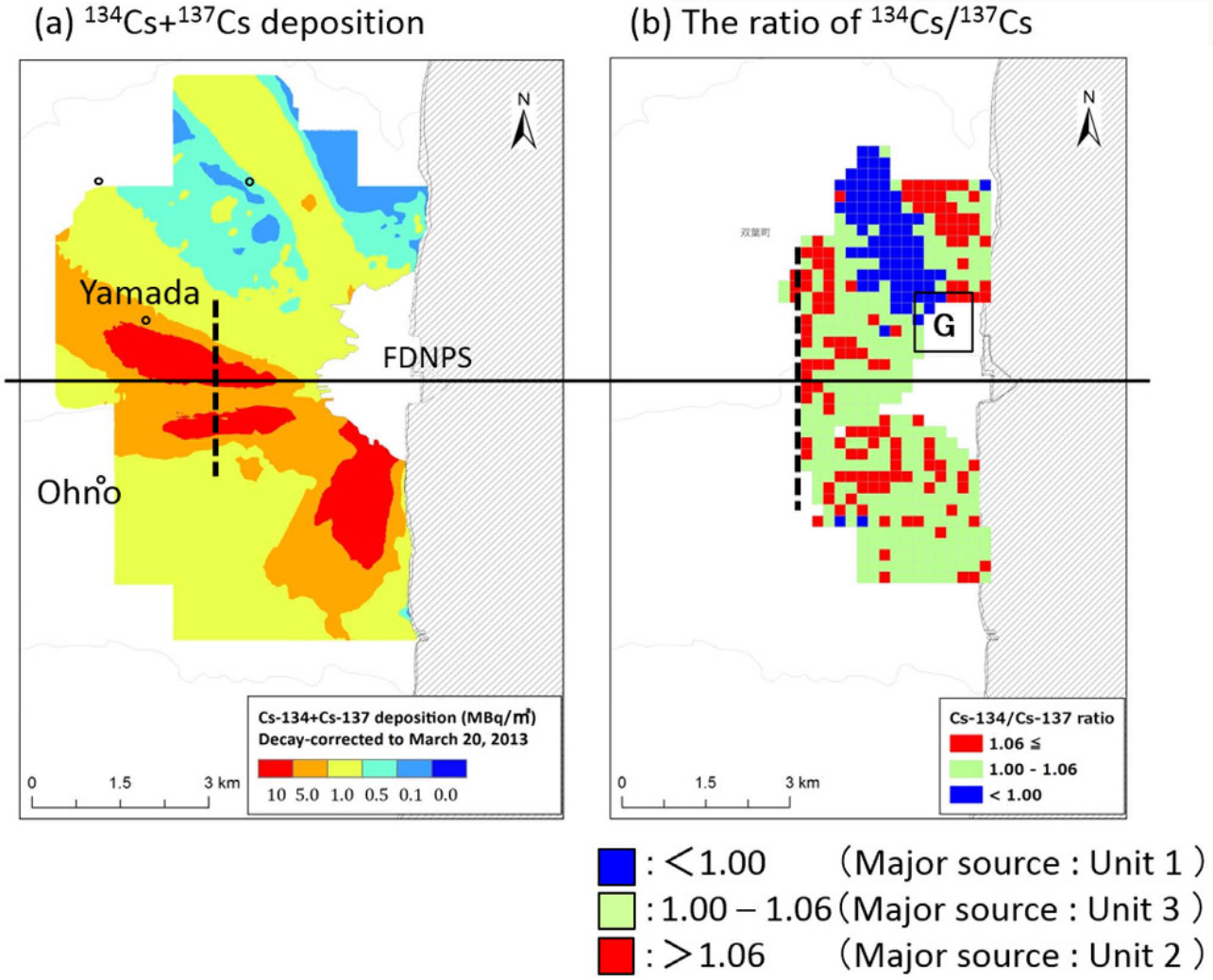
Boiling point of Cs is 670.8 °C. While, that of Sr is 1,382 °C.

	Chernobyl	Fukushima
Explosion	at the core	outside of the core
Ejection of RI	By explosion and fire.	Evapolation
$^{90}Sr/^{137}Cs$	~0.1	~0.001

$^{134}Cs/^{137}Cs$

$$\text{Fission} \rightarrow {}^{137}\text{Cs}$$

$$\text{Fission} \rightarrow {}^{133}\text{Cs} \rightarrow (n,\gamma) \rightarrow {}^{134}\text{Cs}$$

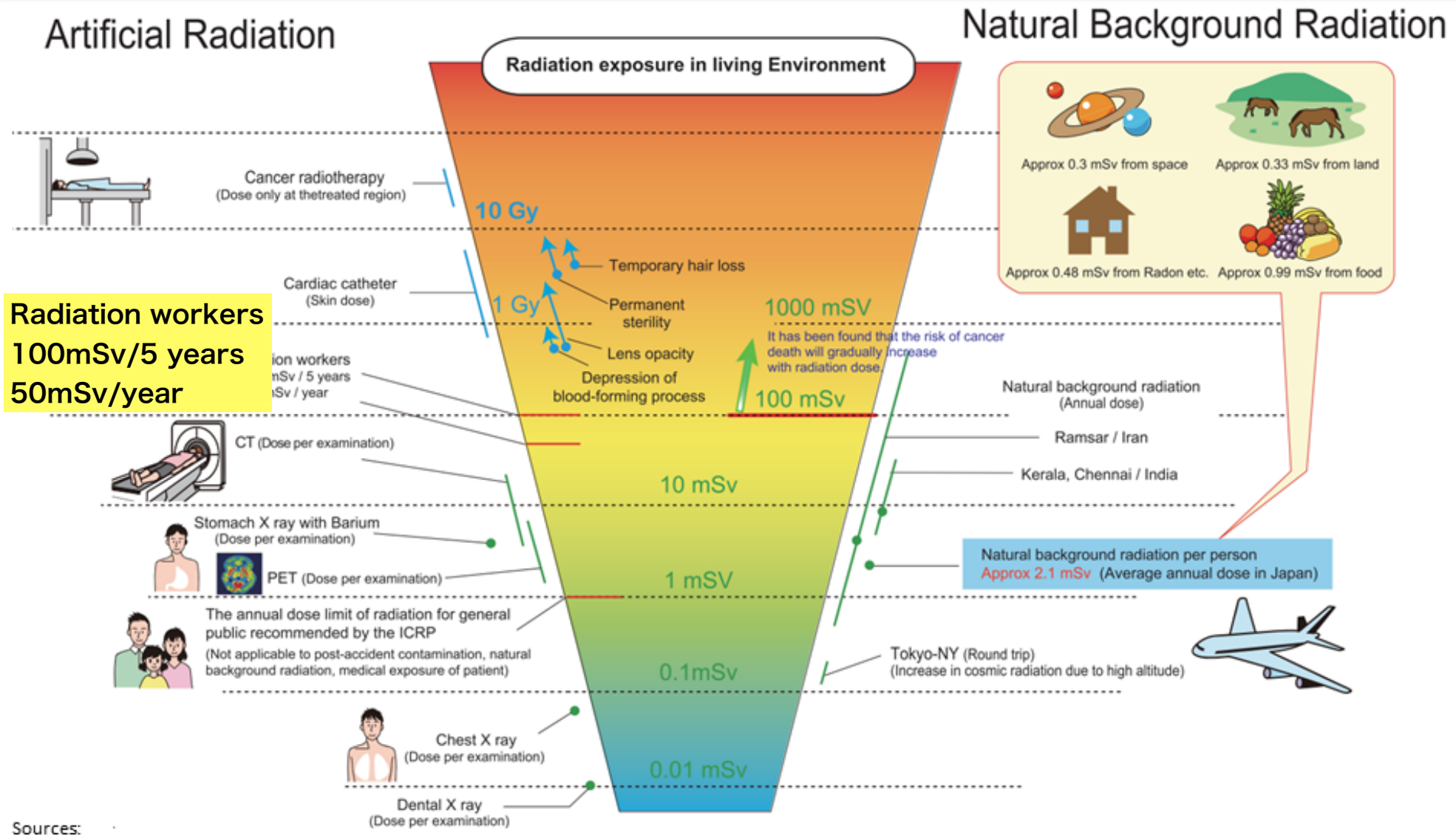


Under the stable irradiation, the activity ratio almost linearly increases with the irradiation period, namely the fuel burn up.

