Understanding the radioactivity at Fukushima

A physics and engineering perspective

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Q&A Panel:
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Prof. Theo Theofanous, UCSB Chem E.
Prof. Patrick McCray, UCSB History

- Introduction to radioactivity
- Radiation hazards and health
- What escapes in a meltdown?
- Where does it go?
- How worried should we be?

Periodic Table of the Elements

Chemistry Reference Sheet

California Standards Test

“Tritium” (hydrogen)

Key

11 **Na** Sodium 22.99

- Atomic number
- Element symbol
- Element name
- Average atomic mass*

	1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8 8B	9	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1	1 **H** Hydrogen 1.01																	2 **He** Helium 4.00
2	3 **Li** Lithium 6.94	4 **Be** Beryllium 9.01											5 **B** Boron 10.81	6 **C** Carbon 12.01	7 **N** Nitrogen 14.01	8 **O** Oxygen 16.00	9 **F** Fluorine 19.00	10 **Ne** Neon 20.18
3	11 **Na** Sodium 22.99	12 **Mg** Magnesium 24.31											13 **Al** Aluminum 26.98	14 **Si** Silicon 28.09	15 **P** Phosphorus 30.97	16 **S** Sulfur 32.07	17 **Cl** Chlorine 35.45	18 **Ar** Argon 39.95
4	19 **K** Potassium 39.10	20 **Ca** Calcium 40.08	21 **Sc** Scandium 44.96	22 **Ti** Titanium 47.87	23 **V** Vanadium 50.94	24 **Cr** Chromium 52.00	25 **Mn** Manganese 54.94	26 **Fe** Iron 55.85	27 **Co** Cobalt 58.93	28 **Ni** Nickel 58.69	29 **Cu** Copper 63.55	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.72	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92	34 **Se** Selenium 78.96	35 **Br** [illegible] 79.90	36 **Kr** Krypton [illegible]
5	37 **Rb** [illegible] 85.47	38 **Sr** Strontium 87.62	39 **Y** Yttrium 88.91	40 **Zr** Zirconium 91.22	41 **Nb** Niobium 92.91	42 **Mo** Molybdenum 95.94	43 **Tc** Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.91	46 **Pd** Palladium 106.42	47 **Ag** Silver 107.87	48 **Cd** Cadmium 112.41	49 **In** Indium 114.82	50 **Sn** Tin 118.71	51 **Sb** Antimony 121.76	52 **Te** Tellurium [illegible]	53 **I** Iodine 126.90	[illegible] **Xe** Xenon [illegible]
6	55 **Cs** Cesium 132.91	[illegible] **Ba** Barium [illegible]	57 **La** Lanthanum 138.91	72 **Hf** Hafnium 178.49	73 **Ta** Tantalum 180.95	74 **W** Tungsten 183.84	75 **Re** Rhenium 186.21	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.22	78 **Pt** Platinum 195.08	79 **Au** Gold 196.97	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.38	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98	84 **Po** [illegible]	85 [illegible]	[illegible] **Rn** [illegible]
7	87 [illegible]	88 **Ra** [illegible]	89 **Ac** [illegible]	104 **Rf** Rutherfordium (261)	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (266)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (269)	109 **Mt** Meitnerium (268)									

Iodine

Cesium

Uranium and Plutonium

58 **Ce** Cerium 140.12	59 **Pr** Praseodymium 140.91	60 **Nd** Neodymium [illegible]	61 **Pm** Promethium (145)	62 **Sm** [illegible]	[illegible] 151.96	[illegible] 157.25	[illegible] 158.93	[illegible] 162.50	[illegible] 164.93	[illegible] 167.26	[illegible] 168.93	[illegible] 173.04	71 **Lu** Lutetium 174.97
90 **Th** Thorium 232.04	91 [illegible]	92 **U** Uranium 238.03	93 **Np** Neptunium (237)	94 **Pu** Plutonium (244)	[illegible]	96 **Cm** Curium (247)	97 **Bk** Berkelium (247)	98 **Cf** Californium (251)	99 **Es** Einsteinium (252)	100 **Fm** Fermium (257)	101 **Md** Mendelevium (258)	102 **No** Nobelium (259)	103 **Lr** Lawrencium (262)

* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.

