

Understanding the radioactivity at Fukushima

A physics and engineering perspective

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Q&A Panel:

Ben Monreal

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?

1 1A H Hydrogen 1.01	2 2A He Helium 4.00																
3 3A Li Lithium 6.94	4 4A Be Beryllium 9.01	5 5A B Boron 10.81	6 6A C Carbon 12.01	7 7A N Nitrogen 14.01	8 8A O Oxygen 16.00	9 9A F Fluorine 19.00	10 10A Ne Neon 20.18										
11 3A Na Sodium 22.99	12 4A Mg Magnesium 24.31	13 5A Al Aluminum 26.98	14 6A Si Silicon 28.09	15 7A P Phosphorus 30.97	16 8A S Sulfur 32.07	17 9A Cl Chlorine 35.45	18 10A Ar Argon 39.95										
19 3A K Potassium 39.10	20 4A Ca Calcium 40.08	21 5A Sc Scandium 44.96	22 6A Ti Titanium 47.87	23 7A V Vanadium 50.94	24 8A Cr Chromium 52.00	25 9A Mn Manganese 54.94	26 10A Fe Iron 55.85	27 11A Co Cobalt 58.93	28 12A Ni Nickel 58.69	29 13A Cu Copper 63.55	30 14A Zn Zinc 65.39	31 15A Ga Gallium 69.72	32 16A Ge Germanium 72.61	33 17A As Arsenic 74.92	34 18A Se Selenium 78.96	35 19A Br Bromine 79.90	36 20A Kr Krypton 83.80
37 3A Rb Rubidium 85.47	38 4A Sr Strontium 87.62	39 5A Y Yttrium 88.91	40 6A Zr Zirconium 91.22	41 7A Nb Niobium 92.91	42 8A Mo Molybdenum 95.94	43 9A Tc Technetium (98)	44 10A Ru Ruthenium 101.07	45 11A Rh Rhodium 102.91	46 12A Pd Palladium 106.42	47 13A Ag Silver 107.87	48 14A Cd Cadmium 112.41	49 15A In Indium 114.82	50 16A Sn Tin 118.71	51 17A Sb Antimony 121.76	52 18A Te Tellurium 127.6	53 19A I Iodine 126.90	54 20A Xe Xenon 131.29
55 3A Cs Cesium 132.91	56 4A Ba Barium 137.33	57 5A La Lanthanum 138.91	58 6A Ce Cerium 140.12	59 7A Pr Praseodymium 140.91	60 8A Nd Neodymium 144.24	61 9A Pm Promethium (145)	62 10A Sm Samarium 150.36	63 11A Eu Europium 151.96	64 12A Gd Gadolinium 157.25	65 13A Tb Terbium 158.93	66 14A Dy Dysprosium 162.50	67 15A Ho Holmium 164.93	68 16A Er Erbium 167.26	69 17A Tm Thulium 168.93	70 18A Yb Ytterbium 173.04	71 19A Lu Lutetium 174.97	72 20A Hf Hafnium 178.49
87 3A Fr Francium (223)	88 4A Ra Radium (226)	89 5A Ac Actinium (227)	90 6A Th Thorium 232.04	91 7A Pa Protactinium 231.04	92 8A U Uranium 238.03	93 9A Np Neptunium (237)	94 10A Pu Plutonium (244)	95 11A Am Americium (243)	96 12A Cm Curium (247)	97 13A Bk Berkelium (247)	98 14A Cf Californium (251)	99 15A Es Einsteinium (252)	100 16A Fm Fermium (257)	101 17A Md Mendelevium (258)	102 18A No Nobelium (259)	103 19A Lr Lawrencium (262)	104 20A Rf Rutherfordium (261)
105 3A Db Dubnium (262)	106 4A Sg Seaborgium (266)	107 5A Bh Bohrium (264)	108 6A Hs Hassium (269)	109 7A Mt Meitnerium (268)	110 8A Ds Darmstadtium (271)	111 9A Rg Roentgenium (272)	112 10A Cn Copernicium (285)	113 11A Nh Nihonium (284)	114 12A Fl Flerovium (289)	115 13A Mc Moscovium (288)	116 14A Lv Livermorium (293)	117 15A Ts Tennessine (294)	118 16A Og Oganesson (294)	119 17A Uu Ununennium (295)	120 18A Ubn Unbinilium (293)	121 19A Uut Untrium (292)	122 20A Uub Unbibium (293)

“Tritium” (hydrogen)

Key

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

Iodine

Cesium

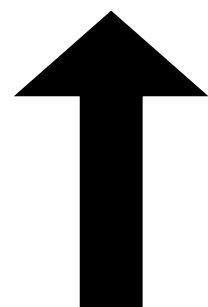
Uranium and Plutonium

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



Boron

6



Different
elements

Boron
Beryllium
Lithium
Helium
Hydrogen

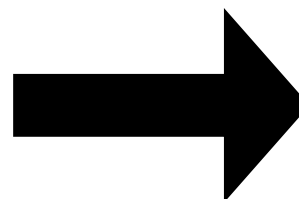
				B7 1.4 MeV (3/2-)	B8 770 ms 2+	B9 0.54 keV 3/2-	B10 3+	B11 3/2-	B12 20.20 ms 1+	
					EC2 α	2p α	19.9	80.1	$\beta^-3\alpha$	β^-
		Be5	Be6 92 keV 0+	Be7 53.29 d 3/2-	Be8 6.8 eV 0+		Be9 3/2-	Be10 1.51E+6 y 0+	Be11 13.81 s 1/2+	β^-
			2p	EC	2 α		100	β^-	$\beta^- \alpha$	β^-
	Li4 2-	Li5 1.5 MeV 3/2-		Li6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

