

Understanding the radioactivity at Fukushima

A physics and engineering perspective

Prof. Ben Monreal
UCSB Department of Physics

Q&A Panel:

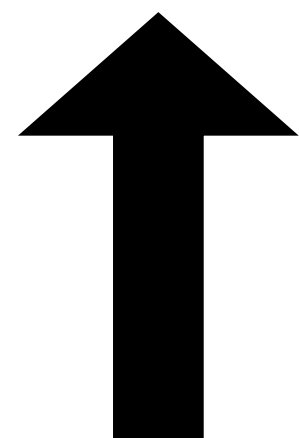
Ben Monreal

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?

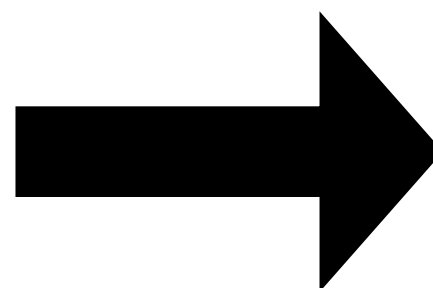
“Tritium” (hydrogen)																																																																																																																																													
Key 11 Na Sodium 22.99 Atomic number Element symbol Element name Average atomic mass*																																																																																																																																													
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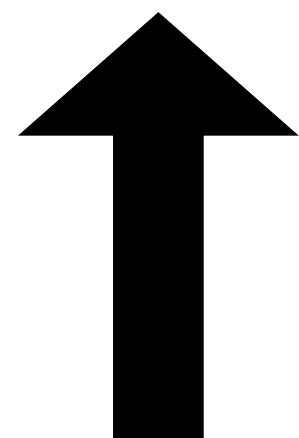


Different
elements

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+	B13 10.46 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+	Be12 16.66 s 1/2+
Lithium		Li4	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 1+	Li11 8.58 s 1+
Helium		He3	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-)	He10 1.98 s 1+
Hydrogen	H1 1/2+ 99.985	H2 1+ 0.015	H3 12.33 y 1/2+ β^-	H4 2-	H5	H6	6		
		n1 614.8 s 1/2+ β^-	2		4				

Different
isotopes

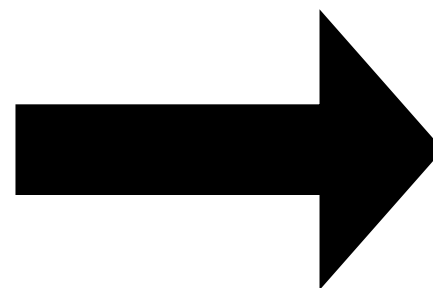




Different
elements

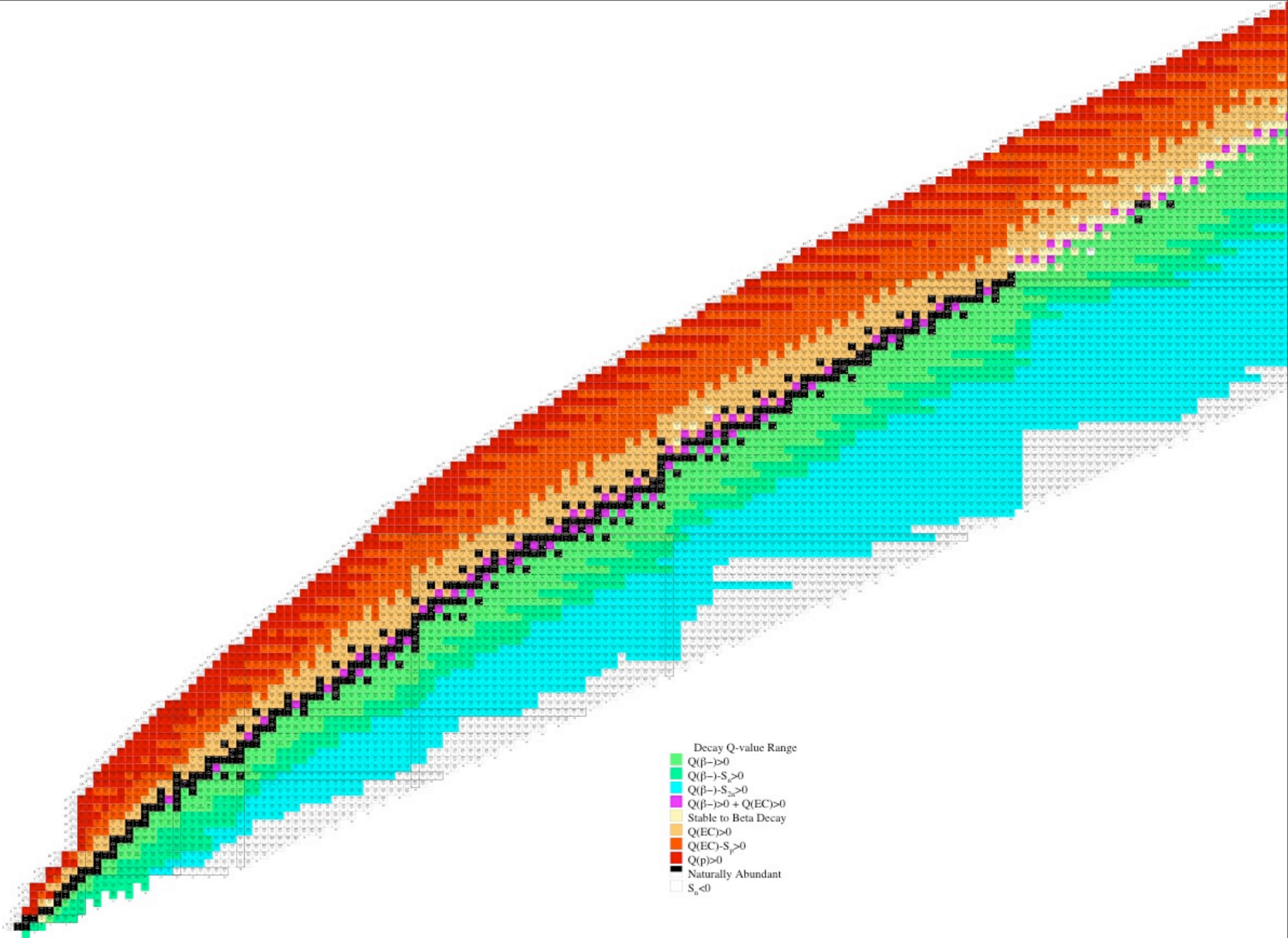
Boron			B7 1.4 MeV (3/2-)	B8 770 ms 2+ EC2α	B9 0.54 keV 3/2- 2pα	B10 3+ 19.9	B11 3/2- 80.1	B12 20.20 ms 1+ β-3α	
Beryllium		Be5	Be6 92 keV 0+ 2p	Be7 53.29 d 3/2- EC	Be8 6.8 eV 0+ 2α	Be9 3/2- 100	Be10 1.51E+6 y 0+ β-	Be11 13.81 s 1/2+ β-α	
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Helium		He3 1/2+ 0.000137	He4 0+ 99.999863	He5 0.60 MeV 3/2- n	He6 806.7 ms 0+ β-	He7 160 keV (3/2)- n	He8 119.0 ms 0+ β-n	He9 0.30 MeV (1/2-) n	
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Different
isotopes



Different
elements
↑

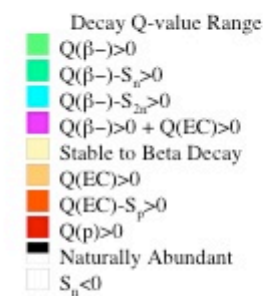
Different
isotopes
→



Different
elements
↑

Different
isotopes
→

Stable isotopes

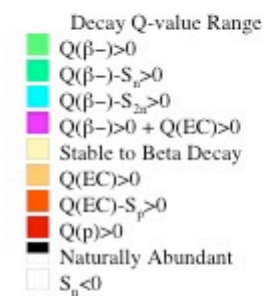


Different
elements
↑

Different
isotopes
→

Stable isotopes

Fission



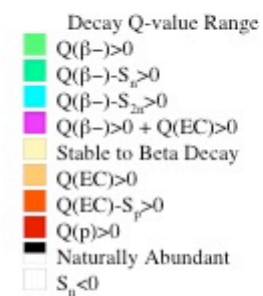
Different
elements
↑

Different
isotopes
→

Stable isotopes

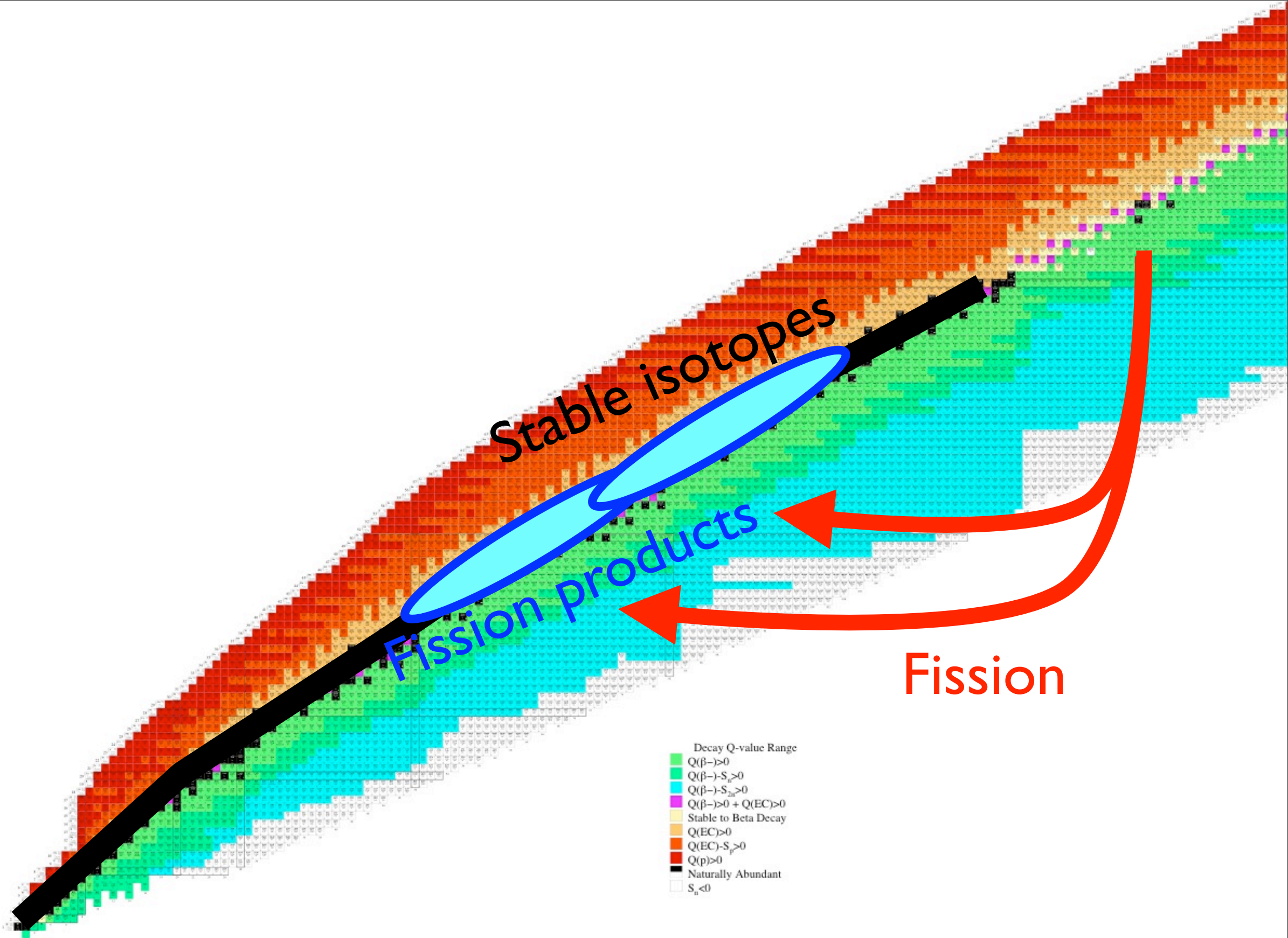
Fission products

Fission



Different
elements
↑

Different
isotopes
→



Decay Q-value Range

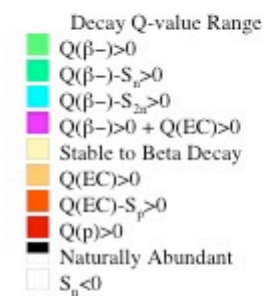
- $Q(\beta^-) > 0$
- $Q(\beta^-) - S_n > 0$
- $Q(\beta^-) - S_{2n} > 0$
- $Q(\beta^-) > 0 + Q(\text{EC}) > 0$
- Stable to Beta Decay
- $Q(\text{EC}) > 0$
- $Q(\text{EC}) - S_p > 0$
- $Q(p) > 0$
- Naturally Abundant
- $S_n < 0$

