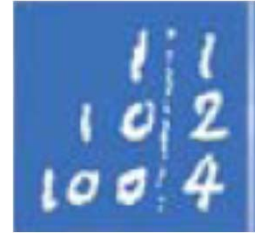




Institut für Radioökologie und Strahlenschutz  
Leibniz Universität Hannover



# The reactor accident of Fukushima Dai-ichi and its radiological consequences for the Japanese population

**Rolf Michel**

80<sup>th</sup> Annual Meeting of the DPG and Spring Meeting,  
Regensburg, 6 - 11 March 2016

# Contents

- **Fukushima Dai-ichi: the plant and the reactor accidents**
- **Releases of radionuclides, transport, and fallout**
- **Dose estimates by UNSCEAR (2014)**
- **A closer look to the radiation exposure in Northern Japan**
  - **Radiation exposures of the thyroid gland**
  - **External radiation exposures in Japan**
  - **Internal radiation exposures in Northern Japan**
- **Health effects**
  - **Casualties among the workers in Fukushima**
  - **Radiation induced effects in the population**
  - **Psychological and social consequences**
- **Comparison of the Fukushima and Chernobyl accidents**



**More than 15,854 deaths and 3,155 missing in Northern Japan as a consequence of the quake (M9,0) and the tsunami on 11.3.2011. (status as of 10.3.2012).**

**Initially, 380,000 evacuees Japan as a consequence of the quake and the tsunami.**

**More than 340,000 evacuees lived still in emergency accommodations in March 2012.**

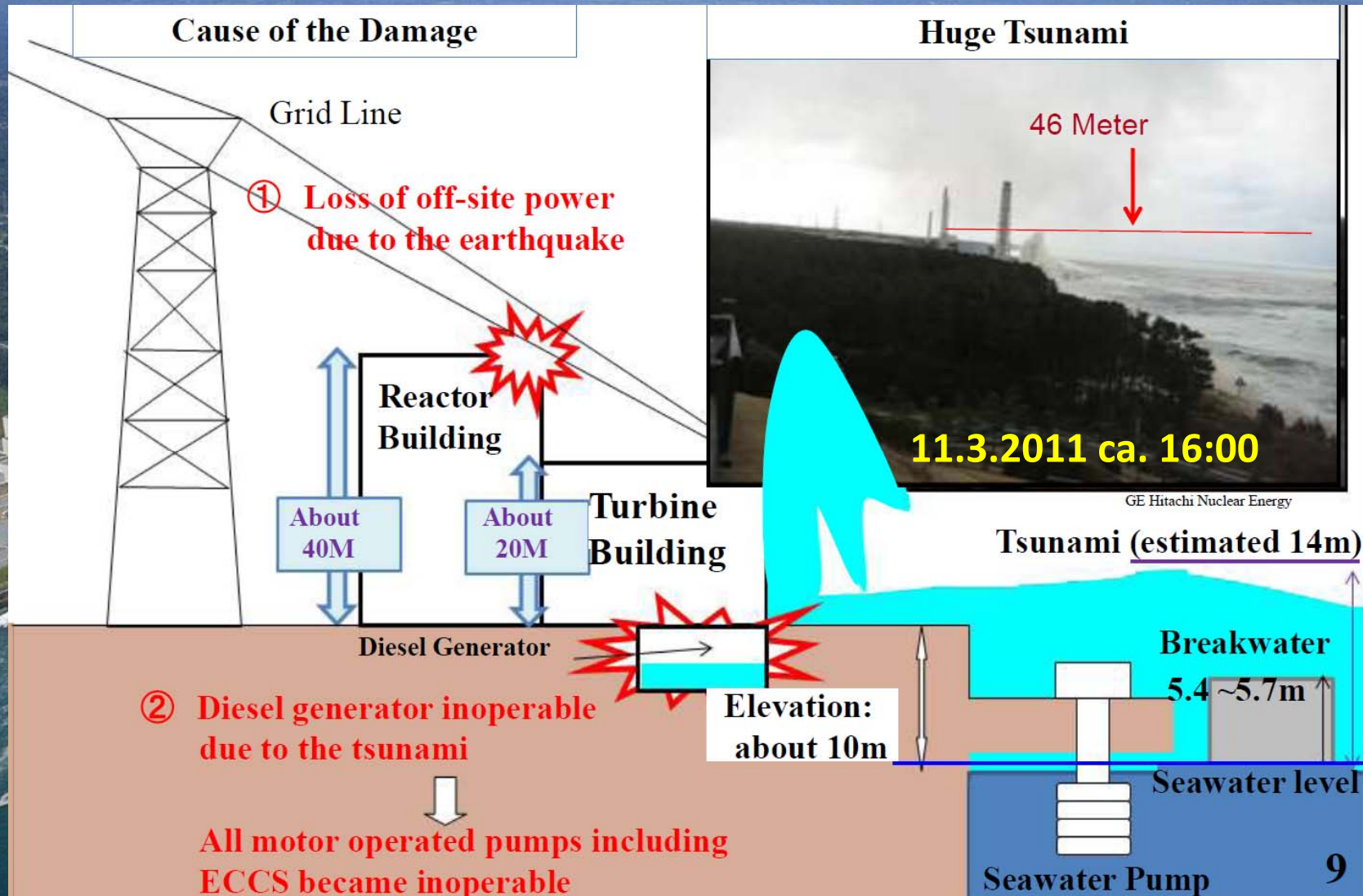
**Left: the destroyed town Onagawa in the prefecture Miyagi**

**photo: 13 March 2011. EPA/BGNES**

**R. Michel, IRS, Leibniz Universität Hannover**

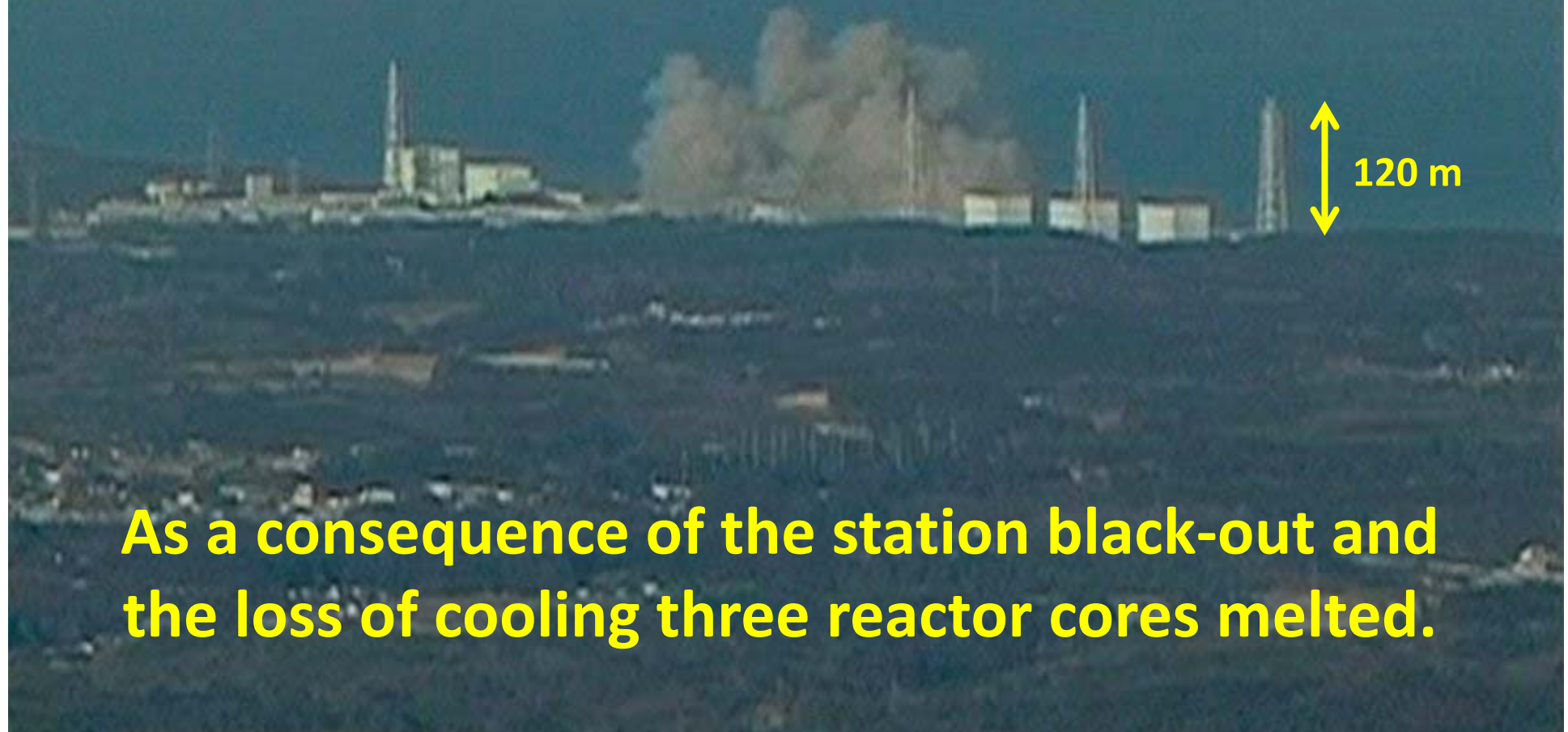
# Fukushima Dai-ichi Nuclear Power Plant

designed to withstand quakes M8 and 5,7 m high tsunamis



TEPCO Tokio Electric Power Company

# Explosion of Unit 1 in Fukushima Dai-ichi on March 12, 2011 16:00



As a consequence of the station black-out and  
the loss of cooling three reactor cores melted.

# 14.03.2011 11:00 LT Explosion of Unit 3



Nhk, 14.3.2011

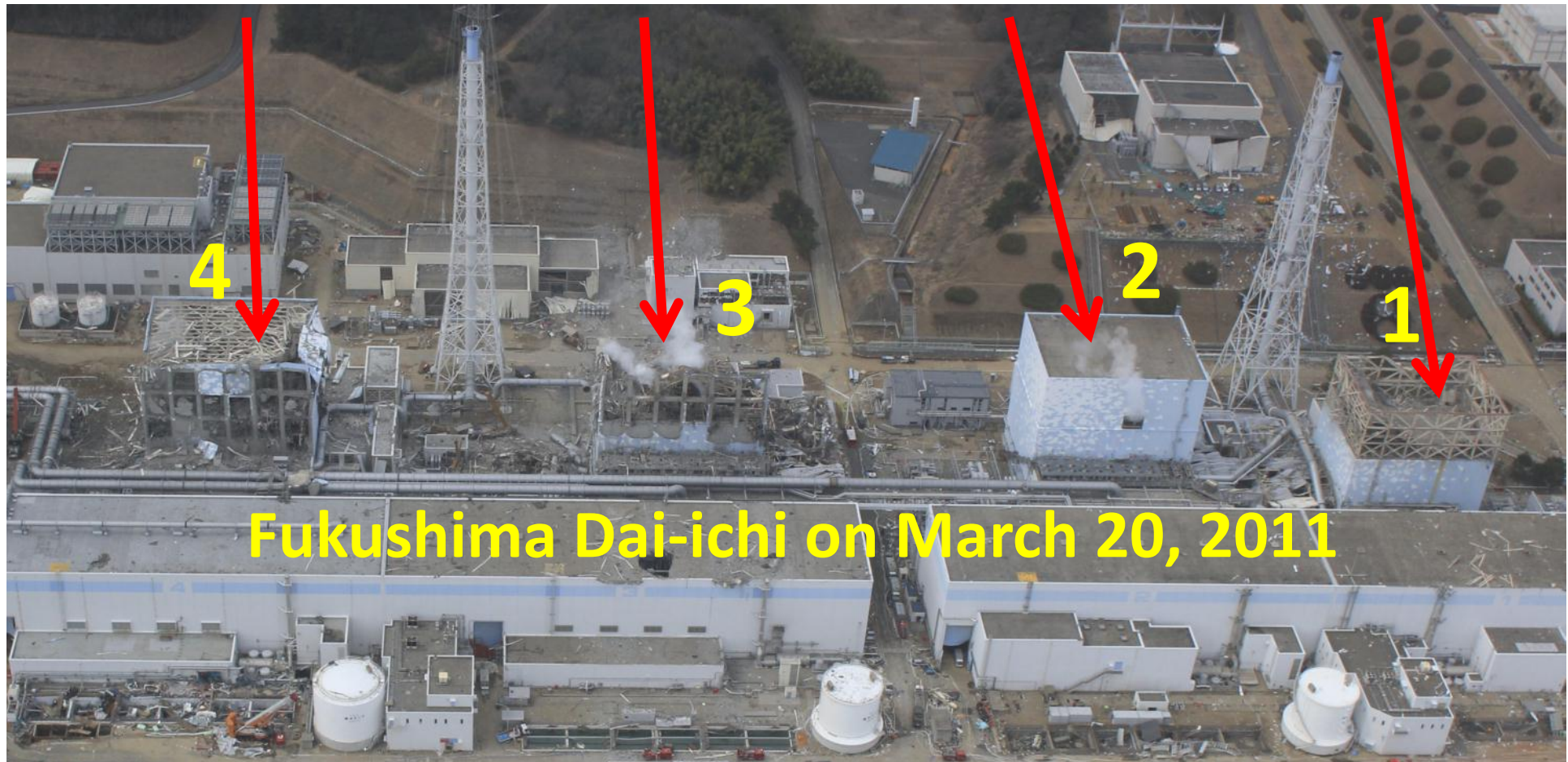
R. Michel, IRS, Leibniz Universität Hannover

15.3.2011 approx. 6:00  
hydrogen explosion in the  
building, H<sub>2</sub> likely to come  
from Unit 3

14.3.2011 11:01  
hydrogen explosion  
below the service  
platform

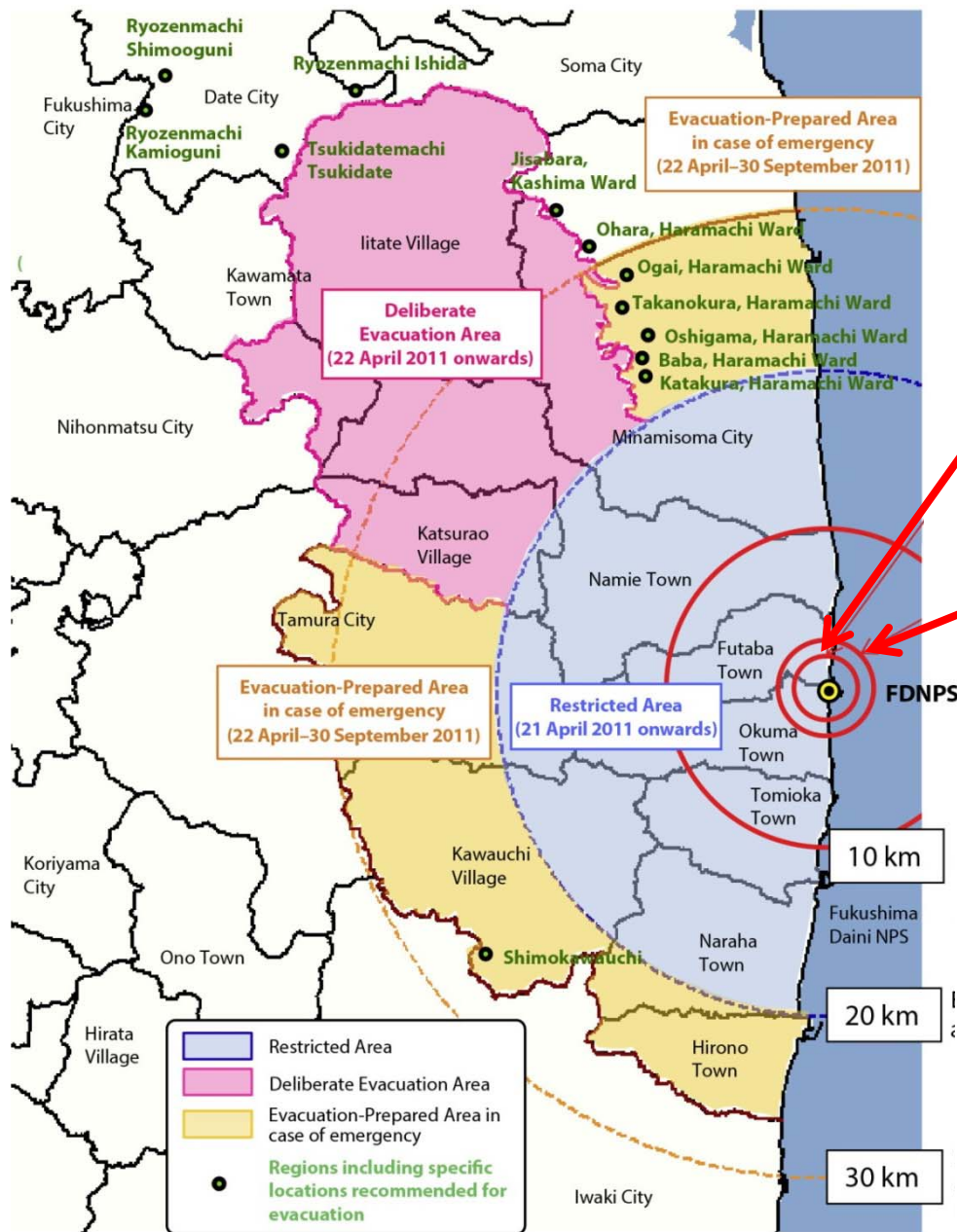
15.3.2011 6:10  
hydrogen explosion (?)  
@ low height of D/W;  
containment failure

12.3.11 ca. 15:36  
hydrogen explosion  
on the service  
platform



**3 core melt-downs (Units 1 – 3) and 4 (?) hydrogen explosions (Units 1 – 4)  
after breakdown of electricity and cooling as a consequence of quake &**

**Air Photo Service Co. Ltd., Japan, 20.3.2011** **Tsunami.** R. Michel, IRS, Leibniz Universität Hannover



## Areas subject to measures to protect the public (as of 3 August 2011). All times are JST.

2 km Evacuation  
at 20:20, 11 March 2011  
by Fukushima Prefecture

3 km Evacuation  
at 21:23, 11 March 2011

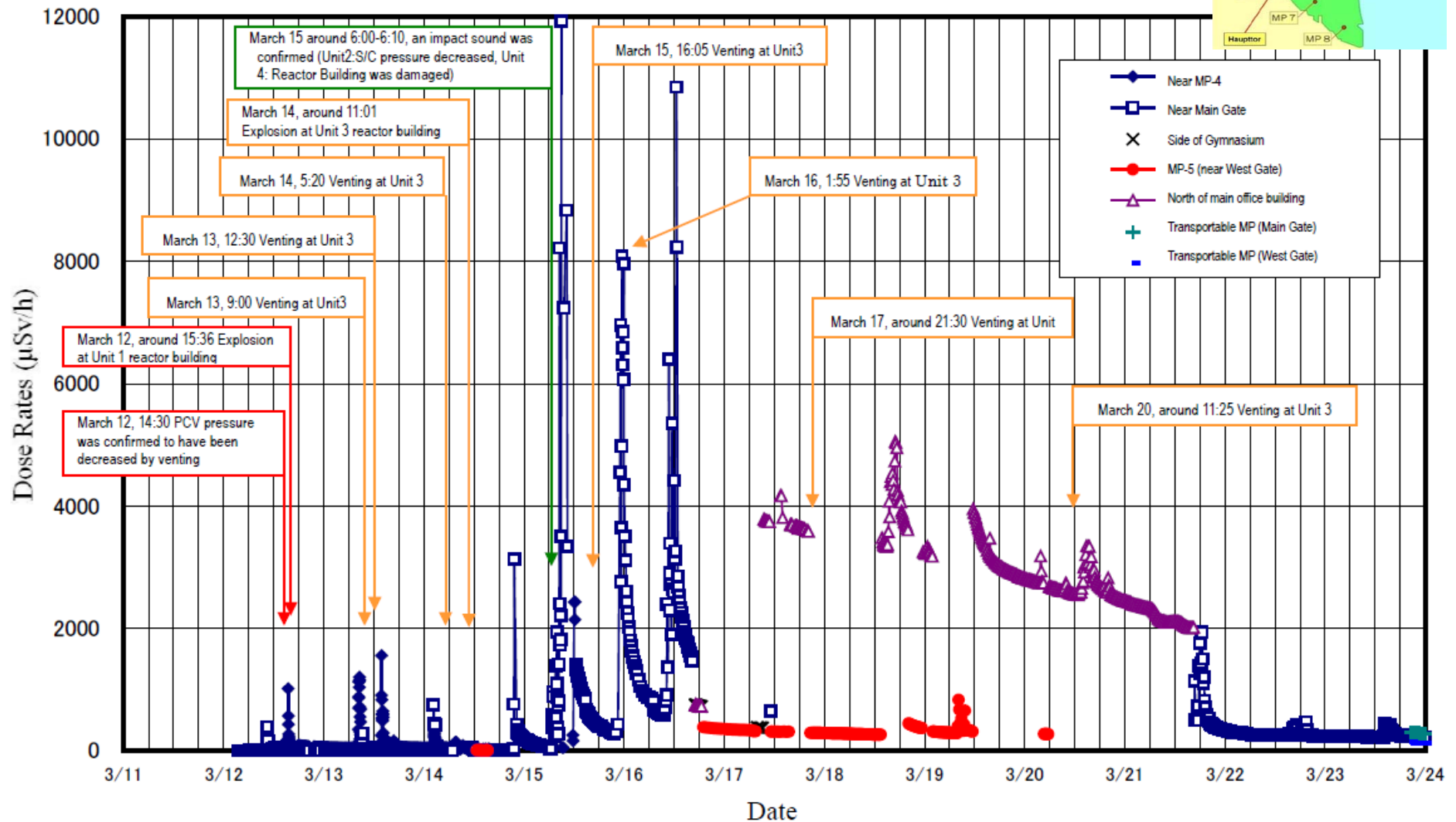
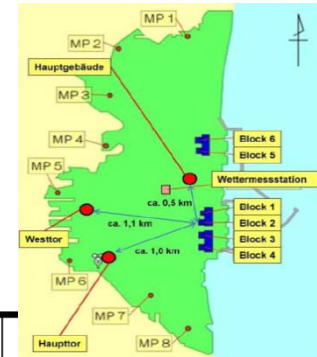
10 km Sheltering  
at 21:23, 11 March 2011