6

2

4

Different
isotopes

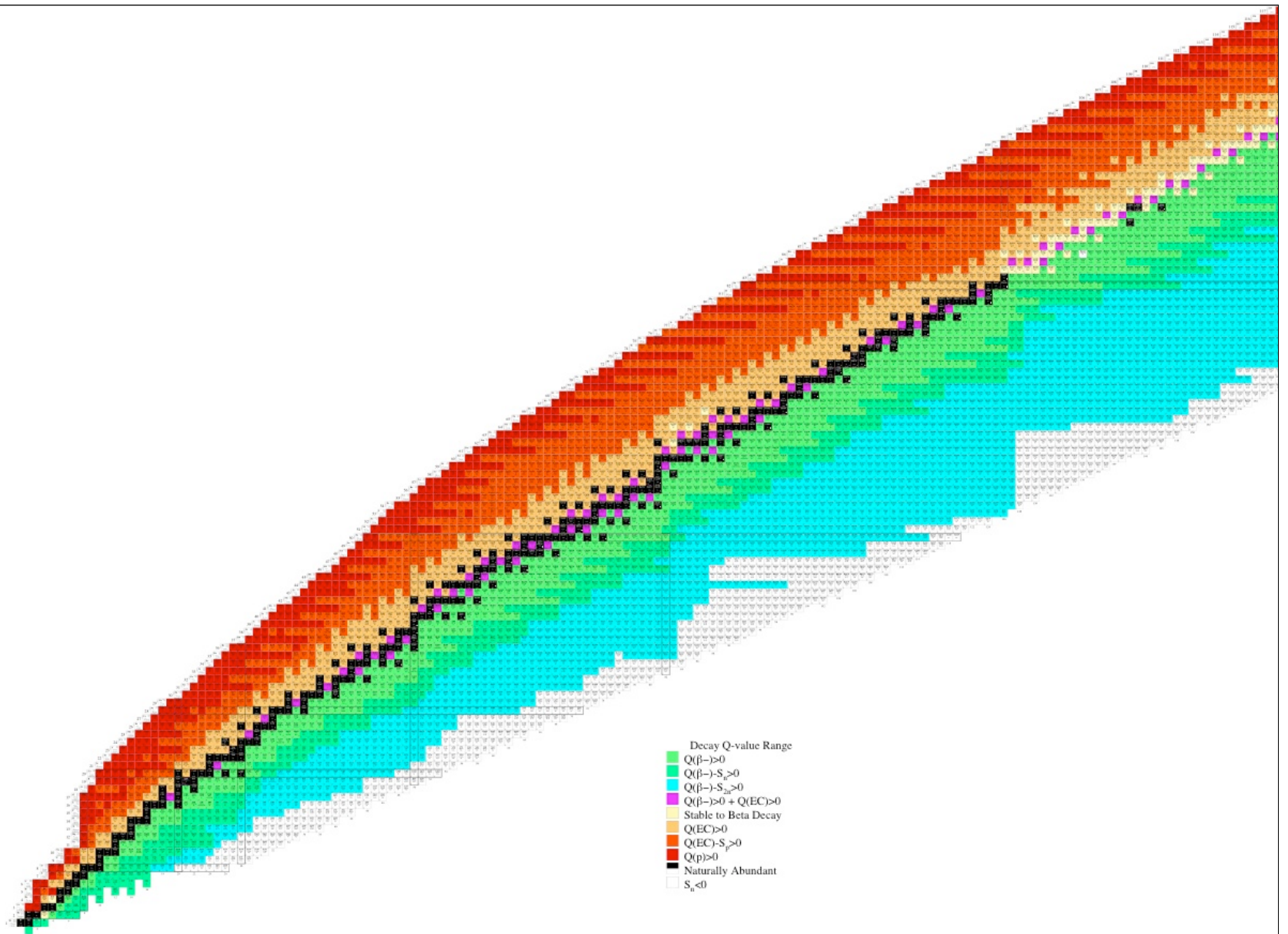


Different
elements



↑
Different
elements

→
Different
isotopes



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

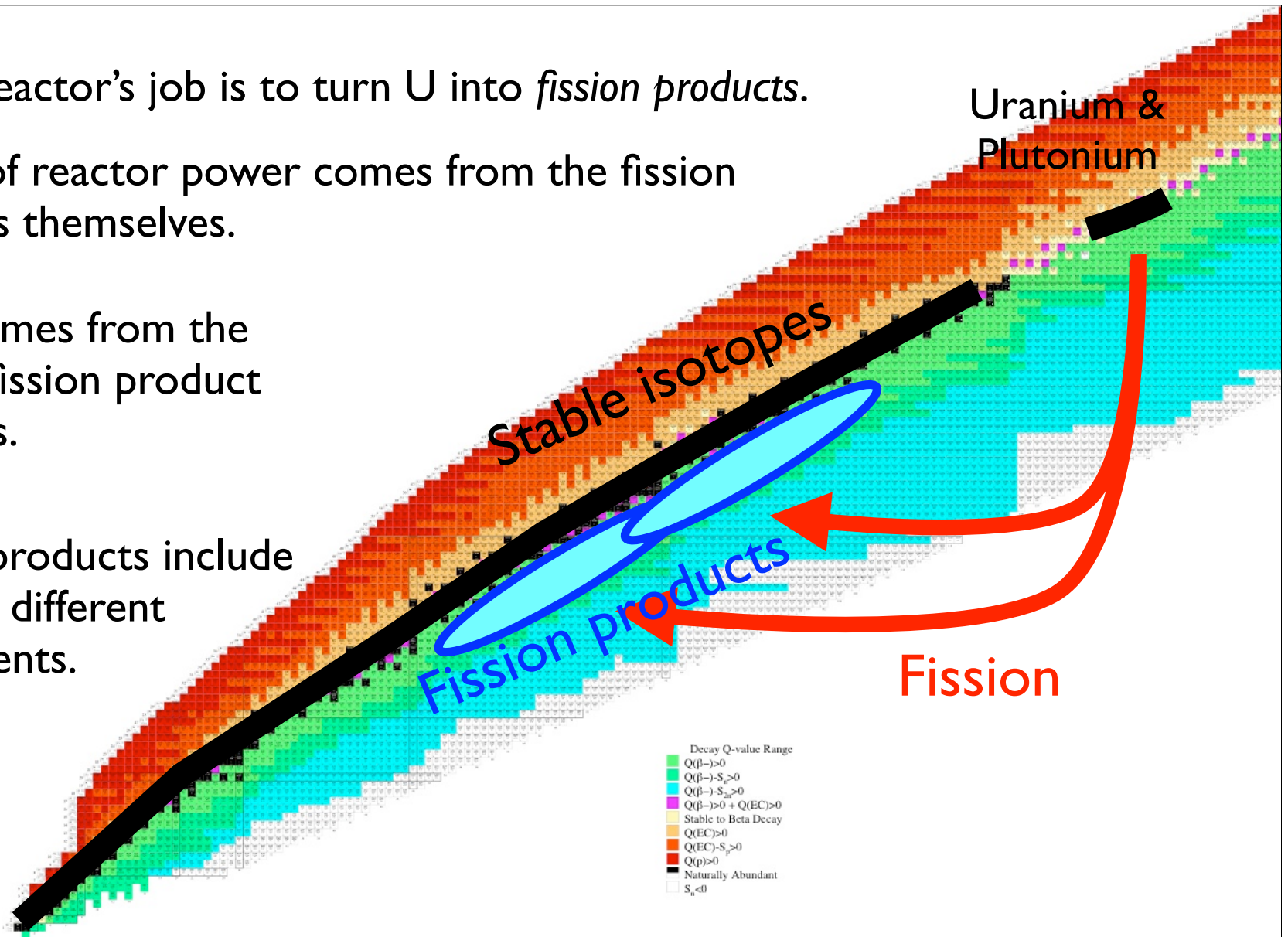
95% of reactor power comes from the fission events themselves.

5% comes from the later fission product decays.

The products include many different elements.