Figure 2. Autonomous unmanned helicopter (AUH) survey; spatial maps of (**a**) $^{134}Cs+^{137}Cs$ deposition over the 5-km area of FDNPS[27] and (**b**) the $^{134}Cs/^{137}Cs$ ratio over the 3-km area. The spatial distribution maps are created using ArcGIS version 10.3 (http://www.esri.com/) with administrative boundary data and background map by The Geospatial Information Authority of Japan (http://maps.gsi.go.jp/).

Radiation around Us

Comparison of Exposure Doses (Simplified Chart)



Sources:

- The 2008 UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) Report
- The 2007 ICRP (International Commission on Radiological Protection) Report
- The exposure guideline of the Japan Association of Radiological Technologists
- "Environmental Radiation in Daily Life (Calculation of the National Doses)," new edition

Prepared by the National Institute of Radiological Sciences, National Institutes for Quantum Science and Technology, based on the sources above (May 2021)

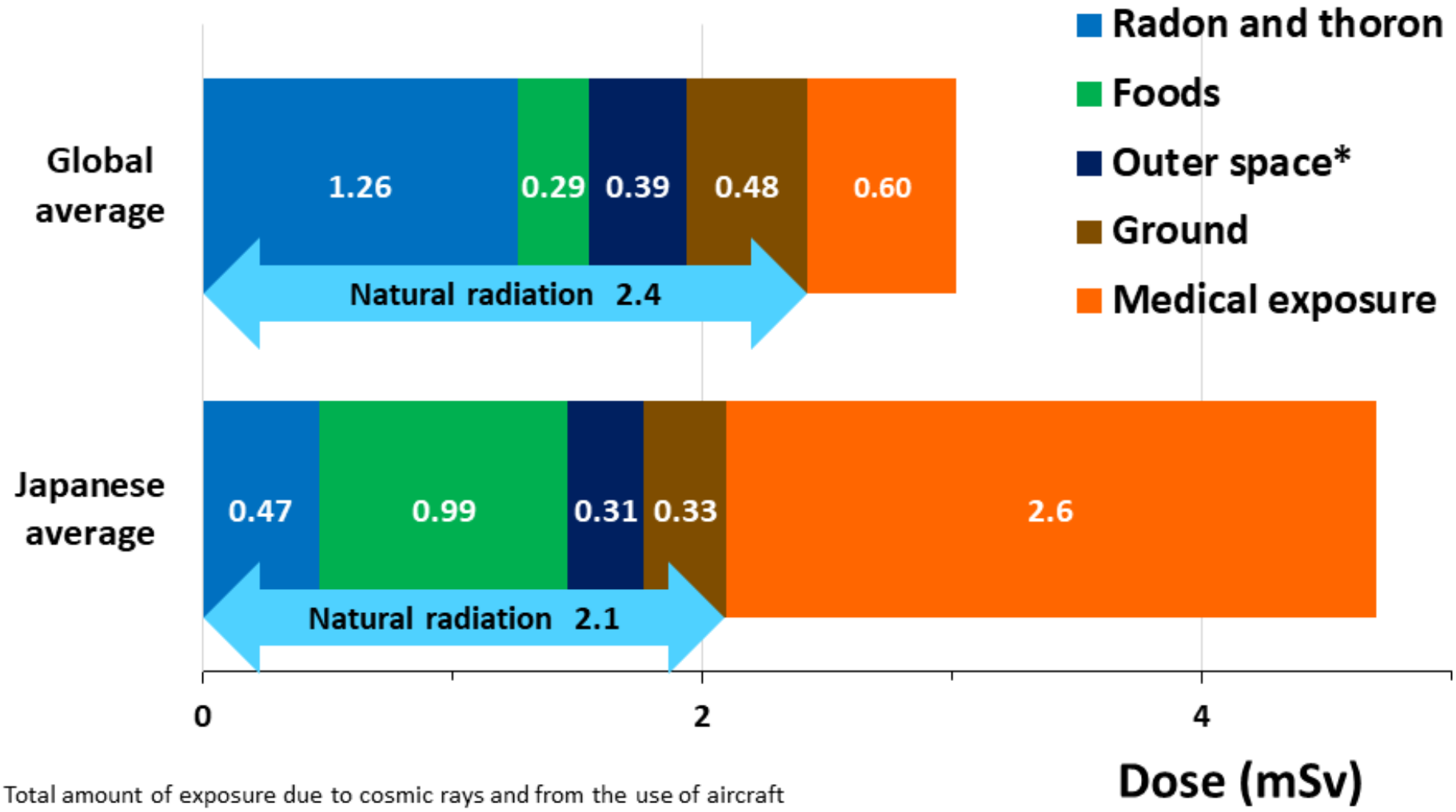
mSv: millisieverts

https://www.env.go.jp/en/chemi/rhm/basic-info/2023/index.html

Radiation around Us

Comparison of Exposure Doses per Year

Exposure in daily life (annual)



* Total amount of exposure due to cosmic rays and from the use of aircraft

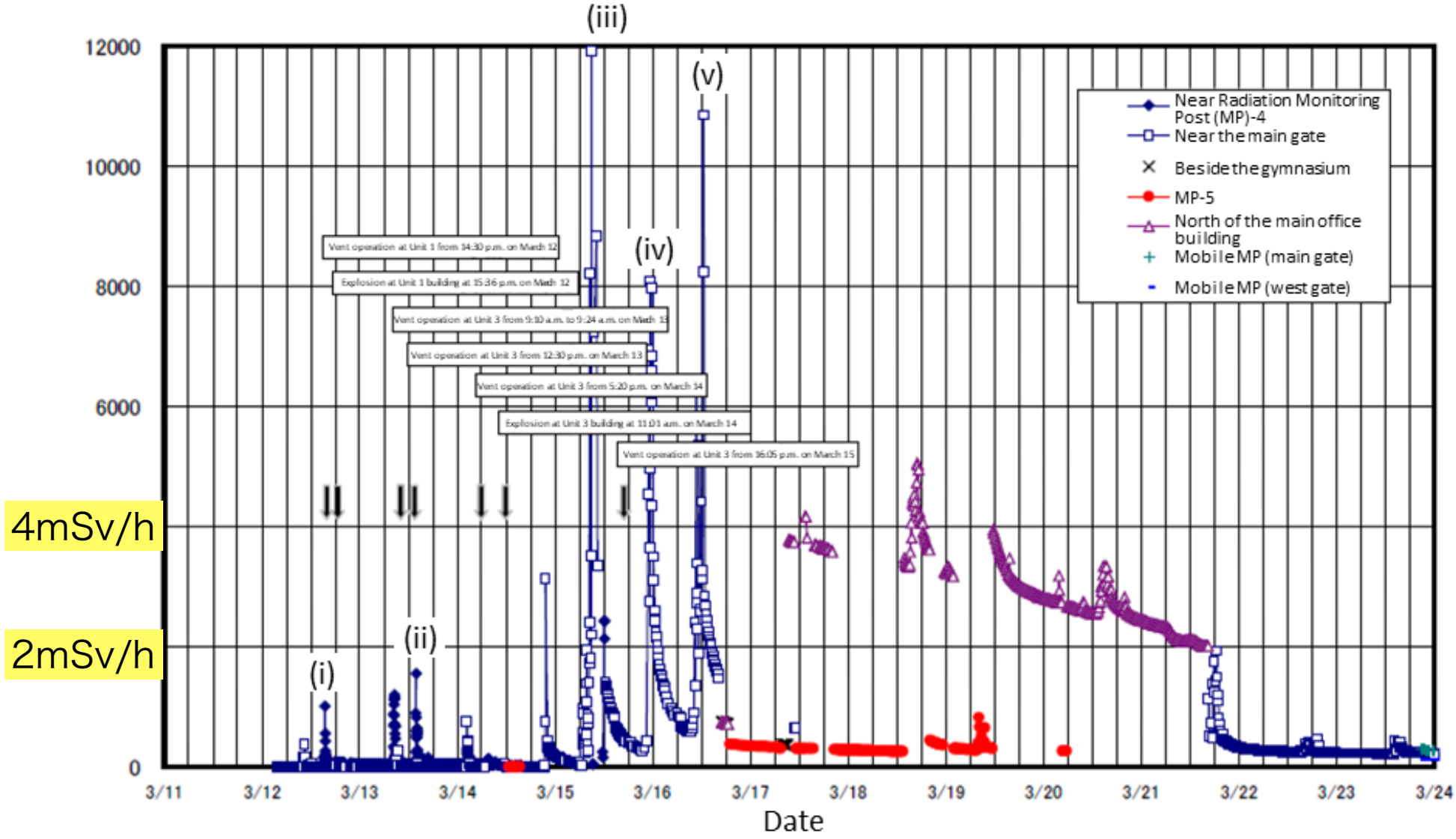
Sources: Prepared based on the 2008 UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) Report; and "Environmental Radiation in Daily Life (Calculation of National Doses), ver. 3" (2020), Nuclear Safety Research Association

https://www.env.go.jp/en/chemi/rhm/basic-info/2023/index.html

Outline of the Accident

Ambient Dose Rates during Two Weeks after the Accident (Within and around of the premises of TEPCO's Fukushima Daiichi NPS)