Different
elements
↑

Different
isotopes
→

Stable isotopes

Fission



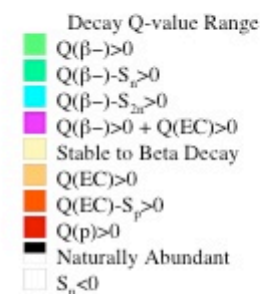
Different
elements
↑

Different
isotopes
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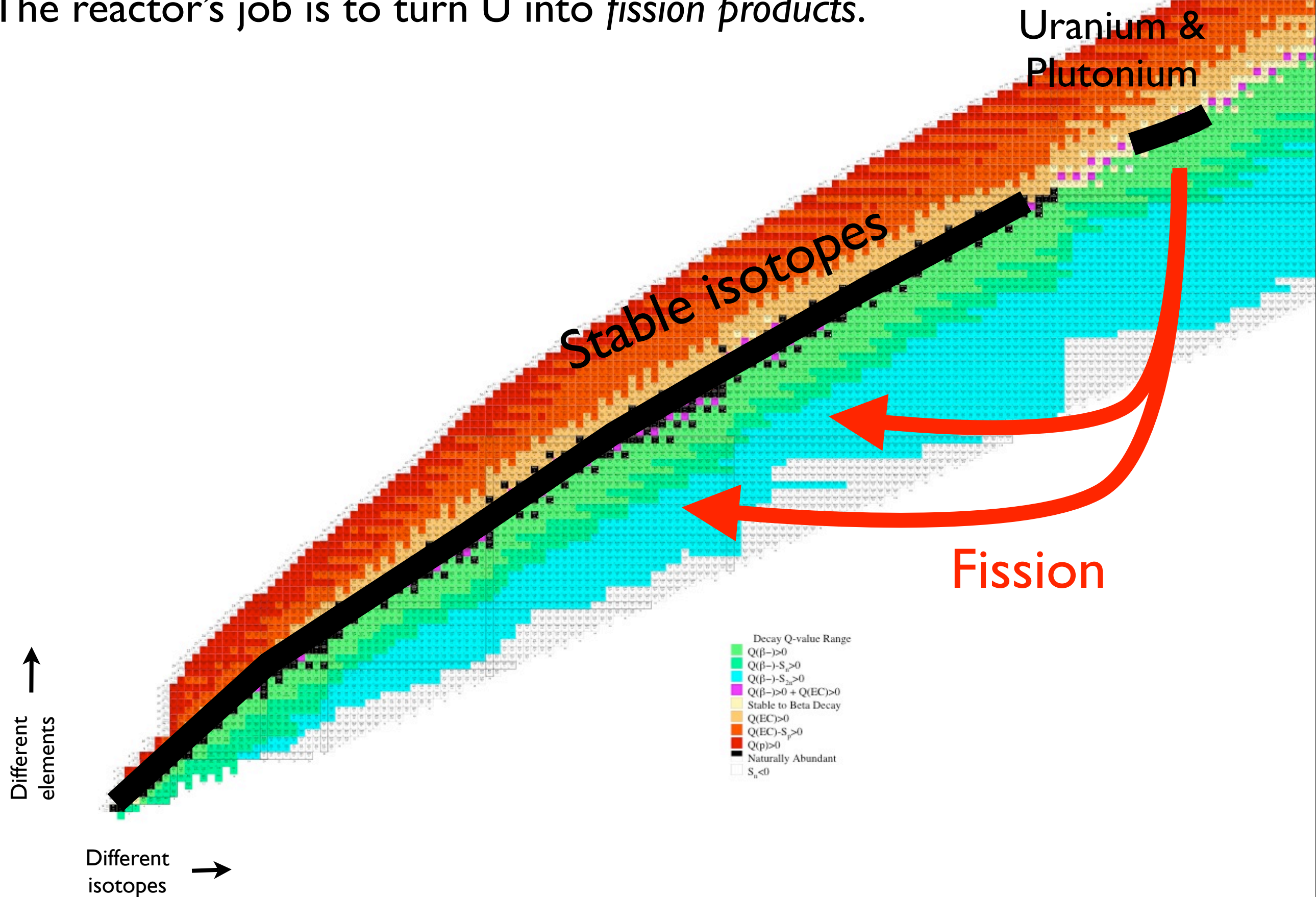
Stable isotopes

Uranium &
Plutonium

Fission

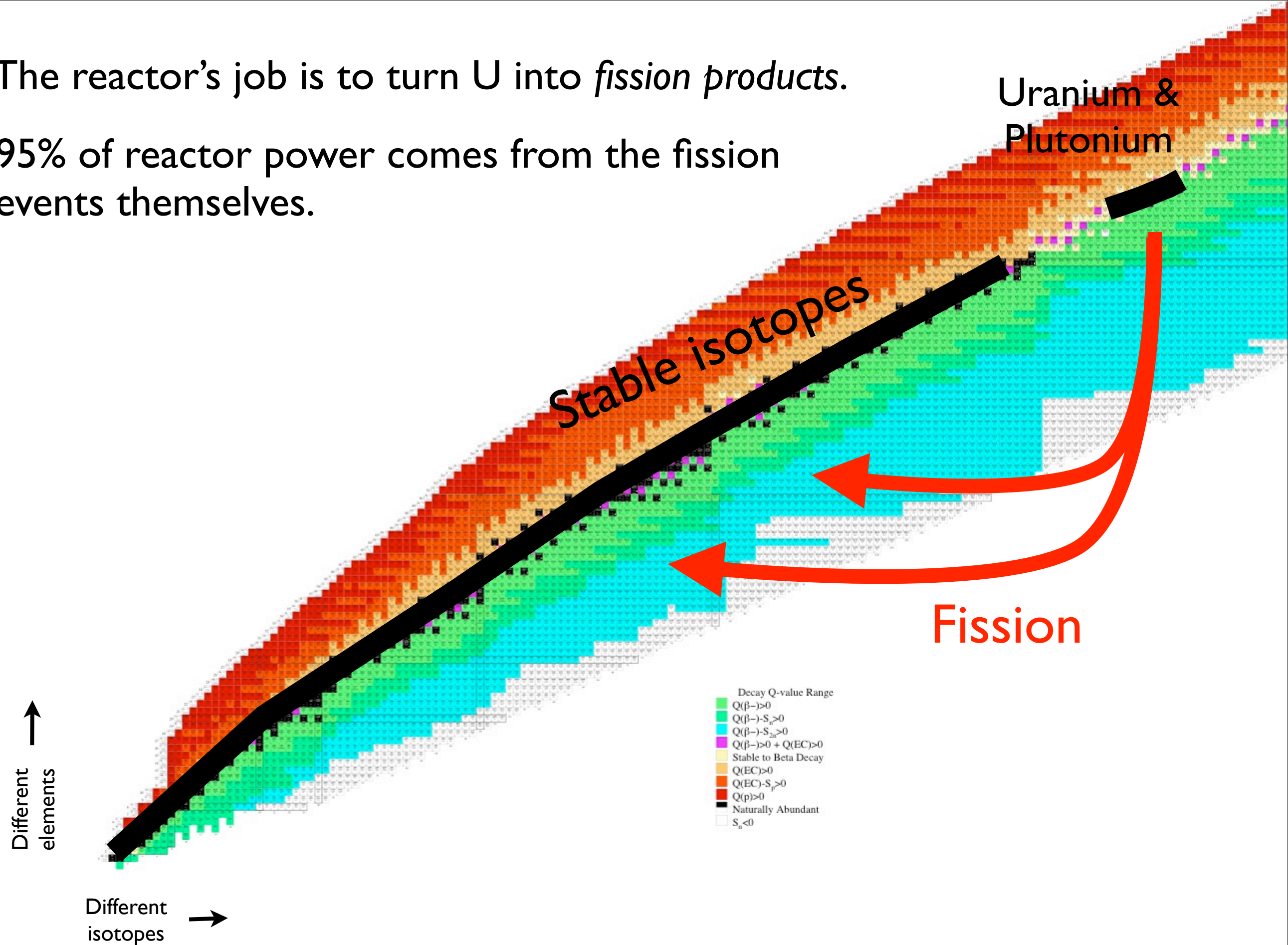


The reactor's job is to turn U into *fission products*.



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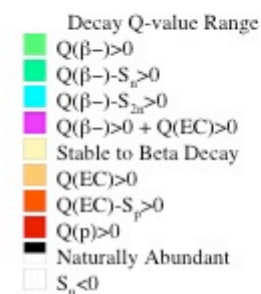
↑
Different
elements

→
Different
isotopes

Stable isotopes

Uranium &
Plutonium

Fission



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

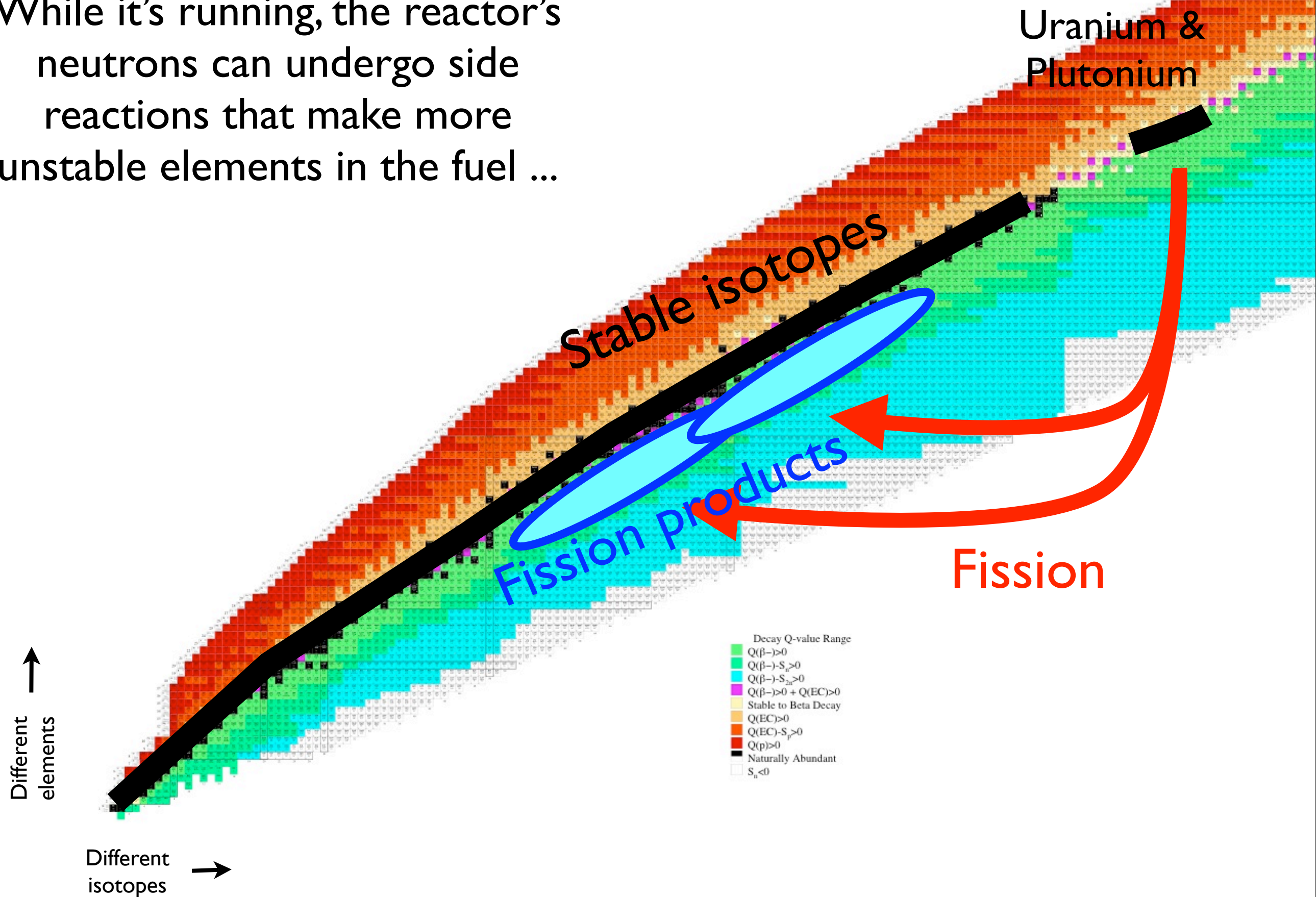
Stable isotopes

Uranium &
Plutonium

Fission



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



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Neutron capture on fuel

Uranium & Plutonium

Stable isotopes

Fission products

Fission

Different elements
↑

Different isotopes
→



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

Neutron capture on fuel

Uranium & Plutonium

Minor Actinides

Stable isotopes

Fission products

Fission

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.