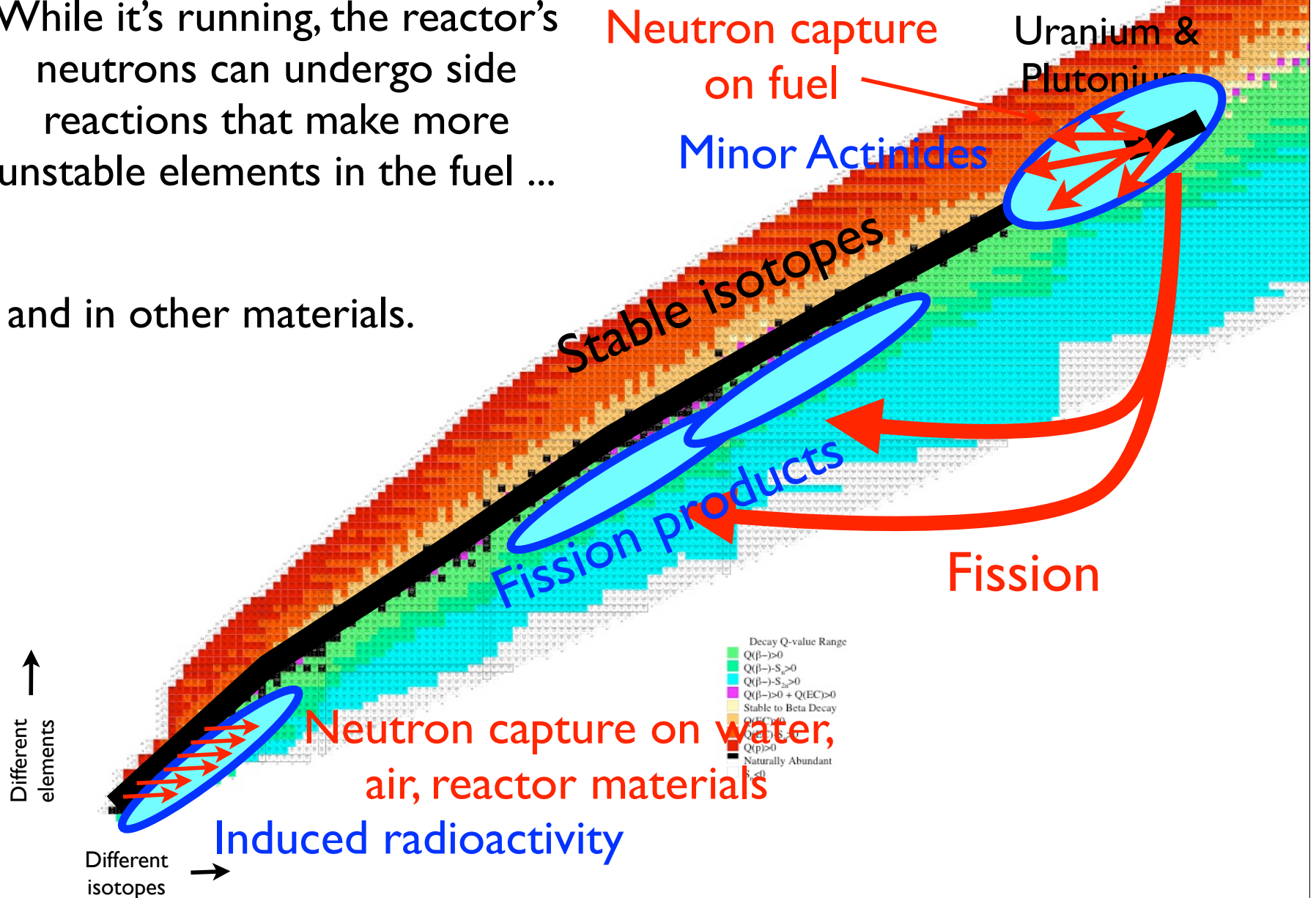
↑
Different
elements

→
Different
isotopes



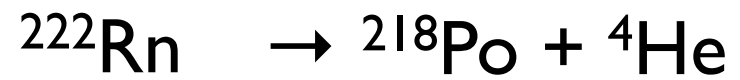
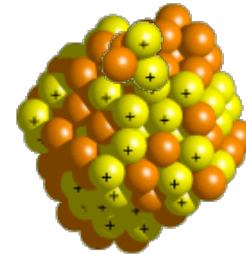
While it's running, the reactor's neutrons can undergo side reactions that make more unstable elements in the fuel ...

and in other materials.



Radiation damage

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



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



How much damage?

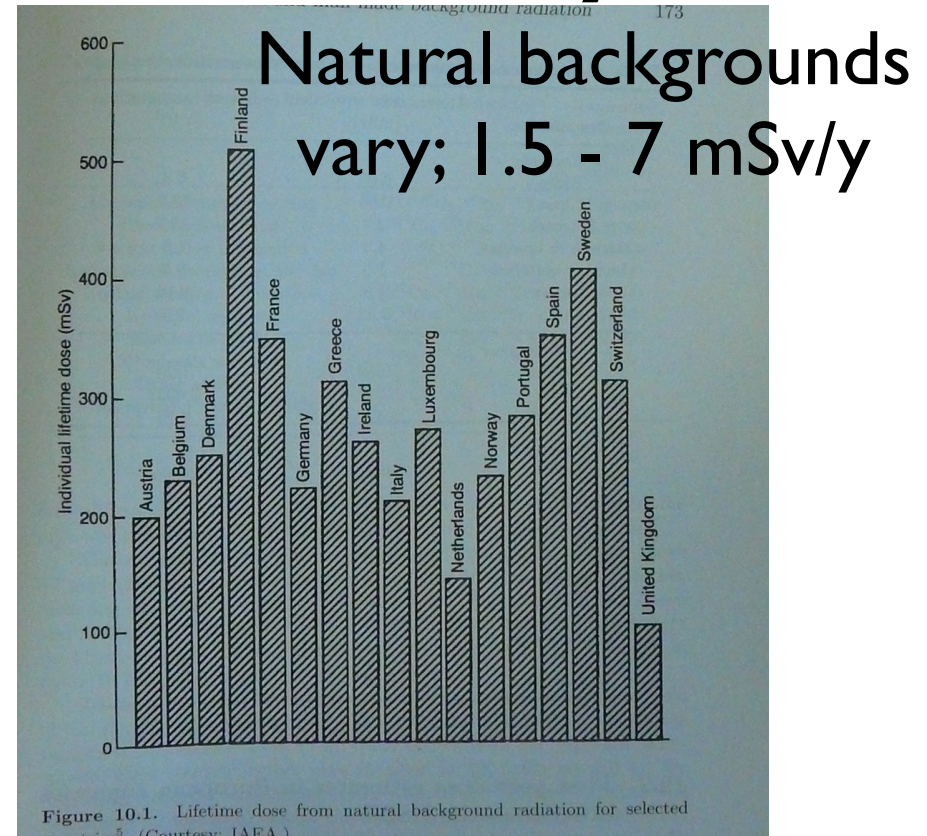


- One **becquerel** = 1 decay per second
- One **curie** = 37 billion decays per second.
- A measure of amount, as in “There are 20 million curies of ^{137}Cs in the fuel pond”
- One **gray** = absorbing 1 billion ^{238}U decays, or 10 billion ^{137}Cs decays, per gram of body mass
- One **sievert** = 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 Sv = 1000 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 $5000 \text{ mSv} = \text{fatal}$
so 400 mSv/hr for would be fatal
if you had $5000/400 = 12$ hours

← 0.6 mSv per hour

$1000 \text{ mSv} = \text{texting while driving}$
 $1000/0.6 = \text{two months}$