● **Changes in ambient dose rates measured by monitoring cars within and around the NPS**



Additional Report of the Japanese Government to the IAEA - The Accident at TEPCO's Fukushima Nuclear Power Stations - (Second Report)

μSv/h: micro sievert per hour

The Secretariat of the Nuclear Regulation Authority

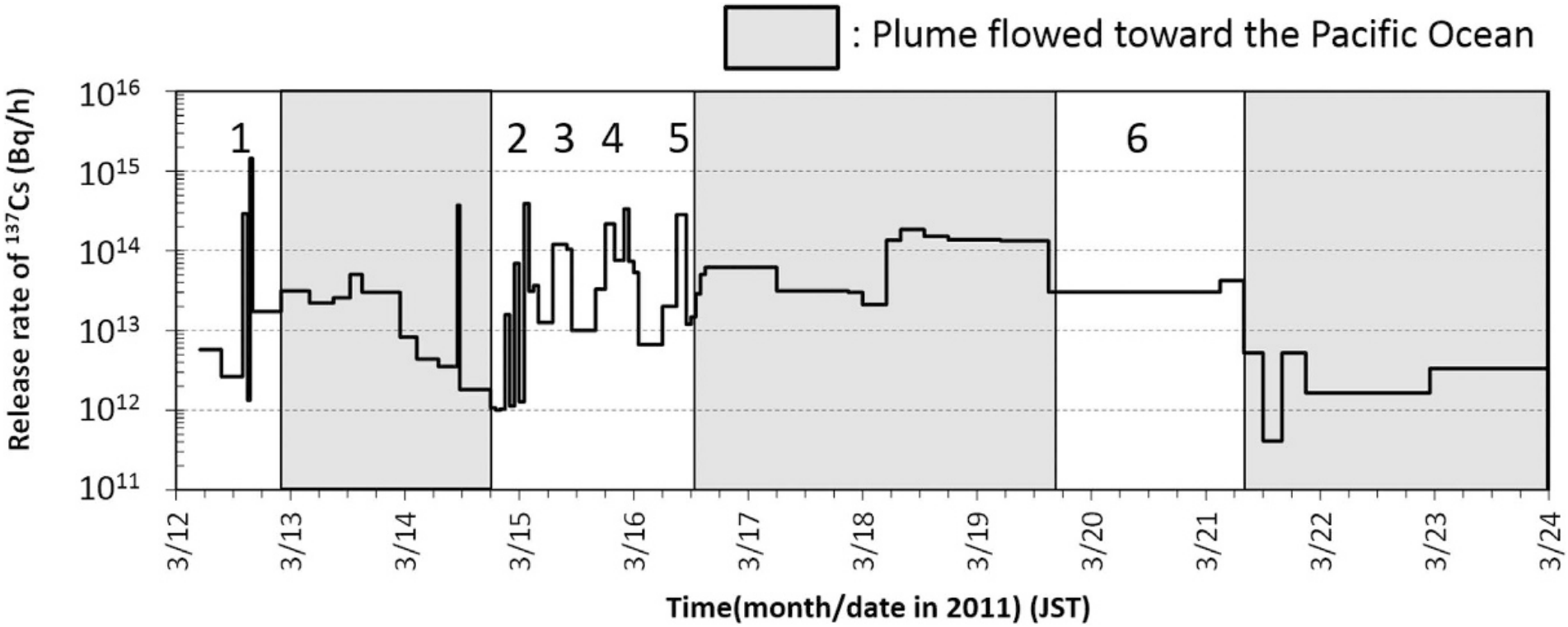


Figure 3. Temporal variation of atmospheric release rate of ^{137}Cs estimated by Katata *et al.*[5]. The number means the major releases which contaminated the land mass of East Japan.

Yamamoto, T. (2022). Activity and weight ratios of cesium, uranium, plutonium, and curium isotopes based on elaborate inventory calculations of Fukushima Dai-ichi NPP units 1 to 3. Journal of Nuclear Science and Technology, 59(11), 1448–1454. https://doi.org/10.1080/00223131.2022.2051764

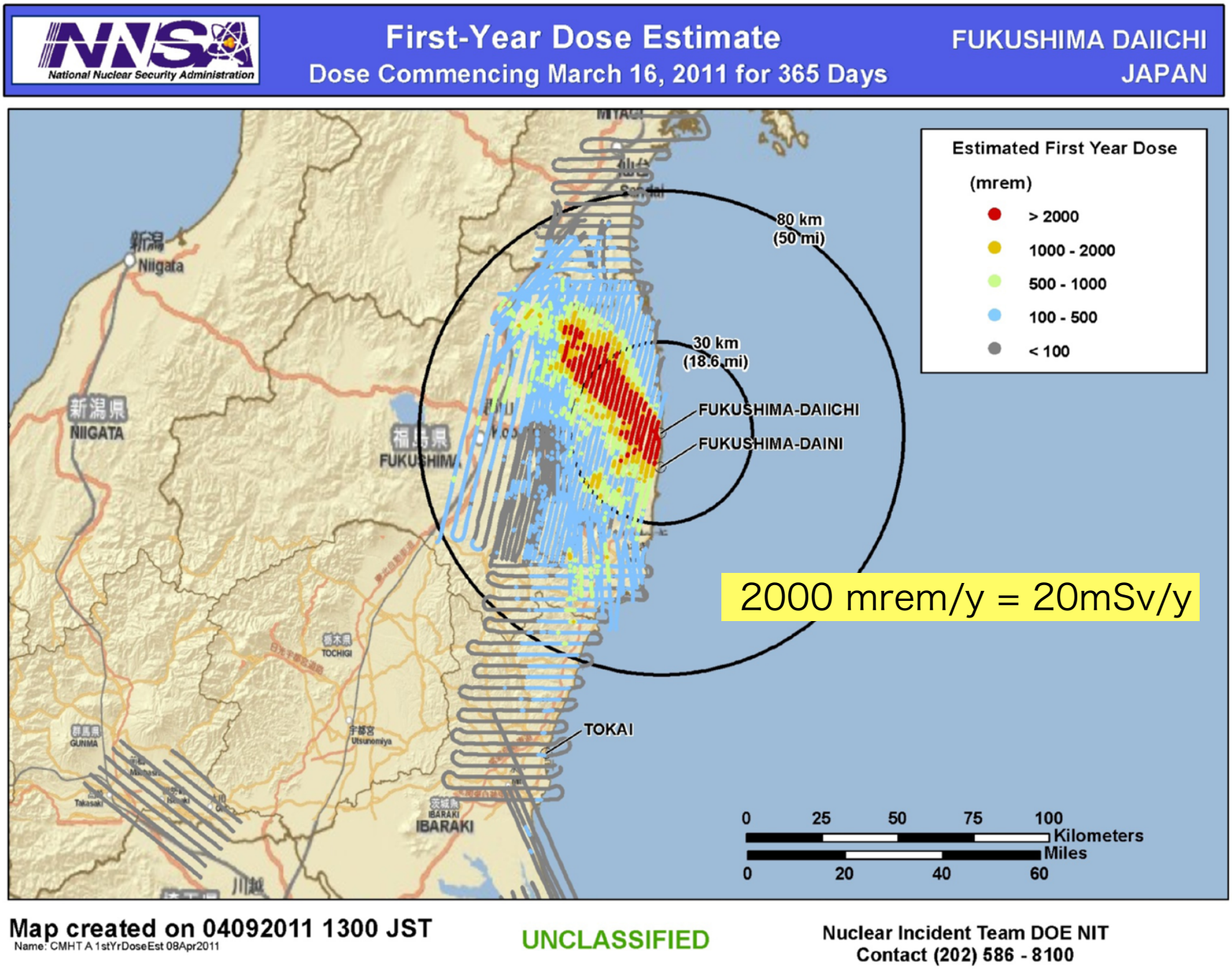


Figure 9. Map of isodose curves for Fukushima region from NNSA measurements. (Courtesy of NNSA.)

