A Rational Environmentalist's Guide to Nuclear Power

-or-

How I Learned to Stop Worrying and Love the Glow

NukeEngineer

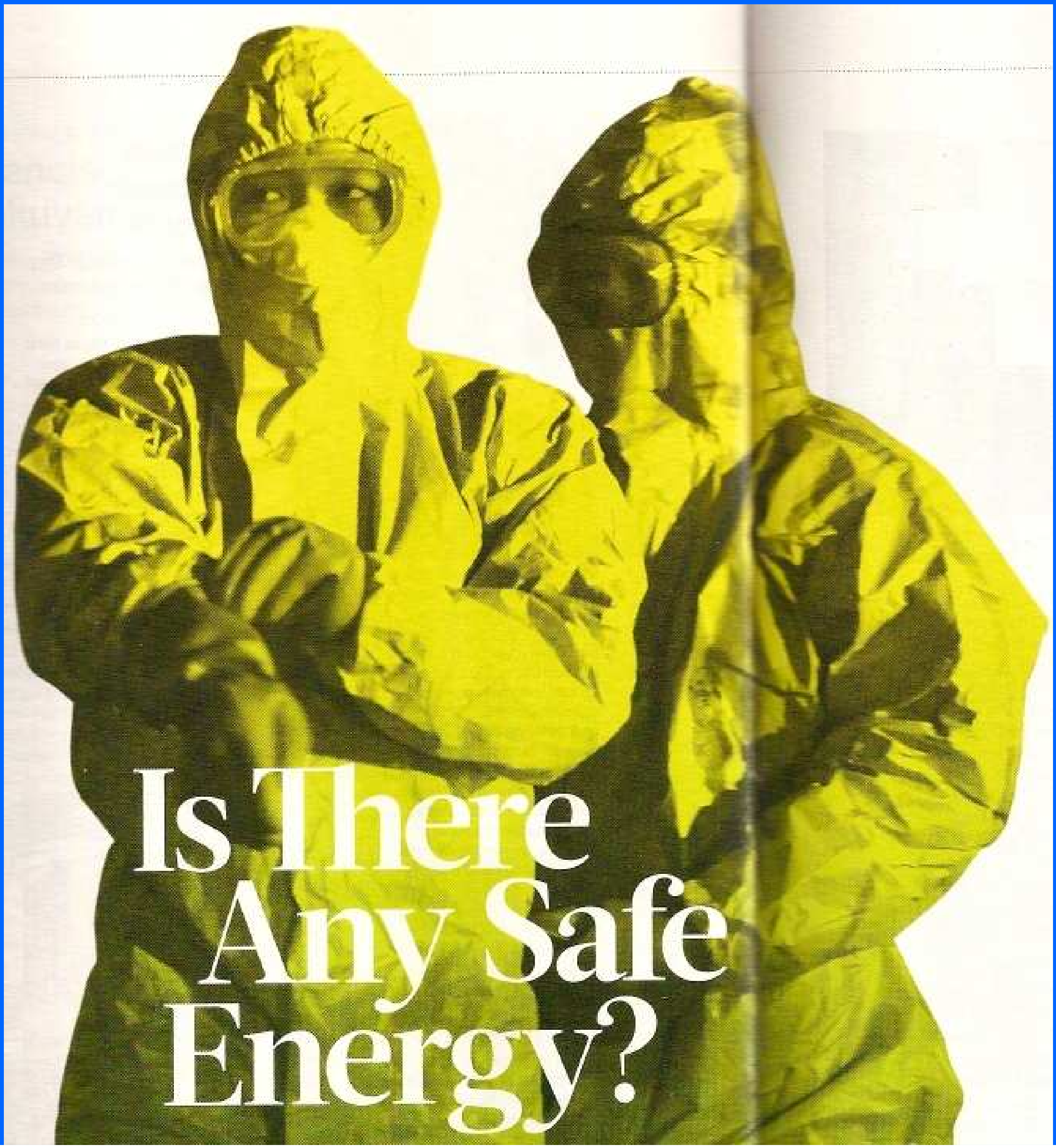
Earth Day, 2011

New Jersey's Sources of Electricity

coal:	9.0 million MWH =	14.0%
oil:	0.3 million MWH	
gas:	20.8 million MWH =	32.4%
other:	1.7 million MWH	
Nuclear:	32.3 million MWH =	**50.4**%
total:	64.1 million MWH	(2008 figures)

Over half of NJ's electric power comes from nuclear energy.

Here's the question:



Short answer:

Er, Ummmm…

No.   Sorry about that.

Sir Winston Churchill famously said:

"…democracy is the worst form of government except all those other forms that have been tried…"

So a slightly longer answer might be:

Nuclear fission is the most dangerous form of large-scale electric power generation, except all those other forms that have been tried.

We Are A Technological Civilization

- We expect our lights, refrigerators, computers, and hospitals to work whenever we need them, 24/7/365.
- Before the Rural Electrification Act (1936), 99% of farms had no electricity. By the 1970's, 98% had utility electric power.
- In 1900, feeding the USA took 41% of all its workers. By 1945, it was 16%. Today, less than 2% of us work on farms, and we are net exporters of food to the world.

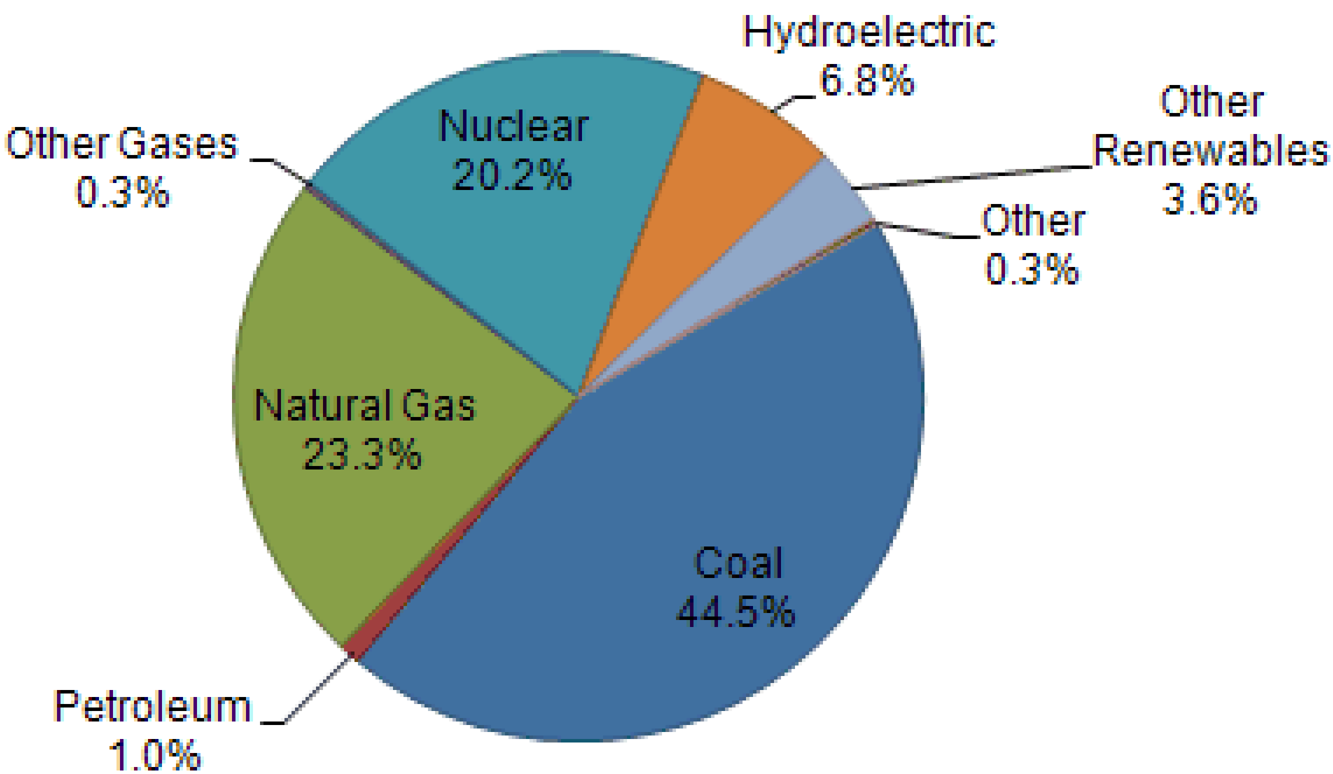
National Power Grid

- Base Load: Constant power which must be always available (coal, nuclear, gas).
- Peaking Load: “Extra” power to meet high demand (e.g. air conditioning on summer afternoons). Mainly natural gas.
- Intermittent: Solar and wind do not yield rated power all the time; *they can’t replace base-load capacity*. Energy storage is possible, but greatly increases cost. Solar peak power often matches peak A/C load.

Coal, natural gas, and nuclear generation accounted for 88.0 percent of total net generation in 2009, and between 85 and 90 percent during the period 1997 through 2009. However, the relative contribution of these energy sources has been shifting; natural gas generation has seen the fastest growth in recent years.

Figure ES 1. U.S. Electric Power Industry Net Generation, 2009

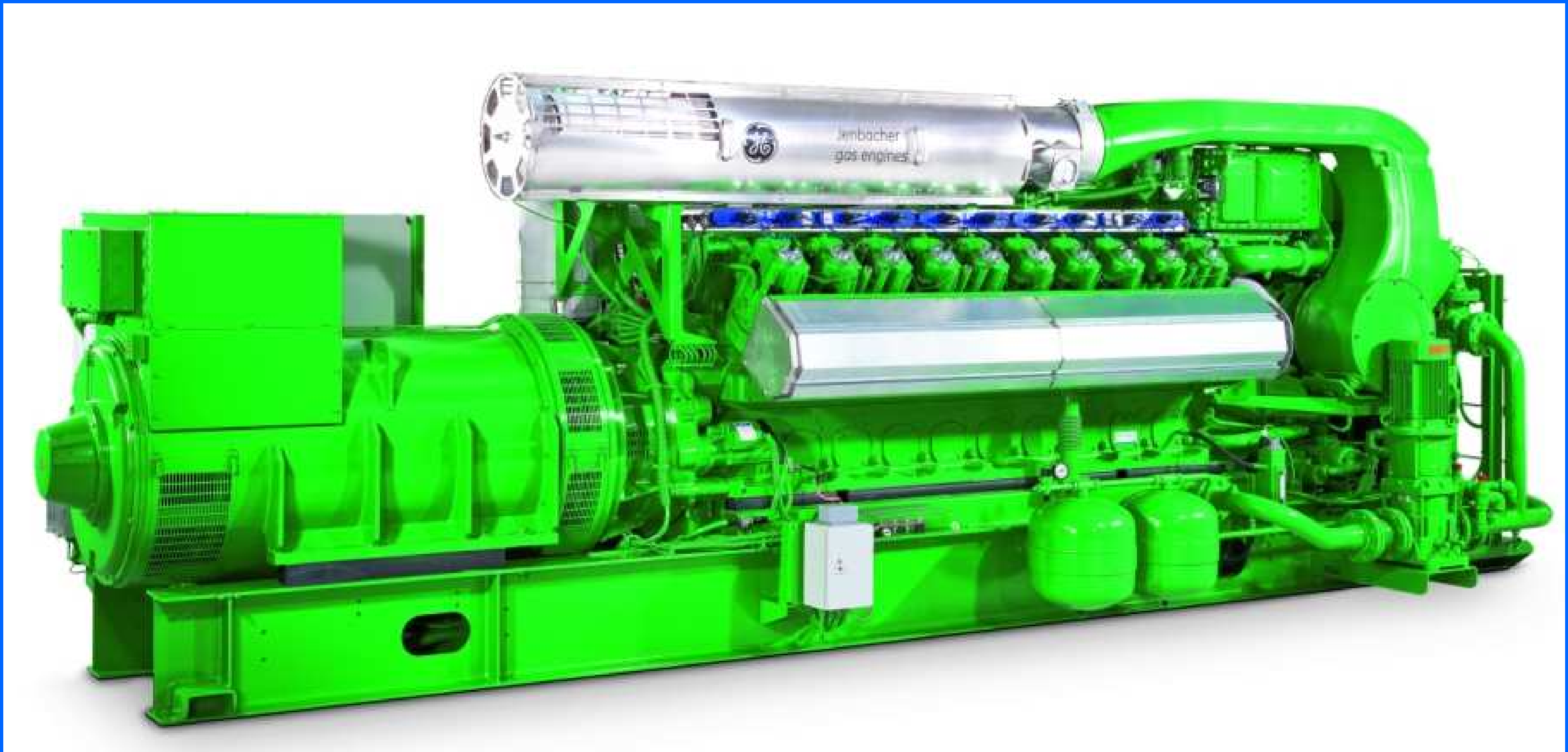
Total = 3,950 billion kWh



Electric Utility Plants = 60.1%
Independent Power Producers and Combined Heat and Power Plants = 39.9%

Source: U.S. Energy Information Administration, Form EIA-923, "Power Plant Operations Report."

