

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



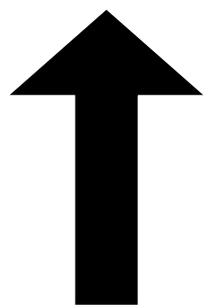
- Introduction to radioactivity
- Radiation hazards and health
- What escapes in a meltdown?
- Where does it go?
- How worried should we be?

Different elements
↑

Boron	B7 1.4 MeV (3/2-)	B8 770 ms 2+	B9 0.54 keV 3/2-	B10 3+	B11 3/2-	B12 20.20 ms 1+	
Beryllium	Be5	Be6 92 keV 0+	Be7 53.29 d 3/2-	Be8 6.8 eV 0+	Be9 3/2-	Be10 1.51E+6 y 0+	Be11 13.81 s 1/2+
Lithium	Li4 2-	Li5 1.5 MeV 3/2-	Li6 1+	Li7 3/2-	Li8 838 ms 2+	Li9 178.3 ms 3/2-	Li10 1.2 MeV
Helium	He3 1/2+	He4 0+	He5 0.60 MeV 3/2-	He6 806.7 ms 0+	He7 160 keV (3/2)-	He8 119.0 ms 0+	He9 0.30 MeV (1/2-)
Hydrogen	H1 1/2+	H2 1+	H3 12.33 y 1/2+	H4 2-	H5	H6	6
	n1 614.8 s 1/2+						

Different isotopes
→

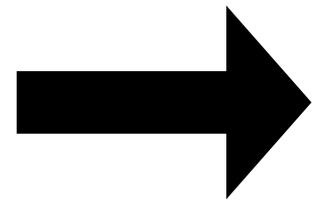




Different elements

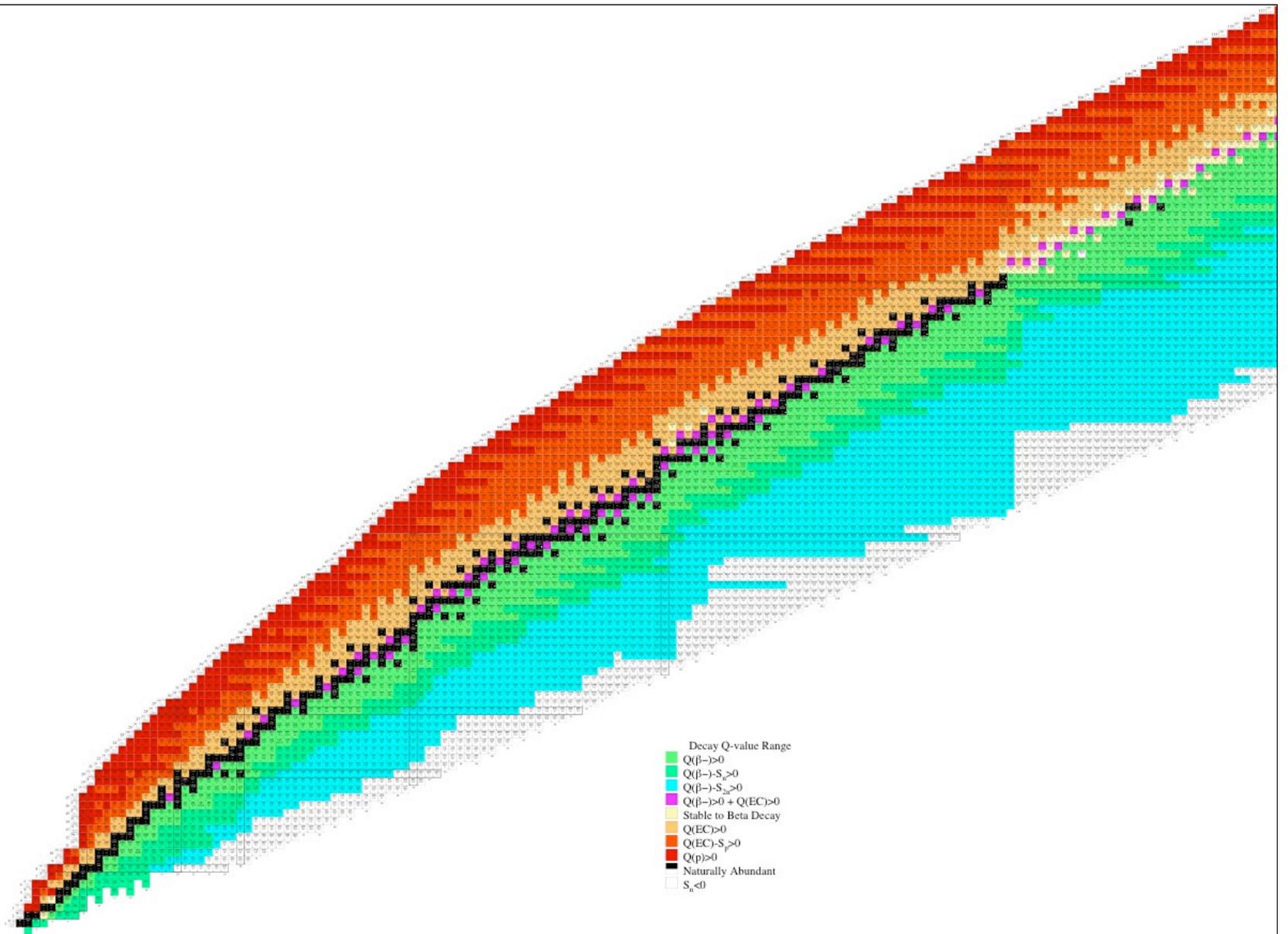
			B7 1.4 MeV (3/2-)	B8 770 ms 2+	B9 0.54 keV 3/2-	B10	B11	B12 20.20 ms 1+	
				EC2 α	2p α	19.9	80.1	β -3 α	β - α
		Be5	Be6 92 keV 0+	Be7 53.29 d 3/2-	Be8 6.8 eV 0+	Be9	Be10 1.51E+6 y 0+	Be11 13.81 s 1/2+	
			2p	EC	2 α	100	β -	β - α	β -
		Li4	Li5 1.5 MeV 3/2-	Li6	Li7	Li8 838 ms 2+	Li9 178.3 ms 3/2-	Li10 1.2 MeV	
			p	7.5	92.5	β -2 α	β -n	n	β - α
		He3	He4	He5 0.60 MeV 3/2-	He6 806.7 ms 0+	He7 160 keV (3/2)-	He8 119.0 ms 0+	He9 0.30 MeV (1/2-)	
		0.000137	99.999863	n	β -	n	β -n	n	n
	H1	H2	H3 12.33 y 1/2+	H4	H5	H6	6		
	99.985	0.015	β -						
		n1 614.8 s 1/2+							
		β -							