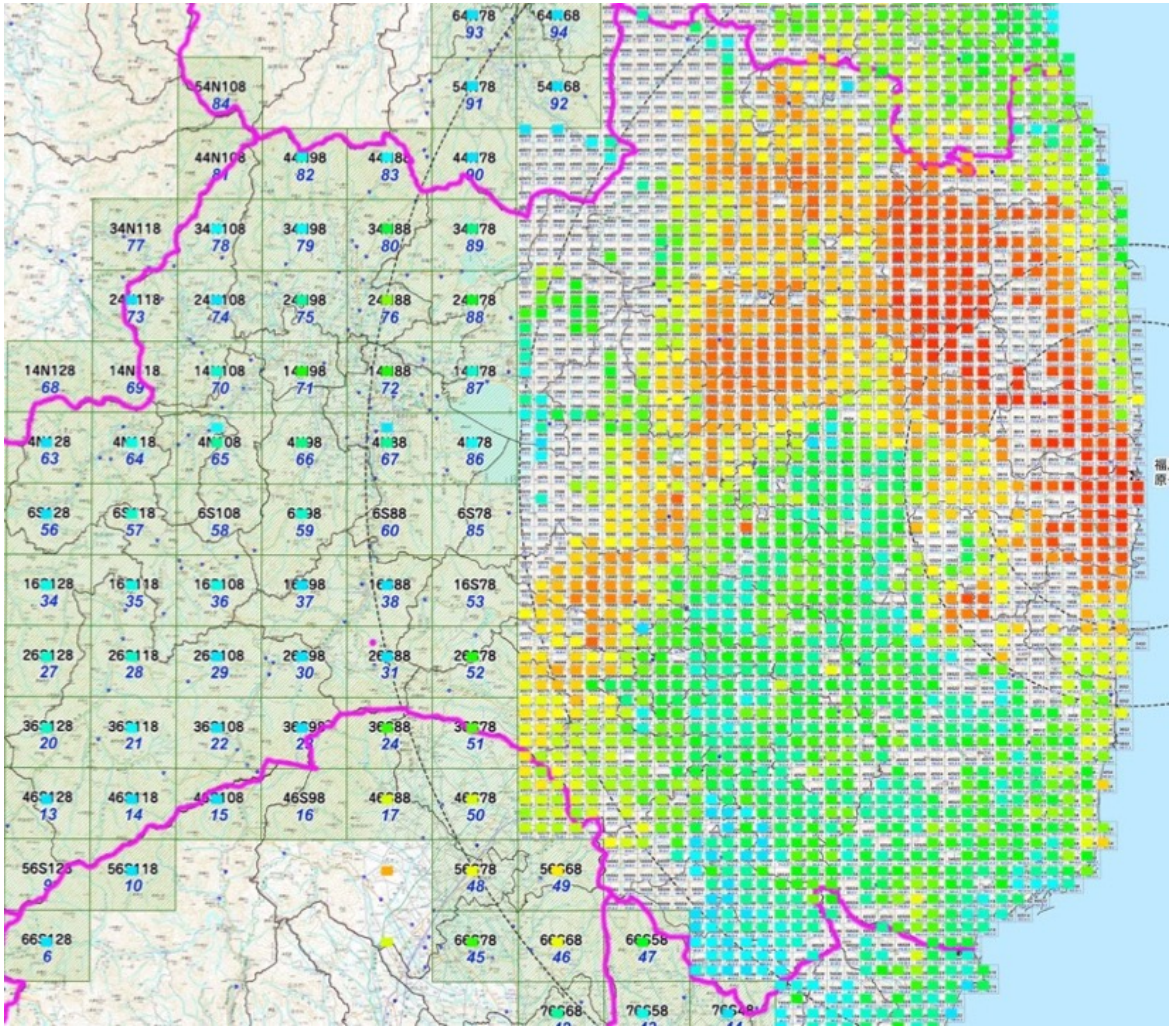
Many radiation scientist in universities volunteered for screening

Survey of Fukushima Soil Radio activities

THE UNIVERSITY OF OSAKA

Osaka university and the Japan Atomic Energy Agency (JAEA) played a key of role in the collection of the soil samples in June - July, 2011.

409 scientists from 94 academic research institutions, and 3 private enterprises participated.



https://www.rcnp.osaka-u.ac.jp/dojo/index_en.php

Conversion from Ambient Dose Rate to Annual Effective Dose

Based on the national approach in Japan

Assumed lifestyle pattern (standard assumptions used by the Japanese government)

Time outdoors	Time indoors	Indoor reduction factor	Days per year
8 hours/day (exposed to ambient dose rate D)	16 hours/day (typical wooden house)	0.4 (indoor dose rate = 0.4 × outdoor dose rate)	365 days

Calculation of annual effective dose

$$E\ (\mu Sv/year) = D \times (8 + 16 \times 0.4) \times 365 = D \times 14.4 \times 365 = D \times 5{,}256$$

E : Annual effective dose (μSv/year)

D : Ambient dose rate (μSv/h)

An ambient dose rate of 1 μSv/h corresponds to **5,256 μSv** per year (= **5.256 mSv/year**) under this lifestyle pattern.

① Criteria for lifting an evacuation order (Annual dose of 20 mSv)

It is confirmed that the estimated annual effective dose based on the ambient dose rate is **20 mSv or less.**

(Nuclear Emergency Response Headquarters, 26 December 2011; quoted in the Ministry of the Environment materials)

Calculation

$$D = \frac{20{,}000\ \mu Sv}{5{,}256} = 3.805\ \mu Sv/h$$

$$\approx 3.8\ \mu Sv/h \text{ (rounded)}$$

Ambient dose rate 3.8 μSv/h ↔ Annual dose 20 mSv

② Long-term radiation protection goal (Additional annual dose of 1 mSv)

Ambient dose rate corresponding to an additional annual effective dose of 1mSv (from the accident).

Calculation (accident-related component only)

$$D = \frac{1{,}000\ \mu Sv}{5{,}256} = 0.1903\ \mu Sv/h$$

$$\approx 0.19\ \mu Sv/h \text{ (rounded)}$$

- Measured values also include natural background radiation (mainly from the ground).
- The Ministry of the Environment assumes a natural background of **0.04** μSv/h.

Ambient dose rate (measured value: accident + natural background)

$$0.190 + 0.040 = 0.230\ \mu Sv/h$$

$$\approx 0.23\ \mu Sv/h \text{ (rounded)}$$

Ambient dose rate 0.23 μSv/h ↔ Additional annual dose 1 mSv

Summary

Purpose / Category	Ambient dose rate D (μSv/h)	Annual effective dose	Remarks
Criterion for lifting an evacuation order	3.8	20 mSv/year	Based on 8 h outdoors, 16 h indoors, indoor factor 0.4
Long-term radiation protection goal (additional dose)	0.19 (accident-related only)	1 mSv/year	Same lifestyle pattern as above
Measured ambient dose rate (reference)	0.23 (accident + natural background)	Corresponds to an additional 1 mSv/year	Includes natural background of 0.04 μSv/h

Sources: Ministry of the Environment, Japan (in Japanese)

- Q&A: "Why is an ambient dose rate of 3.8 μSv/h considered to correspond to an annual dose of 20 mSv?" https://www.env.go.jp/chemi/rhm/h28kisoshiryo/h28qa-02-19.html
- Q&A: "Relationship between 1 mSv per year and an ambient dose rate of 0.23 μSv/h" https://www.env.go.jp/chemi/rhm/h29kisoshiryo/h29qa-02-20.html

Note:

- 0.23 μSv/h is not the criterion for lifting an evacuation order.
- This is a simplified estimation based on a conservative lifestyle pattern.
- Actual individual doses may be lower, depending on behavior, building characteristics, and local conditions.

