



Distinguished  
Lecturer  
Series

# FUTURE PROPULSION

NUCLEAR FISSION,  
FUSION, & BEYOND

WITH JIM CAVERA

Senior Engineer, Blue Origin



## Outline (subject to change without notice):

### Part one: What has come before...

- Nuclear physics in a nutshell
- RTG's (the non-reactor reactor)
- Terrestrial reactors
- NERVA, ROVER, and other small animals
- Bi- and Tri-modal systems
- The scary ideas: pulsed fission rockets



Outline (subject to change without notice):

Part two: Extending the past just a little

- The scarier ideas: liquid and gas core
- The nuclear light bulb
- TRIGA in spaaaaaace!
- Fission fragments
- The holy-crap-what-were-they-thinking, way-beyond-scary



I shouldn't have to say this but... Tsiolkovsky sucks.

Here's what we have today:

Engine	Specific Impulse	Thrust
Thiokol XLR99-RM2 (X-15)	279 sec.	310 kN
Aerojet Rocketdyne RS-25 (SSME, sea level)	366 sec.	1860 kN
Aerojet Rocketdyne RS-25 (SSME, vacuum)	452 sec.	2279 kN
Space Shuttle SRB (sea level)	242 sec.	12000 kN
SpaceX Raptor (sea level, approximate values)	330 sec.	2000 kN
NSTAR (Dawn-1 mission)	3100 sec.	90 mN



Here's what we have to deal with:

$$\Delta v = v_e \ln (m_0 / m_f) = (I_{sp} g_0) \ln (m_0 / m_f)$$

$$(m_0 / m_f) = \exp \{ \Delta v / (I_{sp} g_0) \}$$

So if we want to go to five percent of light speed with a chemical rocket...

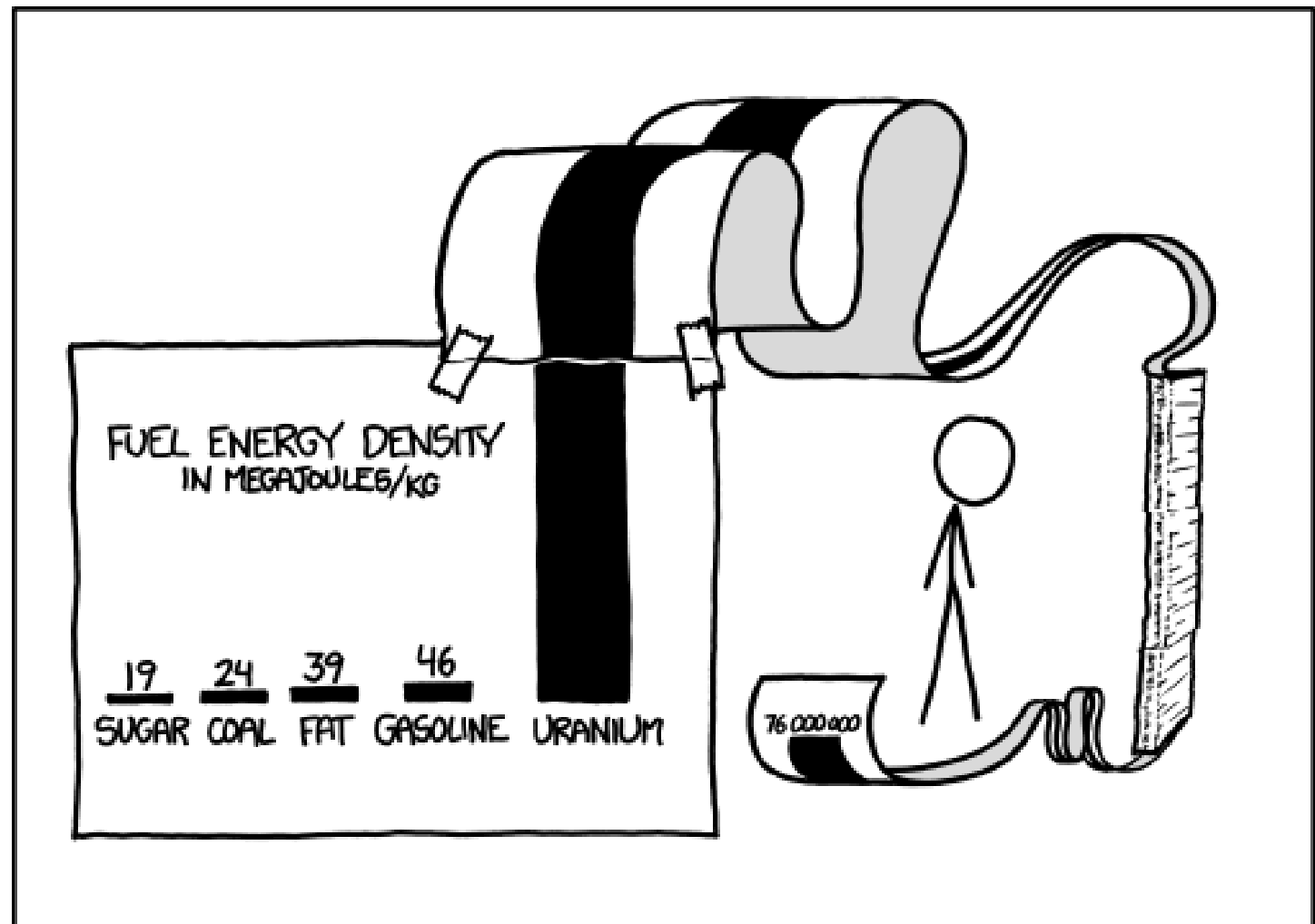
$$(m_0 / m_f) = 9.2 \times 10^{1500}$$

Spoiler: you need more stuff than exists in the known universe.

Clearly, we need to bump up the specific impulse. A lot.



Here's a hint...



SCIENCE TIP: LOG SCALES ARE FOR QUITTERS WHO CAN'T  
FIND ENOUGH PAPER TO MAKE THEIR POINT PROPERLY.



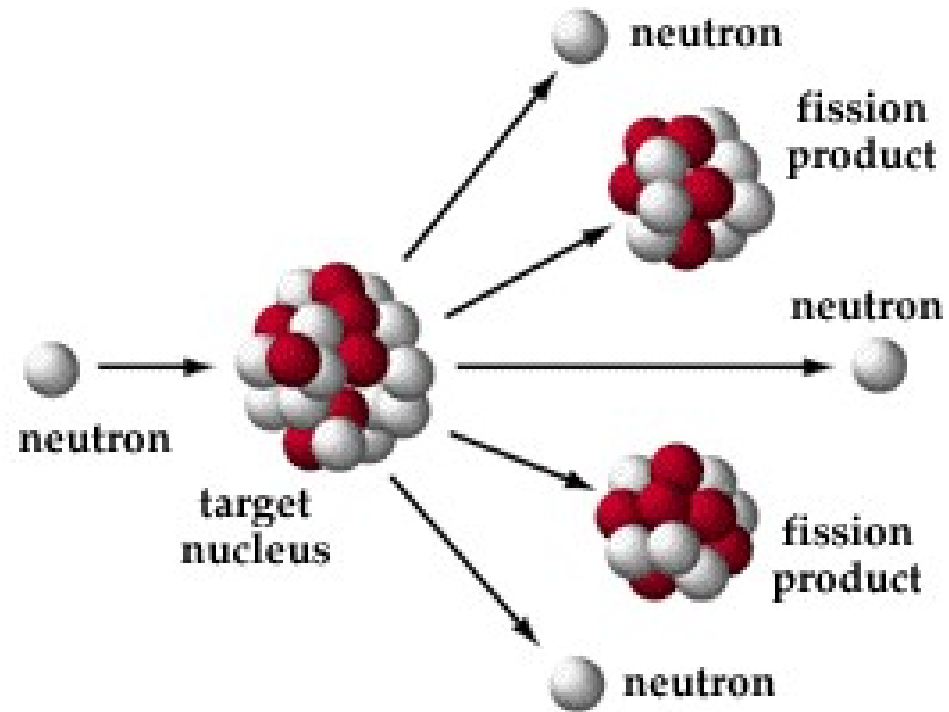
## Nuclear fission 101

Step 1: Get some neutrons

Step 2: Get some stuff  
that splits apart when a  
neutron hits it

Step 3: Make sure that  
there are enough extra  
neutrons to keep it going

Step 4: Stand far away (maybe  
that should have been step 1)



(Do not try this at home)



How many neutrons are needed?

$$n = \frac{\text{Number of neutrons produced by the reaction}}{\text{Number of neutrons needed to sustain it}}$$

The factor, “n” (aka, reactivity), depends on:

- The reactor fuel cycle
- Materials used in the reactor (all of them, not just the fuel)
- The reactor temperature
- The reactor geometry (core and surrounding)
- The phase of the moon (*i.e.*: quantum mechanical randomness)



Some typical values:

$n < 1$	reactor is “sub-critical”
$n = 1.000\dots$	reactor is “critical”
$1 < n < 1.1$ (-ish)	happily generating power
$n > 1.1$	worry
$n > 2$	run
$n > 50$	basically, you just detonated a bomb

Reactivity is also sometimes listed in “dollars and cents”

Less than \$1	reactor is sub-critical
Around \$1	reactor is delayed-critical*
Around \$2	reactor is prompt-critical*
Around a grand	bomb territory

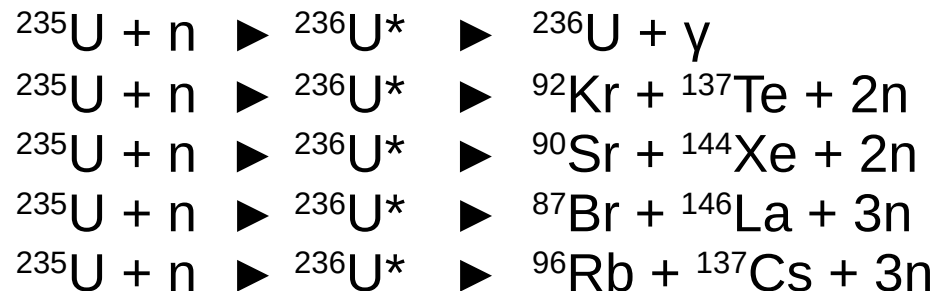
\* these will be explained shortly



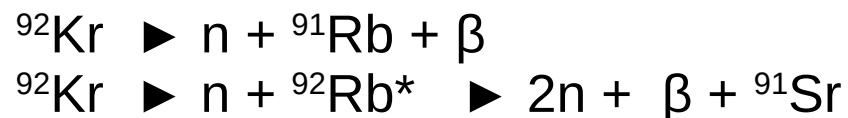
Standard reaction cycle:



But a *lot* happens at the same time:



...and then *those* decay...



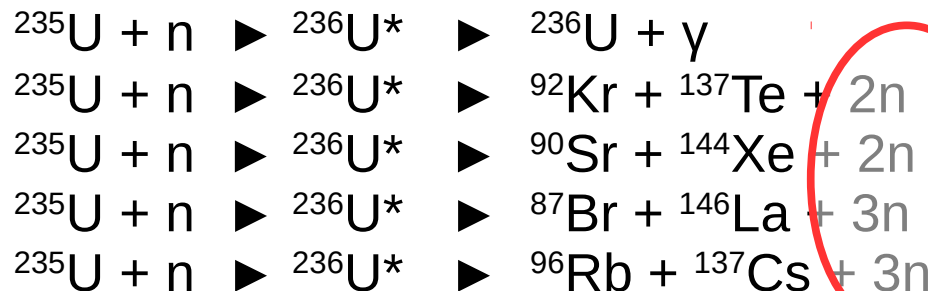
... and so on.



Standard reaction cycle:



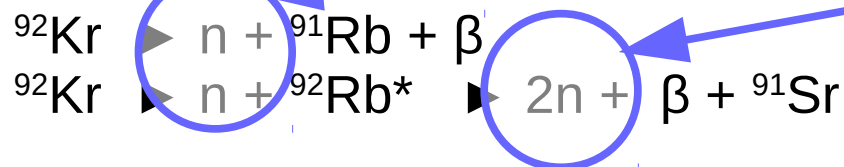
But a *lot* happens at the same time:



Prompt  
Neutrons

...and then *those* decay...