Different isotopes



↑
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
 - $S_n < 0$



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

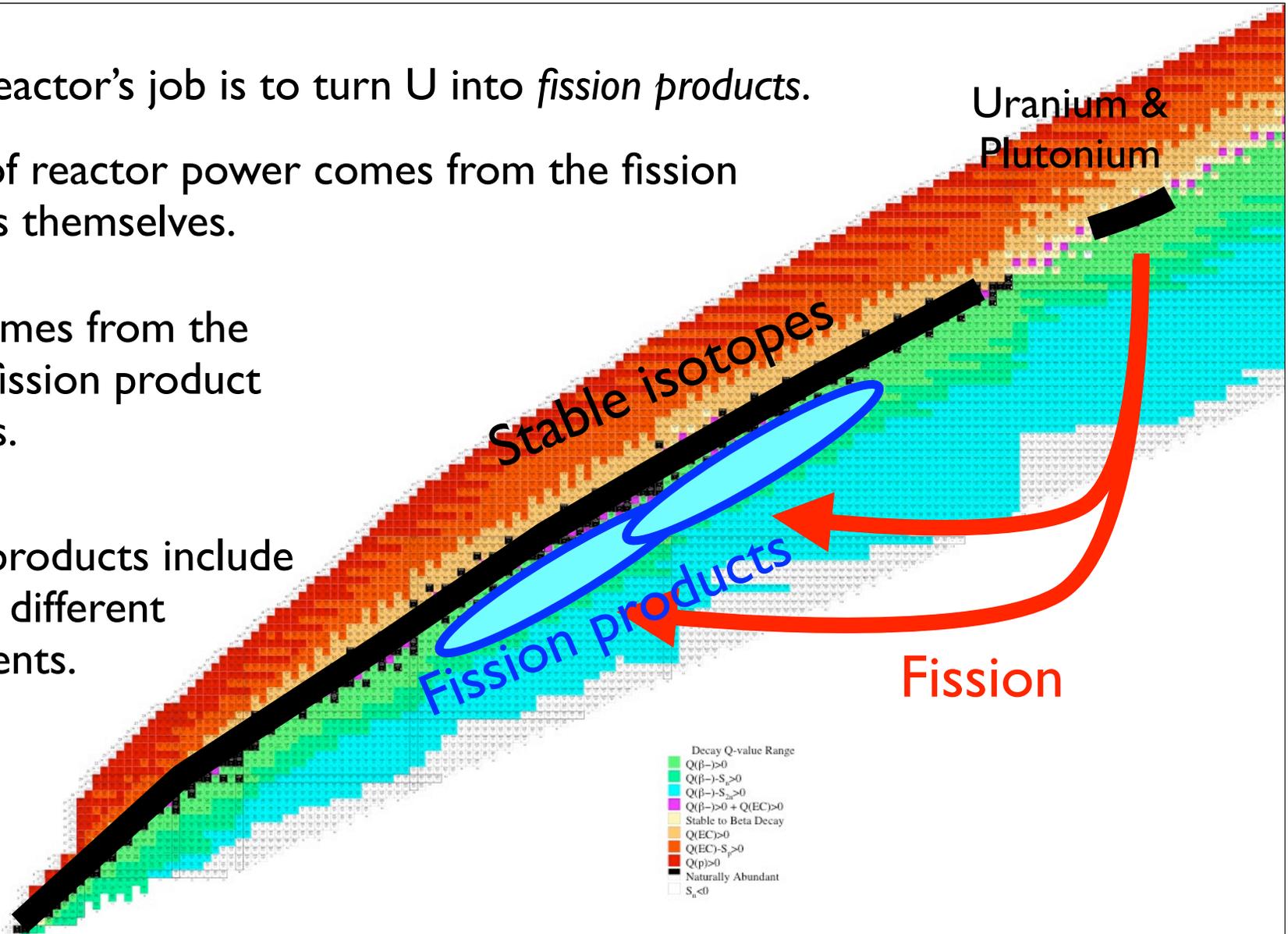
95% of reactor power comes from the fission events themselves.

5% comes from the later fission product decays.

The products include many different elements.

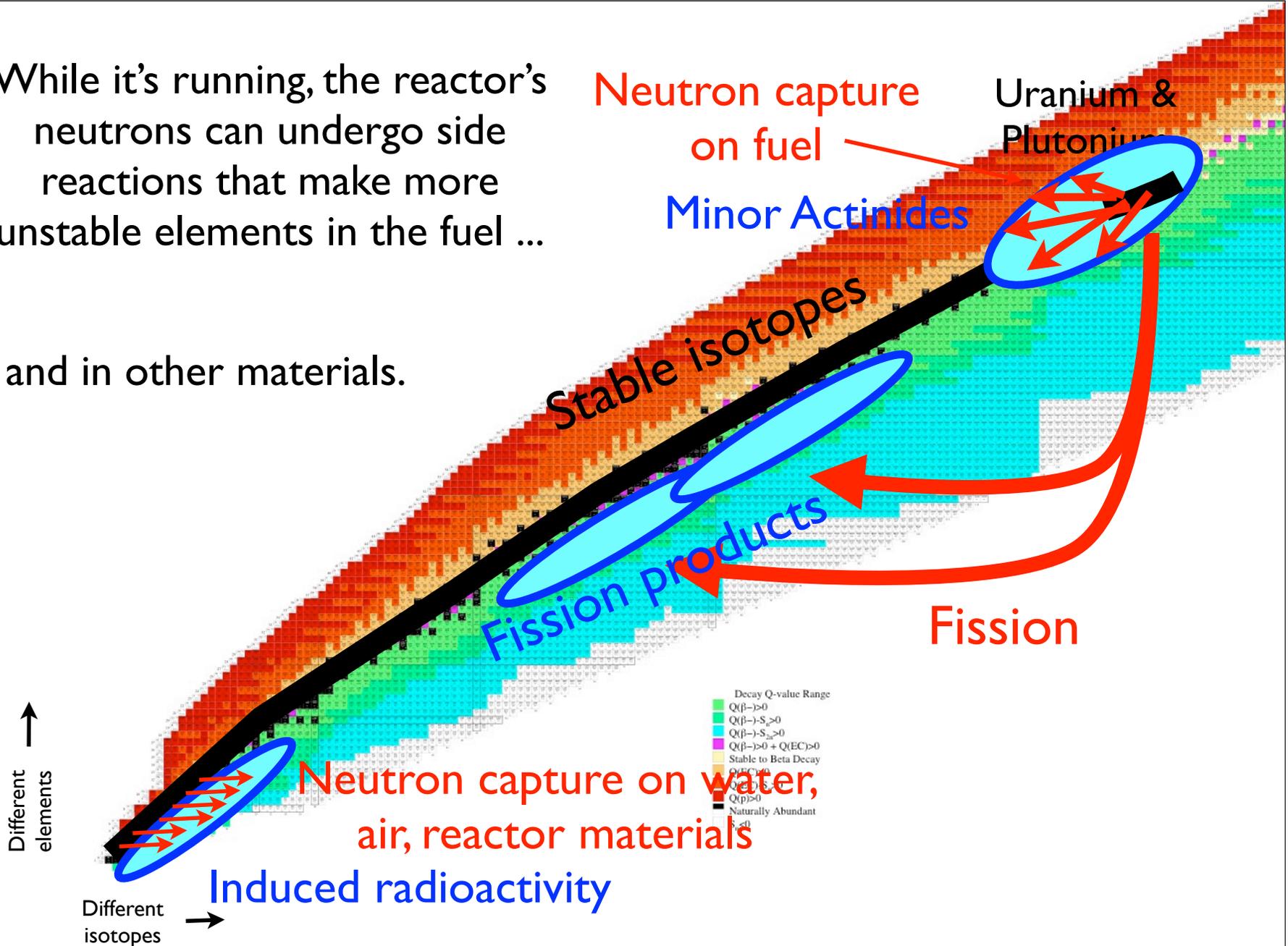
↑
Different elements

→
Different isotopes



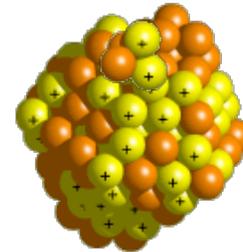
While it's running, the reactor's neutrons can undergo side reactions that make more unstable elements in the fuel ...

and in other materials.



Radiation damage

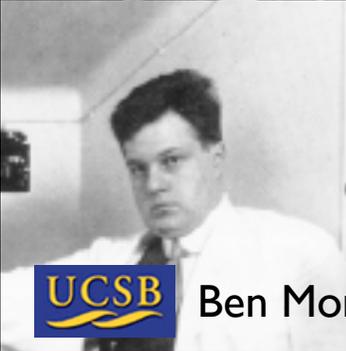
Alpha decay: common
in minor actinides
(damages every 10th
atom it passes.)



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



How much damage?