Neutron capture on fuel

Uranium & Plutonium

Minor Actinides

Stable isotopes

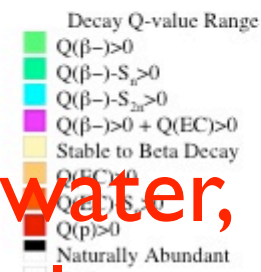
Fission products

Fission

Neutron capture on water, air, reactor materials

Different elements
↑

Different isotopes
→



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

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Neutron capture on fuel

Uranium & Plutonium

Minor Actinides

Stable isotopes

Fission products

Fission

Neutron capture on water, air, reactor materials

Induced radioactivity

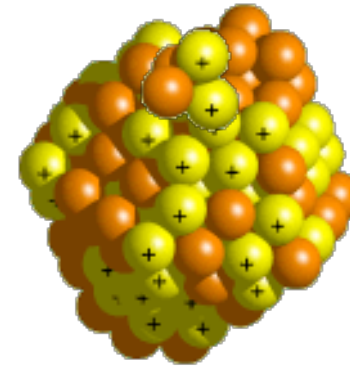
Different elements
↑

Different isotopes
→

Decay Q-value Range
 $Q(\beta^-) > 0$
 $Q(\beta^-) - S_{\nu} > 0$
 $Q(\beta^-) - S_{2\nu} > 0$
 $Q(\beta^-) > 0 + Q(EC) > 0$
Stable to Beta Decay
 $Q(FC) > 0$
 $Q(\alpha) > 0$
 $Q(p) > 0$
Naturally Abundant
 $S_1 < 0$

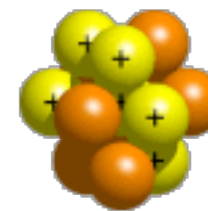
Radiation damage

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



^{226}Ra

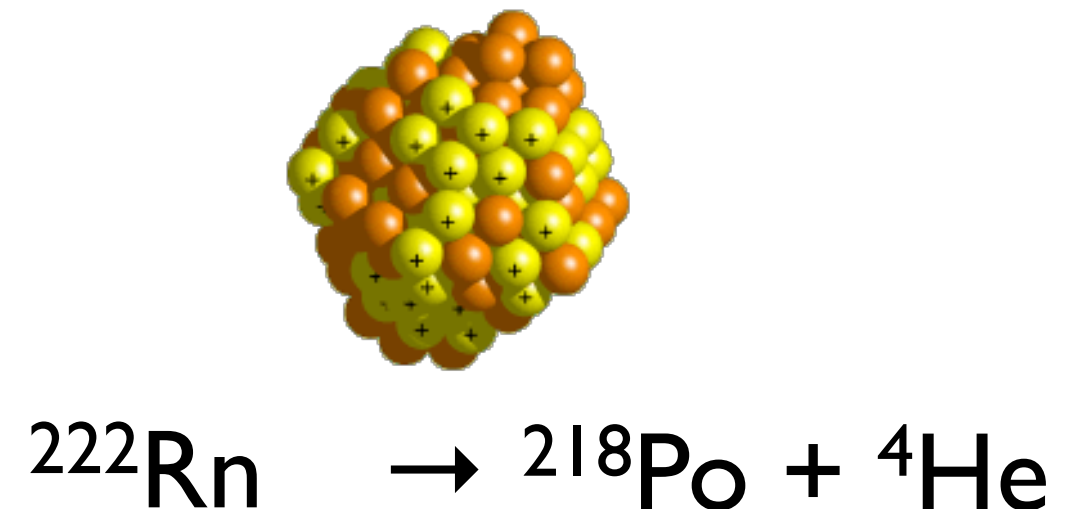
Beta & gamma decay:
fission products
(damages every 3000th
atom it passes.)



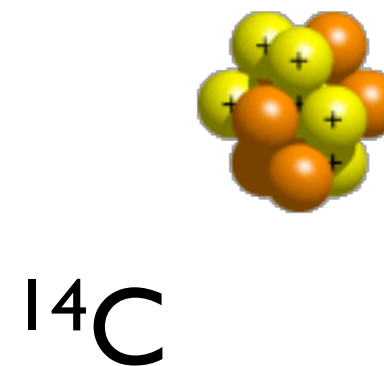
^{14}C

Radiation damage

Alpha decay: common
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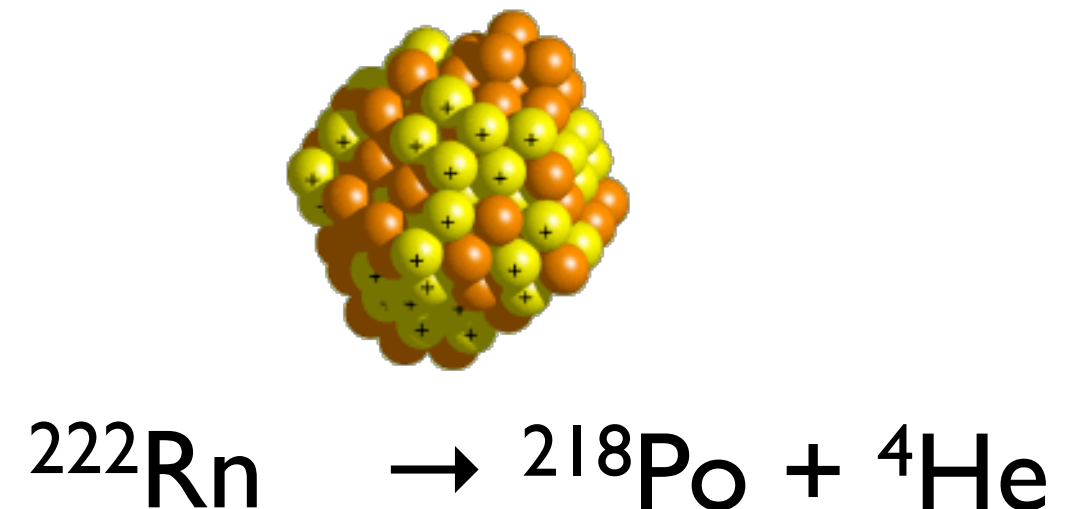


Beta & gamma decay:
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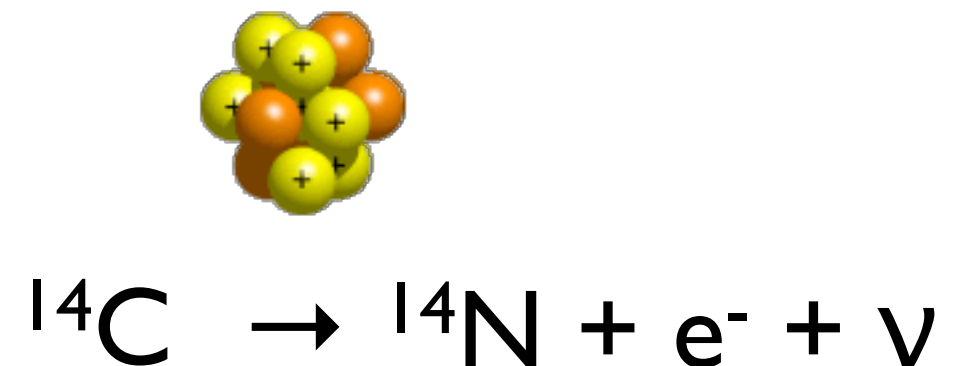


Radiation damage

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Beta & gamma decay:
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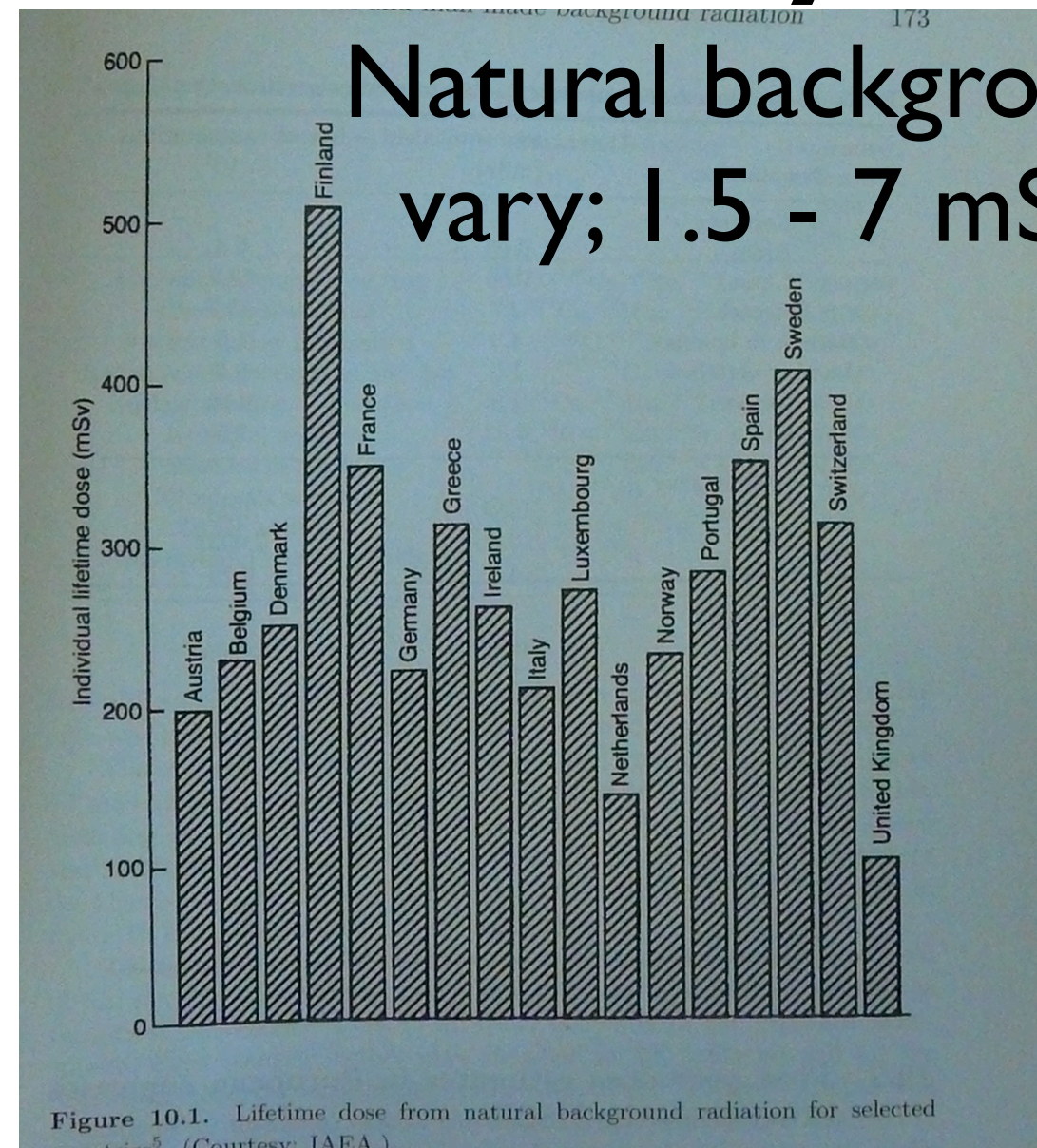
How much damage?

- 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: $>5 \text{ Sv} = \text{run for your life}$

- *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 $> 5 \text{ Sv}$), 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