20 km Evacuation  
at 18:25, 12 March 2011

30 km Sheltering  
around 11:00, 15 – 22 April 2011



# Changes in Ambient Dose Rates on the Premises of the Fukushima Dai-ichi NPP (Monitoring Car)

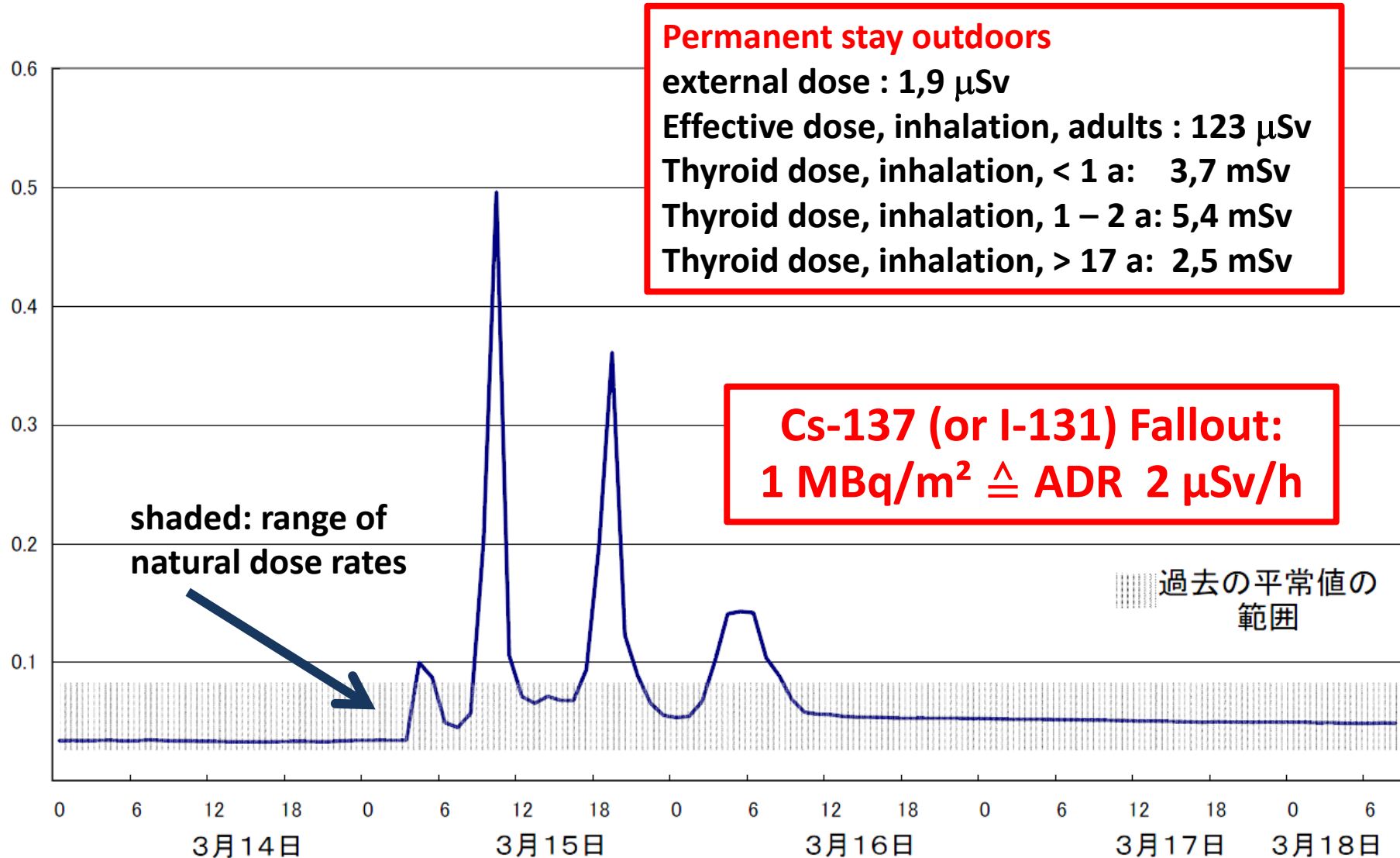


# The East-Asia High mostly was in favor of the Japanese.

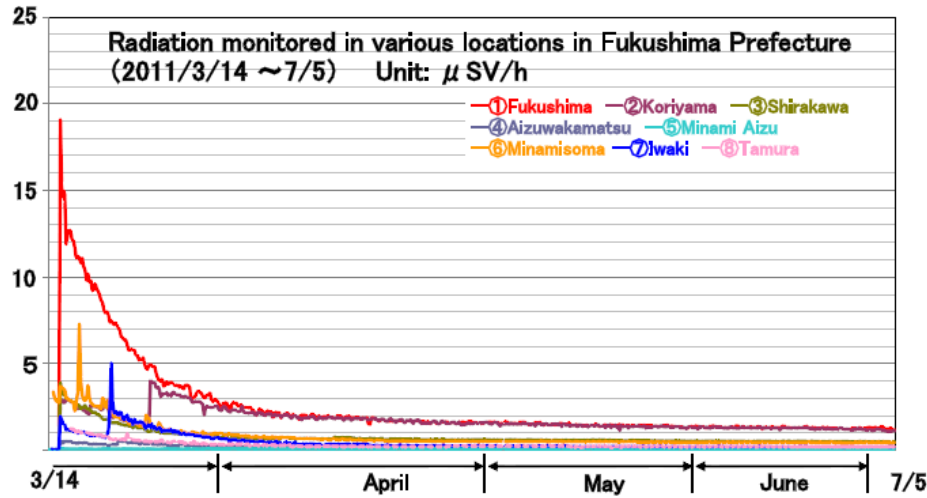
## Predicted wind directions



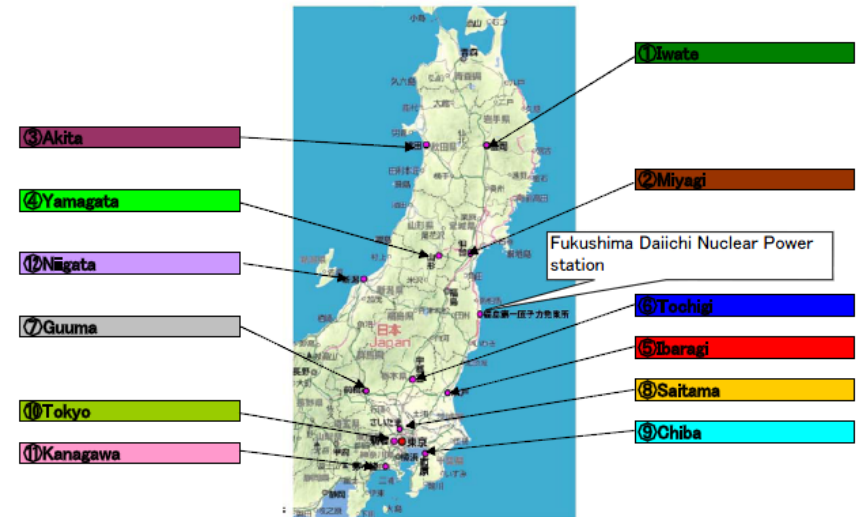
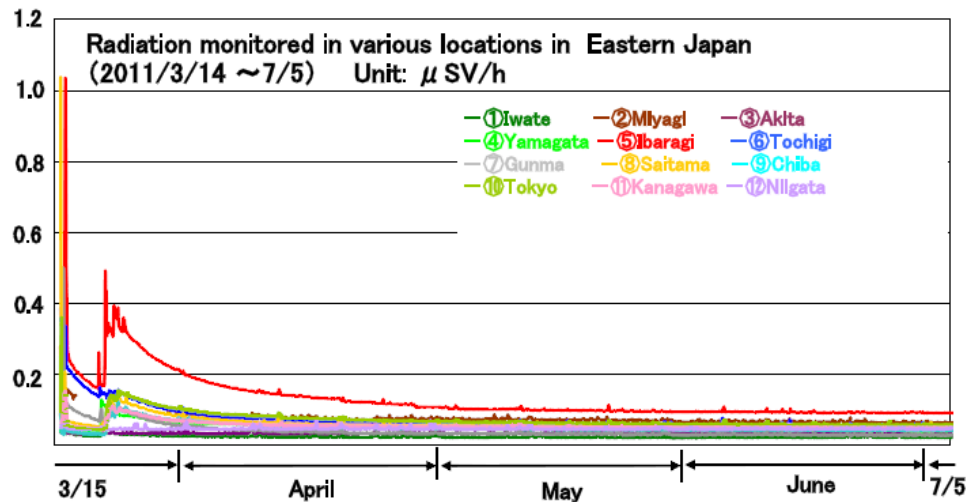
# Ambient dose rates in $\mu\text{Sv/h}$ in **Tokyo** 14. – 17. March during the passage of radioactive clouds



# Ambient dose rates in Fukushima Prefecture (top) and in other prefectures (bottom)

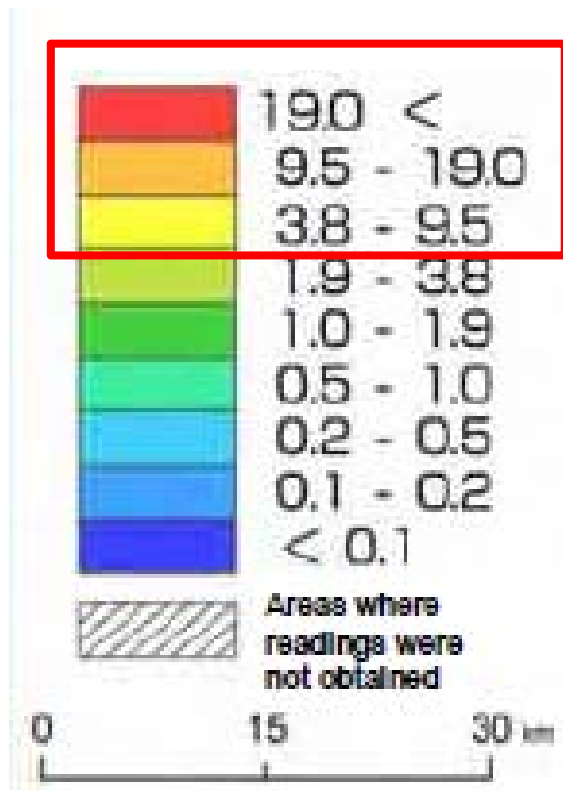


Locations for monitoring



# Ambient dose rates in $\mu\text{Sv/h}$

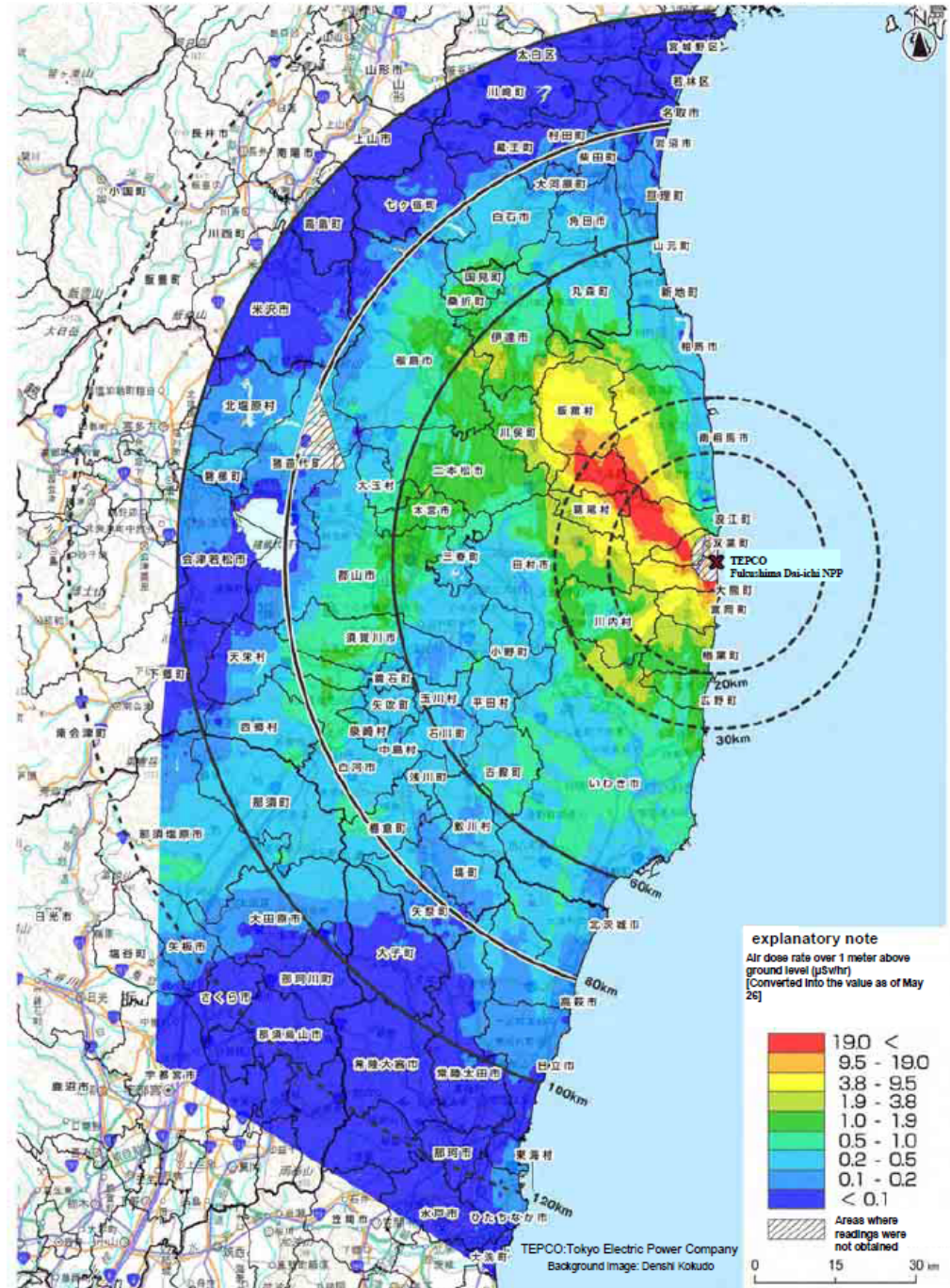
Reference date 26.5.2011



MEXT & DOE 16.6.2011

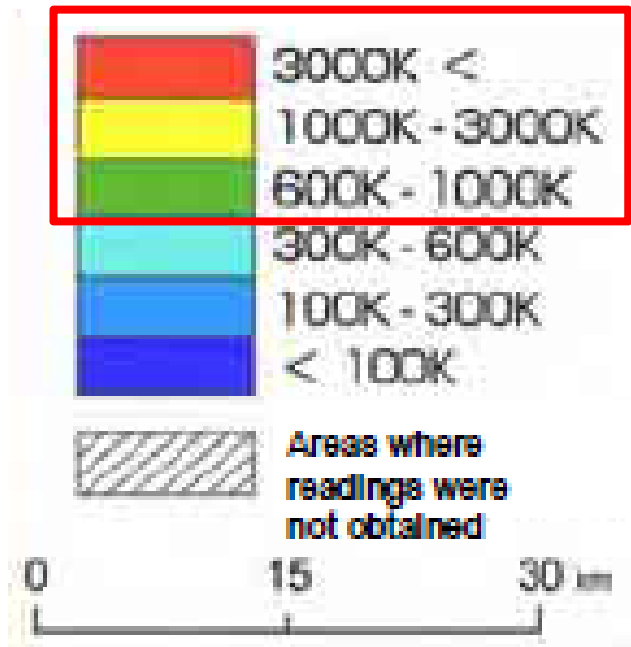
Results of airborne monitoring by MEXT and DOE  
(Readings of air dose monitoring inside 100km zone of TEPCO Fukushima Dai-ichi NPP)