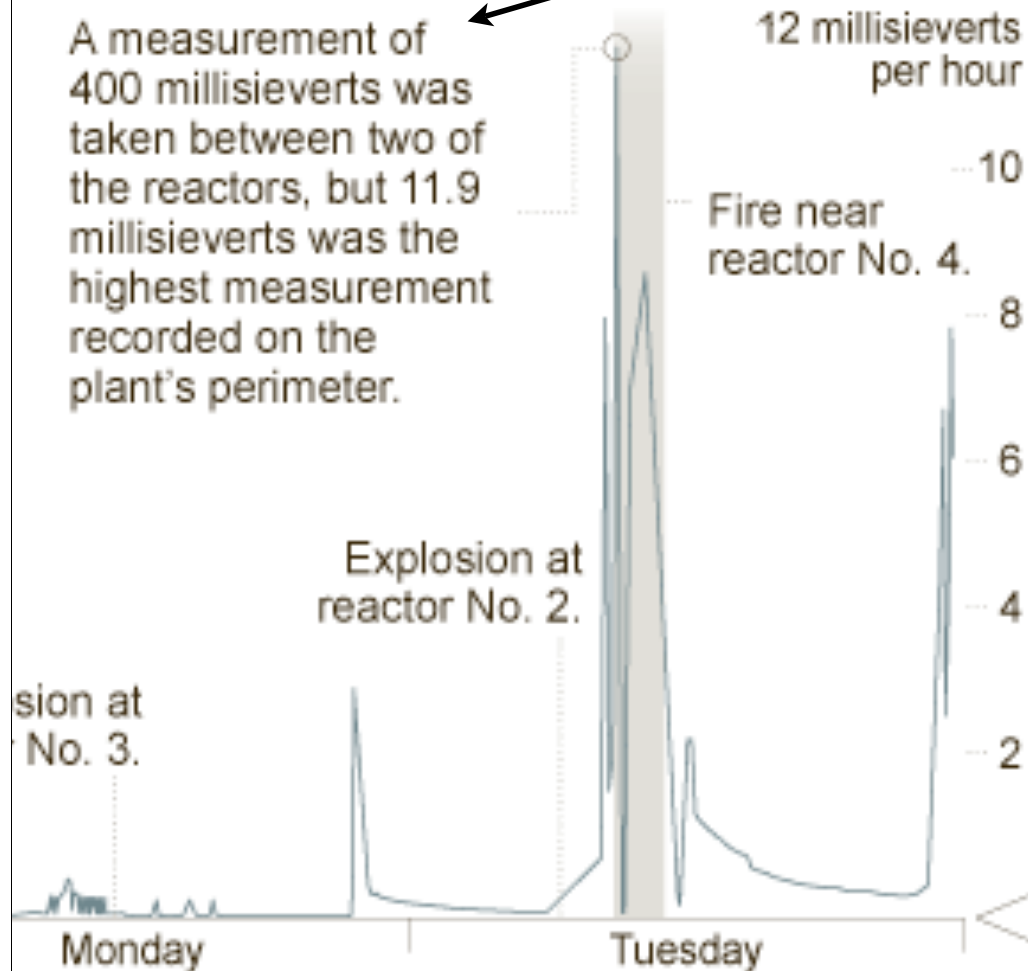


Radiation levels on the edge of the plant compound briefly spiked at 8217 microsieverts per hour but later fell to about a third that.

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

They meant “millisieverts *per hour*”

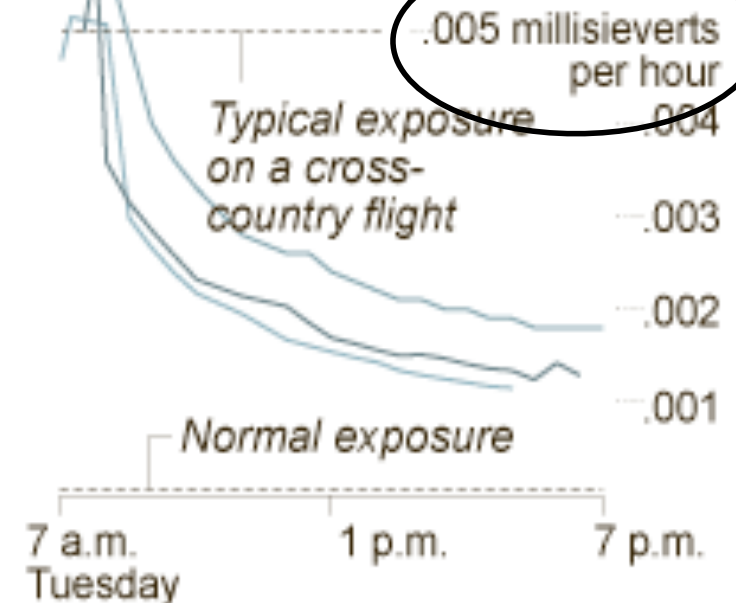
NYTimes.com



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

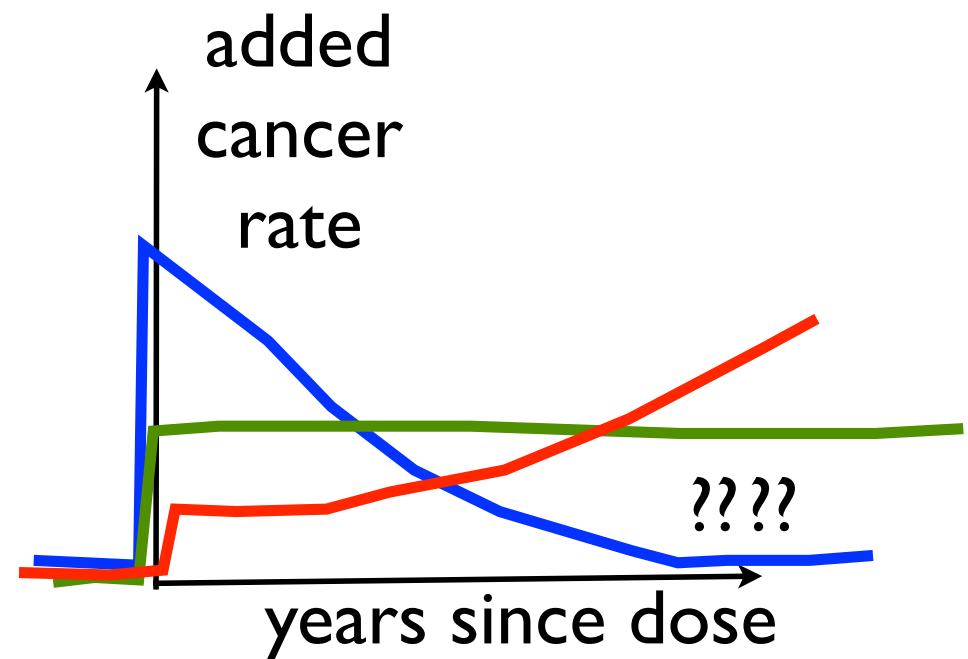
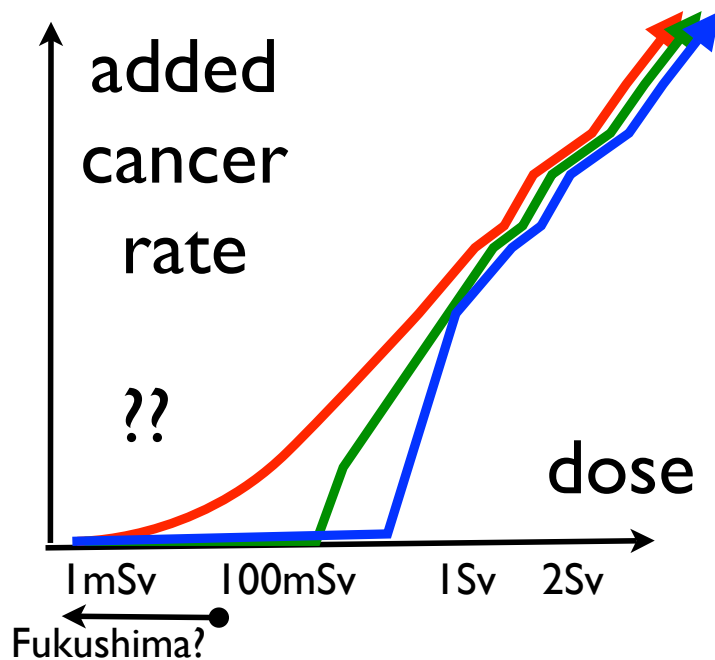
RADIATION AT THREE LOCATIONS IN TOKAI