“Other gases”?? Cow Power!



Smelly, but safe! Four of these monster engines are generating 38,000 MWh per year from the… ummm… “output” of a quarter of a million cows on a farm in China.

Ok, biogas from cow poop is a pretty safe technology. Three-tenths of a percent of our national power requirements doesn’t help much, though.

Wind Is Perfectly Safe, Right?

Oh.   Ok, maybe not…

Wind Power Is Not Pollution-Free

This is the mine

That makes the rare earths

That go in the magnets

That go in the generators

That go in the windmills that greens build.

http://www.dailymail.co.uk/home/moslive/article-1350811/In-China-true-cost-Britains-clean-green-wind-power-experiment-Pollution-disastrous-scale.html (very instructive article despite over-the-top link name)

Coal's Chernobyl

London's Great Smog of 1952: 12,000 deaths in a few months.

How Do We Know? Epidemiology

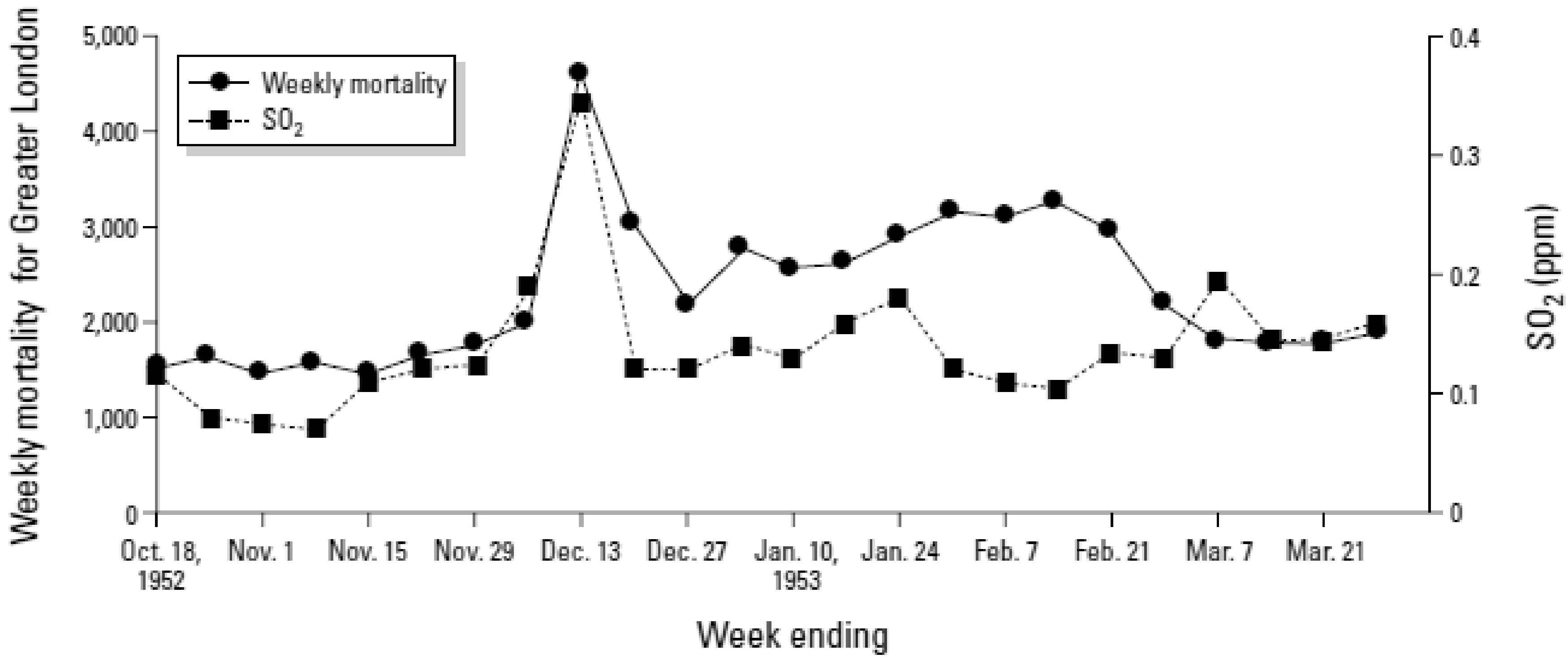


Figure 1. Approximate weekly mortality and SO_2 concentrations for Greater London, 1952–1953.

Epidemiology is the science of using statistics to figure out patterns of disease. The most famous early example was Dr. John Snow. In 1854, a cholera epidemic struck London. Snow noticed that the cases centered on one water pump. He had the pump handle removed, and cholera deaths stopped.

Hydro's Chernobyl

Banqiao Dam, Henan Province, China 1975

Typhoon Nina dropped >1 meter of rain in one day; the dam failed.

The resulting wall of water was 10-20 feet high and 6 miles wide.

At least 26,000 people drowned (estimates range up to 85,000)

Another 145,000 died soon after from starvation, disease

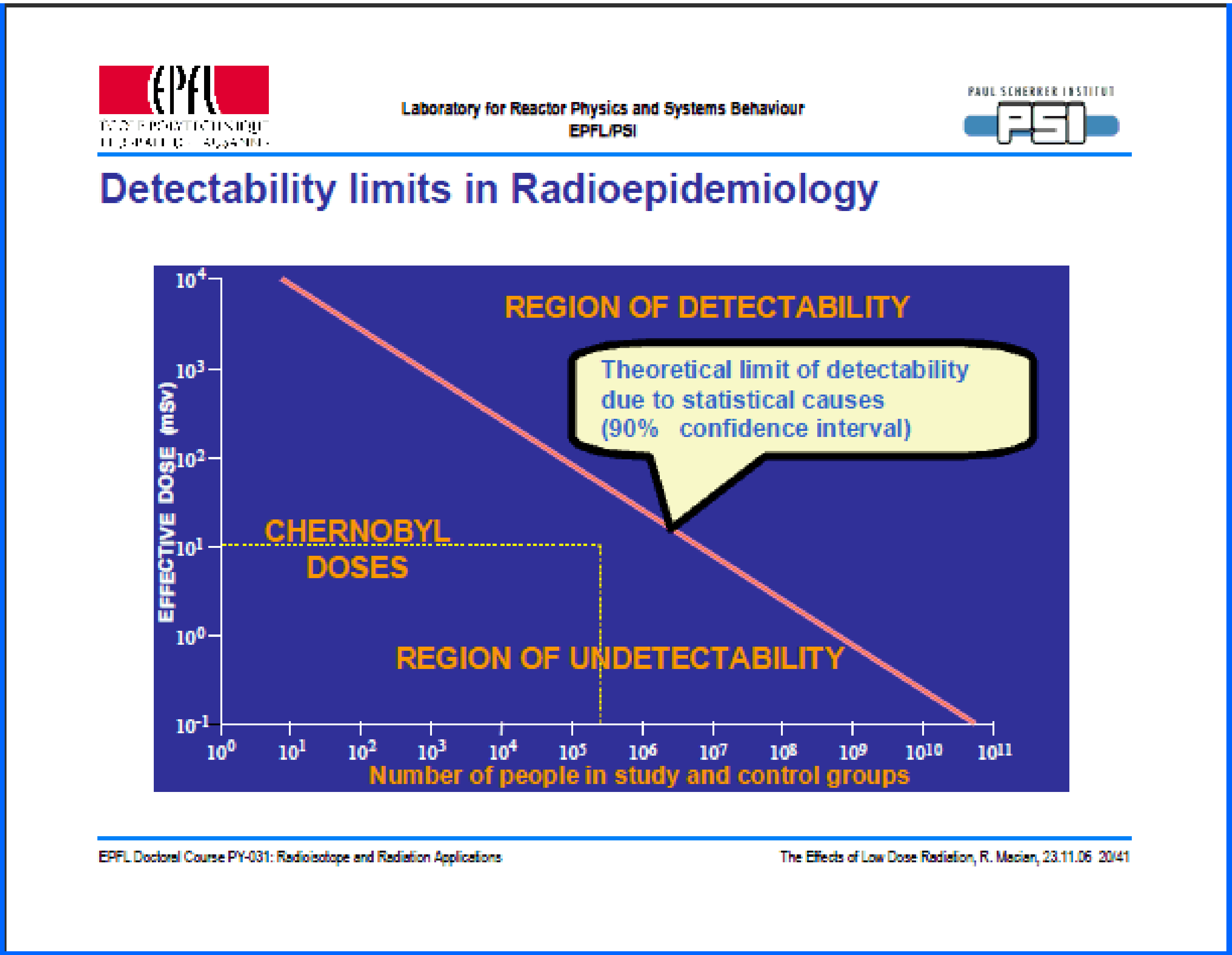
Chernobyl's Chernobyl

In April 1986, a reactor in the Ukraine suffered a meltdown. It had no containment shell. A fire fed by damaged roofing and reactor building materials burned intensely for 9 days, spreading radioactive material over much of Europe, with the heaviest contamination in the four oblasts (counties) nearest to the reactor.

50 emergency workers fighting the fire died within months, **28** from acute radiation exposure.

9-15 deaths from thyroid cancer over 15-20 years are statistically attributable to the accident (screening was rigorous, and thyroid cancer is 99% curable).

The World Heath Organization estimates 4000 “excess” cancer deaths over **70 years** (57/yr) in the 600,000 most-exposed people, statistically invisible against the 150,000 expected “natural” cancer deaths. Furthermore, the model used to predict this risk may be wrong, as we will see.



Radiation is a weak carcinogen, and cancer is a common cause of death (~23%). Studies since Chernobyl have not found significant increases in most cancers.

But natural thyroid cancer is quite rare, so even small increases can be detected as statistically significant compared to a low background rate.

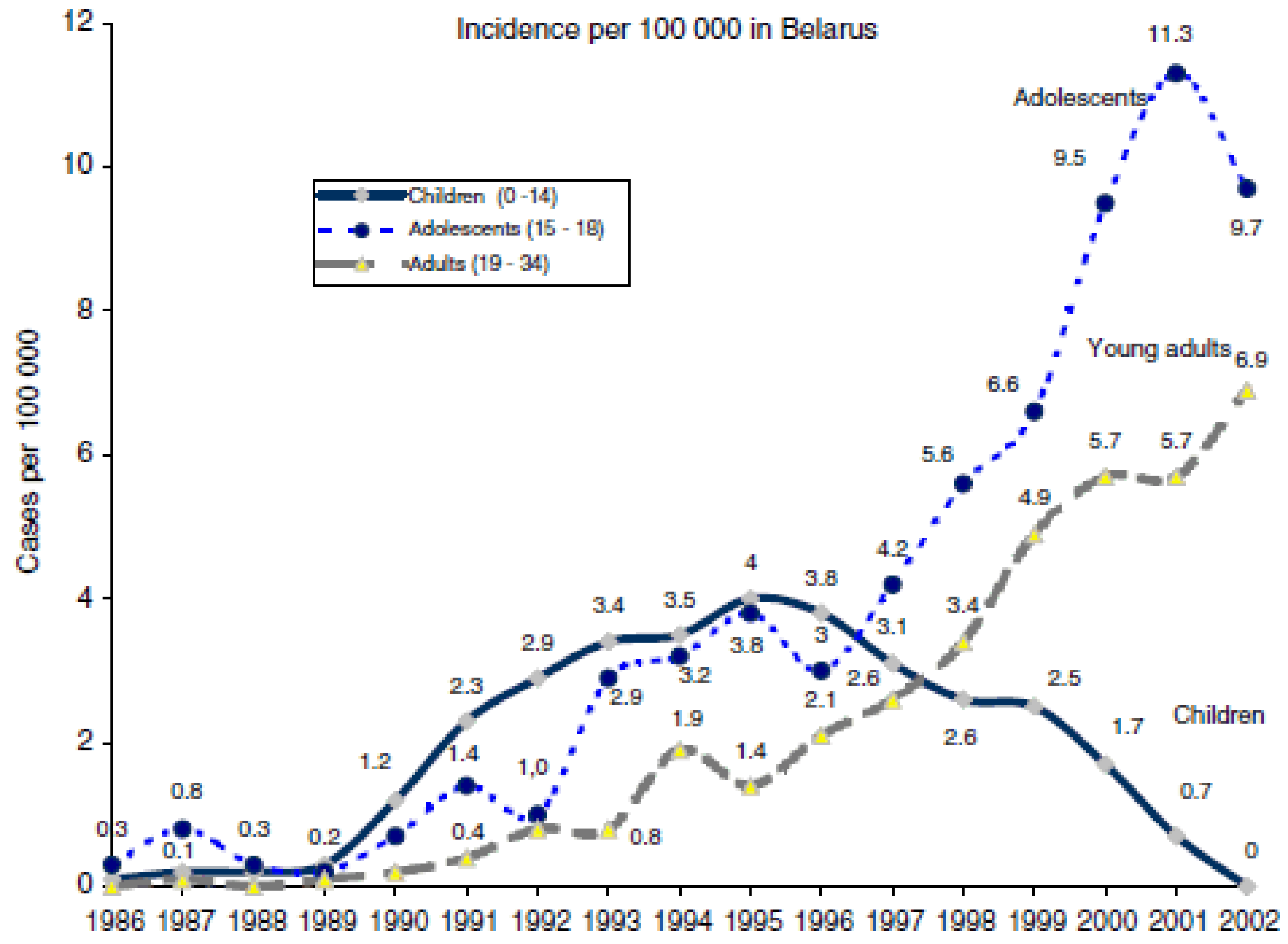


Figure 1. Annual incidence of childhood, adolescent and adult thyroid cancer in Belarus (courtesy of Yu E Demidchik).

