How many deaths did the Chernobyl and Fukushima nuclear disaster cause?

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Seminar: *How do I lie with statistics?*

January 9, 2019

Outline

1. Introduction
2. Chernobyl Disaster
    1. Context
        i. Total death toll(s)
    2. Analyzing the different death tolls
        i. Direct/Short-term
        ii. Long-term
        iii. Predictions
3. Fukushima Daiichi Disaster
4. Conclusion

Quote

"Even then, the number of children and grandchildren with cancer in their bones, with leukemia in their blood, or with poison in their lungs might seem statistically small to some, in comparison with natural health hazards. But this is not a natural health hazard--and it is not a statistical issue. The loss of even one human life, or the malformation of even one baby--who may be born long after we are gone--should be of concern to us all. Our children and grandchildren are not merely statistics toward which we can be indifferent."

- John F. Kennedy

Radio and Television Address to the American People on the Nuclear Test Ban Treaty, July 26, 1963

Audio: https://www.jfklibrary.org/asset-viewer/archives/JFKWHA/1963/JFKWHA-207/JFKWHA-207

Чорнобиль Chernobyl

Image: https://de.wikipedia.org/wiki/Datei:Ukraine_(claims_hatched)_in_Europe.svg

Чорнобиль Chernobyl

Image: https://de.wikipedia.org/wiki/Datei:Ukraine_adm_location_map.svg

Chernobyl and the world on April 26, 1986

- Reactor meltdown caused by improper operation during engineering test
- particular significant radionuclides:
  - iodine-131 (~8 days $t_{1/2}$)
    - high radiation dose to thyroid
  - caesium-137 (~30 years $t_{1/2}$)
    - long-term radioactive exposure

Table 1. Principal radionuclides released in the accident
Refined estimates of the activities released

Radionuclide	*Half-life*	*Activity released (PBq)*
Inert gases[a]		
^{85}Kr	10.72 a	33
^{133}Xe	5.25 d	6 500
Volatile elements[a]		
^{129m}Te	33.6 d	240
^{132}Te	3.26 d	~1 150
^{131}I	8.04 d	~1 760[d]
^{133}I	20.8 h	910
^{134}Cs	2.06 a	~47[b]
^{136}Cs	13.1 d	36
^{137}Cs	30.0 a	~85[e]

a From references [D11, U3].
b Based on ^{134}Cs/^{137}Cs ratio 0.55 as of 26 April 1986 [M8].
c Based on fuel particle release of 1.5% [K13].
d For comparison, the global release of ^{131}I from atmospheric nuclear weapon testing was 675,000 PBq [U3].
e For comparison, the global release of ^{137}Cs from atmospheric nuclear weapon testing was 948 PBq [U3].

Table: UNSCEAR (2008): "Health effects due to radiation from the Chernobyl accident" (Annex D of the 2008 UNSCEAR Report

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    - long-term radioactive exposure
- 5 million inhabitants living in 150.000km² contaminated area
- ~200.000 evacuees
- ~500.000 recovery operation workers

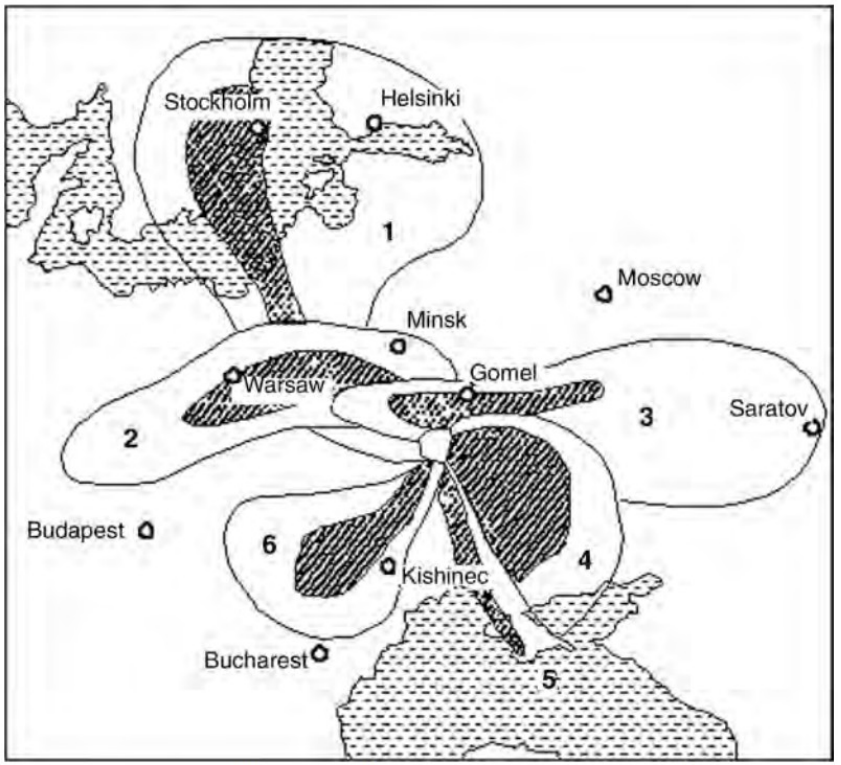
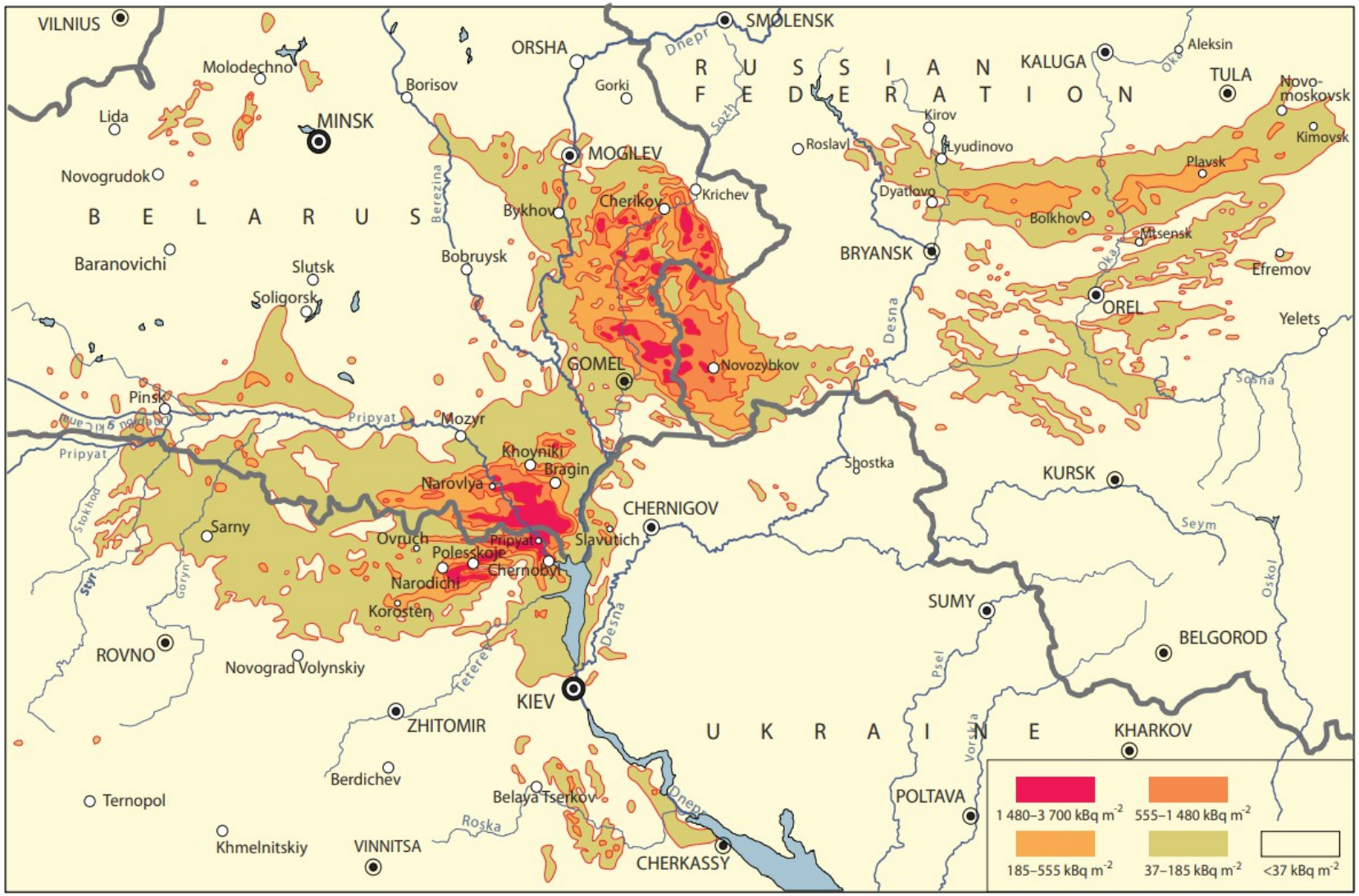