Scale increased 1,000 times

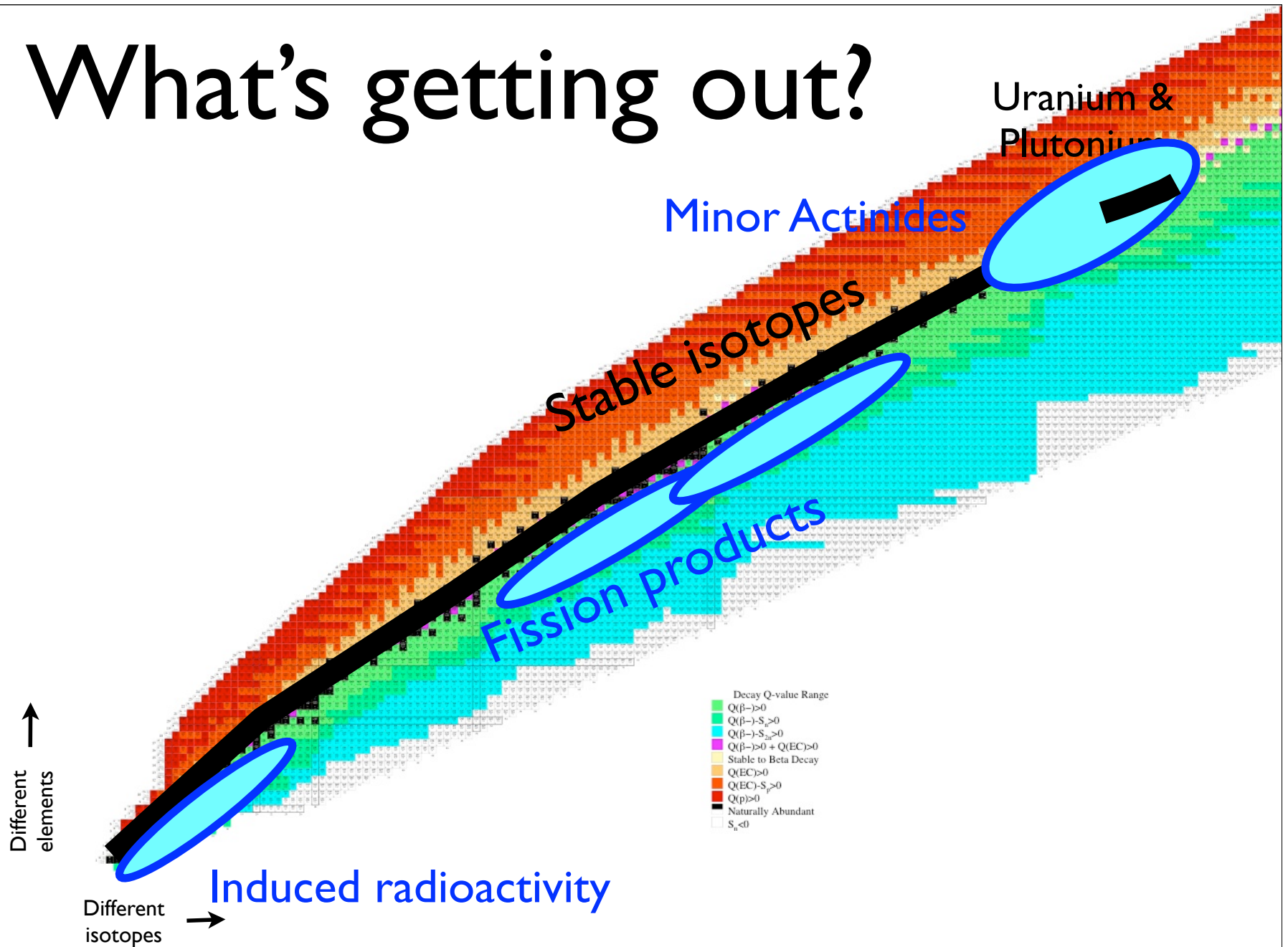


Are low doses proportionally dangerous?

- 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
11	Na	12	Mg	13	Al	14	Si	15	P	16	S	17	Cl	18	Ar	19	K	20	Ca
Sodium	22.99	Magnesium	24.31	Aluminum	26.98	Silicon	28.09	Phosphorus	30.97	Sulfur	32.07	Chlorine	35.45	Argon	39.95	Potassium	39.10	Calcium	40.08
21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn
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
37	Rb	38	Sr	39	Y	40	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd
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
55	Cs	56	Ba	57	La	58	Ce	59	Pr	60	Nd	61	Pm	62	Sm	63	Eu	64	Gd
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
87	Fr	88	Ra	89	Ac	90	Th	91	Pa	92	U	93	Np	94	Pu	95	Am	96	Cm
Francium	(223)	Radium	(226)	Actinium	(227)	Thorium	232.04	Protactinium	231.04	Uranium	238.03	Neptunium	(237)	Plutonium	(244)	Americium	(243)	Curium	(247)
101	Db	102	Hs	103	Mt	104	Lr	105	Db	106	Sg	107	Bh	108	Hs	109	Mt	110	Lr
Dubnium	(262)	Seaborgium	(266)	Bohrium	(264)	Hassium	(269)	Meitnerium	(268)	Darmstadtium	(271)	Roentgenium	(272)	Uubium	(286)	Ununseptium	(289)	Ununoctium	(294)

Fission products

minor actinides

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



Ben Monreal, UCSB Physics 3/11

The periodic table is color-coded and annotated with handwritten labels and circles. The regions are as follows:

- Water soluble:** A purple vertical bar on the far left, covering groups 1A and 2A, with the text "water soluble" written vertically.
- Gases:** A yellow region on the far right, covering groups 17 and 18, with the word "Gases" written in the center.
- Inert metals:** A large cyan region covering groups 3 through 10, with the text "Inert metals" written in the center.

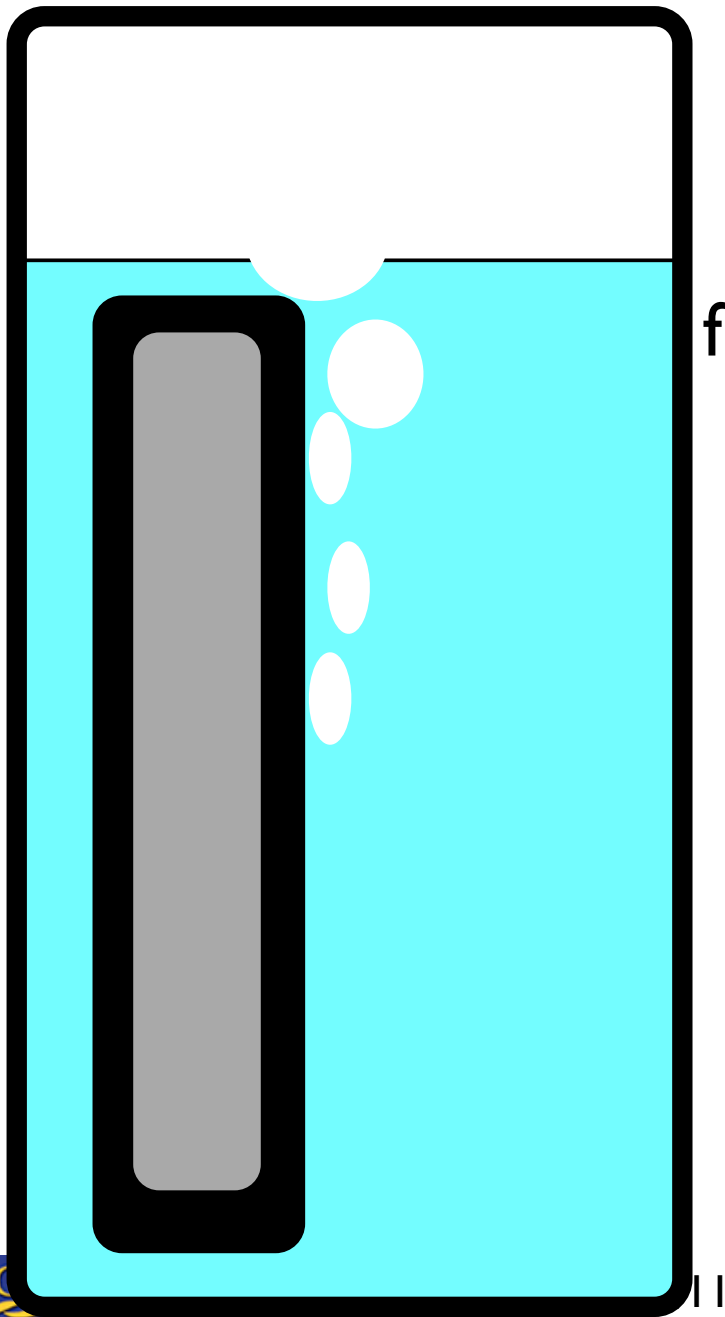
Handwritten annotations include:

- A blue circle around group 1A.
- A blue oval around groups 13, 14, 15, and 16.
- A blue oval around groups 3 through 10.
- A red oval around group 7.
- A red oval around groups 11 and 12.
- A green oval around groups 13 through 16.
- A green oval around groups 17 and 18.