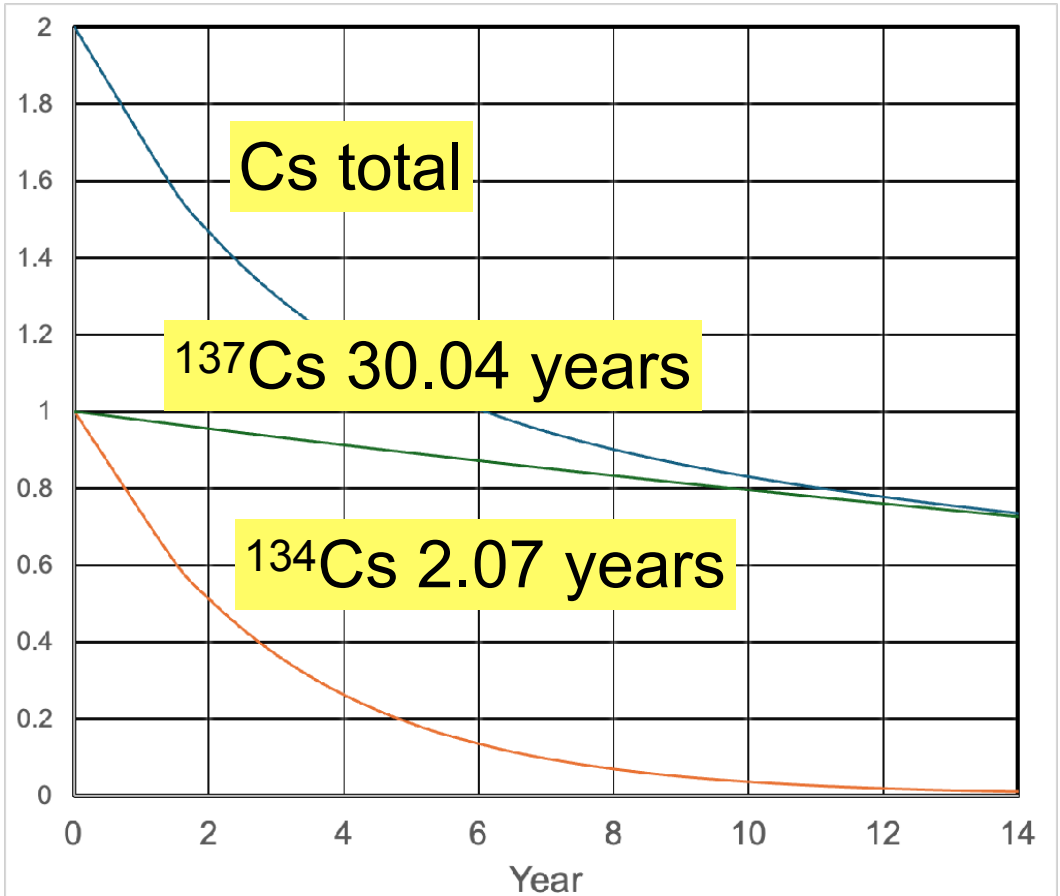
Ministry of the Environment
Government of Japan
環境省

Where is radio activities?

The activities of short-lived radionuclides decreased rapidly.

Activities in early April were ^{131}I : ^{134}Cs : ^{137}Cs = 2:1:1.

one year after, we observed only ^{134}Cs and ^{137}Cs

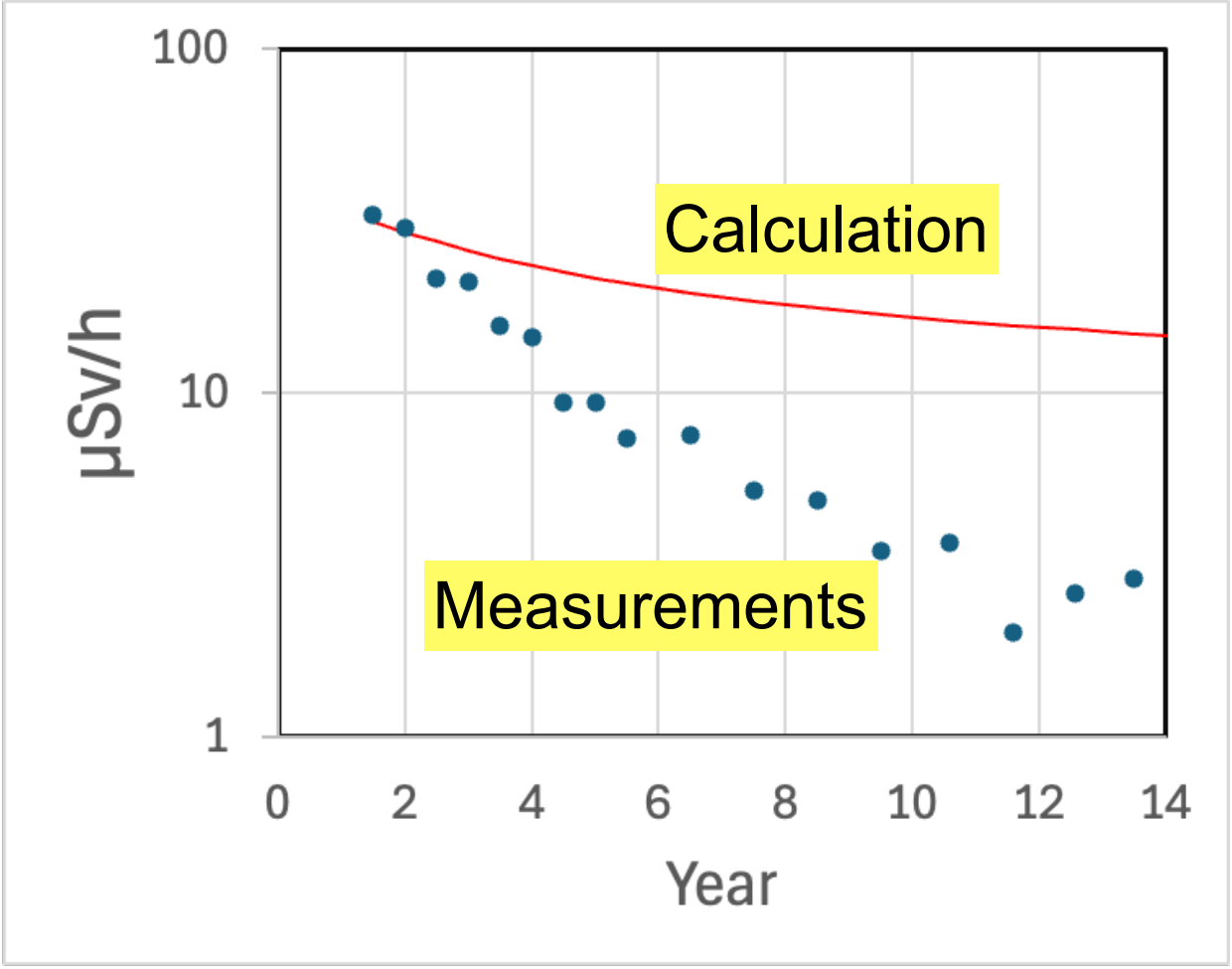


^{131}I 8 days

Where is radio activities?

Okuma town has been measuring air dose rate in untouched area.