Worst-case probability of getting thyroid cancer per year: 1 in 9,000

Probability of death from that (99% cure rate): 1 in 900,000

Annual probability of death in a car accident in the US, 2009: 1 in 9,000

Excessive Fear of Radiation Has Consequences

Thousands of normal pregnancies were terminated unnecessarily in Europe due to fears of radiation effects from Chernobyl

Source: F. P. Castronovo Jr., Teratology 60:100-106 (1999)

Estimates for Italy alone range from 3000-7800

Source: Spinelli & Osborne, Biomedicine and Pharmacology J 6:243-247 (1991)

I-131: Fukushima vs. Chernobyl

- Total iodine-131 release maybe 10% of Chernobyl (NISA/METI: 12 April 2011), much of that blown out to sea by fortuitous offshore winds
- I-131 bio-concentrates in the thyroid gland
- large fraction of the exposed population near Chernobyl was *iodine-deficient;* few received prophylactic KI. Absorbed doses at thyroid up to 1 Sv or more.
- The normal Japanese diet is very high in natural iodine and contains more than 13 mg/day, ~100x US RDA
- Studies of exposed children at Semipalatinsk (USSR nuclear weapons test site) who were <u>not</u> iodine-deficient show no significant increase of thyroid cancers at doses averaging 0.3 Sv (Nat'l Cancer Inst., Radiation Epidemiology Branch).

No Significant Exposure to Children

Fukushima Nuclear Accident Update (25 March 2011, 15:45 UTC)

Japanese authorities have informed the IAEA that on 24 March, examinations of the thyroid glands in 66 children (14 of which are infants) were conducted near the evacuation area around the Fukushima nuclear plant. The exams were conducted at the Kawamata Town Health Center (40-50 kilometres from Fukushima Daiichi NPP) and Kawamata Town Yamakiya Branch Office (30-40 kilometres from Fukushima Daiichi NPP).

According to a 25 March 2011 Nuclear and Industrial Safety Agency press release, the results of the examinations indicated that the dose rate "of all the 66 children including 14 infants from 1 to 6 years old had no big difference from the level of background and was at the level of no problem in light of the view of Nuclear Safety Commission."

From the thyroid cancer curves above, the only significant risk is to children and young adults exposed to I-131.

No bio-concentration of radioactive iodine is evident in this study done two weeks after the accident. Protective doses of potassium iodide (KI) were distributed to all evacuees deemed at risk.

Therefore, it is highly probable that no statistically detectable excess cancers will occur as a result of the Fukushima accident. We will not know with certainty for about 15 years.

Life Cycle Risk

- For each power technology, we need to examine its total risk:
  - Discovering and mining the fuel
  - Transporting the fuel to the power plant
  - Disposing of waste products
  - Risk from emissions into air and water
  - Plant construction, maintenance and decommissioning
  - Risk from accidents

This calculation was done recently by a group of over 100 European scientists. The results are on the next slide…

Power Generation Risk By Source

(normalized as death rate per terawatt-hour produced)

Energy Source	Death Rate (deaths per TWh)
Coal - world average	161 (26% of world energy, 50% of electricity)
Coal - China	278
Coal - USA	15
Oil	36 (36% of world energy)
Natural Gas	4 (21% of world energy)
Biofuel/Biomass	12
Peat	12
Solar (rooftop)	0.44 (less than 0.1% of world energy)
Wind	0.15 (less than 1% of world energy)
Hydro	0.10 (europe death rate, 2.2% of world energy)
Hydro - world including Banqiao)	1.4 (about 2500 TWh/yr and 171,000 Banqiao dead)
Nuclear	0.04 (5.9% of world energy)

(Data from World Health Organization and European ExternE study)

So nuclear power, including Chernobyl, is still:

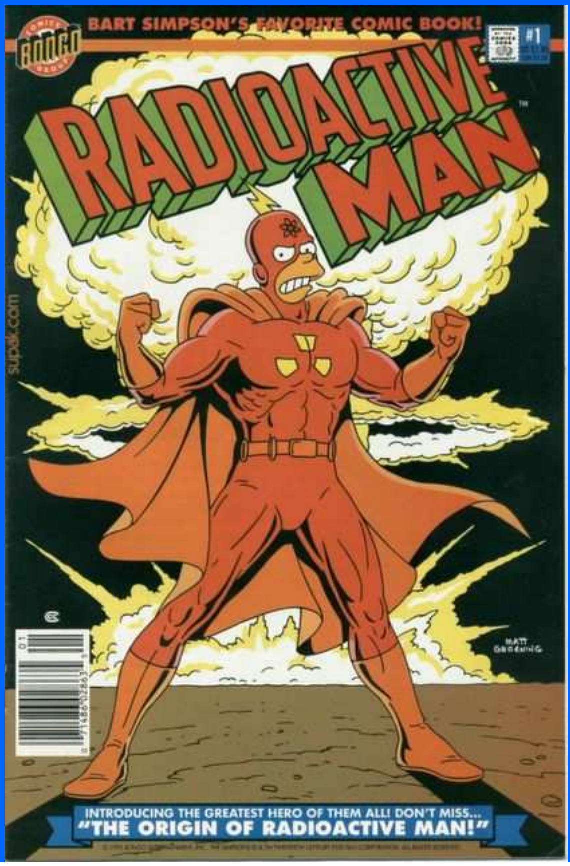
4000 times safer than coal (world average)

375 times safer than coal in the USA (better pollution control)

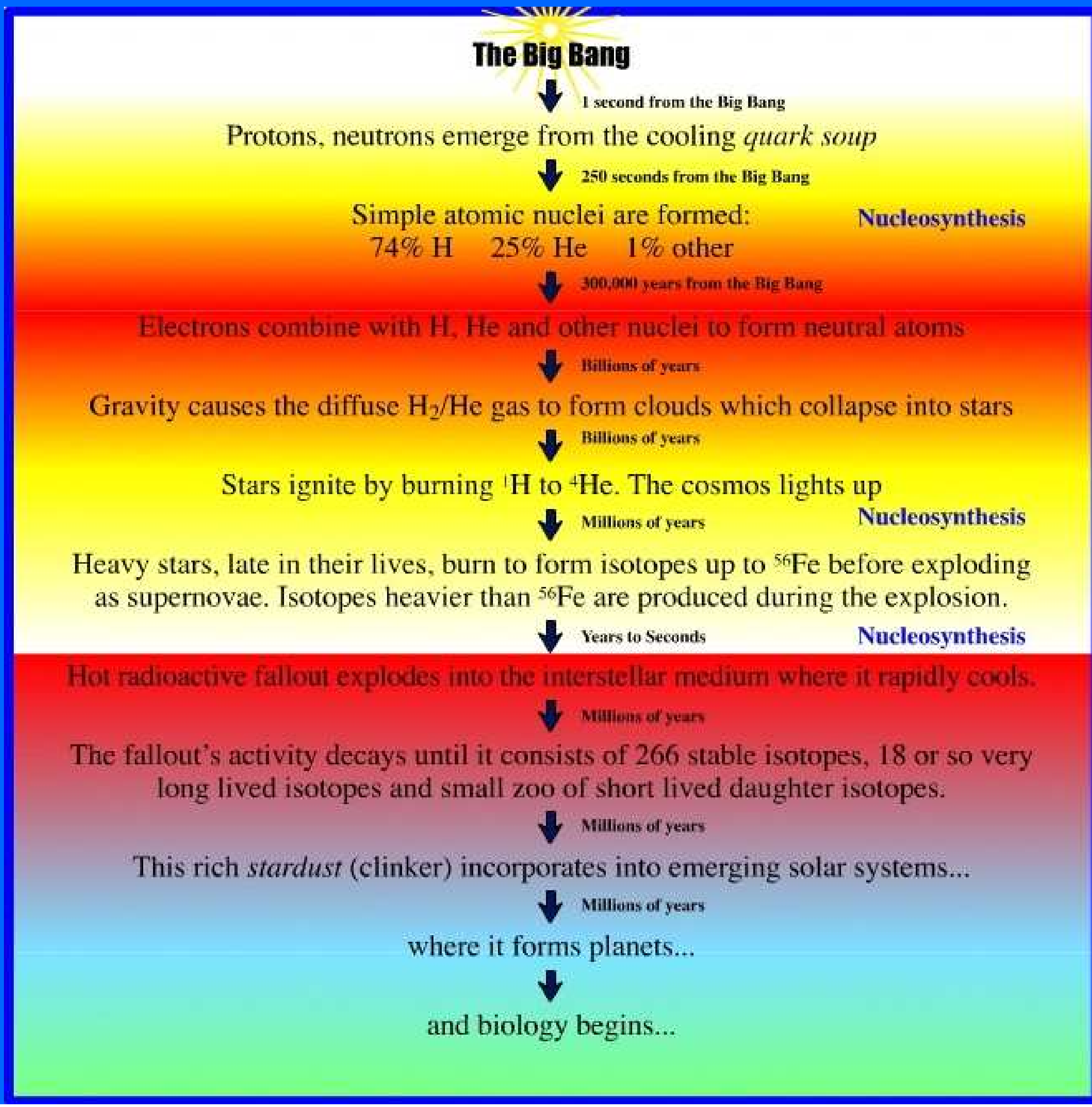
35 times safer than hydroelectric (worldwide)

So, why are we so afraid of it?

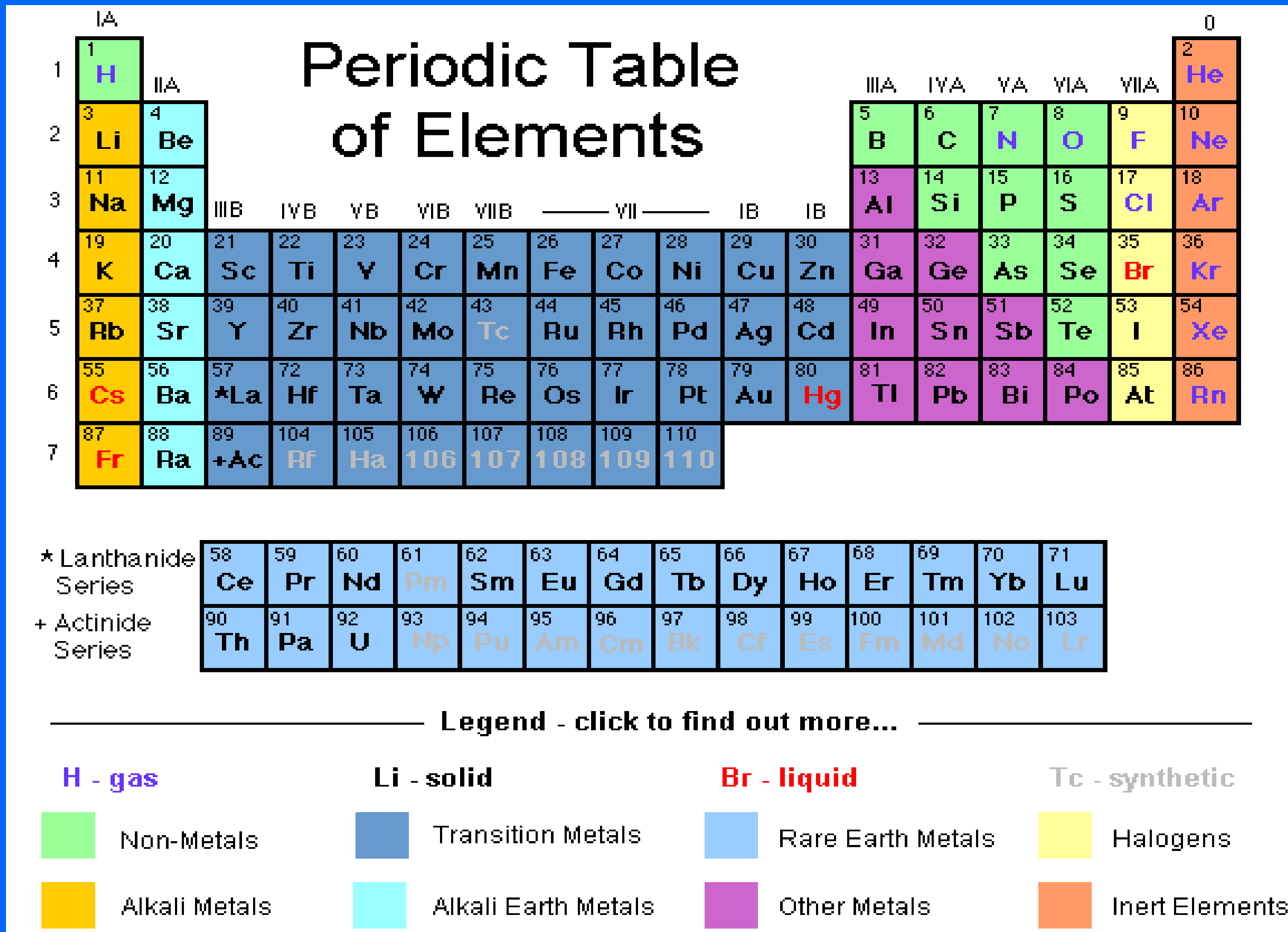
Most of us don't understand radioactivity