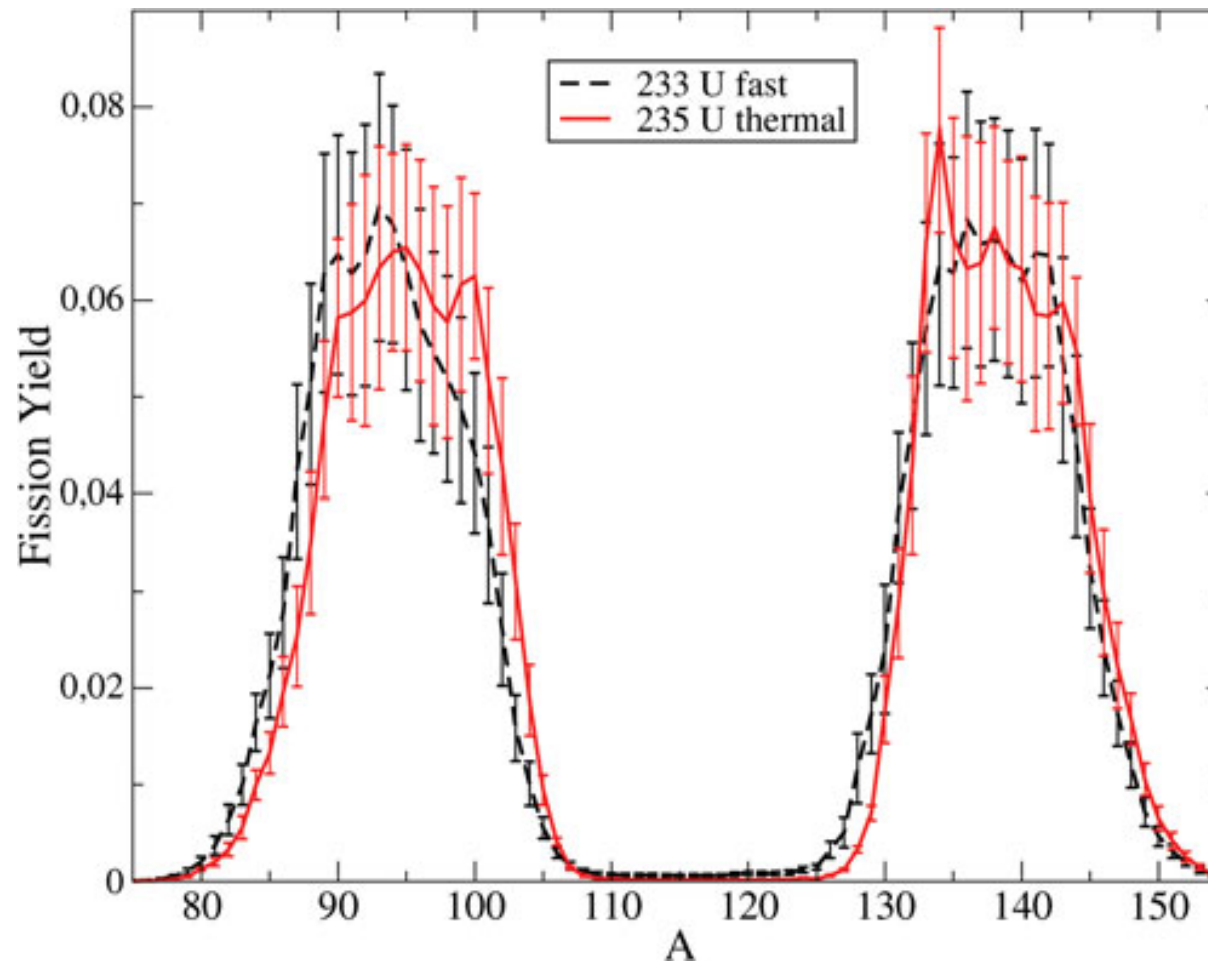
Delayed Neutrons



... and so on.



Reactions are a mess...



... but quantum mechanics runs on statistics



Chemistry is easy...

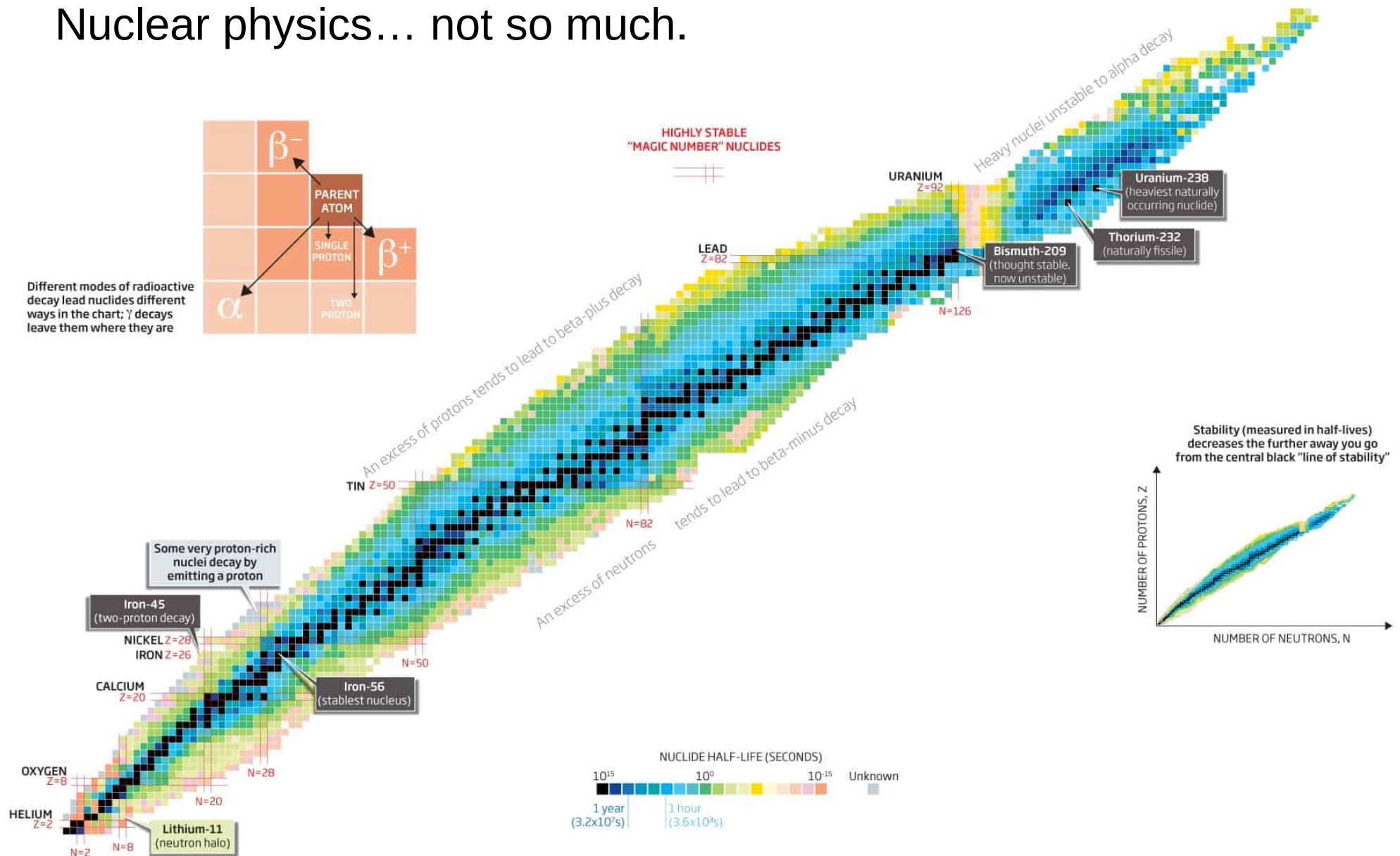
Periodic Table of the Elements

1 H Hydrogen 1.01																	18 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 19.00	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 32.06	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 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	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 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.63	33 As Arsenic 74.92	34 Se Selenium 78.97	35 Br Bromine 79.90	36 Kr Krypton 84.80	
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 95.95	43 Tc Technetium 98.91	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 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29	
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	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 207.20	83 Bi Bismuth 208.98	84 Po Polonium [208.98]	85 At Astatine 209.98	86 Rn Radon 222.02	
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]	
57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	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 173.06	71 Lu Lutetium 174.97				
89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium [262]				
Alkali Metal		Alkaline Earth		Transition Metal			Basic Metal		Metalloid		Nonmetal		Halogen		Noble Gas		Lanthanide	Actinide

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# Nuclear physics... not so much.





## Radioactive decay

Decay Mode	Description	Atomic Mass	Atomic Number
Alpha	Eject an alpha particle (helium nucleus)	-4	-2
Beta	Eject an electron and an antineutrino	0	+1
Inverse beta	Eject a positron and a neutrino	0	-1
Isomeric	Eject a gamma ray	0	0
Fission	Spontaneous fission reaction	special	special
Electron capture	Nucleus absorbs an electron, emits neutrino	0	-1*
Neutron emission	Nucleus ejects a neutron	-1	0
Proton emission	Nucleus ejects a proton	-1	-1
Cluster decay	Nucleus spits in to two specific components	special	special



## A little bit about radiation shielding...

Alpha particles	stopped by skin or paper
Beta particles	thin metal works adequately
X-rays	lead (or other dense substance)
Gamma rays	a <i>lot</i> of lead
Neutrons	... this is the weird one
Thermal neutrons	lowest energy, about 1/40th of an eV
Low-energy (slow)	up to about 10 eV
Medium-energy	up to about 100 eV
High-energy (fast)	above about 100 eV

Different materials have different capture “cross-sections” to different energies of particles. Effective shielding comes from choosing materials that really like to capture those particles.



## Random Fact! Physicists like to have fun with units!

1 barn =  $10^{-28}$  square meters (used for cross-sectional area of particles)

1 outhouse =  $10^{-34}$  square meters (or a “microbarn”)

1 shake =  $10^{-8}$  seconds

1 jerk =  $10^9$  joules (not to be confused with  $d^3x/dt^3$ )

1 FOE =  $10^{51}$  ergs ( $10^{44}$  joules, or about one supernova)

1 BED =  $10^{-7}$  Seiverts (the radiation dose from eating one banana)

1 Crab =  $2.4 \times 10^{-11}$  watts per square meter

And of course...

1 pirate-ninja = 1 kilowatt-hour of energy over the course of 1 martian day



The generation, control (through scattering), and  
absorption of neutrons is called

# NEUTRONICS

... which is kind of like electronics, but dumber.



The chemical properties of nuclear isotopes are absolutely irrelevant. It's only the nucleus that matters.

Neutron absorbers:

Hydrogen ( $^1\text{H}$ )  
Boron ( $^{10}\text{B}$ )  
Xenon ( $^{135}\text{Xe}$ )  
Samarium ( $^{149}\text{Sm}$ )  
Hafnium ( $^{176}\text{Hf}$  -  $^{180}\text{Hf}$ )

Neutron “reflectors”:

Carbon ( $^{12}\text{C}$ )  
Beryllium ( $^9\text{Be}$ )  
Lead ( $^{204}\text{Pb}$  -  $^{208}\text{Pb}$ )  
Tungsten ( $^{182}\text{W}$  -  $^{184}\text{W}$ )

Note: Neutron “reflection” is controlled scattering, and not specular reflection.



“Fissile” materials (sometimes called “fissionable”) can undergo fission when hit with a neutron. Some examples:

Uranium ( $^{233}\text{U}$ ,  $^{235}\text{U}$ ) [cross section of  $^{235}\text{U}$  is around 600 barns]  
Plutonium ( $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ )

“Fertile” materials can be converted to something that is fissile:

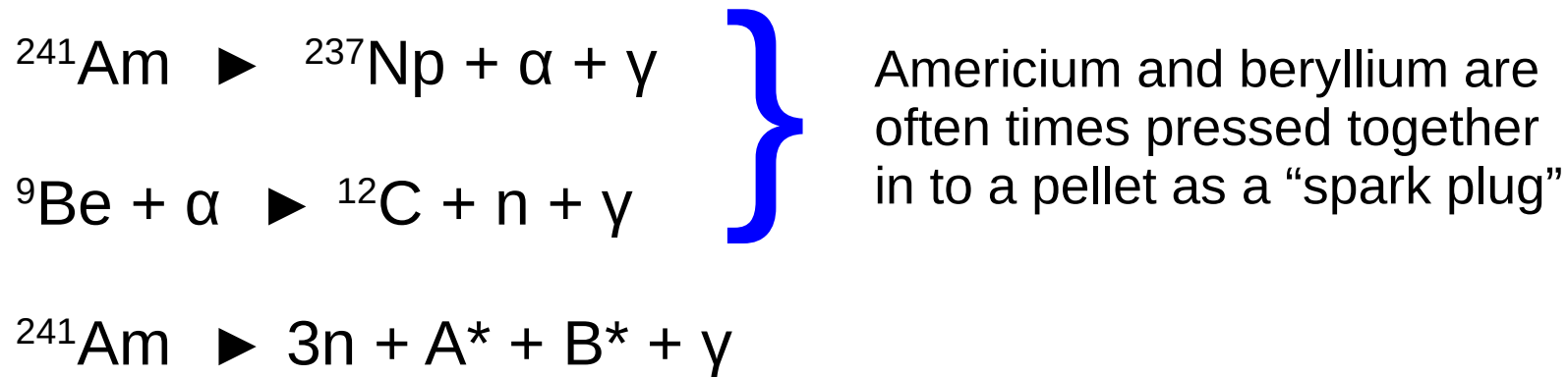
Thorium ( $^{232}\text{Th}$ ) [ $^{232}\text{Th} + n \rightarrow ^{233}\text{U}$ , cross section  $\approx 10$  barns]  
Uranium ( $^{234}\text{U}$ ,  $^{238}\text{U}$ )  
Plutonium ( $^{236}\text{Pu}$ ,  $^{240}\text{Pu}$ )

Desirable materials have:

- A long half-life when it comes to natural decay modes (relatively stable)
- A high neutron-capture cross section
- A tendency to release two or more neutrons per fission event
- Are relatively abundant in nature