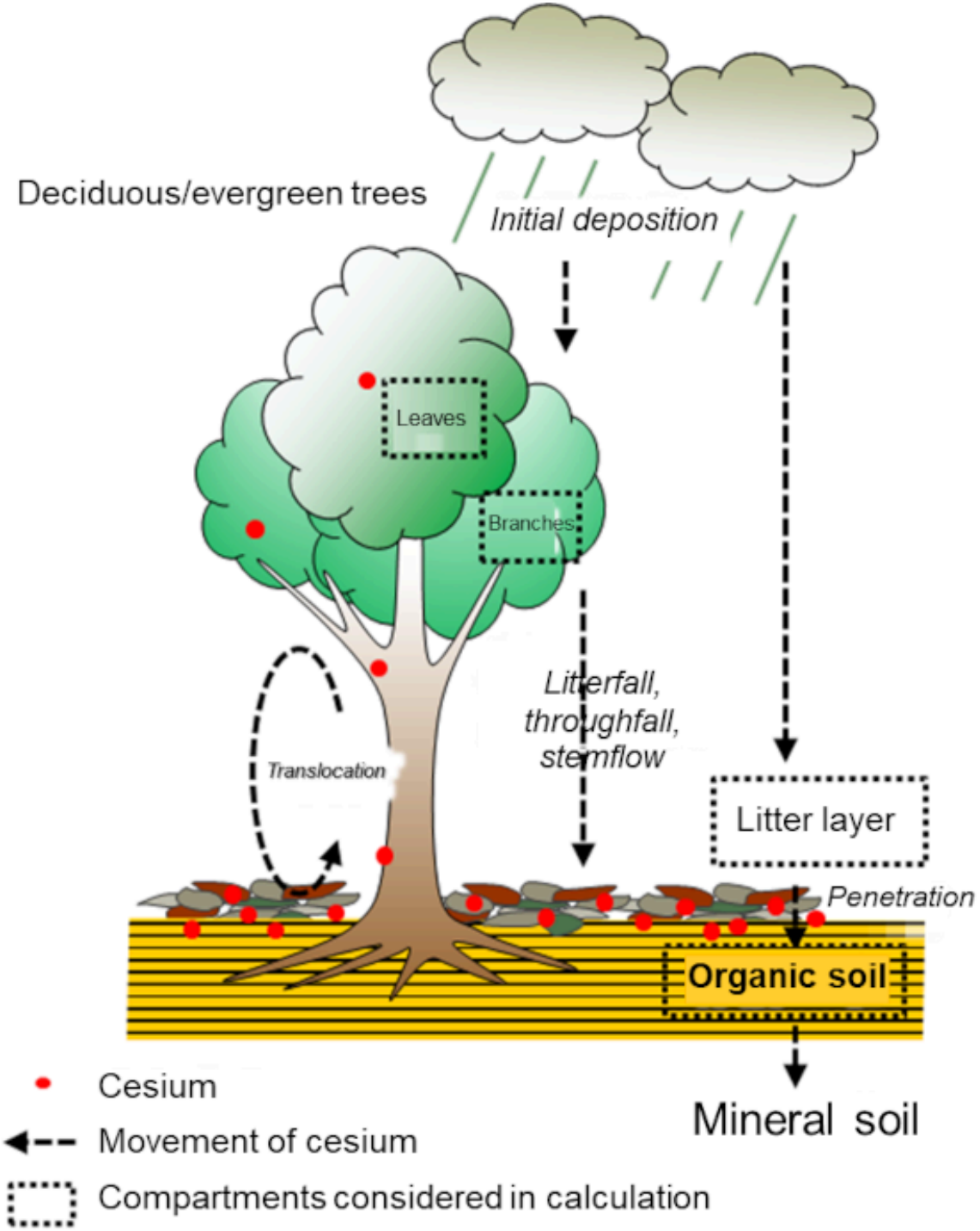
Air dose rate should decrease as decay of ^{137}Cs and ^{134}Cs.



Air dose rate decrease faster than the calculation.

In two years it decreased 1/2.

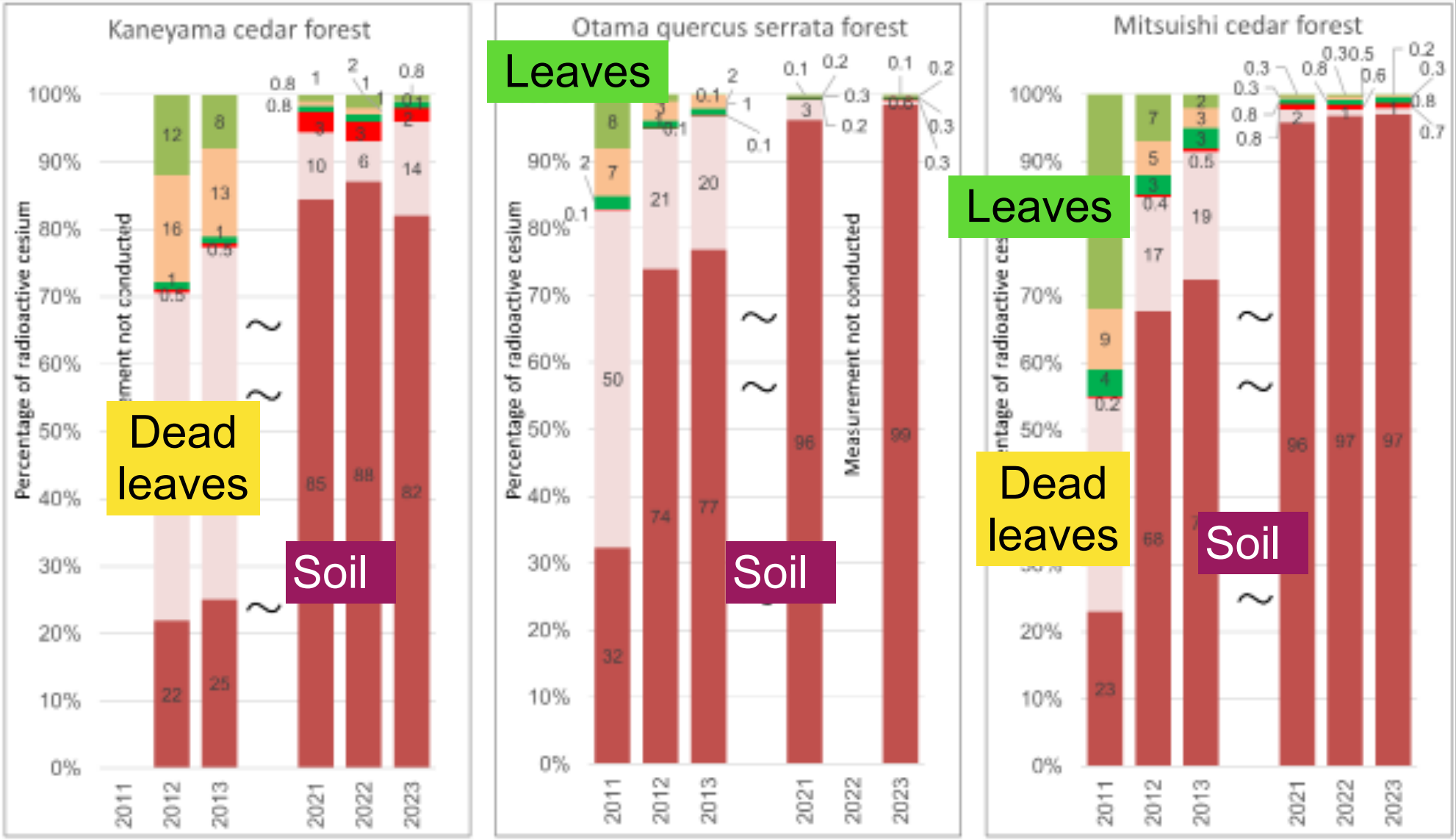
Where has the radioactivity gone?


Deciduous/evergreen trees
Initial deposition
Leaves
Branches
Litterfall,
throughfall,
stemflow
Translocation
Litter layer
Penetration
Organic soil
Mineral soil
Cesium
Movement of cesium
Compartments considered in calculation

Radiation Monitoring of Forest

Changes in Radioactive Cesium Distribution in Forests

Ministry of the Environment
Government of Japan



Prepared based on the "Result of FY2023 Survey on Radioactive Cesium Distribution in Forests" (Forestry Agency)

THE UNIVERSITY OF OSAKA



Contaminated soil particles move deeper slowly.

Most of them remain within the top 5 cm of soil.



Decontamination

Decontamination Methods

Decontamination has been conducted in accordance with the circumstances of respective areas.

Specific methods differ by location.

Effective methods differ depending on the status of contamination with radioactive materials. First, ambient dose rates are measured, and an optimal method is selected on a case-by-case basis. Radiation doses are measured before and after decontamination work to confirm the effects.

Measurement → Selection of decontamination methods → Decontamination work → Confirmation of the effects

Case 1

Decontamination methods employed in areas with relatively low radiation doses

● The following are examples.