We Are All Fallout -- from Supernova Explosions

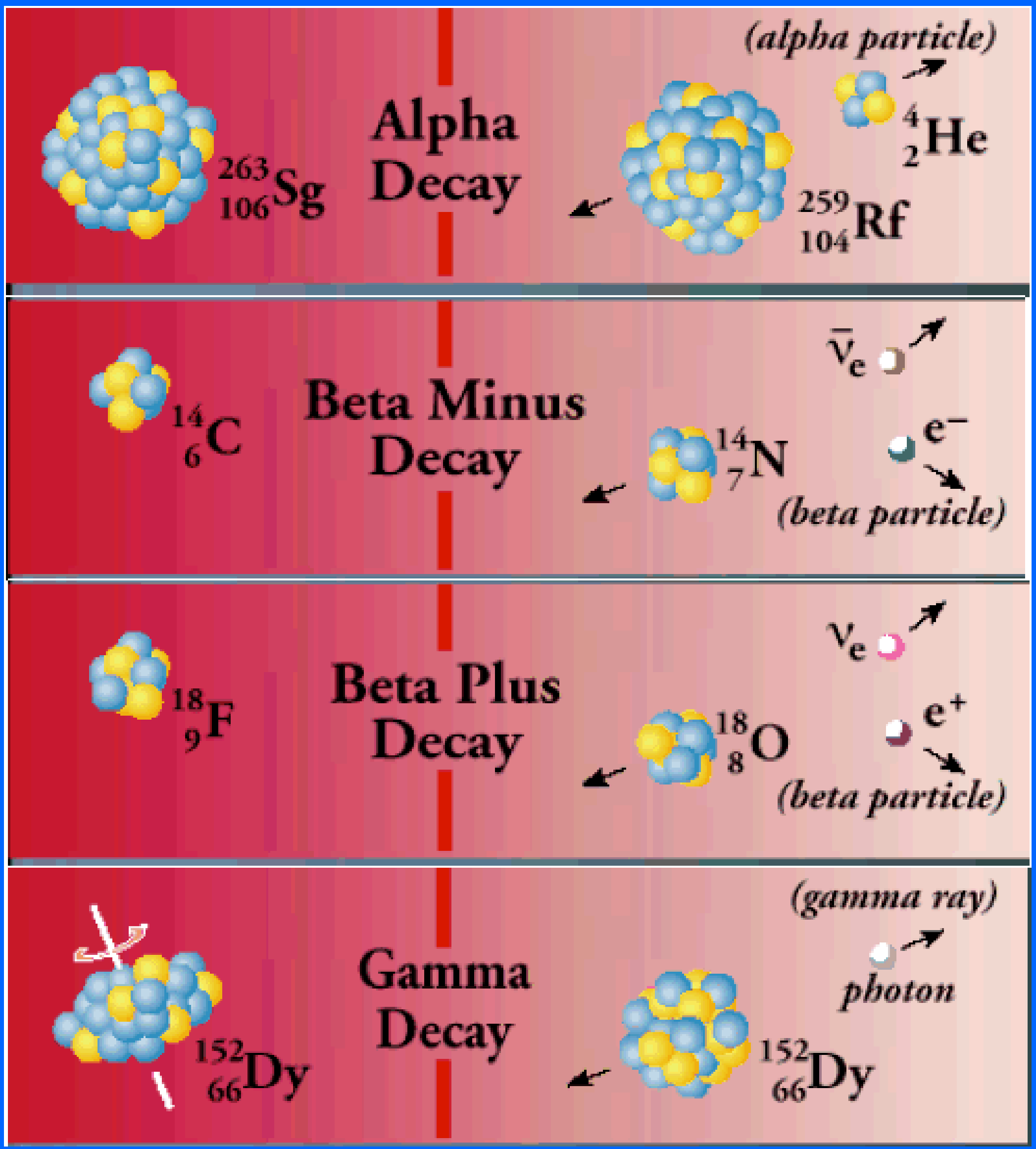


The Chemical Elements



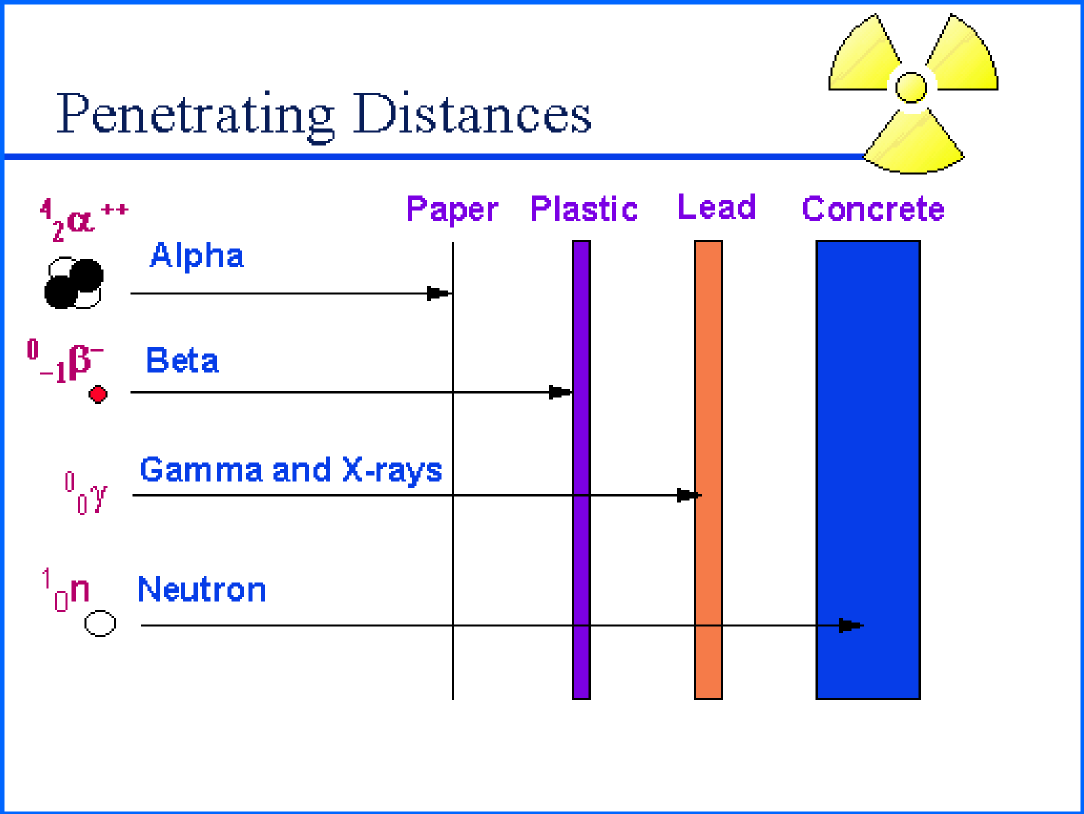
Elements are defined by their number of **protons**. The lightest element, hydrogen (symbol **H**) has 1 proton. Uranium (**U**) has 92 protons.

How Does Radioactivity Work?



"Eat hot death ray, monkey-boy."

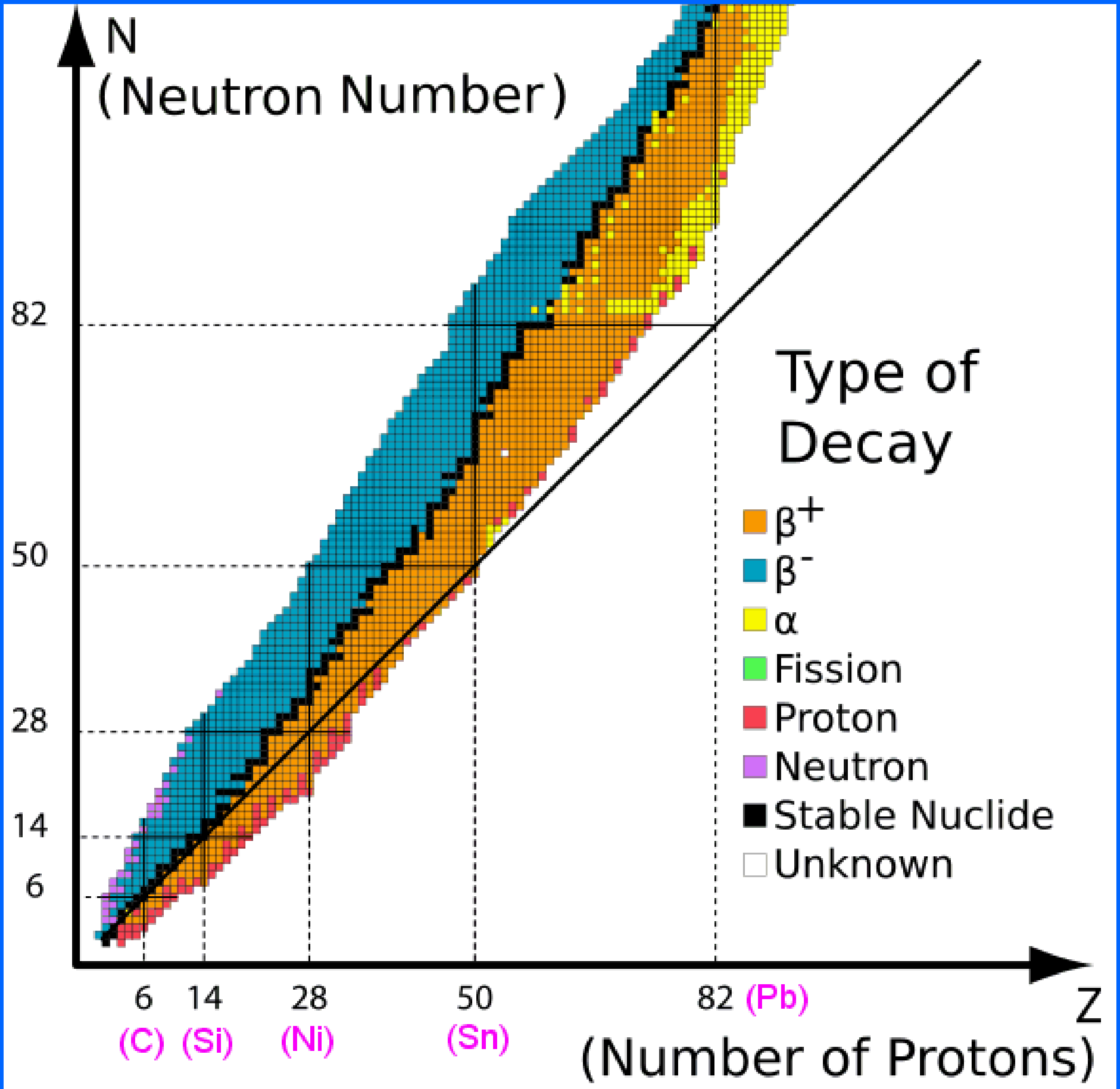
What Blocks Radiation?



Alpha particles are 20x more damaging to tissue than betas or gammas, but are mostly stopped by the dead layer of cells on the top of your skin. They are only harmful if they get inside you (food, drink, air you breathe). That's why Radon is such a problem – it's a gas, so it gets in the lungs.

Betas penetrate about 1 cm in water. You're mostly water.

Transmutation: Proton/Neutron Ratio



Nature seems to have a preferred balance of protons and neutrons. The black staircase in the middle of the cloud of colored squares shows the stable isotopes.