Annex 1

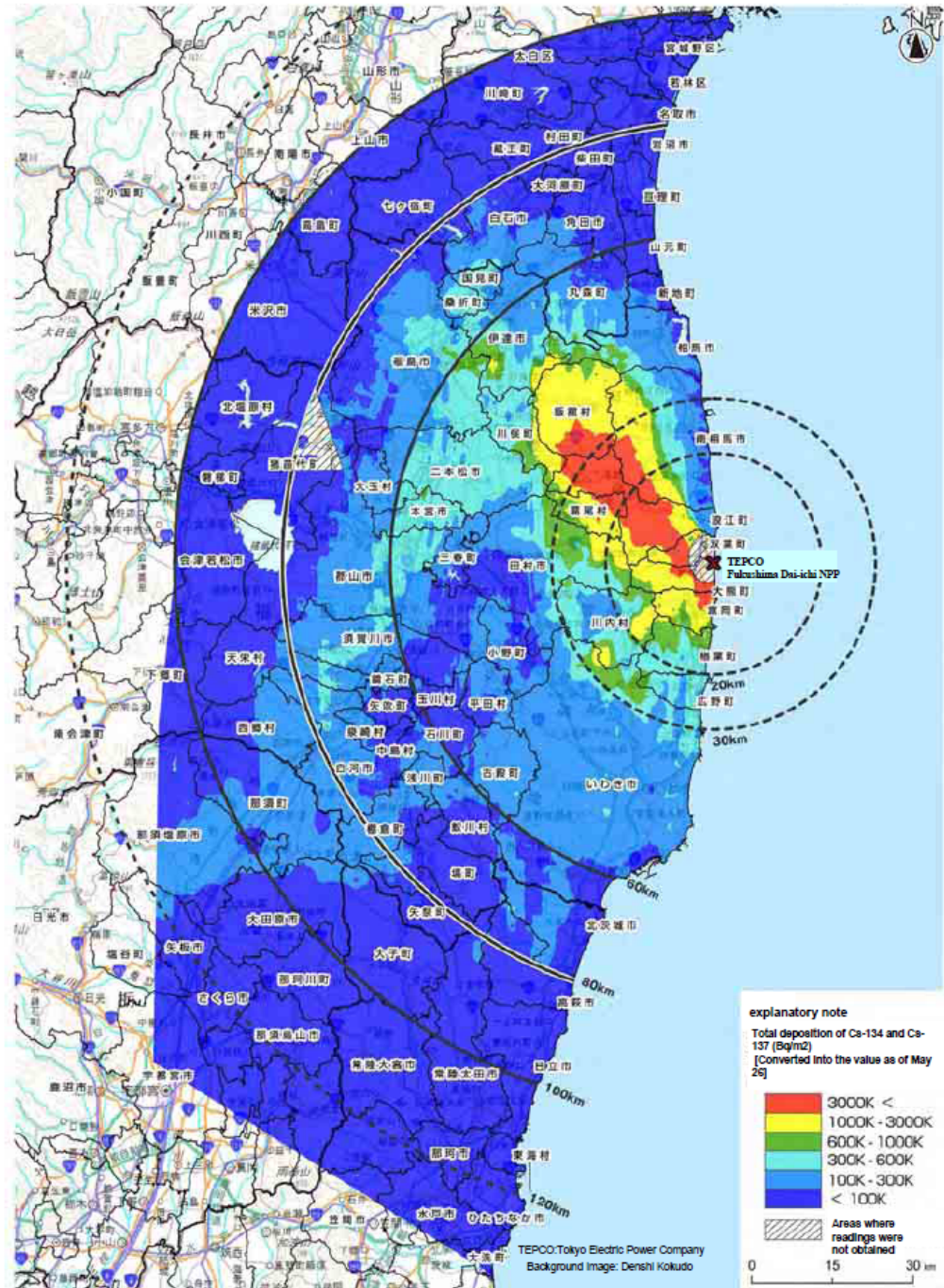


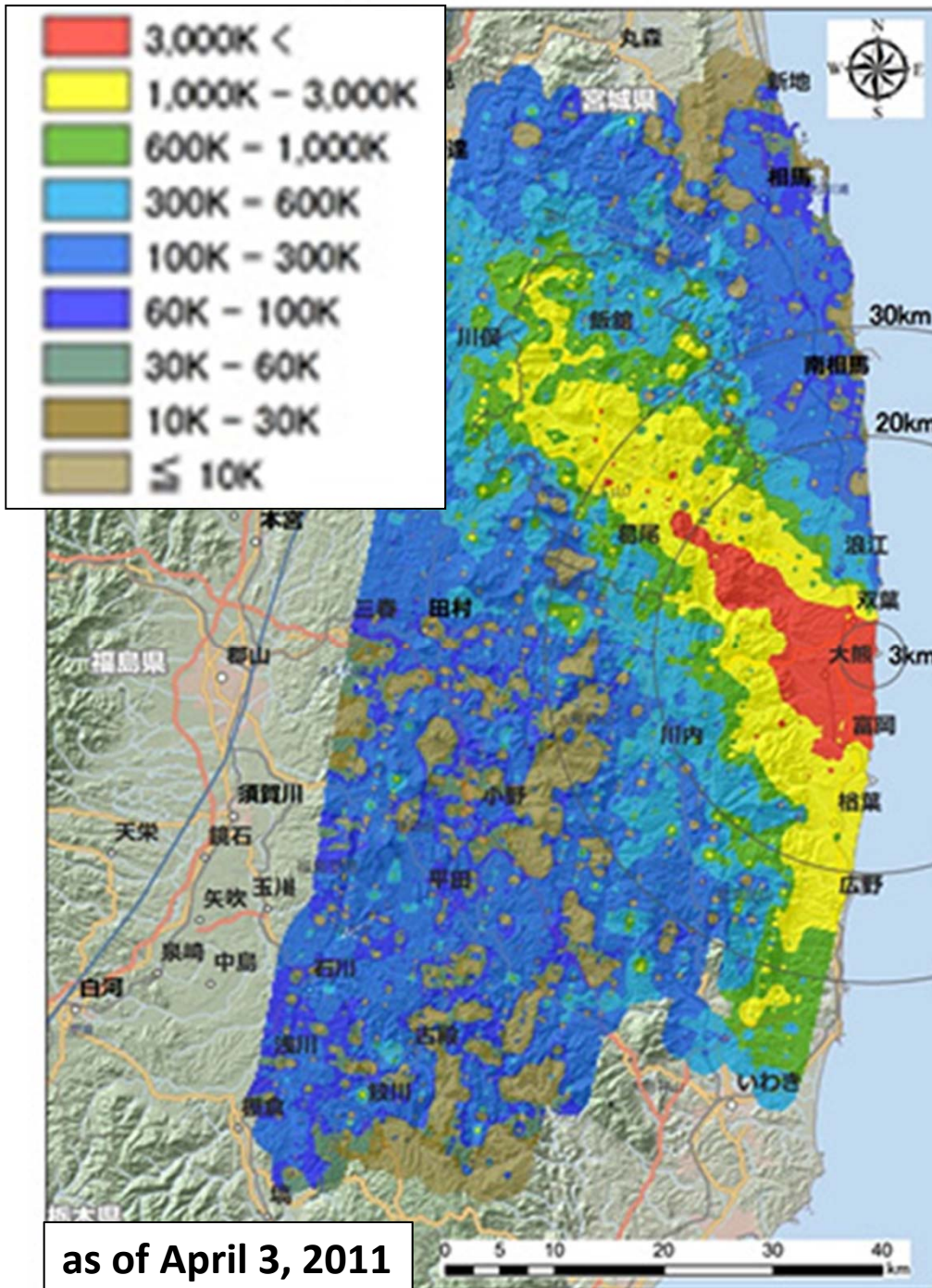
# Cs-134 + Cs-137 Deposition in Bq/m<sup>2</sup>

Reference date 26.5.2011



MEXT & DOE 16.6.2011





I-131 ( $T_{1/2} = 8$  days)  
deposition density in  
Bq/m<sup>2</sup>

*nhk 28.6.2013: “Researchers from the Japan Atomic Energy Agency and the US Department of Energy analyzed radiation data they jointly gathered using aircraft in April 2011.”*

<http://ex-skf.blogspot.de/2013/06/jaea-and-us-dept-of-energy-maps-of.html>, 28.6.2013

R. Michel, IRS, Leibniz Universität Hannover

# Sr-89 ( $T=50,5$ d) and Sr-90 in Fukushima (Reference date 30.9.2011)

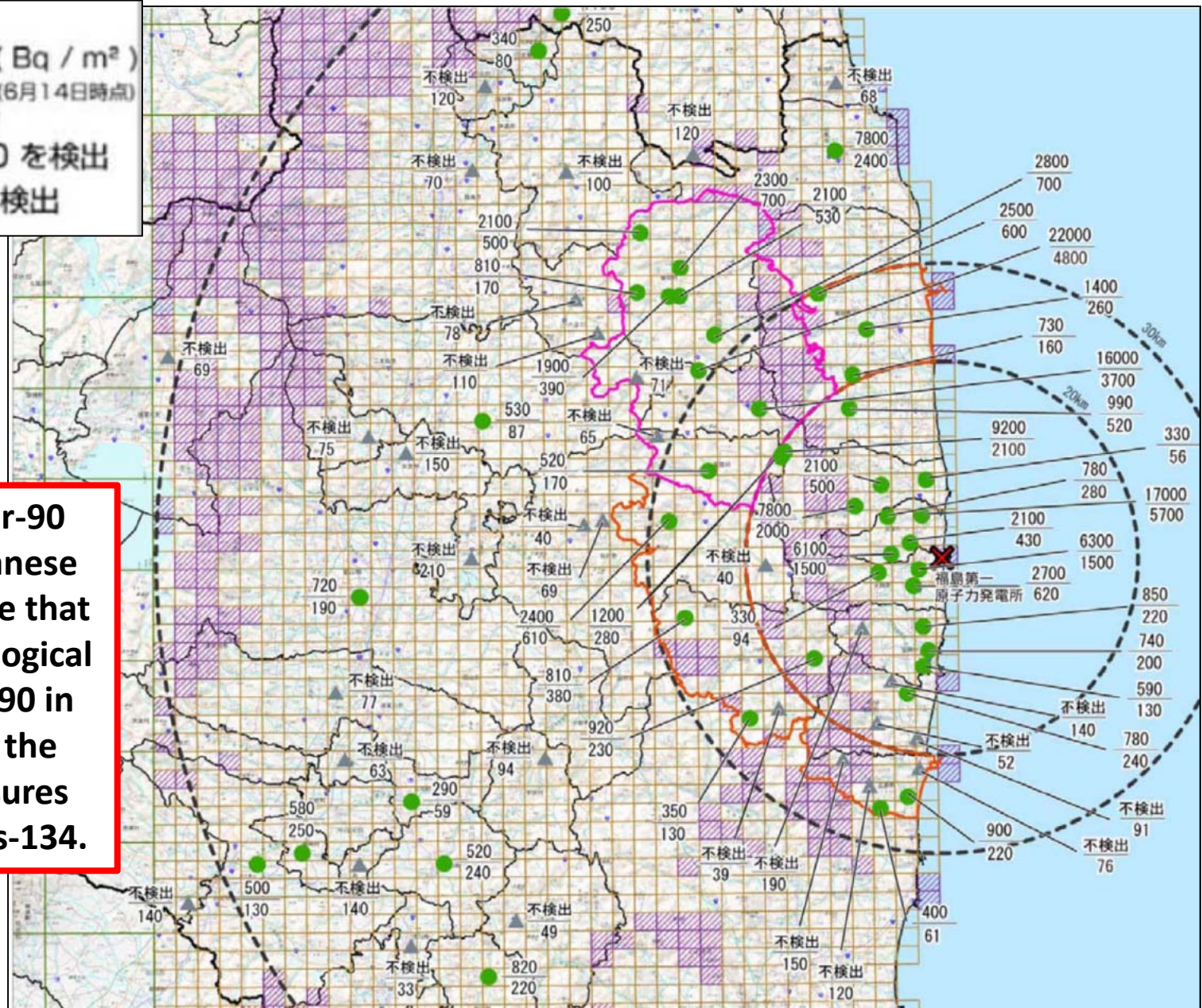
Sr - 89 及び  
Sr - 90の沈着量( Bq / m<sup>2</sup> )  
(6月14日時点)

● Sr - 89 及び  
Sr - 90 を検出

▲ Sr - 90 のみ検出

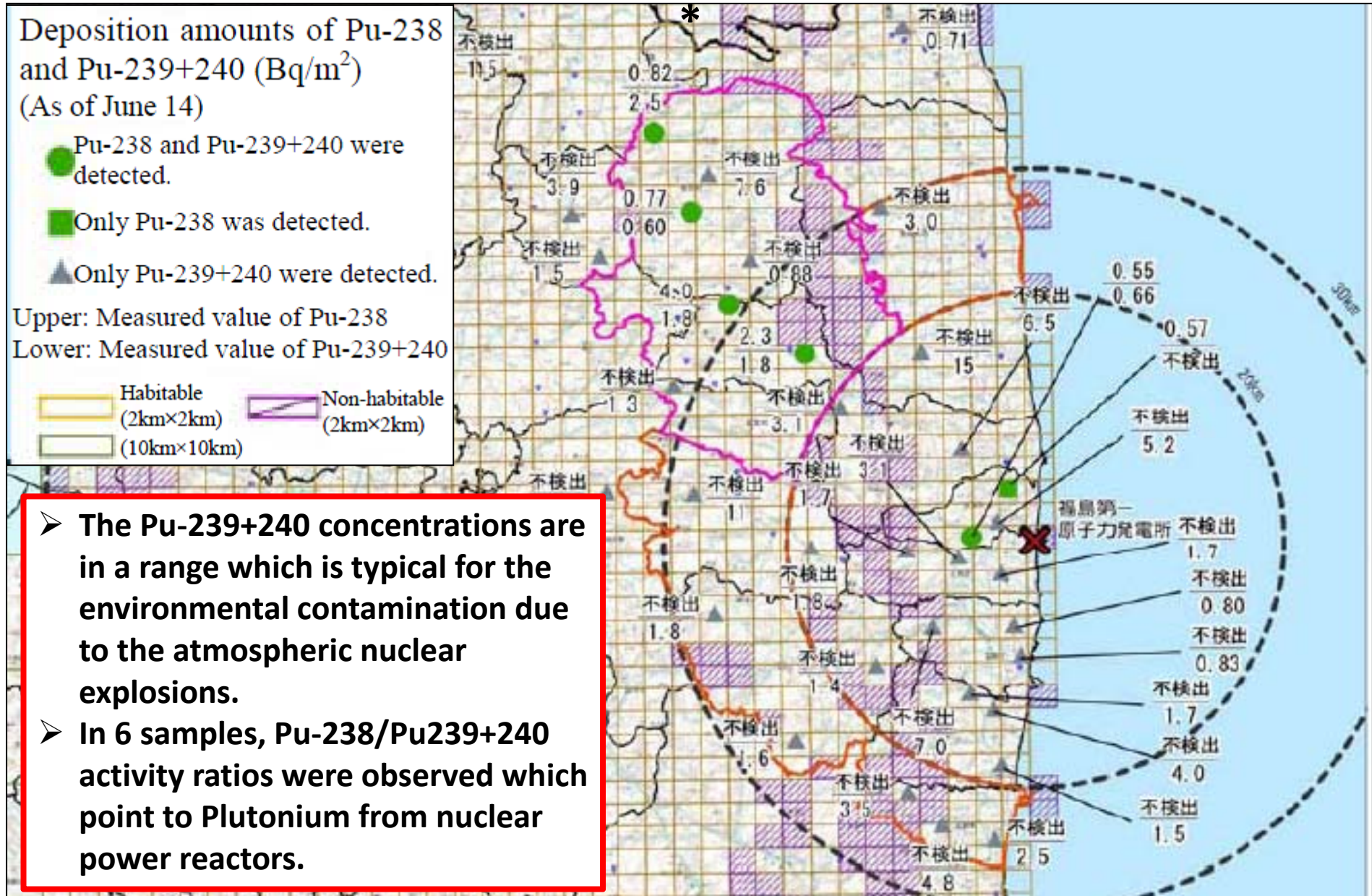
(Bq/m<sup>2</sup>)

The results of Sr-90 analyses of Japanese soils demonstrate that there is no radiological relevance of Sr-90 in comparison to the radiation exposures from Cs-137 & Cs-134.



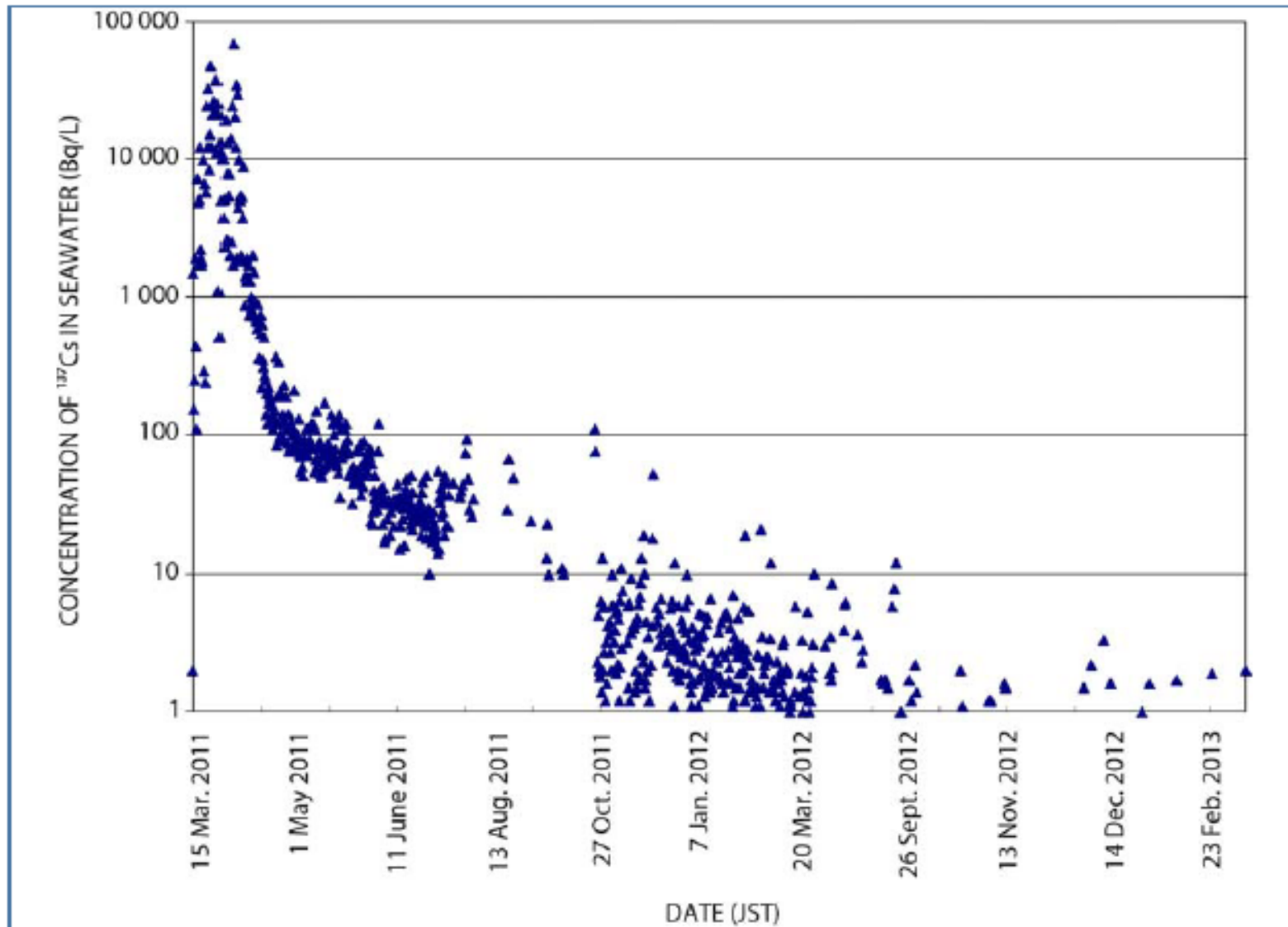


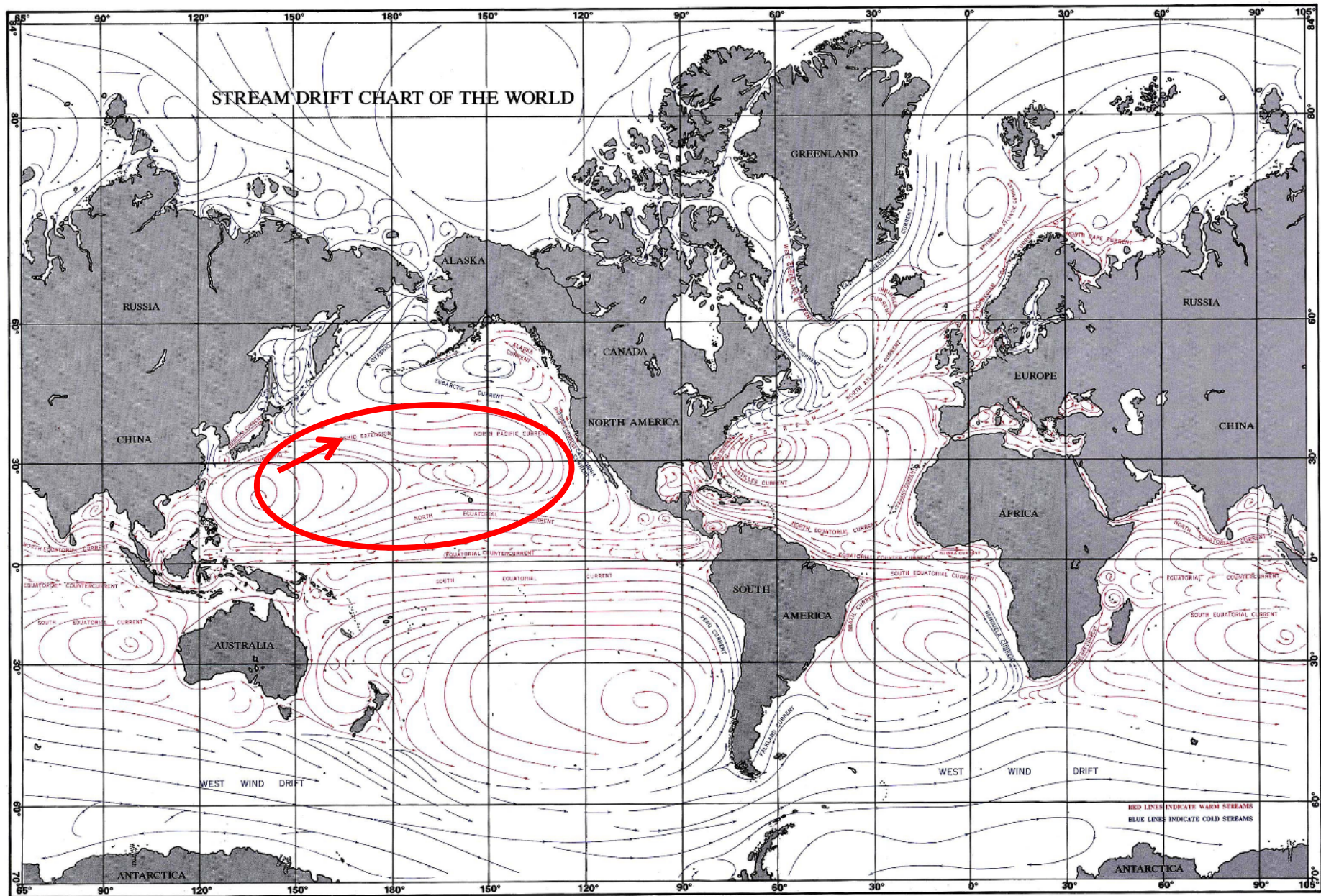
# Deposition densities (Bq/m<sup>2</sup>) of Pu-238 and Pu-239+240



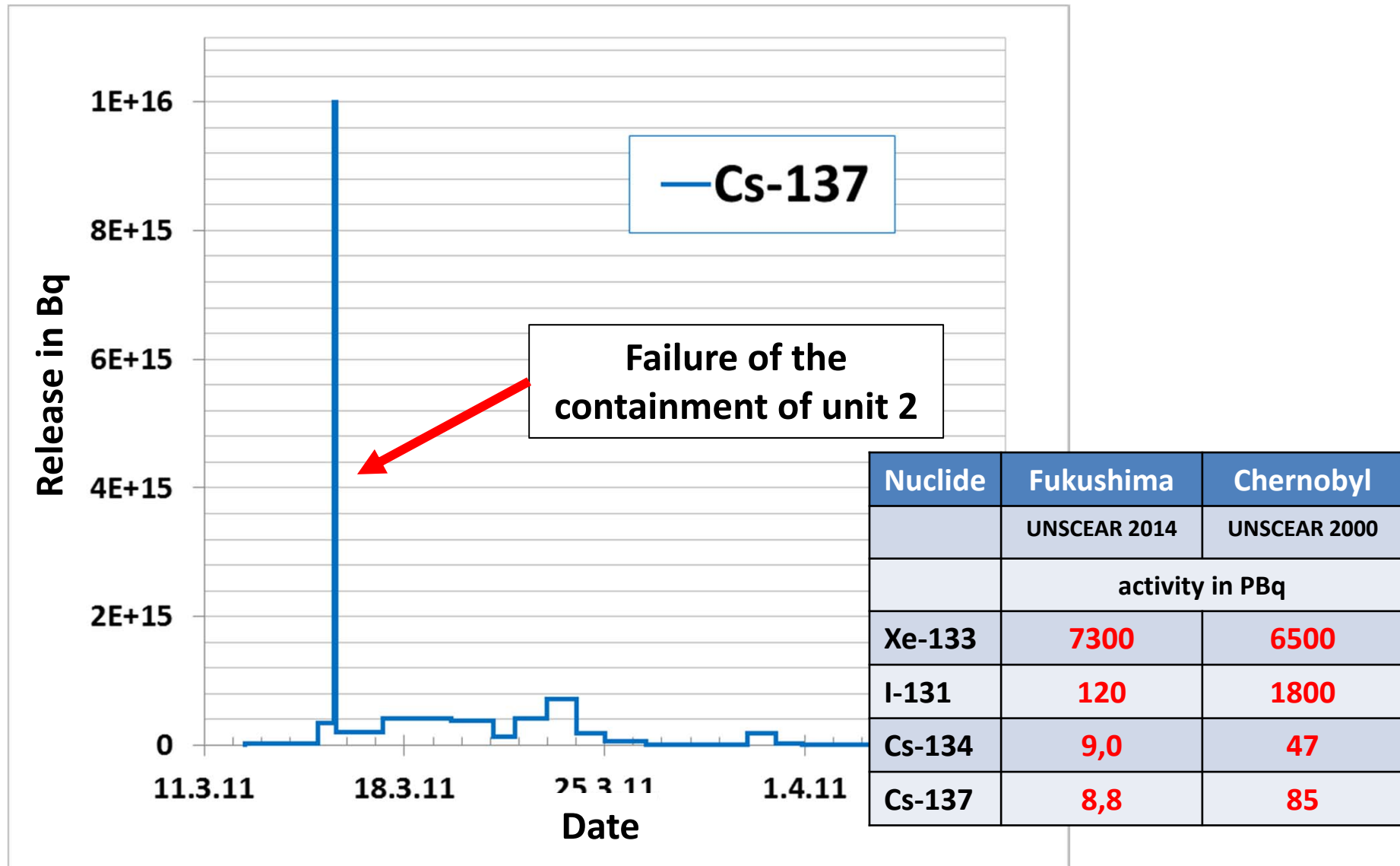
- The Pu-239+240 concentrations are in a range which is typical for the environmental contamination due to the atmospheric nuclear explosions.
- In 6 samples, Pu-238/Pu239+240 activity ratios were observed which point to Plutonium from nuclear power reactors.

