Radioactivity

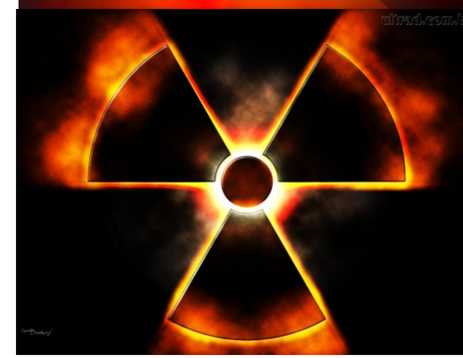
Lecture 22
Chernobyl and Fukushima

Average Human Exposure to Radiation

Average annual human exposure to ionizing radiation in millisieverts (mSv) per year				
Radiation source	World	US	Japan	Remark
Inhalation of air	1.26	2.28	0.40	mainly from radon, depends on indoor accumulation
Ingestion of food & water	0.29	0.28	0.40	(K-40, C-14, etc.)
Terrestrial radiation	0.48	0.21	0.40	depends on soil and building material
Cosmic radiation	0.39	0.33	0.30	depends on altitude
sub total (natural)	2.40	3.10	1.50	sizeable population groups receive 10–20 mSv
Medical	0.60	3.00	2.30	worldwide figure excludes radiotherapy; US figure is mostly CT scans and nuclear medicine.
Consumer items	–	0.13		cigarettes, air travel, building materials, etc.
Nuclear testing	0.005	–	0.01	peak of 0.11 mSv in 1963 and declining since; higher near sites
Occupational exposure	0.005	0.005	0.01	worldwide average to workers only is 0.7 mSv, mostly due to radon in mines; US is mostly due to medical and aviation workers.
Chernobyl accident	0.002	–	0.01	peak of 0.04 mSv in 1986 and declining since; higher near site
Nuclear fuel cycle	0.0002		0.001	up to 0.02 mSv near sites; excludes occupational exposure
Other	–	0.003		Industrial, security, medical, educational, and research
sub total (artificial)	0.61	3.14	2.33	
Total	3.01	6.24	3.83	millisieverts per year **I adopted 3.5 mSv/a**

Nuclear accidents

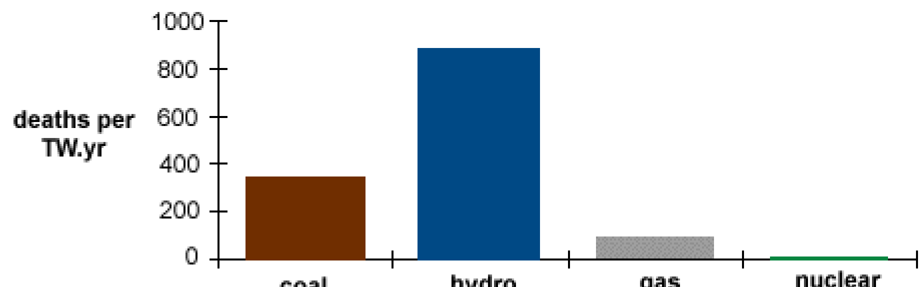
There is no fool-prove technical system, or in short “Shit happens”! Accidents are not avoidable but the likely-hood or the risk should be minimized by appropriate safety features.



Fukushima Daiichi	2011	earthquake
Chernobyl	1986	operator error
Three Mile Island	1979	operator error
Enrico Fermi Unit 1	1966	malfunction of cooling cycle
SL-1	1961	operator error
Sodium Reactor Experiment	1959	malfunction of cooling cycle
Windscale	1957	operator error

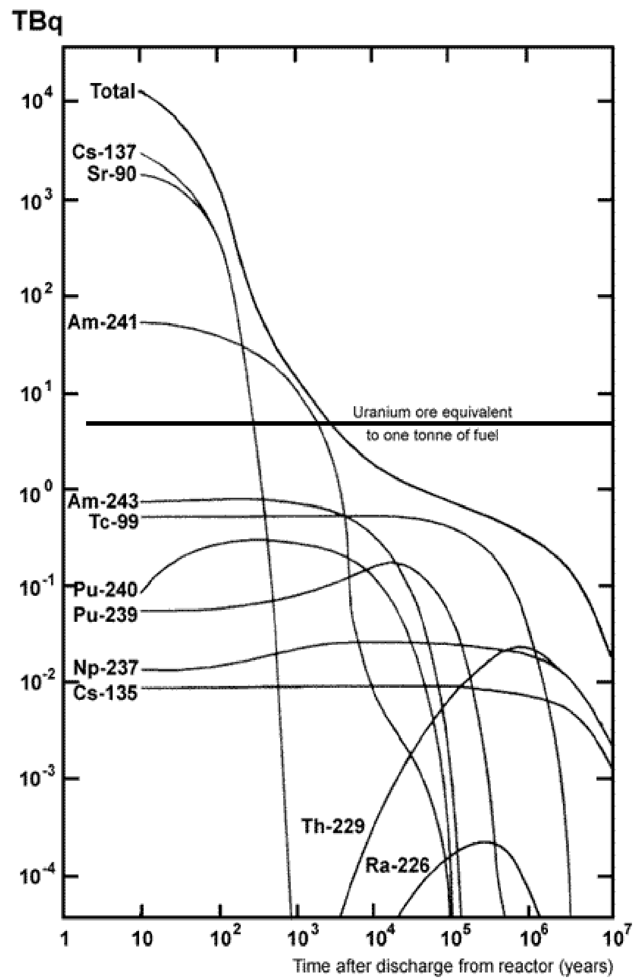
Health Risk	Est. life expectancy lost
Smoking 20 cigs a day	6 years
Overweight (15%)	2 years
Alcohol (US Ave)	1 year
All Accidents	207 days
All Natural Hazards	7 days
Occupational dose (300 mrem/yr)	15 days
Occupational dose (1 rem/yr)	51 days

Risk assessment

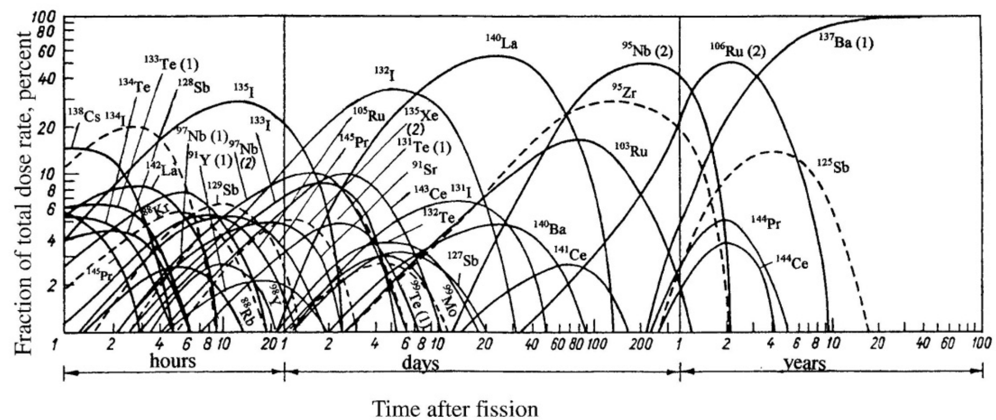


Possible Emission in Case of Accidents

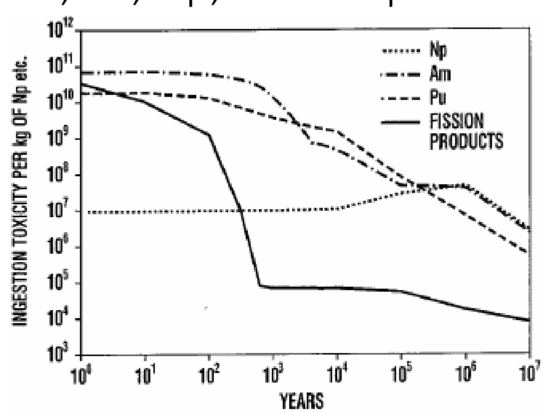
Fission products and fission fuel can be emitted depending on the nature of reactor accident.



Activity of high-level waste from one tonne of spent fuel



Fission fuel elements and associated reaction products, U, Pu, Np, Ac isotopes with long half-lives:



Emitted material will be deposited in the 'local' environment, depending on emission altitude and local climatic conditions, such as wind and rain.

Forms of accidental release of radioactivity

There are three possible forms of release:

1. A fireball from a nuclear explosion when the reactor becomes critical, emitting fission material, fission products and activated debris (nuclear bomb scenario)
2. Chemical explosion in a container of long-lived radioactive waste (WIPP?) causing a local distribution of lower level radioactivity (dirty bomb scenario)
3. Non-nuclear explosion in reactor environment (H gas release), burning of graphite (Chernobyl), burning of fuel elements (Windscale), collapse of cooling, melting of fuel elements by release of decay heat (Fukushima) emission of radioactive material through ground water and fumes.

Comparison of radiation release

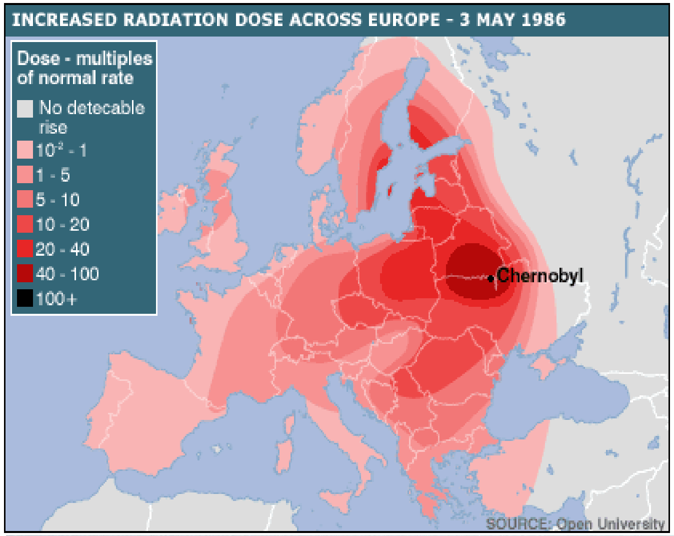
The three largest incidents prior to Fukushima in 2011 have been the Windscale accident in 1957 in the UK, the three-Mile-Island accident in the US in 1983, and the Chernobyl accident in the USSR in 1986. Comparison in the release of radioactive material in each of those incidents compared with the release of radioactivity in the nuclear test program.

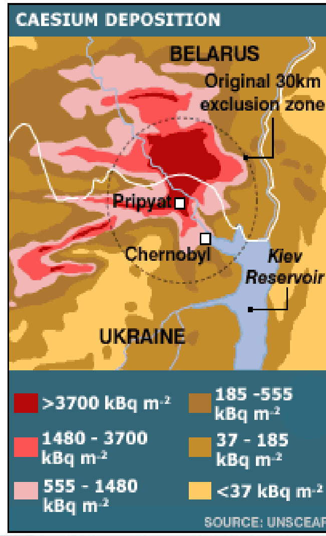
Nuclide	Tests	Chernobyl (former USSR)	Windscale (UK)
^{137}Cs	1500*	89*	0.044
^{134}Cs		48	0.0011
^{90}Sr	1300*	7.4	0.00022
^{131}I	780 000	1300	0.59

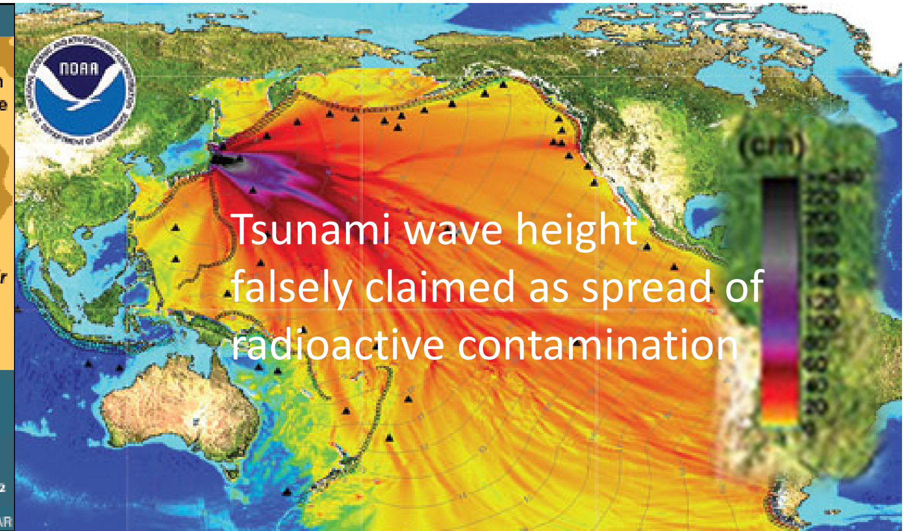
* rough estimates in units pBq (10^{15} Bq)

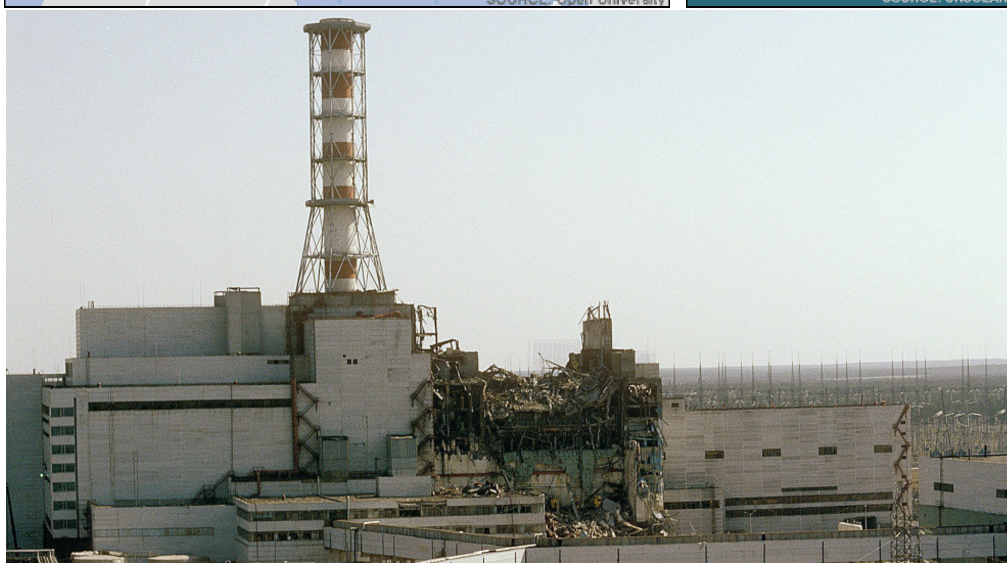
(^{134}Cs is an "induced" nuclide generated by irradiation with reactor neutrons.)