In $beta^-$ decay, a neutron becomes a proton. In $beta^+$ decay, a proton captures an electron and becomes a neutron.

In both cases, the proton count changes, turning the nucleus into a different chemical element!

Alchemy – Ur Doin It Wrong

Extra! Extra! Scientific genius leaves gold in reactor too long, turns gold into lead!!

Au197 + n → Au198 (half-life 2.7 days)

(absorbs a neutron) (Au198 is used in nuclear medicine; chemically inert in the body, short half-life)

Au198 → Hg198 + e^- (beta decay)

Hg198 + 4n → Hg203 (half-life 47 days)

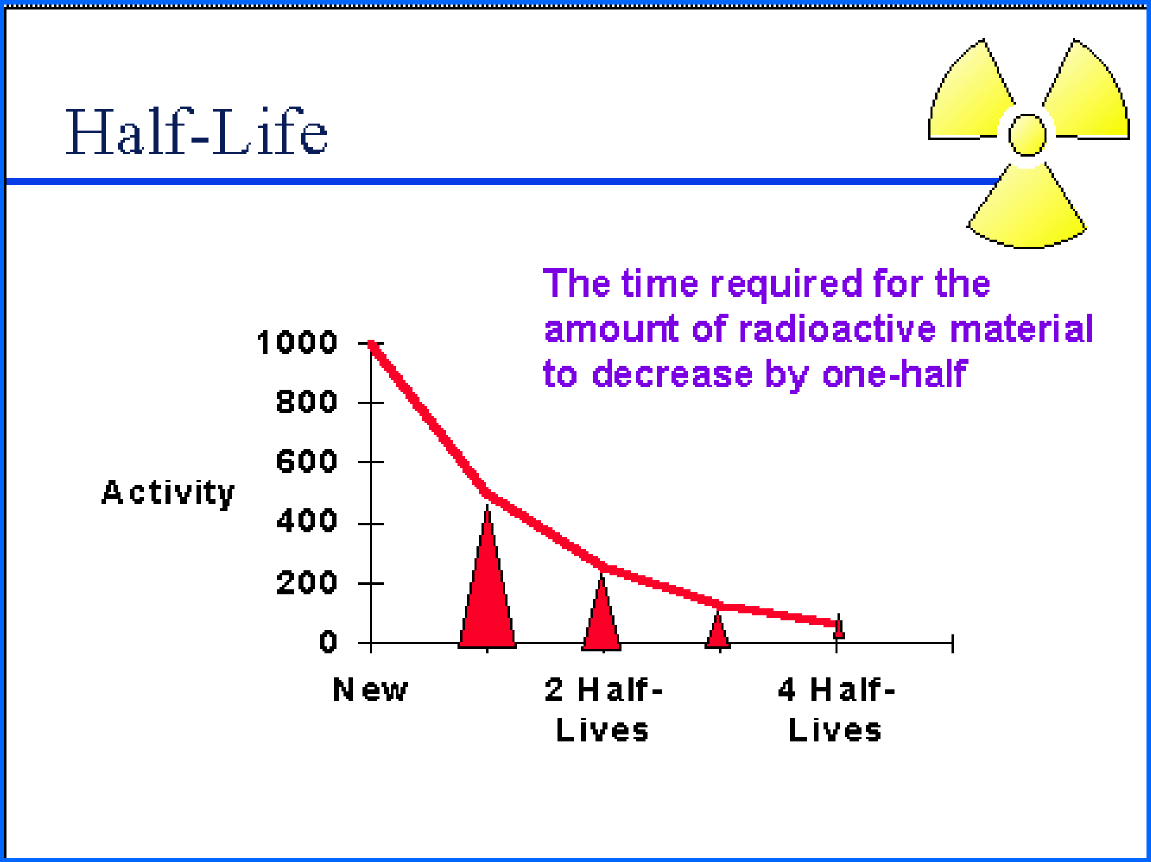
Hg203 → Tl203 + e^- (beta decay)

Tl203 + n → Tl204 (half-life 3.8 years)

Tl204→ Pb204 + e^- (beta decay)

Pb204 is a stable isotope of lead

Half-Life – the key idea



Each radioactive isotope has a unique *half-life*, which is the time required for half the atoms remaining to decay.

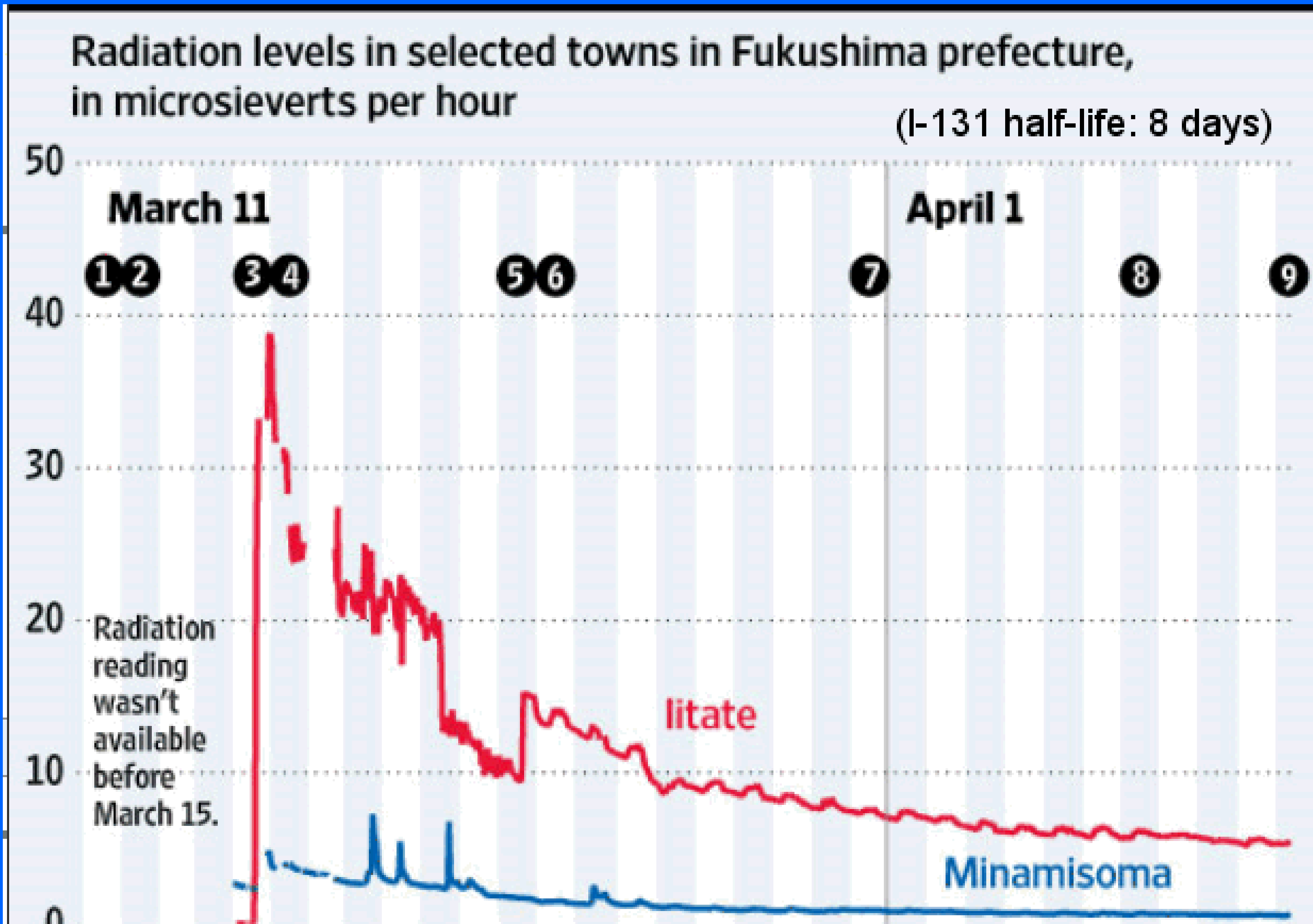
Short half-life mean a lot of radioactivity, which dies away quickly.

A long half-life means less radioactivity for the same initial number of atoms of the isotope, but it sticks around a lot longer.

After 10 half-lives, the radiation intensity is 1000 times smaller.

After 20 half-lives, the radiation intensity is a **million** times smaller.

Exponential Decline From Fukushima



World Health Organization report, 2005

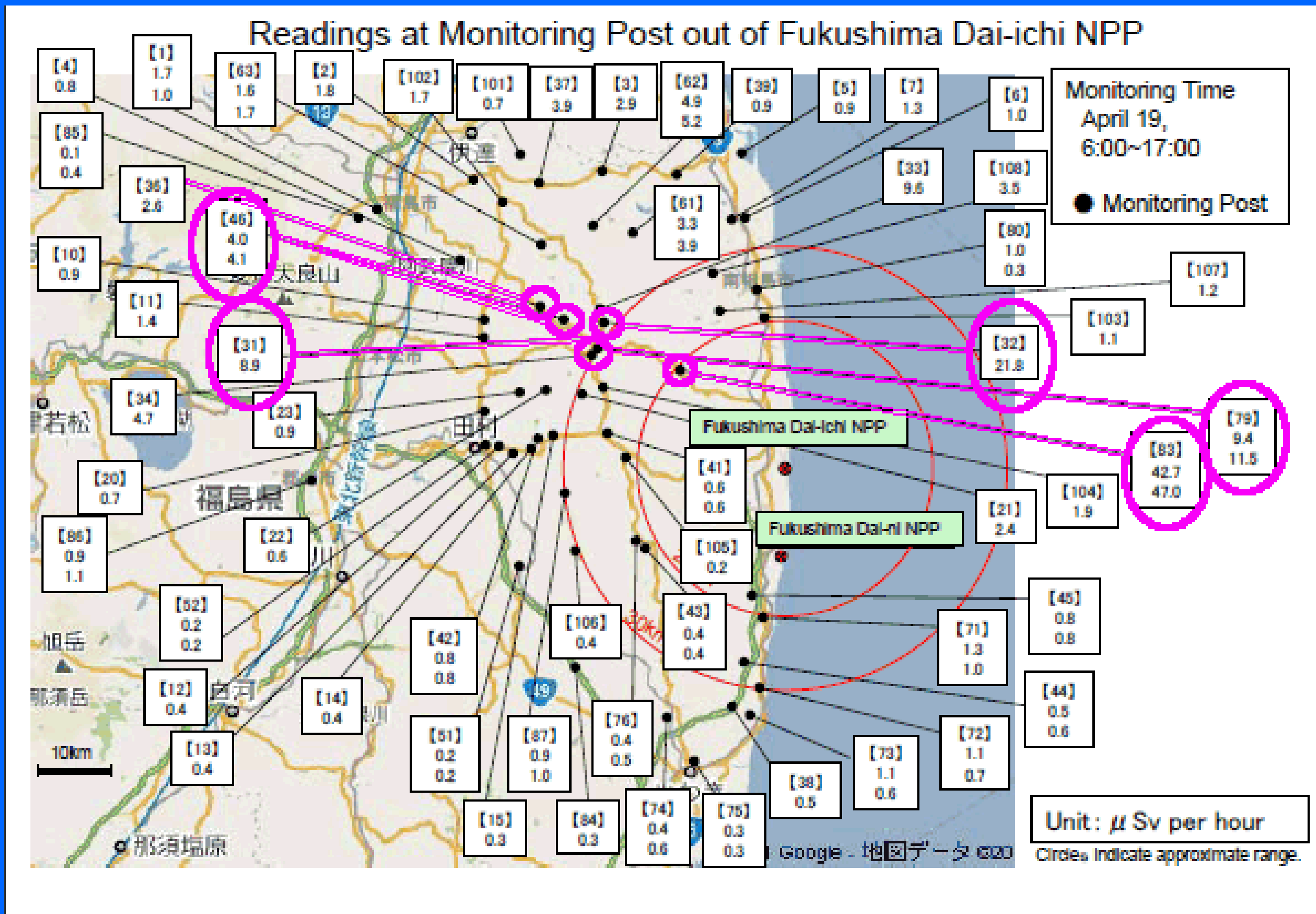
Doses received from the Chernobyl accident

Below are the total average effective doses accumulated over 20 years by the highest Chernobyl exposed populations. These can be compared with the average doses people normally receive from natural background over 20 years. Doses from typical medical procedures are also given for comparison purposes.

Population (years exposed)	Number	Average total in 20 years (mSv)[1]
Liquidators (1986–1987) (high exposed)	240 000	>100
Evacuees (1986)	116 000	>33
Residents SCZs (>555 kBq/m2) (1986–2005)	270 000	>50
Residents low contam. (37 kBq/m2) (1986–2005)	5 000 000	10–20
Natural background	2.4 mSv/year (typical range 1–10, max >20)	48

These doses are in **milli**Sieverts. The peak intensity from the previous slide for Fukushima is 40 **micro**Sieverts/hr, declining to 5 or so after a few weeks. Cumulative dose is the area under the curve: 15 milliSieverts for litate as of 11 April 2011.