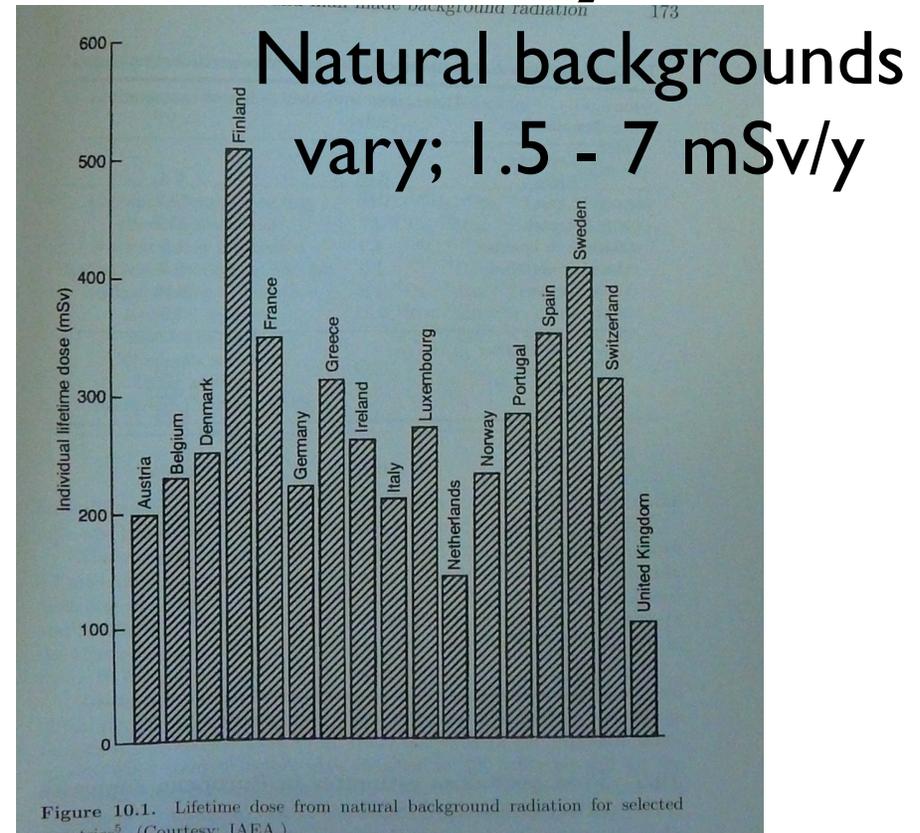


- One **becquerel** = 1 decay per second
- One **curie** = 37 billion decays per second.
- A measure of amount, as in “There are 20 million curies of ^{137}Cs in the fuel pond”
- One **gray** = absorbing 1 billion ^{238}U decays, or 10 billion ^{137}Cs decays, per gram of body mass
- One **sievert** = 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 \sim few mSv/yr.



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

Radiation and cancer

Ionization \approx DNA damage (rarely)

DNA damage \approx changed cells (rarely)

changed cells \approx 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: $1 \text{ Sv} = 1000 \text{ mSv}$ is a risk you would go out of your way to avoid, like texting while driving.

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 between 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

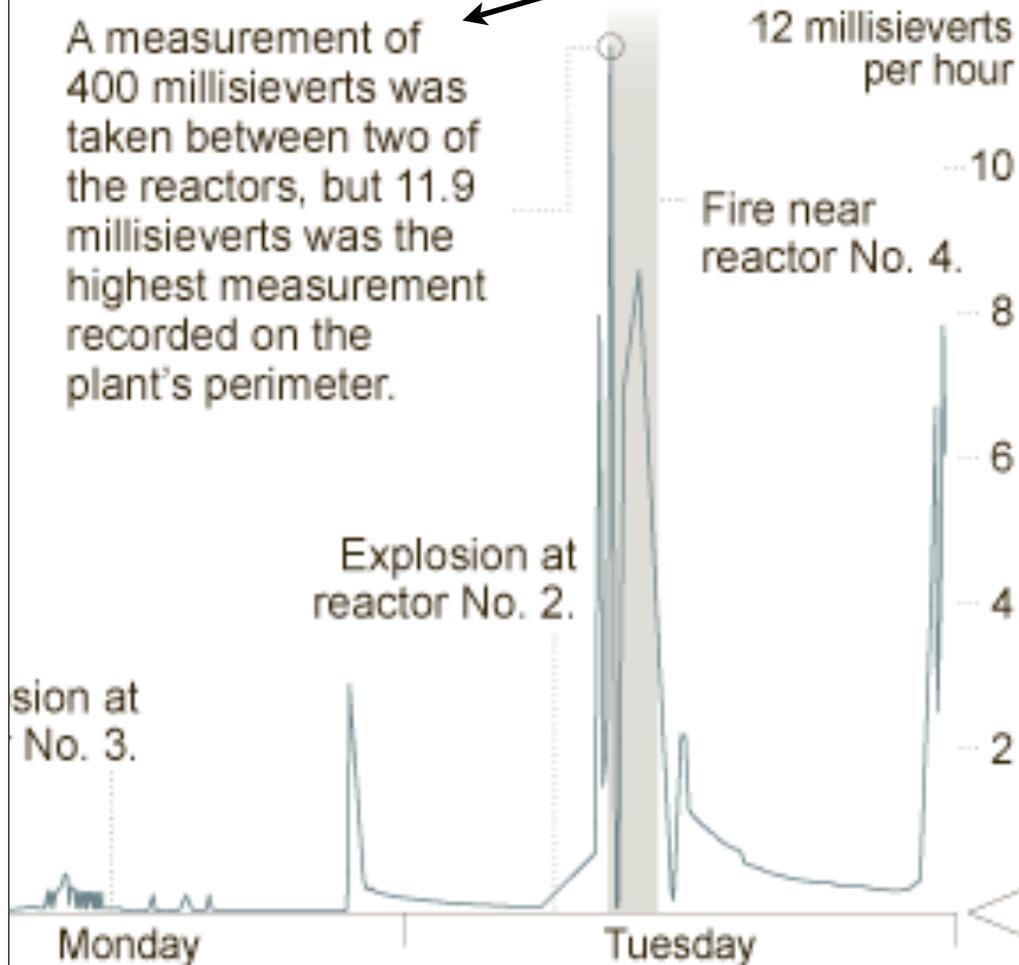


Radiation levels on the edge of the plant compound briefly spiked at 8217 microsieverts per hour but later fell to about a third that.

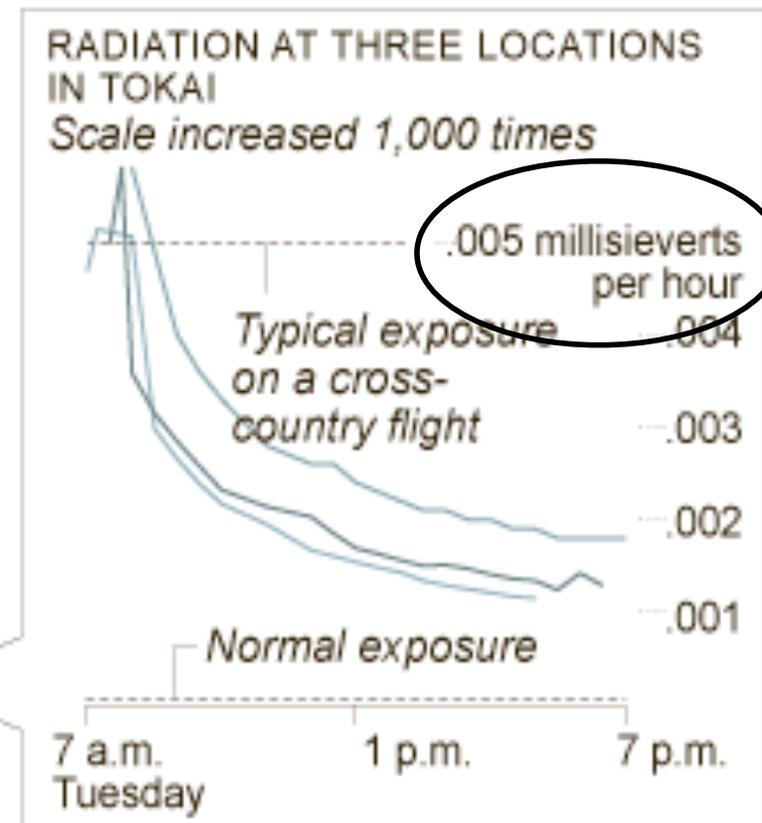
← $8000 \mu\text{Sv/hr} = 8 \text{ mSv/hr}$

They meant “millisieverts *per hour*”