Figure 1.4. Six stages of formation of radioactive gaseous–aerosol emissions from Chernobyl from April 26 to May 4, 1986: (1) April 26, 0 hours (Greenwich time); (2) April 27, 0 hours; (3) April 27, 12.00 hours; (4) April 29, 0 hours; (5) May 2, 0 hours; (6) May 4, 12.00 hours (Borzylov, 1991). Shading indicates the main areas of the radionuclide fallout.

Image: Yablokov et al. (2007): "Chernobyl: Consequences of the Catastrophe for People and the Environment"

Chernobyl and the world on April 26, 1986

Figure II. Map of ^{137}Cs deposition levels in Belarus, the Russian Federation and Ukraine as of December 1989 [I28]



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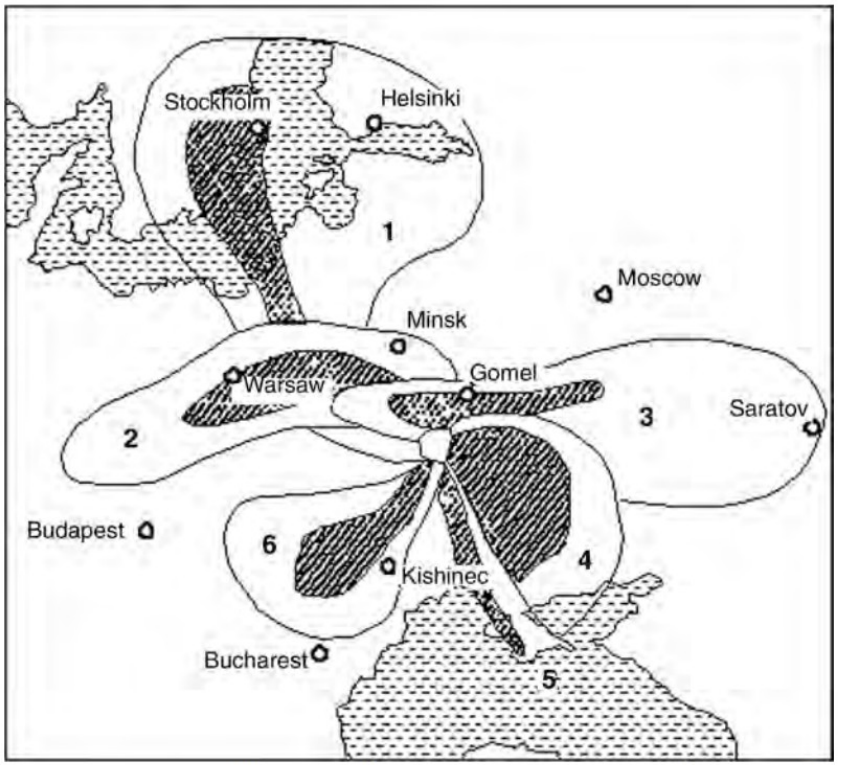

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Nuclear Escalation

31?

Image: https://upload.wikimedia.org/wikipedia/commons/b/b5/Radioactive.svg

Nuclear Escalation

4.000?

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Nuclear Escalation

31?

4.000?

16.000?

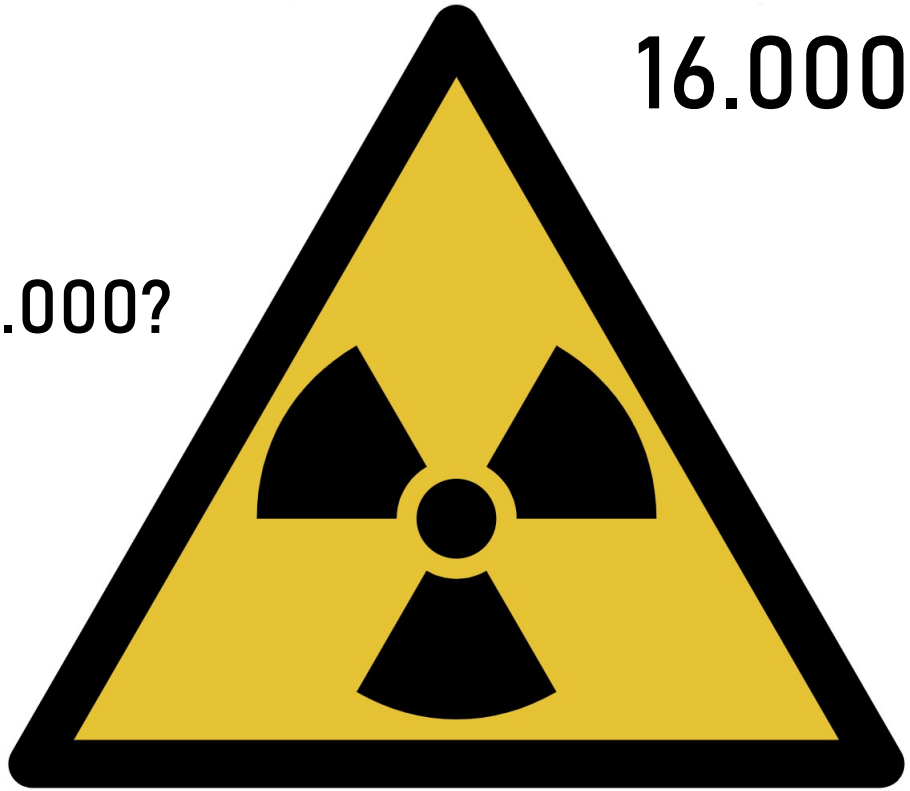

Image: https://upload.wikimedia.org/wikipedia/commons/b/b5/Radioactive.svg

Nuclear Escalation

985.000?