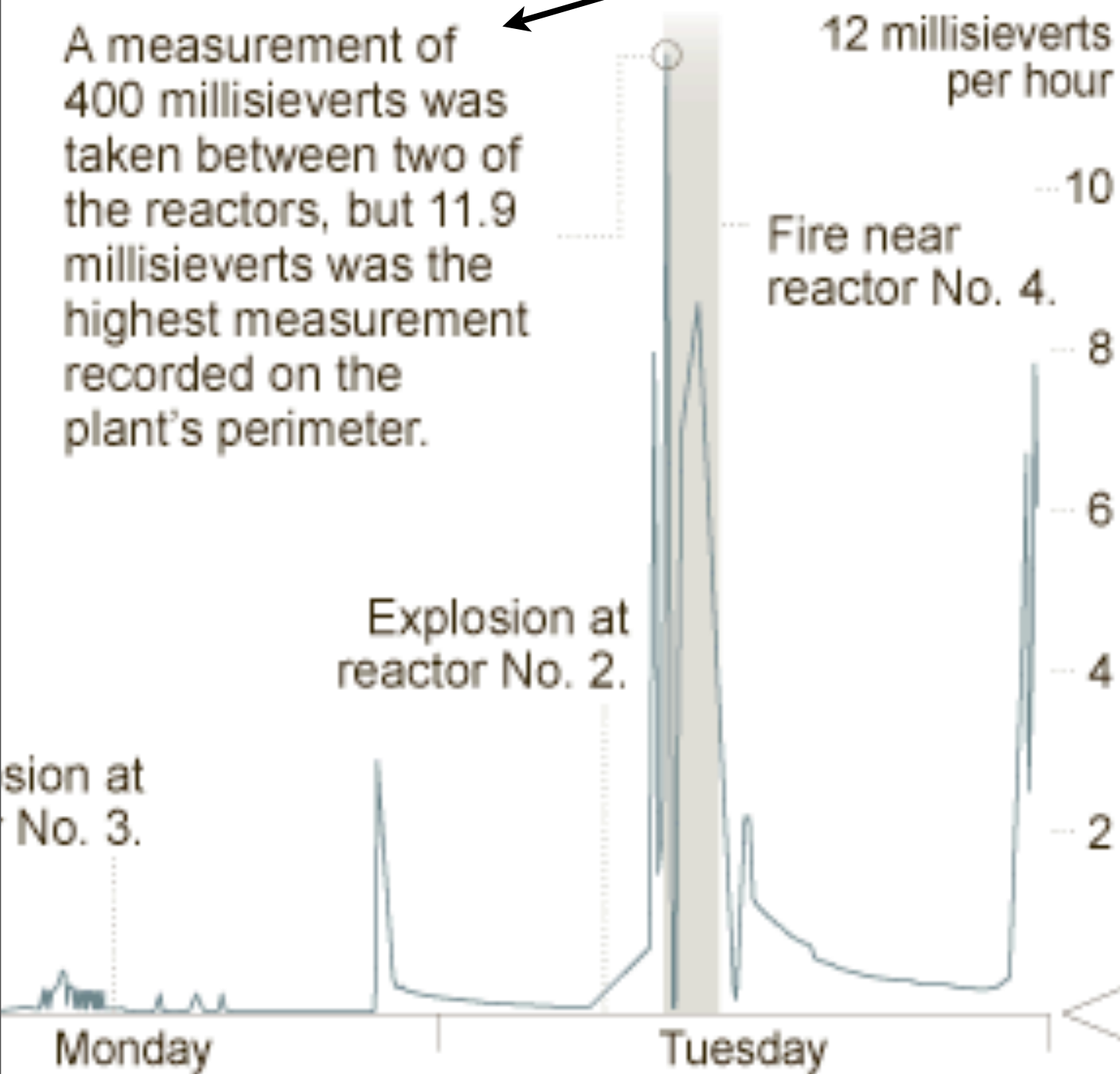
Radiation levels on the edge of the plant compound briefly spiked at 8217 microsieverts per hour but later fell to about a third that.

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

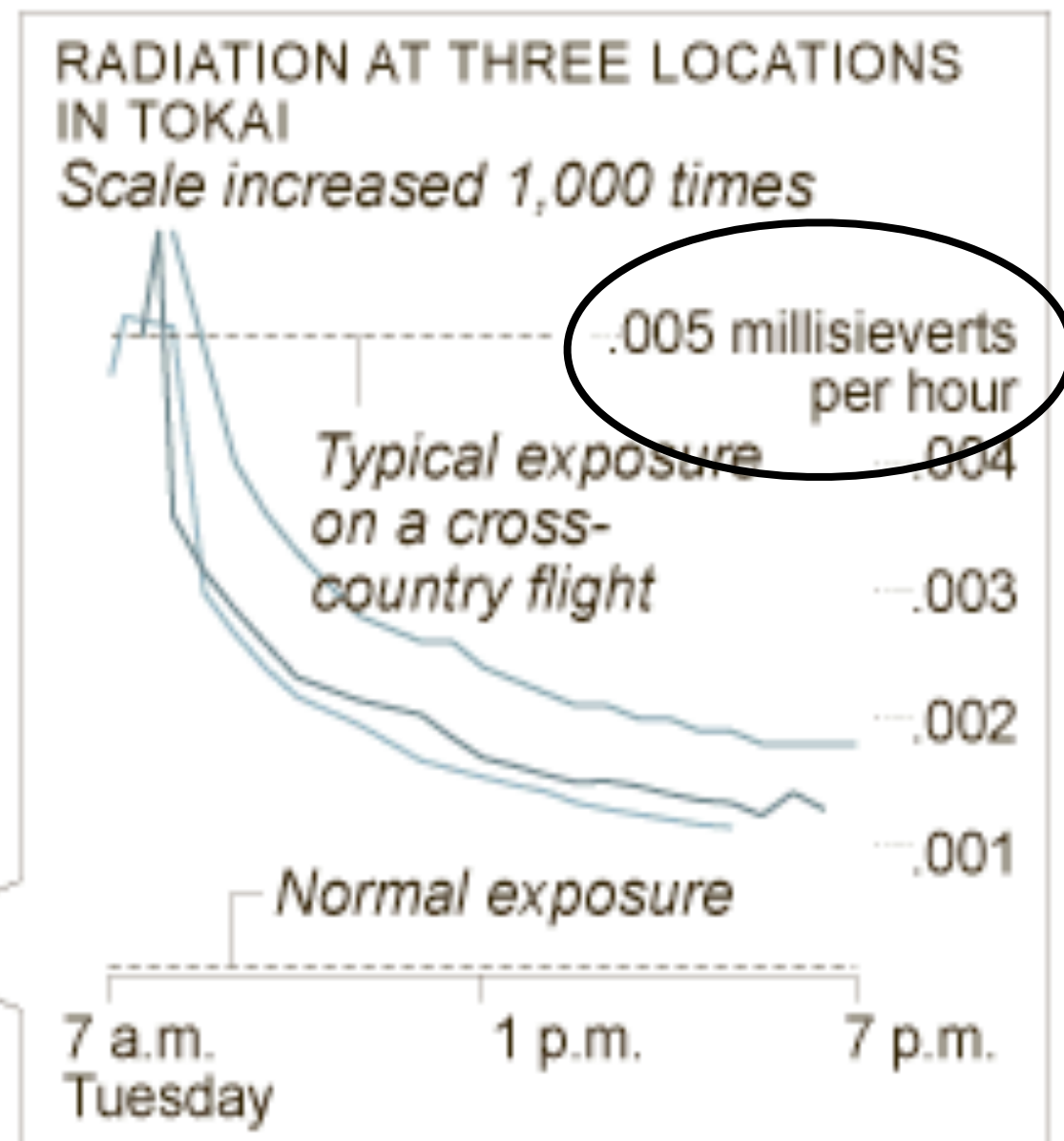
They meant “millisieverts *per hour*”

NYTimes.com

A measurement of 400 millisieverts was taken between two of the reactors, but 11.9 millisieverts was the highest measurement recorded on the plant's perimeter.

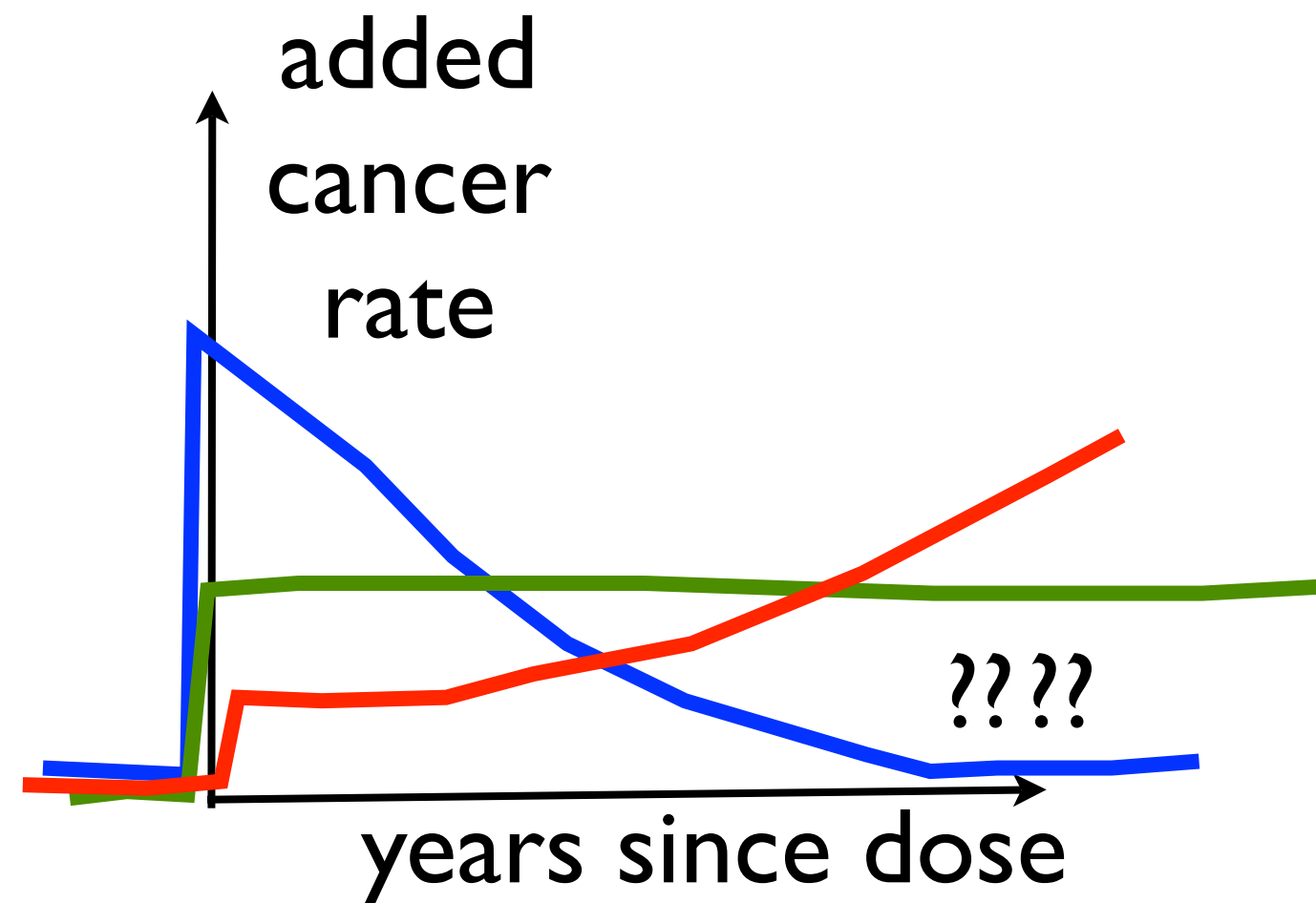
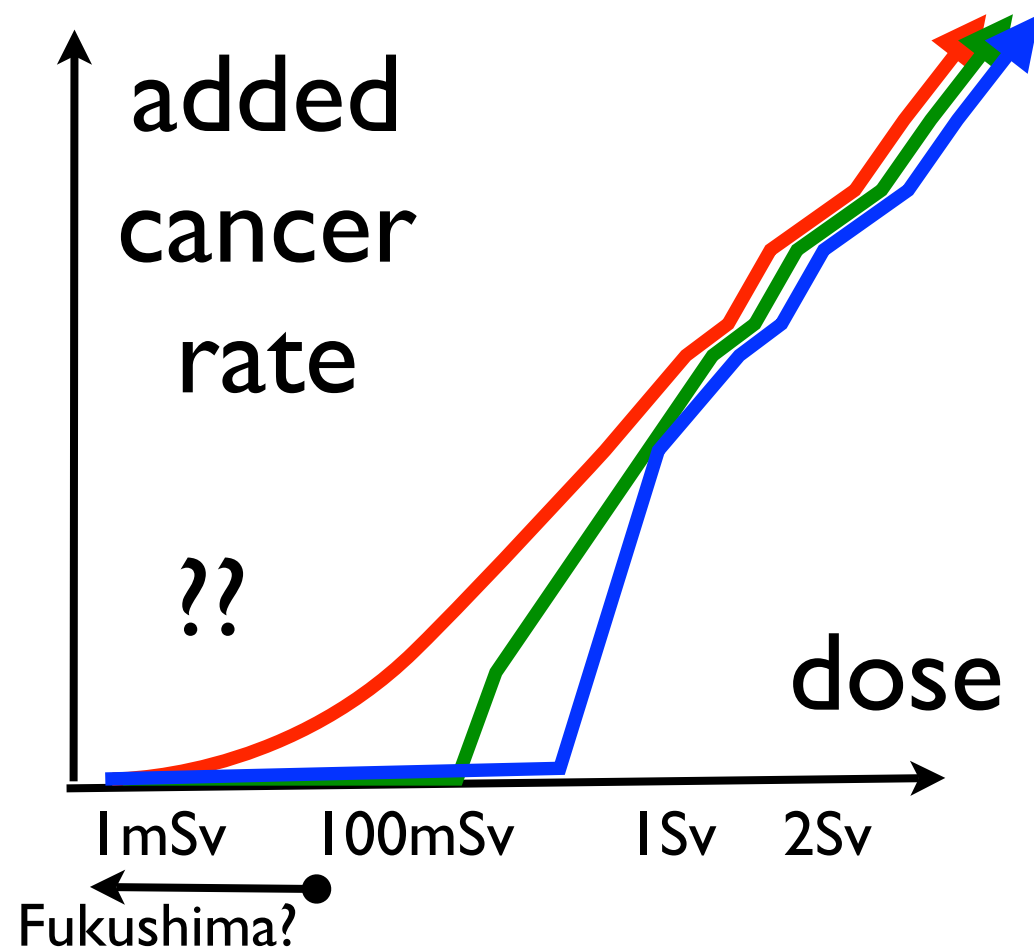


Elevated radiation levels were detected in many southern cities, but levels were far below those that pose health risks, and they were falling.