NYTimes.com

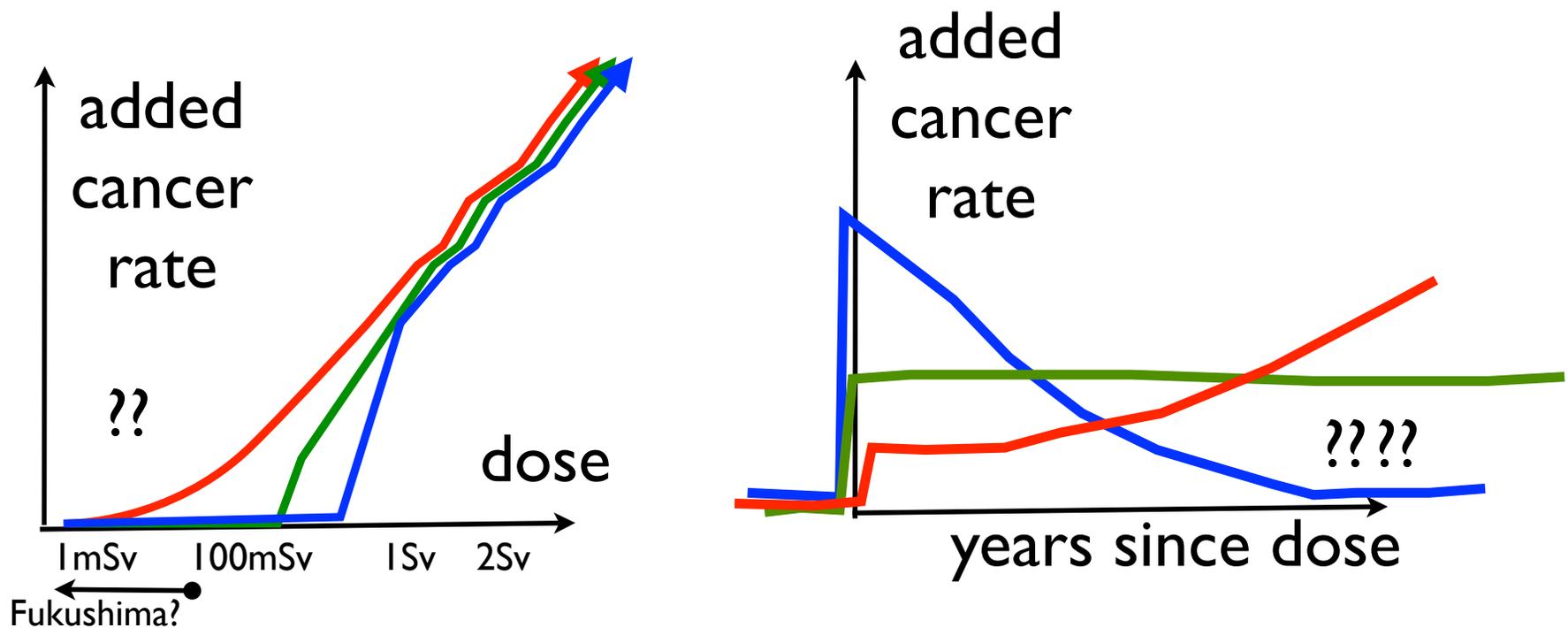


Elevated radiation levels were detected in many southern cities, but levels were far below those that pose health risks, and they were falling.

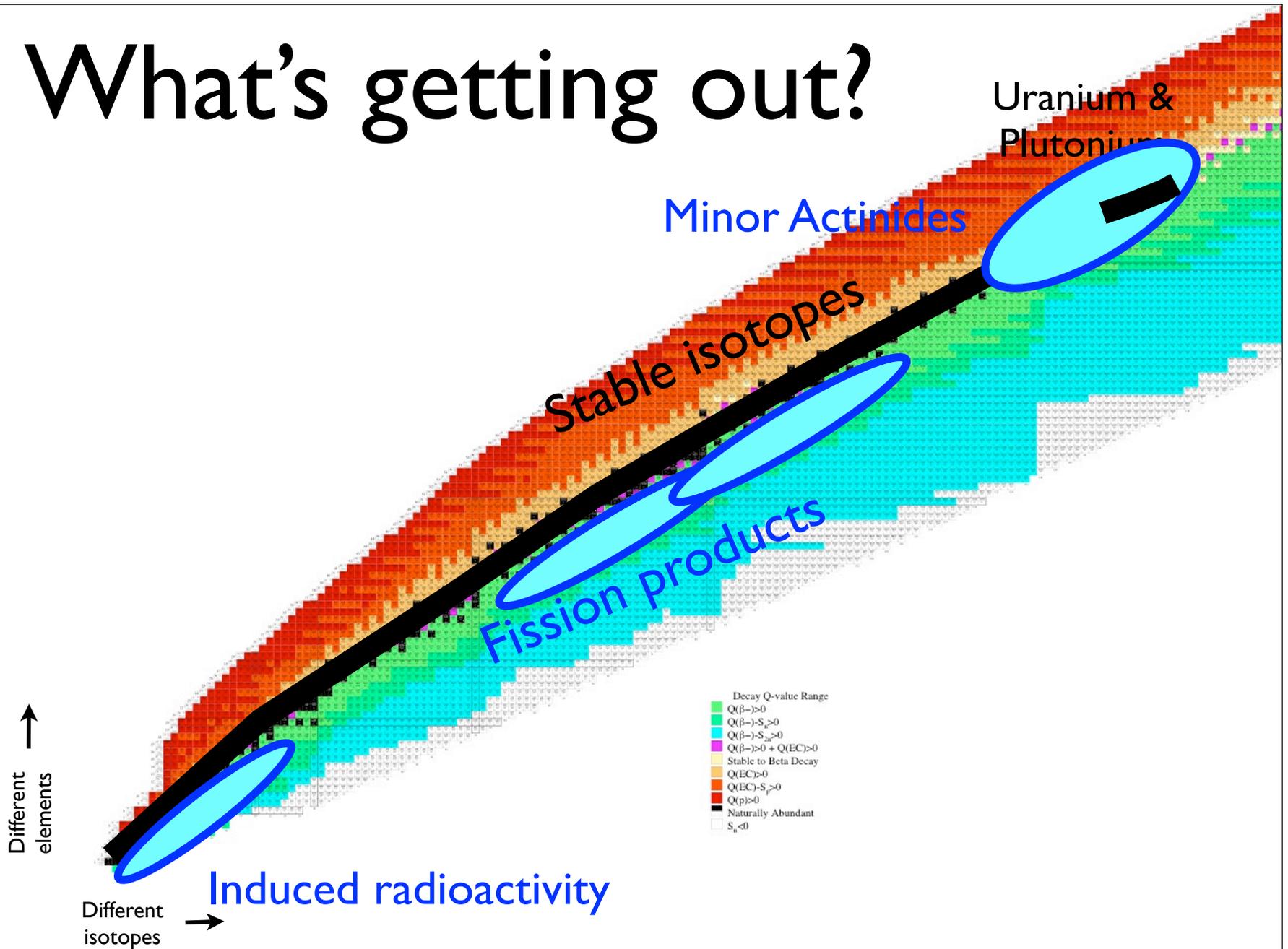


Are low doses proportionally dangerous?

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



What's getting out?