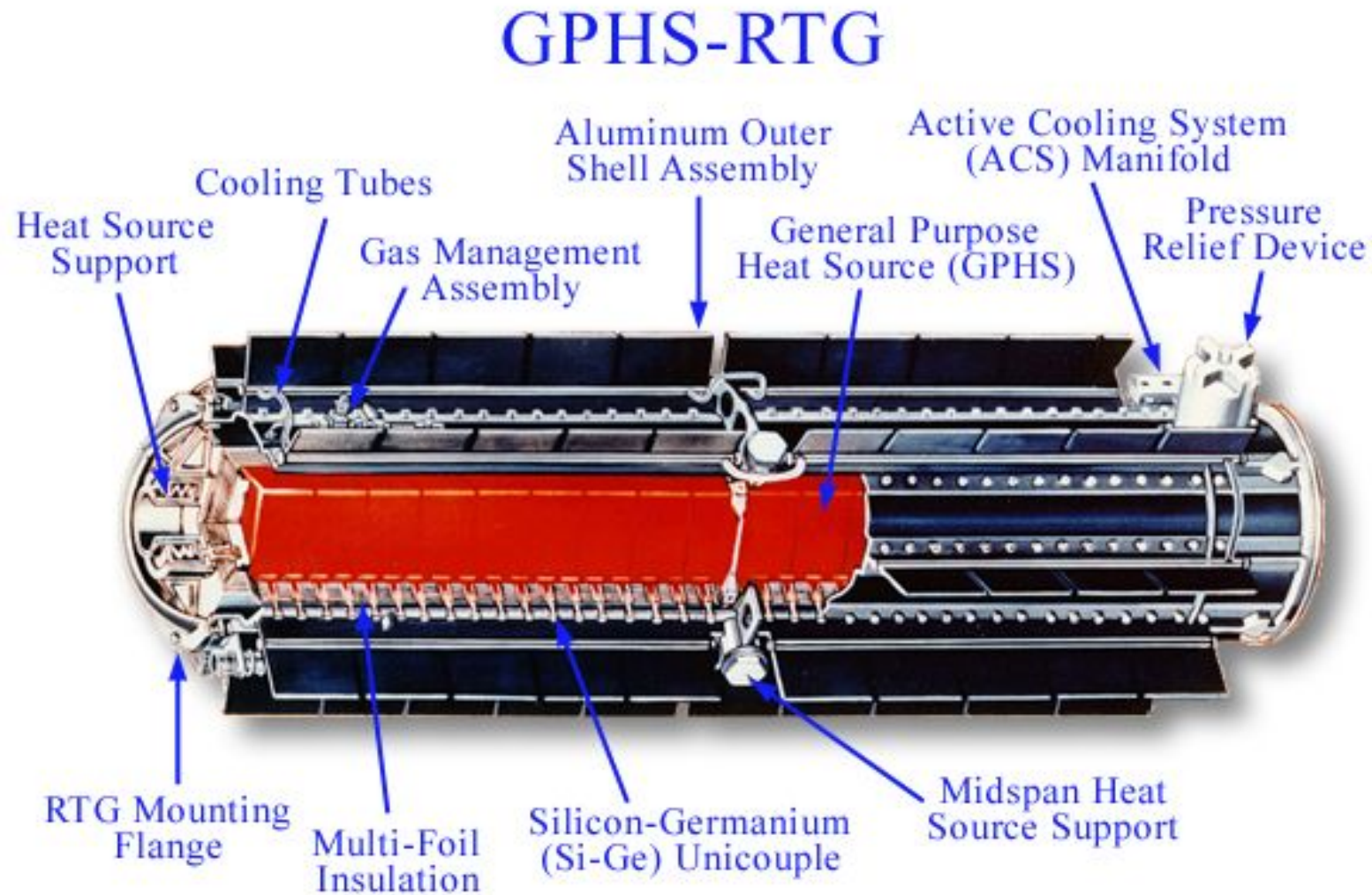
Some isotopes decay by spontaneous neutron emission or by spontaneous fission. These can be useful in kick-starting a reactor.



Moderators are materials that don't completely absorb neutrons but serve to slow them down. Many fissile materials have a higher cross section to slow or thermal neutrons. The materials that work as absorbers will also serve as moderators.



Putting it all together... the non-reactor reactor





## Some real-world examples

Model	Fuel	Half-life (yrs)	Mass (kg)	Power (W)	
				Thermal	Electrical
<u>MMRTG</u> (Curiosity rover)	Pu-238	87.7	45	2000	110
<u>GPHS-RTG</u> (New Horizons mission)	Pu-238	87.7	58	4400	300
<u>BES-5 Buk</u> (Russian research reactor)	U-235	703,800,000	1000	100000	3000

### Advantages:

- Dead simple to build
- Nothing to control
- Can use any unstable isotope
- Predictable operation

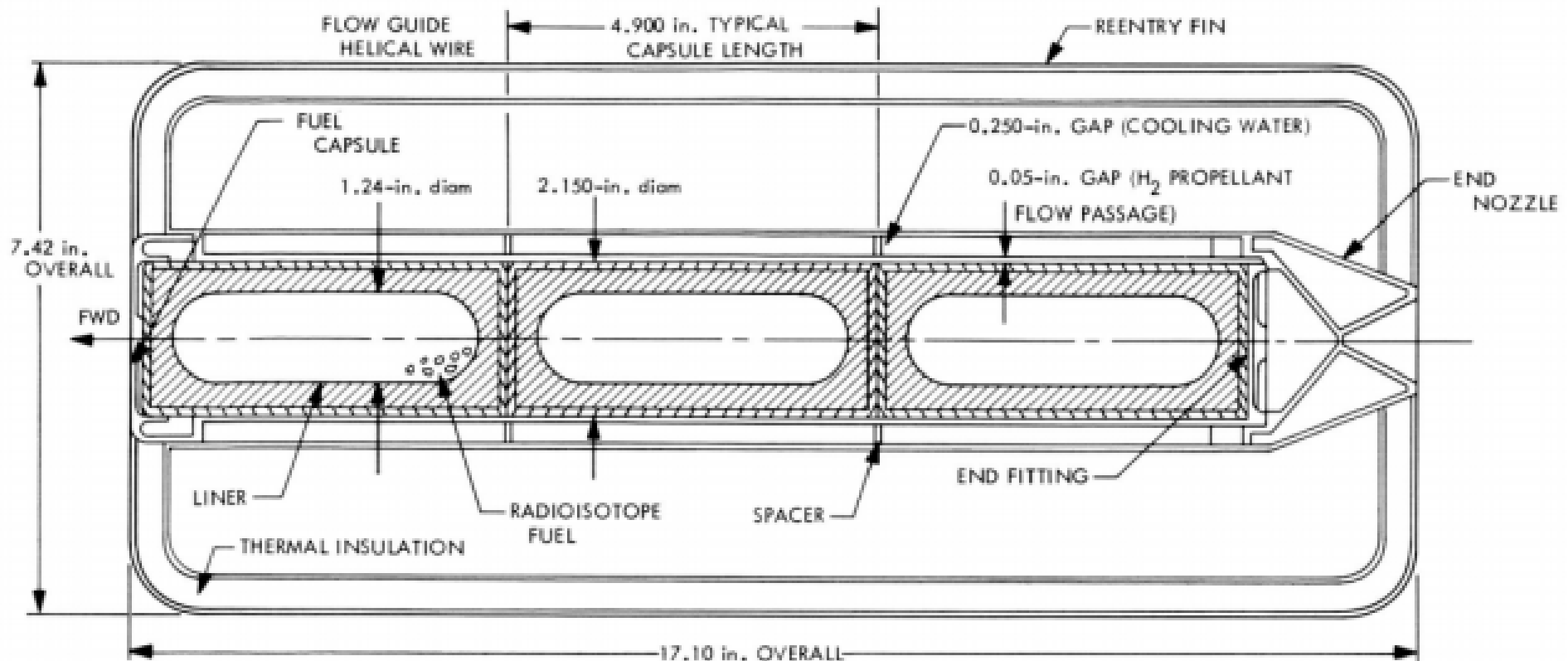
### Disadvantages:

- Always on
- Low energy density
- Potential waste-heat issues
- Not so useful for propulsion

(but not for lack of trying)



The “poodle thruster”: Essentially a resistojet that doesn't require electricity (good); but that you can't turn off (not so good).



$I_{sp}$  = 600-ish sec., Duration = 700 sec., Thrust = almost none



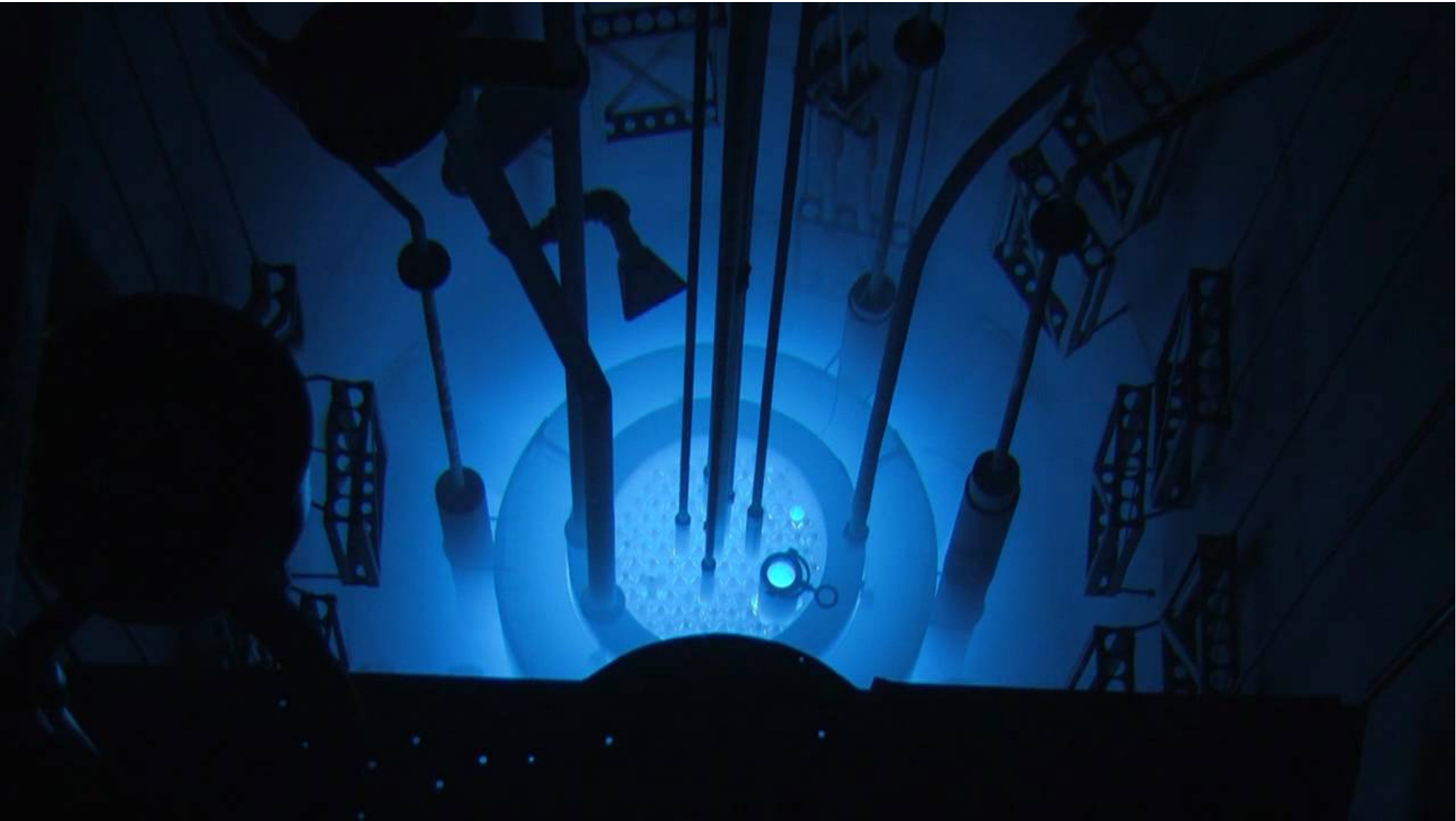
## Terrestrial reactor construction:

- 1) Start with a bundle of soda straws (made of zirconium alloy)
- 2) Fill up some of them with fissile material
- 3) Add some control rods to other straws
- 4) Leave a few empty
- 5) Put the works in to a really big coffee percolator
- 6) Fill it up with water
- 7) And add tons of shielding



Terrestrial reactors are categorized by:

- The fuel used (enriched or depleted uranium, plutonium,...)
  - Natural uranium  $\approx 0.5\%$   $^{235}\text{U}$  (the rest is  $^{238}\text{U}$ )
  - Low-enriched  $< 10\%$  or so
  - High-enriched:  $10\%$  to  $80\%$  or so
  - Weapons-grade  $> 80\%$
- The moderator (water, heavy water, salt,...)
- The coolant (often the same as the moderator, but not always)
- The core configuration (fuel rods, pebble bed,...)



Research reactor at UT Austin. They all look kind of like this.