Chernobyl and Fukushima

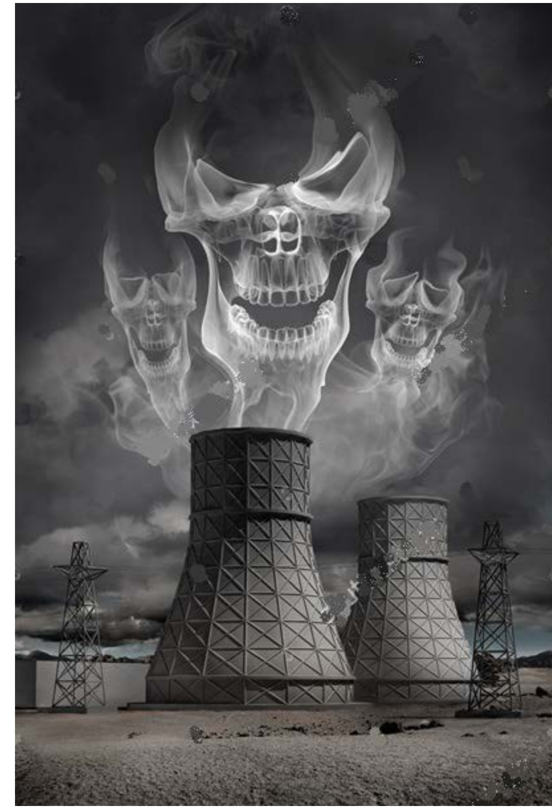








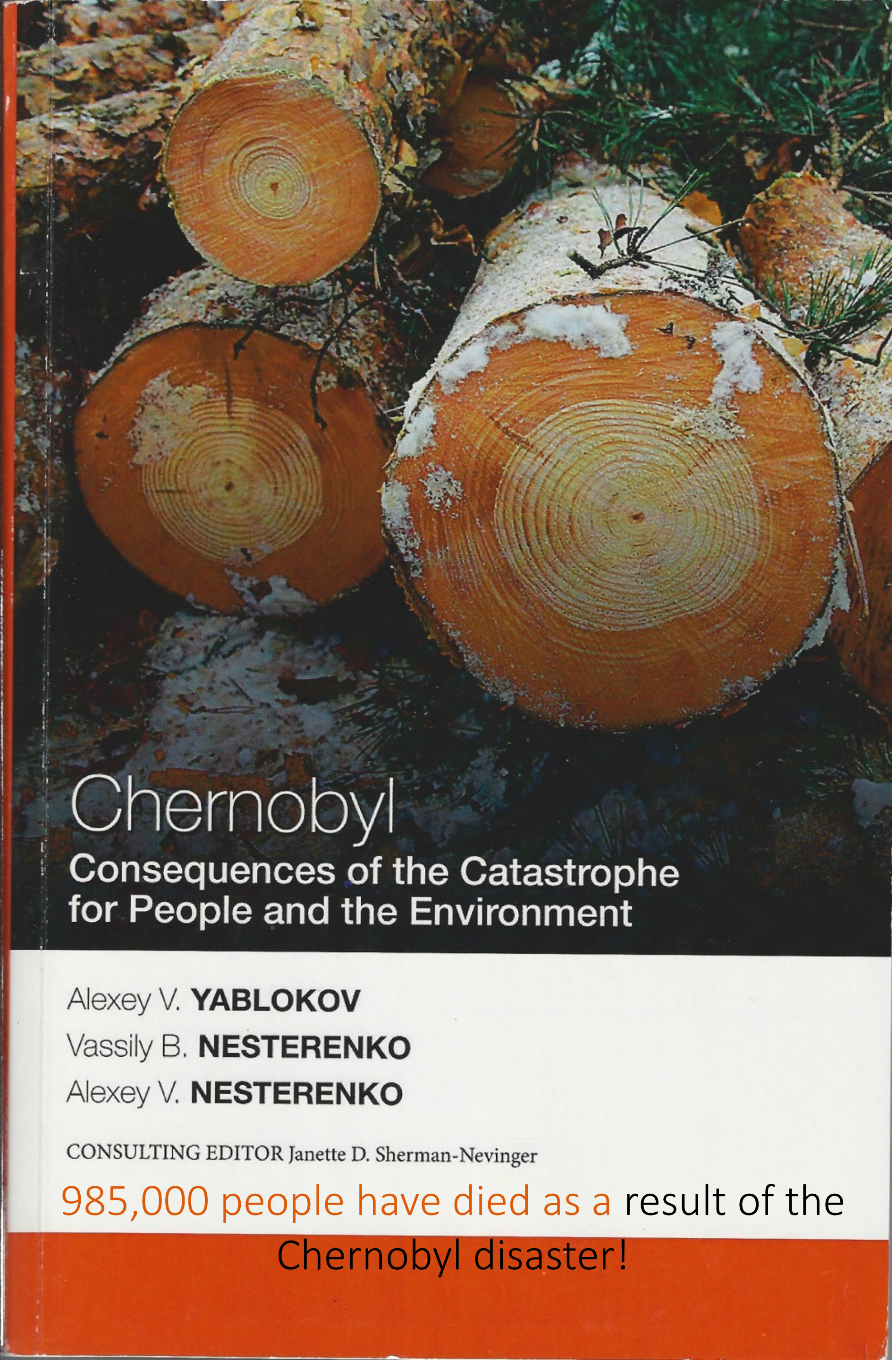
Reactor Accidents strengthened the anti-nuke arguments; Windscale 1956, Three-Mile-Island 1983, Chernobyl 1986, Fukushima 2011



Internet Displays

Horrific pictures increase fear, the pictures are mostly shown on internet sites without any direct source information, while the observed deformations are well known, there is no epidemological evidence that they are correlated to Chernobyl.

Misleading Reports



985,000 people have died as a result of the Chernobyl disaster!

For the past 25 years, anti-nuclear campaigners have been racking up the figures for deaths and diseases caused by the Chernobyl disaster, and parading deformed babies like a mediaeval circus. They now claim that 985,000 people have been killed by Chernobyl, and that it will continue to slaughter people for generations to come. These claims are false.

The journal Radiation Protection Dosimetry points out that the book achieves its figure by assuming that all increased deaths from a wide range of diseases – including many which have no known association with radiation – were caused by the accident. There is no basis for this assumption, the study makes no attempt to correlate exposure to radiation with the incidence of disease. The study also makes no effort to include official government and UN studies with the argument that these studies are false, hiding the truth from the people.

This report as well as a Greenpeace report covers many non-cancer illnesses that have not been observed as radiation-induced diseases even in studies of highly exposed radiation populations but they claim that the Chernobyl accident is 'unique' and, therefore, illnesses for which there is no known association with radiation may be the result of the radiation exposure from Chernobyl.

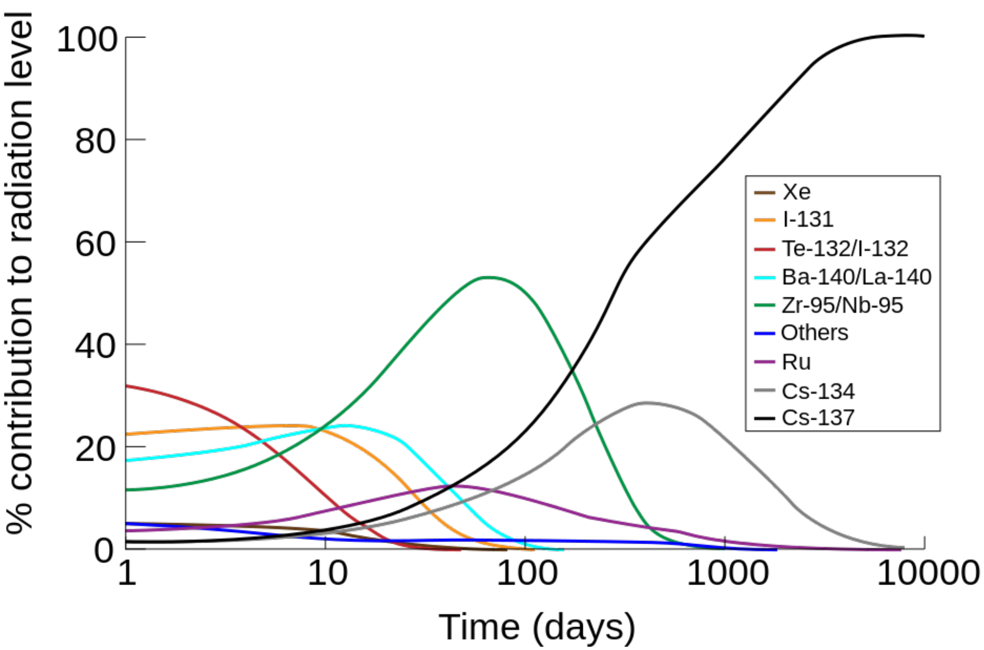
Radioactive Inventory of Chernobyl Reactors at time of accident and the fraction of released radioactive species

Often subject to emotional and political debate

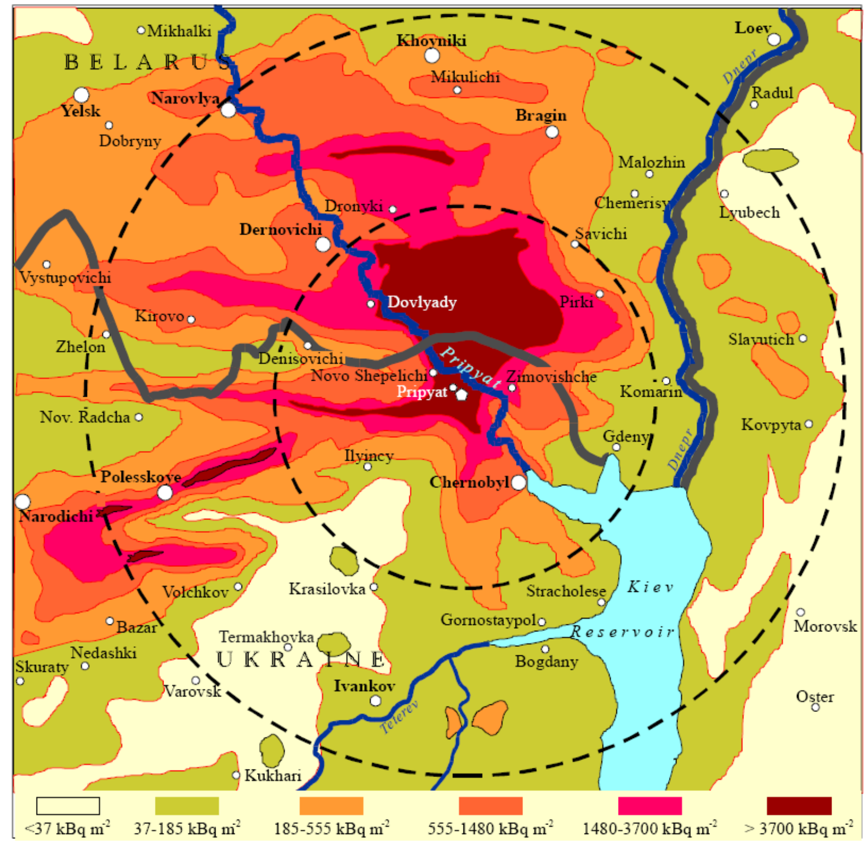
Nuclide	Inventory (Bq) by USSR [1] INSAG [2] Warman [5]	Clough [7]	Anttila [8]	Kirchner & Noack [9]	Little [10]	Sich [4]	Begichev et al. [3]
^{85}Kr	3.3E16	--	--	--	2.5E16	2.8E16	3.3E16
^{133}Xe	7.3E18	--	--	--	6.2E18	6.5E18	6.3E18
^{131}I	3.1E18	2.9E18	2.9E18	2.4E18	3.0E18	3.1E18	3.2E18
^{134}Cs	1.9E17	1.1E17	1.6E17	1.4E17	2.0E17	1.7E17	1.8E17
^{136}Cs	--	--	--	9.0E16	9.6E16	6.3E18 (1.1 E17)	--
^{137}Cs	2.9E17	2.4E17	2.2E17	2.7E17	2.3E17	2.6E17	2.8E17
^{132}Te	3.3E18	4.1E18	4.4E18	4.4E18	4.1E18	4.5E18	2.7E18
^{89}Sr	2.3E18	3.6E18	4.0E18	3.2E18	3.0E18	4.0E18	2.3E18
^{90}Sr	2.0E17	2.0E17	1.8E17	2.0E17	1.7E17	2.3E17	2.0E17
^{140}Ba	5.3E18	5.8E18	5.6E18	5.5E18	5.4E18	6.1E18	4.8E18
^{95}Zr	--	5.8E18	--	5.3E18	5.1E18	5.8E18	5.6E18
^{99}Mo	7.3E19 (7.3E18)	5.5E18	5.7E18	--	5.2E18	6.1E18	4.8E18
^{103}Ru	5.0E18	4.3E18	4.0E18	4.6E18	4.5E18	3.8E18	4.8E18
^{106}Ru	2.0E18	8.9E17	7.9E17	1.1E18	1.2E18	8.6E17	2.1E18
^{141}Ce	5.6E18	5.6E18	5.4E18	--	5.1E18	5.6E18	5.6E18
^{144}Ce	3.2E18	3.9E18	3.4E18	3.8E18	3.4E18	3.9E18	3.3E18
^{238}Pu	1.0E15	--	--	7.3E14	1.6E15	1.3E15	1.0E15
^{239}Pu	8.5E14	--	--	8.0E14	9.6E14	9.5E14	8.5E14
^{240}Pu	1.2E15	--	--	1.6E15	1.6E15	1.5E15	1.2E15
^{241}Pu	1.7E17	--	--	1.9E17	1.8E17	1.8E17	1.7E17
^{239}Np	3.6E18 (3.6E19)	4.7E19	5.1E16	6.1E19	6.7E19	5.8E19	2.7E19
^{242}Cm	2.5E16	--	--	3.3E16	3.3E16	4.3E16	2.6E16