Boron

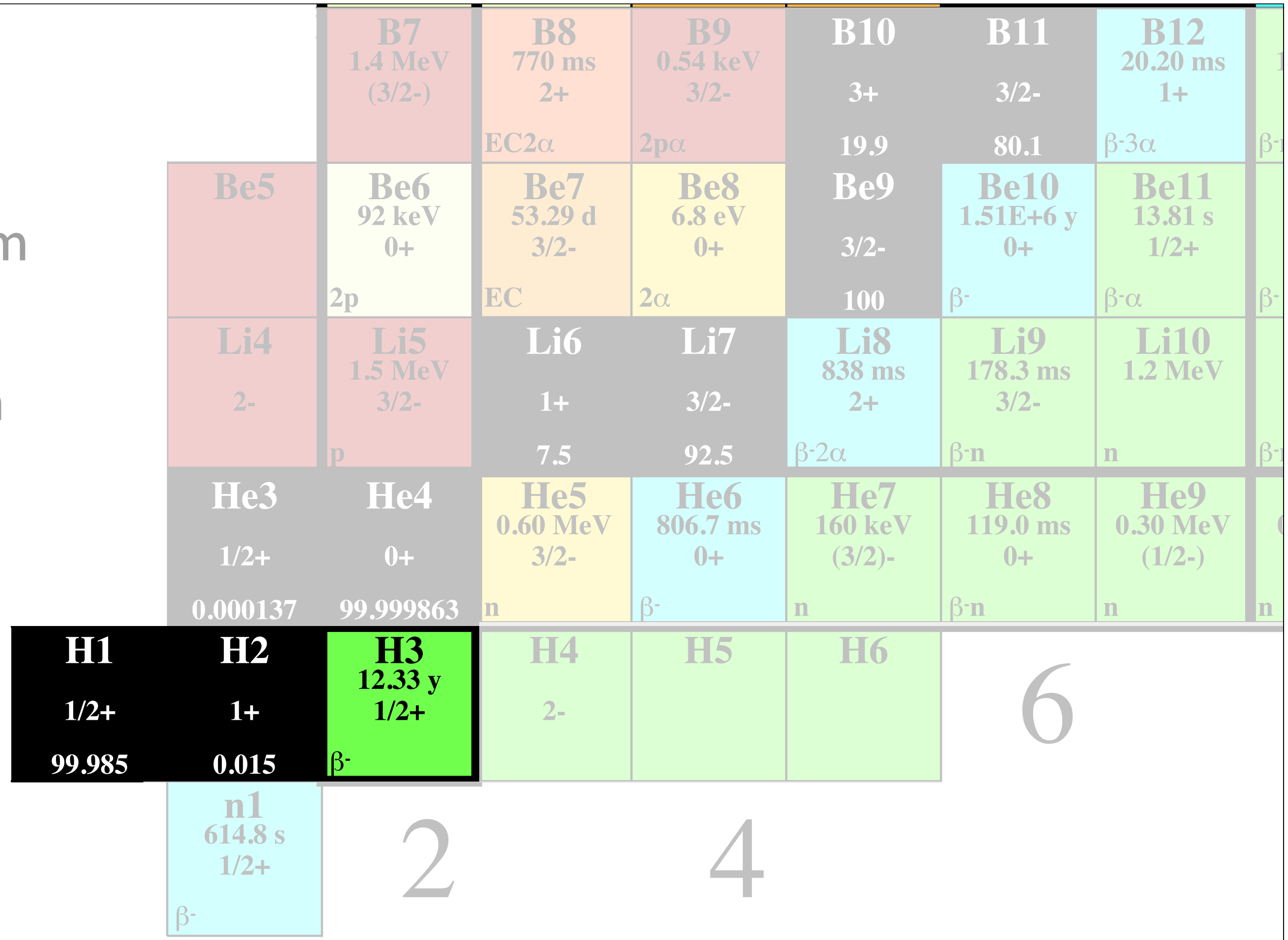
Beryllium

Lithium

Helium

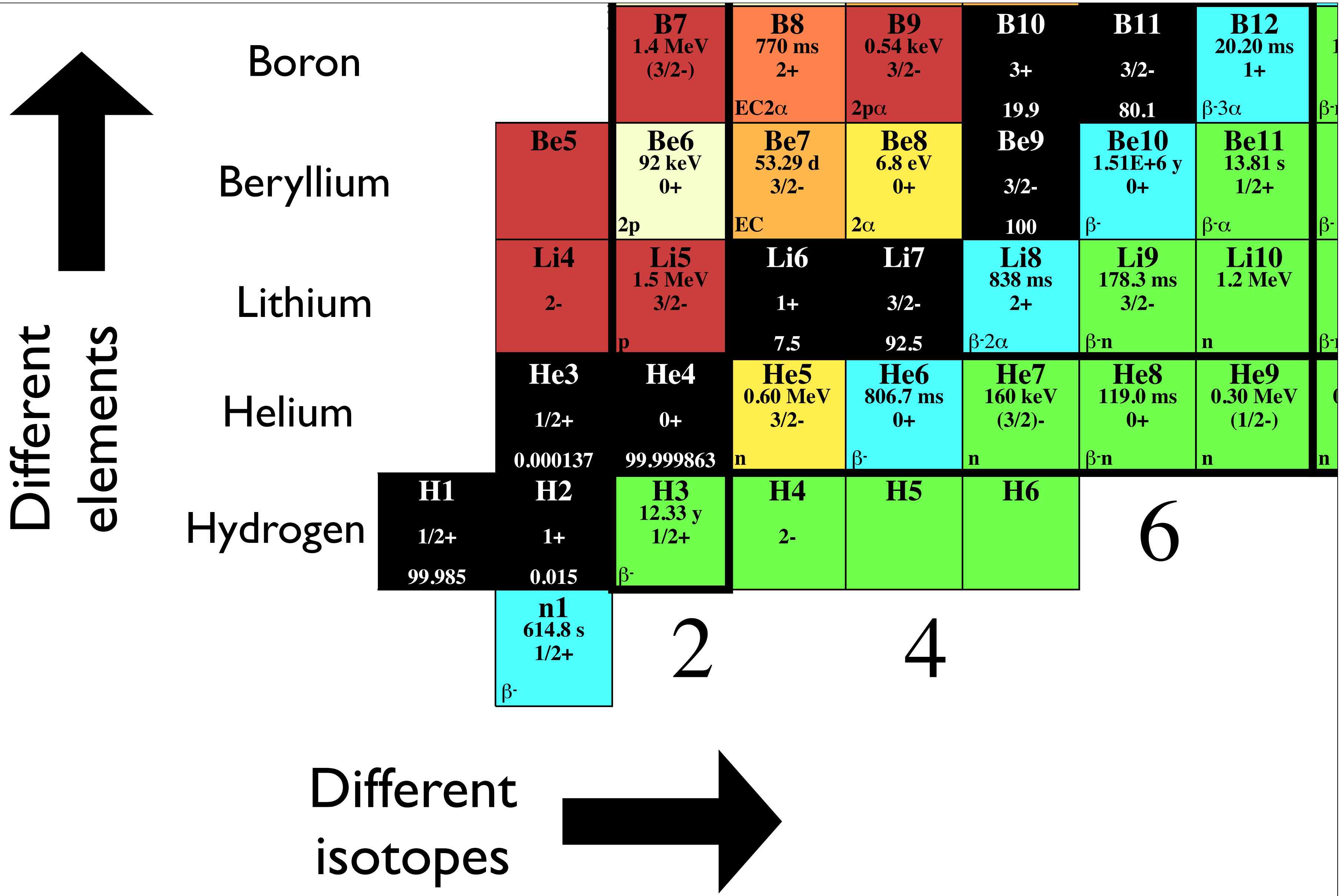
Hydrogen

Different elements

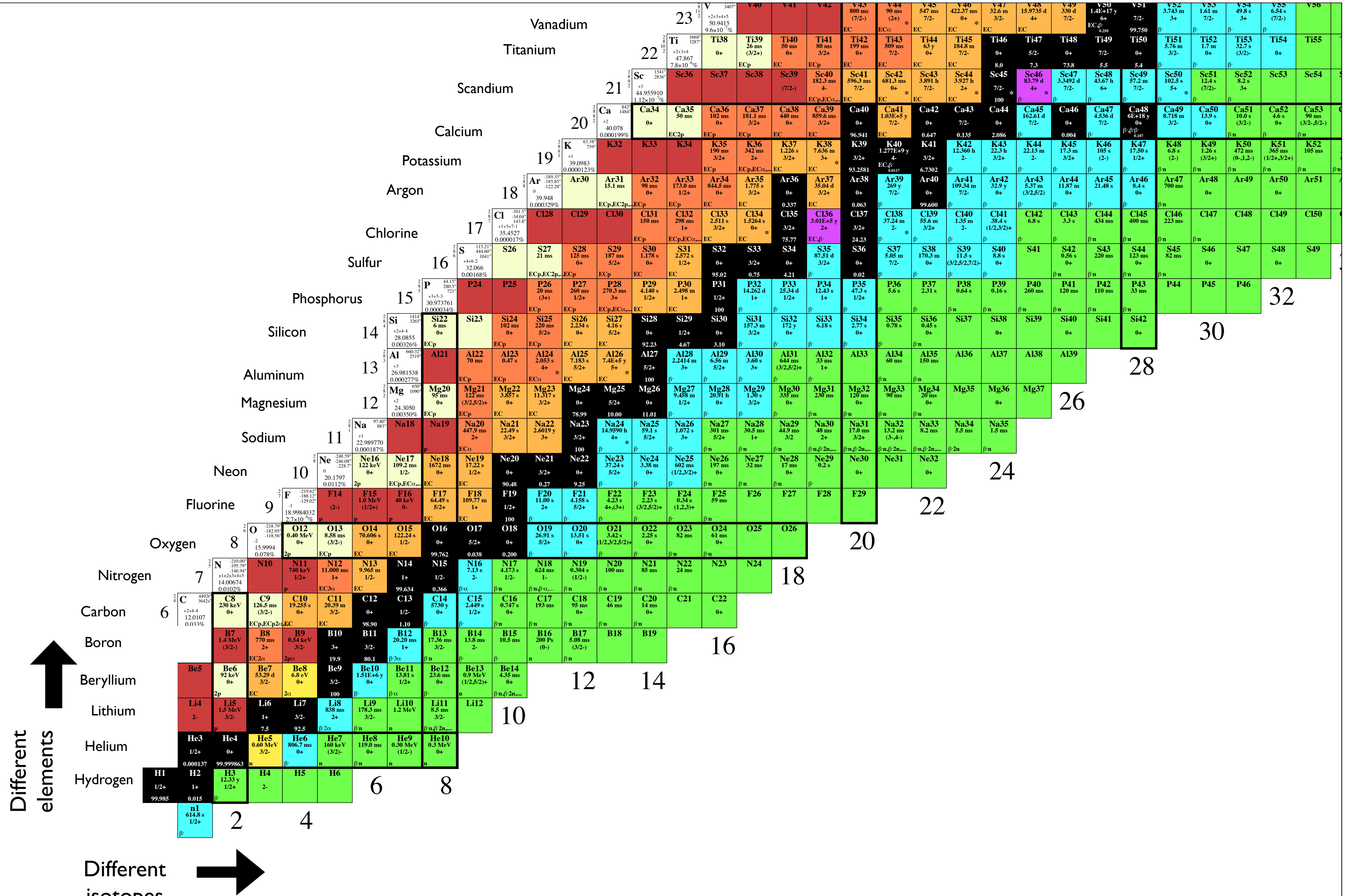


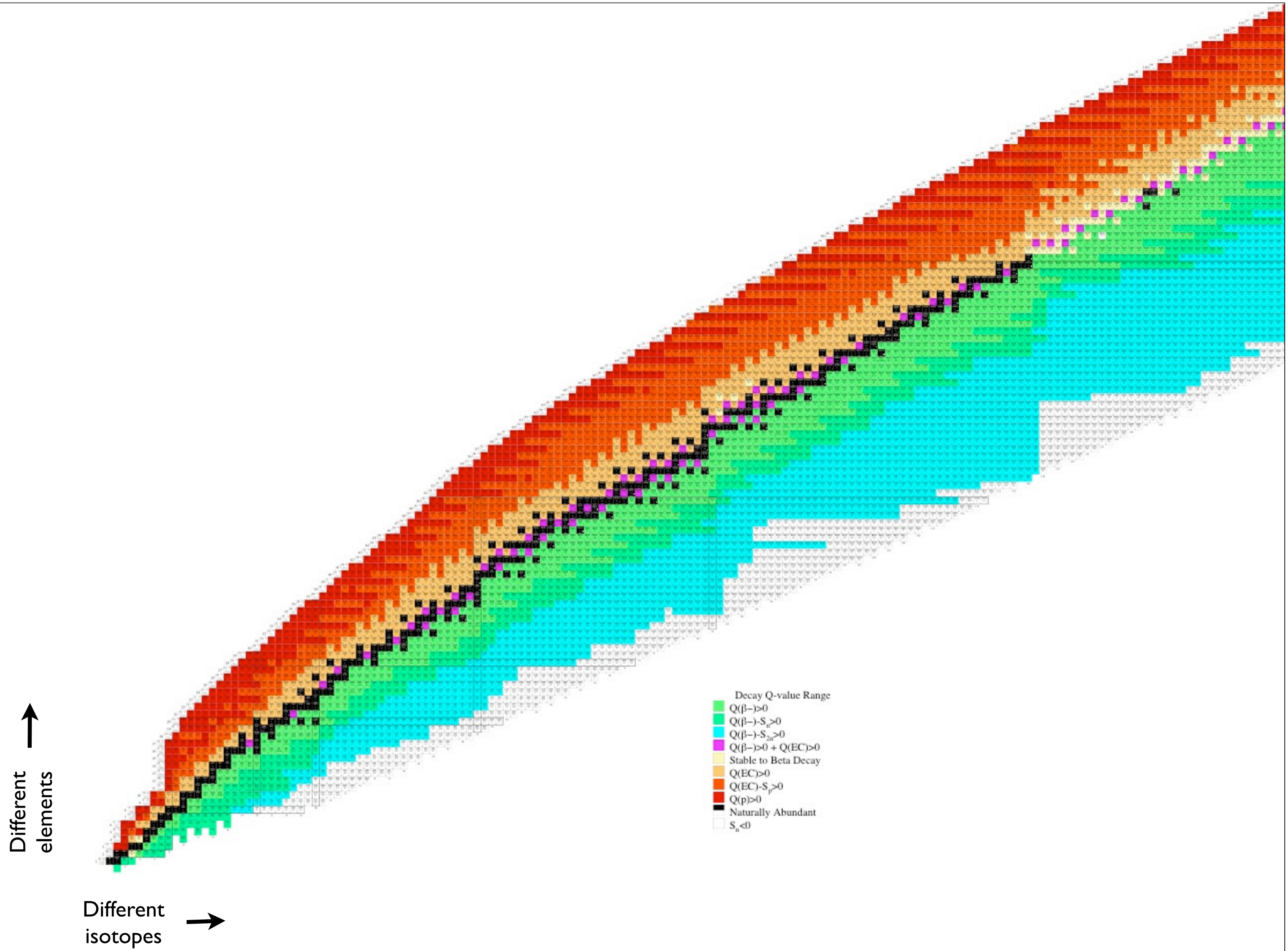
Different isotopes

http://nndc.lbl.gov



http://nndc.lbl.gov


Vanadium
Titanium
Scandium
Calcium
Potassium
Argon
Chlorine
Sulfur
Phosphorus
Silicon
Aluminum
Magnesium
Sodium
Neon
Fluorine
Oxygen
Nitrogen
Carbon
Boron
Beryllium
Lithium
Helium
Hydrogen
Different elements
Different isotopes