16.000?

4.000?

31?

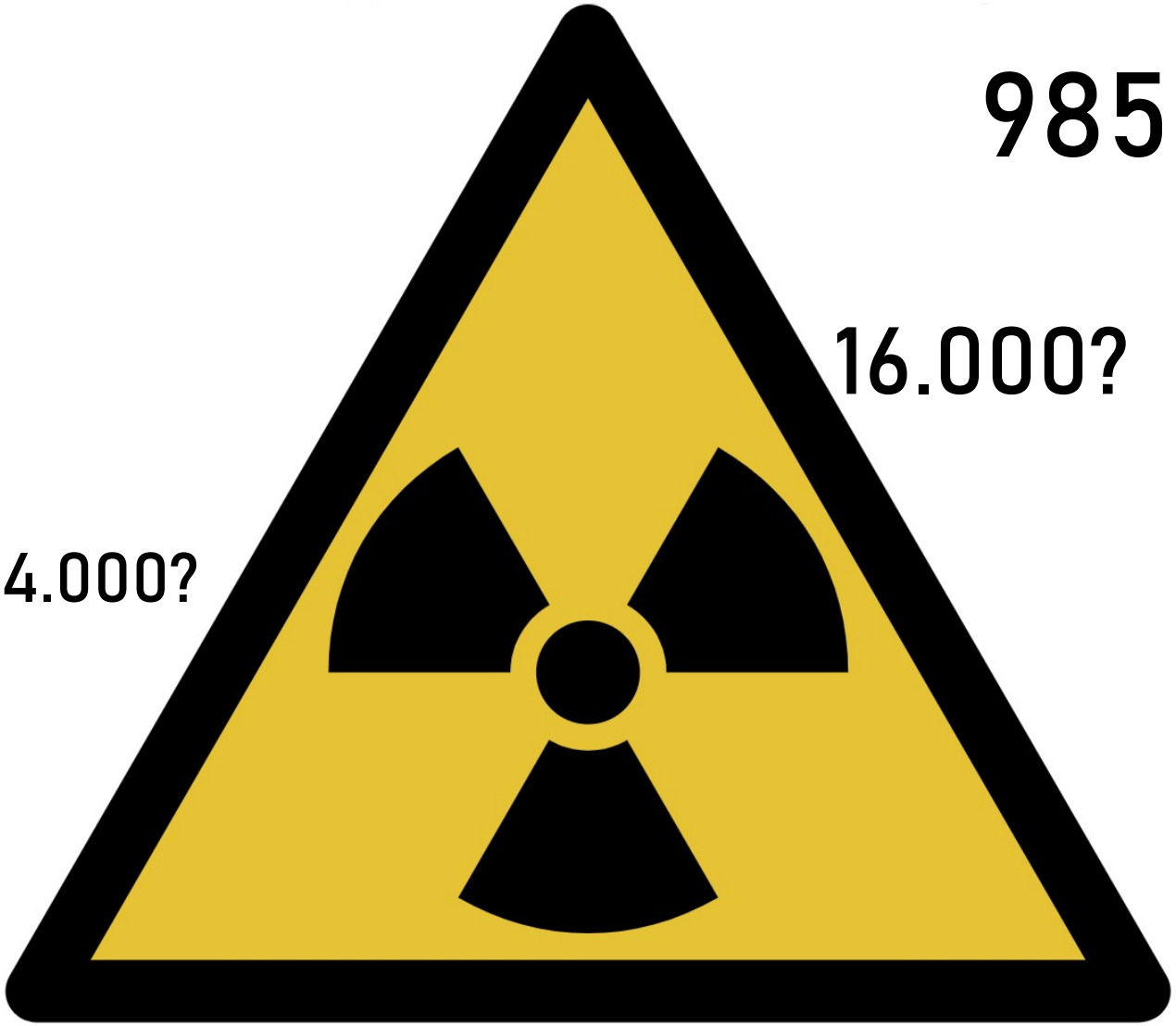

Image: https://upload.wikimedia.org/wikipedia/commons/b/b5/Radioactive.svg

Radiation epidemiology

- effects of radiation exposure:
  - deterministic effects
    - effect is certain to occur under given conditions
  - stochastic effects
    - effect may or may not occur
    - Major stochastic effect = cancer
    - Only able to express a probability that radiation was the cause

Radiation epidemiology

- approaches to asses long-term health effects:
  - risk models
    - e.g. Atomic bombings survivors
    - but: difference in dose level
  - empirical studies
    - relatively low doses and need for long-term follow-up
    - observed associations may not necessarily indicate causality

- factors that may bias the result:
  - frequency of disease detection
  - quality of diagnosis etc.

East vs. West

- Initial death toll: 2
- Official Soviet death toll: 31
  - high radiation doses to 134 of 600 plant staff and emergency personnel resulted in ARS and killed ~29
- Official UN (2006) short-term death toll: 54
  - additional trauma and ARS deaths
  - including journalists, physicians and a helicopter crash

"Health effects due to radiation [...]" UNSCEAR 2008

- based on peer-reviewed reports and information by governments
- main focus: empirical studies
  - estimation of individual doses

- reasonable evidence that acute radiation exposure of large population with doses above 100 mSv increases cancer morbidity/mortality
  - but: no conclusive evidence for increased cancer morbidity at very small doses

    → assumption of a threshold

"Health effects due to radiation [...]" UNSCEAR 2008

1. attributable health risks of radiation:
    1. ARS
    2. leukemia and cataracts
    3. thyroid cancer
    4. no persuasive evidence of any other health effects in general population