Key

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

* 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

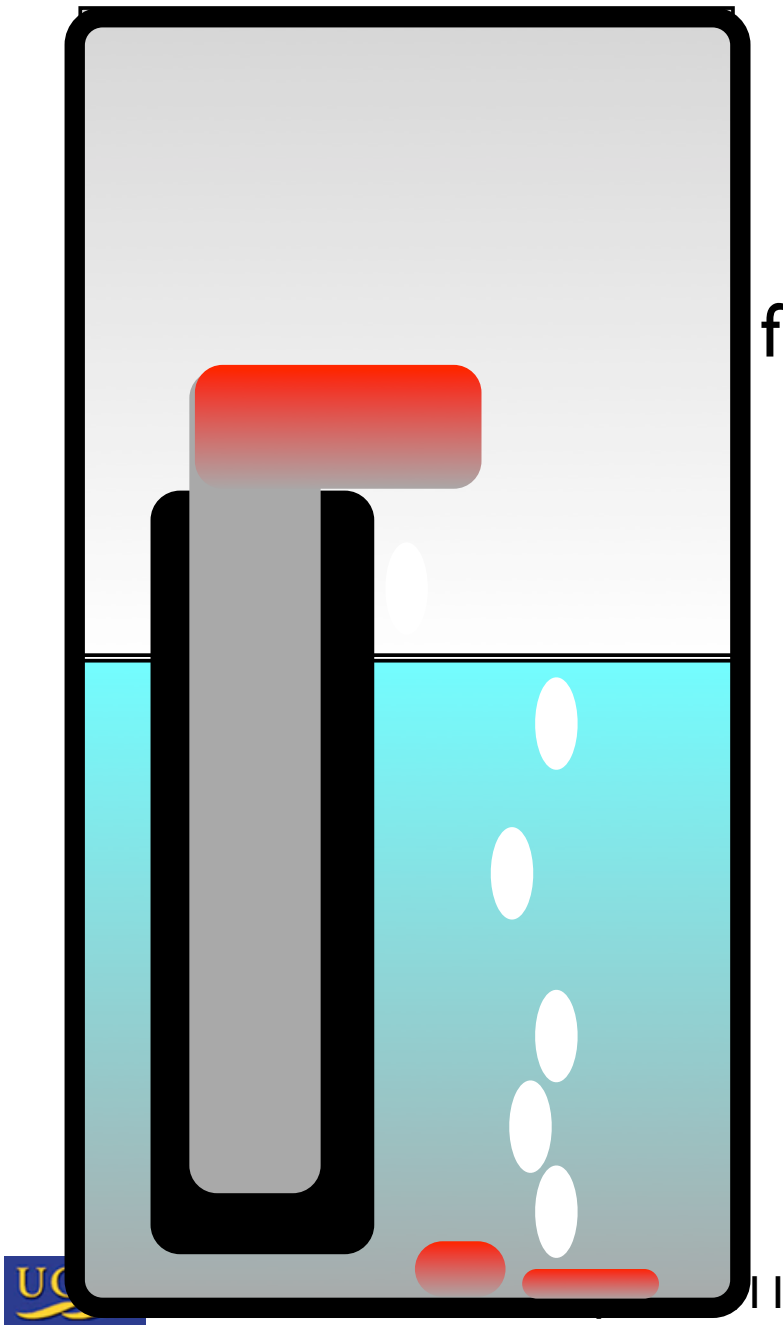
Meltdown:

In Zircalloy casing:
fuel + fission products + actinides

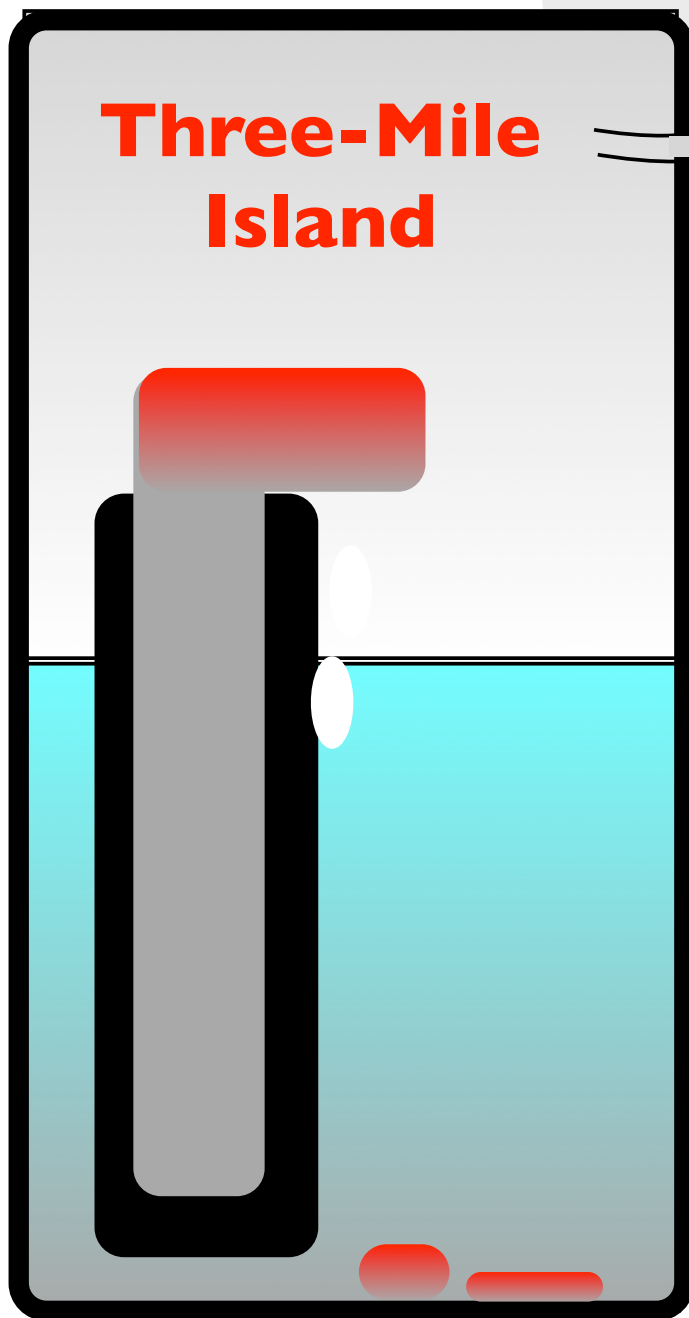
In cooling water:
fission products like Cs, I, Tc

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing



Three-Mile Island



Meltdown + emergency venting:

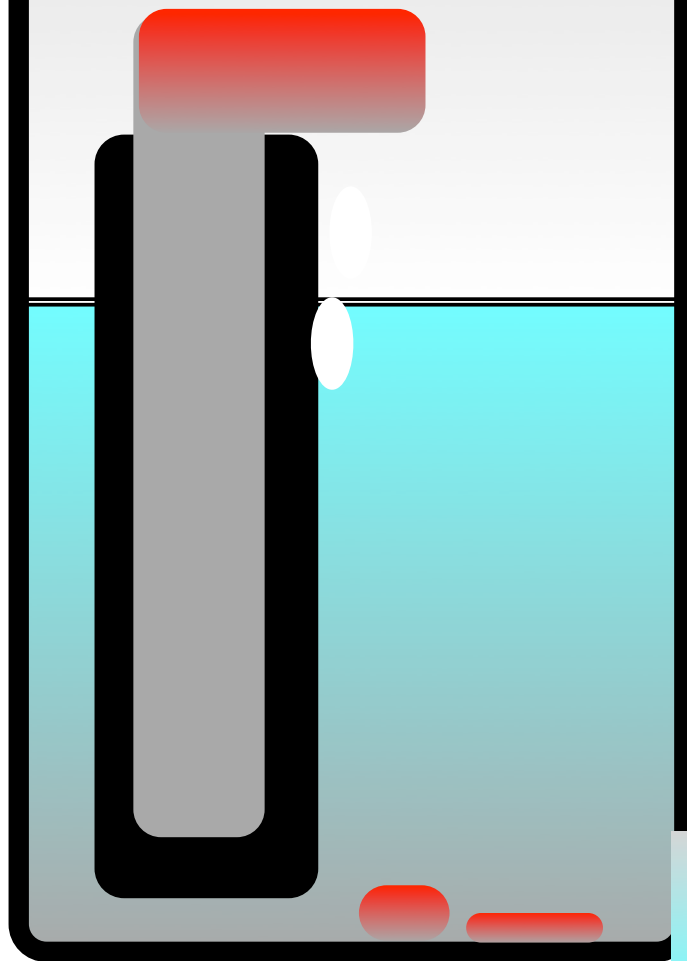
In Zircaloy casing:
fuel + fission products + actinides

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

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing

Fukushima Daiichi 2



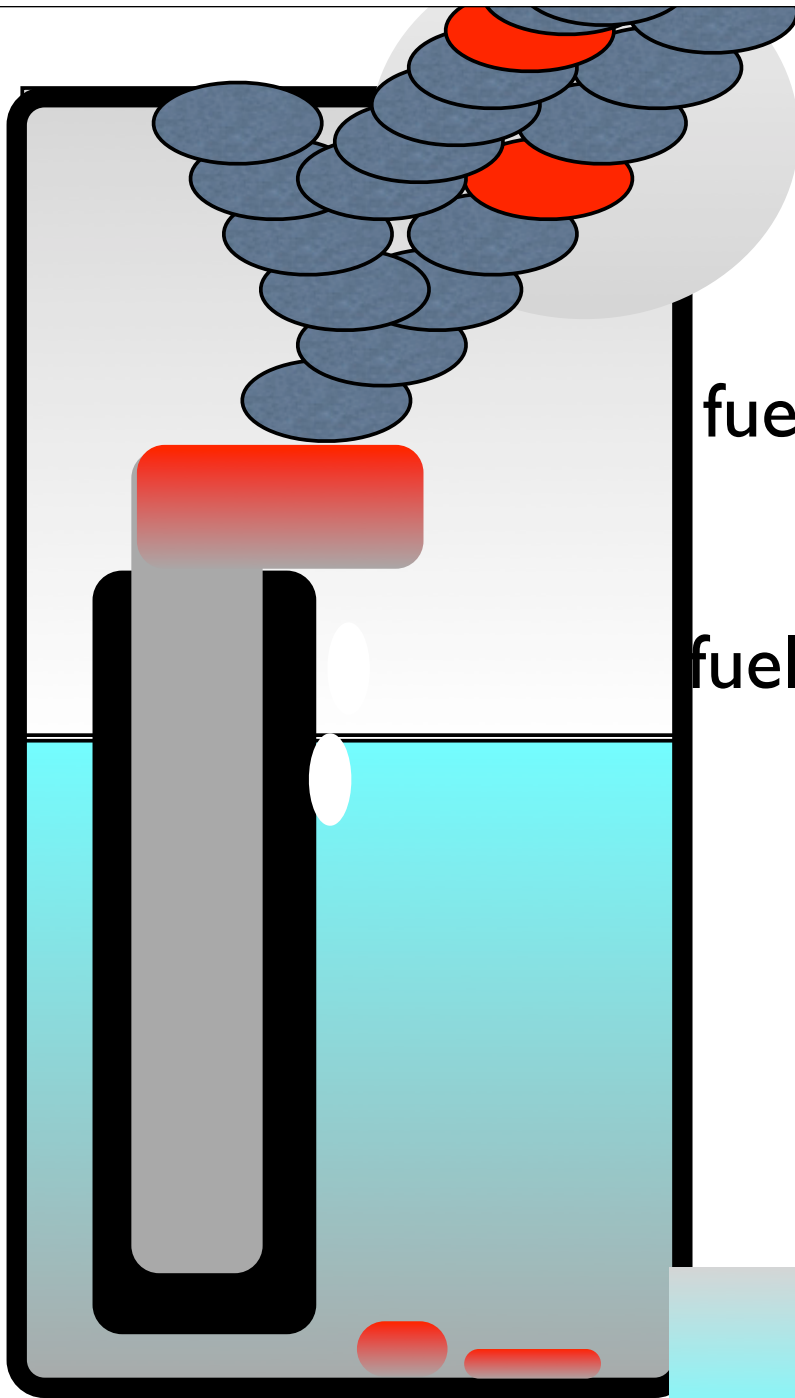
Meltdown + containment failure:

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

<http://mitnse.com>

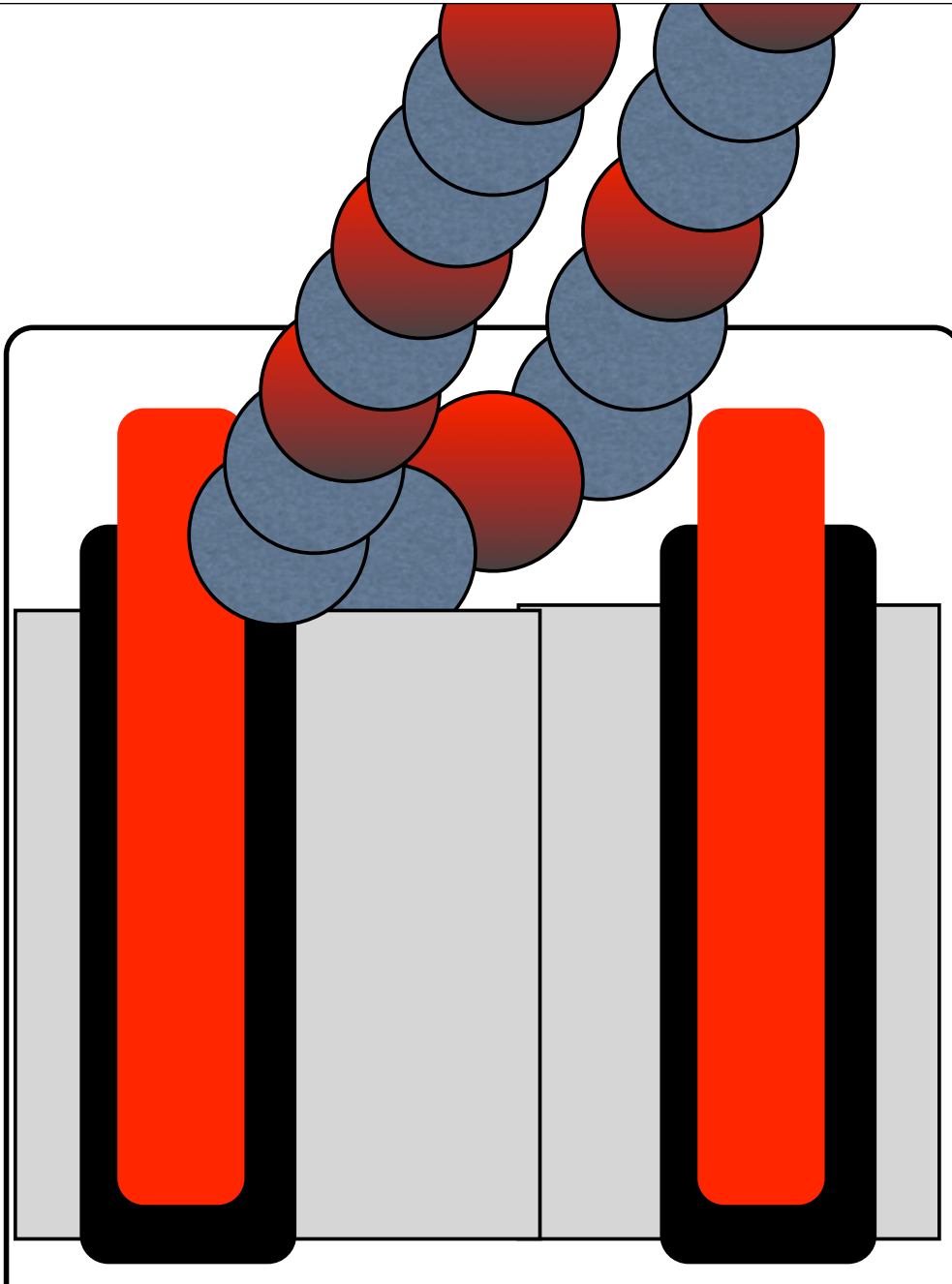
Chernobyl

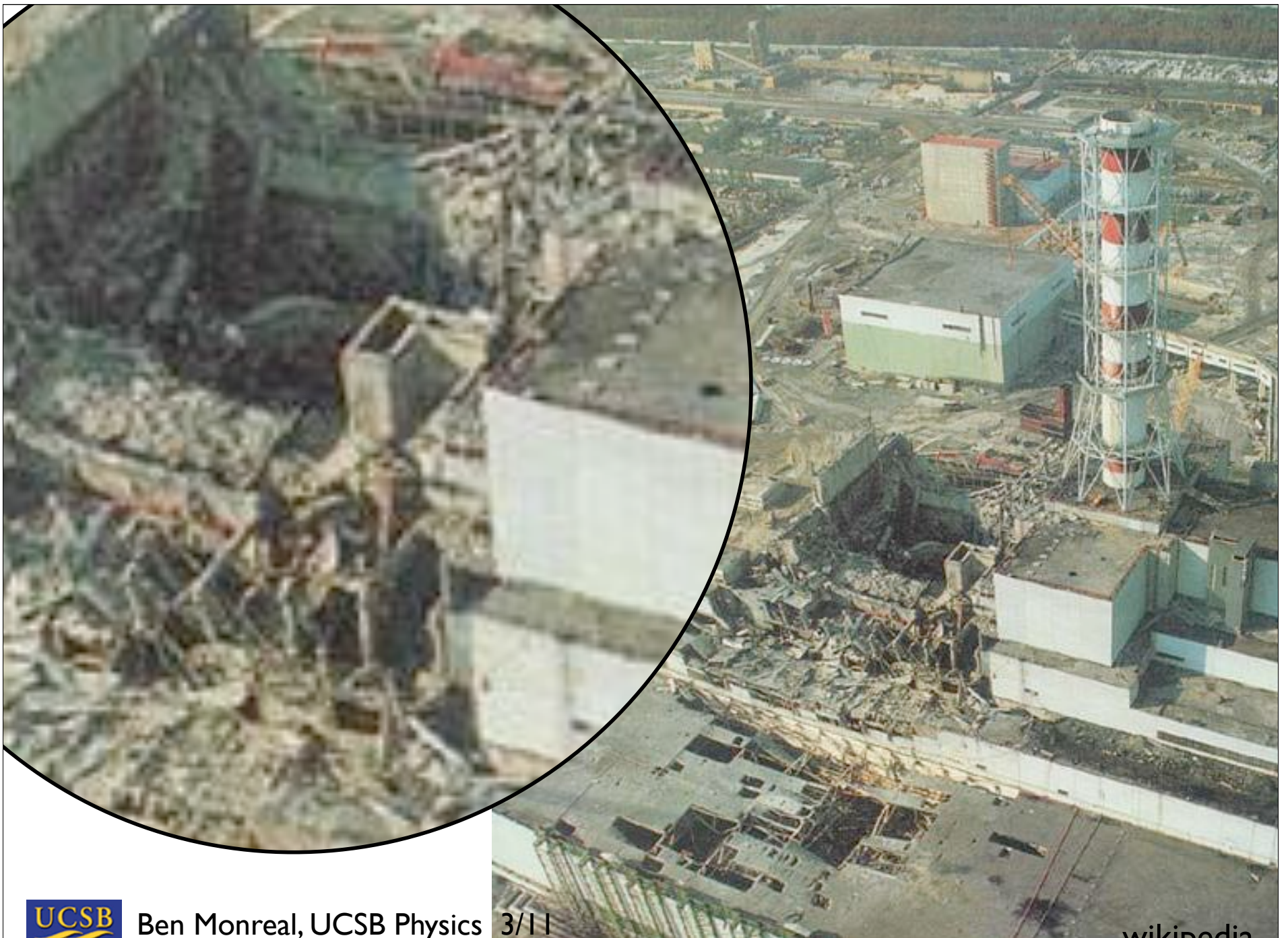
no real “containment vessel”

Core filled with graphite
(fuel for huge fire)

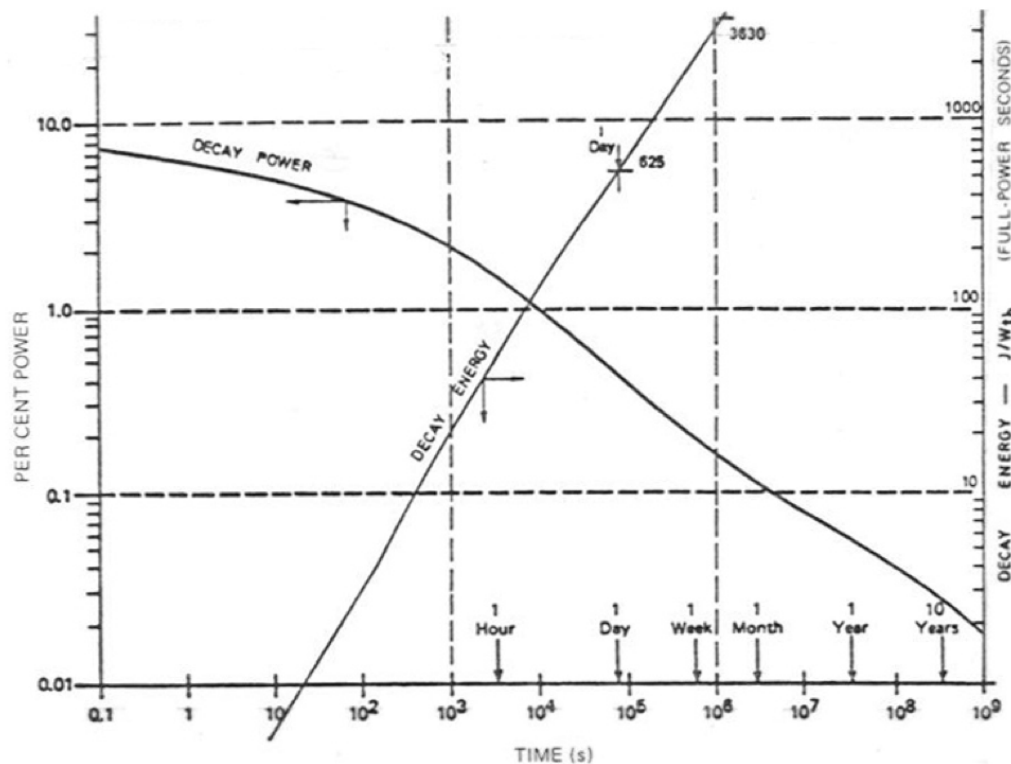
Reactor *fissioning during explosions and fire*

(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