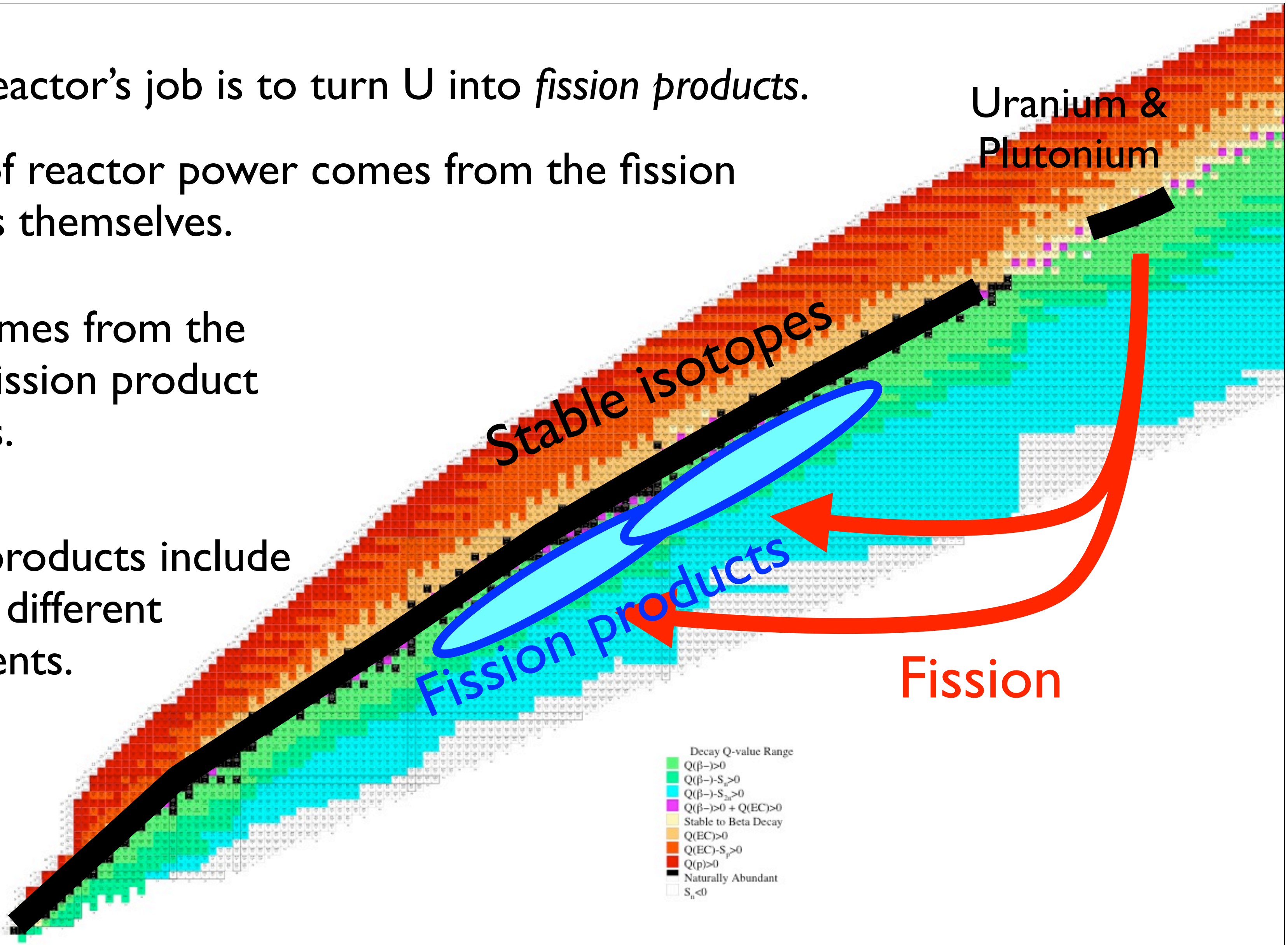
Decay Q-value Range
Q(β−)>0
Q(β−)-S_n>0
Q(β−)-S_{2n}>0
Q(β−)>0 + Q(EC)>0
Stable to Beta Decay
Q(EC)>0
Q(EC)-S_p>0
Q(p)>0
Naturally Abundant
S_n<0
Different elements
Different isotopes

The reactor's job is to turn U into *fission products*.

95% of reactor power comes from the fission events themselves.

5% comes from the later fission product decays.

The products include many different elements.

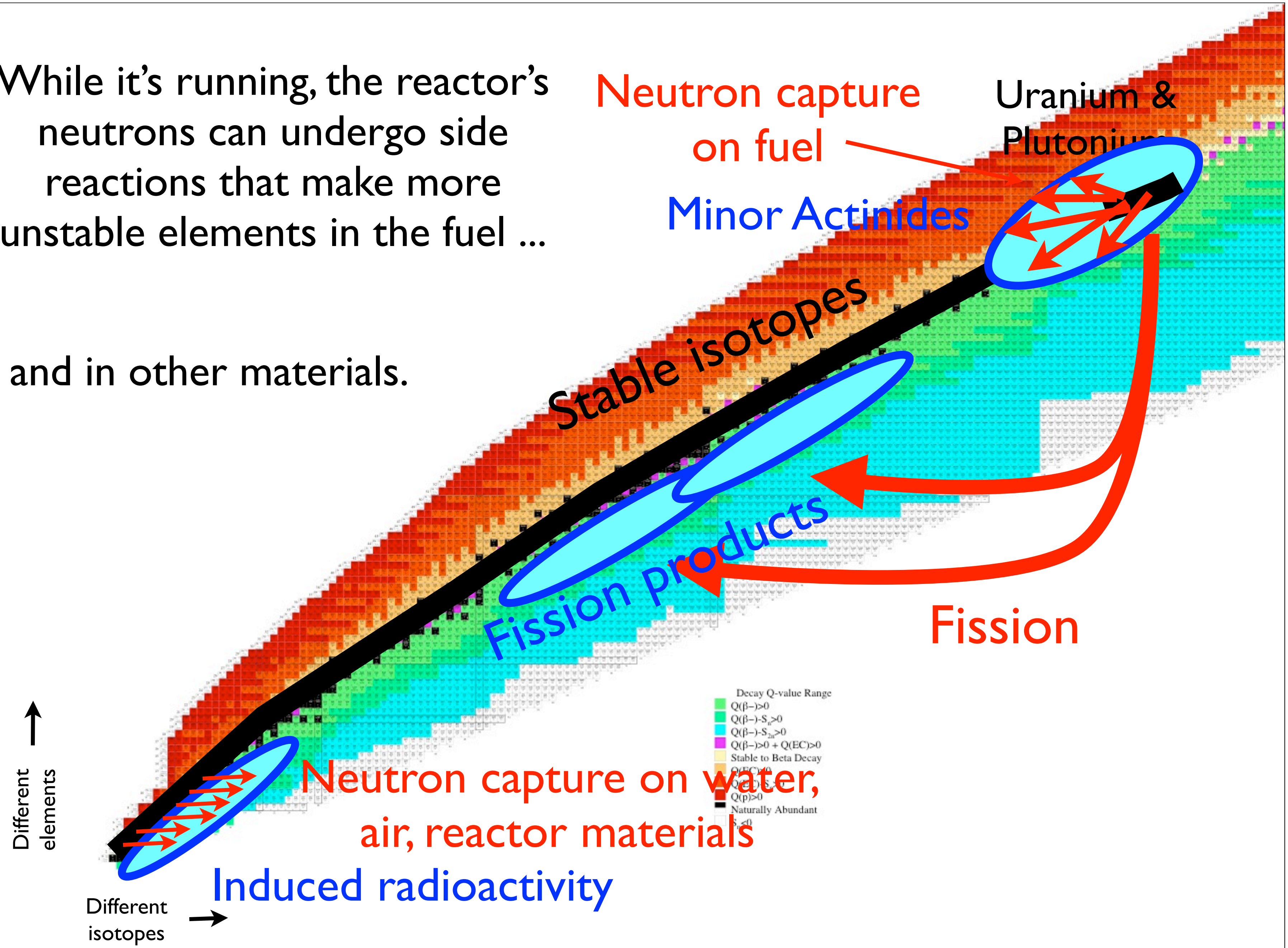


Different elements ↑

Different isotopes →

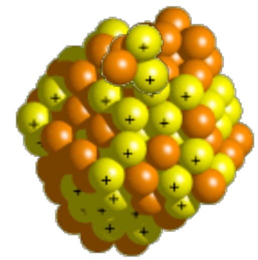
While it’s running, the reactor’s neutrons can undergo side reactions that make more unstable elements in the fuel ...

and in other materials.



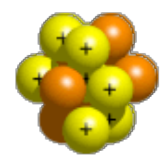
Radiation damage

Alpha decay: common in minor actinides (damages every 10th atom it passes.)



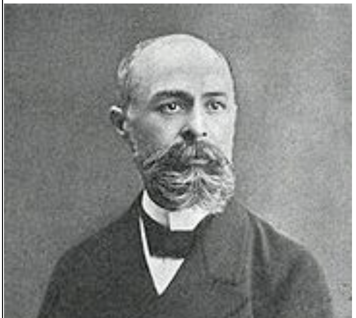
$^{222}Rn \rightarrow {}^{218}Po + {}^{4}He$

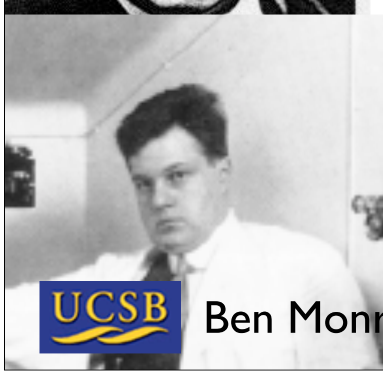
Beta & gamma decay: fission products (damages every 3000th atom it passes.)



$^{14}C \rightarrow {}^{14}N + e^{-} + \nu$

http://education.jlab.org



How much damage?