Radionuclide	Percent of Core Inventory Released: Initial Estimate [1][(a)]	Current Estimate[(b)]
^{85}Kr	100	100
^{133}Xe	100	100
^{131}I	20	50-60
^{132}Te	15	10-60 (c)
^{134}Cs	10	33±10
^{137}Cs	13	33±10
^{140}Ba	5.6	3.5-6 (d)
^{95}Zr	3.2	3.5
^{99}Mo	2.3	3.5-6 (e)
^{103}Ru	2.9	3.5-6 (e)
^{106}Ru	2.9	3.5-6 (e)
^{141}Ce	2.3	3.5
^{144}Ce	2.8	3.5
^{89}Sr	4	3.5-4.5 (d)
^{90}Sr	4	3.5-4.5 (d)
^{239}Np	3	3.5
^{238}Pu	3	3.5
^{239}Pu	3	3.5
^{240}Pu	3	3.5
^{241}Pu	3	3.5
^{242}Cm	3	3.5

Nature and time dependence of exposure in the local area



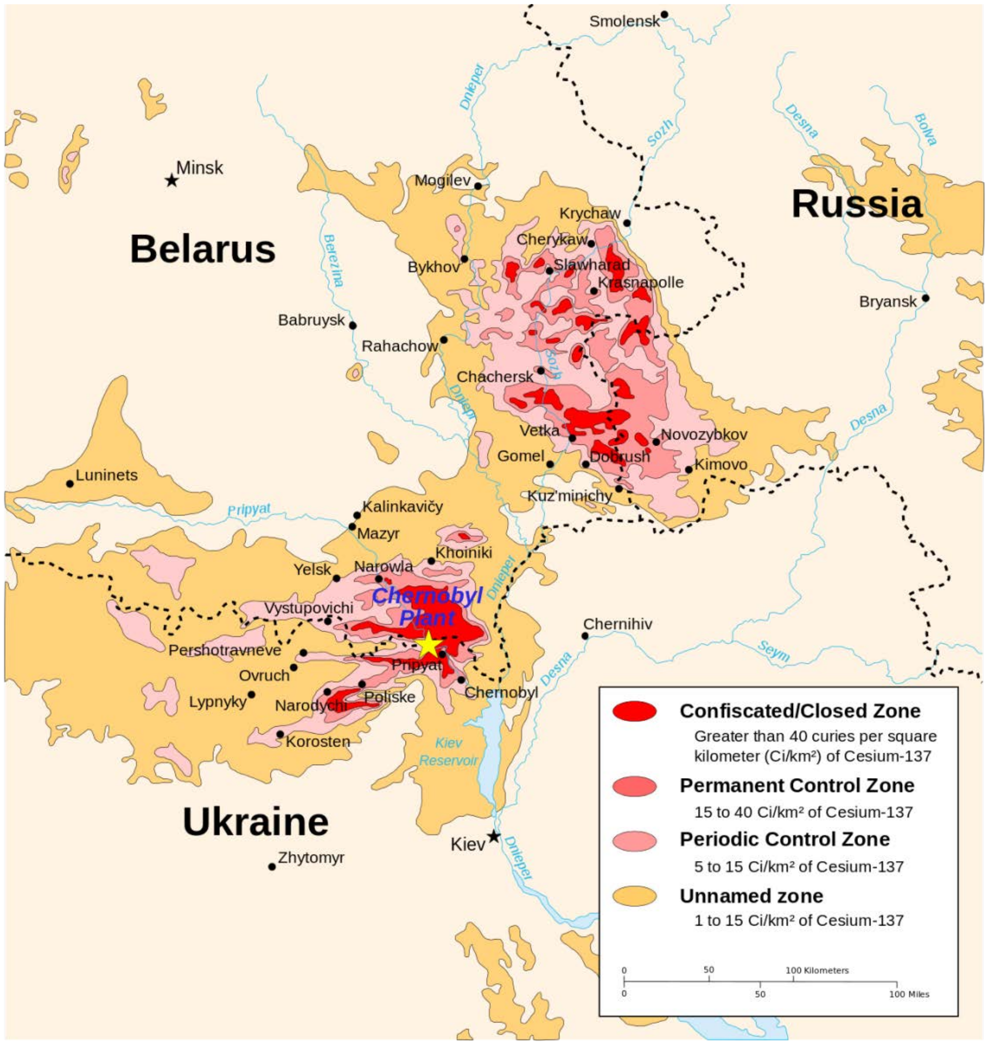
Contributions of the various isotopes to the external (atmospheric) absorbed dose in the contaminated area of Pripyat, from soon after the accident, to years after the accident. ^{137}Cs with ~30 year half-life remains as dominant deposit.



^{137}Cs decay pattern and the local fall-out of ^{137}Cs within a 30 km and a 60 km radius around Chernobyl reactor complex. Wind direction points north-westward.

UNSCEAR. Sources, Effects and Risks of Ionizing Radiation. UNSCEAR 1988 Report. United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 Report to the General Assembly. United Nations sales publication E.88.IX.7. United Nations, New York, 1988. Appendix J

Closed Area and Red Forest



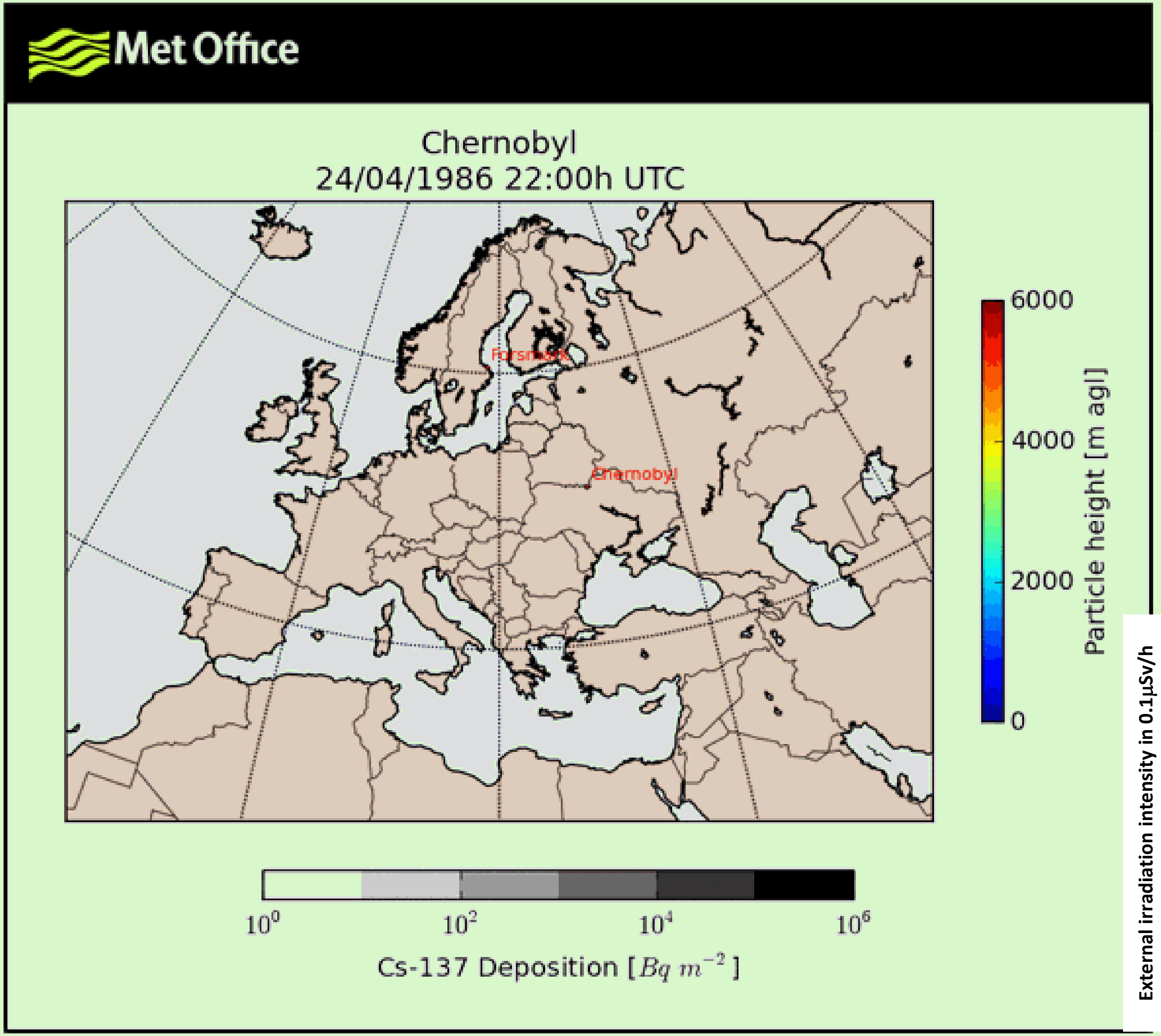
Recovery

After initial decline of wildlife and plant population (red forest), nature has fully recovered in the forbidden zones due to lack of human interference.