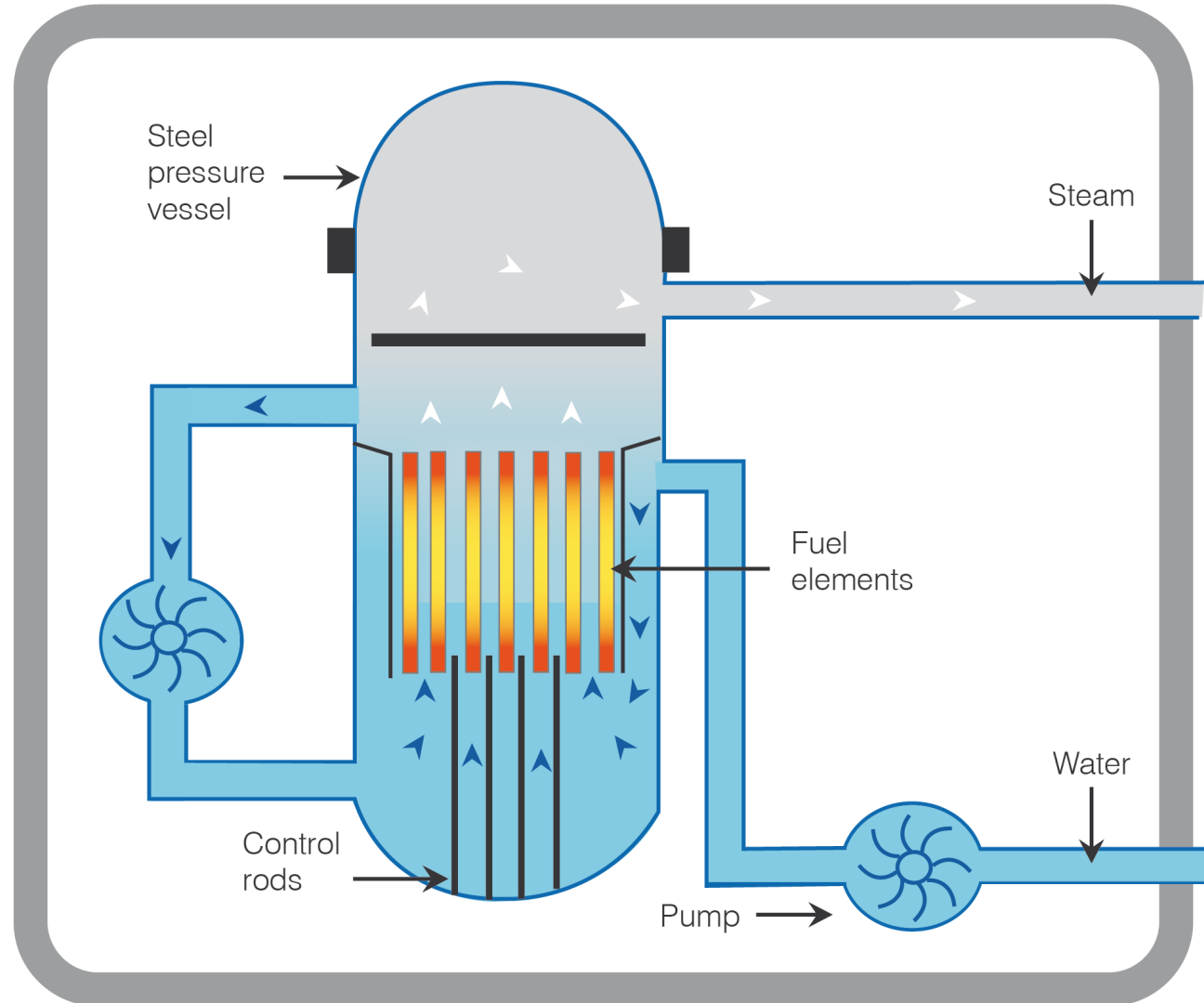


## A Boiling Water Reactor (BWR)

Simple in design

Steam directly  
drives a turbine

Most like a coffee  
percolator

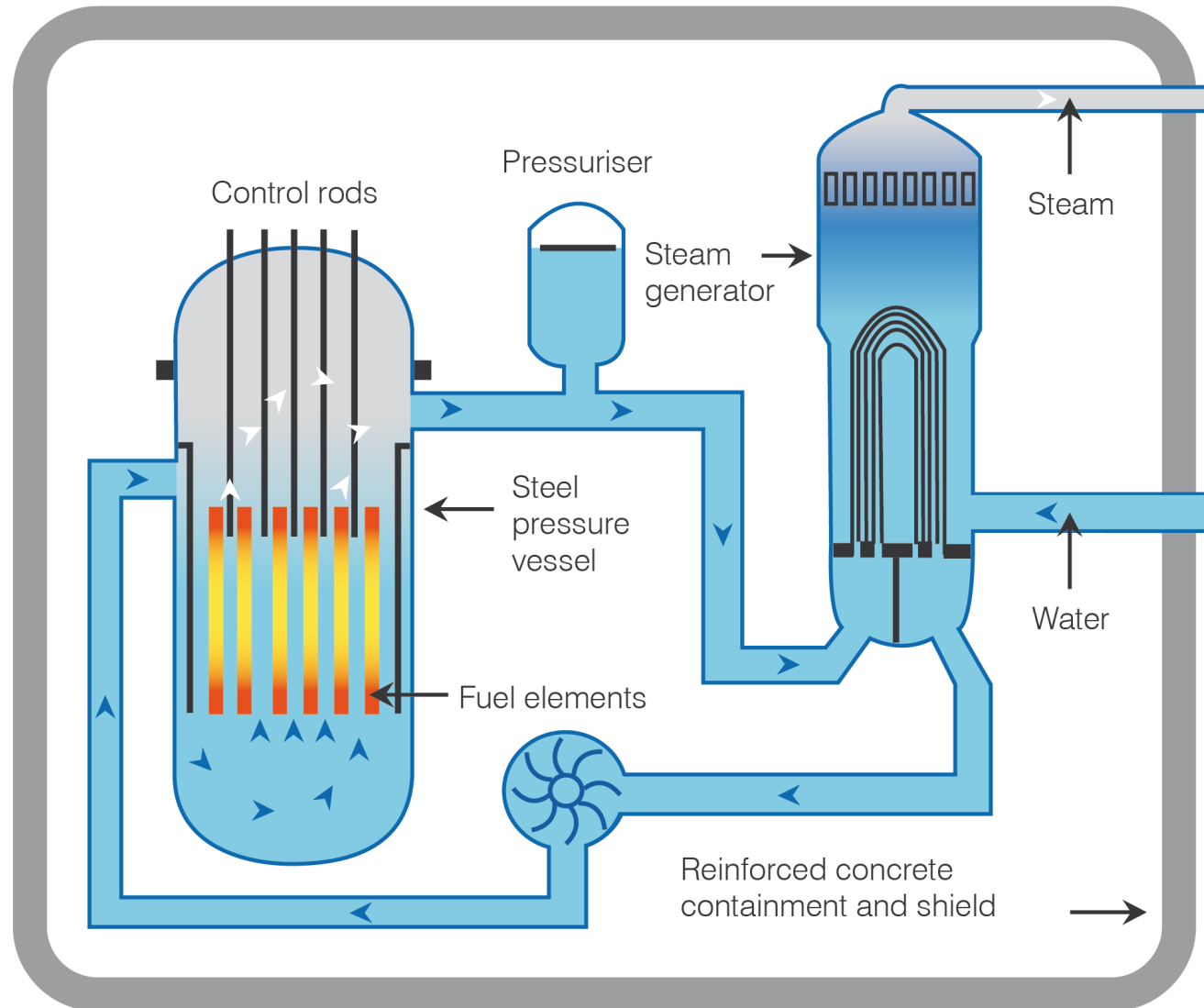




Steam generator  
between the  
reactor and the  
turbine – less  
chance of leakage

A “PHWR” uses  
heavy water ( $D_2O$ )  
to make use of the  
higher cross  
section to fast  
neutrons

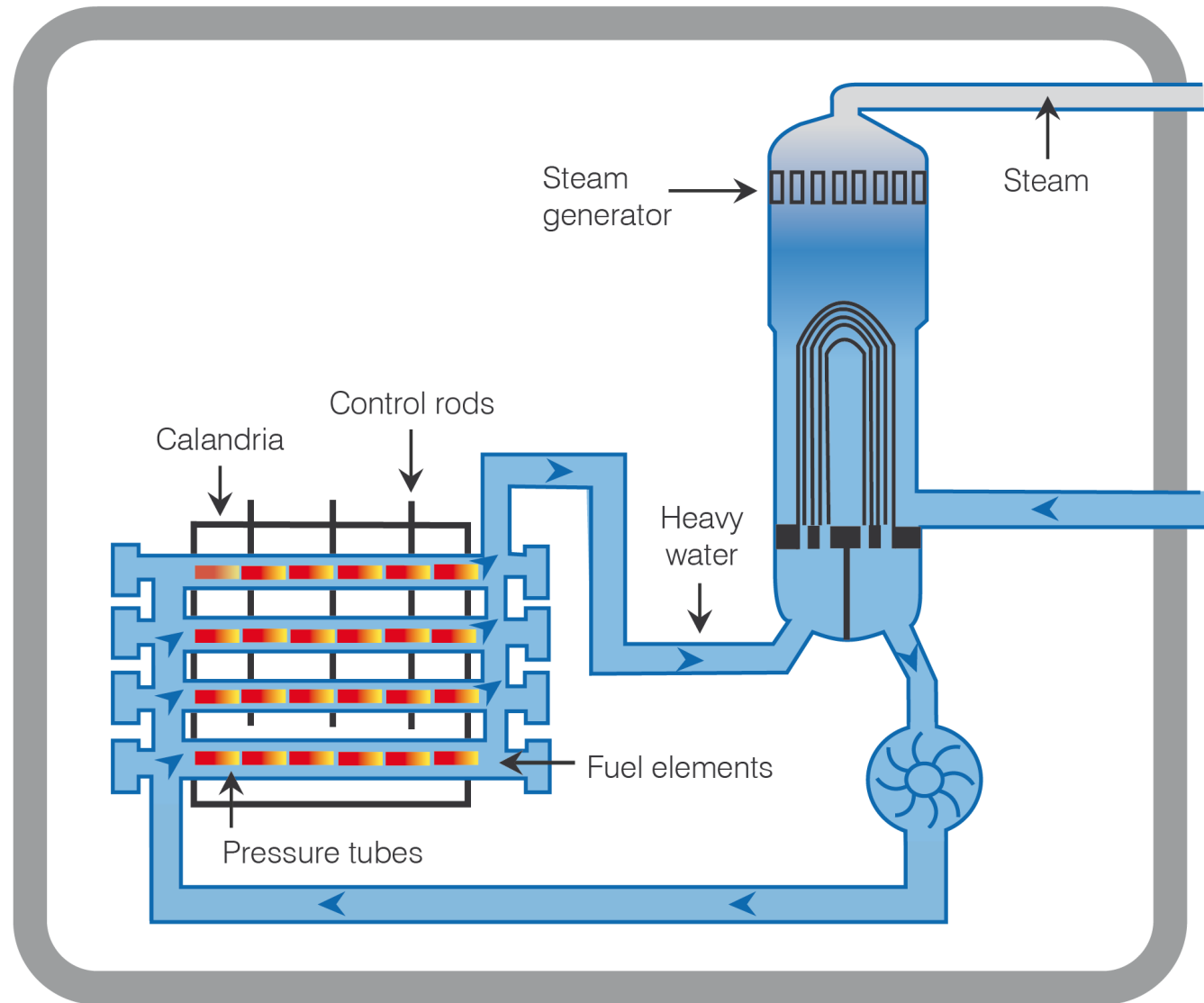
## A Pressurized Water Reactor (PWR)





## A Pressurized Heavy Water Reactor (PHWR/Candu)

The CANDU design changes the PHWR geometry such that natural uranium can be used with no enrichment