- One **becquerel** = 1 decay per second
- One **curie** = 37 billion decays per second.
  - A measure of amount, as in "There are 20 million curies of ^{137}Cs in the fuel pond"

- One **gray** = absorbing 1 billion ^{238}U decays, or 10 billion ^{137}Cs decays, per gram of body mass

One **sievert** = absorbing 0.05B ^{238}U decays, or 10B of ^{137}Cs, per gram of body mass

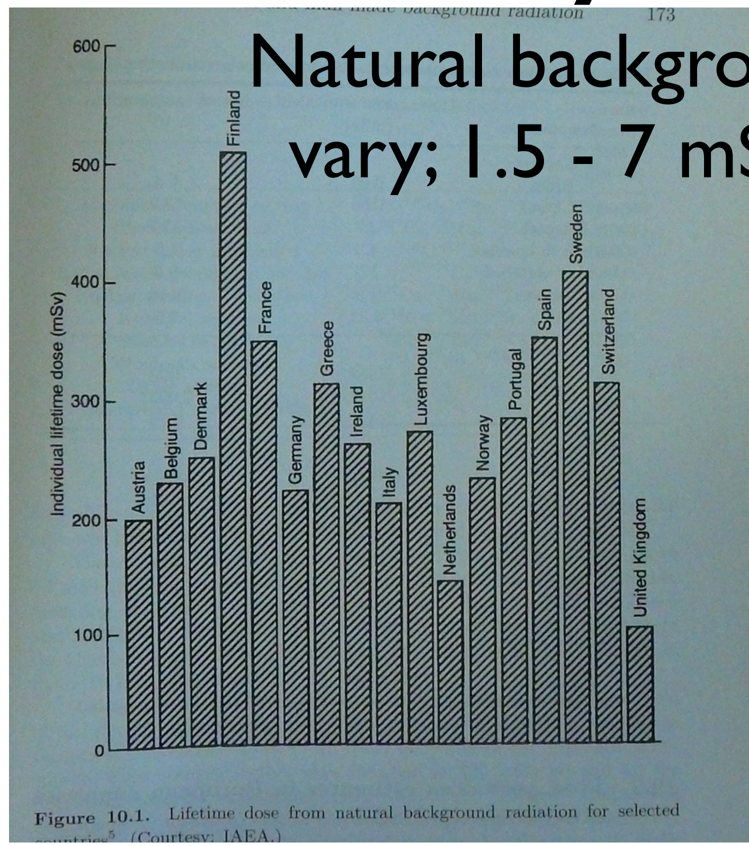
- A measure of "dose" = fraction of body's chemical bonds damaged.

For fission products, gray = sievert

Radiation numeracy

- You are all getting irradiated right now.
  - natural ^{40}K in your body: ~0.2 mSv/yr.
  - natural ^{222}Rn in the air: ~1 mSv/yr.
- Moving to Denver? Add ~1 mSv/yr.
- Are you a flight attendant? Add ~few mSv/yr.

Natural backgrounds vary; 1.5 - 7 mSv/y



Lesson: *a few milliSieverts dose is not worth worrying about at all. (but mSv/h rate can add up.)*

"Chernobyl Record" R.F. Mould, IOP 2000

Radiation and cancer

Ionization ≈ DNA damage *(rarely)*

DNA damage ≈ changed cells *(rarely)*

changed cells ≈ cancer *(rarely)*

Type of cancer	Extra cases per 10000 people with 1000mSv doses
Leukemia	3
Breast	7
Thyroid	1.6
Lung	4
Stomach	5
Colon	2

Lesson: *1 Sv = 1000 mSv is a risk you would go out of your way to avoid, like texting while driving.*

From John D. Boice, Natl. Cancer Institute
in "Health Effects from Exposure to Low-Level Ionizing Radiation", IOP 1996

Acute radiation sickness

Lesson: >5 Sv = *run for your life*

- *Extraordinarily rare.*
  - "Slotin Incident": 21 Sv, victim died 9 d later
  - "Daghlian incident": 5 Sv, victim died 1 month later
  - Goiania accident: 5 Sv/hr medical source got loose. 4 dead (all > 5 Sv), 15 hospitalized (all betwen 0.5 and 5 Sv).
  - Chernobyl first-responders: dose rates of 10 Sv/hr in many areas; 30 dead, 200 hospitalized
  - Many victims of Hiroshima and Nagasaki

Units in the news

The New York Times

Last Defense at Troubled Reactors: 50 Japanese Workers

Radiation close to the reactors was reported to reach 400 millisieverts per hour on Tuesday after a blast inside reactor No. 2 and fire at reactor No. 4, but has since dropped back to as low as 0.6 millisieverts at the plant gate.

← we know 5000 mSv = fatal
so 400 mSv/hr for would be fatal
if you had 5000/400 = 12 hours

← 0.6 mSv per hour
1000 mSv = texting while driving
1000/0.6 = two months

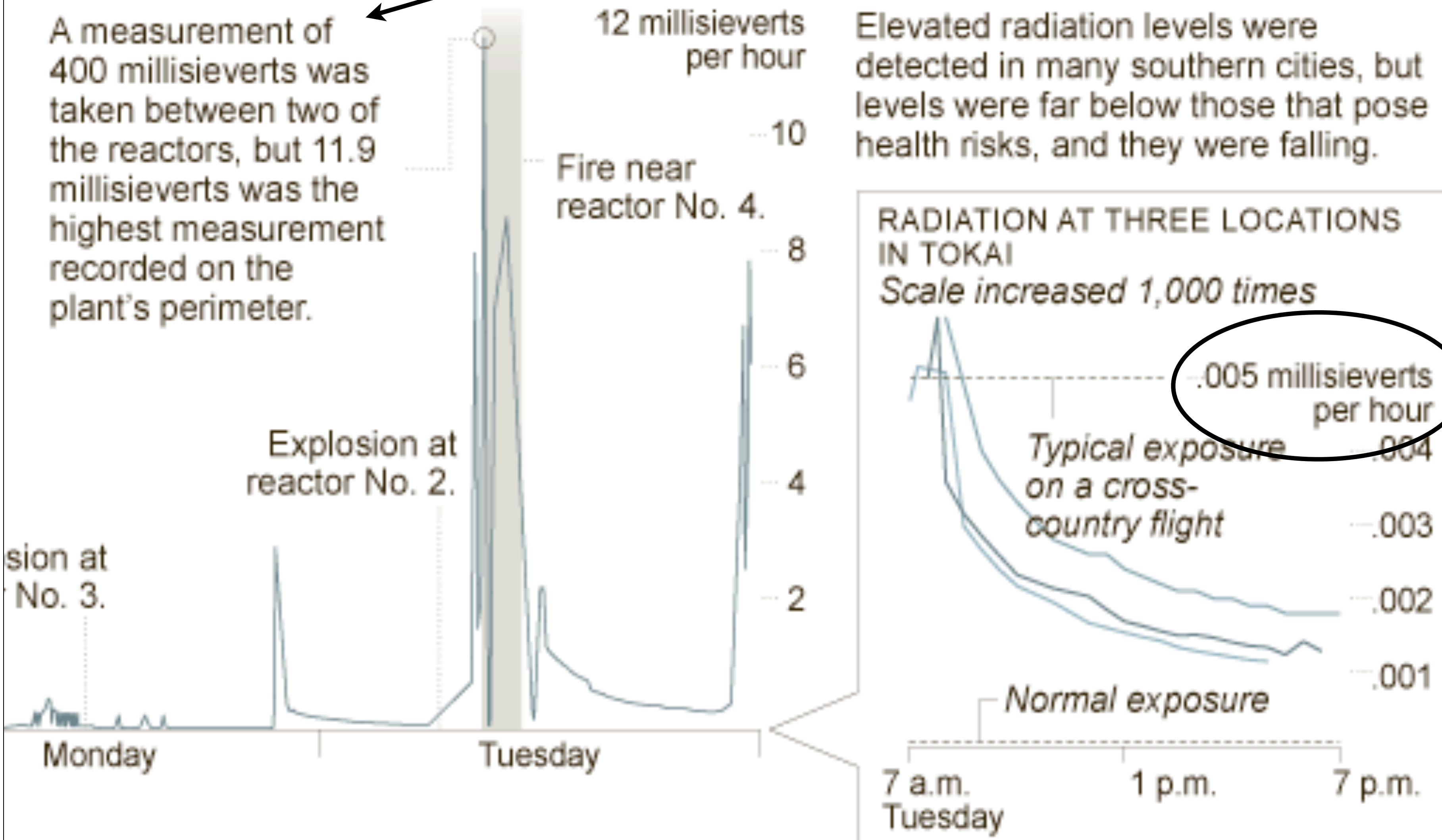
wnn
world nuclear news

Radiation levels on the edge of the plant compound briefly spiked at 8217 microsieverts per hour but later fell to about a third that.

← 8000 μSv/hr = 8 mSv/hr

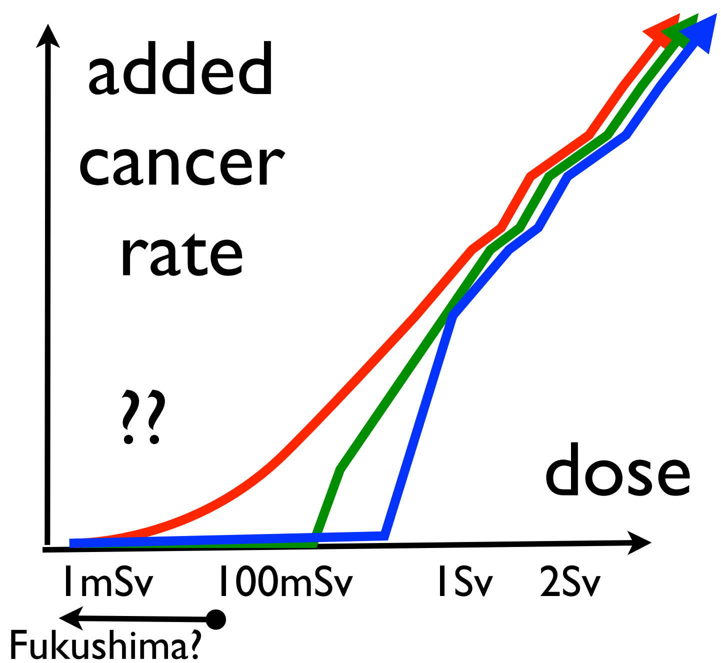
They meant "millisieverts *per hour*"

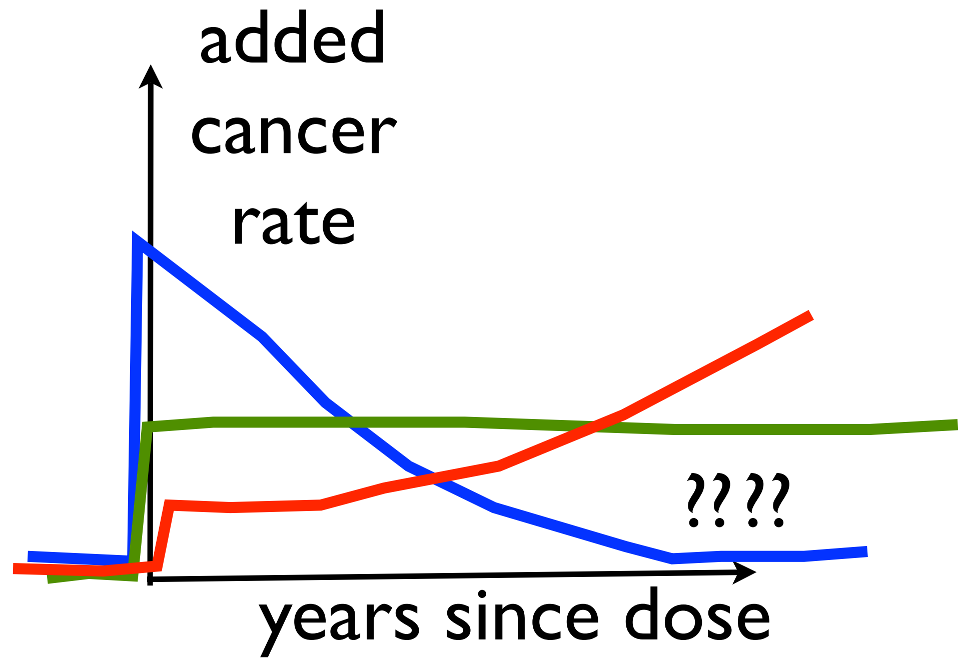
NYTimes.com



Are low doses proportionally dangerous?