# Measured Cs-137 radioactivity concentrations in seawater near the FDNPS





# Dependence on time of Cs-137 releases from Fukushima



United Nations Scientific Committee on the Effects of Atomic Radiation

SOURCES, EFFECTS AND RISKS OF IONIZING RADIATION  
**UNSCEAR 2013 Report**

**Volume I**

REPORT TO THE GENERAL ASSEMBLY

SCIENTIFIC ANNEX A:

Levels and effects of radiation exposure due to the nuclear accident  
after the 2011 great east-Japan earthquake and tsunami



UNITED NATIONS

**We skip all early dose  
estimates and go directly to:**

**UNSCEAR**

**UNITED NATIONS  
New York, April 2014**

Range of estimated average **absorbed doses to the thyroid to adults and to 1-year-old infants** for typical residents of Japan following the Fukushima accident

Residential area	Thyroid absorbed dose in mGy	
	adults	1-year old
Prefecture Fukushima not evacuated	<b>7,8 – 17</b>	<b>33 – 52</b>
Precautionary evacuated settlements: Fotuba, Okuma, Tomioka, Naraha, Hirono, parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	<b>7,2 – 34</b>	<b>15 – 82</b>
Deliberately evacuated settlements; litate village and parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	<b>16 – 35</b>	<b>47 – 83</b>
Six neighboring prefectures: Miyagi, Yamagata, Niigata, Gunma, Tochigi, Ibaraki	<b>0,6 – 5,1</b>	<b>2,7 – 15</b>
40 other prefectures in Japan	<b>0,5 – 0,9</b>	<b>2,6 – 3,3</b>

**Ranges of estimates for districts, biased by conservative prefecture-wide estimates of ingestion doses.**

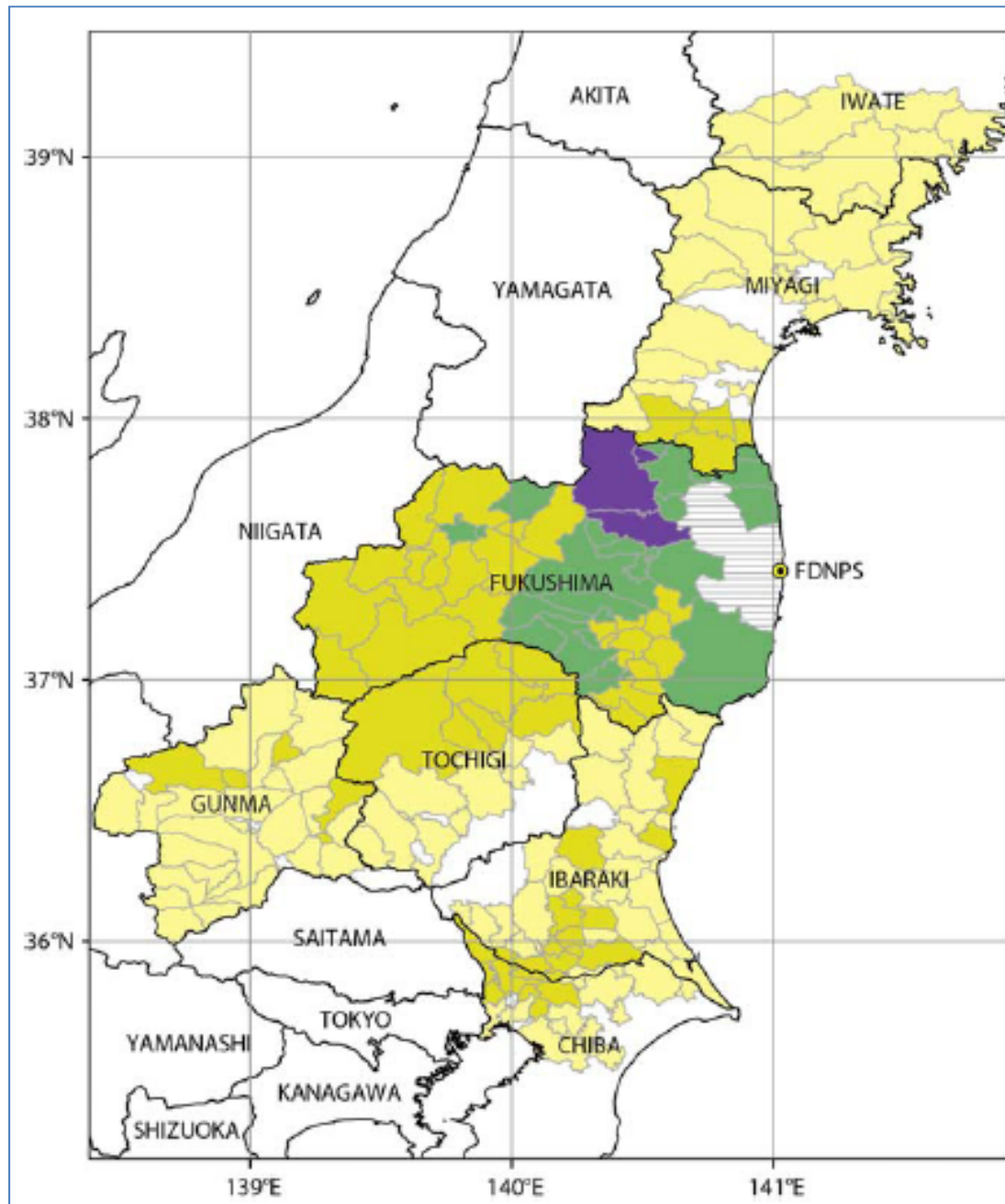
**For Comparison: in an examination of thyroid hypofunction 0,185 MBq – 0,555 MBq I-131 are applied resulting for adults in absorbed doses to the thyroid of 80 mSv – 240 mSv.**

Range of estimated average **effective doses to adults and to 1-year-old infants** for typical residents of Japan **in the first year** following the Fukushima accident

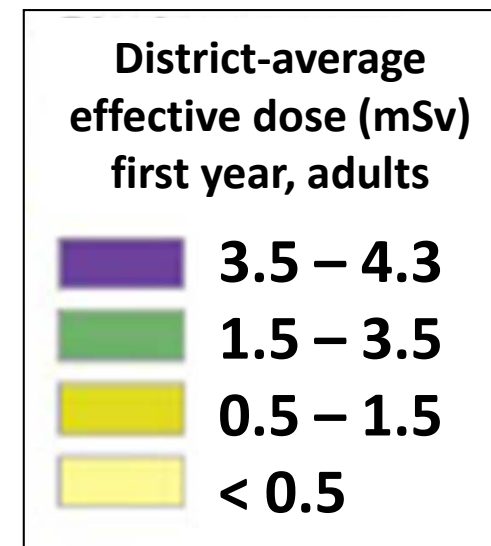
Residential area	Effective dose in mSv	
	adults	1-year old
Prefecture Fukushima not evacuated	1,0 – 4,3	2,0 – 7,5
Precautionary evacuated settlements: Fotuba, Okuma, Tomioka, Naraha, Hirono, parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	1,1 – 5,7	1,6 – 9,3
Deliberately evacuated settlements; litate village and parts of Minamisoma, Namie and Tamura cities and Kawauchi and Katsurao villages	4,8 – 9,3	7,1 – 13
Six neighboring prefectures: Miyagi, Yamagata, Niigata, Gunma, Tochigi, Ibaraki	0,2 – 1,4	0,3 – 2,5
40 other prefectures in Japan	0,1 – 0,3	0,2 – 0,5

Ranges of estimates for districts, biased by conservative prefecture-wide estimates of ingestion doses.

For comparison: the annual natural radiation exposure ranges from 1 mSv – 10 mSv with a worldwide average of 2.4 mSv.

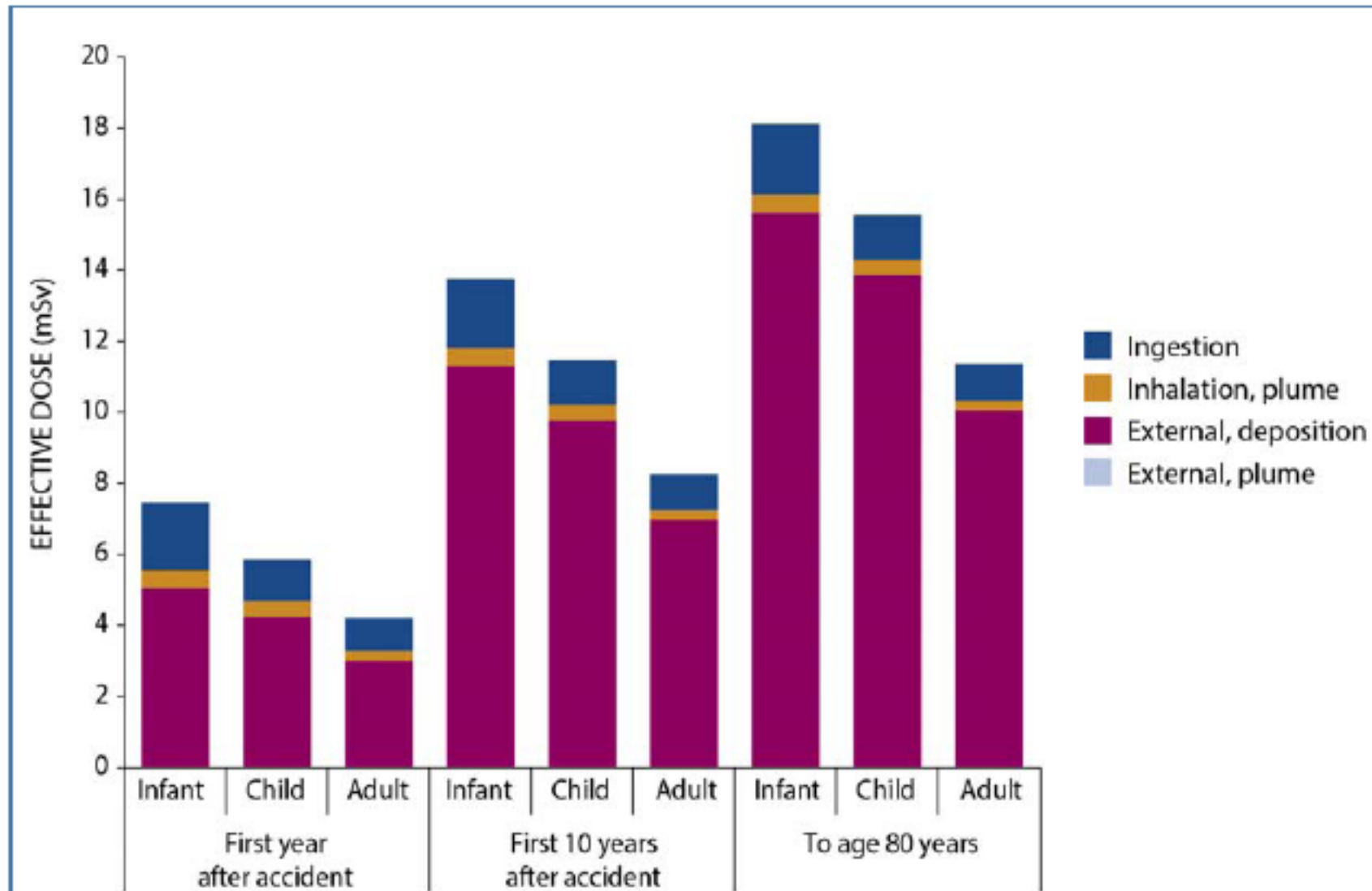


**Estimated district-average effective doses in mSv in the first year following the accident to adults living in districts of Fukushima Prefecture and some districts of neighboring prefectures that were not evacuated**





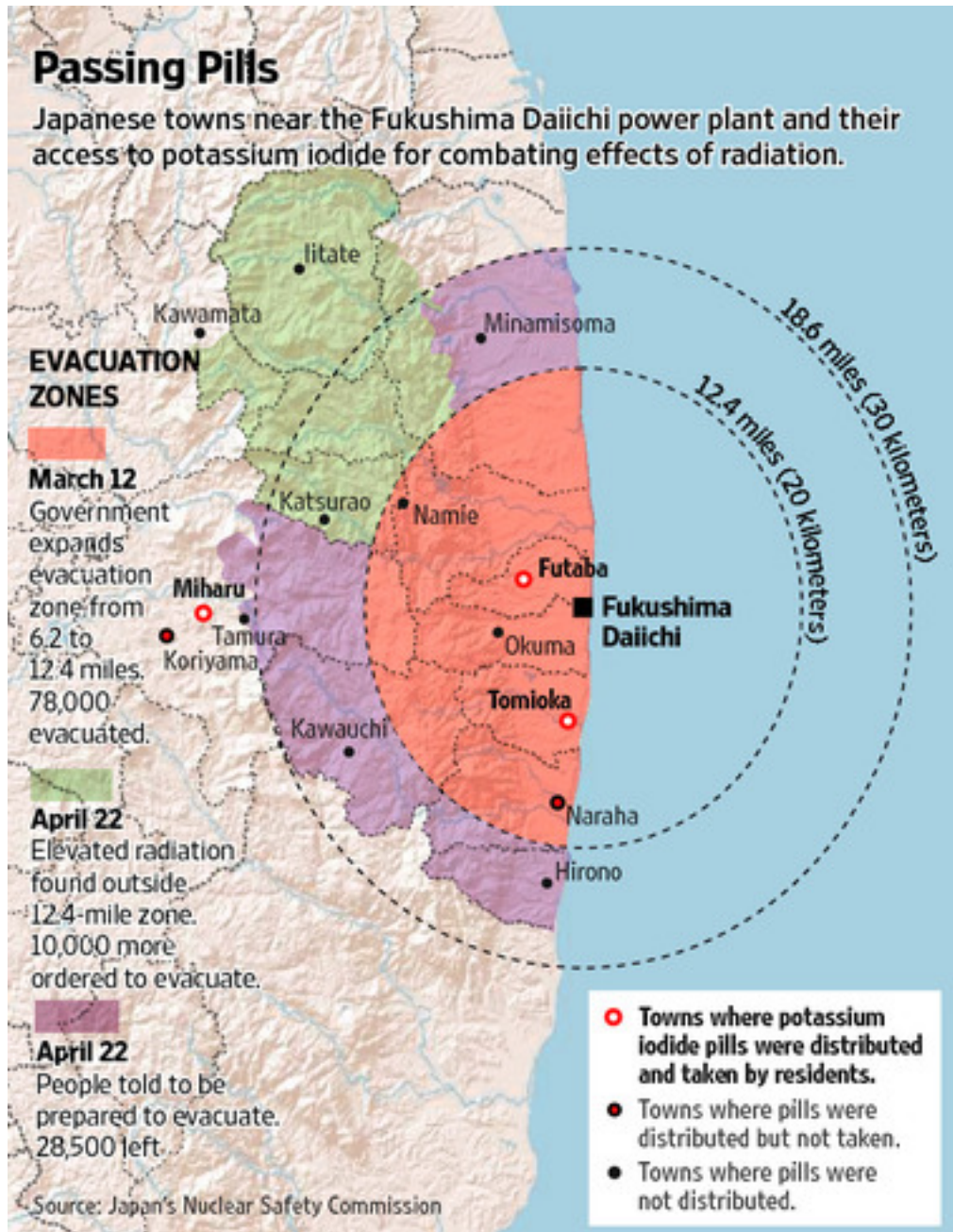
**Estimated district-average effective doses  
to typical adults, children and infants (as of 2011) living in Fukushima City.**



# A closer look to the radiological consequences of the Fukushima accident.

- We are having a relatively simple situation since practically only I-131, Cs-134 and Cs-137 have to be considered.
- Mainly, I-131 ( $T_{1/2} = 8,02$  d) determines the radiation exposure of the thyroid glands by the exposure pathways:
  - ❖ Inhalation while the radioactive cloud is passing
  - ❖ Ingestion of I-131 in foodstuffs.
- Cs-134 ( $T_{1/2} = 2,06$  a) and Cs-137 ( $T_{1/2} = 30,17$  a) cause a long-term whole body exposure via
  - ❖ External irradiation due to Cs-134 & Cs-137 fallout
  - ❖ Ingestion of Cs-134 & Cs-137 in foodstuffs ( $T_{1/2, \text{biol}} \sim 100$  d)