"Health effects due to radiation [...]" UNSCEAR 2008

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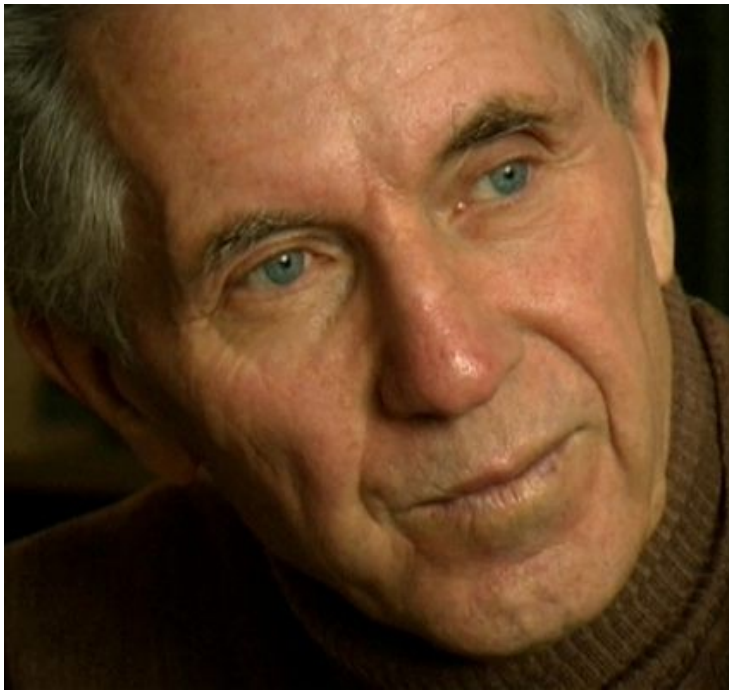
Population group	*Size (thousands)*	*Average thyroid dose in 1986 (mGy)*	*Average effective dose in 1986-2005 (mSv)*	*Collective thyroid dose in 1986 (man Gy)*	*Collective effective dose in 1986-2005 (man Sv)*
Recovery operation workers	530	—[a]	117[b]	—	61 200
Evacuees	115	490	31[c]	57 000	3 600
Inhabitants of contaminated areas[d] of Belarus, Russia and Ukraine	6 400	102	9[c,e]	650 000	58 900
Inhabitants of Belarus, the Russian Federation and Ukraine	98 000	16	1.3[c,e]	1 600 000	125 000[e]
Inhabitants of distant countries[f]	500 000	1.3	0.3[c,e]	660 000	130 000[e]

Table: UNSCEAR (2008): "Health effects due to radiation from the Chernobyl accident" (Annex D of the 2008 UNSCEAR Report

"Chernobyl: Consequences of the Catastrophe [...]"

Image: https://i1.rgstatic.net/ii/profile.image/279971655372800-1443761852931_Q512/Alexey_Yablokov.jpg

"Chernobyl: Consequences of the Catastrophe [...]"



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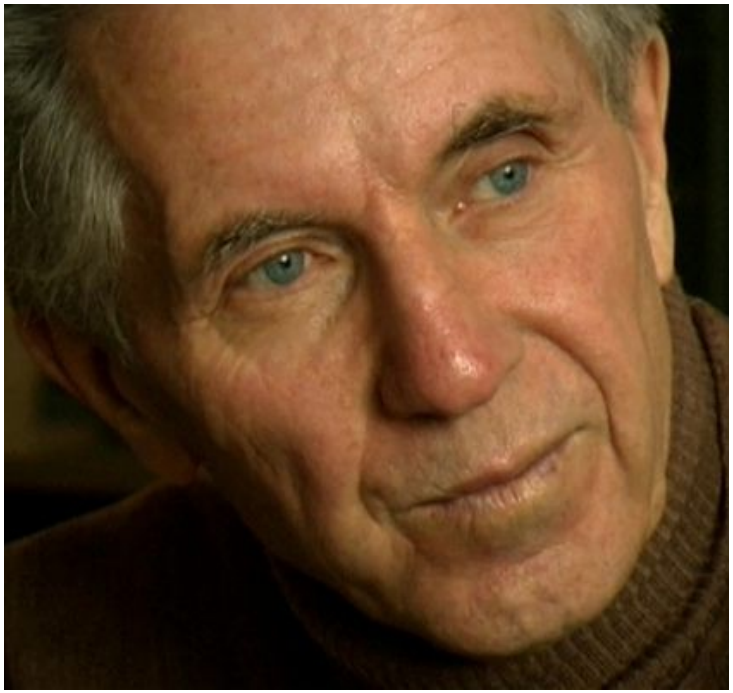

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"Chernobyl: Consequences of the Catastrophe [...]"

- published by the New York Academy of Sciences in 2019
  - not peer-reviewed
- analysis based on over 5.000 mainly Slavic publications
- critical view on previously conducted studies on the Chernobyl accident
  - IAEA's exclusion of data with estimated doses below a certain threshold
  - dismissal of eastern European studies due to questionable scientific practices

- "One nuclear reactor can pollute half the globe."
- "Prior to 1985 more than 80% of children in the Chernobyl territories of Belarus, Ukraine and European Russia were healthy; today fewer than 20% are well."
- "[…] methodologically incorrect to demand a "statistically significant correlation" as conclusive evidence of the harmful effect from Chernobyl."

"Chernobyl: Consequences of the Catastrophe [...]"

- Critical review example by Dr. Monty Charles
  - discounting socioeconomic and screening factors for increased morbidity
  - variations between contaminated ares before the accident not accounted for
  - unclear use of sources have been used and influence on conclusions
  - verifying all quoted sources would require considerable effort
  - dismissal of epidemiological approach to seek correlation of health effects with levels of contamination or dose

- "Tables 6.19 and 6.20 present [...] more realistic mortality and morbidity calculations of Europe and the world."

"Chernobyl: Consequences of the Catastrophe [...]"

TABLE 6.19. Predicted Cancer Morbidity and Mortality (Excluding Leukemia**) Caused by the Chernobyl Cs-137 for Future Generations* (Gofman, 1994b: vol. 2, ch. 24, p. 5)

	Number of cases	
Region	Lethal	Nonlethal
Belarus, Ukraine, Moldova	212,150	212,150
Europe (without CIS)	244,786	244,786
Other countries	18,512	18,512
Total	475,368	475,368

*On the basis of an expected collective dose "indefinitely" of 127.4 million person/rad; **Global death rate from Chernobyl leukemia by J. Gofman calculation as of 1994: 19,500 persons.

Table: Yablokov et al. (2007): "Chernobyl: Consequences of the Catastrophe for People and the Environment"

"Chernobyl: Consequences of the Catastrophe [...]"

TABLE 6.20. Predicted Additional Chernobyl Cancer Morbidity and Mortality in Belarus, Ukraine, and European Russia* (Malko, 1998)

Cancer	Belarus	Russia	Ukraine
Thyroid—morbidity	20,300	8,000	24,000
Thyroid—mortality	2,030	800	2,400
Leukemia—mortality	1,300	760	1,550
Malignant tumors, other than thyroid—mortality	12,700	7,400	15,100
Total mortality	16,030	8,960 44,040	19,050

*Entire world: 90,000 lethal cancers.

Table: Yablokov et al. (2007): "Chernobyl: Consequences of the Catastrophe for People and the Environment"

"Chernobyl: Consequences of the Catastrophe [...]"

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- "Tables 6.19 and 6.20 present [...] more realistic mortality and morbidity calculations of Europe and the world."
- two different estimated ranges from same author

"Chernobyl: Consequences of the Catastrophe [...]"