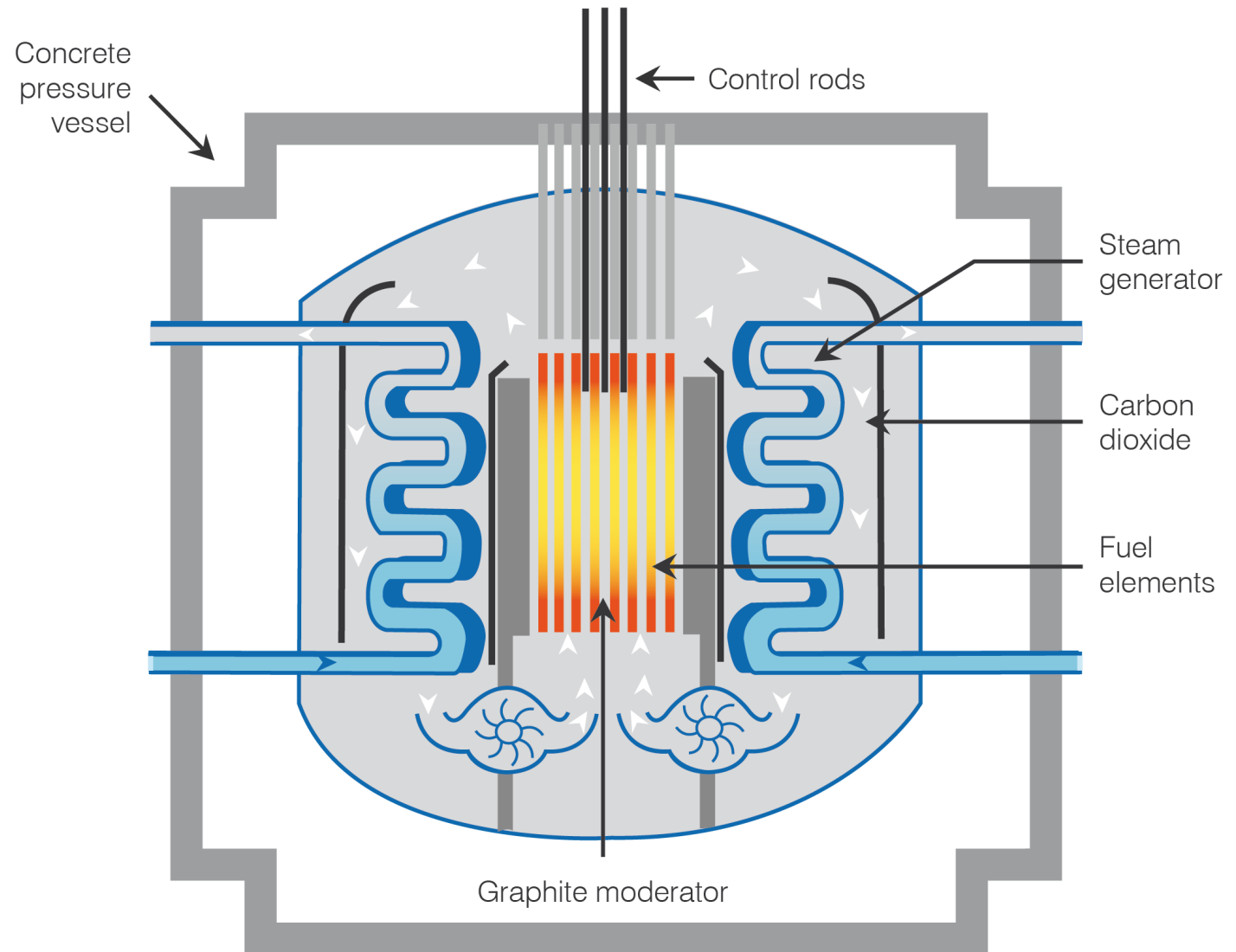


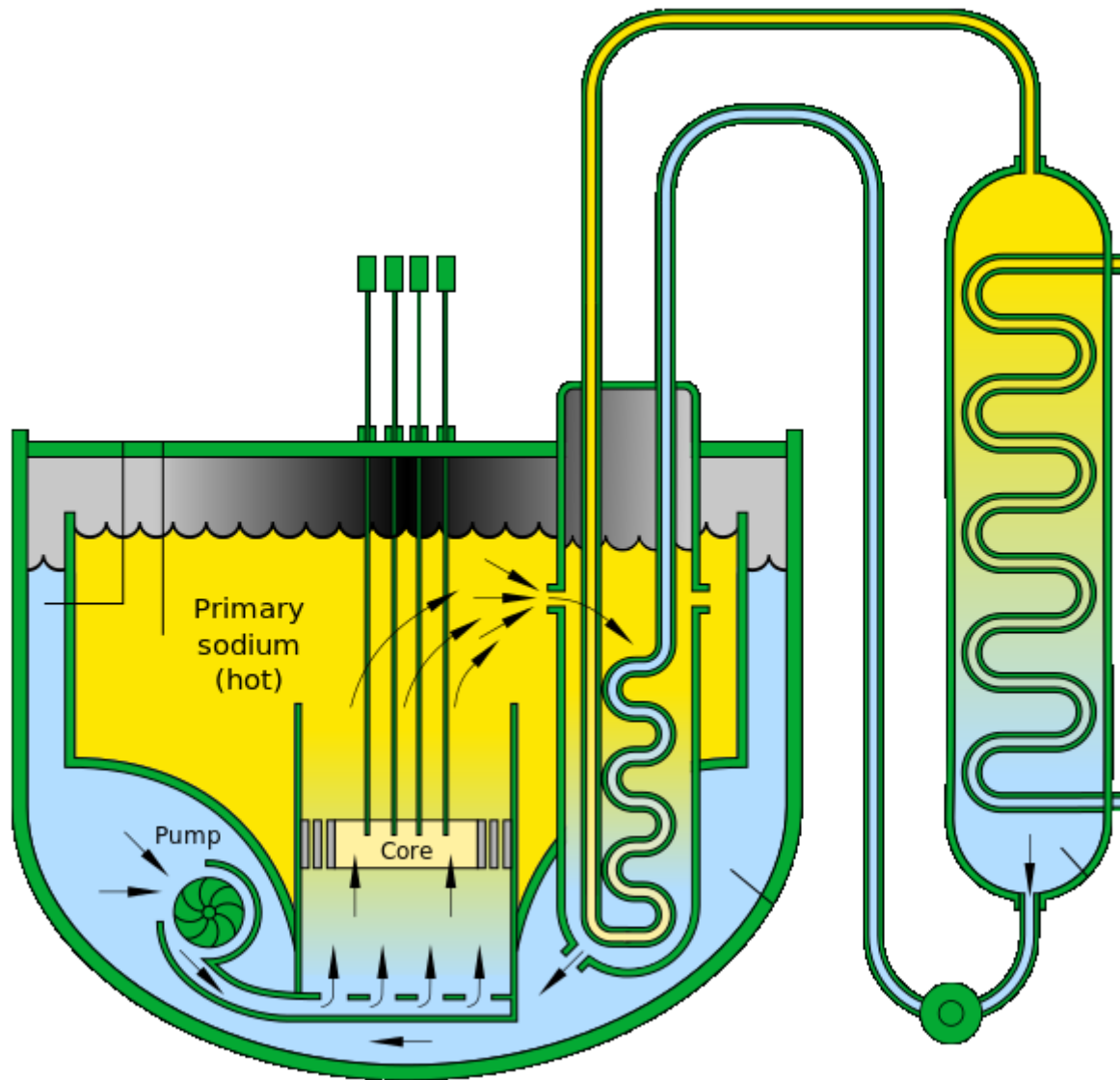
Gas cooled uses  
an inert gas (He,  
Ar, CO<sub>2</sub>, etc.)

For a power  
generator, it needs  
a steam generator

For a rocket... jet  
the gas

An Advanced Gas-cooled Reactor (AGR)





## Liquid metal reactors

Use a metal as a first-stage coolant and moderator

Sodium, lead, salt, and mercury have been tried

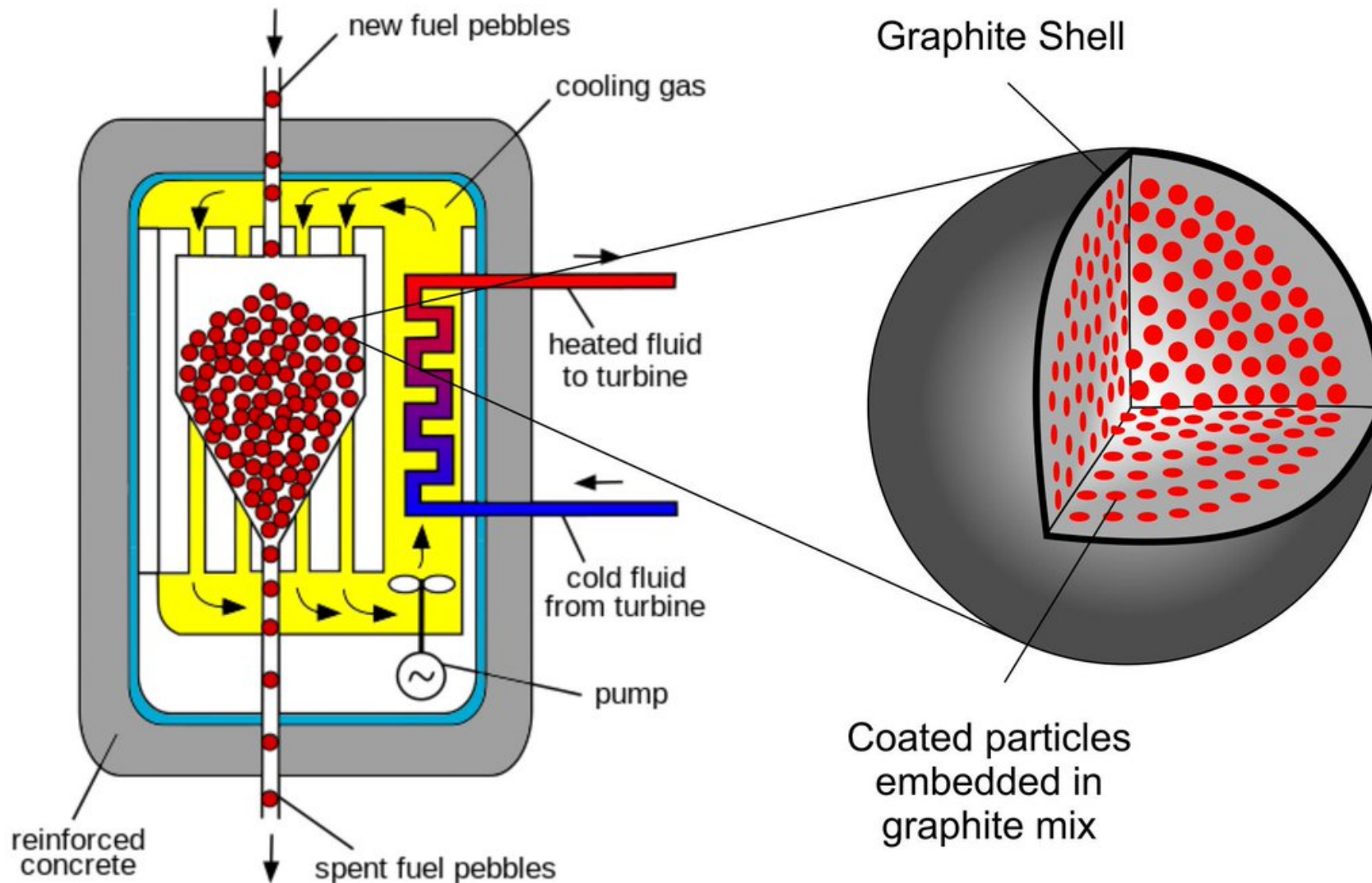
Can “breed” their own fuel from otherwise unusable isotopes

Are fast reactors, without the need for a moderator



## Pebble Bed Reactor scheme

(AKA: gas-cooled nuclear gumball machine)



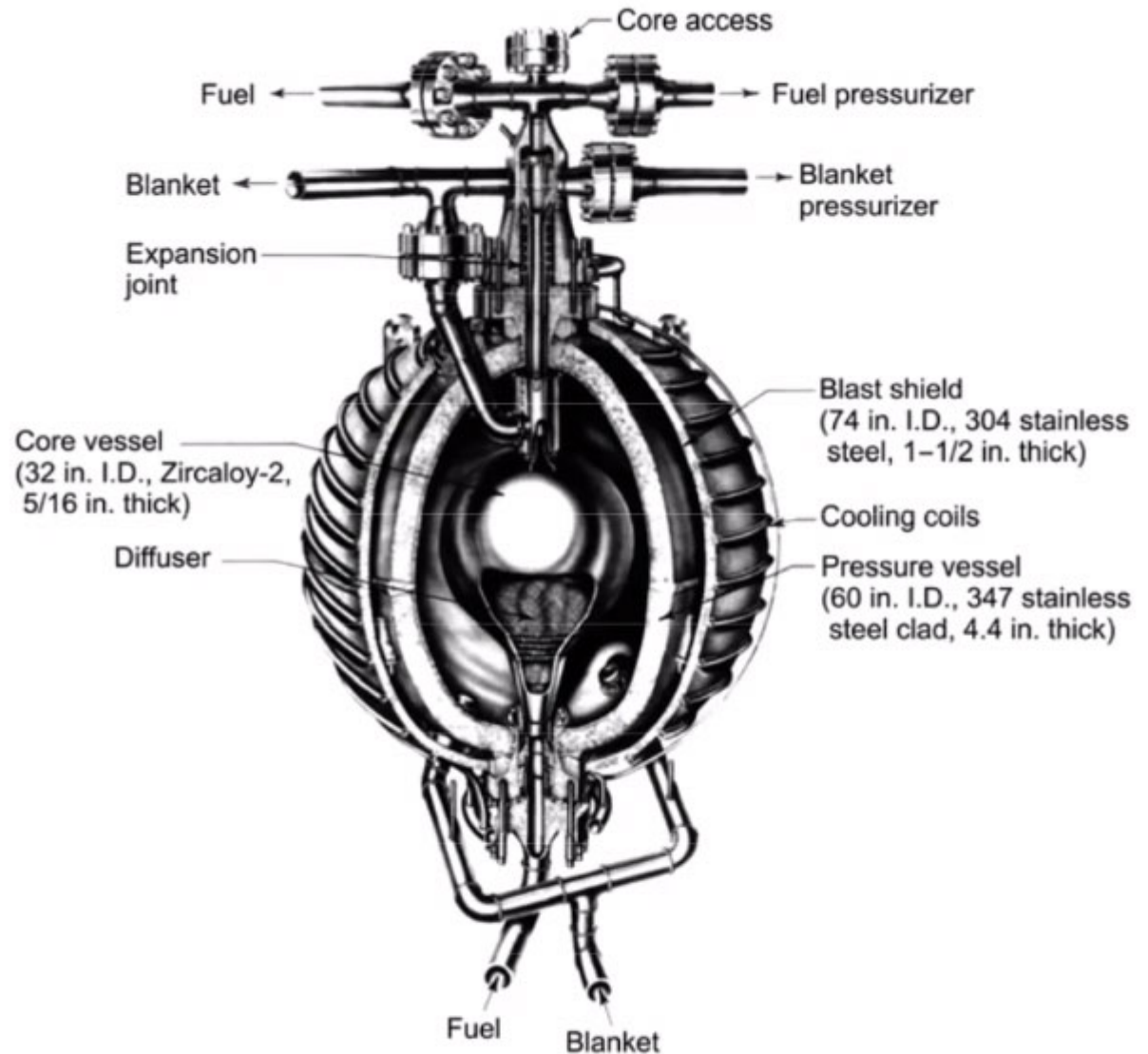


## Aqueous core reactor

The core is a liquid mixture of uranium salt and water

Control is accomplished by adding other salts to the solution or by submerging control rods