Induced radioactivity

Key

11	Atomic number
Na	Element symbol
Sodium	Element name
22.99	Average atomic mass*

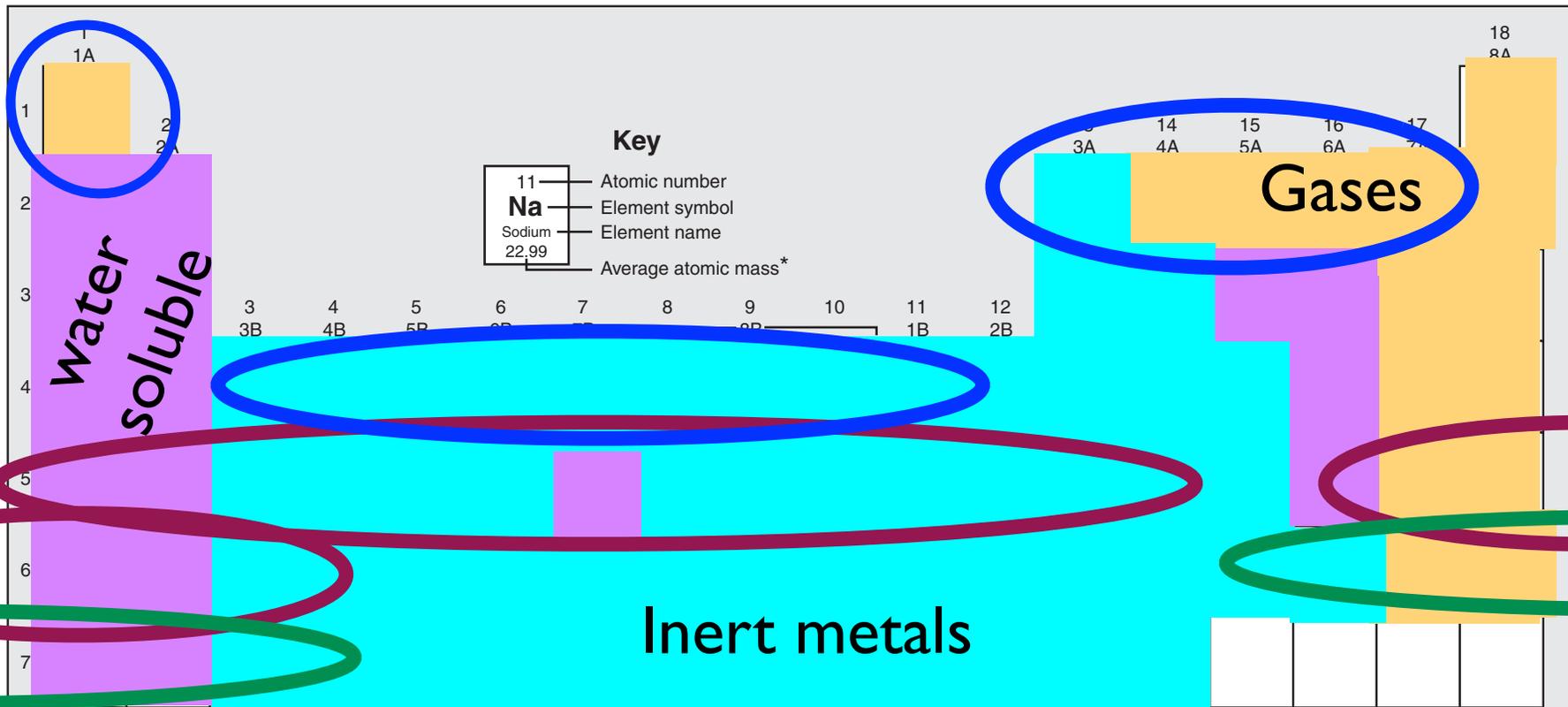
1	1A	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																																												
1	H	2	He	3	Li	4	Be	5	B	6	C	7	N	8	O	9	F	10	Ne																																												
Hydrogen	1.01	Helium	4.00	Lithium	6.94	Beryllium	9.01	Boron	10.81	Carbon	12.01	Nitrogen	14.01	Oxygen	16.00	Fluorine	18.99	Neon	20.18																																												
2	Na	Mg	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B	13B	14B	15B	16B	17B	18B																																													
Sodium	22.99	Magnesium	24.31	Scandium	44.96	Titanium	47.88	Vanadium	50.94	Chromium	52.00	Manganese	54.94	Iron	55.85	Cobalt	58.93	Nickel	58.69	Copper	63.55	Zinc	65.39	Gallium	69.72	Germanium	72.61	Arsenic	74.92	Selenium	78.96	Bromine	79.90	Krypton	83.80																												
3	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr																																													
Potassium	39.10	Calcium	40.08	Scandium	44.96	Titanium	47.88	Vanadium	50.94	Chromium	52.00	Manganese	54.94	Iron	55.85	Cobalt	58.93	Nickel	58.69	Copper	63.55	Zinc	65.39	Gallium	69.72	Germanium	72.61	Arsenic	74.92	Selenium	78.96	Bromine	79.90	Krypton	83.80																												
4	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe																																													
Rubidium	85.47	Strontium	87.62	Yttrium	88.91	Zirconium	91.22	Niobium	92.91	Molybdenum	95.94	Technetium	(98)	Ruthenium	101.07	Rhodium	102.91	Palladium	106.42	Silver	107.87	Cadmium	112.41	Indium	114.82	Tin	118.71	Antimony	121.76	Tellurium	127.60	Iodine	126.90	Xenon	131.29																												
5	Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn																															
Cesium	132.91	Barium	137.33	Lanthanum	138.91	Cerium	140.12	Praseodymium	140.91	Neodymium	144.24	Promethium	(145)	Samarium	150.36	Europium	151.96	Gadolinium	157.25	Terbium	158.93	Dysprosium	162.50	Holmium	164.93	Erbium	167.26	Thulium	168.93	Ytterbium	173.05	Lutetium	174.97	Hafnium	178.49	Tantalum	180.95	Tungsten	183.84	Rhenium	186.21	Osmium	190.23	Iridium	192.22	Platinum	195.08	Gold	196.97	Mercury	200.59	Thallium	204.38	Lead	207.2	Bismuth	208.98	Polonium	(209)	Astatine	(210)	Radon	(222)
6	Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr																																														
Francium	(223)	Radium	(226)	Actinium	(227)	Thorium	232.04	Protactinium	231.04	Uranium	238.03	Neptunium	(237)	Plutonium	(244)	Americium	(243)	Curium	(247)	Berkelium	(247)	Californium	(251)	Einsteinium	(252)	Fermium	(257)	Mendelevium	(258)	Nobelium	(259)	Lawrencium	(262)																														
7	Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr																																														
Francium	(223)	Radium	(226)	Actinium	(227)	Thorium	232.04	Protactinium	231.04	Uranium	238.03	Neptunium	(237)	Plutonium	(244)	Americium	(243)	Curium	(247)	Berkelium	(247)	Californium	(251)	Einsteinium	(252)	Fermium	(257)	Mendelevium	(258)	Nobelium	(259)	Lawrencium	(262)																														

Fission products

minor actinides

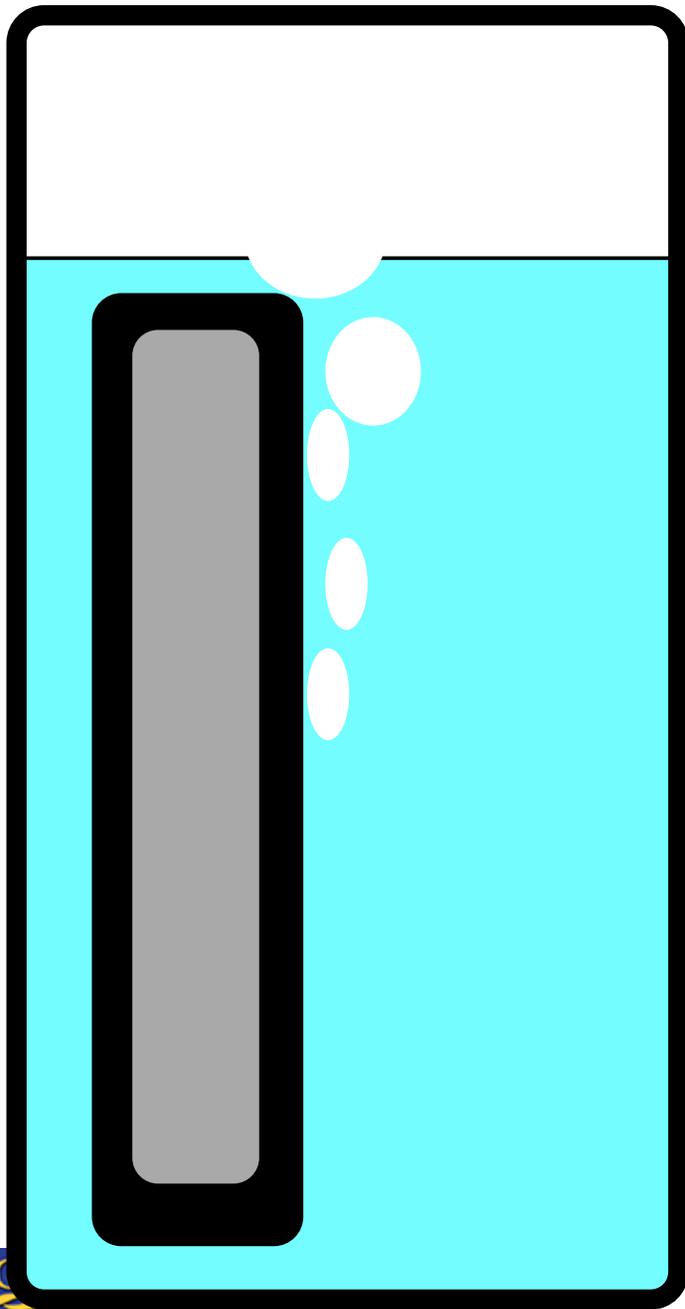
* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.