Table 6.21 presents the average data. The confidence limits for the incidence of cancer are between 62,206 and 196,611, and the death toll is between 40,427 and 121,277 (Malko, 2007). These numbers could increase for many future generations because of continued radiation from the further release of Cs-137, Sr-90, Pu-241, Am-241, Cl-36, and Tc-99.

The number of illnesses and deaths determined by Malko's (2007) calculations cannot be dismissed as grossly overestimated: 10,000–40,000 additional deaths from thyroid cancer, 40,000–120,000 deaths from the other malignant tumors, and 5,000–14,000 deaths from leukemia, for a total of 55,000 to 174,000 deaths for the "Chernobyl generation" from 1986 to 2056.

"Chernobyl: Consequences of the Catastrophe [...]"

- claim: 3,8-4,0% of all deaths in contaminated areas caused by radiation
- total number of Chernobyl victims until 2004:
  - Belarus, Ukraine, Russia: ~237.500
  - additional 10 million people in less contaminated areas: ~170.000
  - another 150 million Europeans: ~255.000
  - assuming 20% of radionuclides were deposited outside Europe: ~323.000

  → ~985.000 deaths

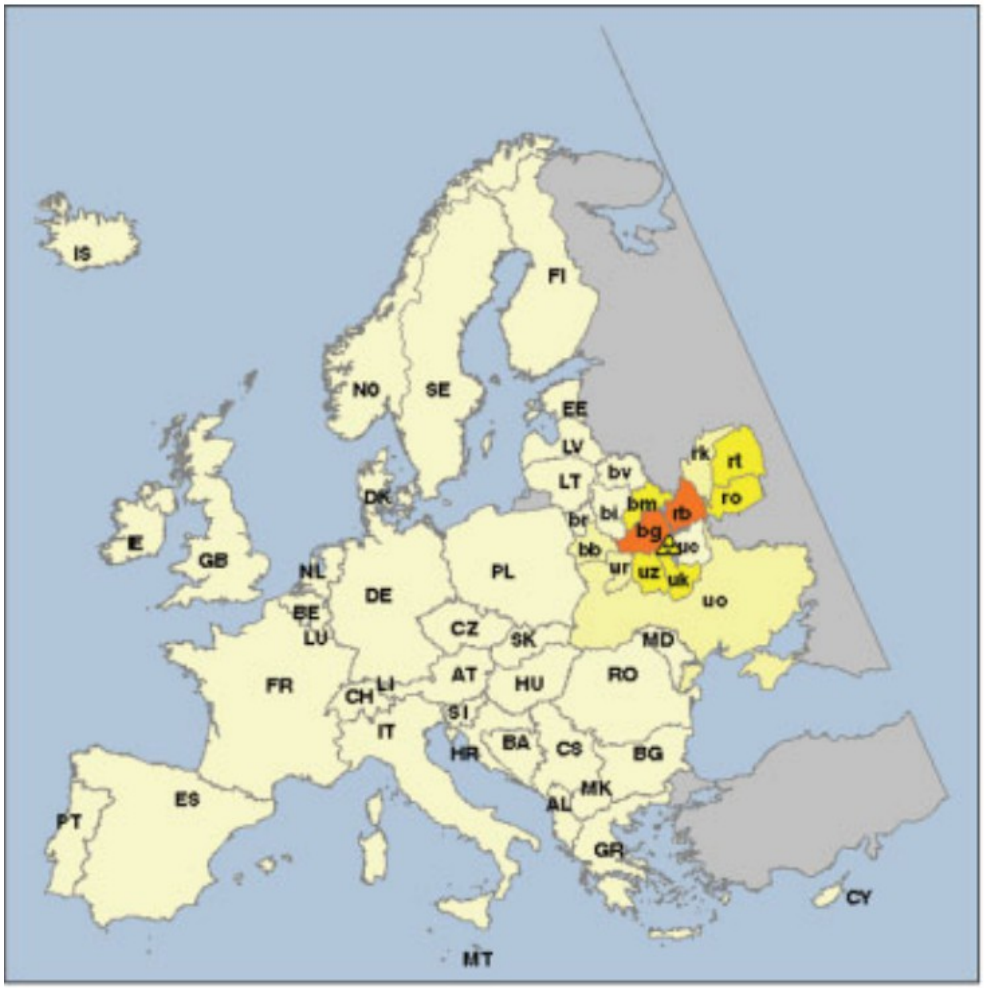
"Estimates of the cancer burden in Europe [...]"

- using risk projection models and incidence and mortality rate studies
- average whole body doses were estimated for 1986-2005 and projected to 2065
- based on country-specific radiation monitoring data and estimates by UNSCEAR and Chernobyl Forum
- risk models developed by US National Research Council's Committee on the Biological Effects of Ionizing Radiation (BEIR VII)
  - Linear-No-Treshold model
  - data from Japanese atomic bomb survivors and medically exposed cohorts

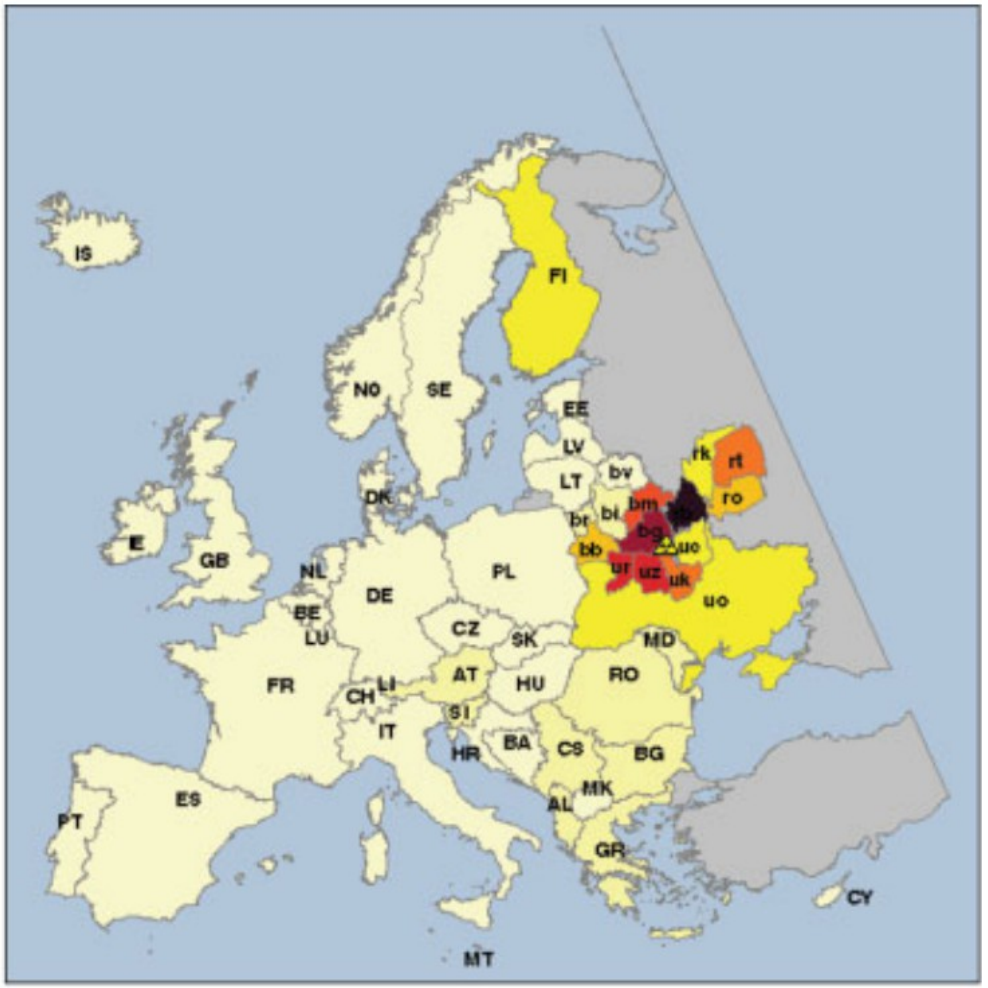
"Estimates of the cancer burden in Europe [...]"