**We start with the radiation exposures of thyroid glands.**



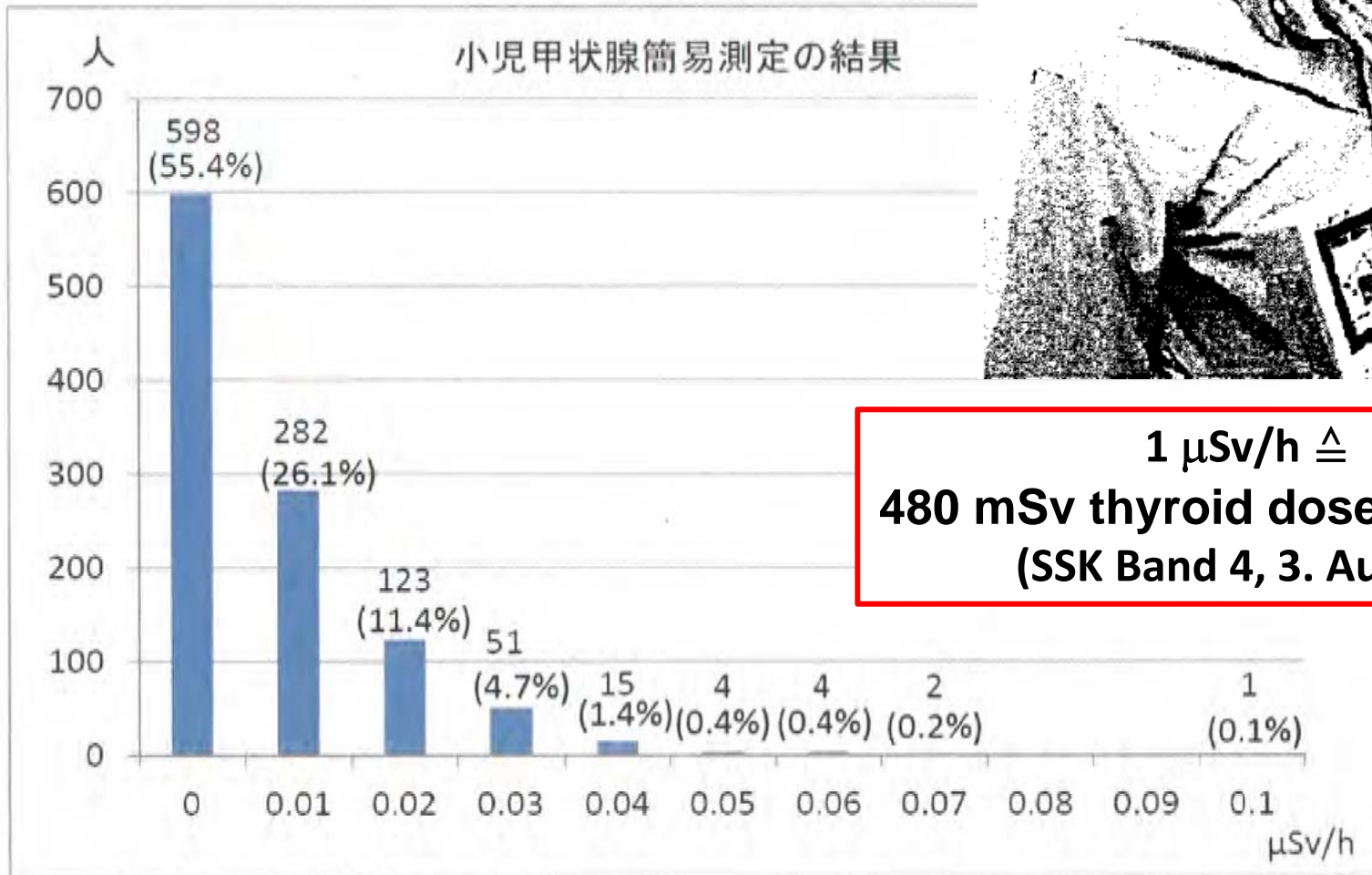
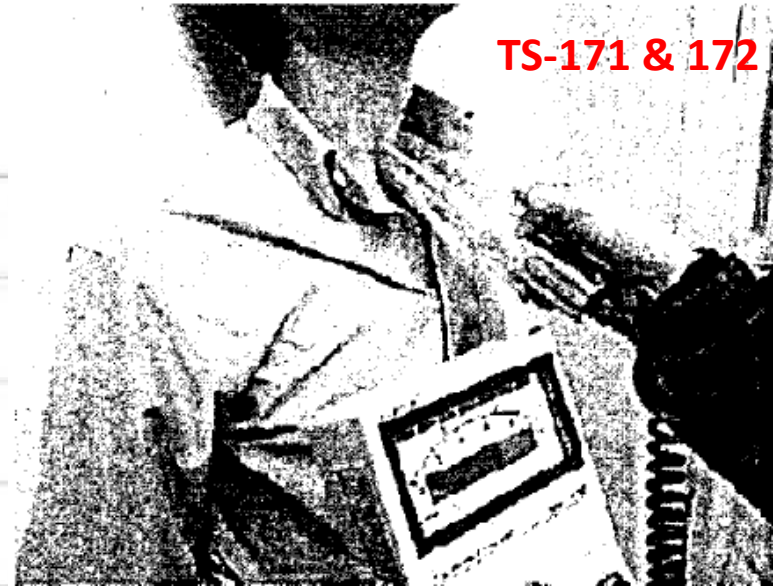
## Thyroid blocking by administration of stable iodine pills

According to the Japanese Nuclear safety Commission stable iodine pills

- were distributed and taken just in three towns;
- were distributed in one more town, but not taken;
- were not distributed elsewhere.

# Thyroid measurements 26.3. – 30.3.2011 of 1.080 children from Kawamata (after two half-lives of I-131)

TS-171 & 172



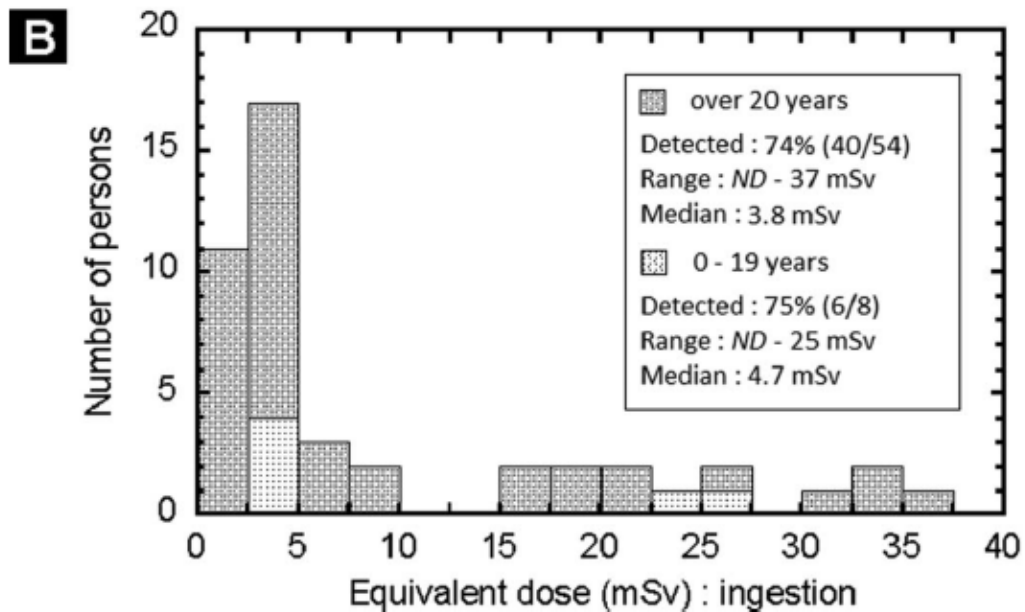
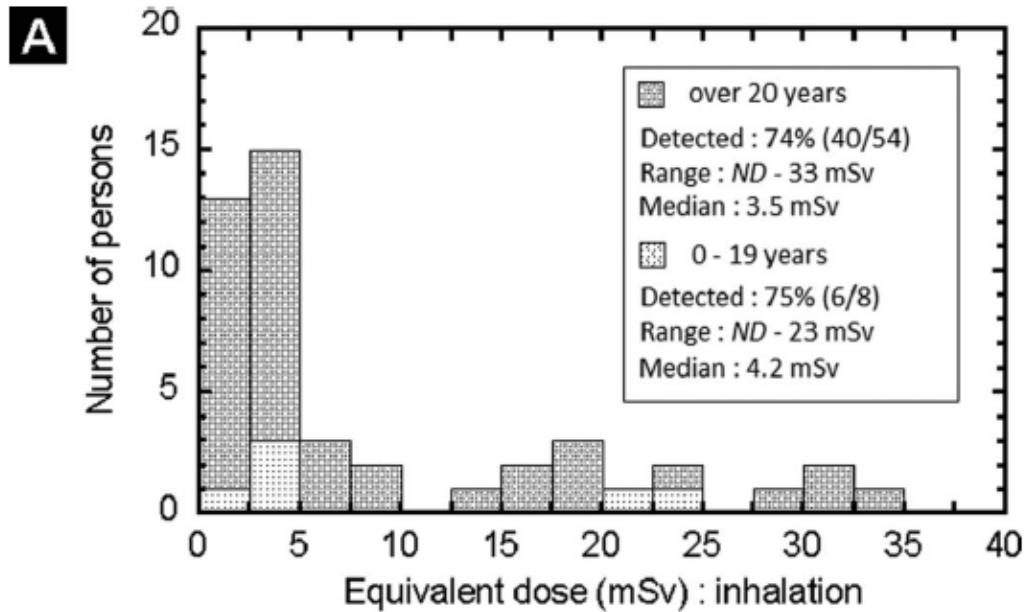
**1 μSv/h  $\triangleq$   
480 mSv thyroid dose for infants  
(SSK Band 4, 3. Auflage)**

**0 20 40 60 80 100 120 140 160 180 200 mSv Thyroid dose infant**

<http://www.nsc.go.jp/anzen/shidai/genan2011/genan067/siryo1.pdf>

Recalculated acc. to SSK Volume 4, 3<sup>rd</sup> ed.

R. Michel, IRS, Leibniz Universität Hannover



## Distribution of measured persons by thyroid equivalent dose from inhalation (A) and ingestion (B) of I-131.

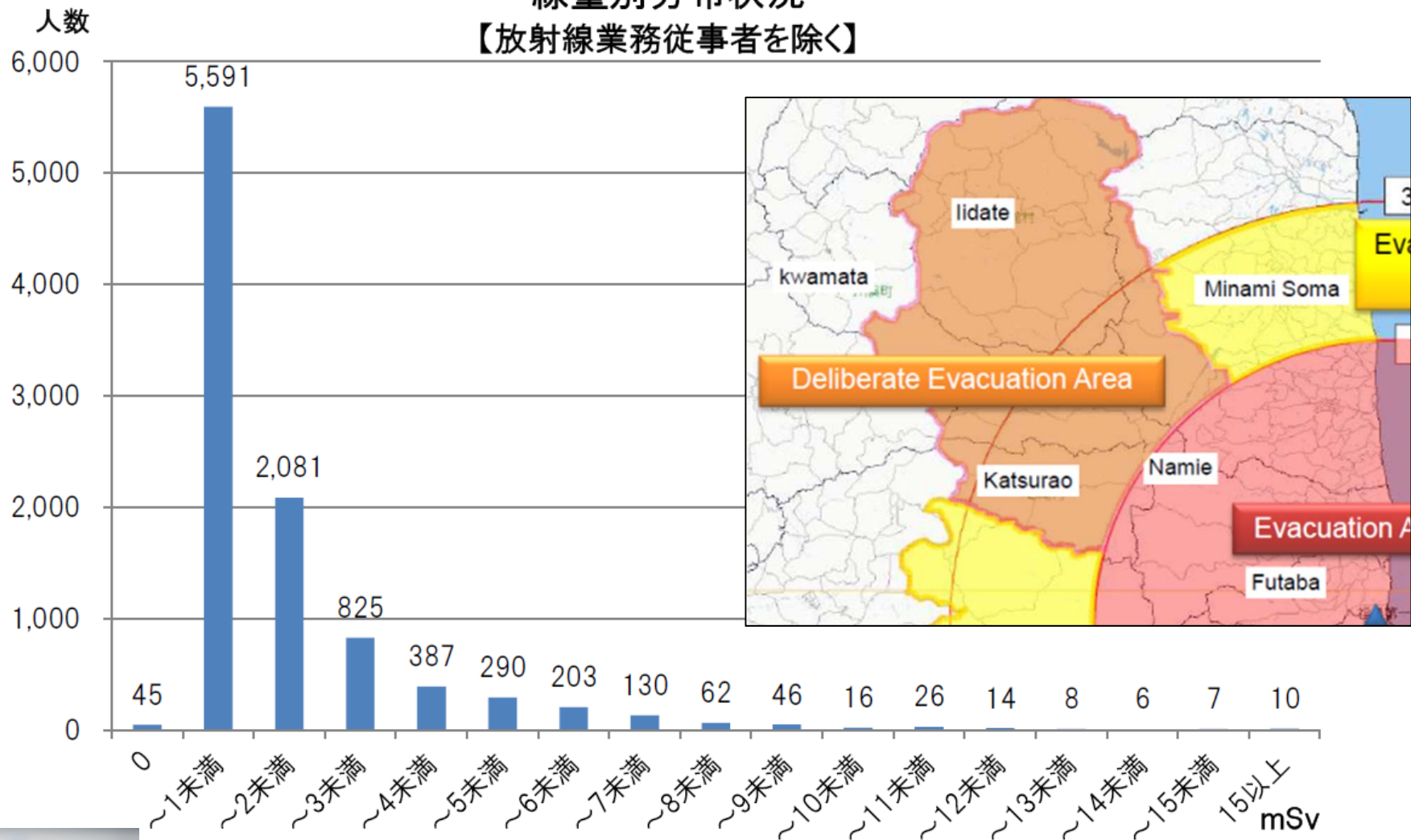
Each dose was calculated according to I-131 activity in the thyroid, measured by NaI detector calibrated with phantoms, and the age-dependent equivalent thyroid dose coefficients of ICRP assuming exposure by inhalation respectively ingestion on March 15, 2011.

# The external radiation exposure decides about relocation.



# Reconstruction of the external radiation exposure of 9,747 inhabitants of Namie Town ( $n = 7,250$ ), Iitate Village ( $n = 1,944$ ) and Kawamata Town ( $n = 553$ ) during the first 4 months after the accident (24.2.2012)

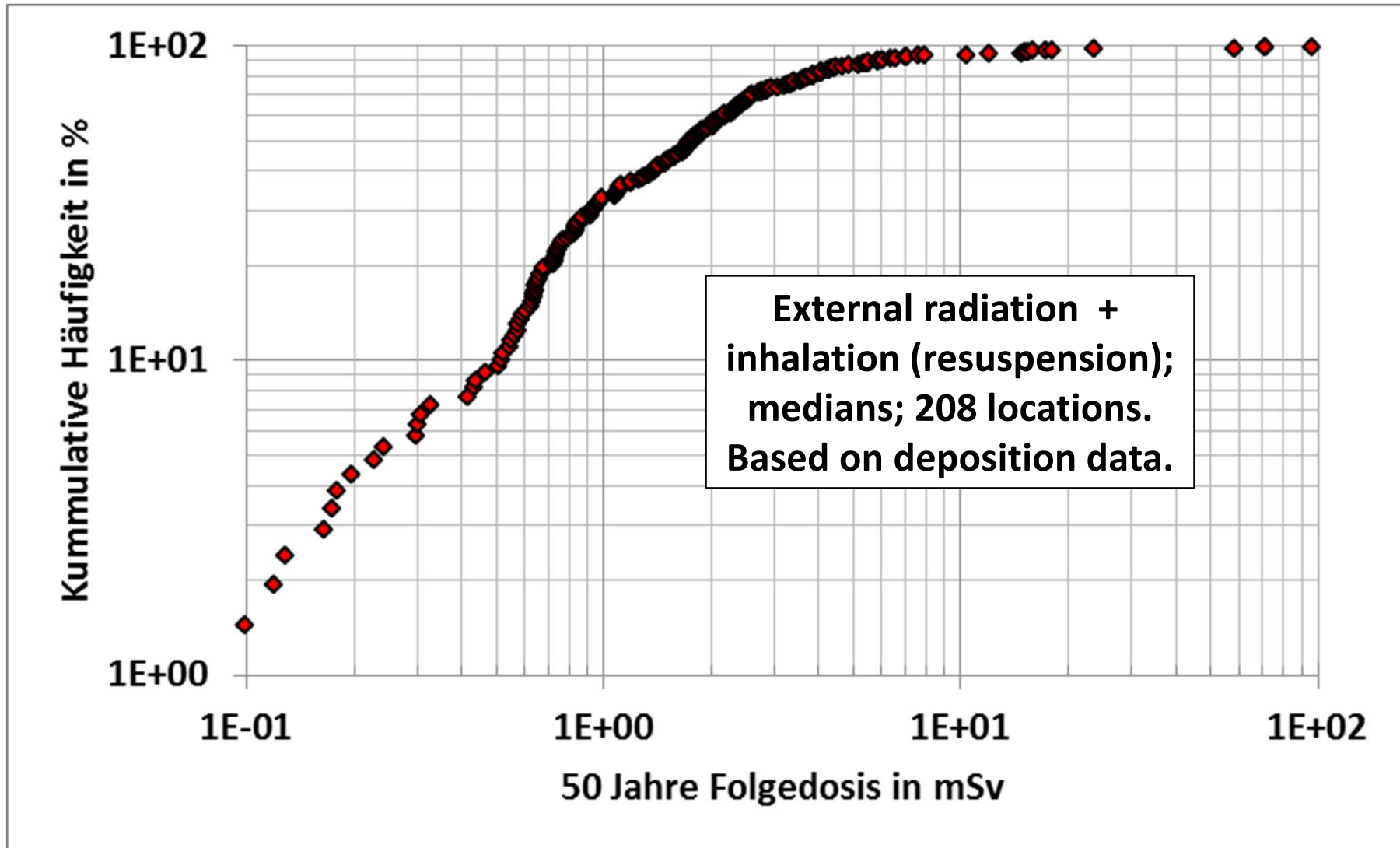
線量別分布状況  
【放射線業務従事者を除く】



240220siryo.pdf -

## 50-years effective doses

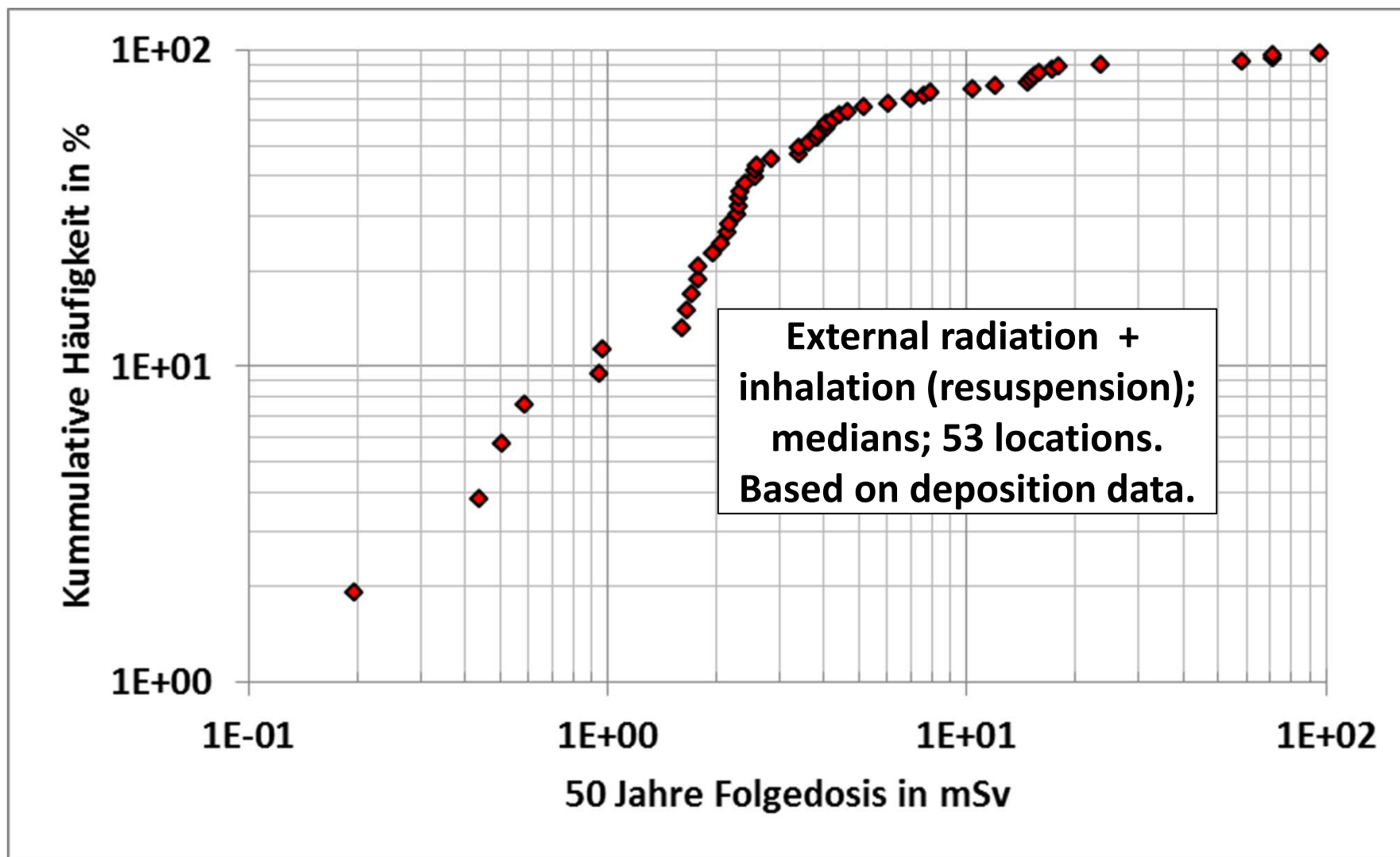
according to IAEA Tec-Doc 1162 in the Prefectures Fukushima, Iwate, Miyagi, Ibaraki, Tochigi, Gunma, Chiba, Saitama und Tokyo





## 50-years effective doses

according to IAEA Tec-Doc 1162 in the Prefecture Fukushima



# Internal radiation exposure due to I-131, Cs-134 and Cs-137



[http://de.wikipedia.org/wiki/Japanische\\_Küche](http://de.wikipedia.org/wiki/Japanische_Küche)



<http://www.tabibito.de/japan/essen.html>

**End of March and in the beginning of April 2011  
high activity concentrations in tap water, leafy vegetables,  
and fish caused much concern.**