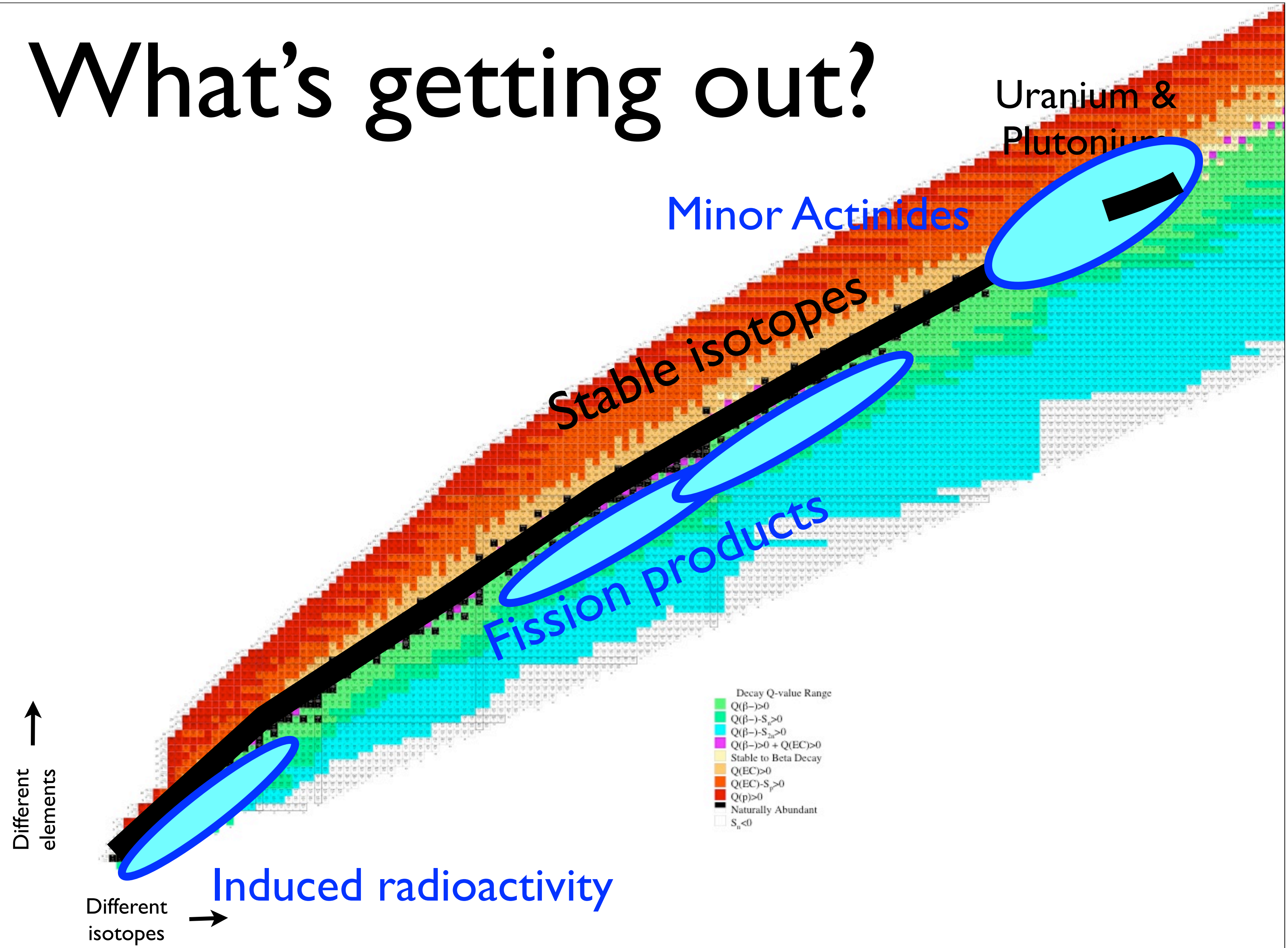
- Probably?? There is no case where a small extra risk was *detectable*. (Chernobyl area: thyroid cancer at 100 mSv)



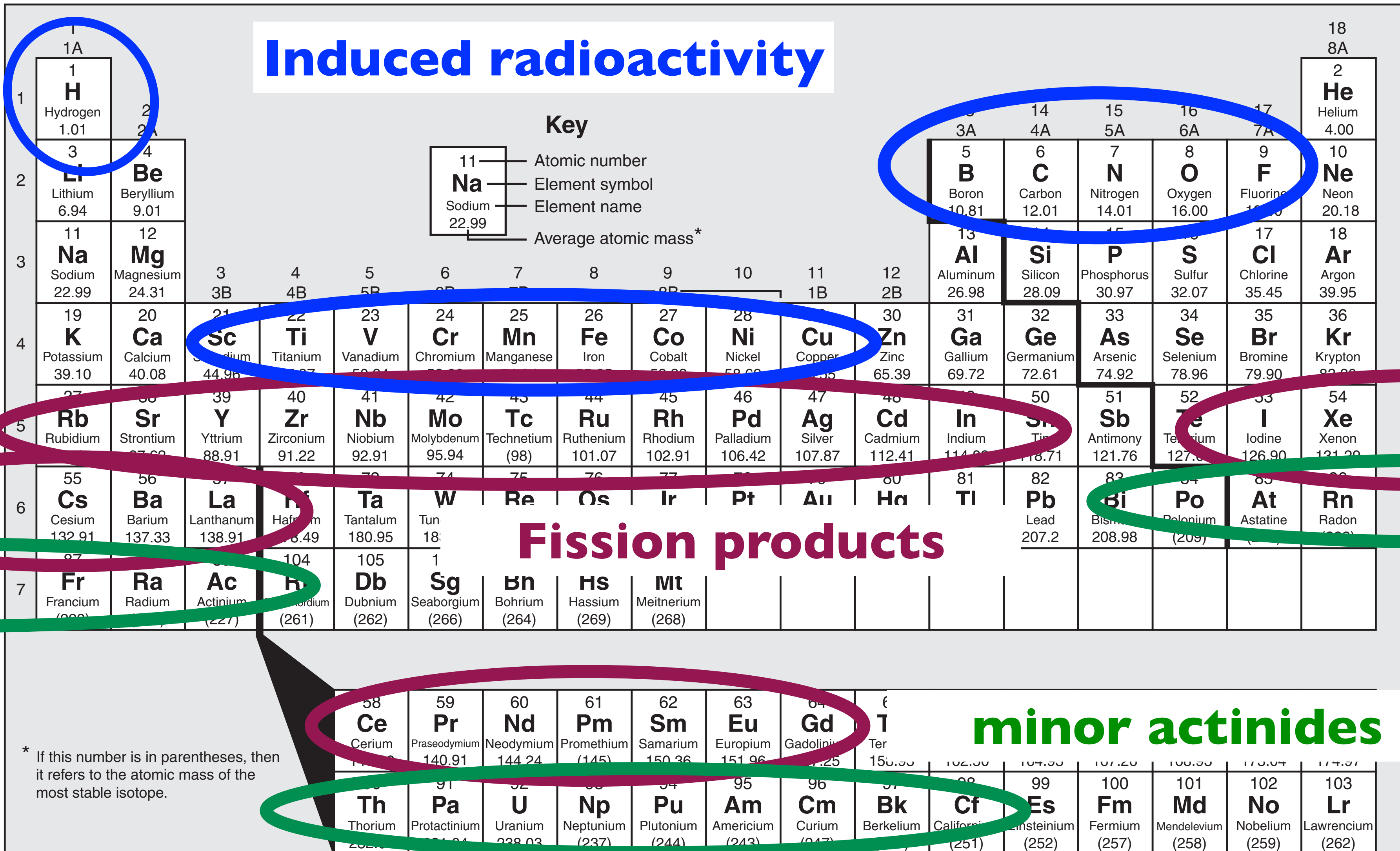


"Health effects of low-level exposure to ionizing radiation", ed. Hendee & Edwards, IoP 1996

What's getting out?