- analysis of mortality based on data from recent study on mortality and smoking in developed countries (1950-2000)
  - mortality rates were calculated and standardized to world population
- 1986-2005:
  - Belarus: ~2,8 mSv
  - Ukraine: ~2,1 mSv
  - Finland: ~1,4 mSv
  - Europe: ~0,5 mSv

"Estimates of the cancer burden in Europe [...]"



a. 1986



b. 1986-2005

Image: Cardis et al. (2006): "Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident"

"Estimates of the cancer burden in Europe [...]"

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- 1986-2005:
  - Belarus: ~2,8 mSv
  - Ukraine: ~2,1 mSv
  - Finland: ~1,4 mSv
  - Europe: ~0,5 mSv
- Comparison: natural background radiation: ~20 mSv (over 20 years)
- by 2065 ~16.000 (3.400-72.000) cases thyroid cancer and 25.000 (11.000-59.000) cases of other cancers

"Estimates of the cancer burden in Europe [...]"

- total predicted cancer cases: ~41.400
- total predicted cancer deaths: ~15.700

- estimates are subject to substantial uncertainty
- attributable fractions (% of all cancer deaths):
  - thyroid cancer: 0,08% - 12% (least – most contaminated)
  - leukemia: 0,01% - 0,66% (least – most contaminated)
  - other: 0,002% - 0,23% (least – most contaminated)

福島第一 Fukushima Daiichi

Image: https://upload.wikimedia.org/wikipedia/commons/6/6f/Location_Map_Asia.svg

福島第一 Fukushima Daiichi

Image: https://upload.wikimedia.org/wikipedia/commons/3/31/Provinces_of_Japan.svg

March 11, 2011 – Japan's Chernobyl?

- Ōkuma City, Fukushima Prefecture
- series of equipment failures following earthquake and subsequent tsunami
- 3 nuclear meltdowns
- sea water that had been exposed to melting rods was returned to the sea for several months
- Observed radioactive materiel released:
  - I-131:130 – 160 Pbq (Chernobyl = 1760 Peta Bq)
  - Cs-137: 6,1 – 15 Pbq (Chernobyl = 81 Peta Bq
- some 80% of radioactivity was deposited over the Pacific ocean

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別紙2

文部科学省及び米国DOEによる航空機モニタリングの結果
（福島第一原子力発電所から80km圏内のセシウム134，137の地表面への蓄積量の合計）

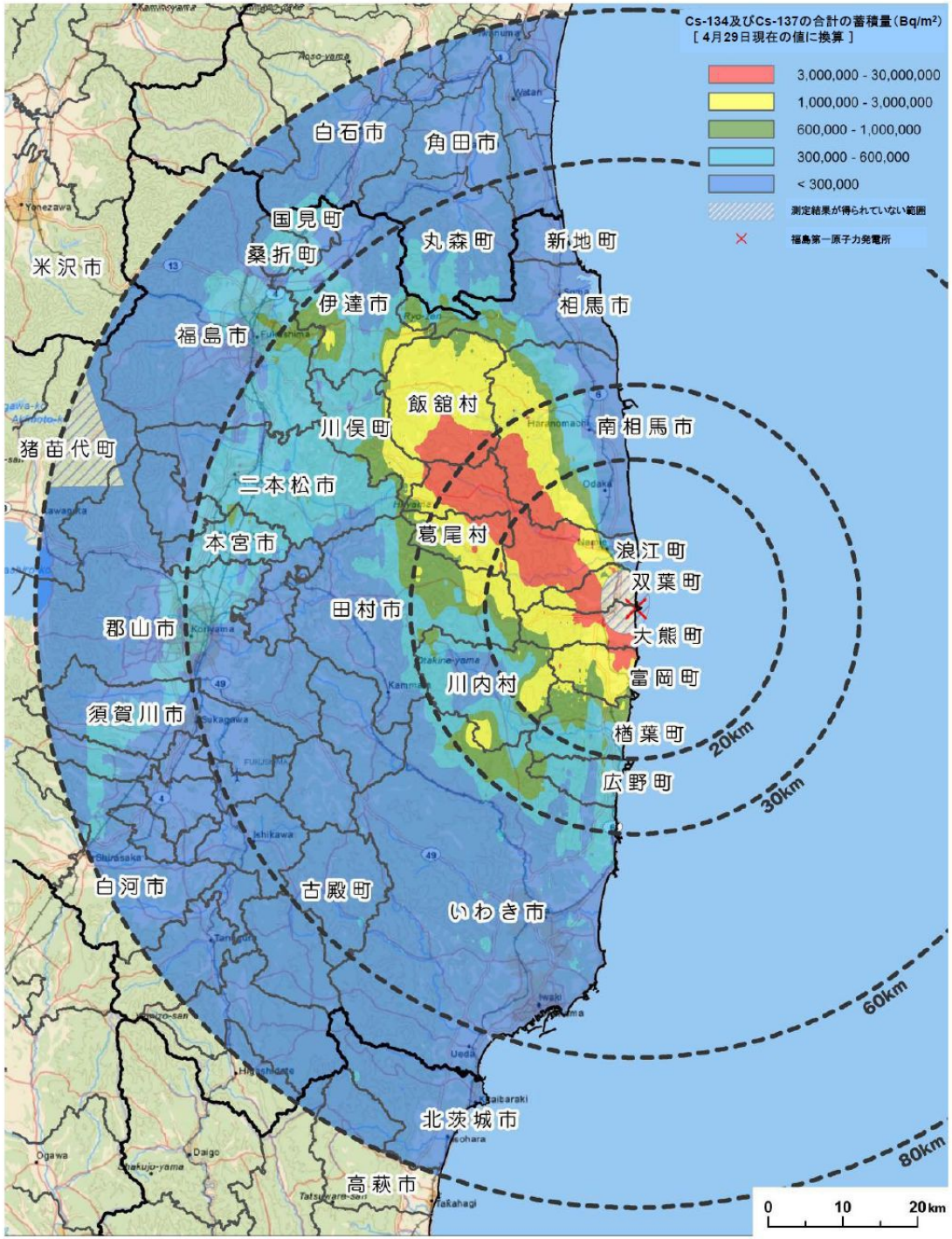

Image: http://onodekita.sakura.ne.jp/sblo_files/onodekita/image/2011050701.jpg

March 11, 2011 – Japan's Chernobyl?