Plume to Northwest



Much of the contamination blew out to sea, but you can see a narrow track of higher contamination to the northwest. Peak levels 20km from the plant are a little more than the peak March 15 Iitate slide (43-47 uSv/hr vs. 40). (Source: http://www.mext.go.jp/english/incident/1304082.htm)

Radiation Units Are Confusing

(there are two of everything, and activity and dose are different)

Becquerel (Bq): Standard unit of **radioactivity**. Number of nuclear decays per second. The traditional unit of radioactivity is the Curie.

1 Bq = 27 picoCuries (pCi) = 1 decay per second

1 Bq is a pretty small amount of radioactivity. We generally use millions of Bq (MBq), and exposure to MBq of activity may result in microSv/hr of dose (see below and following slides).

Sievert (Sv): Standard unit of **dose**, the amount of radiation absorbed by the body. Radiation goes in all directions, so the dose from a given number of Bq of radioactivity depends on its energy, how close you are to it, and how long you are exposed to it. The traditional unit of dose is the 'rem'.

1 Sv = 100 rem

Sv is a very large unit (4-5 sV in a short time will kill half the people exposed to it), so we generally use milliSv or microSv.

The exception is I-131, which concentrates in the thyroid gland. Very high localized doses in the thyroid are possible unless it is saturated (e.g. using KI).

Radiation is Everywhere…

RADIOACTIVE ELEMENTS IN THE HUMAN BODY

Radioactive Isotope	Half Life (years)	Isotope Mass in the Body (grams)	Element Mass in the Body (grams)	Activity within the Body (Disintegrations/sec)
Potassium 40	1.26×10^{9}	0.0165	140	4,340
Carbon 14	5,730	1.6×10^{-8}	16,000	3,080
Rubidium 87	4.9×10^{10}	0.19	0.7	600
Lead 210	22.3	5.4×10^{-10}	0.12	15
Tritium (^{3}H)	12.43	2×10^{-14}	7,000	7
Uranium 238	4.46×10^{9}	1×10^{-4}	1×10^{-4}	3 - 5
Radium 228	5.76	4.6×10^{-14}	3.6×10^{-11}	5
Radium 226	1,620	3.6×10^{-11}	3.6×10^{-11}	3

… including inside you. There are about 8,000 nuclear decays (8000 Bq) in your body every second! Note the roughly similar activity from K-40 and C-14. The body mass of C-14 is a million times less, but the half-life is 220,000 times shorter, and because C is lighter, for the same mass of material there are nearly 3x as many C atoms as K atoms. Activity is proportional to the number of atoms and inversely proportional to half-life.

Potassium-40 (K-40)

Radioactive Properties of Potassium-40

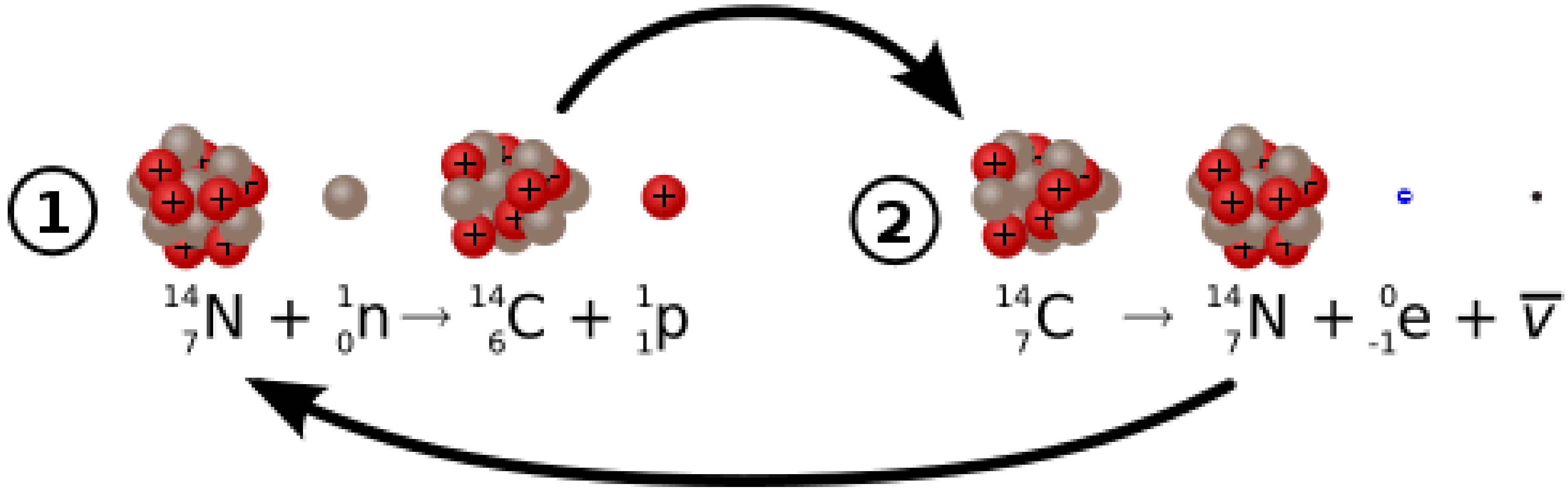
Isotope	Half-Life (*yr*)	Natural Abundance (*%*)	Specific Activity (*Ci/g*)	Decay Mode	Radiation Energy (*MeV*)		
					Alpha (α)	Beta (β)	Gamma (γ)
K-40	1.3 billion	0.012	0.0000071	β, EC	-	0.52	0.16

EC = electron capture, Ci = curie, g = gram, and MeV = million electron volts; a dash means that the entry is not applicable. (See the companion fact sheet on Radioactive Properties, Internal Distribution, and Risk Coefficients for explanation of terms and interpretation of radiation energies.) Potassium-40 decays by both emitting a beta particle (89%) and electron capture (11%). Values are given to two significant figures.

Potassium is the 7th most abundant element on Earth. Its radioactive isotope is "primordial", meaning it's been there since the planet formed 4.5 billion years ago.

Its half-life of 1.3 billion years means that when life appeared on Earth, 2.5 billion years ago (2 half-lives), background radiation from K-40 was about 4 times higher than it is now.

C14 Generated By Cosmic Rays



$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p \qquad ^{14}_{7}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e + \overline{\nu}$$

C-14 is continuously generated from nitrogen by cosmic rays in the upper atmosphere. It is used to establish dates in archaeology, because all living things (plants and animals) take in C-14 while they are alive. After they die, the C-14 decays at a predicable rate. So the amount of C-14 remaining establishes the age quite accurately for sites up to about 50,000 years old (10 half-lives).

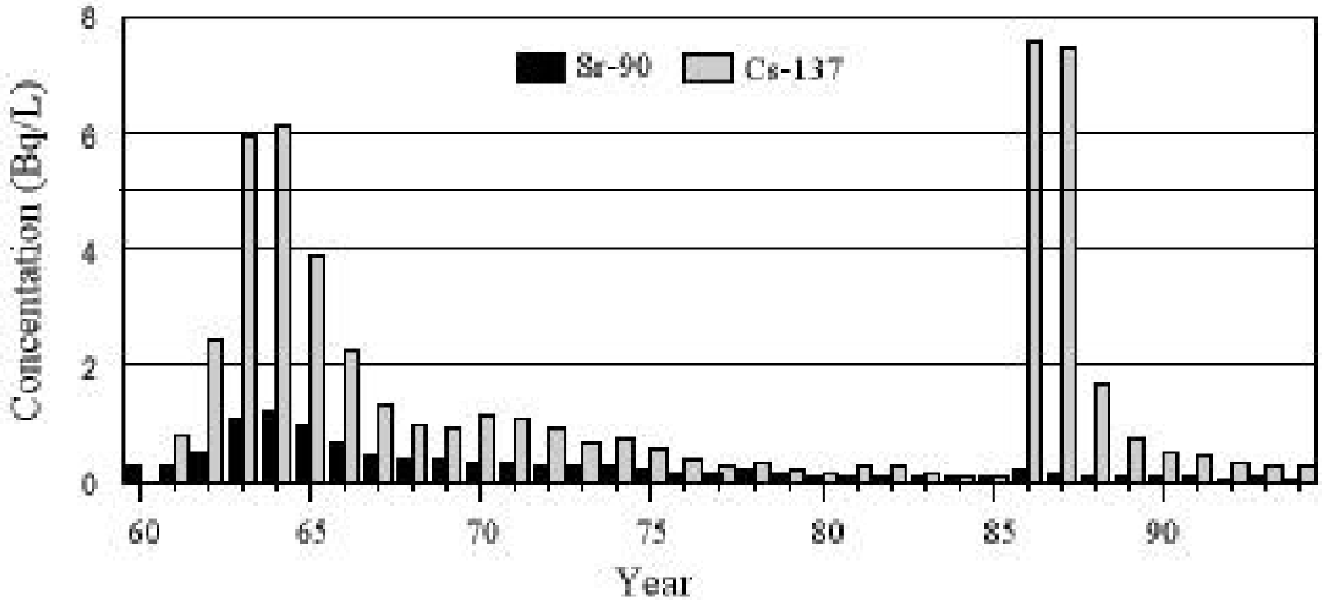
Natural Radioactivity in Food

Potassium-40 in Food*

Specific activity (picocuries of potassium-40 per gram of potassium) = 818 pCi/g
1 picocurie (pCi) = one trillionth part of a curie = 0.000000000001 curie

	Potassium (mg)	Item	Serving or Item Size (g)	Potassium Content (g-K/g)	Potassium-40 concentration (pCi/g)	Potassium-40 content (pCi/serving)
Dairy Products					**1.5 - 1.3**	
Yogurt	500	1 container	277	0.002	1.5	409
Skim Milk	406	1 cup	226	0.002	1.5	332
Low Fat milk	348	1 cup	226	0.002	1.3	285
Vegetables					**4.3 - 0.9**	
Potato	844	1 medium	159	0.005	4.3	690
Acorn Squash (cooked)	896	1 cup	226	0.004	3.2	733
Spinach (cooked)	838	1 cup	226	0.004	3.0	685
Lentils (cooked)	731	1 cup	226	0.003	2.6	598
Kidney Beans (cooked)	713	1 cup	226	0.003	2.6	583
Split Peas (cooked)	710	1 cup	226	0.003	2.6	581
White Navy Beans (cooked)	669	1 cup	226	0.003	2.4	547
Butternut Squash (cooked)	583	1 cup	226	0.003	2.1	477
Tomato	273	1 medium	114	0.002	2.0	223
Carrot	233	1 medium	100	0.002	1.9	191
Brussel Sprouts (cooked)	494	1 cup	226	0.002	1.8	404
Zucchini (cooked)	456	1 cup	226	0.002	1.7	373
Green Beans)cooked)	185	1/2 cup	113	0.002	1.3	151
Broccoli (cooked)	332	1 cup	226	0.001	1.2	272
Spinach (fresh)	119	1/2 cup	113	0.001	0.9	97
Meat & Fish					**4.3 - 2.1**	
Cod	449	3 oz. Fillet	85	0.005	4.3	367
Chicken	220	3 oz. Breast	85	0.003	2.1	180

Chernobyl and Bomb Tests vs. K-40 in Milk



Activity in milk in Germany. Increases due to fallout from weapons testing and Chernobyl are apparent. Natural levels may be assumed to be the same as between 1980 and 1985.
Source: Umweltbundesamt, *Daten zur Umwelt* (Erich Schmidt Verlag, 1998), Fig. 11.21

Atmospheric H-bomb testing prior to the 1963 Test Ban Treaty contributed almost as much Cs-137 as Chernobyl. ***But the natural level of K-40 in milk is 48 Bq/L!*** More than 6 times as much as the peak contamination from Chernobyl.

(From previous slide: low-fat milk has 1.3 pCi/g, times 1000 g/liter = 1300 pCi/L = 48 Bq/L)

Health Effects of Radiation

- At very high doses, acute sickness or death (studies of atomic bomb survivors)
- At moderate doses, increases the risk of cancer (also from atomic bomb studies)
- At moderate to high doses, risk is proportional to dose
- At low and very low doses…
  - *Nobody knows for sure! No health effects have ever been proven below 100 mSv*

Linear No-Threshold (LNT)

- The current default model for radiation risk says there is no “safe” dose. All exposure to radiation carries risk.
- Biological model: assume single cell strike can initiate cancer with some probability, simple linear increase in probability with dose.
- 80 aspirin at once will kill half the people “exposed” to them. LNT would therefore predict 2 aspirin would kill 1.25% of users. So don’t “take two aspirin and call me in the morning”….