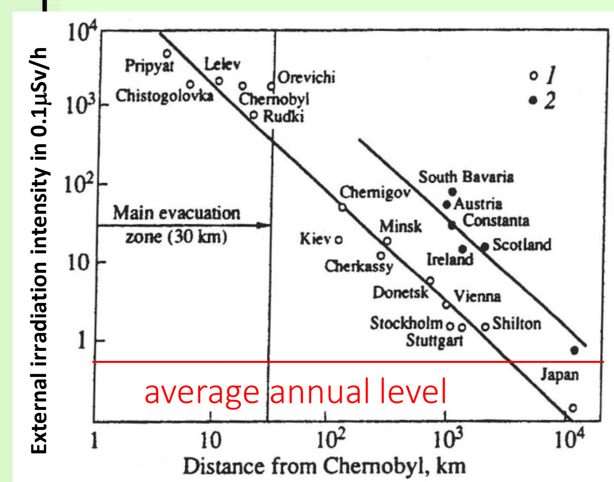
"Chernobyl's abundant and surprisingly normal-looking wildlife has shaken up how biologists think about the environmental effects of radioactivity. The idea that the world's biggest radioactive wasteland could become Europe's largest wildlife sanctuary is completely counterintuitive for anyone raised on nuclear dystopias."

http://www.slate.com/articles/health_and_science/nuclear_power/2013/01/wildlife_in_chernobyl_debate_over_mutations_and_populations_of_plants_and.html

^{137}Cs distribution and deposition



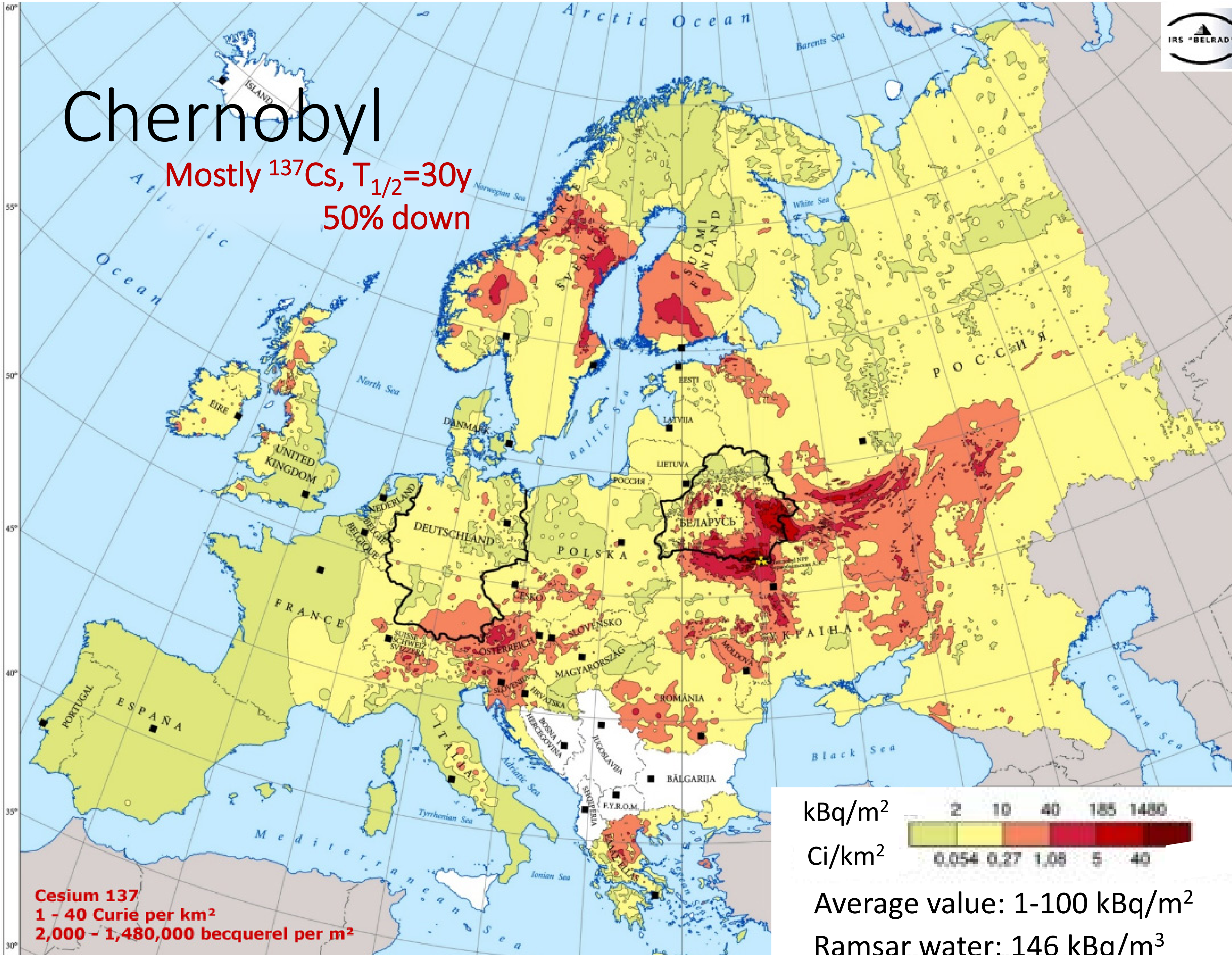
The color code signifies the altitude of the radioactive cloud distributing the material across Europe, the gray shaded areas indicate the location and the amount of deposited ^{137}Cs material with it's 30 years half-life.



Chernobyl

Mostly ^{137}Cs, $T_{1/2}$=30y

50% down



Average value: 1-100 kBq/m²

Ramsar water: 146 kBq/m³

Deposition in Russia, Belarus, and Ukraine

^{137}Cs *deposition density (kBq m^{-2})*	*Population*	*Collective effective dose (man Sv)*			
		External	*Internal*	*Total*	
Belarus [S46]					
37–185 185–555 ≥555	1 543 514 239 505 97 593	3 682 2 521 3 433	2 409 1 945 1 150	6 091 4 466 4 583	
Total	1 880 612	9 636	5 504	15 140	0.0081 Sv
Russian Federation [B37, M17, S46]					
37–185 185–555 ≥555	1 654 175 233 626 95 474	3 778 2 065 2 611	3 009 1 183 799	6 787 3 248 3 410	
Total	1 983 275	8 454	4 991	13 445	0.0068 Sv

Ukraine [L44]									
^{137}Cs *deposition density (kBq m^{-2})*	*Population*		*Collective effective dose (man Sv)*						
			External		*Internal*		*Total*		
	Rural	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	*Rural*	*Urban*	
37–185 185–555 >555	881 800 40 400 300	306 800 66 300	3 715 610 11.0	999 769	6 610 375 13.8	717 140	10 330 986 24.8	1 717 909	
Total	922 500	373 100	4 336	1 768	7 000	857	11 340	2 626	0.0097 Sv

The collective dose (sum of the single doses) exposure of the population in Belarus, Russia, and Ukraine in units Sievert. 1 man Sv gives the collective dose of 1000 Persons, that were exposed to a dose of 1 mSv each, or 10 persons exposed to 100 mSv. The average single person dose is achieved by dividing the collective dose by the population, ~ 0.05-0.01 Sv. Compared to average natural annual dose of 0.0035 Sv.

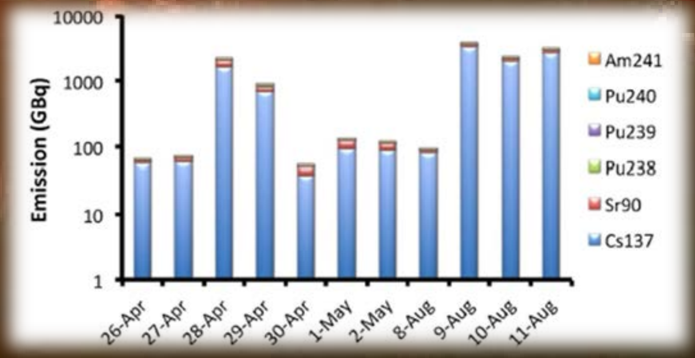
Estimate of average individual dose levels for world population

Group	Number of individuals	Average individual dose, mSv
USSR liquidators[a]	240,000	100
Evacuees	116,000	33
USSR heavily contaminated areas	270,000	50
USSR less contaminated areas	5,000,000	10
Other areas in Europe	600,000,000	≥ 0.4
Outside Europe	4,000,000,000	$\geq 2.5 \times 10^{-2}$

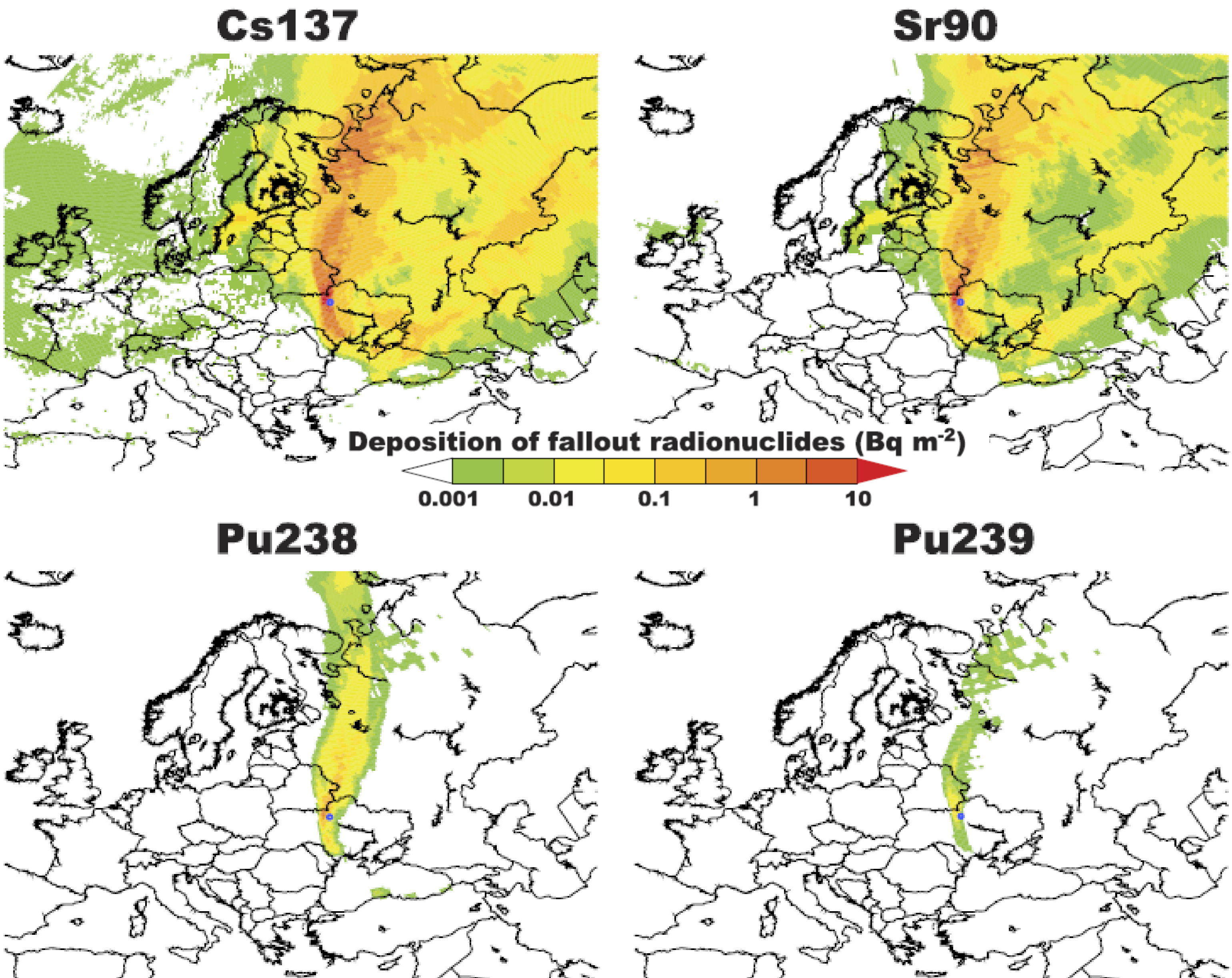
[a]Presumably 1986–1987 (A.Y.).

1	mSv/a	(0.1	µSv/h avg)	ICRP recommended maximum for external irradiation of the human body, excluding medical and occupational exposures.
3.5	mSv/a	(0.4	µSv/h avg)	Human exposure to natural background radiation, global average
24	mSv/a	(2.7	µSv/h avg)	Natural background radiation at airline cruise altitude
130	mSv/a	(15	µSv/h avg)	Ambient field inside most radioactive house in Ramsar, Iran
(800	mSv/a)	90	µSv/h	Natural radiation on a monazite beach near Guarapari, Brazil.
(9	Sv/a)	1	mSv/h	NRC definition of a high radiation area in a nuclear power plant, warranting a chain-link fence

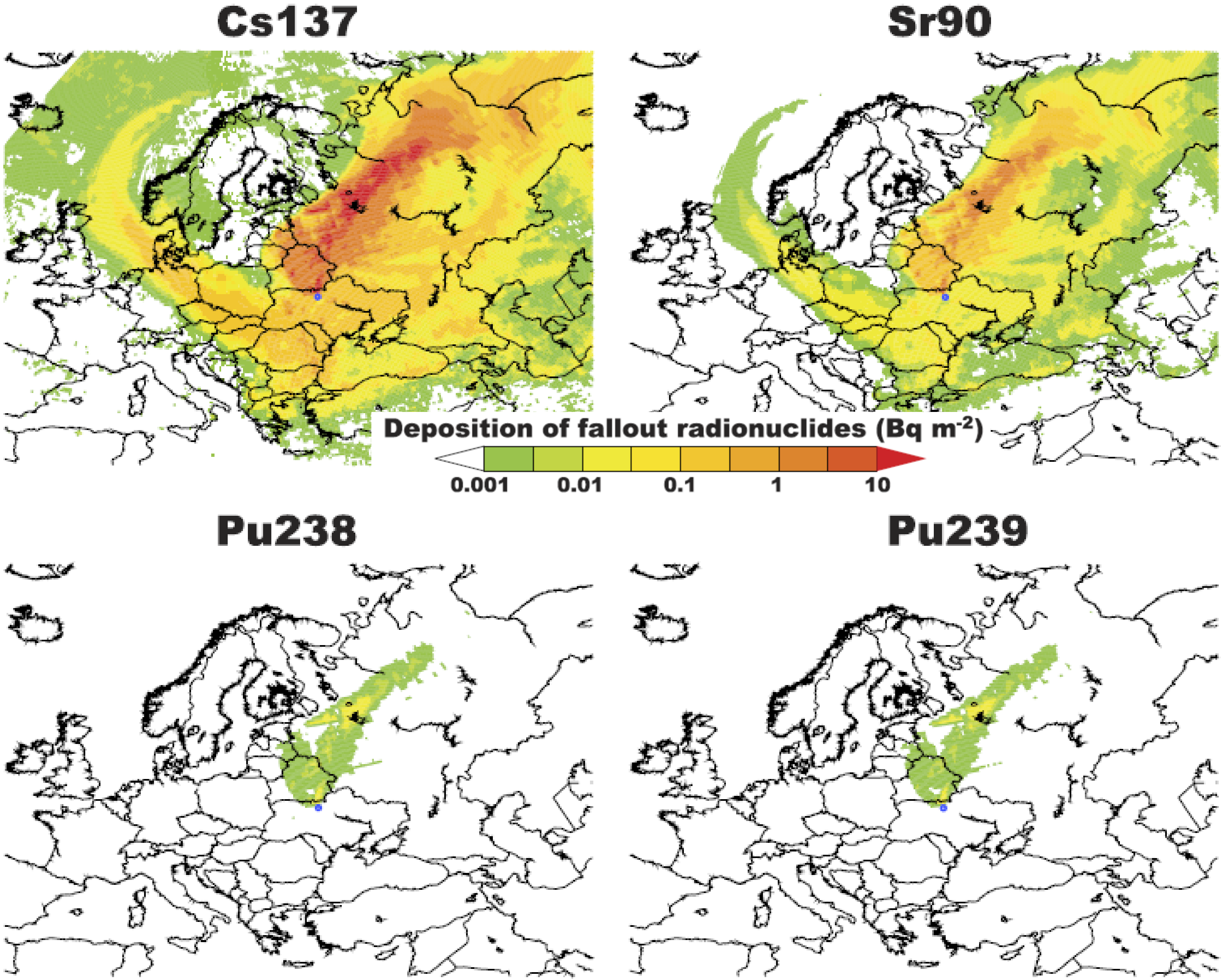
Forest Fires at Chernobyl Woods in April and August 2015