Some experiments at ORNL and as low-power research reactors, but no widespread use



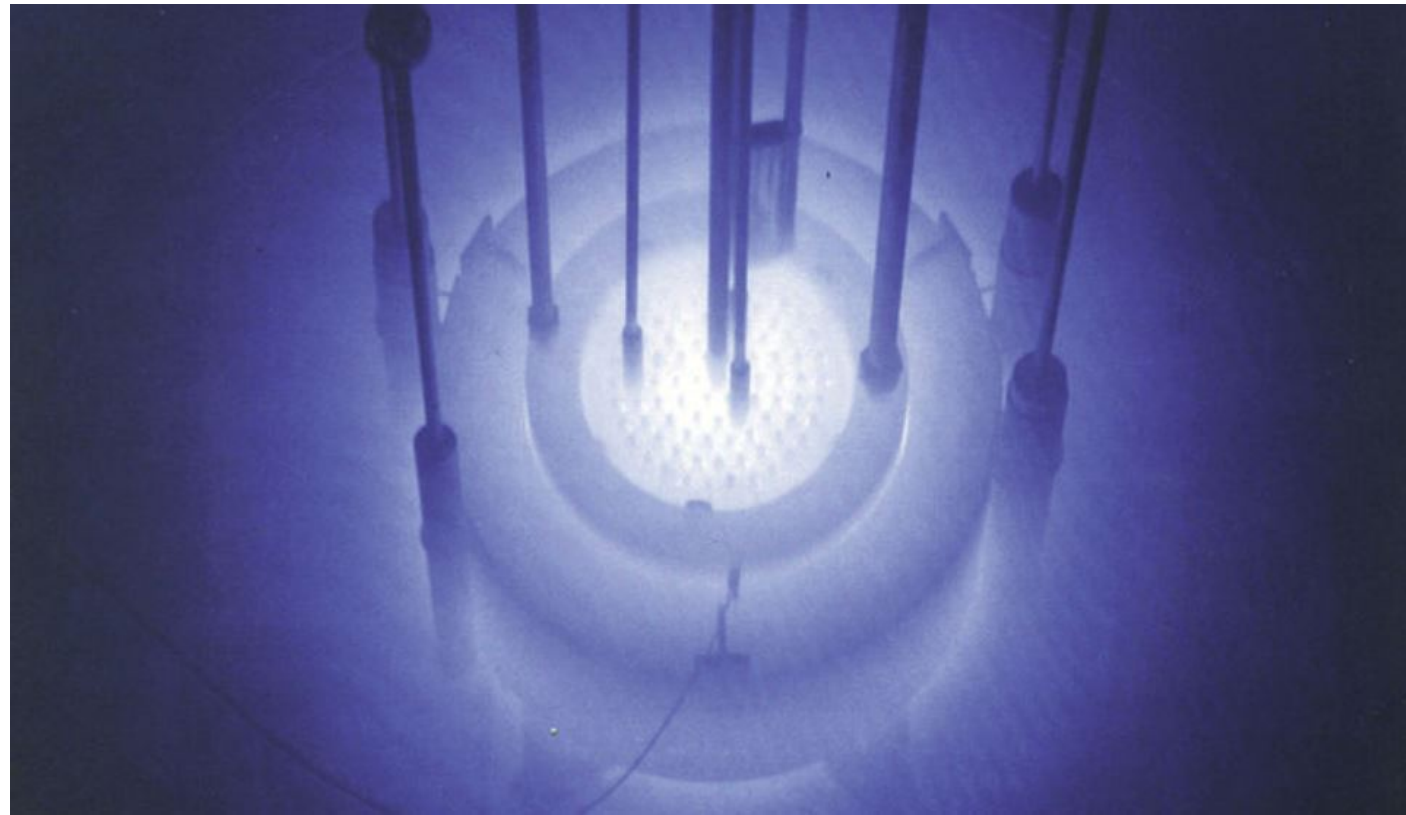


## TRIGA

Operates in pulsed mode  
by rapidly firing fuel rods  
through the core

Reactivity ( $\rho$ ) can be  
around “weapon” levels

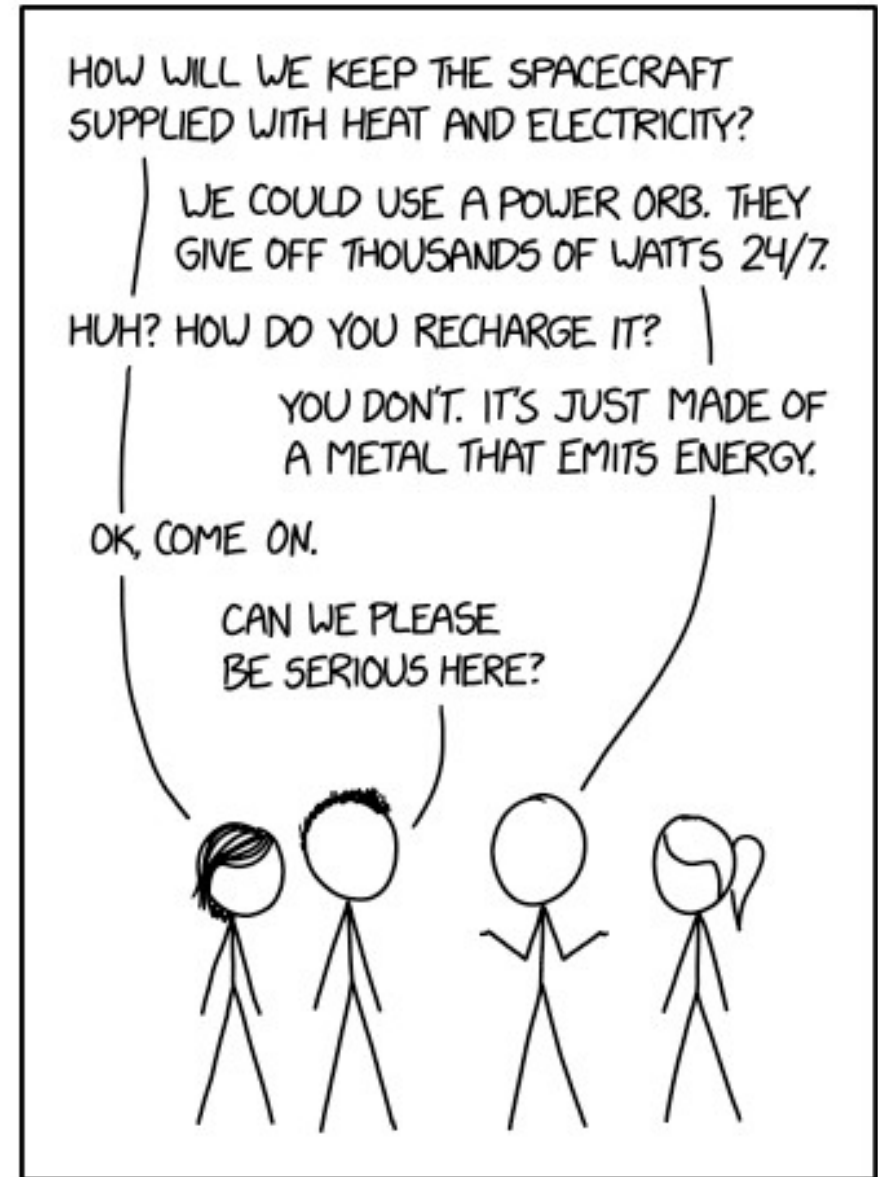
Offers an intriguing  
possibility for propulsion





Going from terrestrial power reactors to propulsion systems

- 1) Start by getting rid of the coolant
- 2) And as much shielding as possible
- 3) Add a big tank of cryogenic hydrogen
- 4) Run the hydrogen through the core
- 5) And jet it out the back



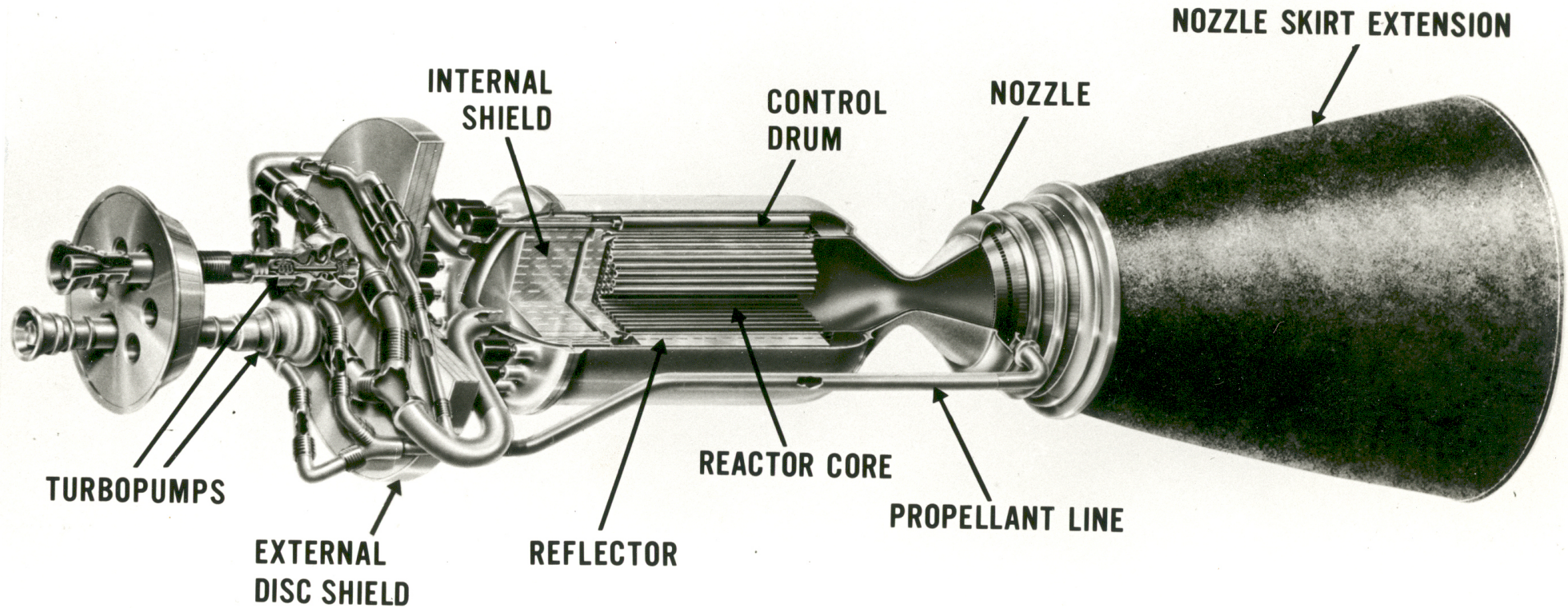
FOR SOMETHING THAT'S REAL,  
PLUTONIUM IS SO UNREALISTIC.



Test Article	Test Date	Power (Mw)	Test Time (s)	Exit Temp (K)	Press (kPa)	Flow (kg/s)	Isp (s)	Est. Thrust (N)
Kiwi A	1959-07	70	300	1778	unk.	3.2	724	20,000
Kiwi A'	1960-07	88	307	2206	1125	3.0	807	22,000
Kiwi A3	1960-10	112	259	2172	1415	3.8	800	28,000
Kiwi B1A	1961-12	225	36	1972	974	9.1	763	60,000
Kiwi B1B	1962-09	880	briefly	> 2278	2413	34.5	820	215,000
Kiwi B4A	1962-11	450	briefly	1556	1814	19.0	677	135,000
Kiwi B4D	1964-05	990	64	2539	3606	31.1	865	230,000
Kiwi B4E	1964-08	937	480	2356	3427	31.0	834	225,000
NRX-A2	1964-09	1096	40	2229	4006	34.3	811	275,000
NRX-A3	1965-04	1093	990	> 2400	3930	33.3	> 841	265,000
Phoebus 1A	1965-06	1090	630	2444	3772	31.4	849	260,000
NRX/EST	1966-02	1144	830	> 2400	4047	39.3	> 841	275,000
NRX-A5	1966-06	1120	580	> 2400	4047	32.6	> 841	270,000
Phoebus 1B	1967-02	1450	1800	2456	5075	38.1	851	345,000
NRX-A6	1967-11	1199	3623	2558	4151	32.7	869	289,000
Phoebus 2A	1968-06	4082	744	2283	3827	119.0	821	1,000,000
Pewee	1968-11	503	2400	2750	4344	18.8	901	110,000
XE-Prime	1969-03	1137	1680	> 2400	3806	32.8	849	270,000
NF-1	1972-06	44	6528	2444	unk.	1.7	> 841	10,000