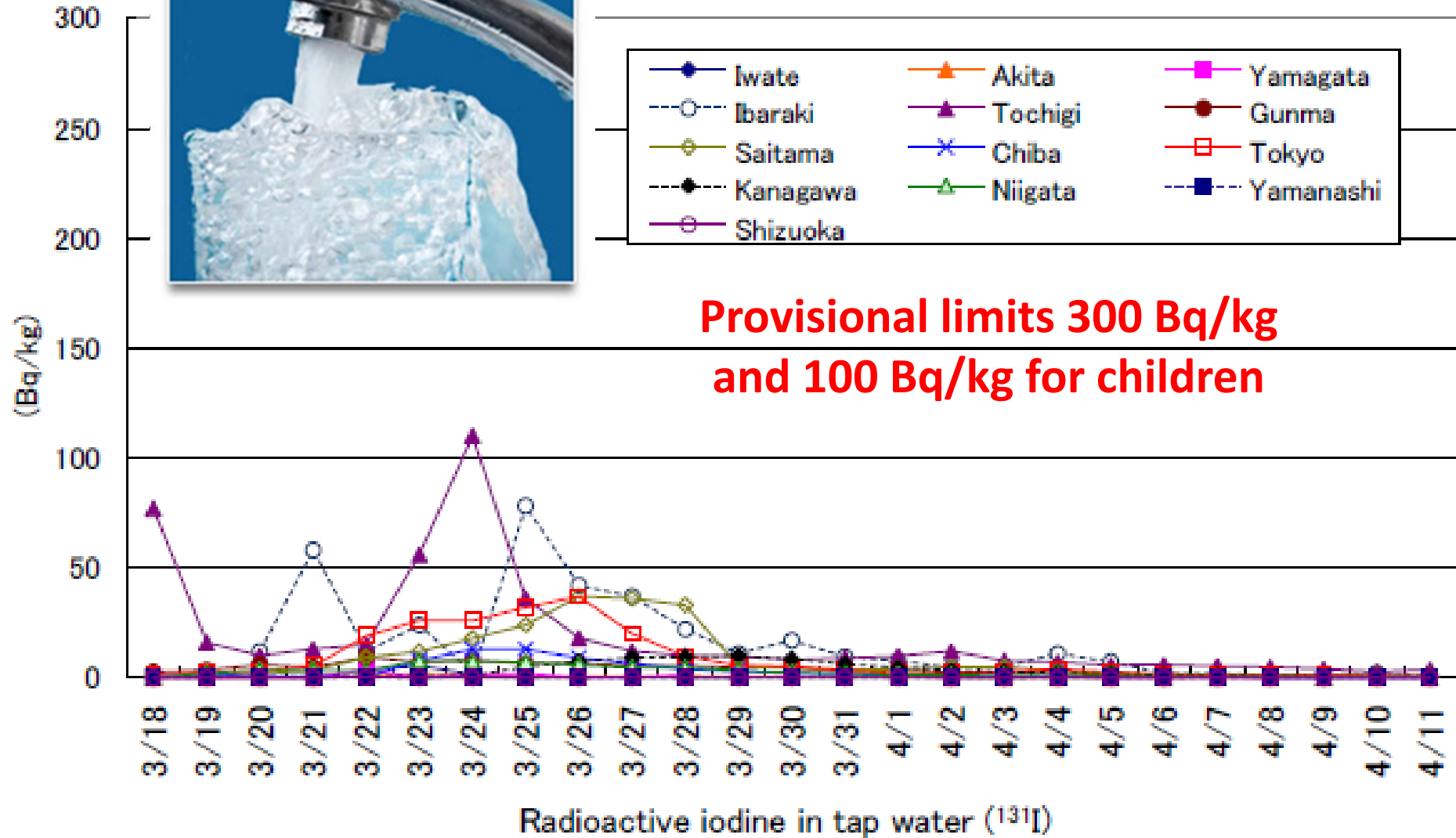
**Since 15.9.2011 EXCEL sheets are available in English under:**

**<http://www.mhlw.go.jp/english/topics/2011eq/index.html>**

**Data for fish : <http://www.jfa.maff.go.jp/e/inspection/index.html>**

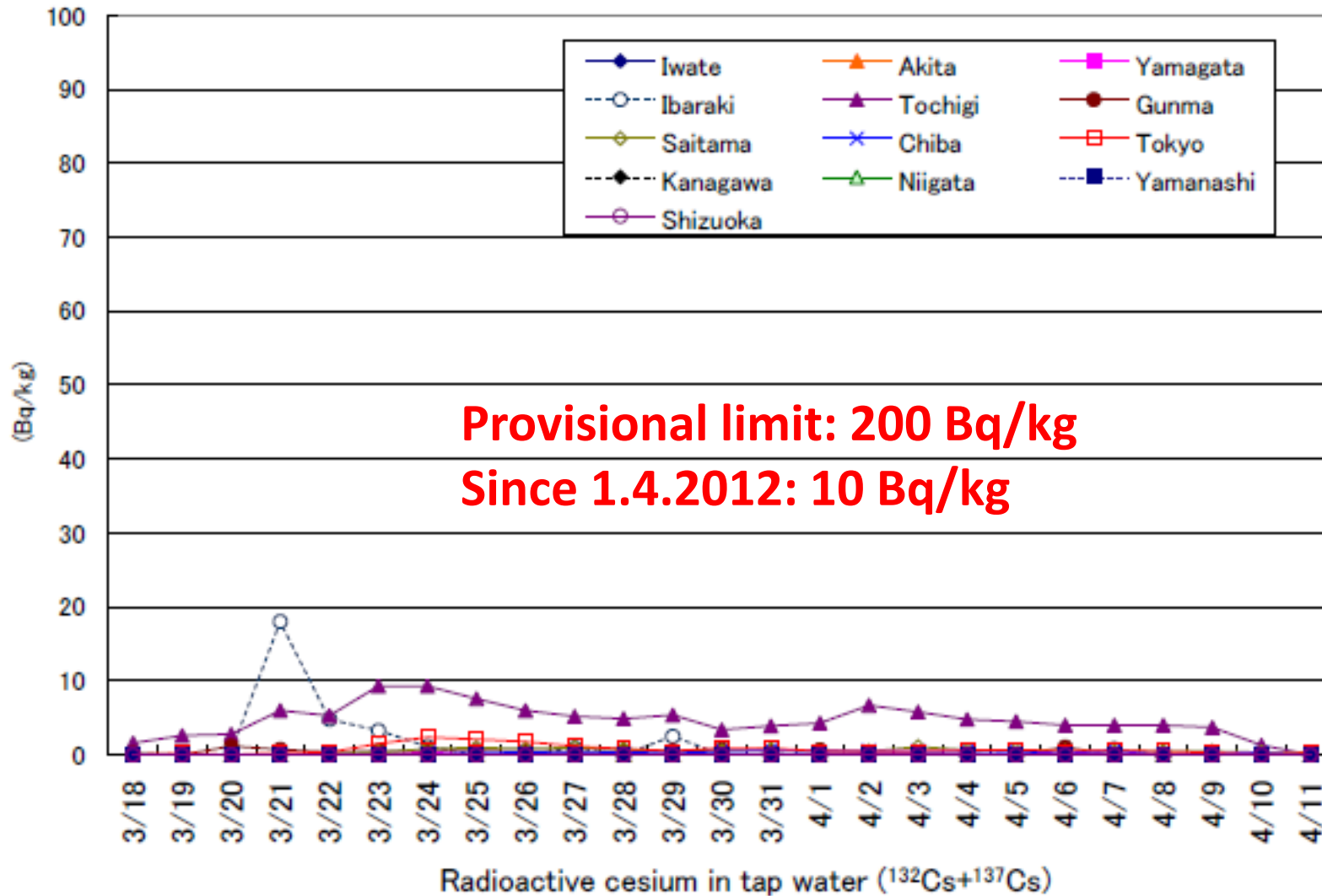
**Data for Prefecture Fukushima: <http://www.new-fukushima.jp/monitoring/en/>**

# Iod-131 in tap water



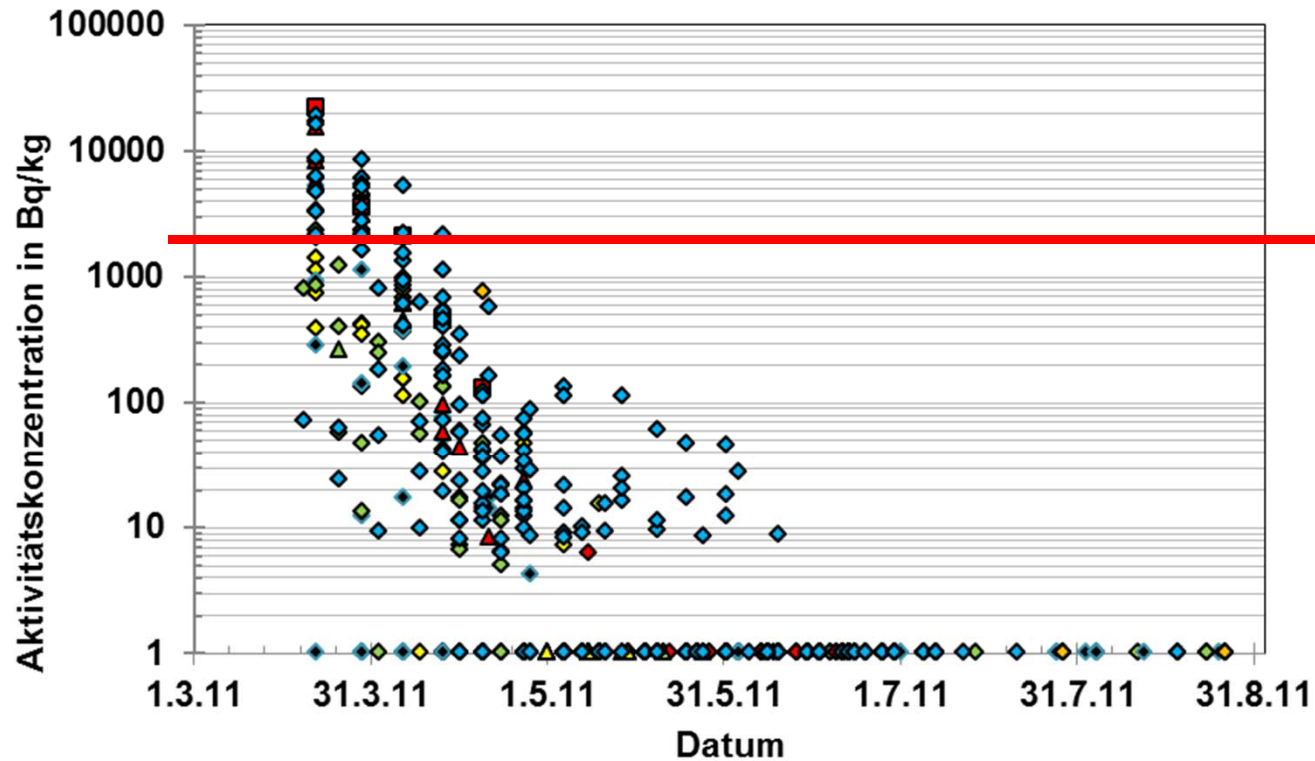
<http://www.mhlw.go.jp/english/topics/2011eq/dl/Document2.pdf>

# Cs-134 + Cs-137 in tap water



<http://www.mhlw.go.jp/english/topics/2011eq/dl/Document2.pdf>

## I-131 in leafy vegetables from Fukushima



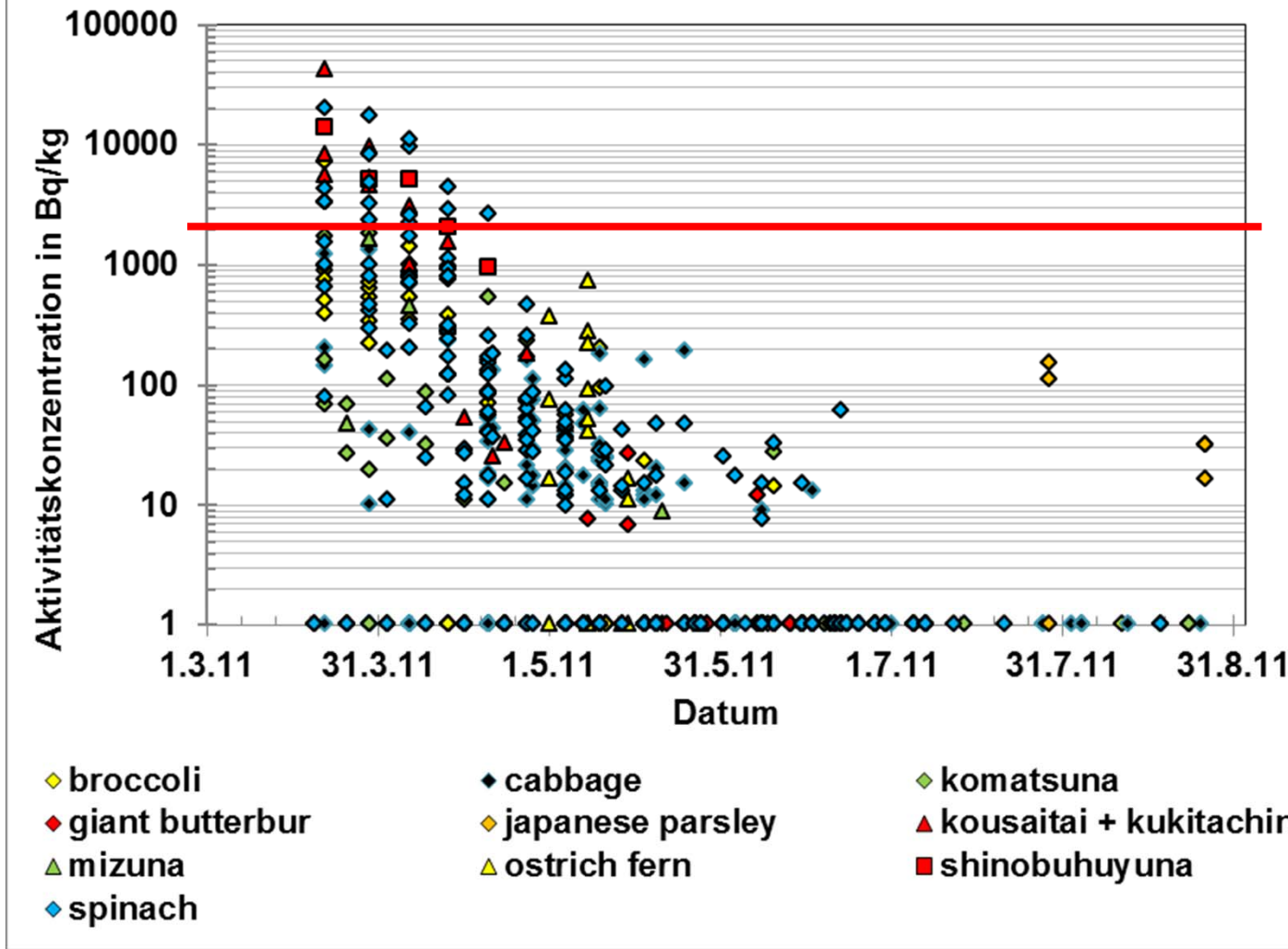
- ◆ broccoli
- ◆ cabbage
- ◆ komatsuna
- ◆ giant butterbur
- ◆ japanese parsley
- ▲ kousaitai + kukitachina
- ▲ mizuna
- ▲ ostrich fern
- shinobuhuyuna
- ◆ spinach



**Provisional limits:**  
**I-131: 2000 Bq/kg**

„Not detected“ is  
plotted as 1 Bq/kg.

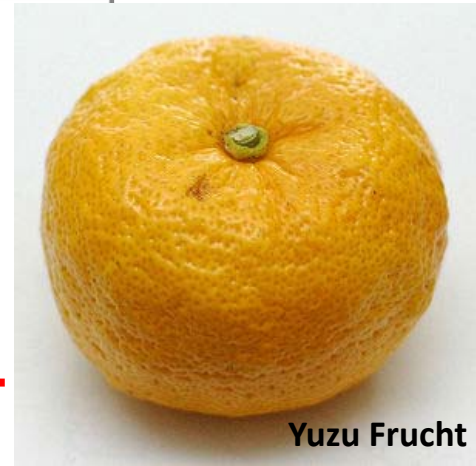
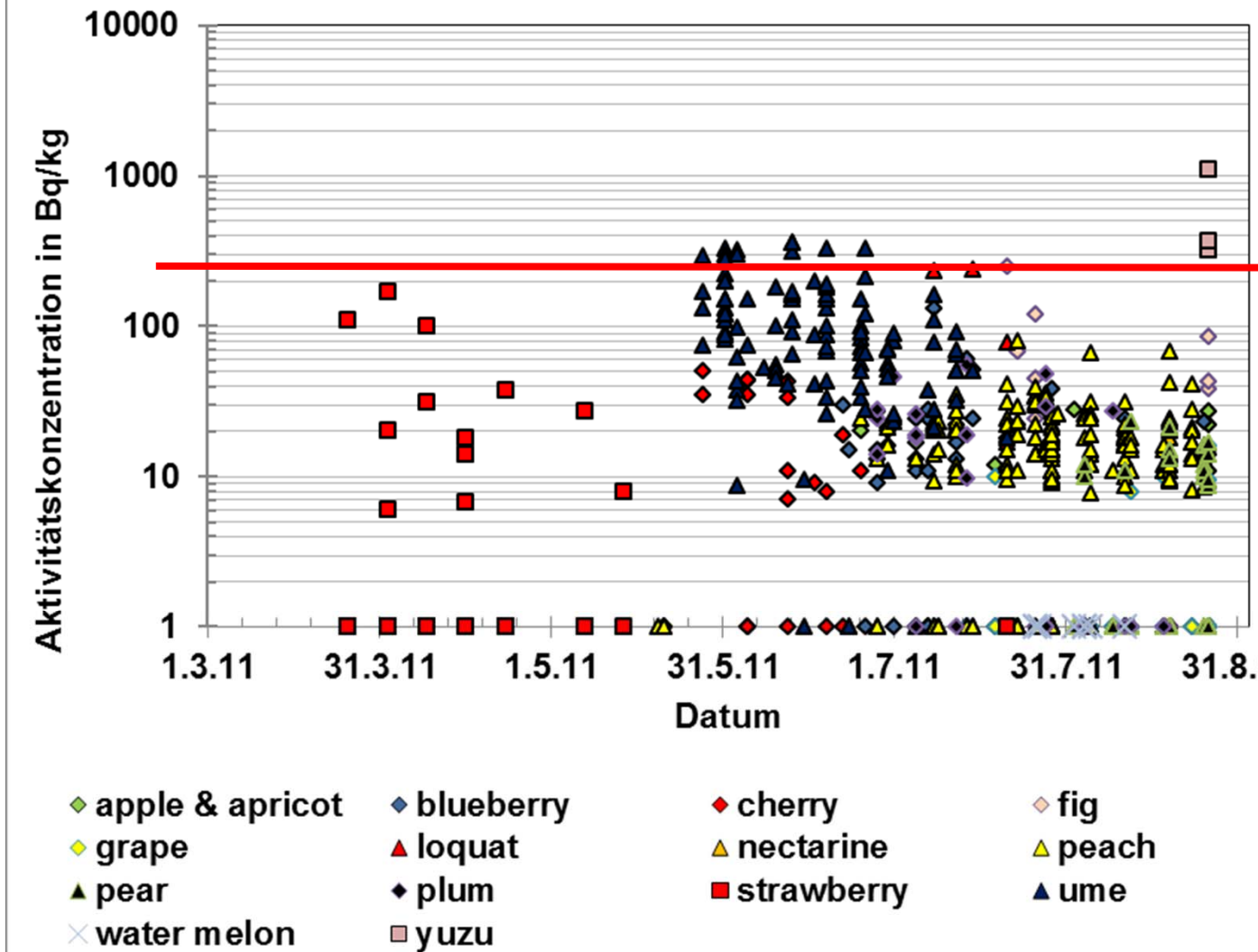
## Cs-134 in leafy vegetables from Fukushima



**Provisional limits:  
I-131: 2000 Bq/kg**

„Not detected“ is plotted as 1 Bq/kg.