- government set 20 mSv/year as limit for occupation
- estimations of cumulative dose outside 80km radius and much area inside that are less than 1 mSv/year
- 20km radius evacuation zone
- 25.000 workers
- workers stay until they reach radiation limit of 50 mSv/year
- about 170.000 people live close to the plant
- December 16, 2011 the plant was declared stable

Nuclear Escalation

14.000?

1.400?

50?

1?

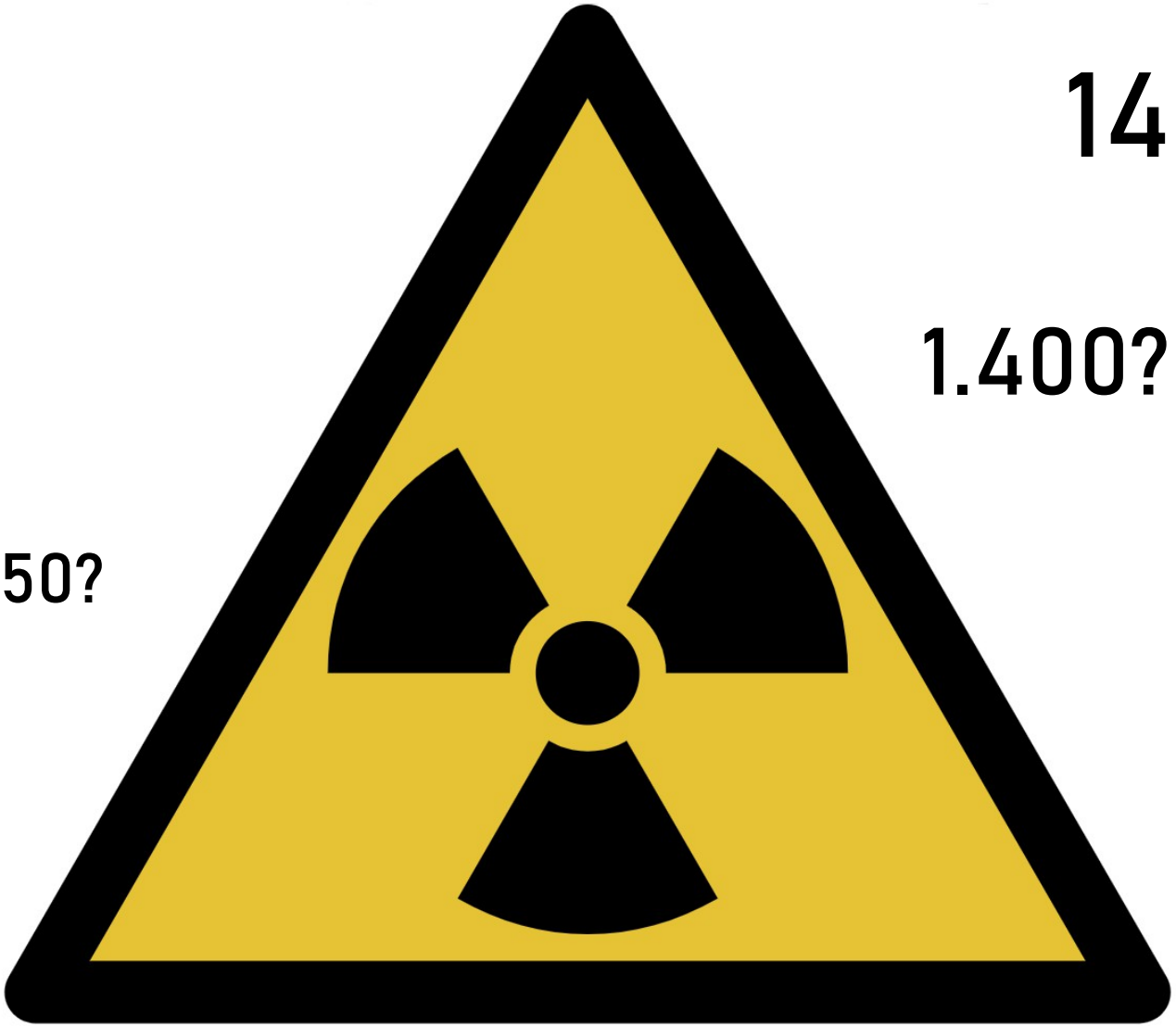

Image: https://upload.wikimedia.org/wikipedia/commons/b/b5/Radioactive.svg

Zero Casualties?

- no deaths caused by ARS
- many deaths due to the evacuation and ensuing long-term displacement
- deaths during and immediately after transit: 34-50
  - mostly hospital inpatients, elderly people
  - disruption of hospital operations, stress, etc.

  → "disaster-related deaths"
- April 14 2011, oldest resident of liate, a 102-year-old, committed suicide rather than to evacuate

“An Unexpected Mortality Increase in the U.S. [...]"

- evaluate potential changes in US mortality from exposure to Fukushima fallout
- use of EPA (US Environmental Protection Agency) and CDC (US Centers for Disease Control and Prevention) data
- EPA: air, water and food samples

“An Unexpected Mortality Increase in the U.S. [...]"

Table 1

Concentrations of radioisotopes in the environment, United States:
10 isotopes measured by the EPA, March and April 2011 (after Fukushima)

	Number (%) of samples with detectable levels reported			
	Air (n = 229)	Precipitation (n = 157)	Milk (n = 67)	Drinking water (n = 153)
Barium-140	4.4 (10)	0.0 (0)	0.0 (0)	0.0 (0)
Cesium-134	14.8 (34)	5.7 (9)	3.0 (2)	0.7 (1)
Cesium-136	2.2 (5)	0.0 (0)	0.0 (0)	0.0 (0)
Cesium-137	20.1 (46)	7.0 (11)	6.0 (4)	0.7 (1)
Cobalt-60	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Iodine-131	77.3 (177)	49.0 (77)	13.4 (9)	22.2 (34)
Iodine-132	13.1 (30)	0.0 (0)	0.0 (0)	0.0 (0)
Iodine-133	0.4 (1)	0.0 (0)	0.0 (0)	0.0 (0)
Tellurium-129	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Tellurium-129m	0.4 (1)	0.0 (0)	0.0 (0)	0.0 (0)
Total all	13.3 (304)	6.2 (97)	2.2 (15)	2.4 (36)
Total excluding I-131	6.2 (127)	1.4 (20)	1.0 (6)	0.1 (2)

Source: U.S. Environmental Protection Agency (16).