●Cleaning of eaves and gutters of private houses



●Mowing of vegetation (Provided by Date City)



●Removal of sludge from ditches (Provided by Fukushima City)

Case 2

Decontamination methods employed in areas with relatively high radiation doses (in addition to the above methods)



●Scraping off of topsoil of school yards (Provided by JAEA)



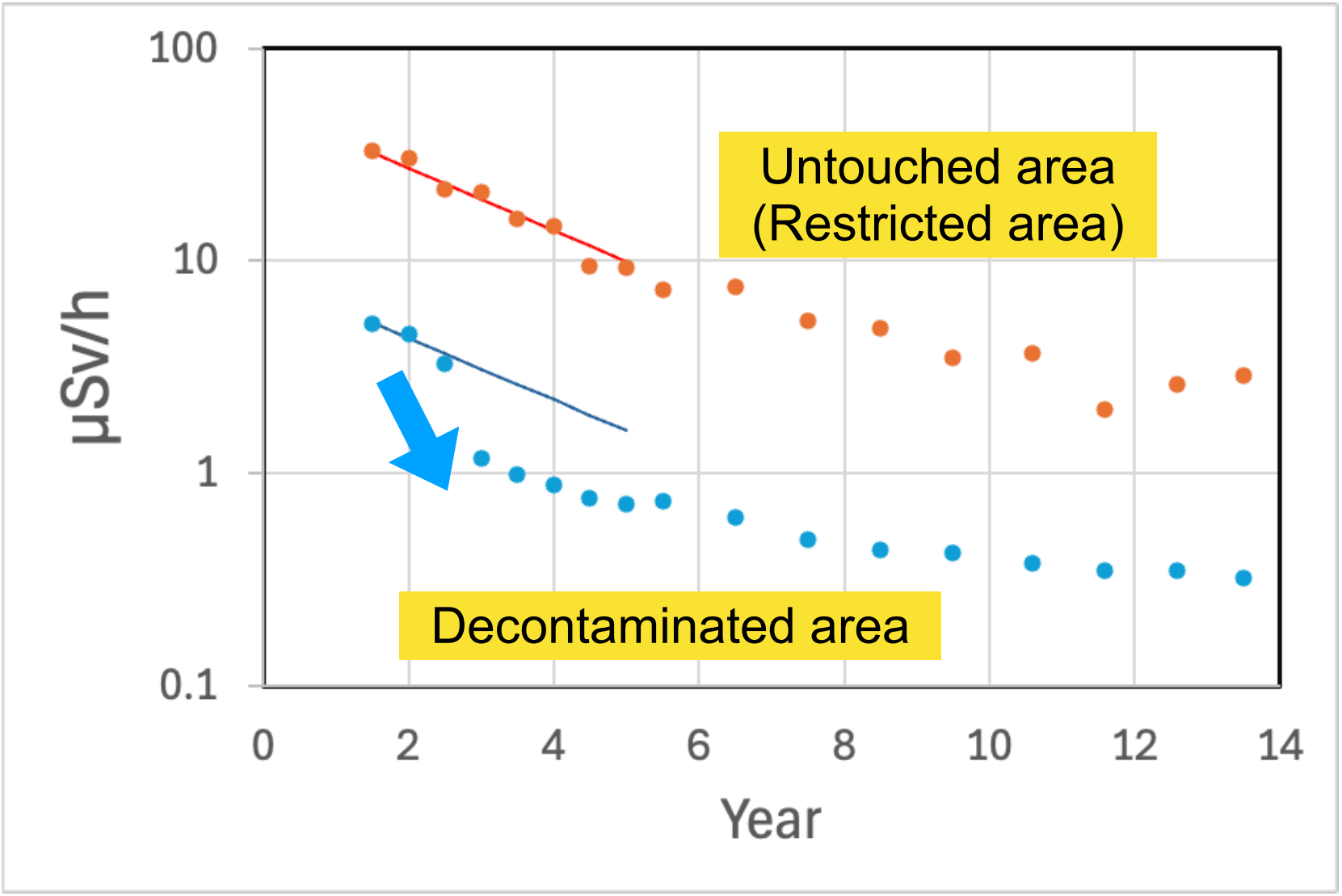
●Washing of building roofs, etc.



●Scraping off of garden soil, etc. (Provided by Date City)

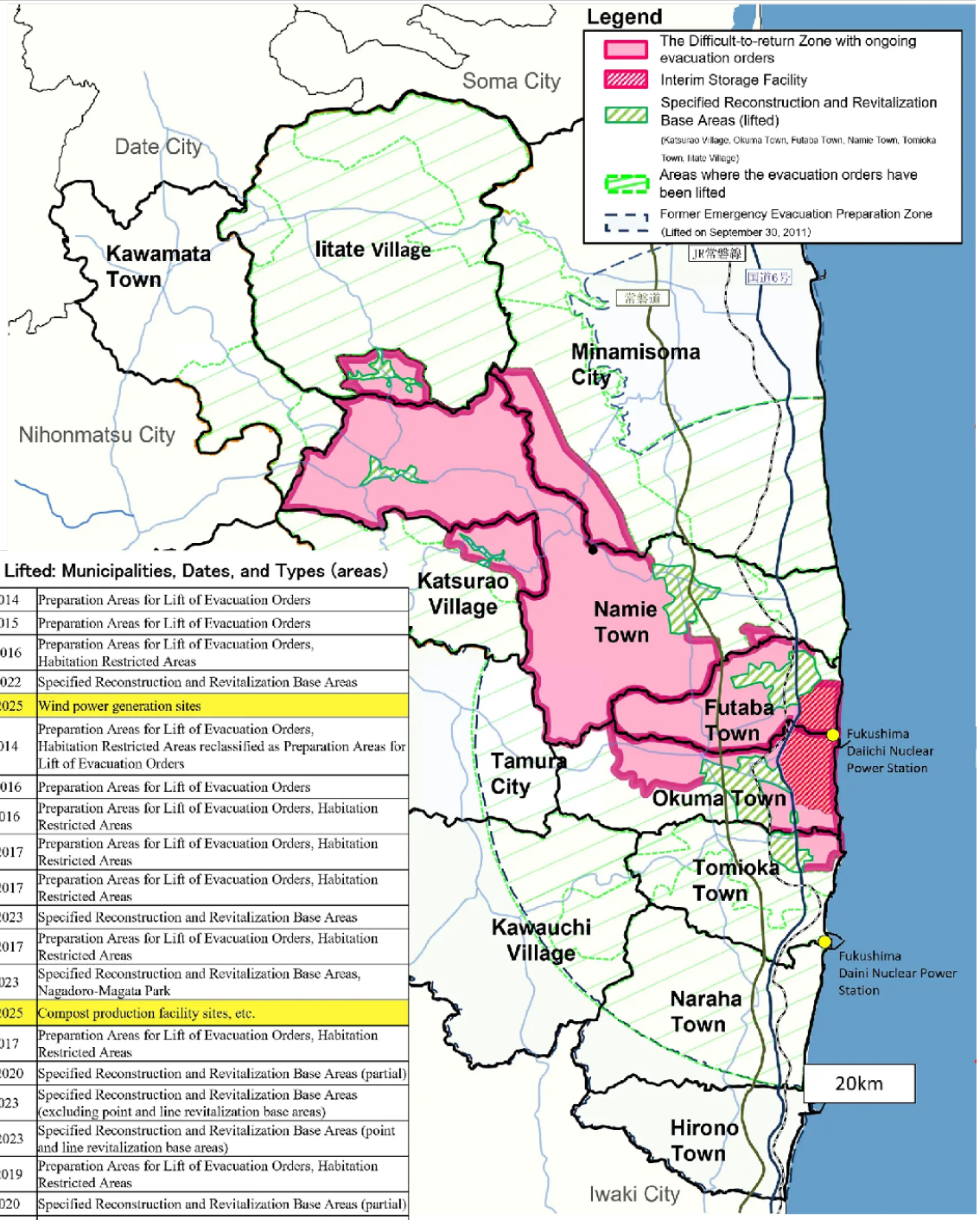
Prepared based on the website, "Environmental Remediation," of the Ministry of the Environment

Decontamination



Concept map of evacuation-designated zones

Status of evacuation zones (as of 31 Mar. 2025)



Evacuation Orders Lifted: Municipalities, Dates, and Types (areas)