Periodic Table of the Elements | Chemistry Reference Sheet | California Standards Test



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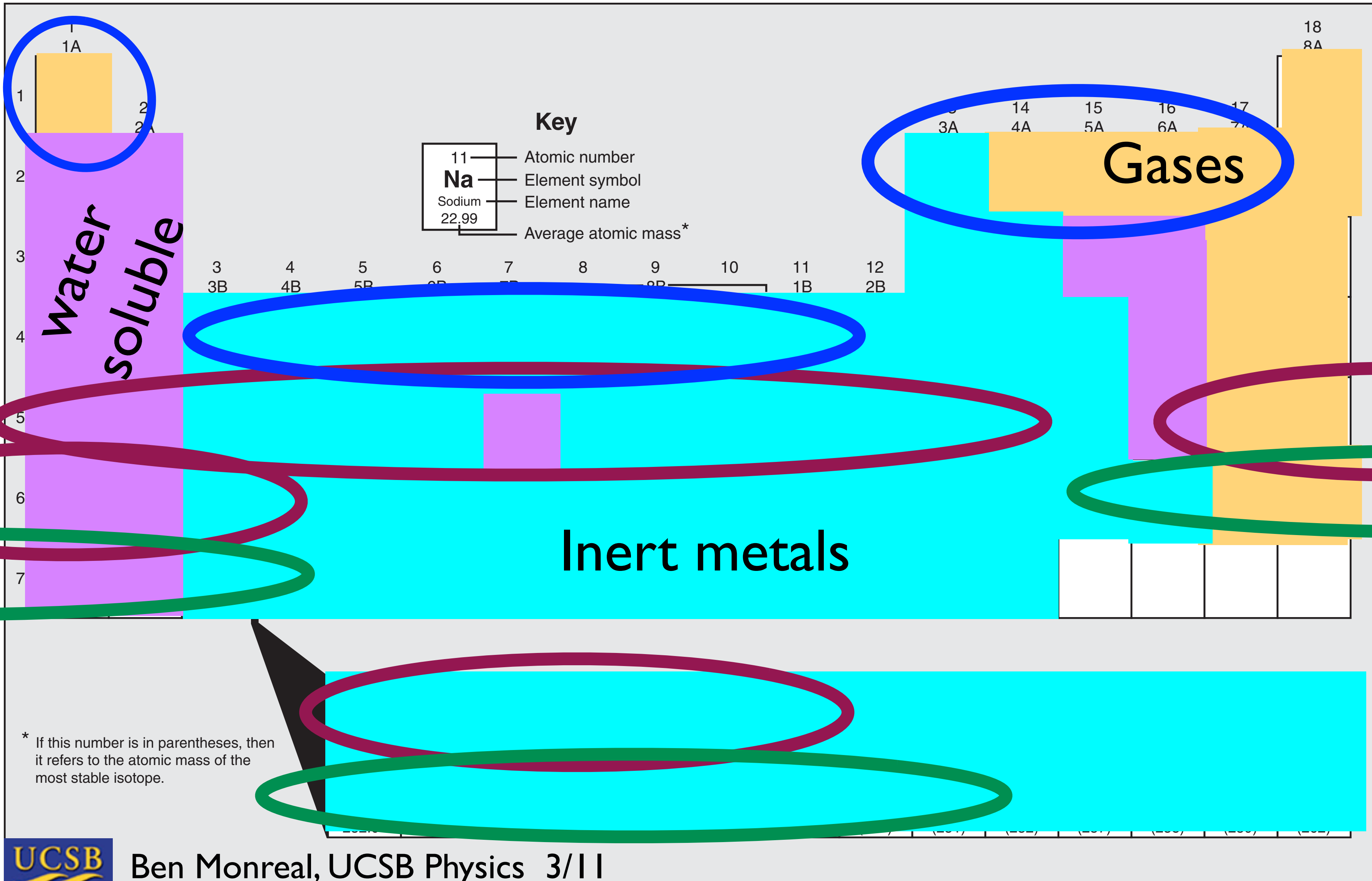
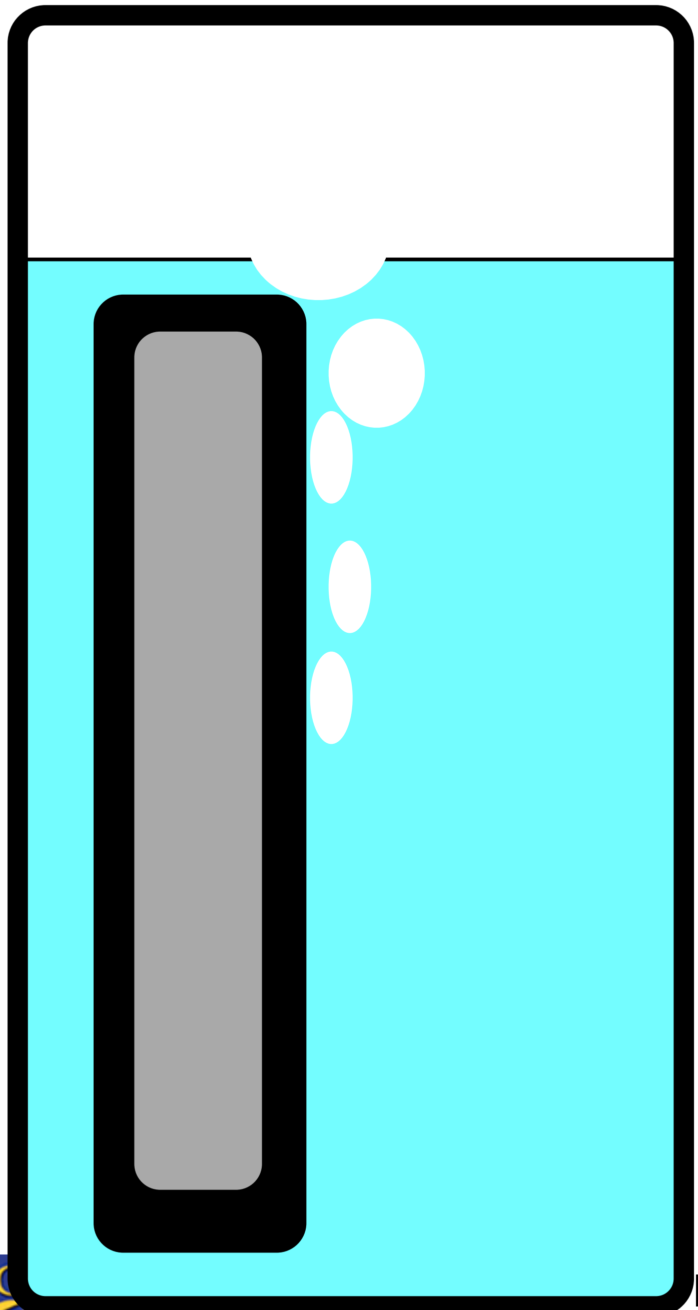




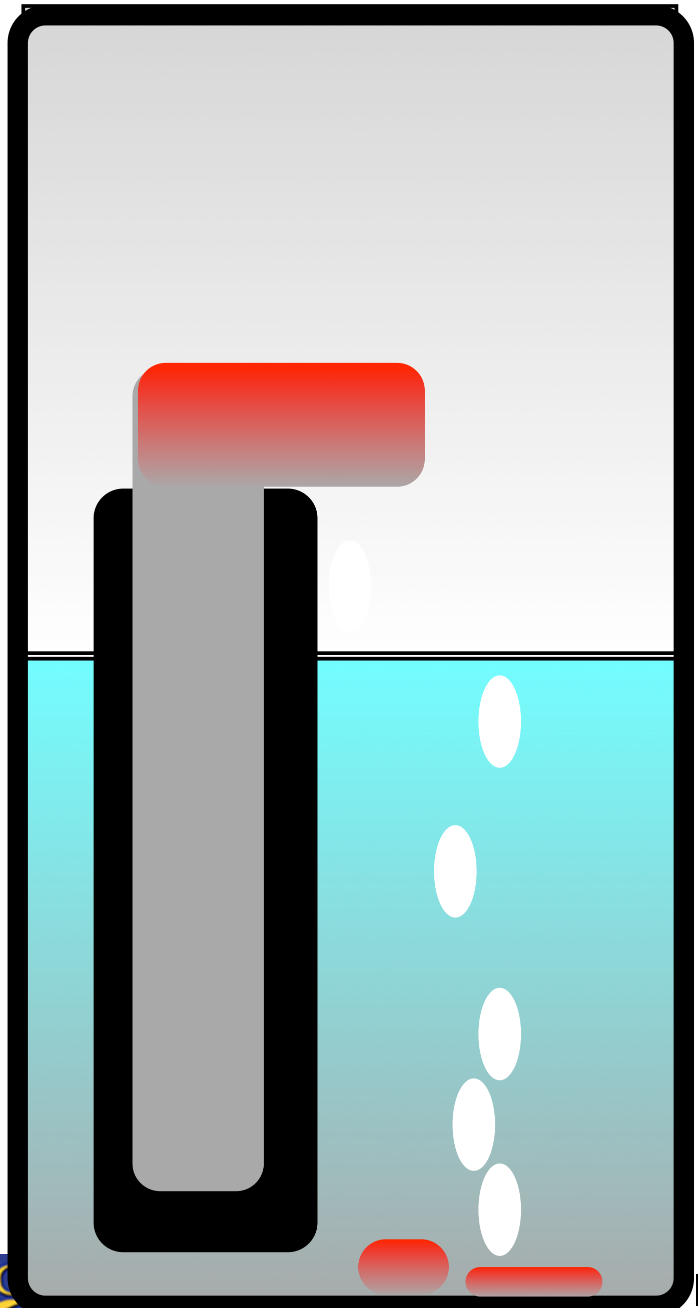
Healthy reactor:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
activation products

In steam:
activation products

In environment:
practically nothing



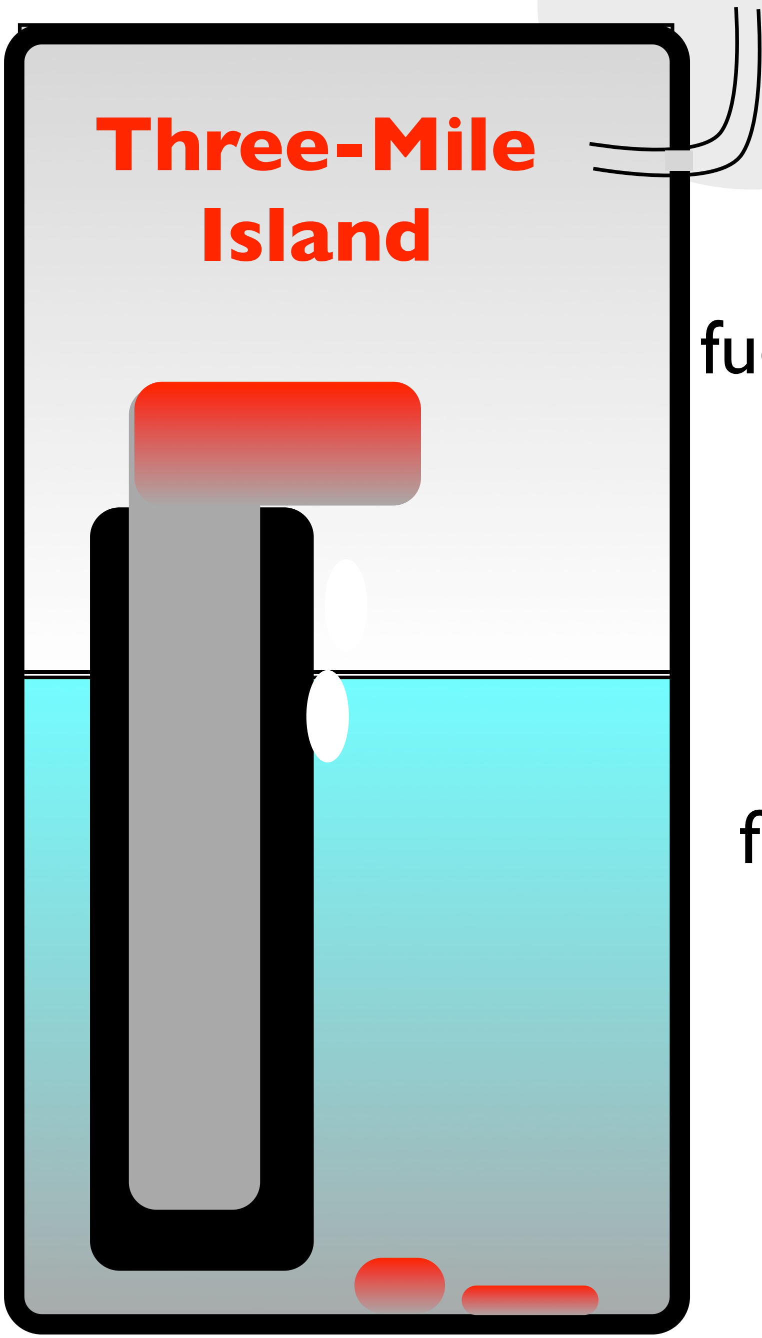
Meltdown:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing



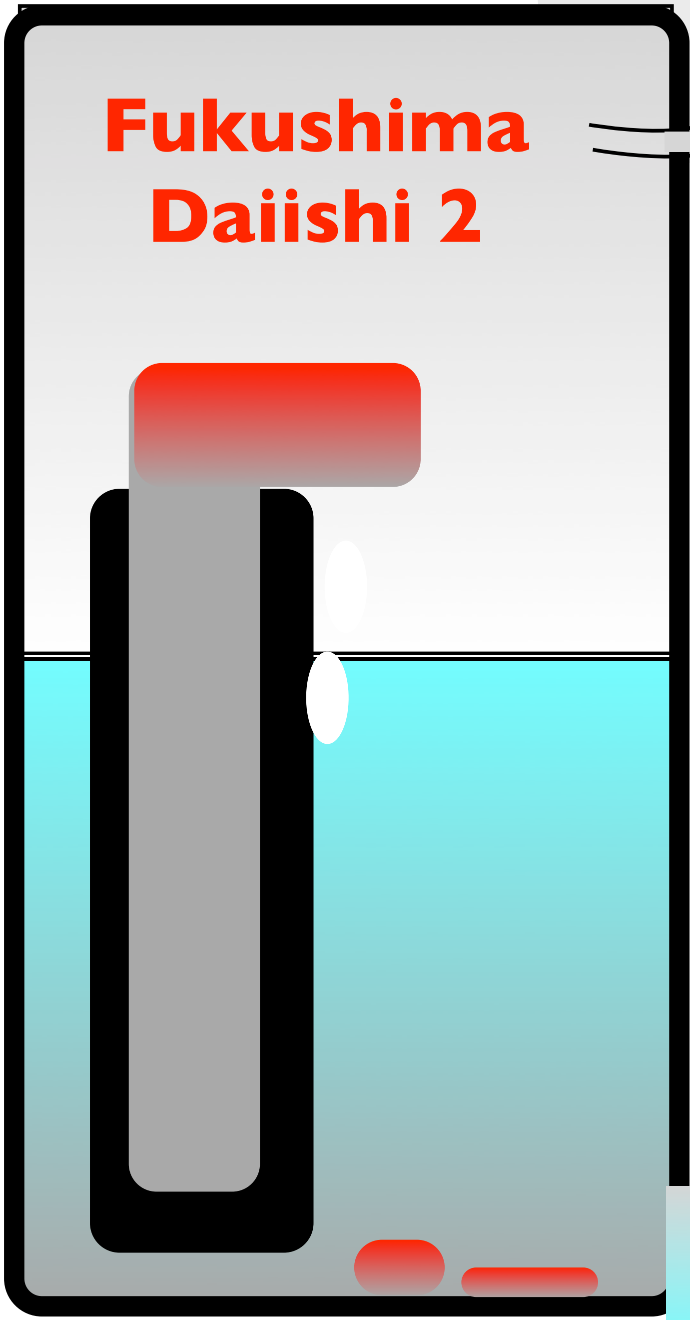
Meltdown + emergency venting:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing
Xe, Kr, Rn



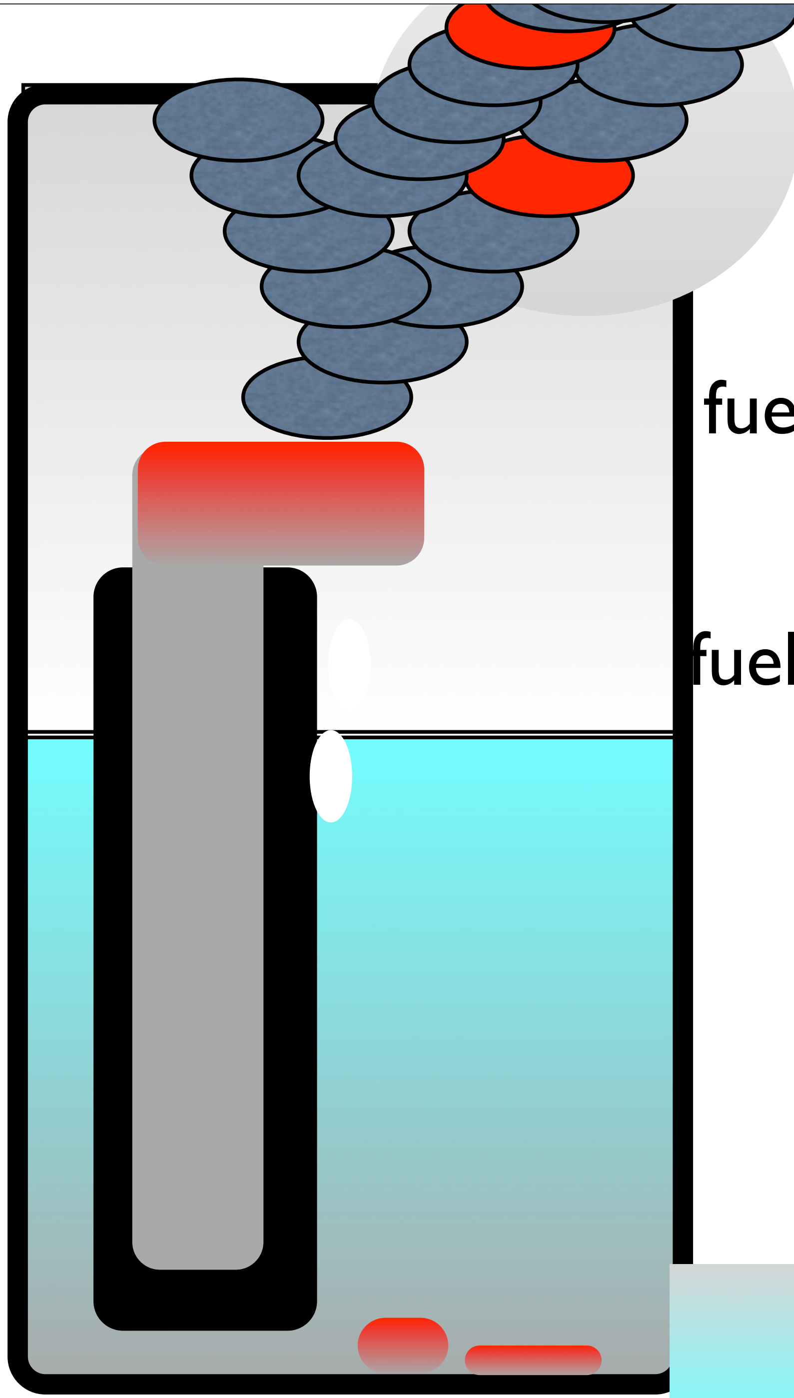
Meltdown + containment failure:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
Xe, Kr, Rn, Cs, I, Tc



Meltdown + fuel fire

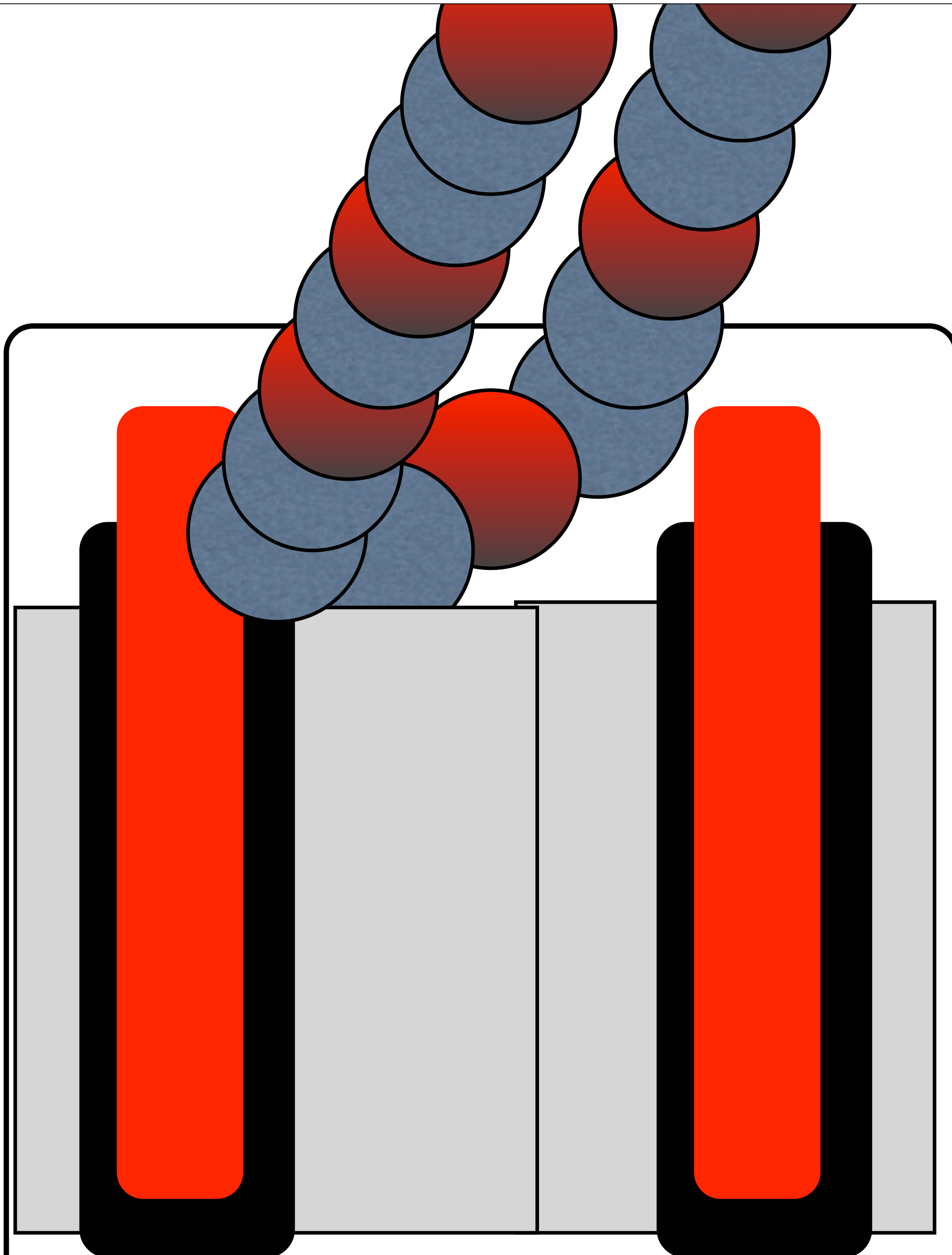
In Zircalloy casing:
fuel + fission products + actinides