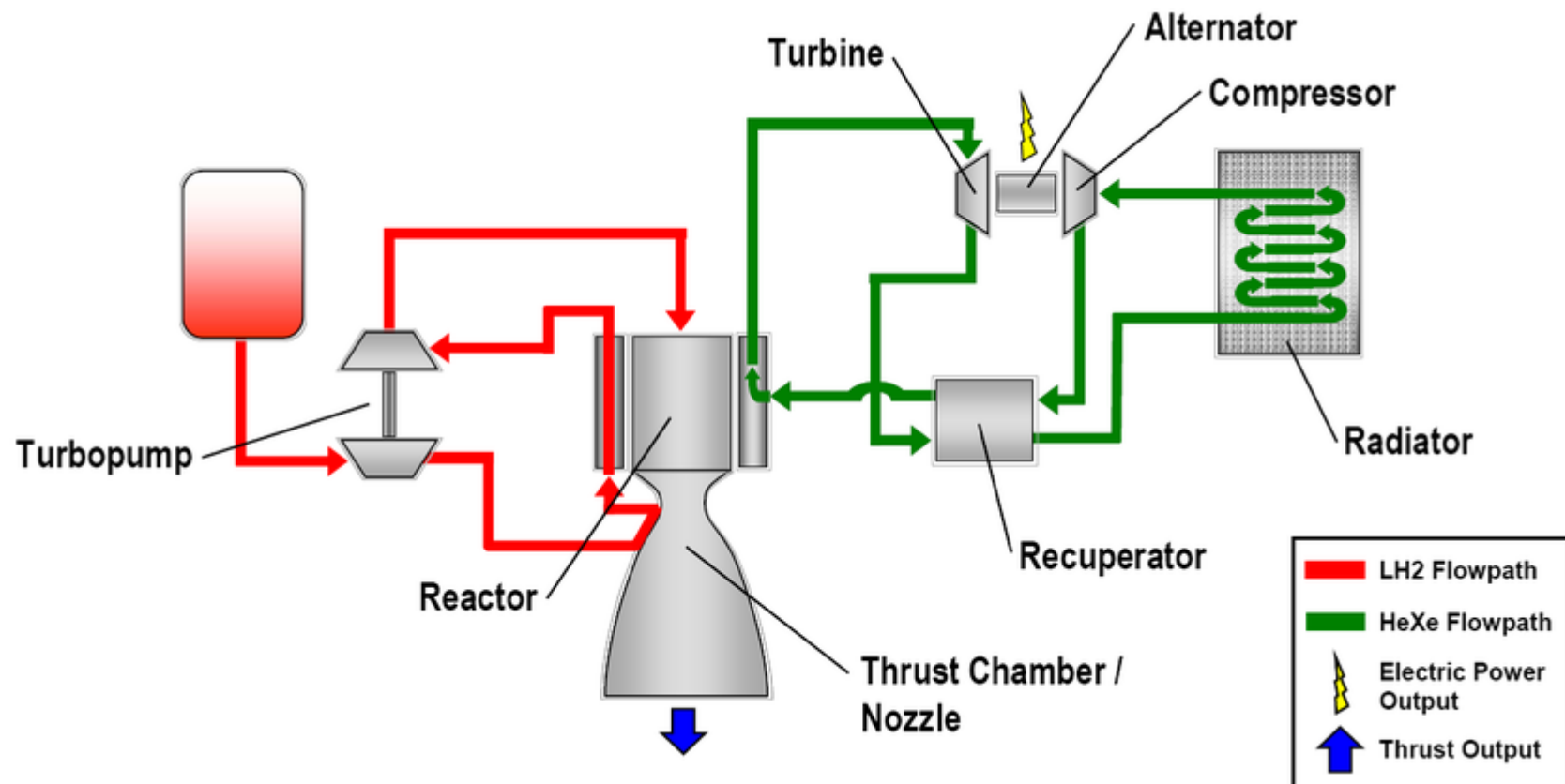
Pretty much all of solid-core, nuclear thermal rockets look like this...





Bi-Modal: Since we already have a nuclear reactor, we may as well get some electricity out of it at the same time.

Tri-Modal (or LANTR): And while we're at it, let's add the option to inject some LOX into the hydrogen exhaust as an "afterburner".





## **The legend of the world's fastest manhole cover...**

During the heyday of nuclear testing (around 1956, as the story goes), a fairly standard underground test was prepared on a hundred-kiloton-or-so nuclear bomb. It was placed a few hundred feet below the Nevada desert at the bottom of a shaft, four feet in diameter. This shaft was capped with a manhole cover. I think you see where this is going...

The high-speed camera recorded the manhole in just a single frame, but from that, a lower limit on its speed could be extrapolated. The manhole cover in question has possibly left the solar system, going at a good 65 km/sec clip.



Moving fast by blowing things up

- 1) Get a few thousand small, nuclear bombs (10 kton or so)
- 2) Stuff them in to an ejector system like cans of soda in a vending machine
- 3) Throw them out the back of your spaceship, about one per second and detonate them from a (not very) safe distance
- 4) Use a pusher plate connected to giant shock absorbers to ride the shockwave

- or -

- 4) Use a sail instead of a plate and detonate them in front of you!



Unlike other rockets, the Orion system is easy to scale up

$I_{sp} \approx 50,000$  sec.

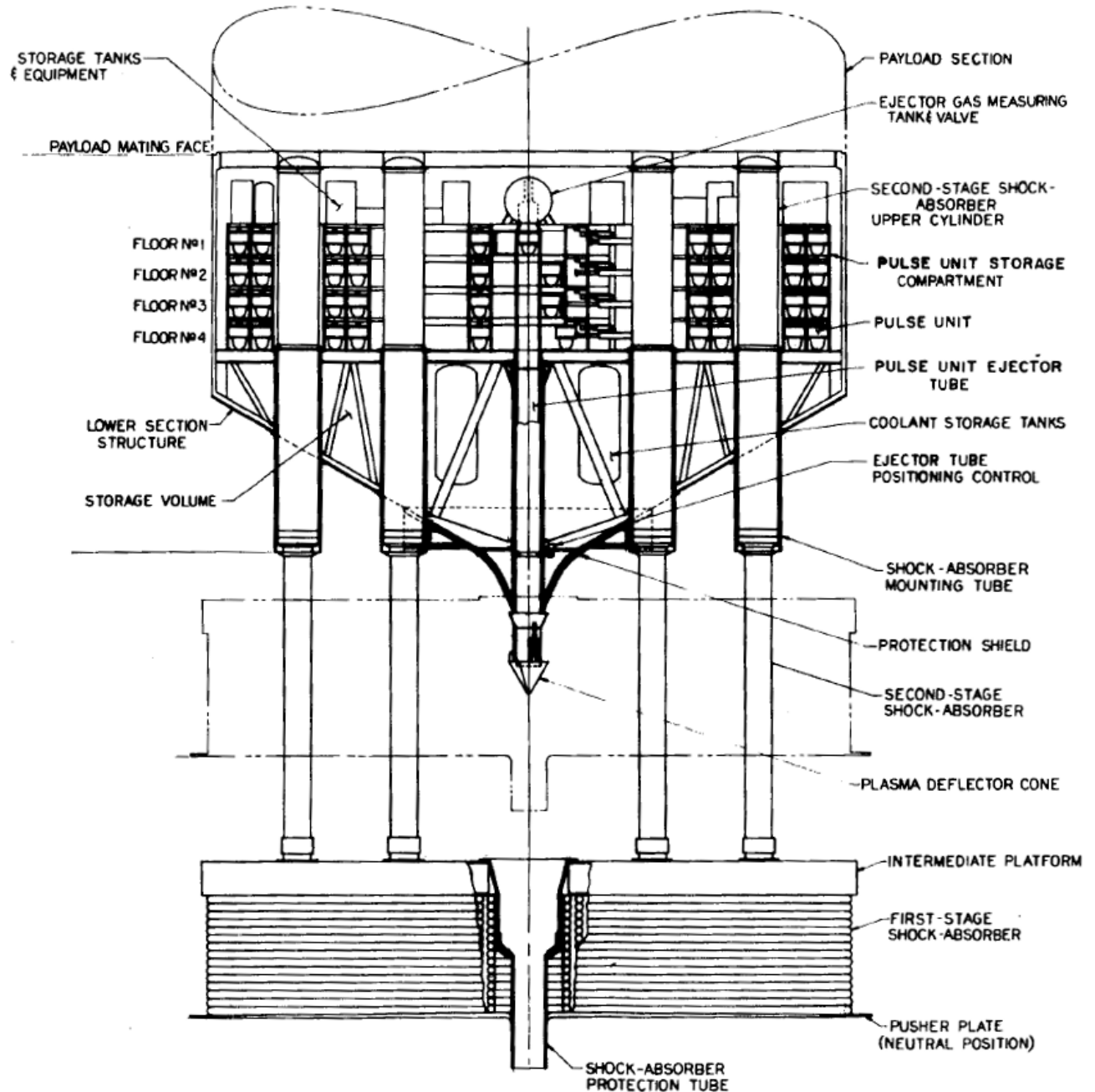
Thrust  $\approx$  mega-newtons

Vehicle mass  $\approx$  lots

Environmental impact...

... well ...

... ummmm ...





A few Orion designs (ranked in ascending order of crazy):

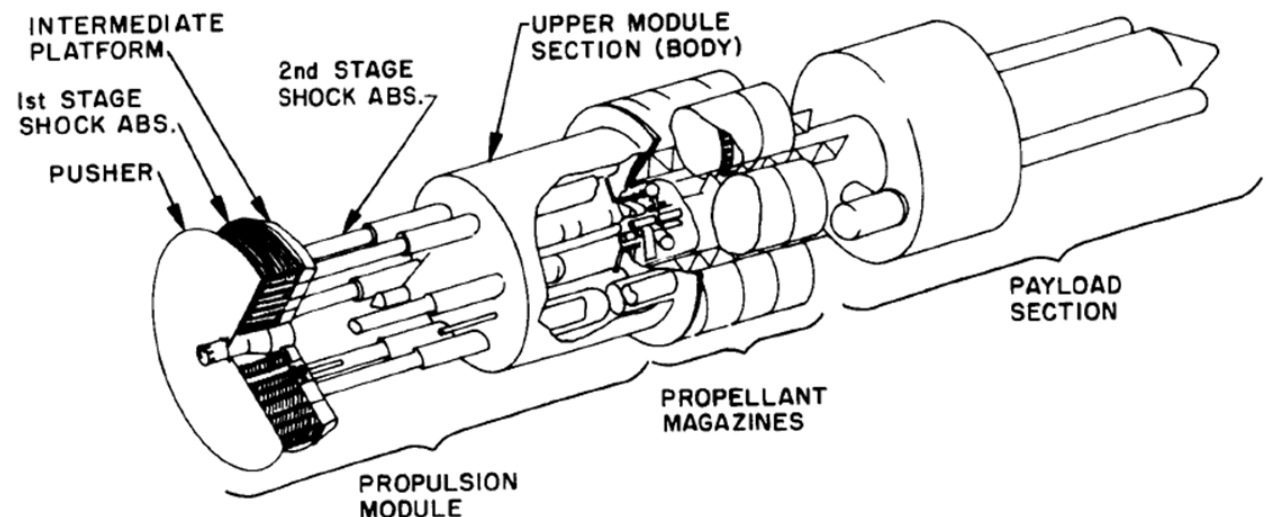
Ship Mass	Diameter	Bomb Yield	Bomb Qty	Notes
300 t	20 m	25 t	500	This is about as small as it gets
880 t	25 m	30 t	800	Still considered a “test article”
1500 t	40 m	100 t	1000	
4000 t	40 m	140 t	800	
10,000 t	56 m	350 t	800	Set up a lunar colony
400,000 t	100 m	1 Mt	300,000	Go to Alpha Centauri
8,000,000 t	400 m	3,000 t	1000	Set up a base on Ganymede
40,000,000 t	20 km	1 Mt	30 million	Colonize Alpha Centauri

Yes, propulsion engineers thought that these were good ideas. And note that there might not be enough fissile material in the world to make thirty million, one megaton bombs.



## Orion takeaways...

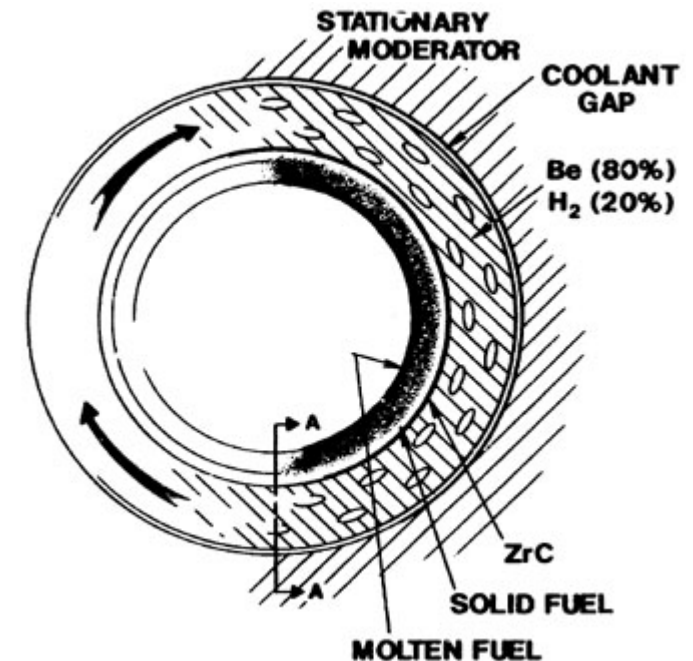
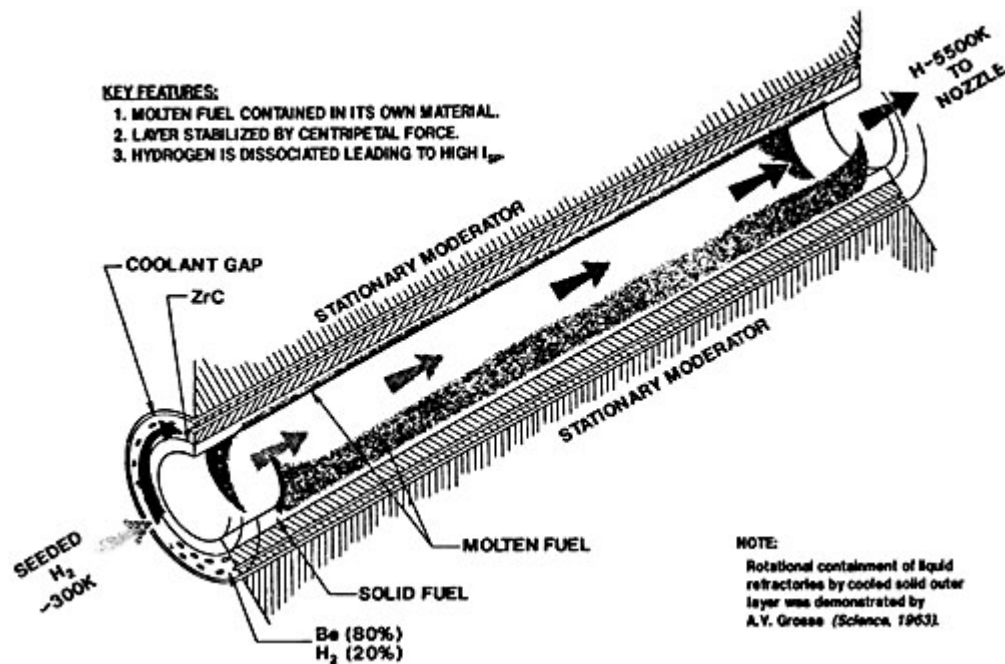
- 1) If we ever needed to evacuate the planet in a hurry, this would be the only way to do it (at our current level of technology).
- 2) Orion is a useful model for any high-energy, pulsed propulsion system.
- 3) Getting off the ground would be disastrous, but in-space? Maybe so.
- 4) Turn fission to fusion, the bombs to pellets, and we may have something.