Tamura City	1 Apr. 2014	Preparation Areas for Lift of Evacuation Orders
Naraha Town	5 Sep. 2015	Preparation Areas for Lift of Evacuation Orders
Katsurao Village	12 Jun. 2016	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
	12 Jun. 2022	Specified Reconstruction and Revitalization Base Areas
	31 Mar. 2025	Wind power generation sites
Kawauchi Village	1 Oct. 2014	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas reclassified as Preparation Areas for Lift of Evacuation Orders
	14 Jun. 2016	Preparation Areas for Lift of Evacuation Orders
Minamisoma City	12 Jul. 2016	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
Kawamata Town	31 Mar. 2017	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
Namie Town	31 Mar. 2017	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
	31 Mar. 2023	Specified Reconstruction and Revitalization Base Areas
Iitate Village	31 Mar. 2017	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
	1 May 2023	Specified Reconstruction and Revitalization Base Areas, Nagadoro-Magata Park
	31 Mar. 2025	Compost production facility sites, etc.
Tomioka Town	1 Apr. 2017	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
	10 Mar. 2020	Specified Reconstruction and Revitalization Base Areas (partial)
	1 Apr. 2023	Specified Reconstruction and Revitalization Base Areas (excluding point and line revitalization base areas)
	30 Nov. 2023	Specified Reconstruction and Revitalization Base Areas (point and line revitalization base areas)
Okuma Town	10 Apr. 2019	Preparation Areas for Lift of Evacuation Orders, Habitation Restricted Areas
	5 Mar. 2020	Specified Reconstruction and Revitalization Base Areas (partial)
	30 Jun. 2022	Specified Reconstruction and Revitalization Base Areas
Futaba Town	4 Mar. 2020	Preparation Areas for Lift of Evacuation Orders, Specified Reconstruction and Revitalization Base Areas (partial)
	30 Aug. 2022	Specified Reconstruction and Revitalization Base Areas

Hamadohri Environmental Radiation Measurements international school
19-24 July 2026

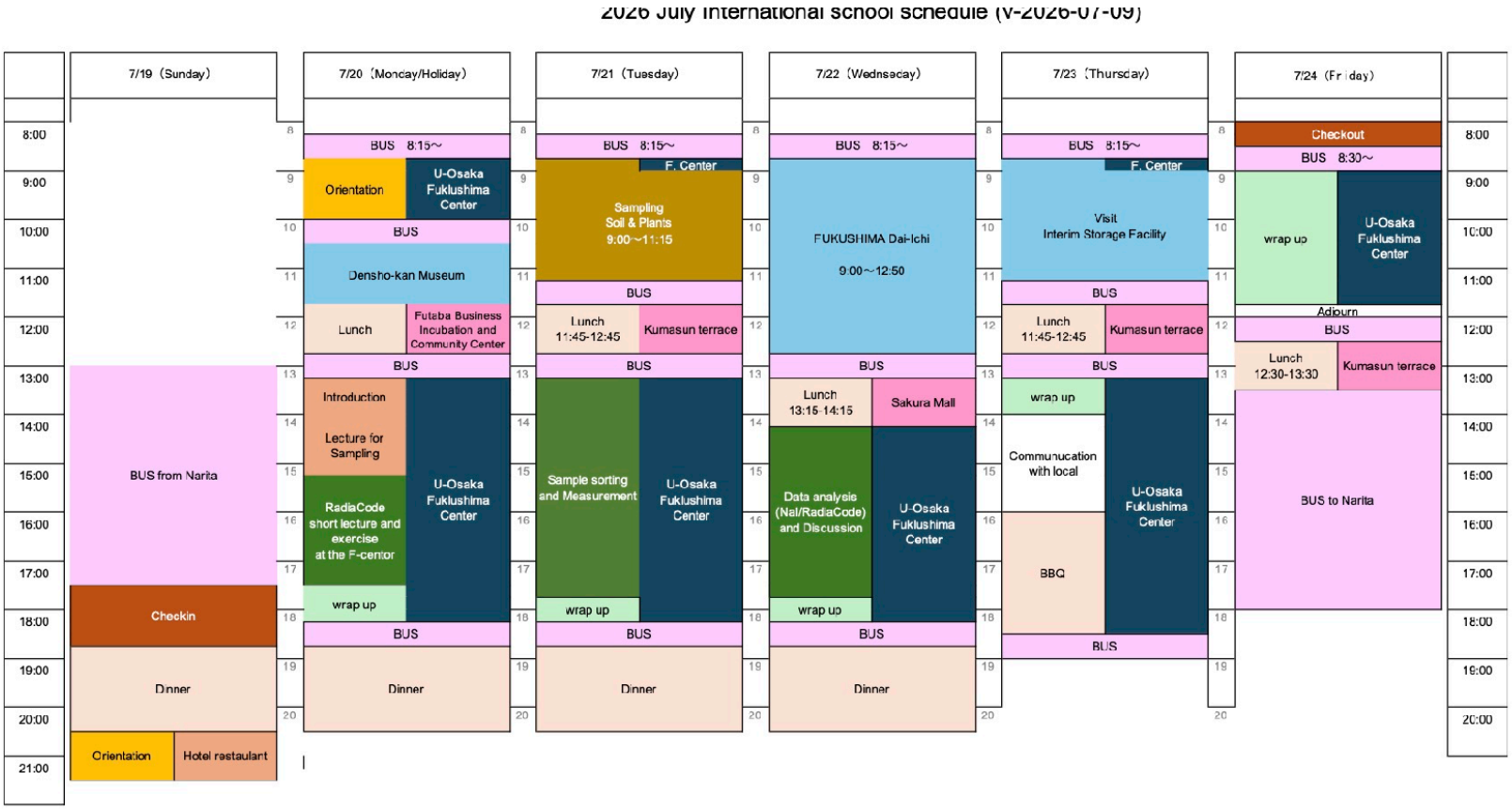
大阪大学 OSAKA UNIVERSITY

IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

School in English

26 students! (24 from abroad / 2 students in Japan)

IAEA International Atomic Energy Agency



Sampling

- Sampling (including at restricted area)
- Air Dose rate measurements



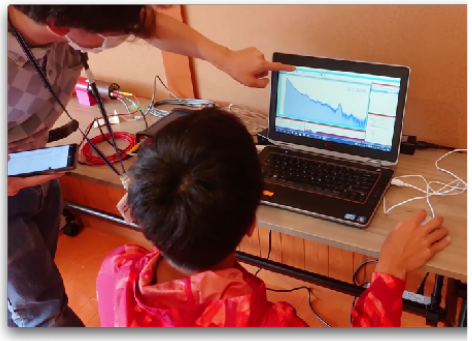




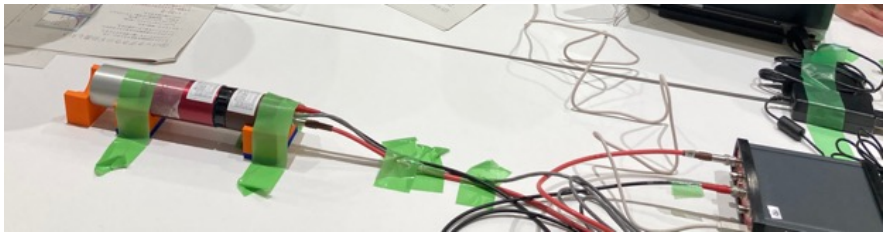
CLEAR-PULSE

Measurements

- Measurements of samples (NaI detector)







Communication with locals





Discussions



Visit





Visit Fukushima Daiichi Nuclear Power plants

	From	Nationality
Japan	11	9
Germany	5	7
Malaysia	4	3
Saudi Arabia	3	3
Thailand	3	3
Singapore	3	3
Indonesia	2	2
Philippines	2	2
United States	2	1
Spain	1	1
United Kingdom	1	1
Pakistan		1
Sri Lanka		1
Zimbabwe		1
Switzerland	1	







Hamadohri Environmental Radiation Measurements international school
July 2027

School in English

The Fukushima school can be found at
https://indico.rcnp.osaka-u.ac.jp/e/Hamadohri-International-2025
https://indico.rcnp.osaka-u.ac.jp/e/Hamadohri-International-2026
and we will repeat
https://indico.rcnp.osaka-u.ac.jp/e/Hamadohri-International-2027