Health Physics Society Position Statement
March, 1996

In accordance with current knowledge of radiation health risks, the Health Physics Society recommends against quantitative estimation of health risk below an individual dose of 5 rem[1] in one year, or a lifetime dose of 10 rem in addition to background radiation. Risk estimation in this dose range should be strictly qualitative accentuating a range of hypothetical health outcomes with an emphasis on the likely possibility of zero adverse health effects. The current philosophy of radiation protection is based on the assumption that any radiation dose, no matter how small, may result in human health effects, such as cancer and hereditary genetic damage. There is substantial and convincing scientific evidence for health risks at high dose. Below 10 rem (which includes occupational and environmental exposures) risks of health effects are either too small to be observed or are non-existent.

Converting to standard units, 10 rem = 100 mSv (milliSieverts)

Dose-Response Hypotheses

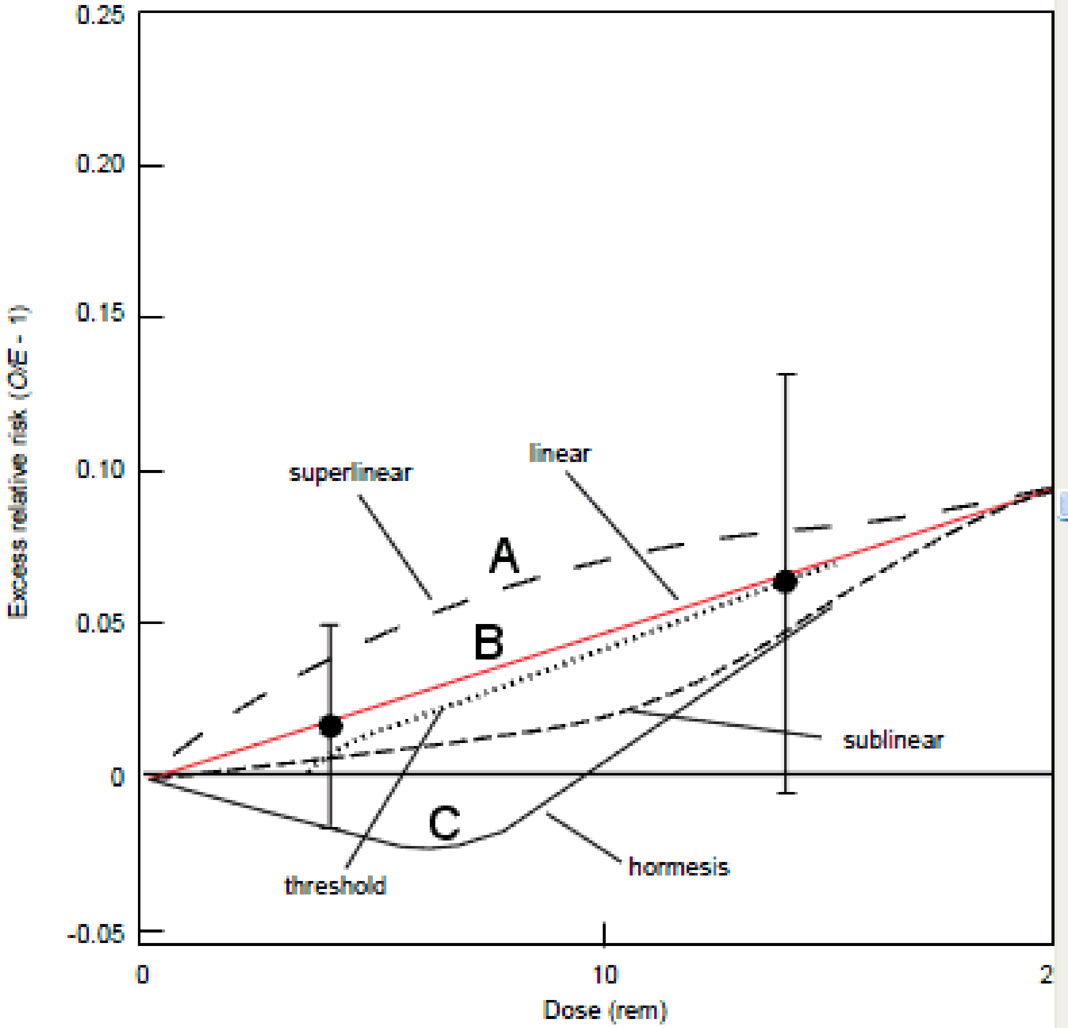


Figure 5. Extrapolation of High-Dose Data to Doses below 20 Rem
The low-dose data from Figure 4 with a straight-line extrapolation from the high-dose data, as well as other possible fits to the data, including (a) threshold/linear, (b) sub-liner, (c) superlinear, and (d) adaptive, or hormetic, response.

(note: 10 rem = 100 milliSieverts)

Until recently the only statistically valid data we had on human radiation risk came from studies of the Hiroshima and Nagasaki survivors. Cancer risk is widely accepted as linear at high dose.

Curve B (red) is the “standard” LNT, but new data suggest this is incorrect for low doses. Estimates of Chernobyl cancer deaths vary wildly from 4000 (WHO) to 250,000 (Greenpeace).

Both figures are “model deaths”, statistically invisible against the background of natural cancer deaths (1.3 million estimated for the EU in 2011 alone, or ~50 million over 40 years).

The scientifically correct answer is: *the Chernobyl cancer toll is statistically indistinguishable from zero* except for the 15 thyroid deaths discussed above.

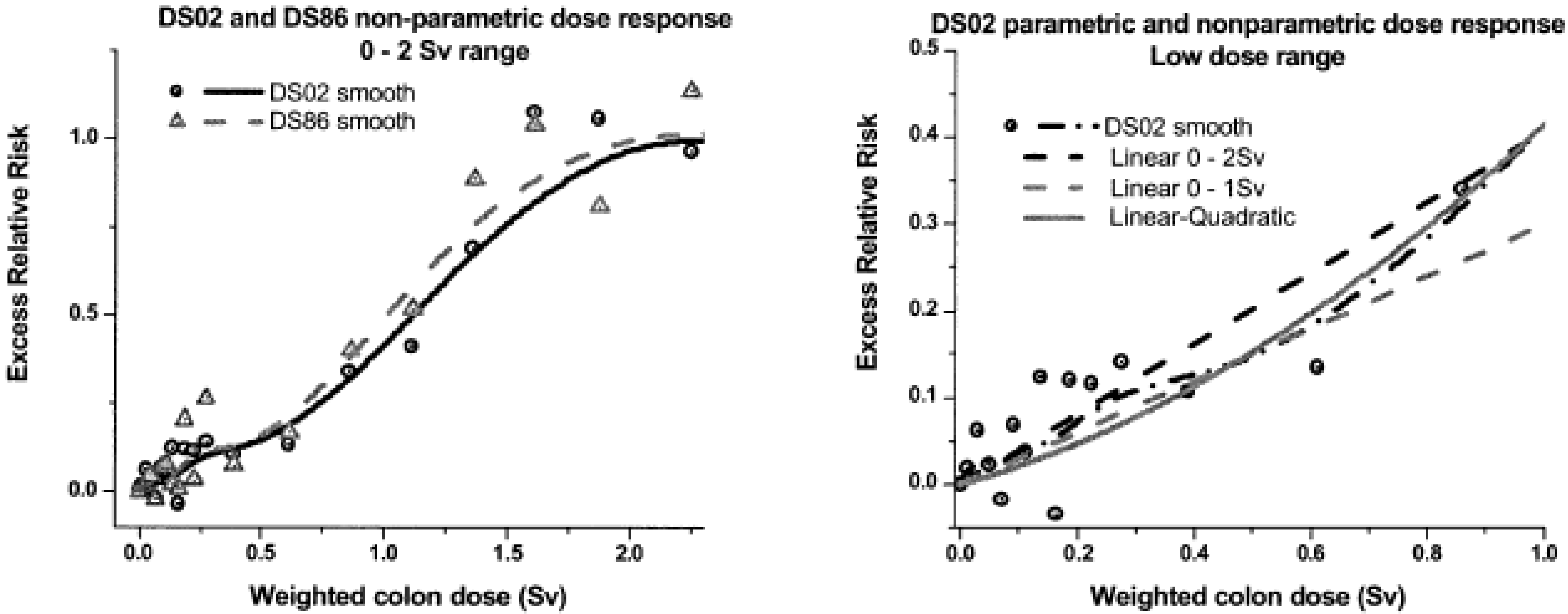


FIG. 4. Solid cancer dose–response pattern. The left panel presents dose-category-specific ERR estimates based on DS02 (circles) and DS86 (triangles) with nonparametric smooth curves are locally weighted regressions as described in the Materials and Methods section. The right panel displays the DS02 dose response on a low-dose range together with linear fits based on dose ranges of 0–1 Sv and 0–2 Sv and the linear-quadratic fit based on the 0–2-Sv range. These curves fit the data about equally well.

Above 0.5 Sv, there's dose-response relationship; below 0.15-0.2 Sv (150-200 mSv) it's just a blob of data, including some *negative* points (less than background risk). The middle of the previous slide corresponds to 0.1 here.

Source: Preston *et. al*., Radiation Research **162**, 377-389 (2004)

There are studies suggesting that small doses of radiation may be **beneficial**

Radiation Hormesis

- Hormesis: low dose stimulation and high dose inhibition (Calabrese, 2003).
- Radiation hormesis: low doses of radiation protect, high doses harm.

Calabrese EJ. Annu. Rev. Pharmacol. Toxicol 43:175-197, 2003.

Source: Bobby R. Scott, Lovelace Respiratory Research Inst.

http://www.radiation-scott.org

The Linear No-Threshold Relationship Is Inconsistent with Radiation Biologic and Experimental Data

"The LNT relationship implies proportionality between dose and cancer risk. … The advances during the past 2 decades in radiation biology, the understanding of carcinogenesis, and the discovery of defenses against carcinogenesis challenge the LNT model, which appears obsolete (2–6)."

. . .

"Upregulation of protective mechanisms at the cell and tissue levels by low doses likely also operates against carcinogenic factors other than ionizing radiation and against spontaneous cancer, as demonstrated in various experiments in vitro and in vivo (46,87–93). Indeed, a dose of 10 mGy reduces the rate of spontaneous transformation in culture cells below the background level. Some epidemiologic data suggest that hormesis also exists in humans (94)."