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





Healthy reactor:

In Zircalloy casing:
fuel + fission products + actinides

In cooling water:
activation products

In steam:
activation products

In environment:
practically nothing

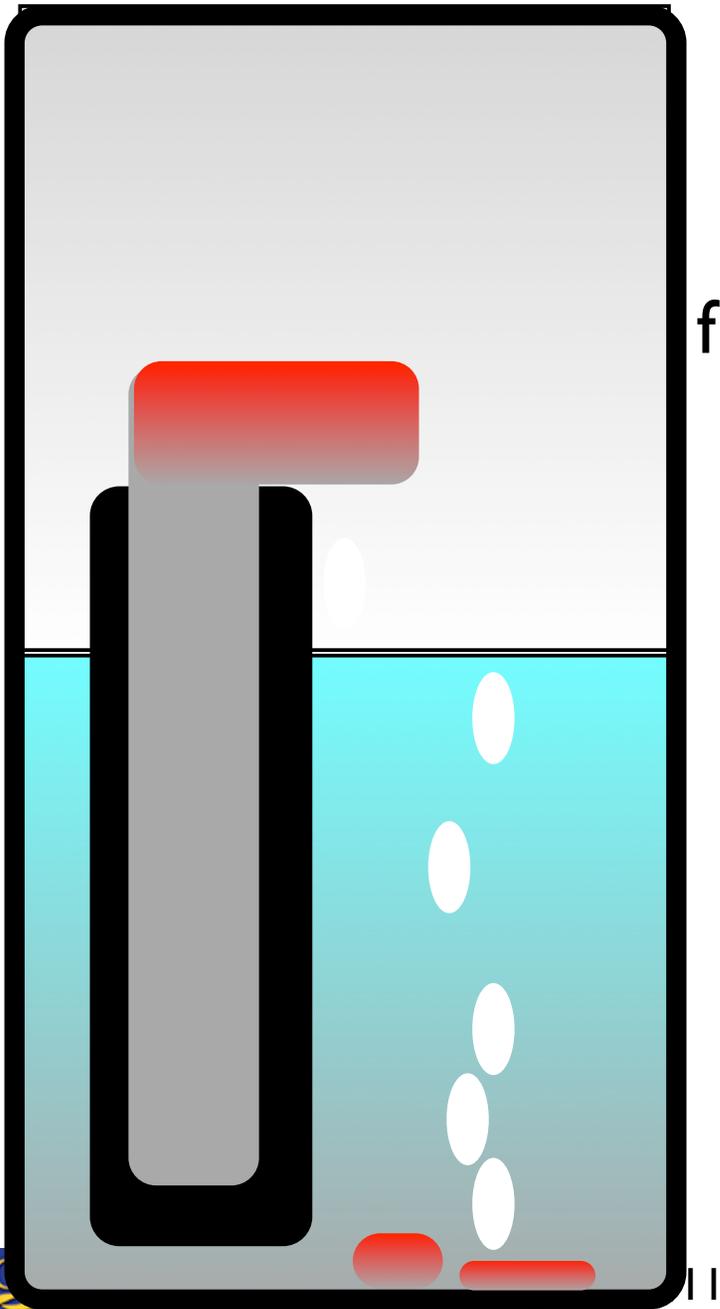
Meltdown:

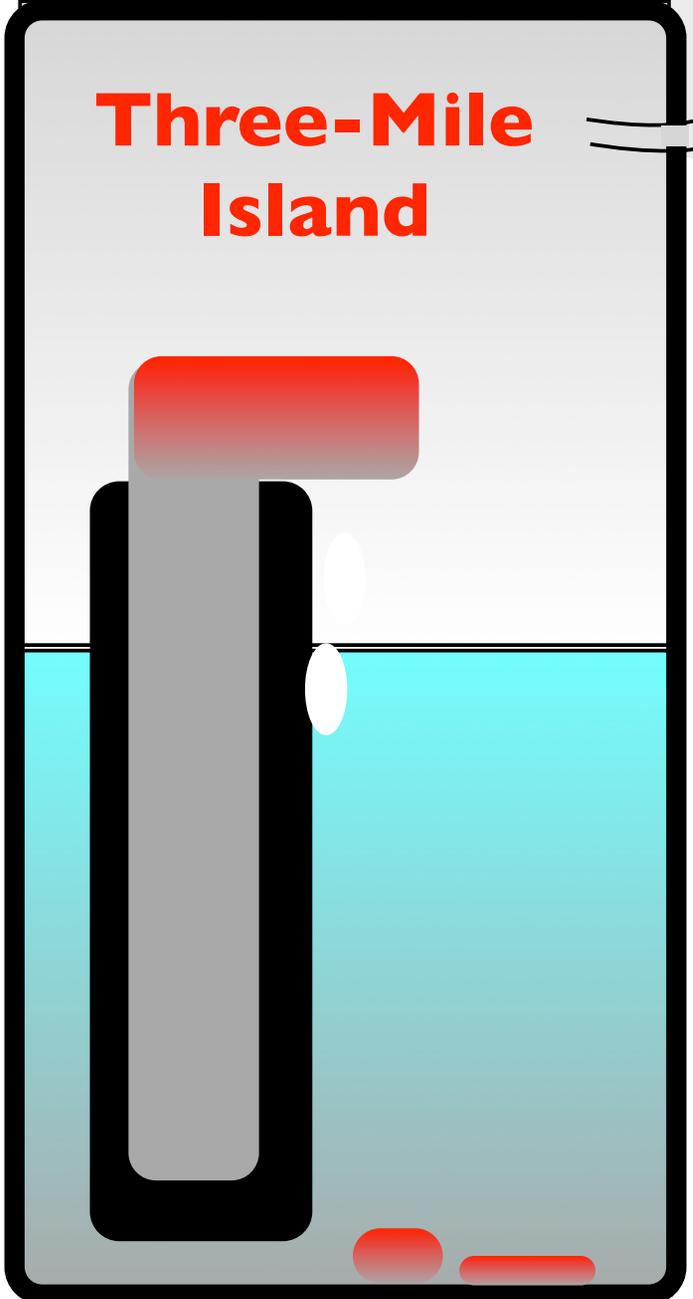
In Zircalloy casing:
fuel + fission products + actinides