Release in April-May 2015

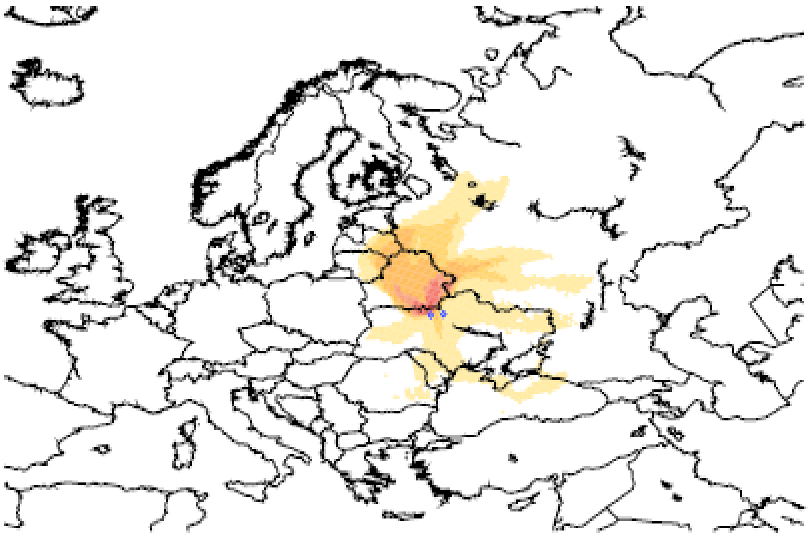


Release in August 2015

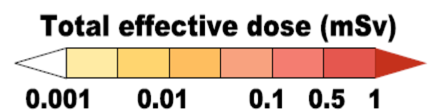


Exposure of Central Europe

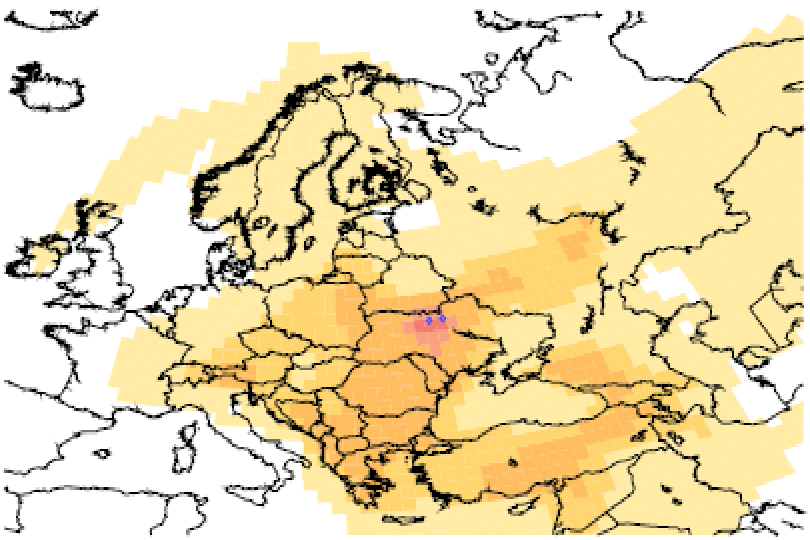
FIRES



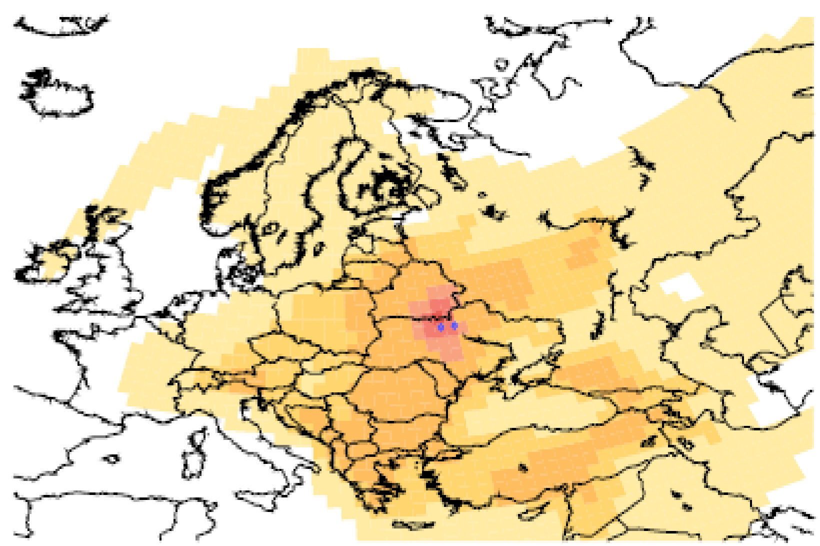
Average human exposure 0.35 mSv/y
= 0.03 mSv/month
Total = 0.06 mSv/ fire period
Ramsar: 140 μSv/h = 0.1 Sv/month



BACKGROUND



FIRES + BACKGROUND



Fukushima Tsunami 2011


Reactor unrelated failure


Fukushima Daiichi 2011

Emitted fission products from Fukushima

Release to the Atmosphere

Radionuclide	T1/2	*Total release (PBq)*	*Radionuclide*	T1/2	*Total release (PBq)*
^{132}Te	76h	29	^{133}Xe	5.3d	7 300
^{131}I	8d	120	^{134}Cs	2y	9.0
^{132}I	2.3h	29	^{136}Cs	13d	1.8
^{133}I	21h	9.6	^{137}Cs	**30y**	8.8

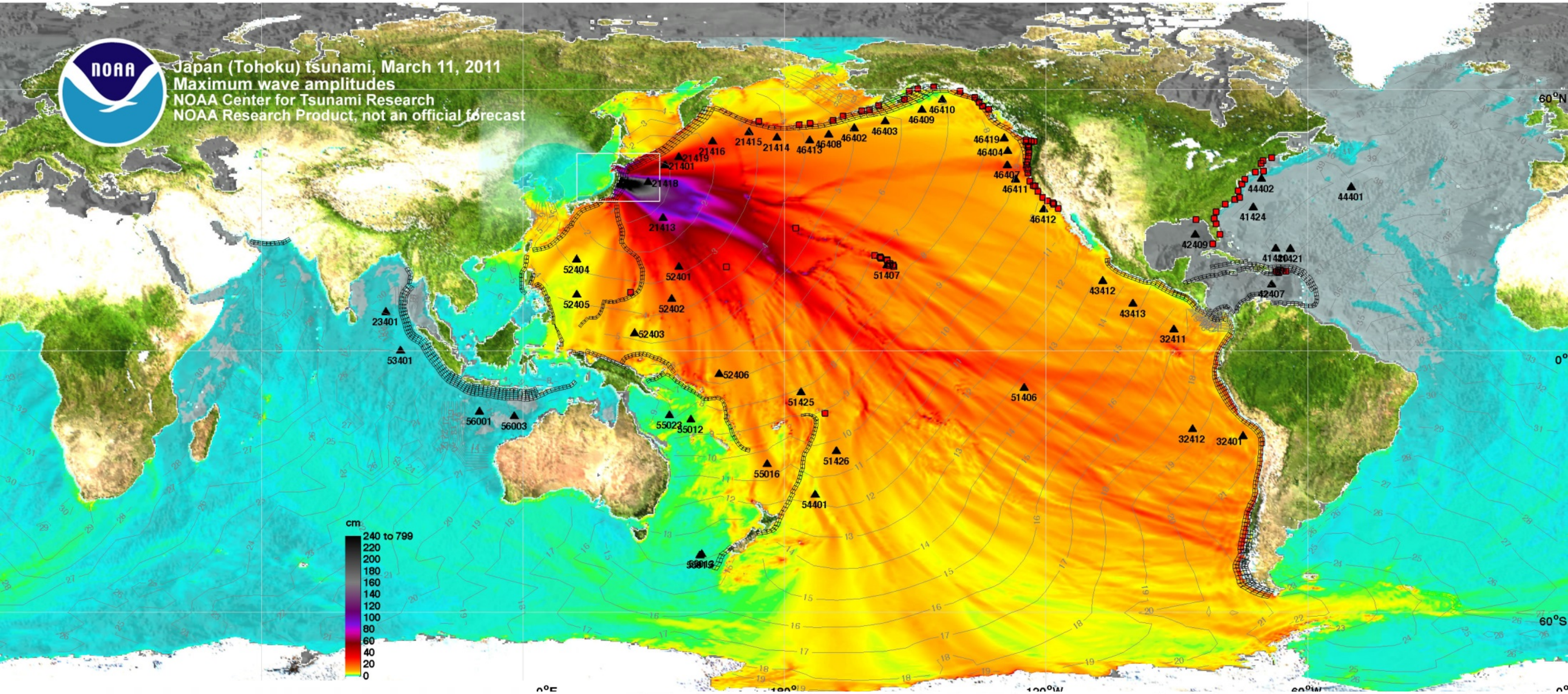
Release to the Environment

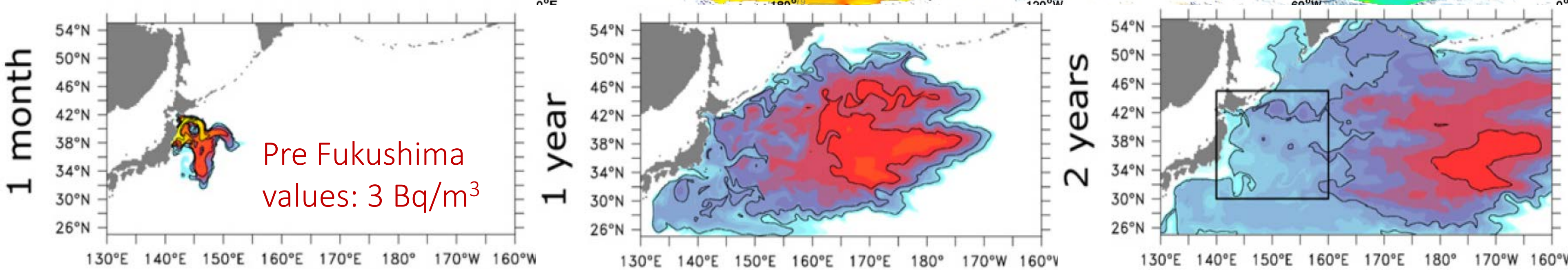
Radionuclide	*Inventory in Units 1 to 3 at reactor shutdown[a] (PBq)*	*Release to the atmosphere (PBq)*	*Release to the ocean (PBq)*	
			Direct	*Indirect[b]*
^{131}I	6 000	100 to 500[c]	about 10 to 20[e]	60 to 100[g]
^{137}Cs	700	6 to 20[d]	3 to 6[f]	5 to 8[g]

^{134}Cs down to 18%, the rest gone except ^{137}C, down to 89%

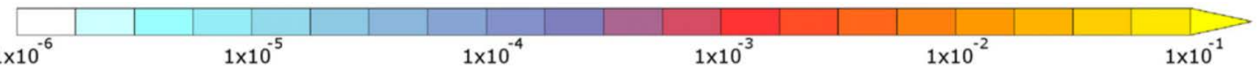
according to the decay law: $N(5y) = N_0 \cdot e^{-\frac{\ln 2}{T_{1/2}} \cdot 5y}$

Tsunami and Radioactivity



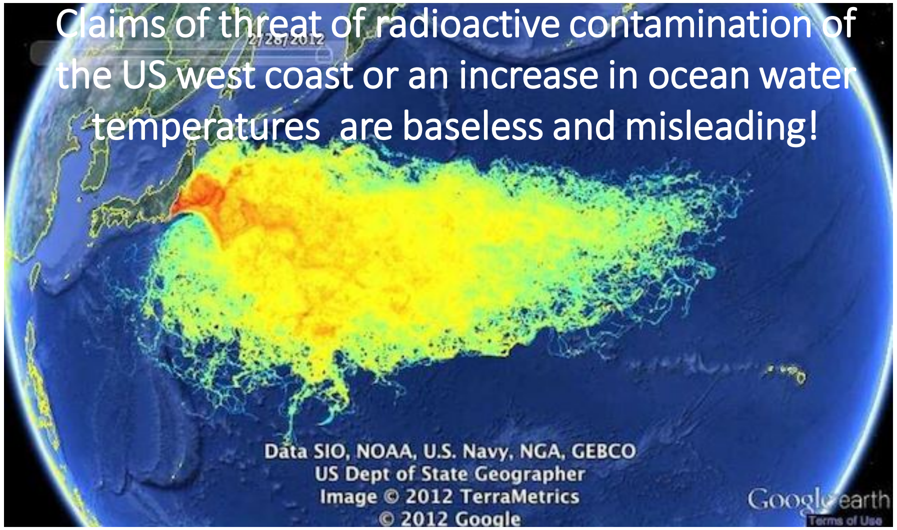


Peak values: $3 \cdot 10^4$ Bq/m^3



Sea Water Contamination

Last year, at the behest of the United States, TEPCO intentionally released 3 million gallons of radioactive waste into the Pacific ocean and now the world is set to experience the consequences of this disastrous decision.