Tubiana et. al. ***Radiology:*** Volume 251: Number 1—April 2009

More recent citations:
Feinendegen, British Journal of Radiology, 78 (2005), 3-7

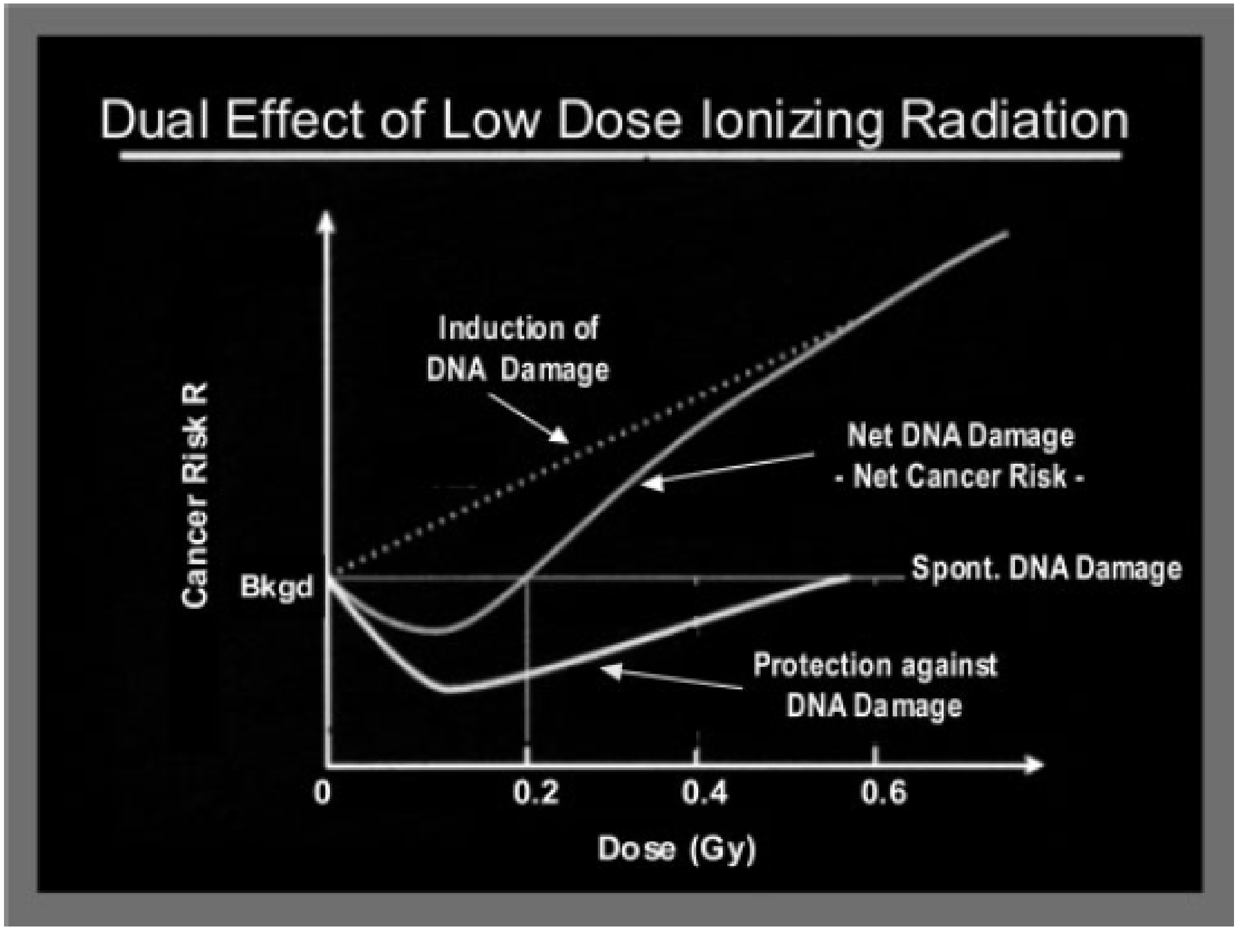
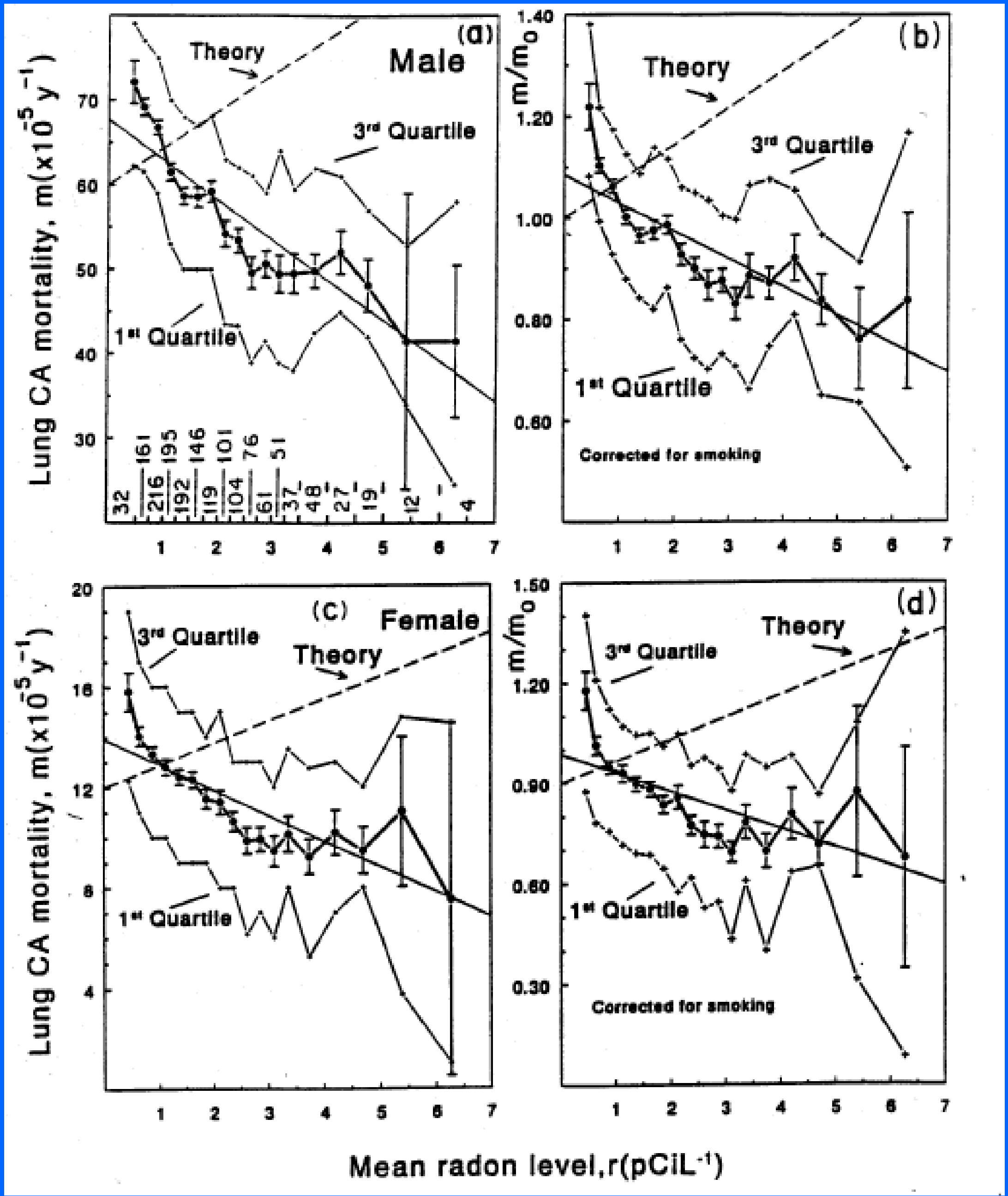


Figure 3. The dual effect of single low dose irradiation is schematically analysed according to a simplified model [10]. The net cancer risk derives from the difference between cancer induction through DNA damage and its prevention at the various dose levels (additional protection against damage accumulation from apoptosis is not shown here).

Evidence Against LNT



Bernard L. Cohen, Health Physics, Feb. 1995, Vol. 68, No. 2, pp 157-174

http://www.phyast.pitt.edu/~blc/LNT-1995.PDF

Radon mitigation is a large issue in US real estate. The EPA mandates remediation above 4 pCi/L.

Cohen measured lung cancer deaths vs. radon levels in 1600 counties. His results contradict LNT (dashed line) as risk **decreases** with exposure for low doses (corrected for confounding factors such as smoking).

The introduction to the paper (link above) gives many references to cell and mouse studies showing possible protective effects of low dose-rate exposure.

Nuclear Shipyard Workers Study

- Conducted by G. Matanowski, Johns Hopkins Univ., Dept of Epidemiology.
- Studied workers in shipyards which maintained nuclear naval vessels between 1957 and 1981
- Direct study of low exposures (none, < 5 mSv, 5-50 mSv). Unlike Chernobyl and A-bomb studies, doses were <u>measured</u> with sensitive monitors, not estimated.
- Very good matching of control cohort (NNW, “non-nuclear workers”) vs. exposed cohort minimizes “healthy worker” effect. Study design and conduct reviewed by independent 8-member Technical Advisory Panel.
- High statistical power (~30,000 in the >5 mSv and no-exposure cohorts, 10x most Phase 3 clinical trials)
- Intent was to quantify risk of low-level radiation exposure

Matanowski, G. M. "Health effects of low-level radiation in shipyard workers, Final report, June 1991". DOE DE-AC02-79 EV10095, 1991

What's this? The **exposed** workers had 24% **lower** mortality than the others???

Table 3.1.B Deaths From All Causes, Person-Years and Death Rates[1] for NNW, $NW_{<0.5}$ and $NW_{\geq 0.5}$

	$NW_{\geq 0.5}$	$NW_{<0.5}$	NNW
Part A. All Workers Sampled			
Workers in sample	28,089	10,413	33,213
Total deaths	2,797	1,168	4,453
Part B. Workers Selected for Analysis[2]			
Workers in subset	27,872	10,348	32,510
Person-years	356,091	139,746	425,070
Deaths	2,215	973	3,745
Death Rates Per 1,000[3]	6.4	7.1	9.0
SMR[4] (95% C.I.)[5]	0.76 (0.73, 0.79)	0.81 (0.76, 0.86)	1.00 (0.97, 1.03)

What the Numbers Mean

- SMR is “standardized mortality ratio”, correct for external factors such as age
- The 95% confidence interval is very tight (+/- 0.03) so the result is highly significant
- While the confidence intervals overlap, the data appear to suggest a dose-response relationship (SMR for <0.5 mSv is higher than for >=0.5 mSv)

Extrapolating Down from High Dose Is Not Valid

264 Health Physics March 2001, Volume 80, Number 3

paper low dose is defined as <100 mGy in adult populations.) All biologically-plausible theories, including the LNT, are inadequate in the Popperian sense (Popper 1959) because they are untestable (i.e., unfalsifiable) in the low dose region. Theory falsification requires bona fide counter-evidence in the low-dose range. Falsification cannot be based on dose extrapolation because of the very large uncertainties when extrapolating over a wide range of doses (2 orders of magnitude or more). Therefore, selecting a particular theory to the exclusion of biologically plausible alternatives will remain an intractable problem until experimental approaches are developed to make observations of radiogenic health effects possible in the low dose range.

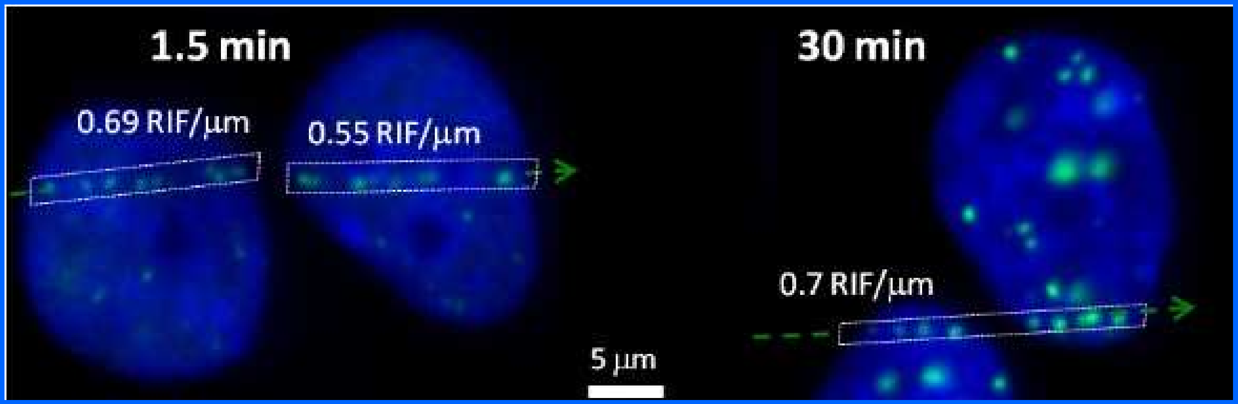
Kenneth L. Mossman, “Deconstructing Radiation Hormesis”

(for our purposes, mGy and mSv are equivalent)

(“LNT” – Linear No Threshold, curve B in previous slide)

Now, 11 years later, the next slide shows direct low-dose observations!

2012: Time-Lapse Imaging of DNA Repair Processes in Living Cells



The green dots are “Radiation Induced Foci”, locations within a cell where repair activity is taking place.

Says co-author Mina Bissell of Lawrence Berkeley National Lab: *“Our data show that at lower doses of ionizing radiation, DNA repair mechanisms work much better than at higher doses. This non-linear DNA damage response casts doubt on the general assumption that any amount of ionizing radiation is harmful and additive.”* http://newscenter.lbl.gov/news-releases/2011/12/20/low-dose-radiation/

Full paper: Neumaier *et. al*., “Evidence for formation of DNA repair centers and dose-response nonlinearity in human cells”, Proc. Natl. Acad. Sci. 108, not yet printed

http://www.pnas.org/content/early/2011/12/16/1117849108.full.pdf+html

One final safety note…

Radioactive Man sez:

Don't

Eat the

Smoke

Detectors!!!

(because they have million-pCi alpha emitters in them – Am-241 or Po-210)

Giant Project, Small Benefit

About 80 percent of the new solar power system being installed on Princeton University property will be composed of SunPower T0 Trackers, which use a global positioning system to track the sun each day to maximize energy capture. *(Photo by Tom Grimes Photography for SunPower)*

Princeton is installing a huge solar array. 27 acres, 17,000 solar panels, roughly $30-40 million – for a net savings of 5.5% of the university's energy consumption.

A Micro-Nuke for Princeton

(www.nucleartigers.org)

Princeton already has a cogeneration plant. A Hyperion Power Module is a tiny reactor (8 feet tall, fits on a truck) which is installed underground to supply maintenance-free power for 8-10 years.

It could generate nearly 100% of the University's electric needs, plus a lot of steam heat for buildings, for $80-100 million. Zero CO_2 emission.

It would pay for itself in 4-5 years at current electric rates, and generate 4-5 years more power savings after that. (Computing the solar array's IRR is left as an exercise for the reader.)

Land used: 400 square feet or so.

Waste: a little bigger than a grapefruit.

Which option looks better to you?