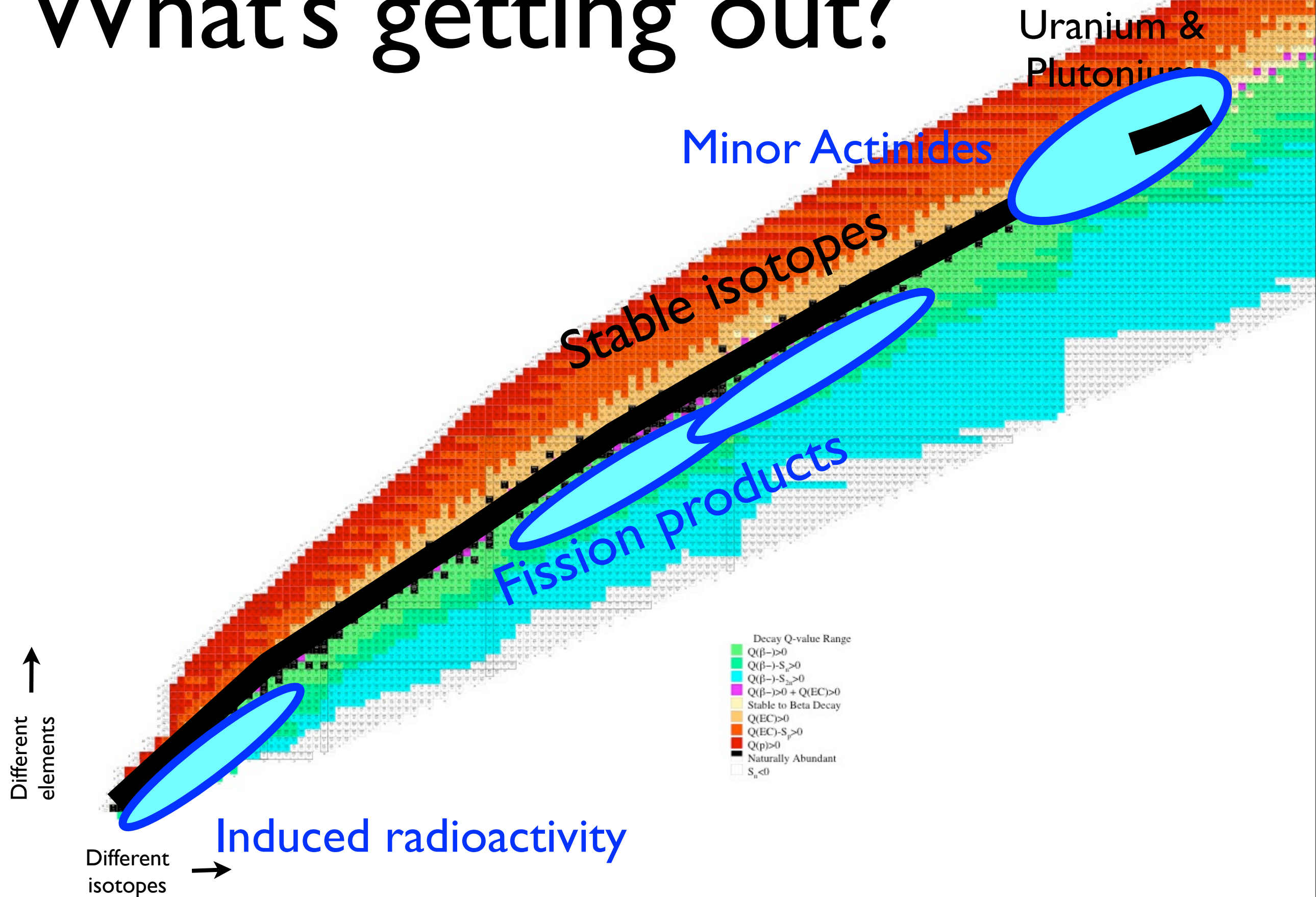


Are low doses proportionally dangerous?

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



What's getting out?



1 1A																	18 8A	
1 H Hydrogen 1.01	2 2A																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01																	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31	3 3B	4 4B	5 5B	6 6B	7 7B	8	9	10	11 1B	12 2B	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	
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 Bromine 79.90	36 Kr Krypton 83.80	
37 Rb Rubidium 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 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29	
55 Cs Cesium 132.91	56 Ba Barium 137.33	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 Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)	
87 Fr Francium (223)	88 Ra Radium (226)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)										
																		58 Ce Cerium 140.12
																		59 Pr Praseodymium 140.91
																		60 Nd Neodymium 144.24
																		61 Pm Promethium (145)
																		62 Sm Samarium 150.36
																		63 Eu Europium 151.96
																		64 Gd Gadolinium 157.25
																		65 Tb Terbium 158.93
																		66 Dy Dysprosium 162.50
																		67 Ho Holmium 164.93
																		68 Er Erbium 167.26
																		69 Tm Thulium 168.93
																		70 Yb Ytterbium 173.04
																		71 Lu Lutetium 174.97
																		90 Th Thorium 232.04
																		91 Pa Protactinium 231.04
																		92 U Uranium 238.03
																		93 Np Neptunium (237)
																		94 Pu Plutonium (244)
																		95 Am Americium (243)
																		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)

Key

11

Na

Sodium

22.99

Atomic number

Element symbol

Element name

Average atomic mass*

*

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.

Key

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

Induced radioactivity

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

1 H Hydrogen 1.01	2 He Helium 4.00																
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 18.99	10 Ne Neon 20.18
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										
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 Bromine 79.90	36 Kr Krypton 83.80
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* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.

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90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	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)

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Induced radioactivity

Key

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Na	—	Element symbol
Sodium	—	Element name
22.99	—	Average atomic mass*

Fission products

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

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Induced radioactivity

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11	—	Atomic number
Na	—	Element symbol
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22.99	—	Average atomic mass*

1	2																	18
1A	2A																	8A
1	2																	2
H	He																	Helium
Hydrogen	Helium																	4.00
1.01	20.18																	
3	4																	10
Li	Be																	Ne
Lithium	Beryllium																	Neon
6.94	9.01																	20.18
11	12	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
Na	Mg	3B	4B	5B	6B	7B	8B	9B	10B	1B	2B	3A	4A	5A	6A	7A	8A	
Sodium	Magnesium											Aluminum	Silicon	Phosphorus	Sulfur	Chlorine	Argon	
22.99	24.31											26.98	28.09	30.97	32.07	35.45	39.95	
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	
Potassium	Calcium	Scandium	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt	Nickel	Copper	Zinc	Gallium	Germanium	Arsenic	Selenium	Bromine	Krypton	
39.10	40.08	44.96	47.88	50.94	52.00	54.94	55.85	58.93	58.69	63.55	65.39	69.72	72.61	74.92	78.96	79.90	83.80	
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon	
85.47	87.62	88.91	91.22	92.91	95.94	(98)	101.07	102.91	106.42	107.87	112.41	114.82	118.71	121.76	127.60	126.90	131.29	
55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	
Cs	Ba	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
Cesium	Barium	Lanthanum	Cerium	Praseodymium	Neodymium	Promethium	Samarium	Europium	Gadolinium	Terbium	Dysprosium	Holmium	Erbium	Thulium	Ytterbium	Lutetium		
132.91	137.33	138.91	140.12	140.91	144.24	(145)	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.05	174.96		
87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103		
Fr	Ra	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		
Francium	Radium	Actinium	Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium	Berkelium	Californium	Einsteinium	Fermium	Mendelevium	Nobelium	Lawrencium		
(223)	(226)	(227)	(232)	(231)	(238)	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(262)		

Fission products

minor actinides

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

The periodic table is color-coded as follows: Group 1A is yellow; Groups 2A, 3A, 4A, 5A, 6A, and 7A are purple; Groups 8A and 9A are orange; Groups 3B through 10 are cyan; Group 11 is magenta; and Groups 12 through 18 are white. Handwritten annotations include a blue circle around Group 1A, a blue oval around Groups 14-17, a large blue oval around Groups 3B-10, a large red oval around Groups 3B-10 and 11, a large green oval around Groups 12-18, and a large red oval around Groups 12-18. The text 'water soluble' is written vertically in the purple region, and 'Inert metals' is written in the cyan region.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1A	2A	3B	4B	5B	6B	7B	8	9	10	1B	2B	3A	4A	5A	6A	7A	8A
1																		
2																		
3																		
4																		
5																		
6																		
7																		

Key

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Gases

Inert metals

water soluble

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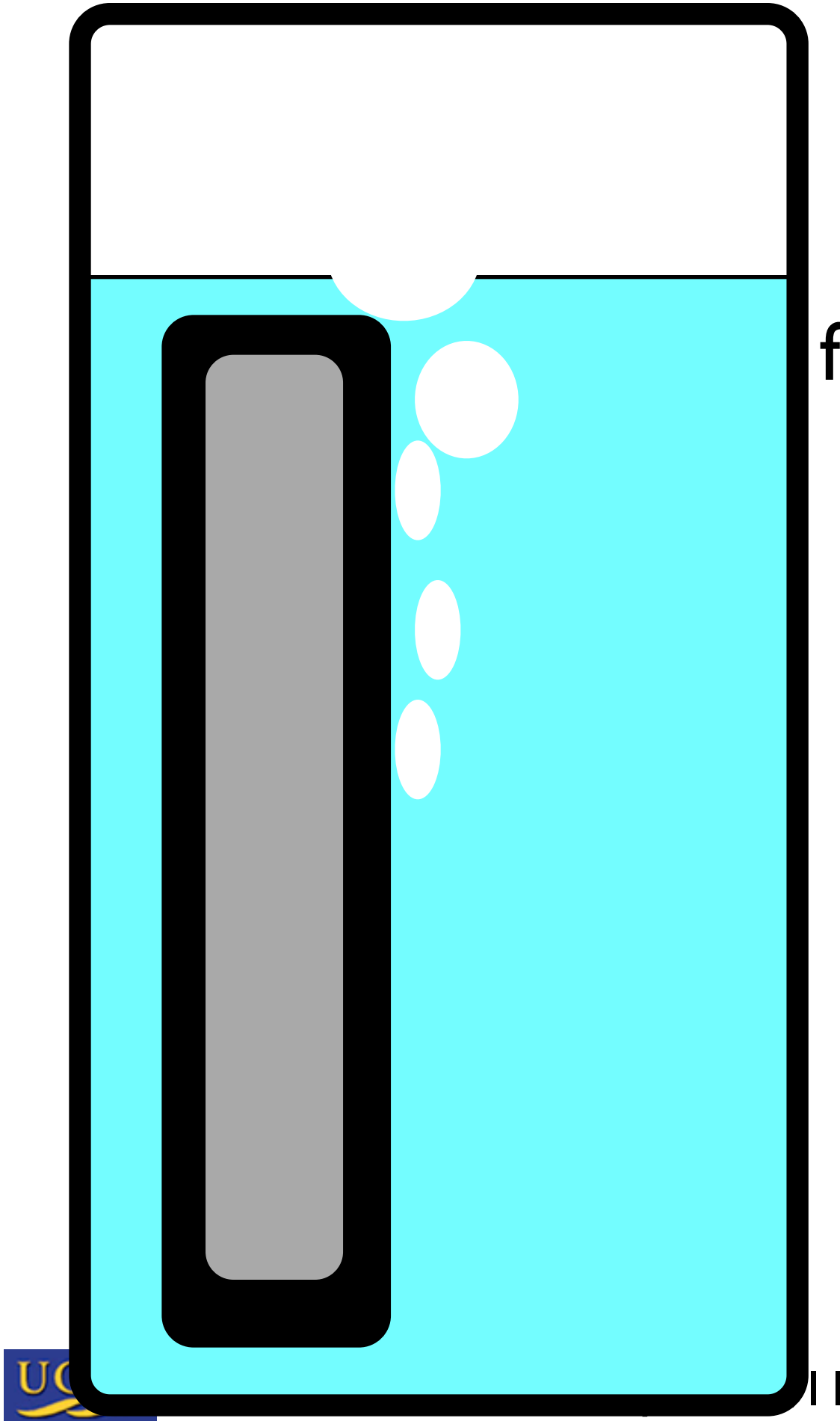
Healthy reactor:

In Zircaloy casing:
fuel + fission products + actinides

In cooling water:
activation products

In steam:
activation products

In environment:
practically nothing



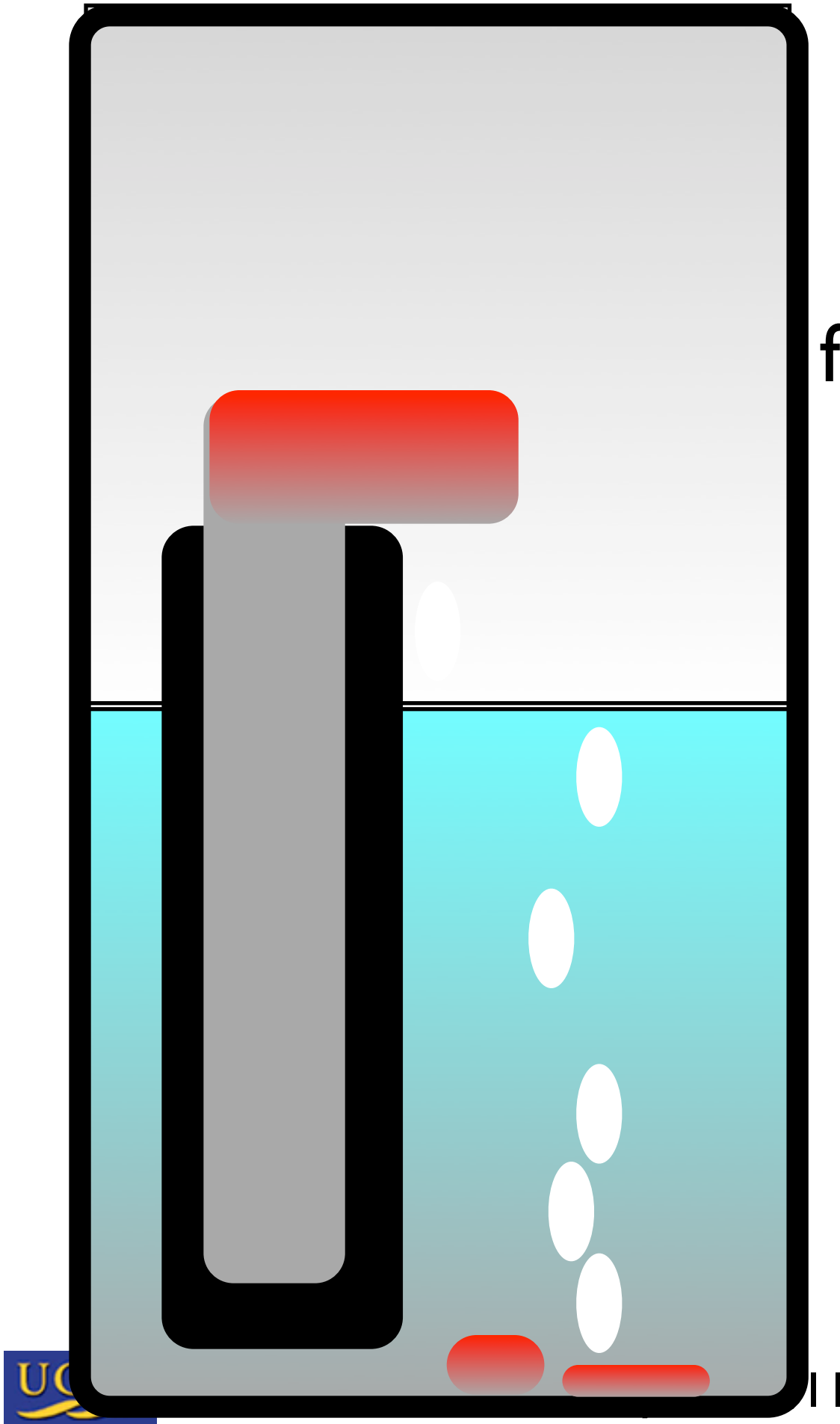
Meltdown:

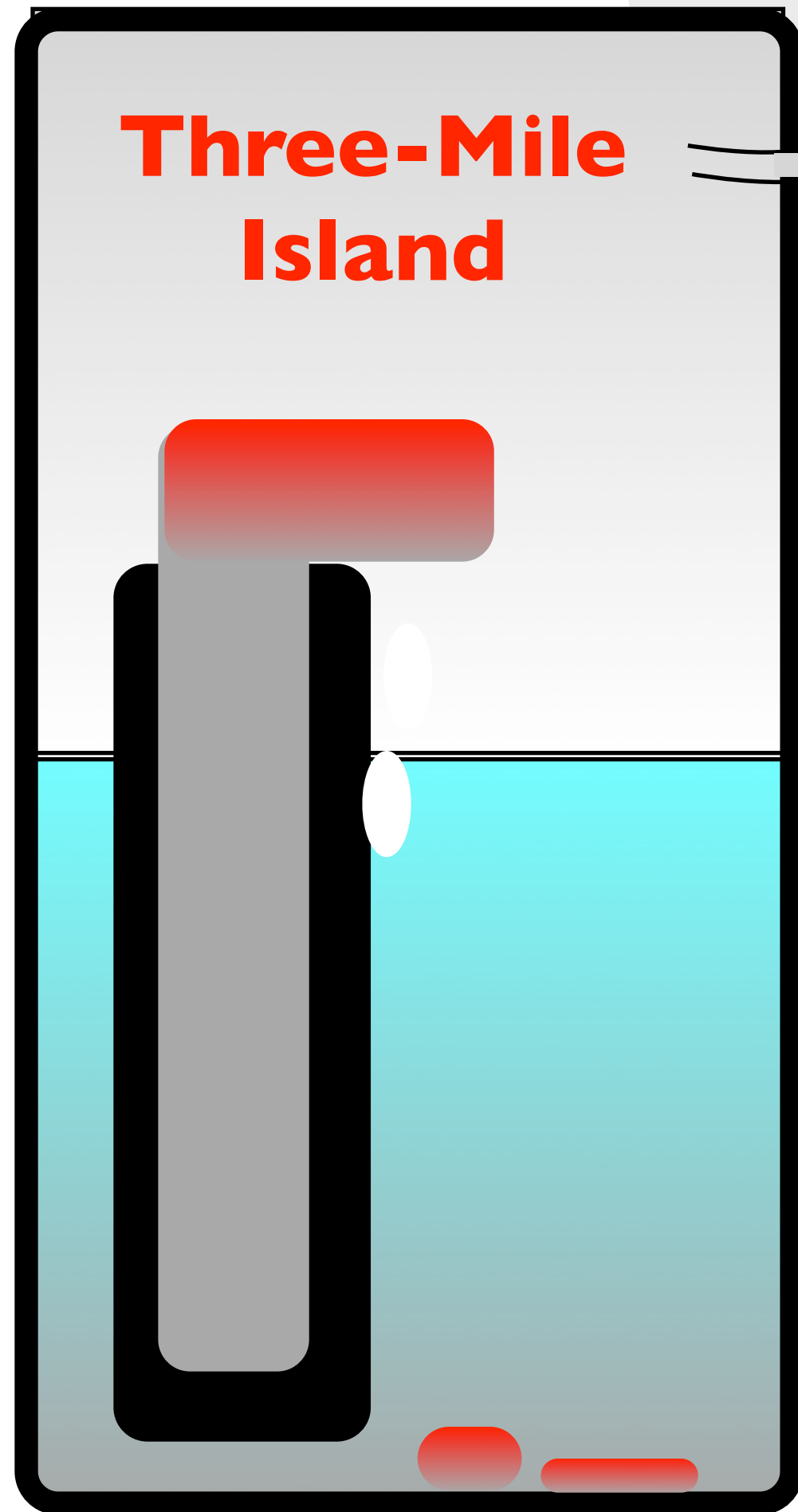
In Zircalloy casing:
fuel + fission products + actinides

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

In steam:
fission products like Xe, Kr, Rn

In environment:
practically nothing





**Three-Mile
Island**

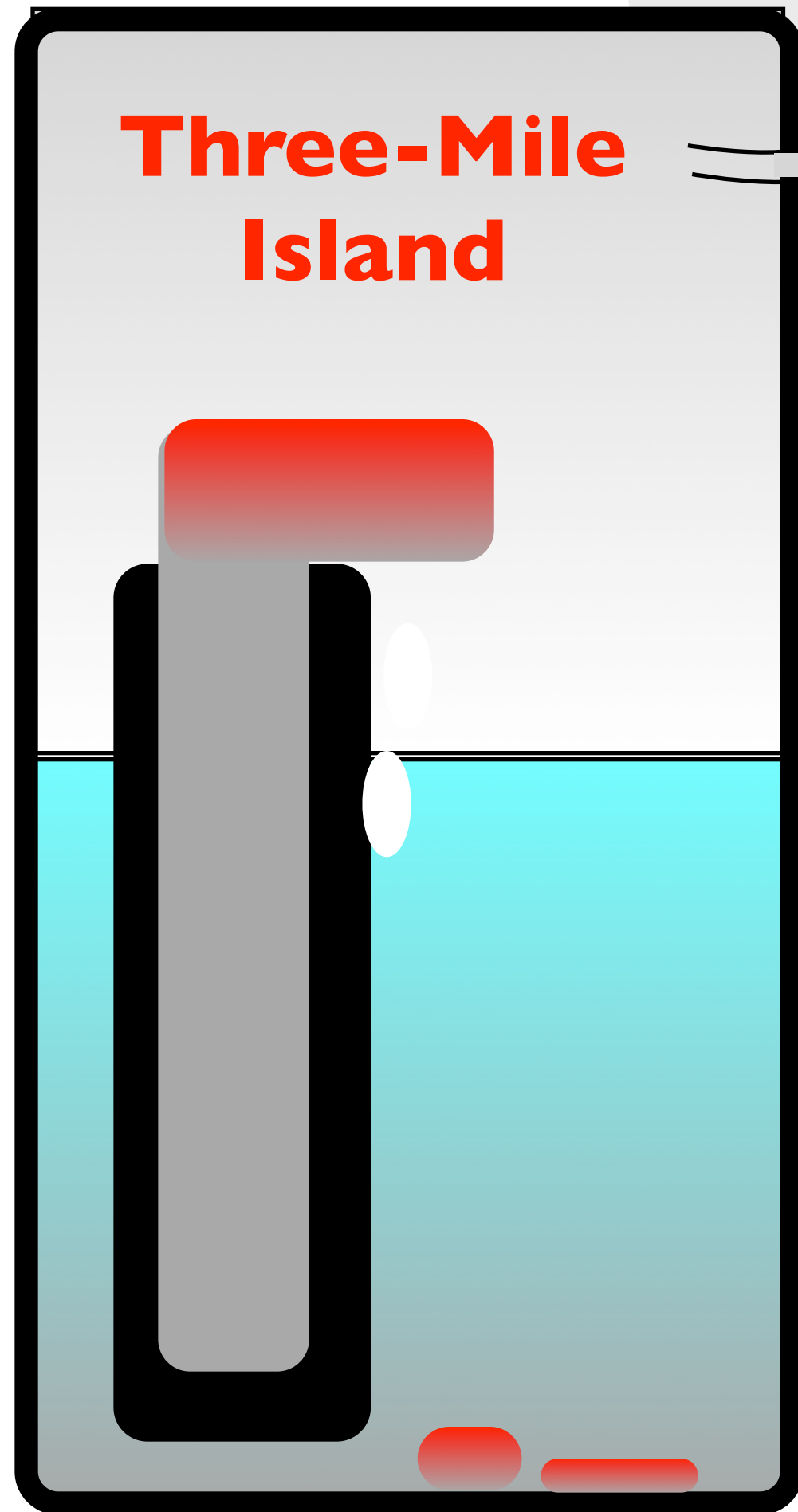
Meltdown + emergency venting:

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



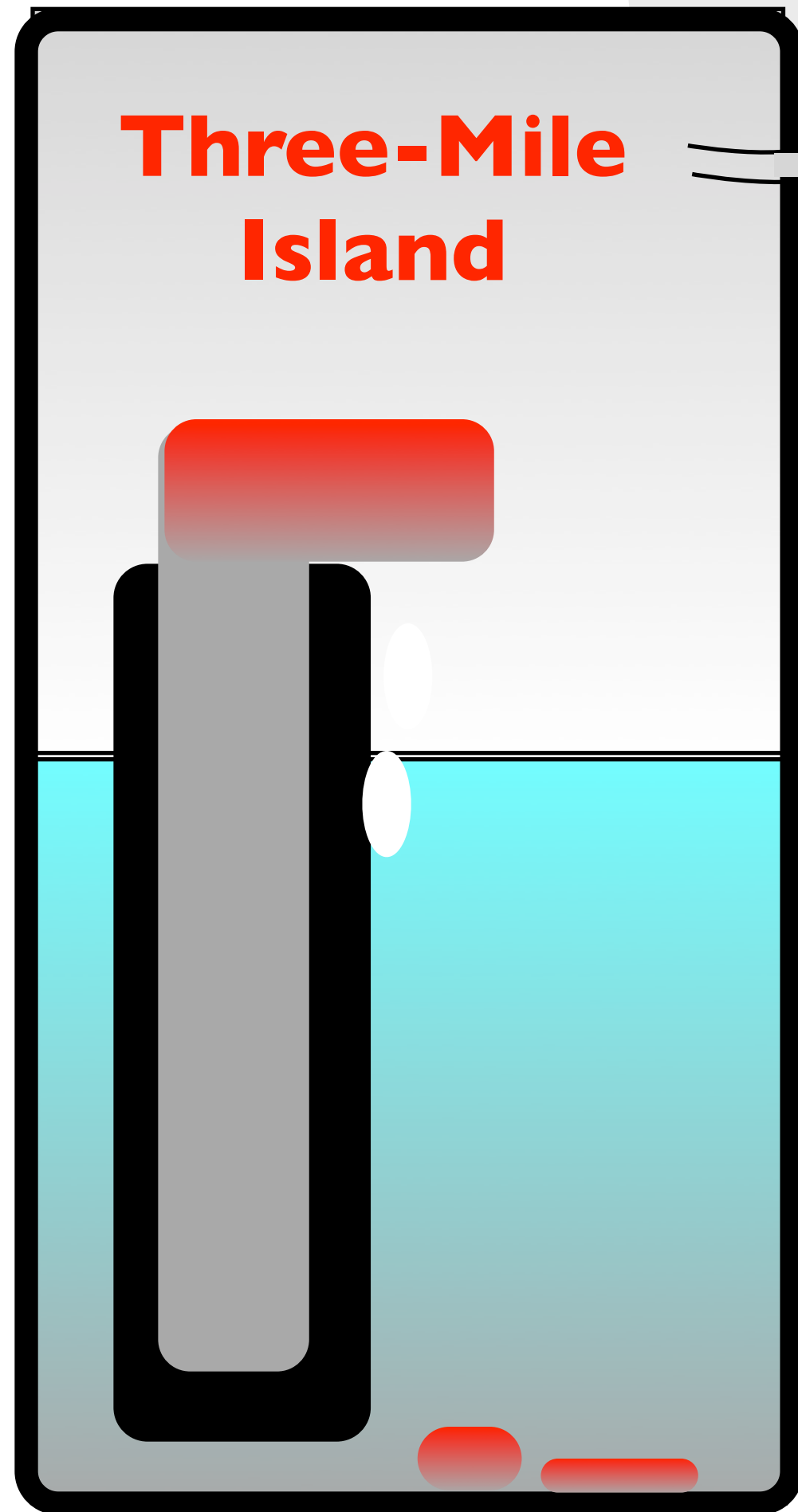
Three-Mile Island

Meltdown + emergency venting:

In Zircalloy casing:
fuel + fission products + actinides

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

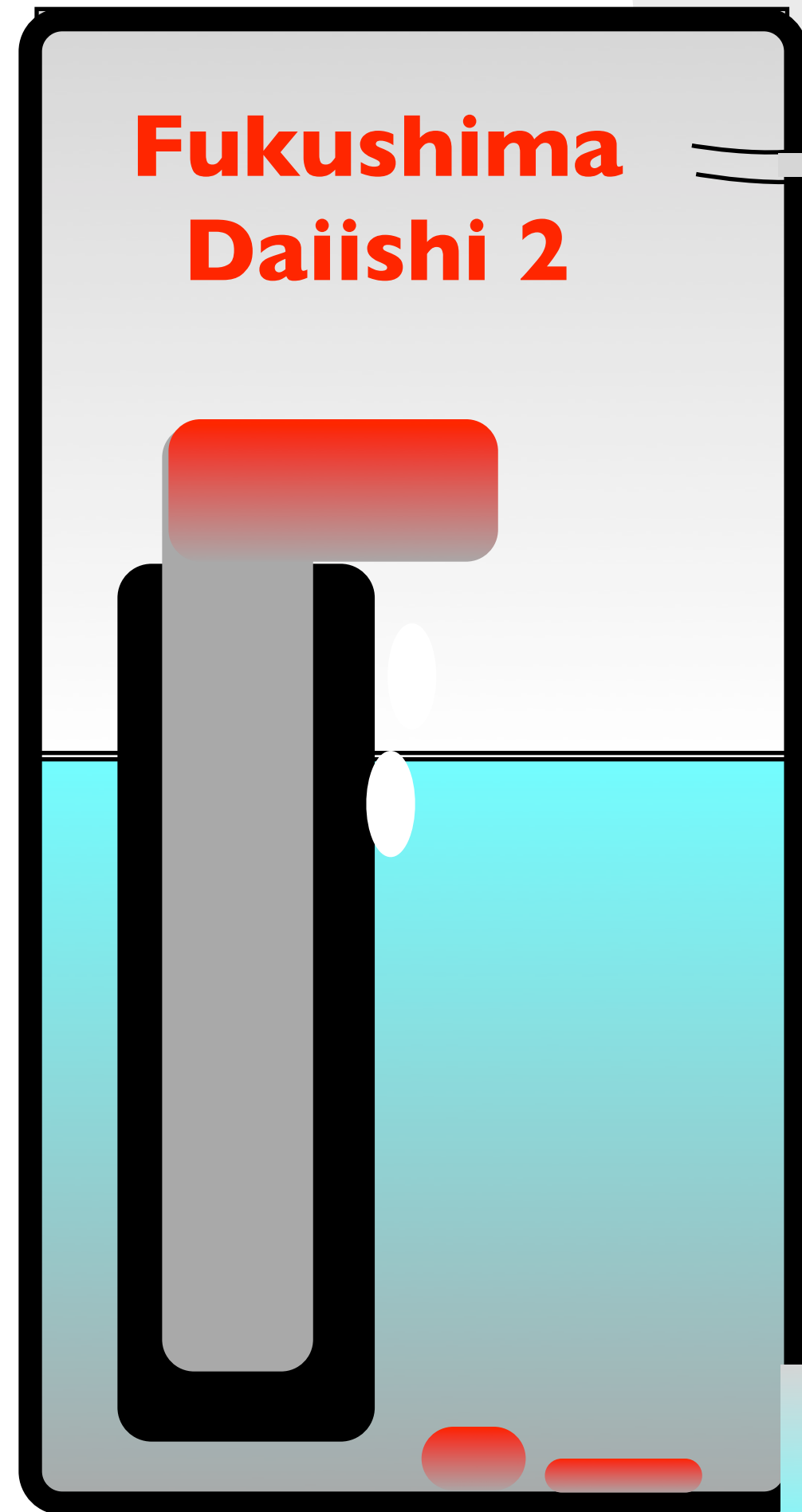
In environment:
fission products like Xe, Kr, Rn



Meltdown + emergency venting:

In Zircalloy casing:
fuel + fission products + actinides

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



Fukushima Daiichi 2

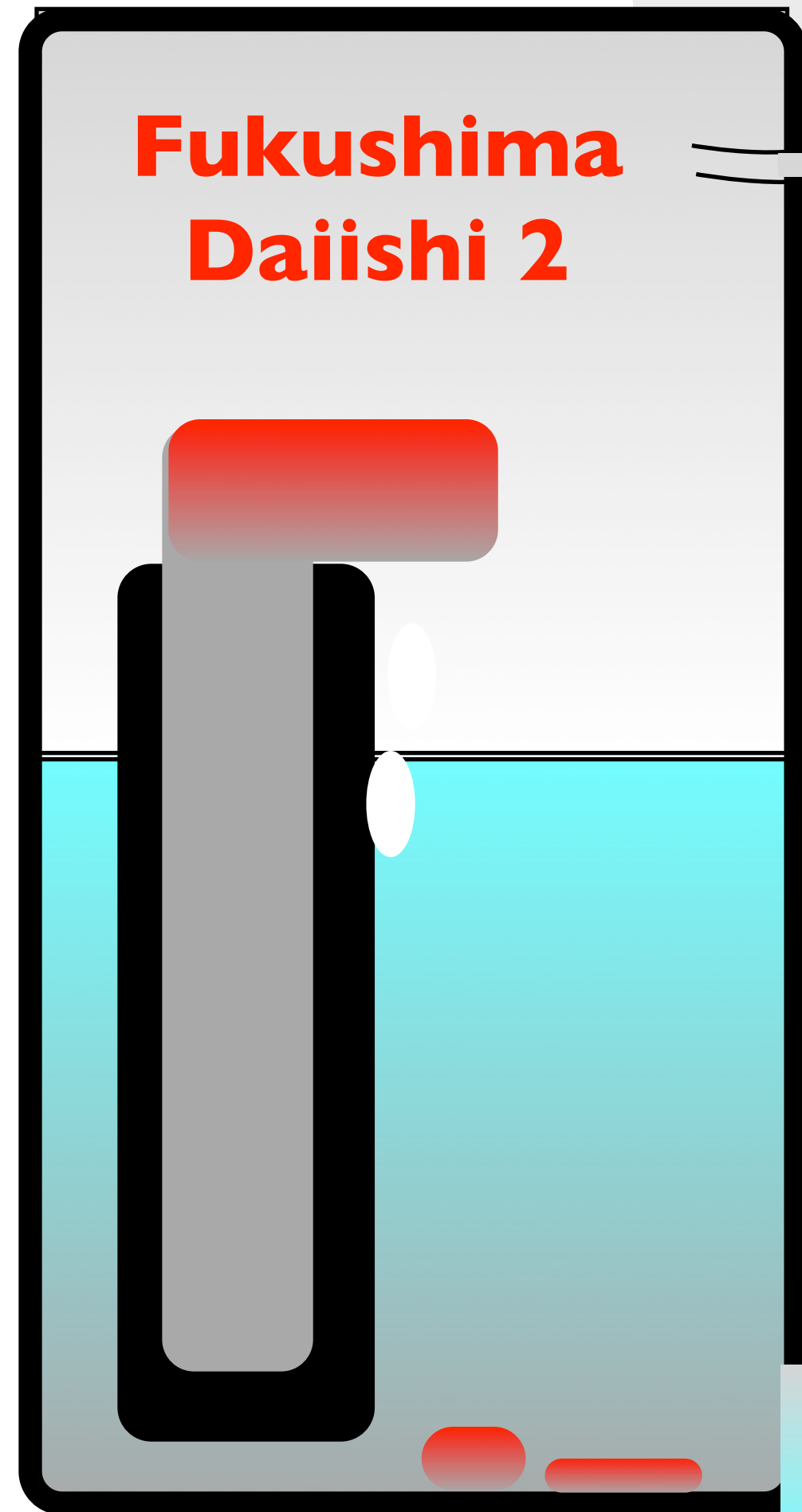
Meltdown + containment failure:

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



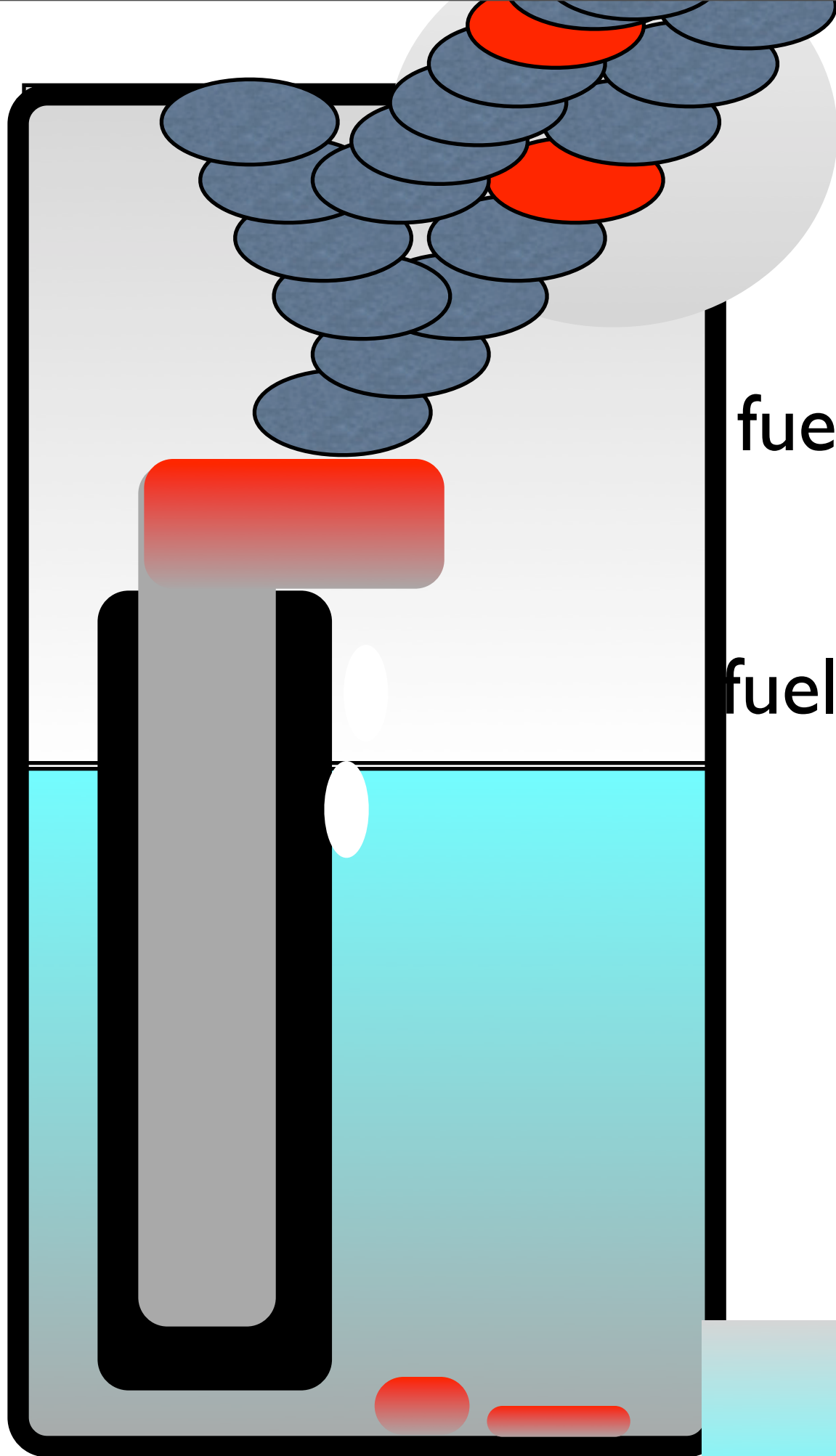
**Fukushima
Daiichi 2**

Meltdown + containment failure:

In Zircalloy casing:
fuel + fission products + actinides

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

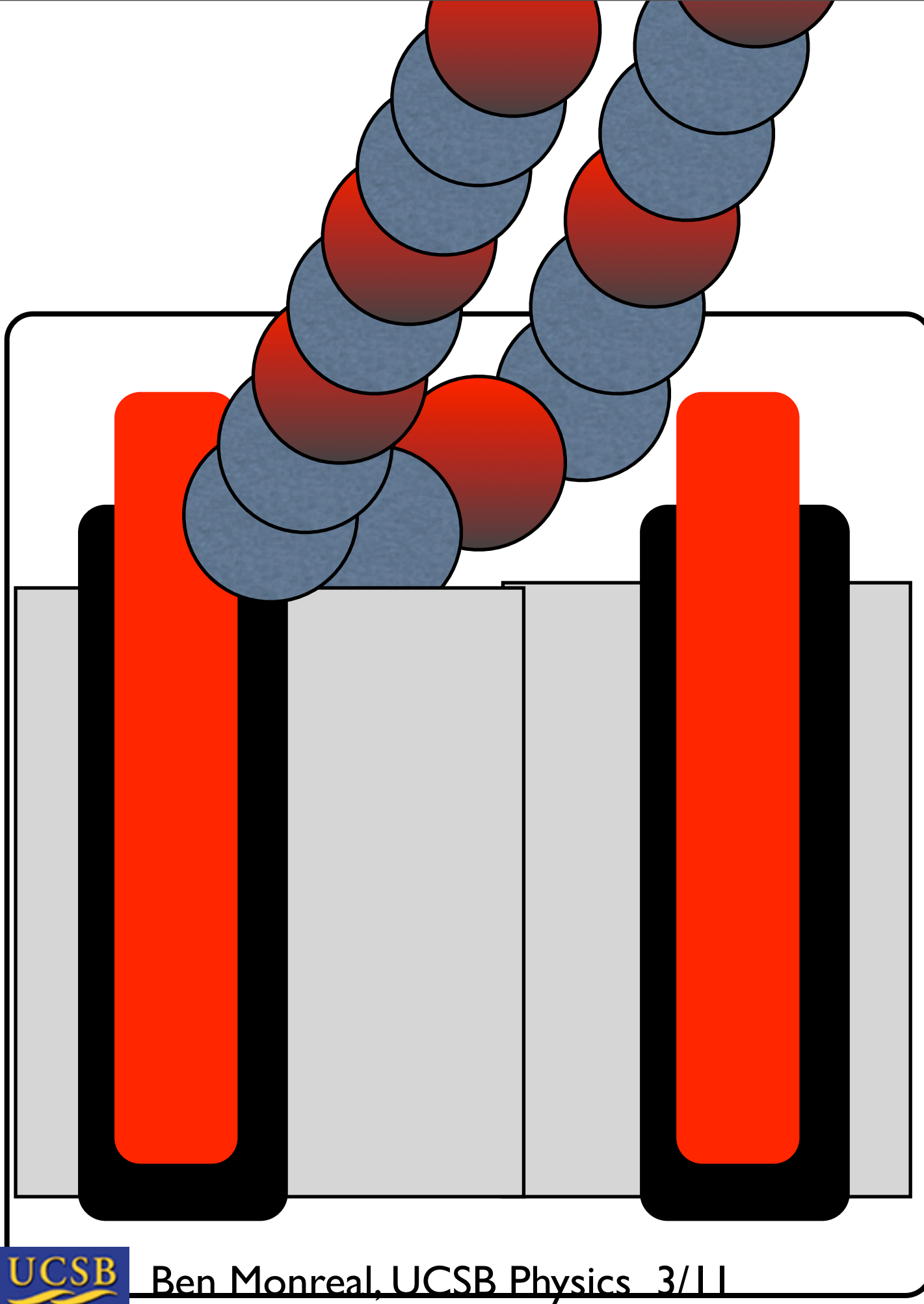
Chernobyl

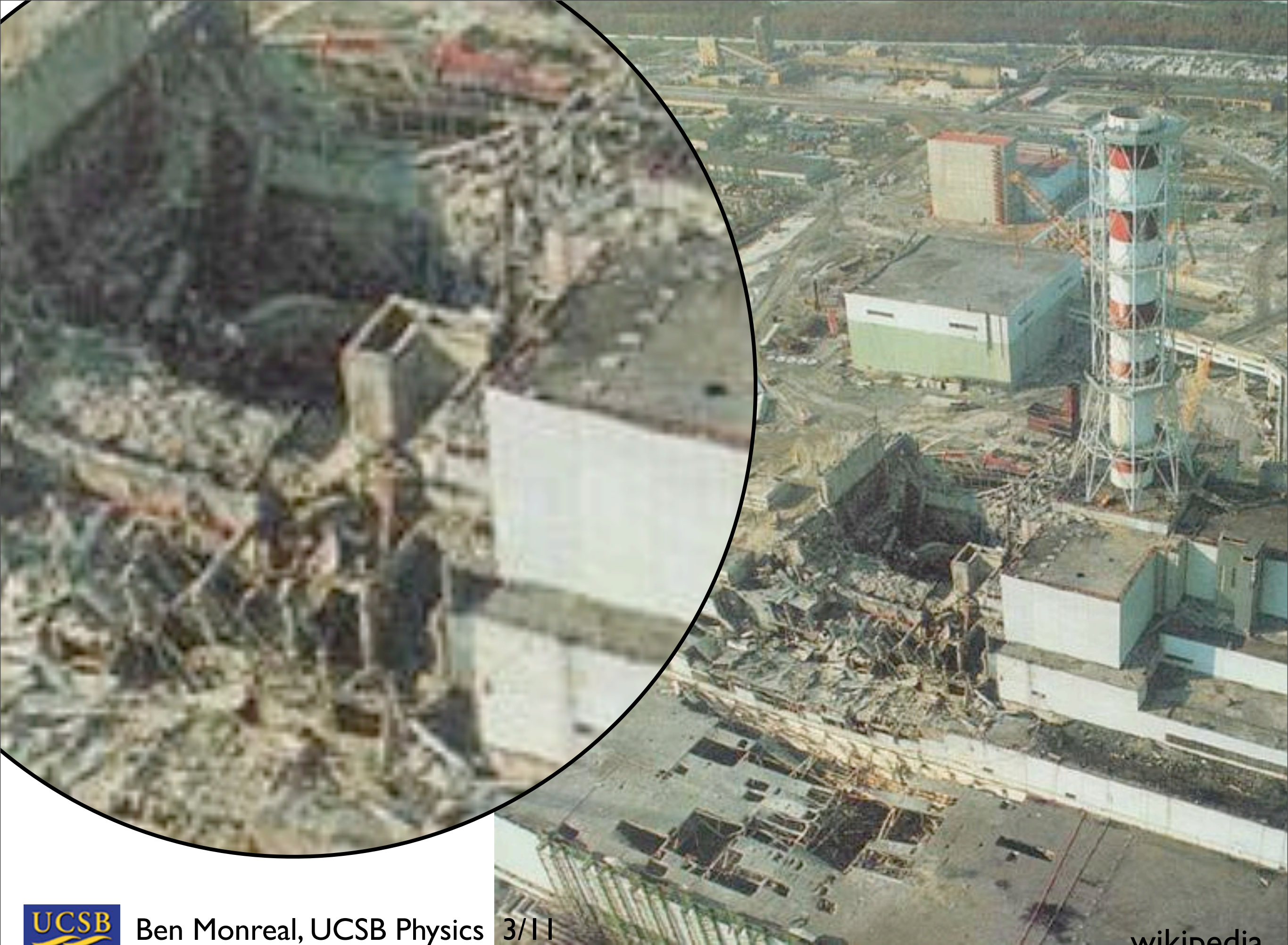
no real “containment vessel”

Core filled with graphite
(fuel for huge fire)

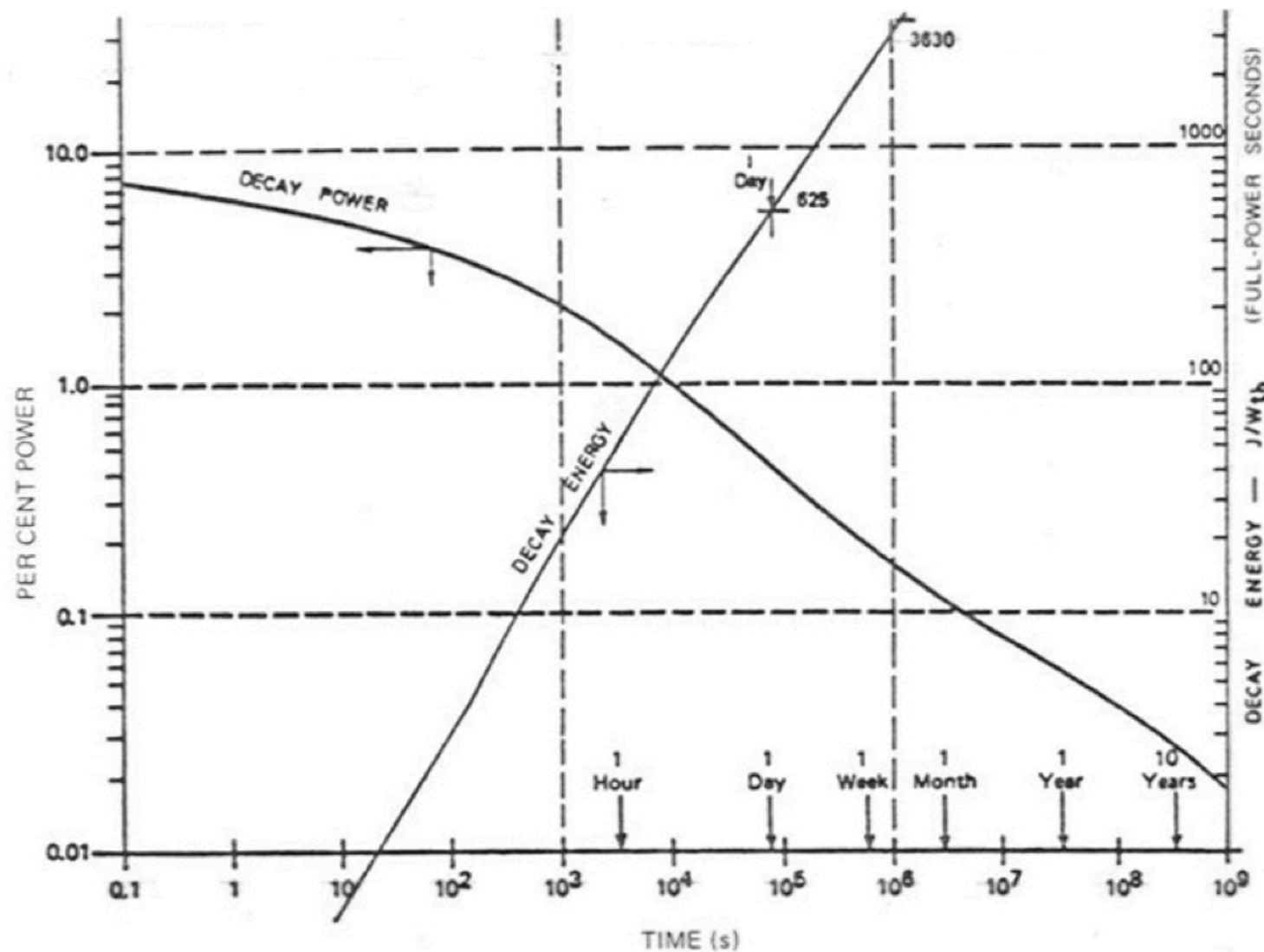
Reactor *fissioning during
explosions and fire*

(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