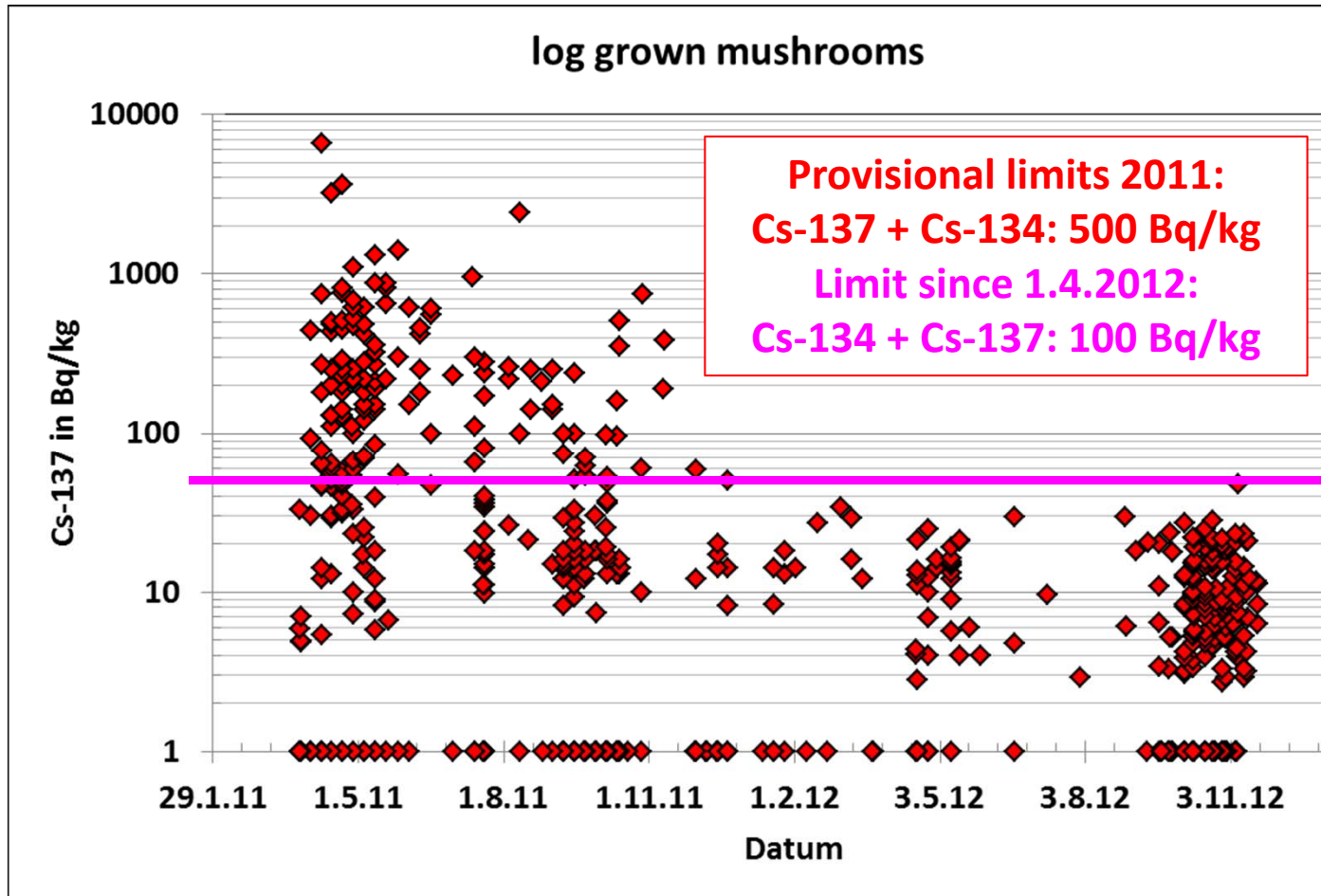
## Cs-134 in fruits from Fukushima



**Provisional limits:**  
**Cs-137 + Cs-134: 500 Bq/kg**

„Not detected“ is  
 plotted as 1 Bq/kg.

# Cs-137 in mushrooms from Fukushima Prefecture

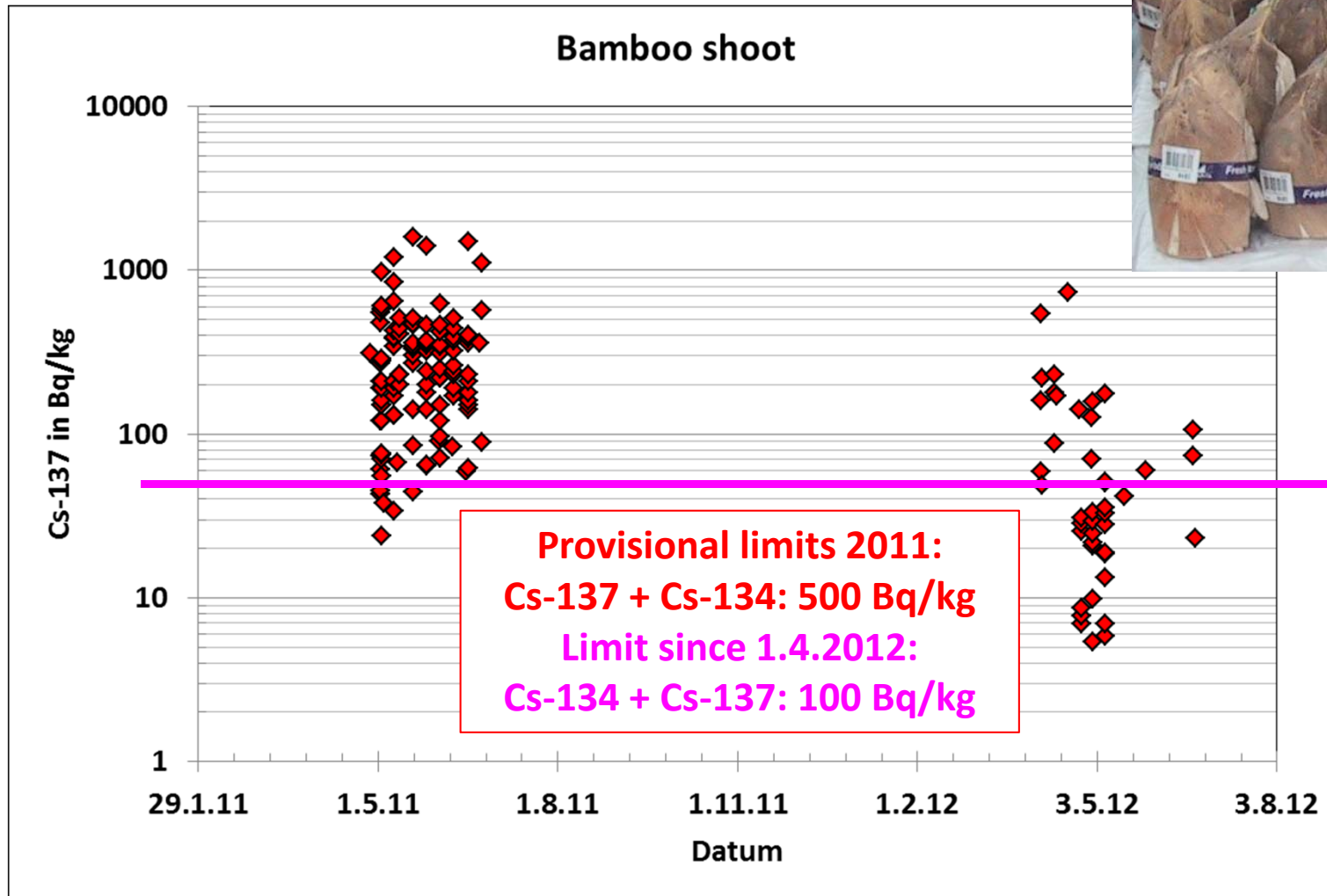


Not detected is plotted as 1 Bq/kg.

R. Michel, IRS, Leibniz Universität Hannover



# Cs-137 in bamboo shoots from Fukushima Prefecture



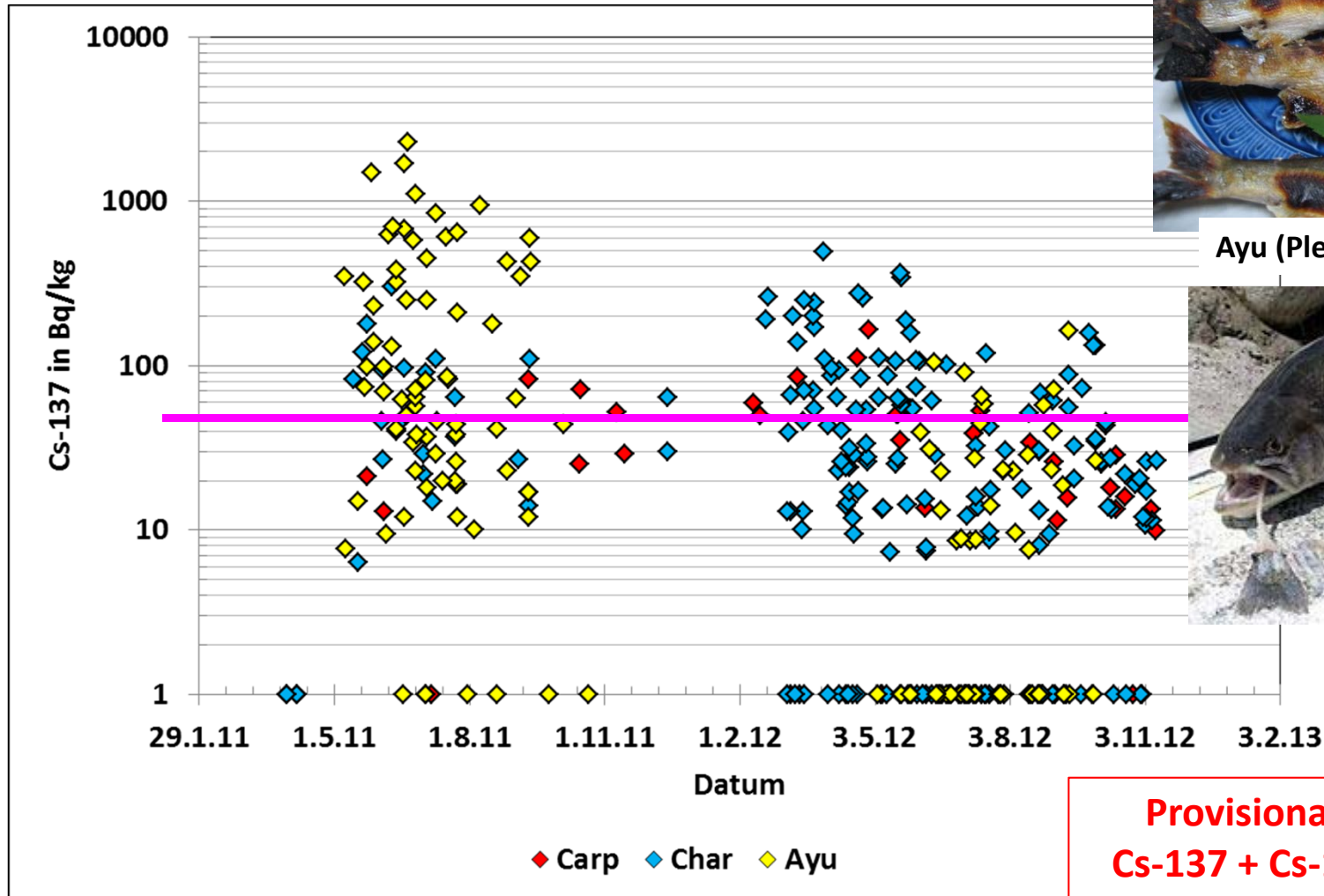
# Cs-137 in freshwater fish from Fukushima Prefecture



Ayu (*Plecoglossus altivelis*)



Arctic Char



**Provisional limits 2011:**  
**Cs-137 + Cs-134: 500 Bq/kg**  
**Limit since 1.4.2012:**  
**Cs-134 + Cs-137: 100 Bq/kg**

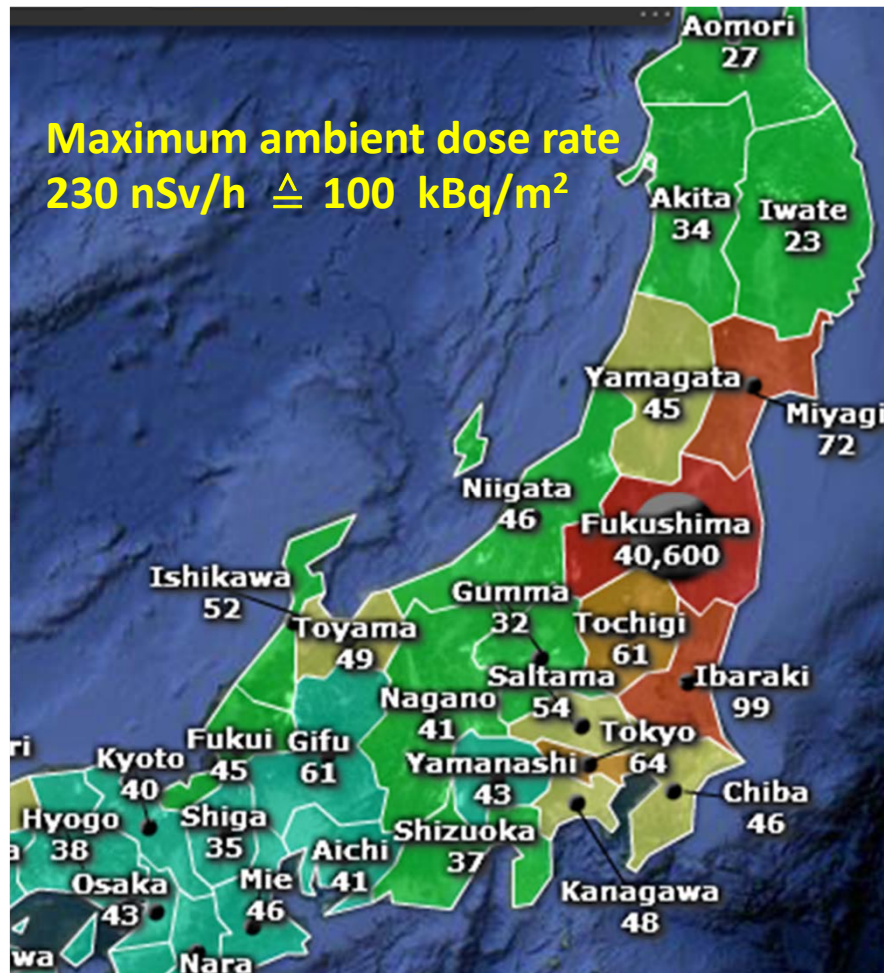
Not detected is plotted as 1 Bq/kg.

R. Michel, IRS, Leibniz Universität Hannover

**If the provisional limits are exceeded, the foodstuff is banned by the Japanese Government from marketing and it is recommended not to consume it.**

**The enforcement of the directives of the government and the surveillance of radioactivity in foodstuff rests with the prefectures.**

# Maximum ambient dose rates in May 2011 due to Cs-134 & Cs-137 Fallout (left) and survey on food data 1.4.2012 – 31.10.2012

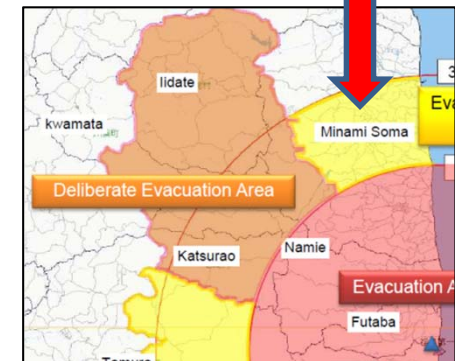
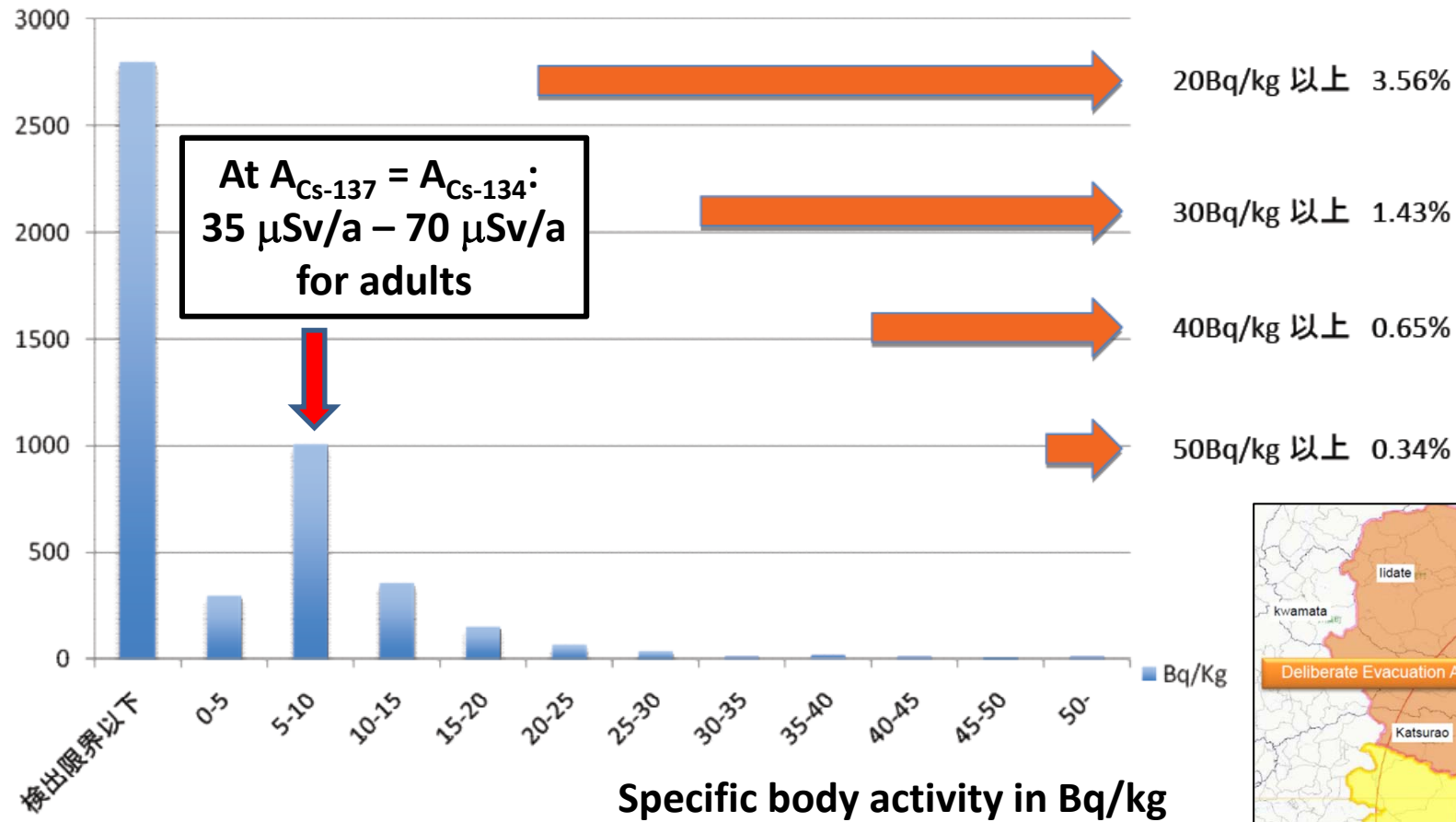


Prefecture	Number of samples	Fraction of samples > limits in %
Miyagi	15.424	0,8
Yamagata	9.537	0,02
Fukushima	19.397	4,3
Tochigi	14.996	1,2
Ibaraki	12.114	0,8
Niigata	2.198	0,1
Gunma	12.651	0,4
Saitama	2.440	0,2
Chiba	4.300	0,5
Tokyo	438	0,7

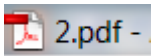
Exceeding limits in 2012: **mainly bamboo shoots, mushrooms, berries, fish & game, tea.**  
**In Fukushima Prefecture also other foodstuffs.**

**But how large is the internal exposure really?**

# Specific Cs-137 body activity of 4.745 persons in Minami Soma, Fukushima Prefecture, measured with whole body counter from 26.9.2011 to 27.12.2011

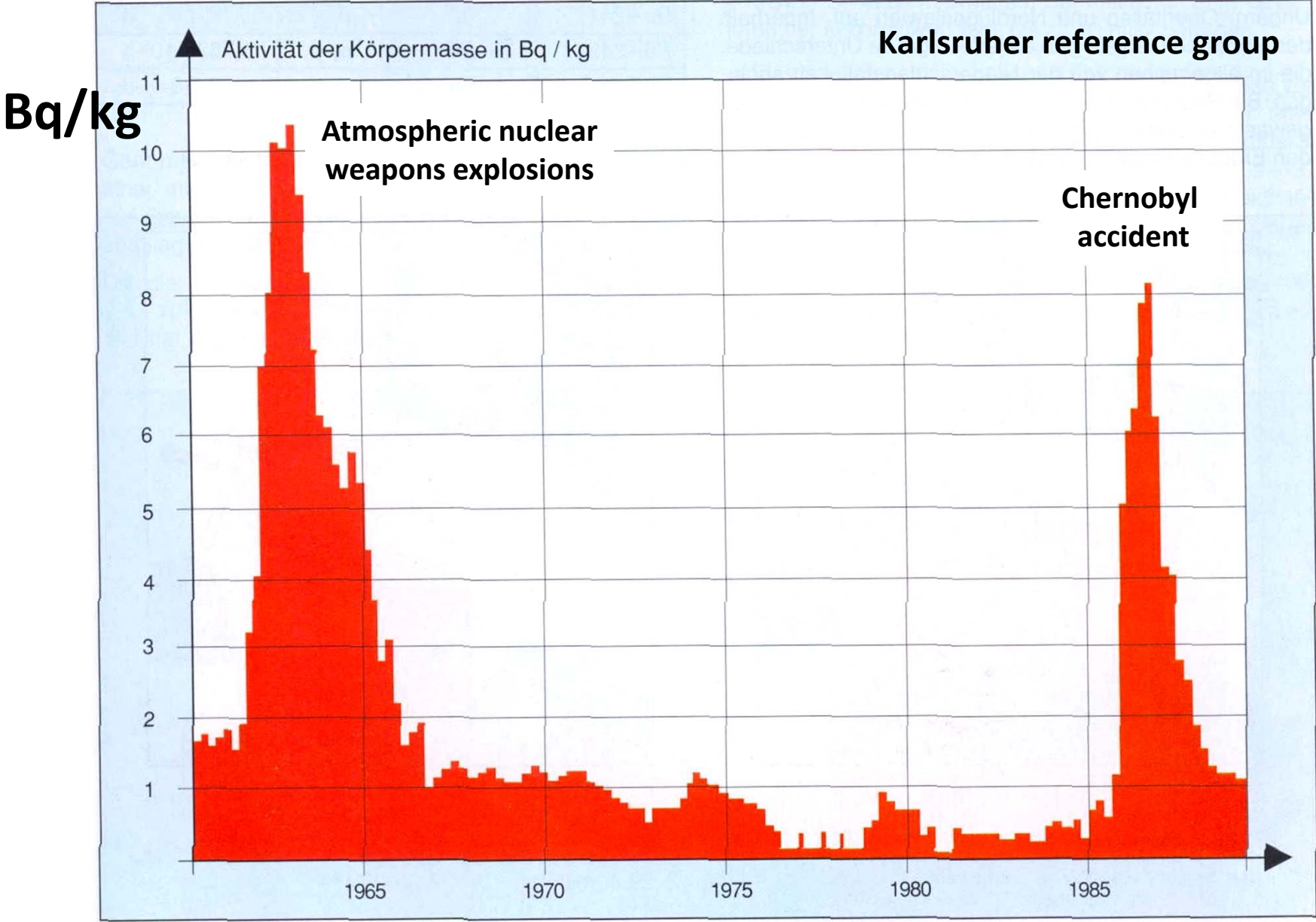


検出限界以下	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-
2802	305	973	351	145	64	37	16	21	9	6	16
59.05	6.43	20.51	7.40	3.06	1.35	0.78	0.34	0.44	0.19	0.13	0.34