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

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing





**Three-Mile
Island**

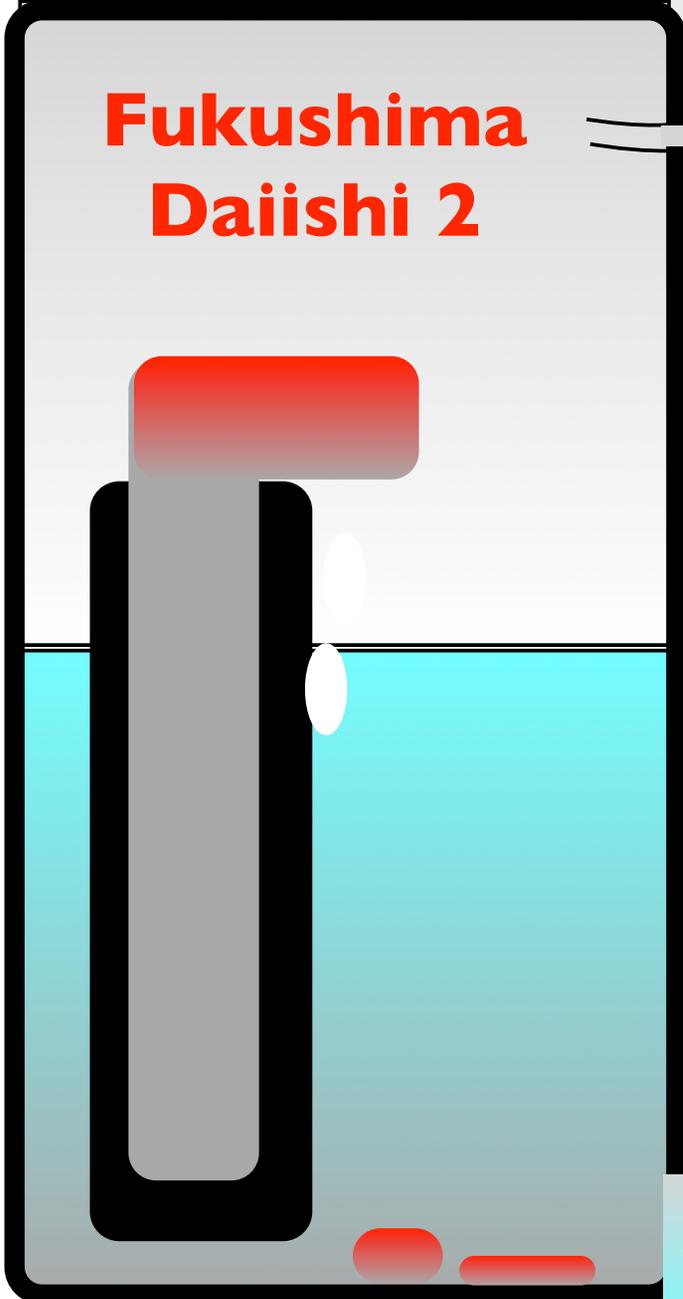
Meltdown + emergency venting:

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



**Fukushima
Daiichi 2**

The diagram shows a cross-section of a reactor core. A central fuel assembly is depicted with a red top cap and a grey shaft. The core is partially submerged in a light blue liquid, representing cooling water. At the bottom of the core, there are two red oval shapes, likely representing molten fuel. A grey pipe or duct is shown on the right side of the core, with a grey circular area above it indicating a breach or failure. The entire reactor assembly is contained within a grey rectangular structure.

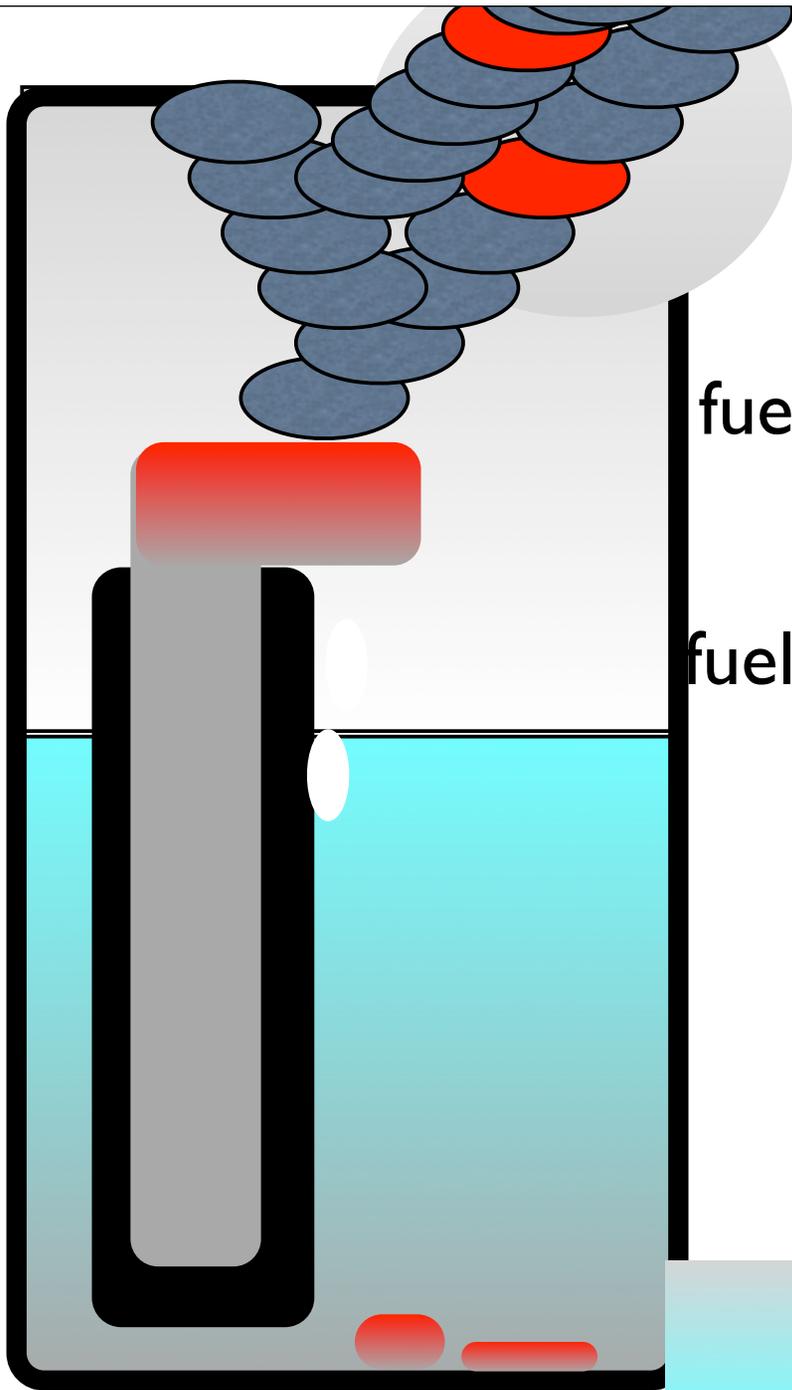
Meltdown + containment failure:

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

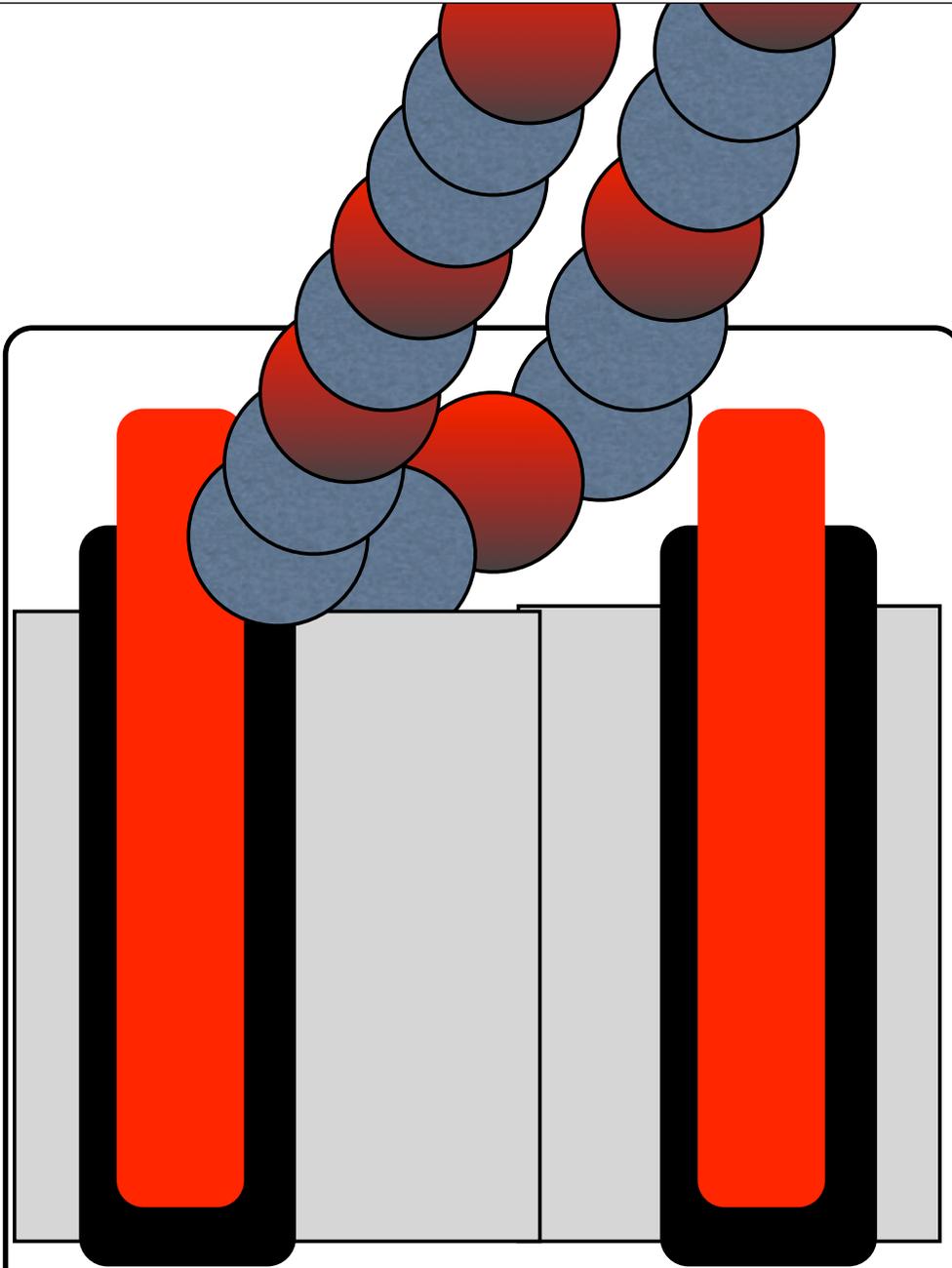
In Zircalloy casing:
fuel + fission products + actinides