In environment:
fuel + fission products + actinides

Briefly happened at Fukushima spent-fuel pools? (reports vary?)

This is very bad but
still not as bad as Chernobyl

Chernobyl

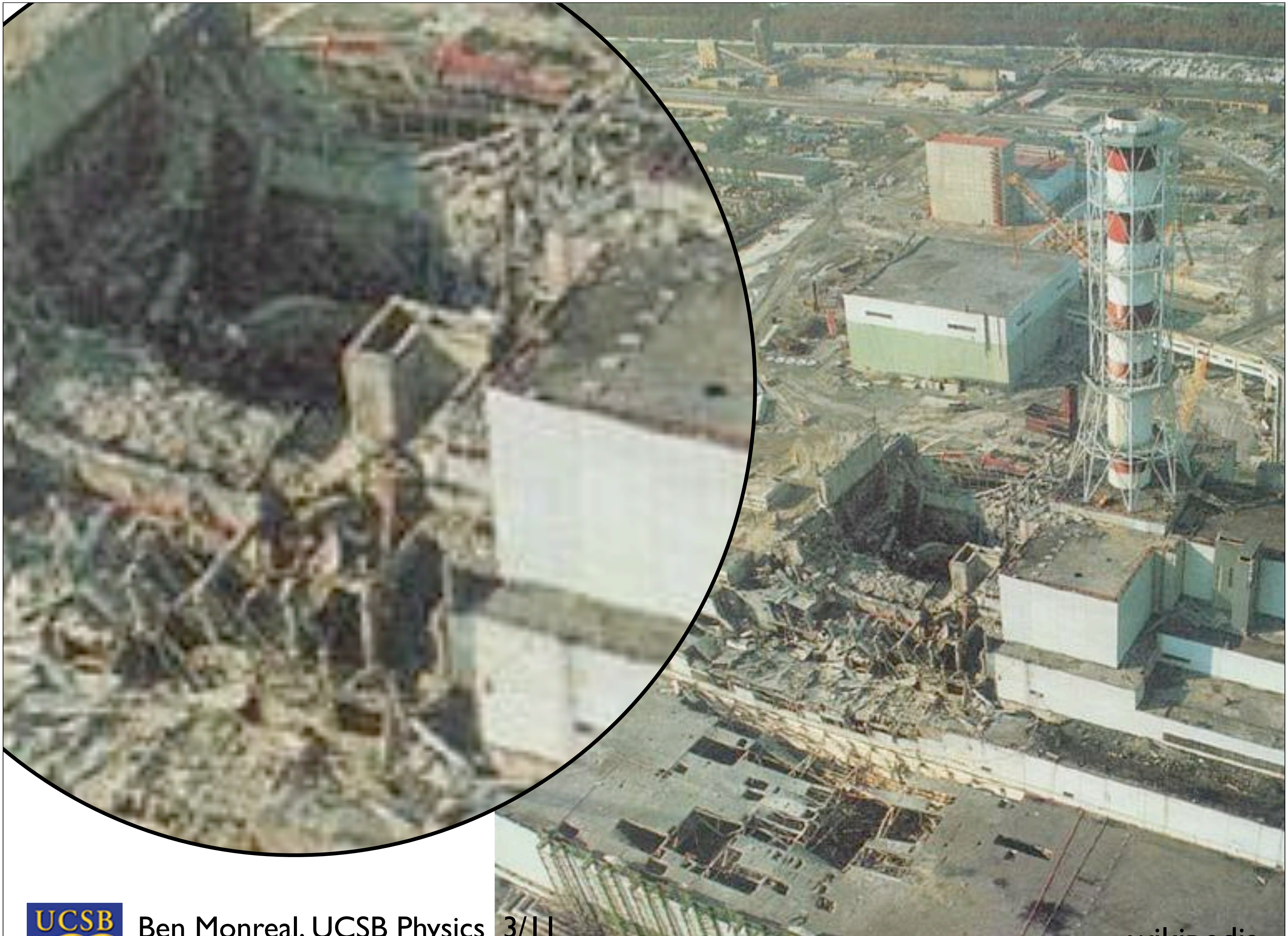


no real "containment vessel"

Core filled with graphite (fuel for huge fire)

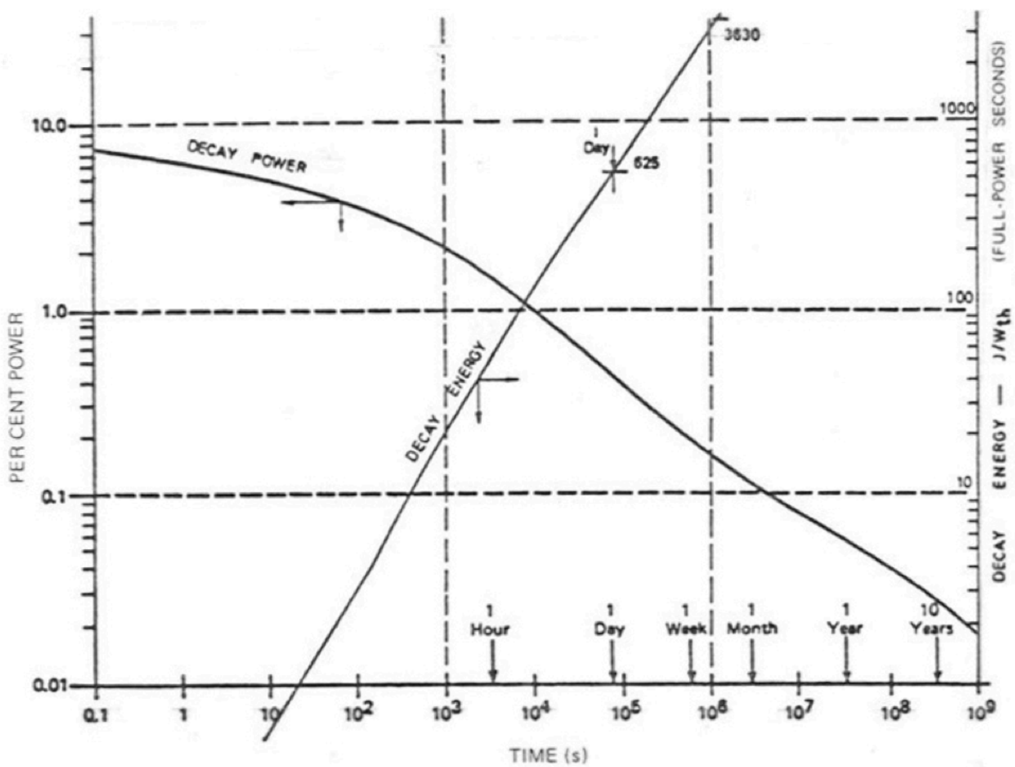
Reactor *fissioning during explosions and fire*

(Fukushima reactors have now been "off" for 5 days)



wikipedia

Saving graces at Fukushima



- *Reactor survived earthquake intact (!!!!!)*
- Shut down properly
- First hour of containment saved factor of 5x
- First day: factor 20x
- Evacuation
- Biggest fire risk is 100-day-old spent fuel, i.e. 100x less radioactive than Chernobyl material

Nuclides to watch

Nuclide	Half-life	Effect at Chernobyl
^{131}Iodine	8 days	quick ~0.5 mSv dose to everyone in Eastern Europe
^{137}Cesium	30 years	Additional ~1 mSv over 30y
^{90}Strontium	30 years	Lower amount than Cs, but accumulates in bone
^{241}Plutonium	9 years	Large doses near reactor site; easier to decontaminate

Cooper, Randle, and Sokhi, Wiley 2003

In case of fire ... soot

Nuclide	Half-life
^{95}Zirconium	60 days
^{99}Molybdenum	3 days
^{103}Ruthenium	40 days
^{141}Cerium	30 days
^{140}Barium	14 days

- Worst concern to first responders. Weather may move soot plumes around (Chernobyl: bad plumes to 60km)
- *This is what the "stay indoors" advisories are talking about. Soot in your driveway doesn't dose you; soot on your clothes does.*
- Can be cleaned from streets/buildings. Agriculture, fisheries have to wait it out (or remove top 10cm soil)

Conclusions

- The worst general-public effects of Chernobyl were *stress/fear;* HUGE education/communication failure
  - You have the information: count the millisieverts and decide how to respond
- My feeling: the worst-case radiation hazards from Fukushima are mitigatable and local
  - (early evacuation + controls on ^{131}I in food)
- My feeling: the global radiation hazard is nil.
  - The best way to reduce worldwide low-level radiation releases is ... stop burning coal
- Save your energy for those affected by the tsunami and "50 plant workers" at Fukushima