<http://www.city.minamisoma.lg.jp/shinsai2/kensa/hibakukenshinkeka.jsp>

# Specific Cs-137 body activity of people from Karlsruhe

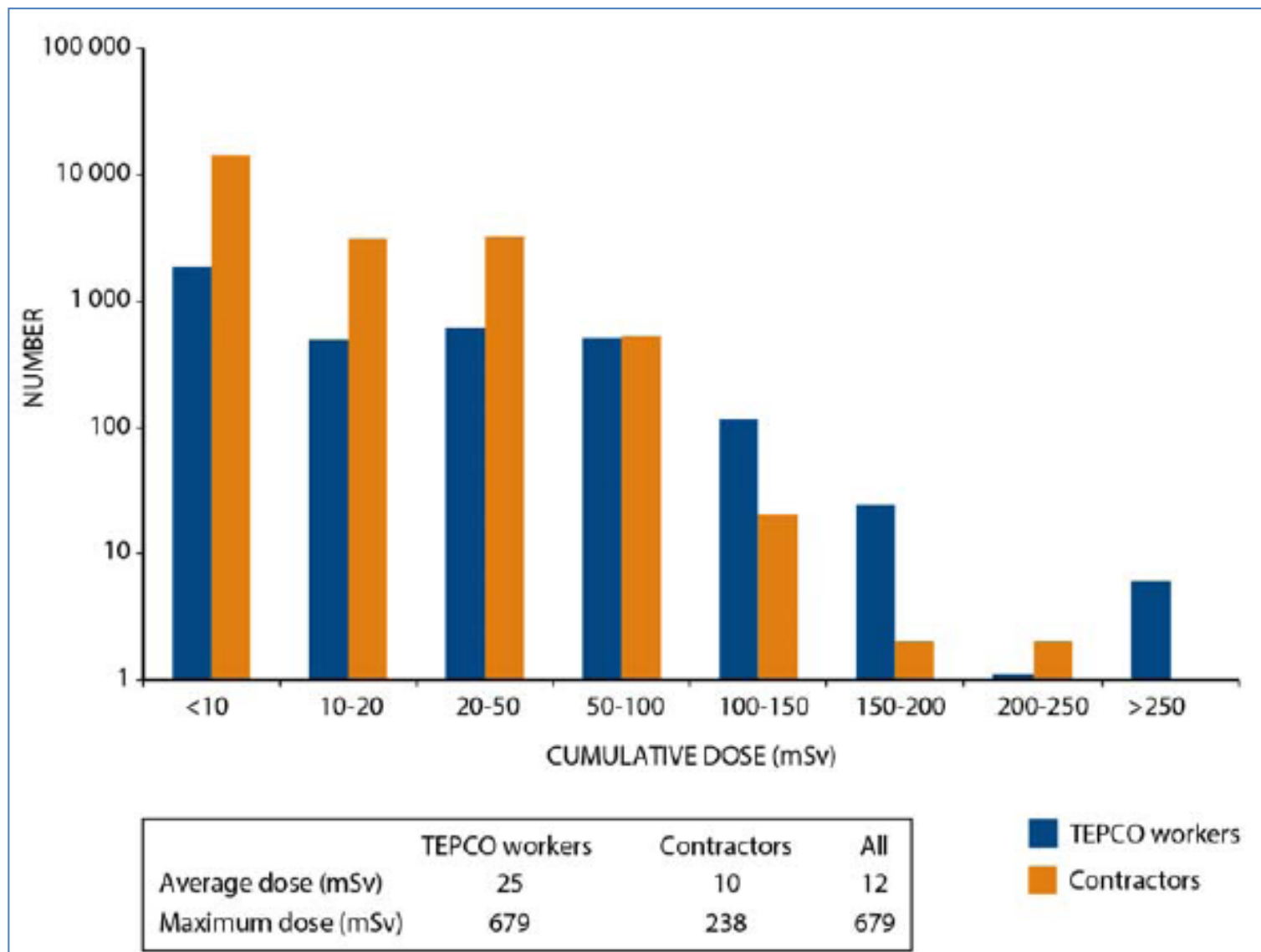


## Casualties among the workers at Fukushima Dai-ichi; as of 3.4.2011

- 2 worker drowned from the tsunami inside the turbine building. They were found on 30.3.2011.
- Injuries as consequence of the earthquake:
  - ❖ 2 slightly injured TEPCO workers
  - ❖ 2 workers from contractor companies (broken legs)
- Injuries due to the explosion at Unit 1 on 12.3.2011:
  - ❖ 2 workers outside the controlled area
- Injuries due to the explosion at Unit 3 on 14.3.2011:
  - 4 TEPCO workers, 3 workers from contractor companies, 4 members of the Self Defense Forces
- Other injuries:
  - 2 workers from contractor companies on 22./23.3.2011 when working at a temporary switch box of the power supply of the central spent fuel storage facility
  - 1 case of leukemia compensated as radiation induced in 2015 (exposure 20 mSv). Compensation is granted if a nuclear power plant worker has been exposed to annual radiation of 5 mSv and has developed cancer more than a year afterward.
  - At **Fukushima Daini** one worker died as a consequence of the earthquake in a crane accident and four others were injured.



Numbers of occupationally exposed FDNPS workers with effective doses in each cumulative dose band for the periods in which they worked between 11 March 2011 and 31 October 2012. The effective doses include contributions from external and internal exposure



# Radiation exposure of 18.846 workers at Fukushima Dai-ichi (as of 12/2011)

171 workers received more than 100 mSv

- 100 mSv – 150 mSv: 139 workers
- 150 mSv – 200 mSv: 23 workers
- 200 mSv – 250 mSv: 3 workers,
- more than 250 mSv (309 mSv – 678 mSv): 6 workers.

Radiation exposures of three workers who worked for about half an hour in contaminated water.			
	Worker 1	Worker 2	Worker 3
Whole body dose acc. to dosimeter	180 mSv	179 mSv	173 mSv
Dose to the skin	466 mSv	466 mSv	3 mSv
Internal dose	39 mSv	35 mSv	0 mSv
Thyroid dose	259 mSv	137 mSv	1.7 mSv

**Reports about radiation burns in German TV were false and fakes.**

# Health risks I\*

- WHO has estimated the life-long health risks for the most exposed people in Fukushima Prefecture.
- The exposures were too low to provoke deterministic effects among the general population and the workers at the NPP.
- The exposures were also too low to cause fetal dysplasia.
- No increase of miscarriages, perinatal mortality, malformations or reduction of mental capabilities is to be expected.
- WHO calculated increased risks for leukemia, solid tumors, breast – and thyroid cancer for the most exposed people in Fukushima Prefecture. The results of the WHO calculations can be regarded as upper limits of the expected risks and it is not clear whether they will be detectable or not.

\* WHO (2013) Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on a preliminary dose estimation, ISBN 978 92 4 150513 0.

# Radiation exposures in Fukushima Prefecture in the year 2011

For 99 % of the people in the evacuated zones and in the „deliberate“ evacuation zones were:

- below 10 mSv external dose during the first year
- below 1 mSv internal dose
- below 50 mSv thyroid dose

There were no deterministic effects and no causalities due to radiation.

**Ultrasonic investigations of 40.000 children exhibited for 35% of the children knots and/or cysts in their thyroid glands.\***

\* Nagati, Eur Thyroid J (2012) 1: 148-158 DOI: 10.1159/000342697

**ZDF, 18.11.2011 daily news 19:00**

**ZDF: After the reactor accident in Fukushima thyroid diseases increased. To blame is the radioactive Cesium.**

**A Japanese scientist emphasized in an interview that no control data of comparative groups do exist.**

## Results of ultrasonic examination of thyroids of children

Fukushima Prefecture			Prefectures Aomori, Yamanashi, Nagasaki		
S. Nagataki, Eur Thyroid J 2012;1:148-158			N. Taniguchi et al., J Medical Ultrasonic 2013; 40: 219 – 224		
Children aged 0 – 18 years			Children aged 3 – 18 years		
Status	No of children	fraction	Status	No of Children	fraction
A1	24.468	64,2 %	A1	1855	42,5 %
A2	13.460	35,3 %	A2	2466	56,5 %
B	186	0,5 %	B	44	1 %
C	0	0 %	C	0	0 %

**A1** without nodules or cysts,

**A2** with nodules less than 5,0 mm and/or cysts less than 20,0 mm;

**B** with nodules greater than 5,1 mm and/or cysts greater than 20,1 mm;

**C** immediate further examination required

S. Nagataki, Eur Thyroid J 2012; 1: 148-158 DOI: 10.1159/000342697

N. Taniguchi et al., J Medical Ultrasonic 2013; 40: 219 – 224 DOI: 10.1007/s10396013-0456-1

R. Michel, IRS, Leibniz Universität Hannover

## **Further evaluations revealed a new aspect :**

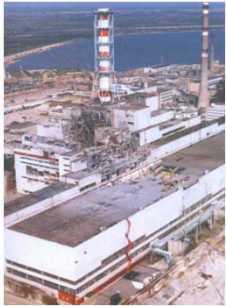
**In a survey of evacuees on mental health issues related to the disaster, 20 percent were judged to likely be in need of counseling:**

- ❖ Regarding children who were junior high school students or younger, 18 percent of the 13,000 who responded by February were considered likely to need some form of assistance or counseling in the future. The figure is nearly twice as high as the percentage for children under normal circumstances.**
- ❖ On the adult side, 24 percent of the 35,000 people who responded to the survey were deemed to be in a high-risk category regarding mental health issues.**

# **Consequences of the reactor accident, the earth quake and the tsunami**

- **Post-traumatic stress**
- **Loss of homes, economical basis and social structure**
- **Stigmatization**
- **Social marginalization**





# Chernobyl and Fukushima Dai-ichi: two man-made reactor accidents



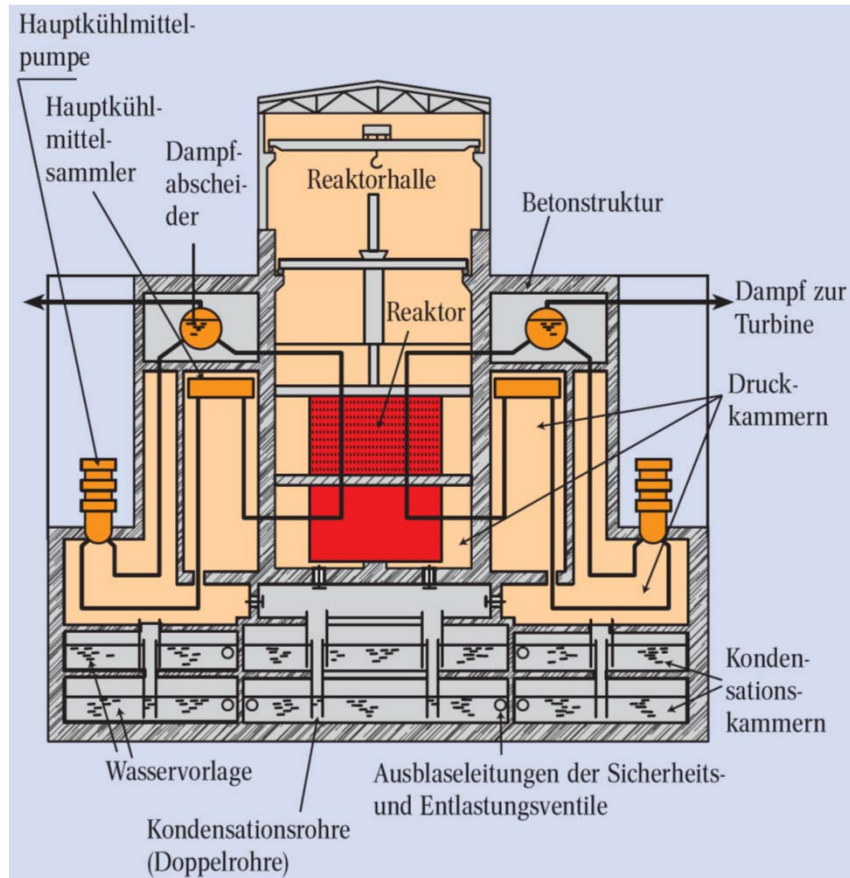
## Chernobyl

- **Design faults**
- ❖ Physically inherently unsafe because of positive void and temperature coefficients
- ❖ Positive scram effect of shut-down rods
  
- **Human faults**
- ❖ Experiment with untrained personnel
- ❖ Too few control rods inserted
- ❖ Shut-down criteria blocked
- ❖ No safety culture

## Fukushima Dai-ichi

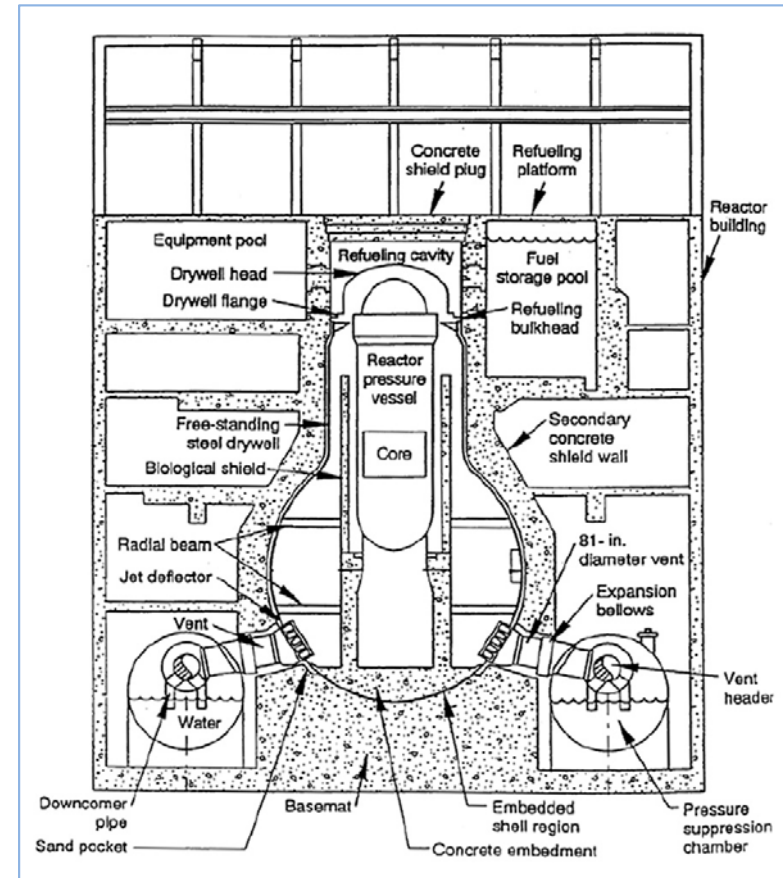
- **Design faults**
- ❖ Insufficient tsunami protection in spite of existing predictions
- ❖ Insufficient redundancy of external power supply in case of a strong earthquake
- ❖ Insufficient design of internal electricity supplies as well as of emergency power and cooling devices
  
- **Human faults**
- ❖ Severe deficits in safety culture due to Japanese cultural peculiarities

## Graphite-moderated, water-cooled pressure tube reactor in **Chernobyl**



1693 pressure tubes, no containment, uncontrolled power excursion, graphite fire and melting of the core as a consequence of design deficits and human malpractice.

## Water-moderated, water-cooled boiling water reactor in **Fukushima**



Reactor pressure vessels & containments, 3 cores melted, 4 hydrogen explosions and multiple venting as a consequence of loss of cooling of the fuel elements after station blackout due to tsunami.

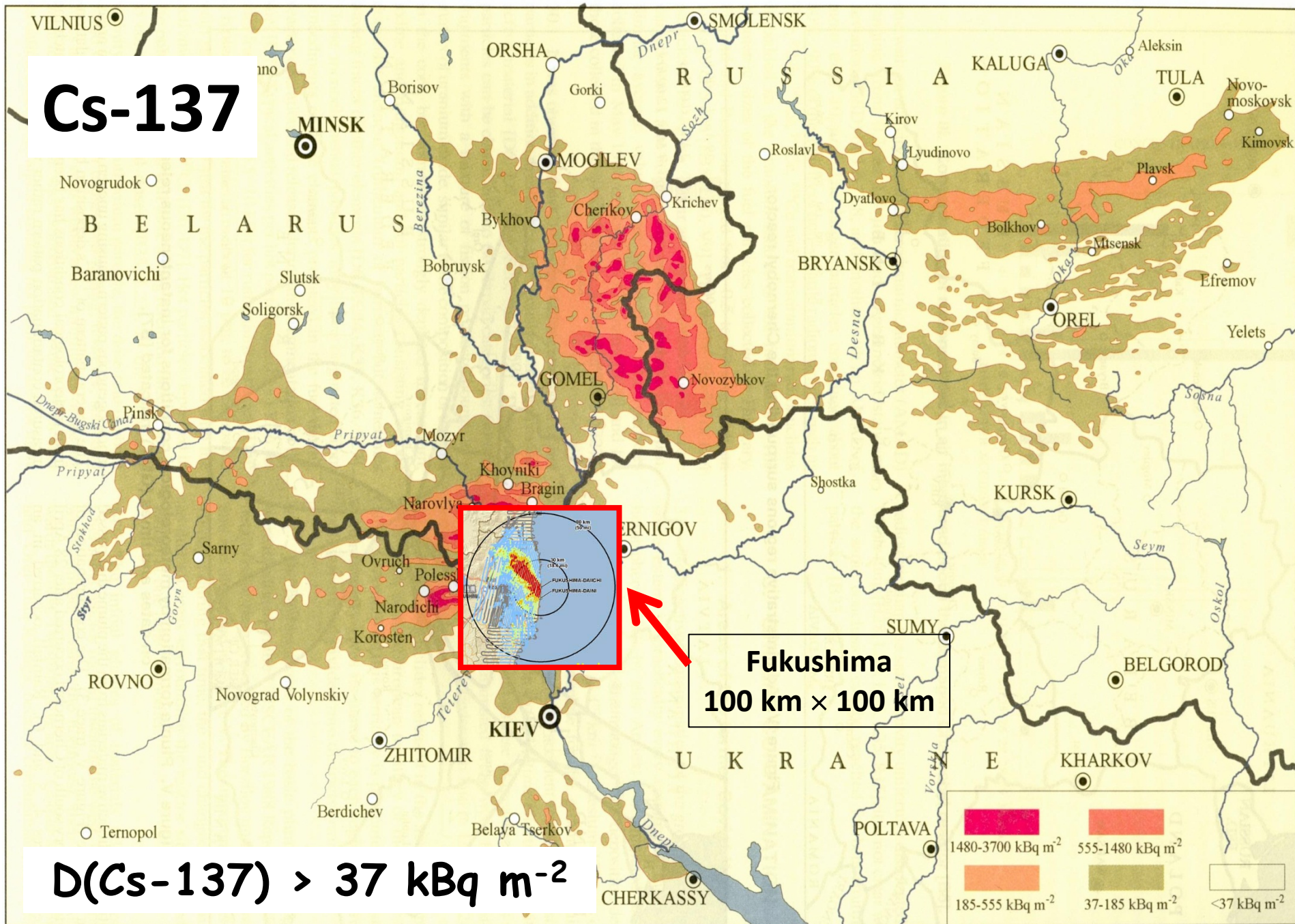


Figure VI. Surface ground deposition of caesium-137 released in the Chernobyl accident [[1, 13]. **UNSCEAR (2000)**

A photograph of a pond with several colorful koi fish swimming near dark rocks. The text "The End" is overlaid in yellow.

# The End

Download unter [www.irs.uni-hannover.de/3.html](http://www.irs.uni-hannover.de/3.html)