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

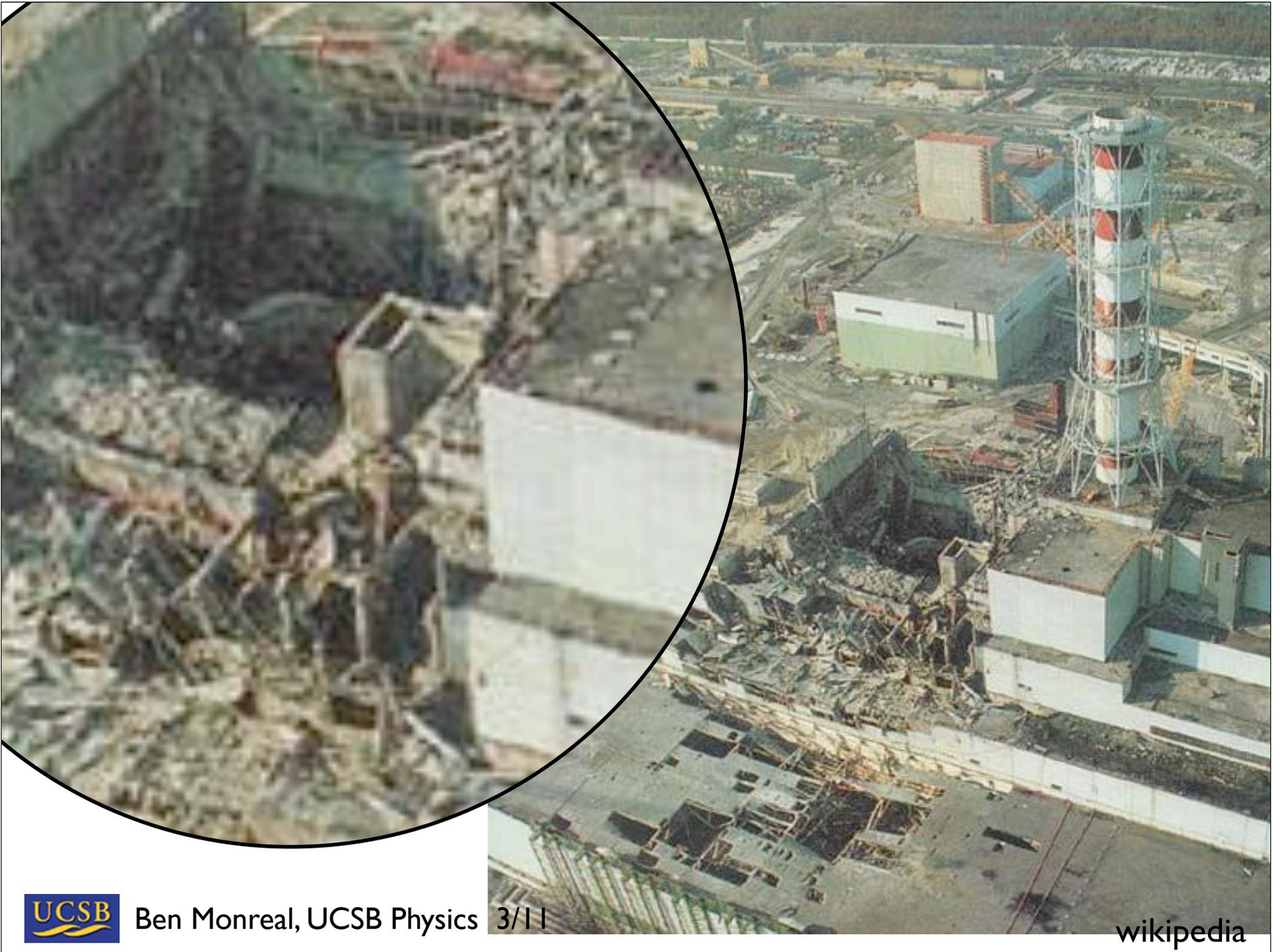


no real “containment vessel”

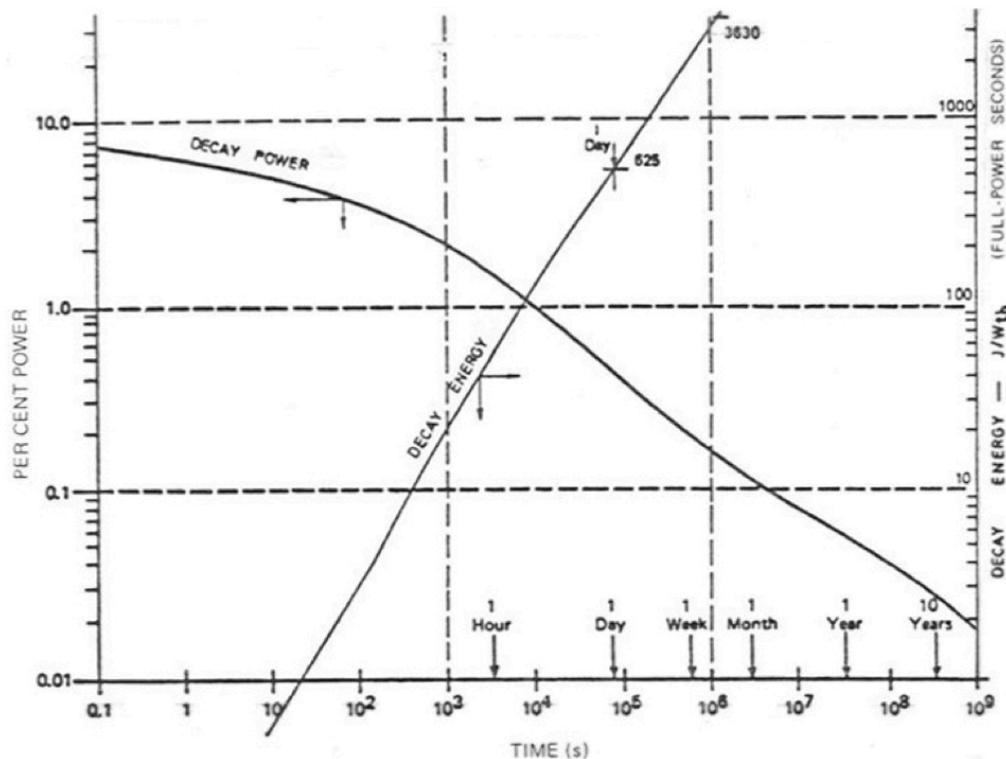
Core filled with graphite
(fuel for huge fire)

Reactor *fissioning during explosions and fire*

(Fukushima reactors have now been “off” for 5 days)



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

In case of fire ... soot

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