Table: Joseph J. Mangano and Janette D. Sherman (2012). "An Unexpected Mortality Increase in the United States Follows Arrival of the Radioactive Plume from Fukushima: Is There a Correlation?".

“An Unexpected Mortality Increase in the U.S. [...]"

- evaluate potential changes in US mortality from exposure to Fukushima fallout
- use of EPA (US Environmental Protection Agency) and CDC (US Centers for Disease Control and Prevention) data
- EPA: air, water and food samples
- CDC: report of weekly deaths by age in 122 cities (25-35% of national total)

"An Unexpected Mortality Increase in the U.S. [...]"

Table 2

Changes in reported deaths, all ages: weeks 12 to 25 and 14 weeks prior, 2010 versus 2011, 122 U.S. cities

	Total deaths					Total deaths			
Week	2010	2011	No. (%) change		Week	2010	2011	No. (%) change	
12	11,010	12,137	+1,127	(+10.24)	50	10,323	10,702	+379	(+3.67)
13	11,097	11,739	+642	(+5.79)	51	7,942	8,339	+397	(+5.00)
14	11,075	12,052	+977	(+8.82)	52	8,288	8,194	–94	(–1.13)
15	10,712	10,928	+216	(+2.02)	1	11,557	11,804	+247	(+2.14)
16	10.940	10,743	–197	(–1.80)	2	11,299	10,775	–524	(–4.64)
17	10,549	10,826	+277	(+2.63)	3	10,110	10,689	+579	(+5.73)
18	10,637	11,251	+614	(+5.77)	4	10,832	10,420	–412	(–3.80)
19	10,389	11,300	+911	(+8.77)	5	10,524	10,295	–229	(–2.18)
20	10,491	11,132	+641	(+6.11)	6	9,877	10,700	+823	(+8.33)
21	10,352	10,839	+487	(+2.77)	7	9,802	10,952	+1,150	(+11.73)
22	9,894	9,538	–356	(–3.60)	8	10,198	10,762	+564	(+5.53)
23	10,781	10,770	–11	(–0.10)	9	10,586	10,779	+193	(+1.82)
24	10,178	10,981	+803	(+7.89)	10	10,699	10,639	–60	(–0.56)
25	10,290	10,779	+489	(+4.75)	11	9,969	10,274	+305	(+3.06)
Total	148,395	155,015	+6,620	(+4.46)*	Total	142,006	145,324	+3,318	(+2.34)

Note: For weeks 12 to 25, actual numbers of deaths were available for 1,653 (99.22%) in 2010 and 1,650 (99.04%) in 2011 of the 119 cities for the 14 weeks. For weeks 50 to 52 and 1 to 11, actual numbers of deaths were available for 1,445 (99.24%) in 2010 and 1,443 (99.11%) in 2011 of the 104 cities for the 14 weeks.

*$p < 0.000001$

Table: Joseph J. Mangano and Janette D. Sherman (2012). "An Unexpected Mortality Increase in the United States Follows Arrival of the Radioactive Plume from Fukushima: Is There a Correlation?".

“An Unexpected Mortality Increase in the U.S. [...]"

- evaluate potential changes in US mortality from exposure to Fukushima fallout
- use of EPA (US Environmental Protection Agency) and CDC (US Centers for Disease Control and Prevention) data
- EPA: air, water and food samples
- CDC: report of weekly deaths by age in 122 cities (25-35% of national total)
- Comparison of a 14-week period March to June in 2010 and 2011
  - statistical significance between the two death trends was calculated by using the difference between two means
  - observed difference vs the expected difference of the 2010-2011 change for the preceding 14 weeks

“An Unexpected Mortality Increase in the U.S. [...]"

- total deaths increased 4,46% from 148.395 (2010) to 155.015 (2011) in 119 cities
- previous 14 weeks increase: 2,34% in 104 cities
- difference between actual and expected changes of 2,12 percentage points translates to 3.286 excess deaths
  - 13.983 projected total deaths (assuming a total of 2.450.000 US deaths) during 14-week period
- infant deaths increased 1,8% from 2.674 (2010) to 2.722 (2011)
- previous 14 weeks decline: 8,37% in („highly significant, p<0,0002)
- 277 excess infant deaths
  - 822 projected total infant deaths (assuming 30.000 US infant deaths in 2011)

“An Unexpected Mortality Increase in the U.S. […]"

- CDC report flaws (by author):
  - deaths are categorized when death certificate was filed not necessarily the date of death
  - raw numbers, not mortality rates
- “Recent assessments have suggested that the amount of radioactivity released from Fukushima equals or exceeds that released from Chernobyl“
- 14.000 figure based on acute deaths from low radiation doses, which there is no known mechanism for

More disaster-related deaths

- long-term displacement evacuees died at increased rate
  - reasons: degraded living conditions, separation from support networks
- suicides due to mental stress, despair, anxiety and depression caused by media coverage and long periods of evacuation
- 33 cases of heat strokes among recovery workers
  - two workers died from heart failure

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Image: https://i.pinimg.com/originals/79/92/99/7992991ff0cbaa20ca7cf5c12f283cbc.jpg

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- total nuclear-disaster-related-deaths (2016): 1368
- one worker died from radiation induced lung cancer
- >160.000 people in the general population were screened in March 2011 → no health affects

Image: https://i.pinimg.com/originals/79/92/99/7992991ff0cbaa20ca7cf5c12f283cbc.jpg

Evacuation worse than radiation?

- UNSCEAR report from 2013:
  - average effective dose of recovery workers: ~12 mSv
  - “ “ of adults living in the City of Fukushima: ~4 mSv
  - no increased incidence of radiation-related health effects are expected
- WHO study from 2013:
  - ~1% absolute increase of cancer during lifetime for infants ATA
  - health impacts likely to be below detectable levels
- Stanford University study from 2012:
  - ~130 additional cancer deaths
  - ~2-12 deaths due to radiation exposure to workers

Why do claims in literature differ?

- wide range of estimates in scientific literature mainly due to
  - different estimates of population dose
    - difficulty in reconstructing doses from radionuclides
    - difficulty determining levels of external and internal radiation for average person/group, doses only based on assumptions
  - unclear impact of ultra-low doses
    - correctness of the contested LNT model
  - use of different radiation risk models
  - different interpretations of epidemiological data
    - risk models for predictions based on populations exposed to higher doses for brief periods
  - long average latency of most radiation related cancers

Science or Science Fiction?

- screening and diagnostic suspicion bias
  - Frequent examination → greater likelihood of detection of small tumors
  - physician knowing that patient had been exposed to radiation, might be more inclined to look more thoroughly for cancer etc.
- visible trends appear in countries with average whole-body dose of >1 mSv
  - but: increase in cancer mortality accompanied by similar increase in non-cancer mortality
  - trends unlikely to reflect effect of radiation
- predictions only provide an idea of the order of magnitude

Sources

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