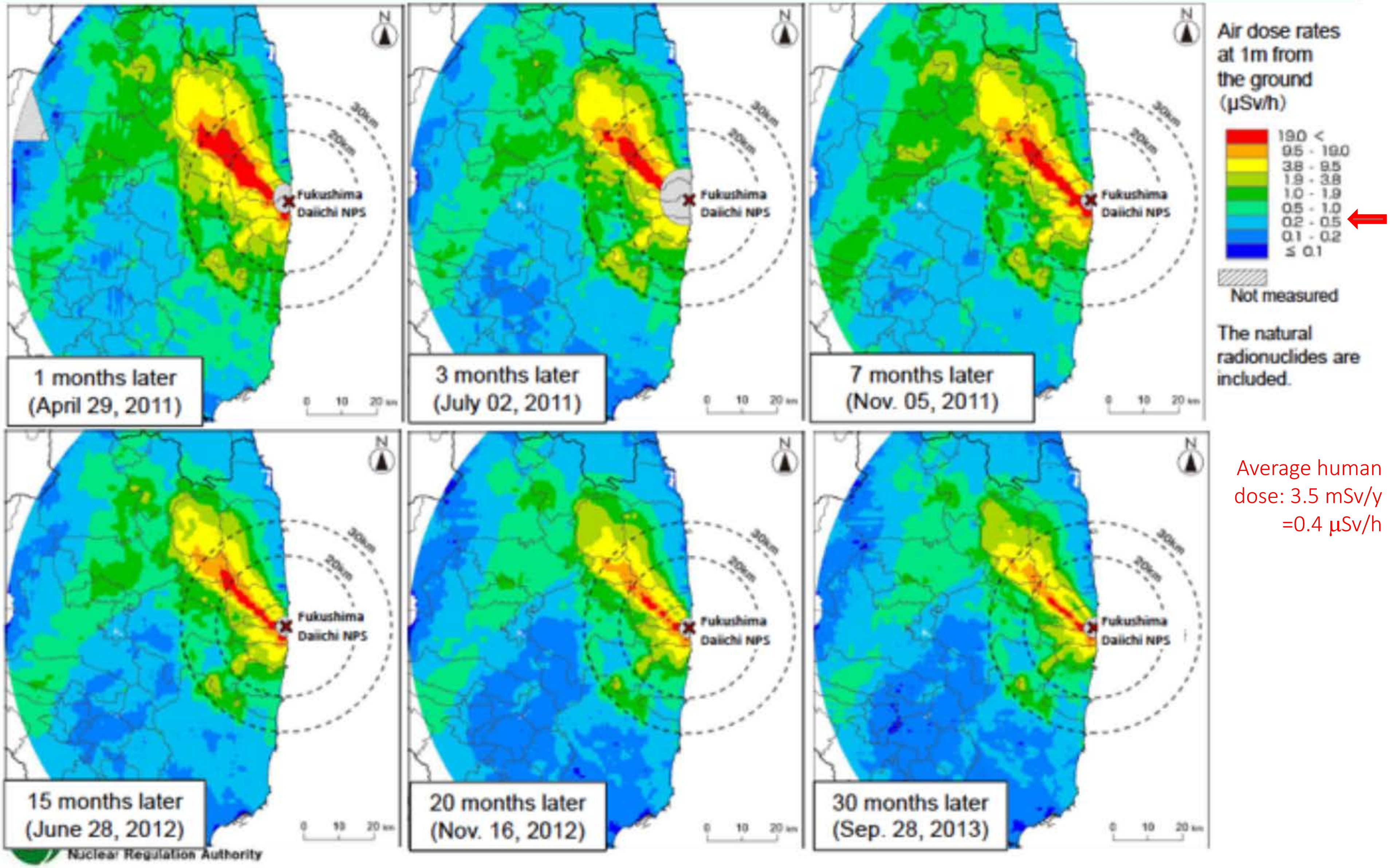


187,000,000,000,000,000,000 Gallons, or **187** quintillion Gallons of water in the Pacific Ocean. This translates to $1.6{\cdot}10^{-14}$ Gallons of radioactive water / Gallons or ocean water

The natural ^{137}Cs activity of ocean water is between 1 and 2 Bq/m^3 (0.001-0.002 Bq/l). With peak values of $3{\cdot}10^4$ Bq/m^{3}or 30 Bq/l, the overall increase by dilution is $5{\cdot}10^{-8}$ %.

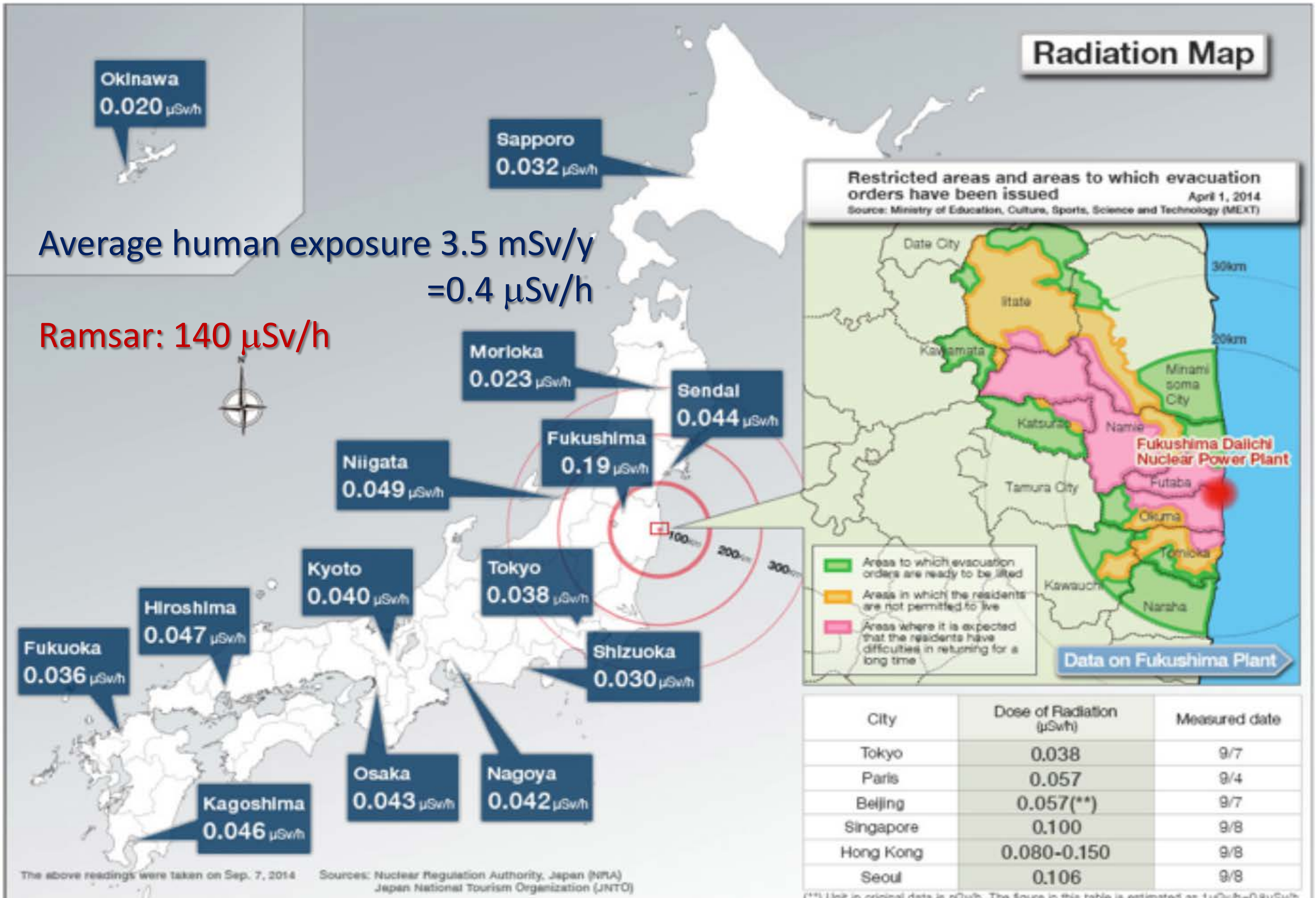
What are the health effects? Available evidence leads the NRC to conclude the Fukushima situation will not affect U.S. public health. For the last six months, radioactive Cesium levels where the Fukushima harbor meets the ocean have been below 10 Bq/L , which is the World Health Organization drinking water standard. The U.S. Environmental Protection Agency's (EPA) limit is 7.41 Bq/L. Seawater sampling at points 30 to 200 km out to sea from Fukushima shows very low Cesium 137 concentrations; typically below .004 Bq/L, compared to pre-accident concentrations of around 0.003 Bq/L. Concentrations nearer to the coast tend to be somewhat higher (about .01- 0.2 Bq/L), well below EPA drinking water standards.

Air dose rates in the 80km zone from Fukushima Daiichi NPS



Average human dose: 3.5 mSv/y =0.4 μSv/h

Contamination of Japan in μSv/h



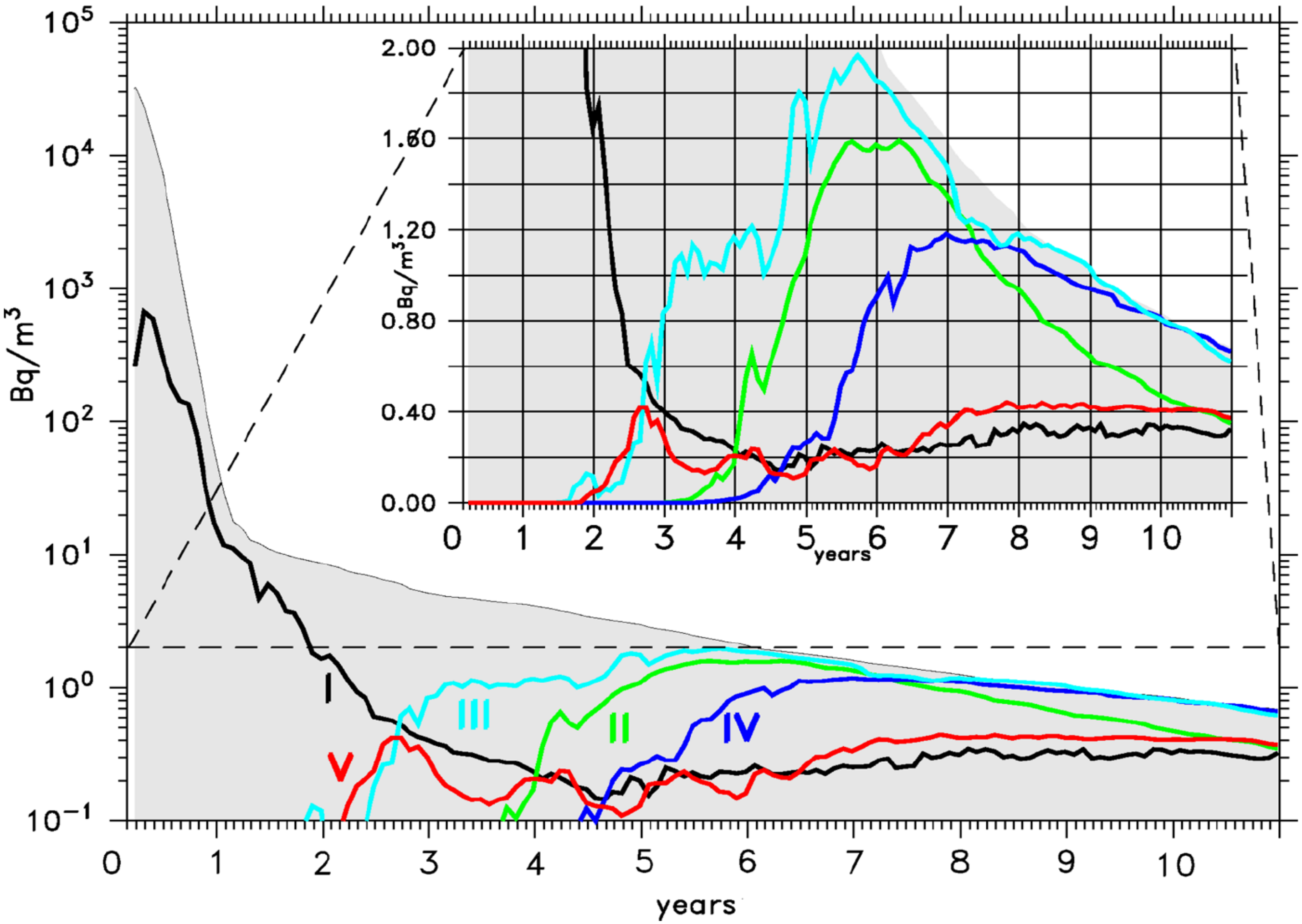
City	Dose of Radiation (μSv/h)	Measured date
Tokyo	0.038	9/7
Paris	0.057	9/4
Beijing	0.057(**)	9/7
Singapore	0.100	9/8
Hong Kong	0.080-0.150	9/8
Seoul	0.106	9/8

(**) Unit in original data is nGy/h. The figure in this table is estimated as 1uGy/h=0.8uSv/h.

Average human exposure 3.5 mSv/y
=0.4 μSv/h

Ramsar: 140 μSv/h

Time evolution of ^{137}Cs $T_{1/2}$=30y



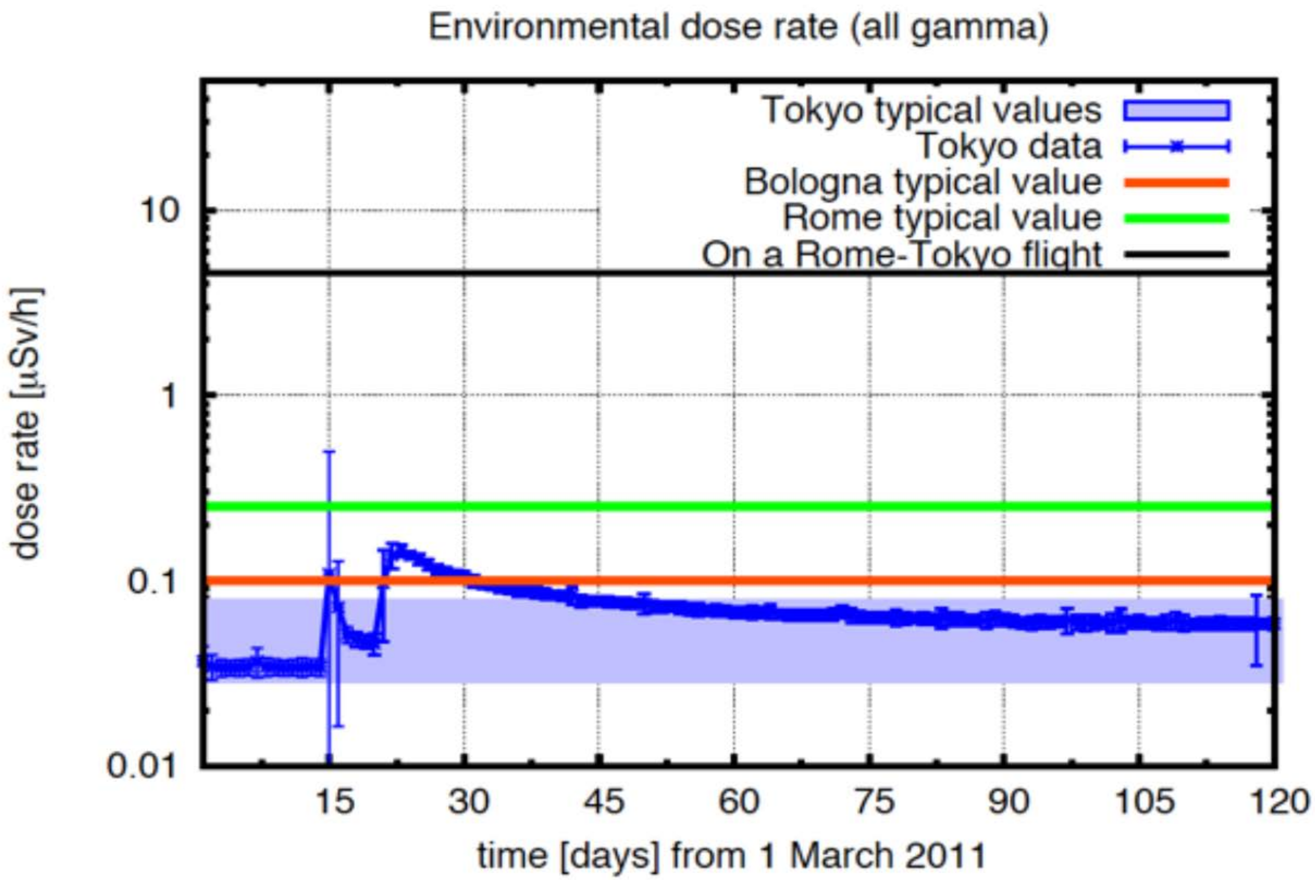
Black: western pacific
Green: North America
Light blue: Hawaii
Dark blue: Baja California
Red: Aleutian Islands
10 PBq peak value

Deposition and Dose

Geographical Location	Effective Dose Estimate in milli-Sievert		
	Adult	Child (10 year old)	Infant (1 year old)
Fukushima City	4.0	4.5	12
Fukushima County	0.24	0.24	0.72
Neighboring Counties	0.024-0.75	0.024-0.75	0.05-1.5
Japan	0-0.25	0-0.25	0-0.67
Europe	7.5×10^{-4}	7.5×10^{-4}	1.25×10^{-3}

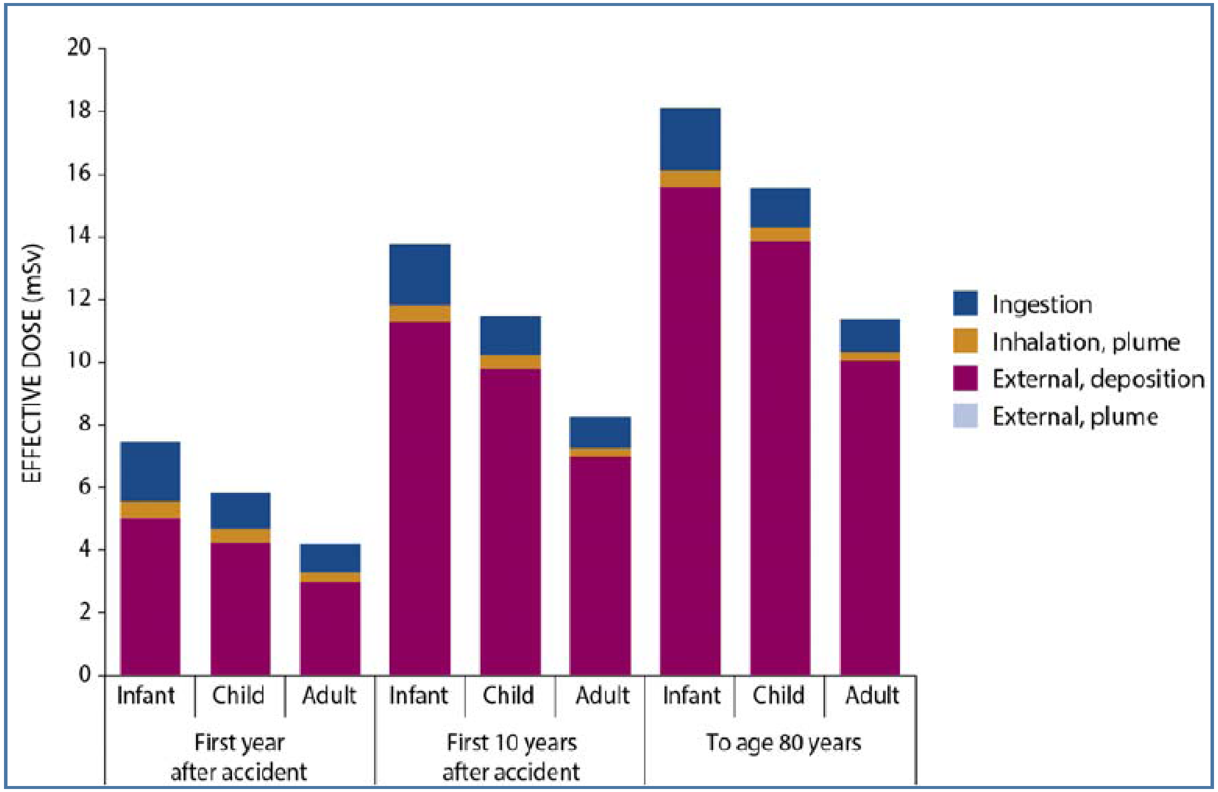
The effective dose resulting from deposited ^{137}Cs for three different age groups at different geographical locations accumulated withing the first year. After the Fukushima event. Die average annual dose of the world population is about 3.5 mSv per person. This indicates that only in the near Fukushima area the dose exceeds the annual average dose of 3.5 mSv.

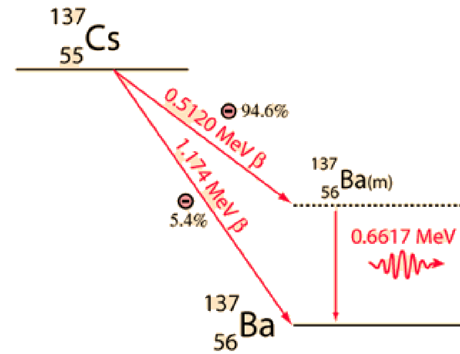
Radioactivity level in Tokyo

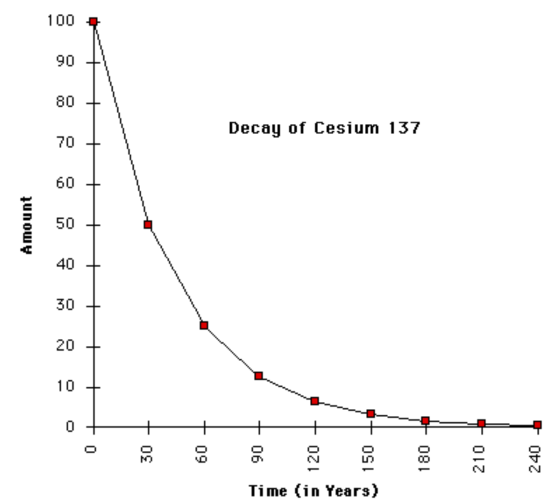


Credit: Alberto Mengoni: "We did not evacuate the Embassy (we remained in Tokyo all the time), but there were people, Italians amongst others, that escaped back from Tokyo to their home countries. In our case, this was not really meaningful from the point of view of radioprotection. The radiation level in Tokyo (environmental gamma-field) remained always below the typical value we have in Rome. I enclose a plot with the actual data.
It is also true that the major of Rome had to issue a press release, after we disclosed the data measured at the Embassy, that stated that "There is no risk due to radioactivity in Rome"."

Long term exposure and dose development

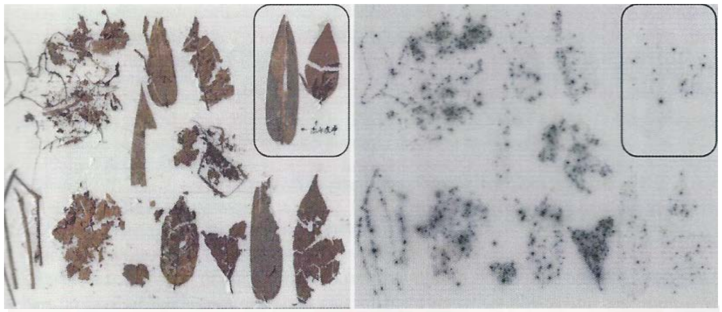


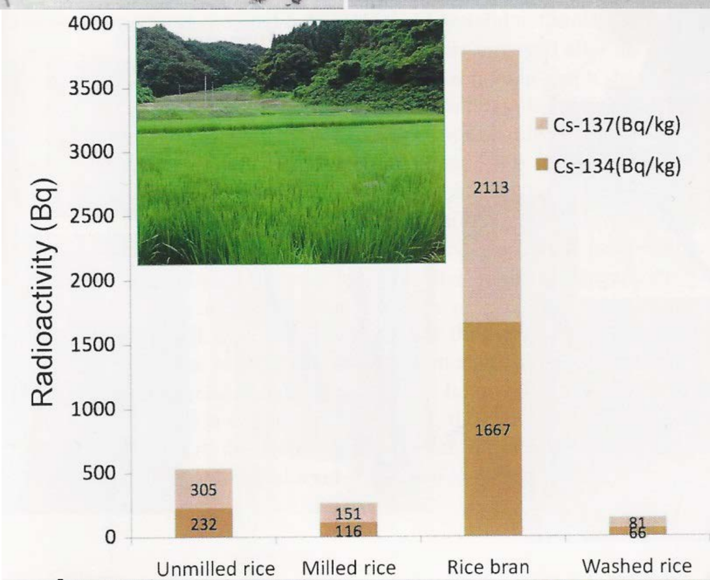


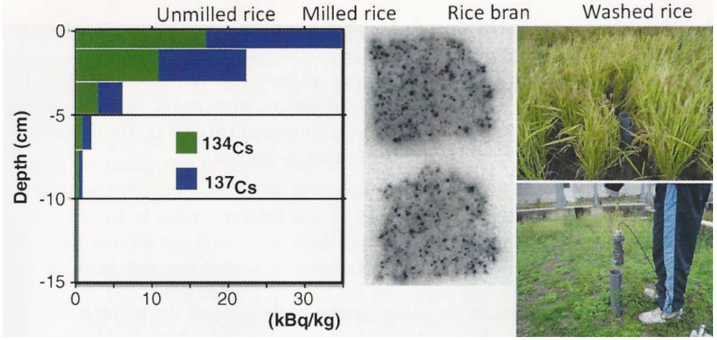


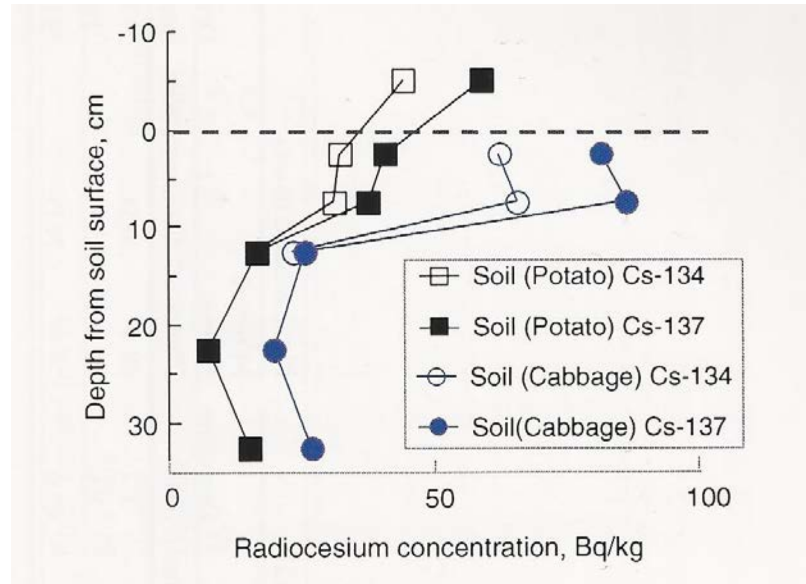
The distribution of exposure for the three population groups within the first year and the first decade after Fukushima and the anticipated dose estimated for a lifetime expectation of 80 years. The first year shows the highest dose, after ten tyears the first year dose is doubled and at age 80 the dose is tripled.

Agricultural effects of ^{137}Cs fall-out

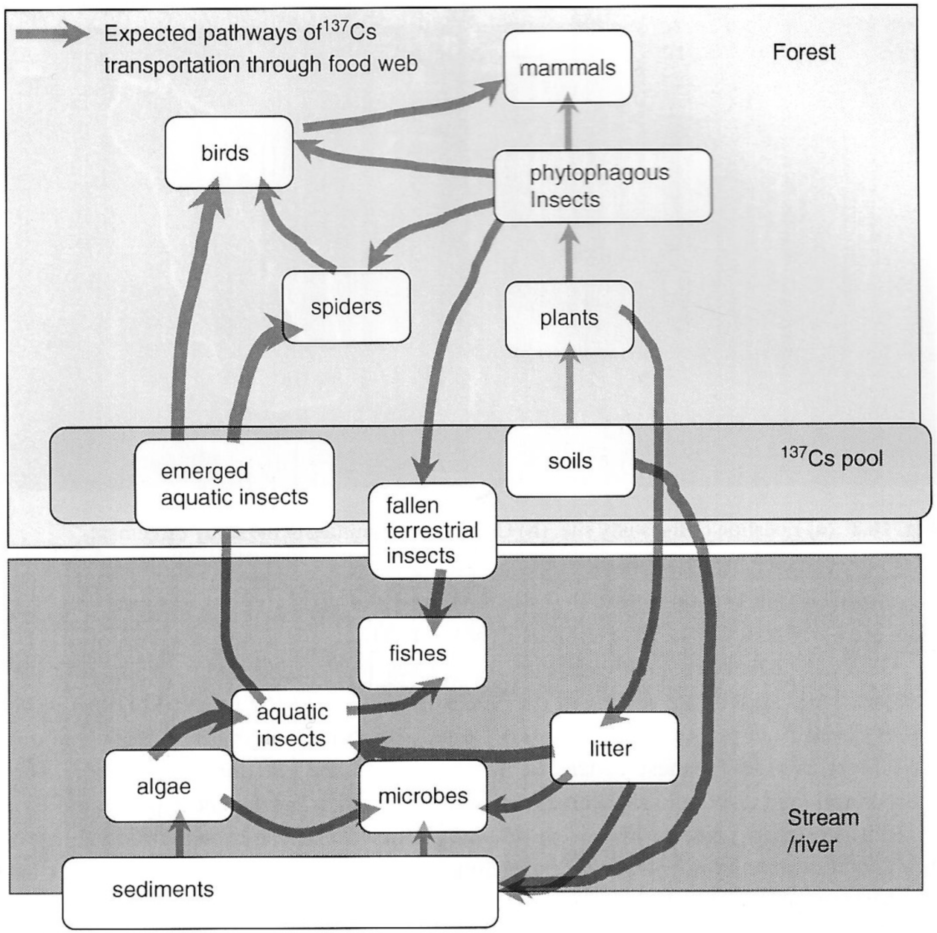


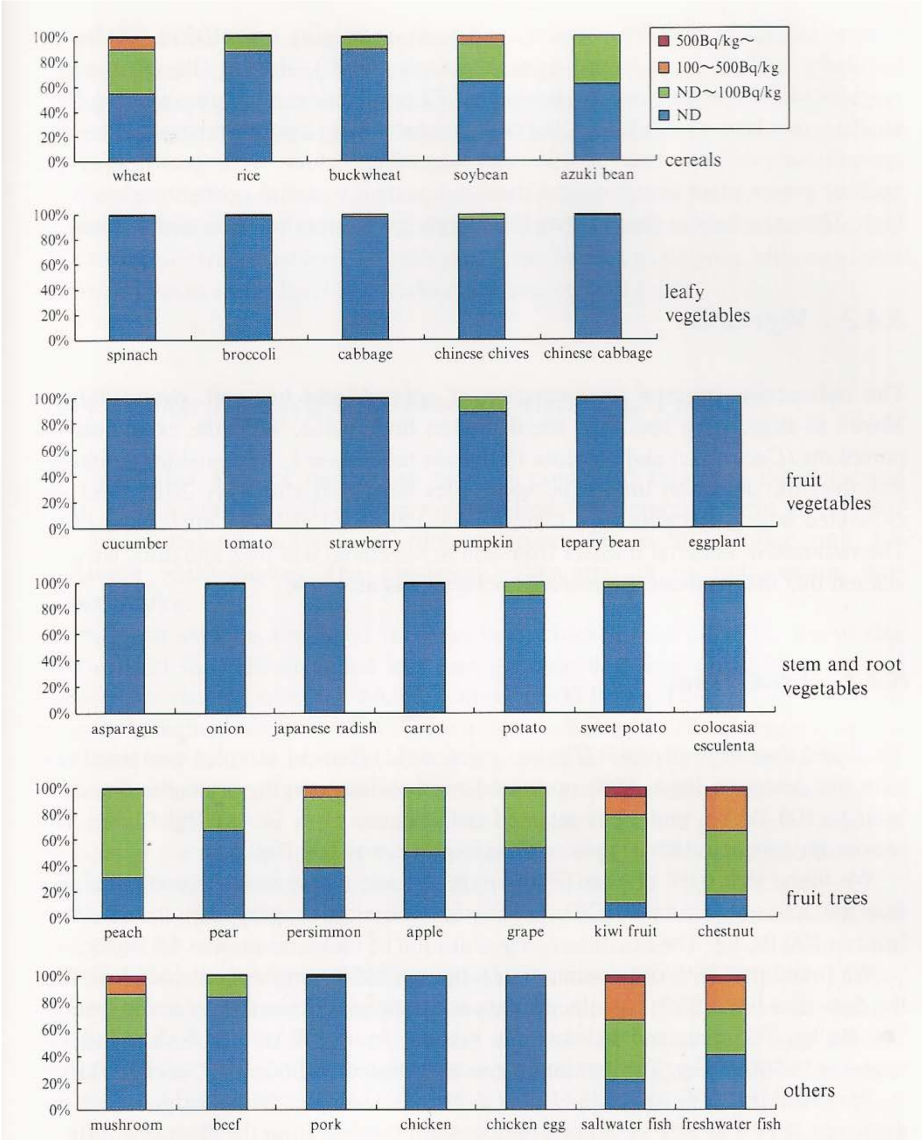




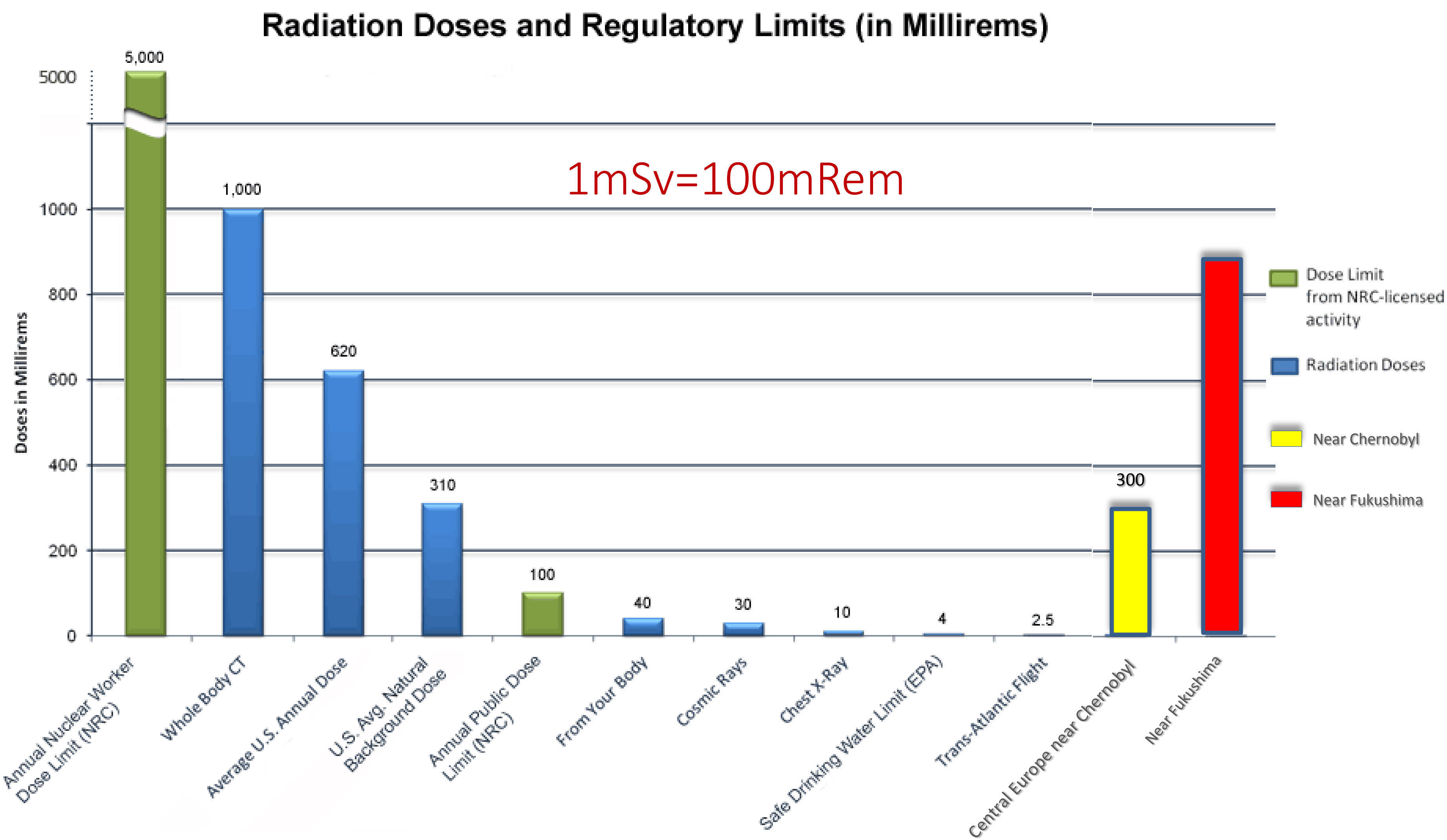


^{137}Cs distribution (within one year after Fukushima event)





Comparison with typical human exposure values



In Summary

- Reactor Accidents are devastating, but unlike nuclear bomb explosions they remain local events!
- They lead to contamination of local area depending on accident and weather conditions!
- The contamination is typically dominated by ^{137}Cs fall-out with a half life of 30 years as confirmed by measurements at Chernobyl and Fukushima.
- Global environmental and health consequences of radioactive fall-out or dispersion are limited!
- Emotional and political fall-out consequences are enormous!