The problem: Nuclear thermal rockets are heat engines and subject to the laws of thermodynamics. In particular, the hotter they are, the more efficient they are.

Solution: Screw it. We'll let the core melt.



Uranium fuel rods melt between 1500K and 2500K (depending on composition)  
And vaporize between 4000K and 6500K (again, composition dependent)



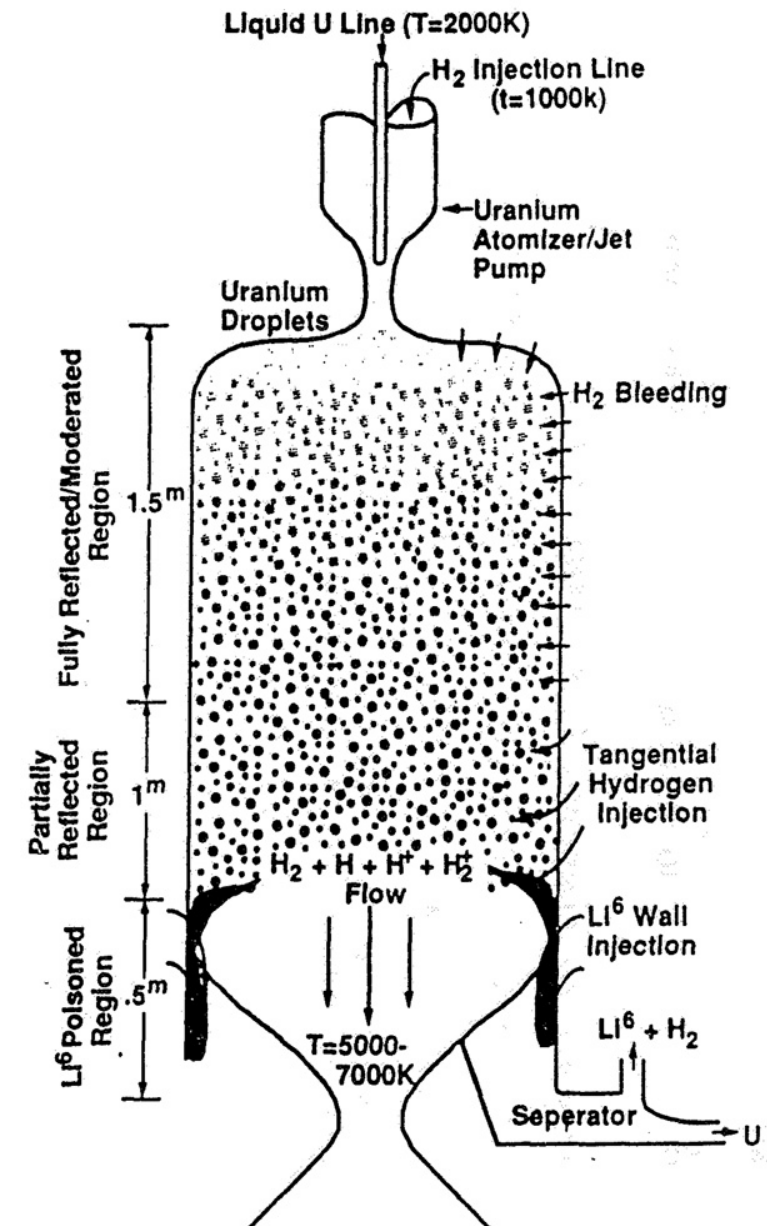
Liquid core can give an  $I_{sp}$  of about 1500 sec.  
But why stop there?

Droplet core: fuel is around 7500 and injected  
as a “wet vapor”.  $I_{sp}$  is bumped to 2000 sec.

Now we have even more of a problem of  
keeping the fissile stuff from escaping out  
of the nozzle.

But since we’ve come this far...

## DROPLET CORE NUCLEAR ROCKET (DCNR)





The gas core NTR – nuclear light bulb edition

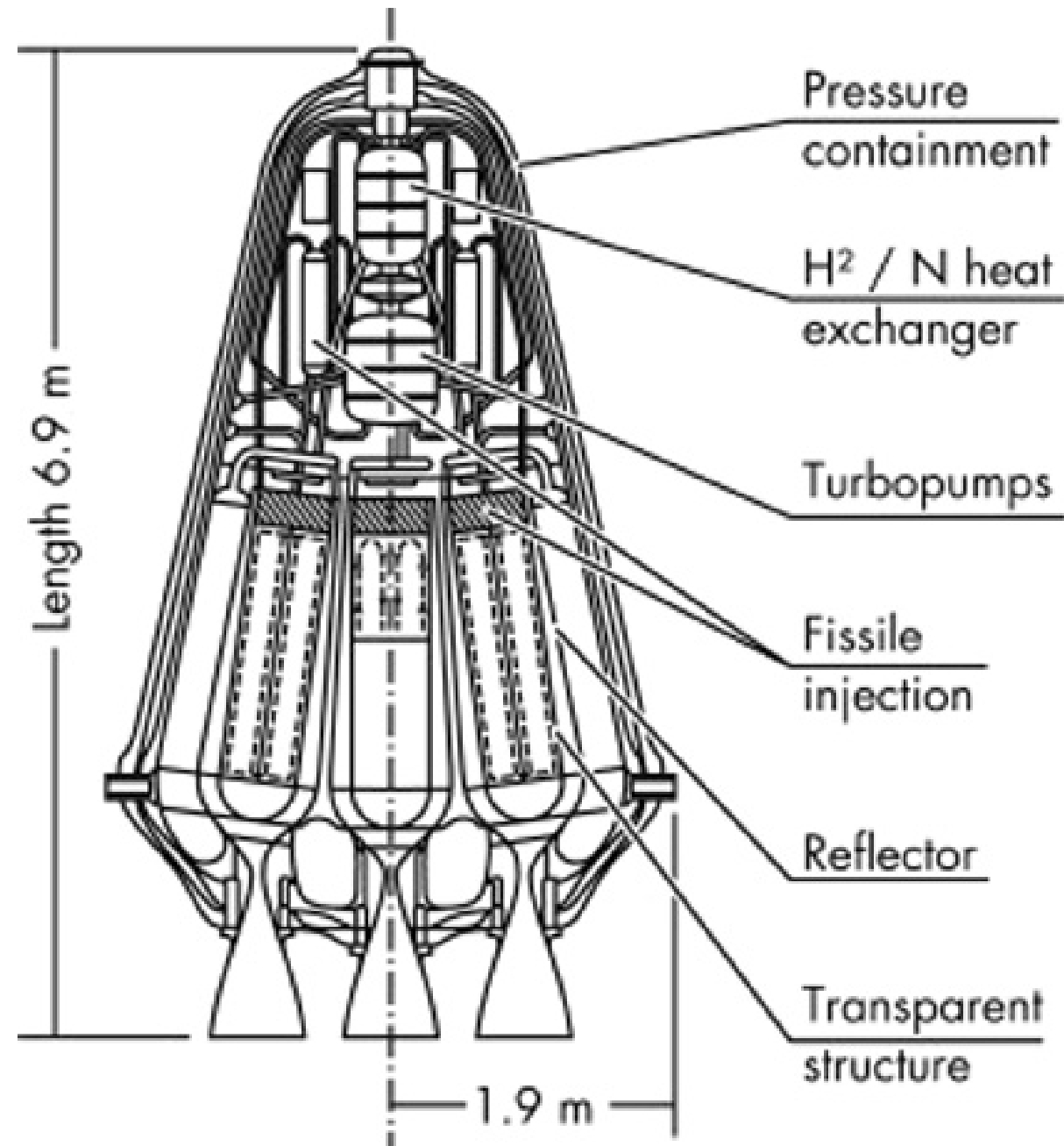
Enriched uranium hexafluoride is contained in a quartz bulb

Hydrogen is passed around the bulb fast enough to keep the quartz from melting

$I_{sp}$  up to 5000 sec.

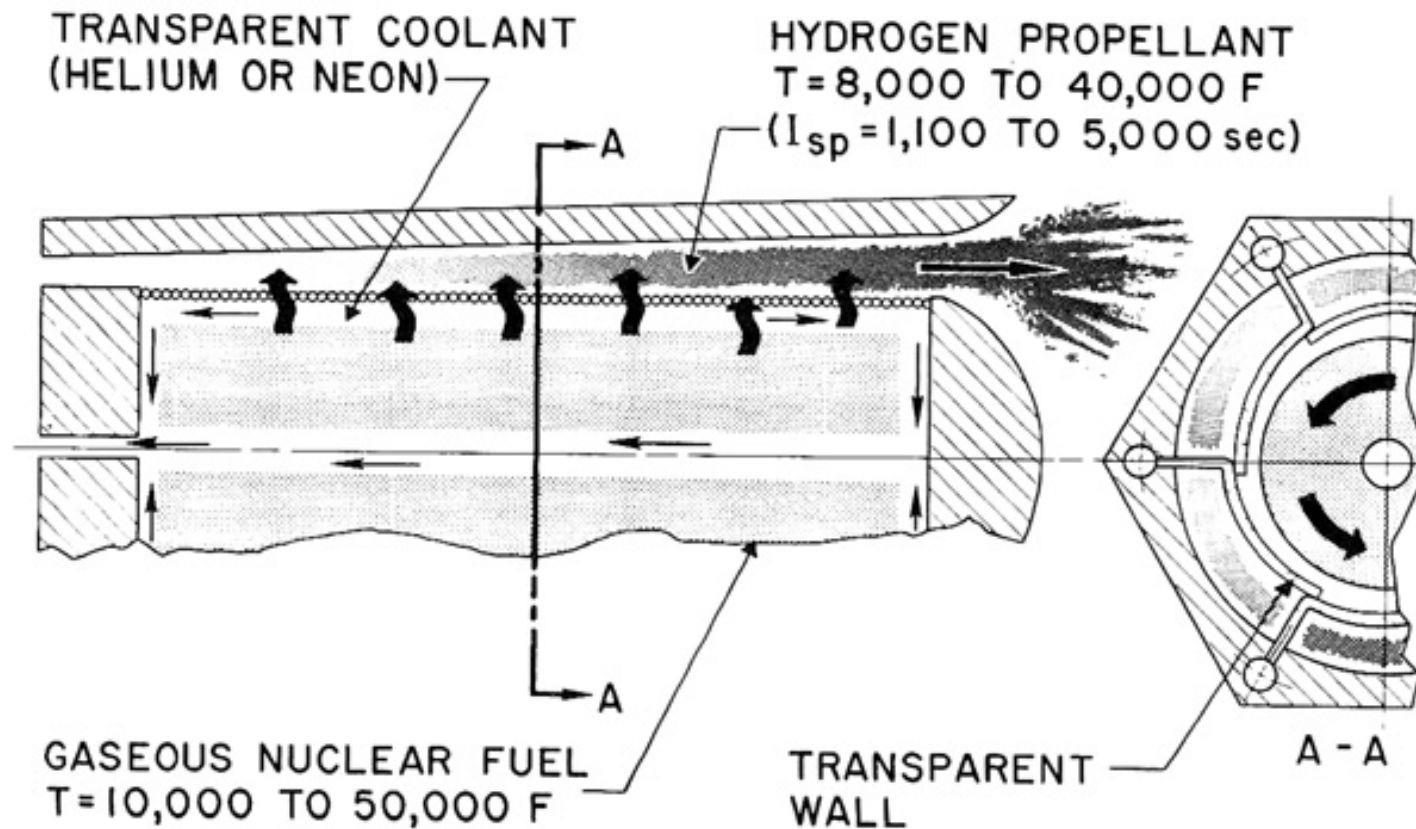
Thrust in the MN range

Throttling may be a bit of a problem





From a fission rocket standpoint (at least one that doesn't involve detonating a weapon) the nuclear lightbulb may be the best that we can do...



... but there are still some serious engineering challenges.



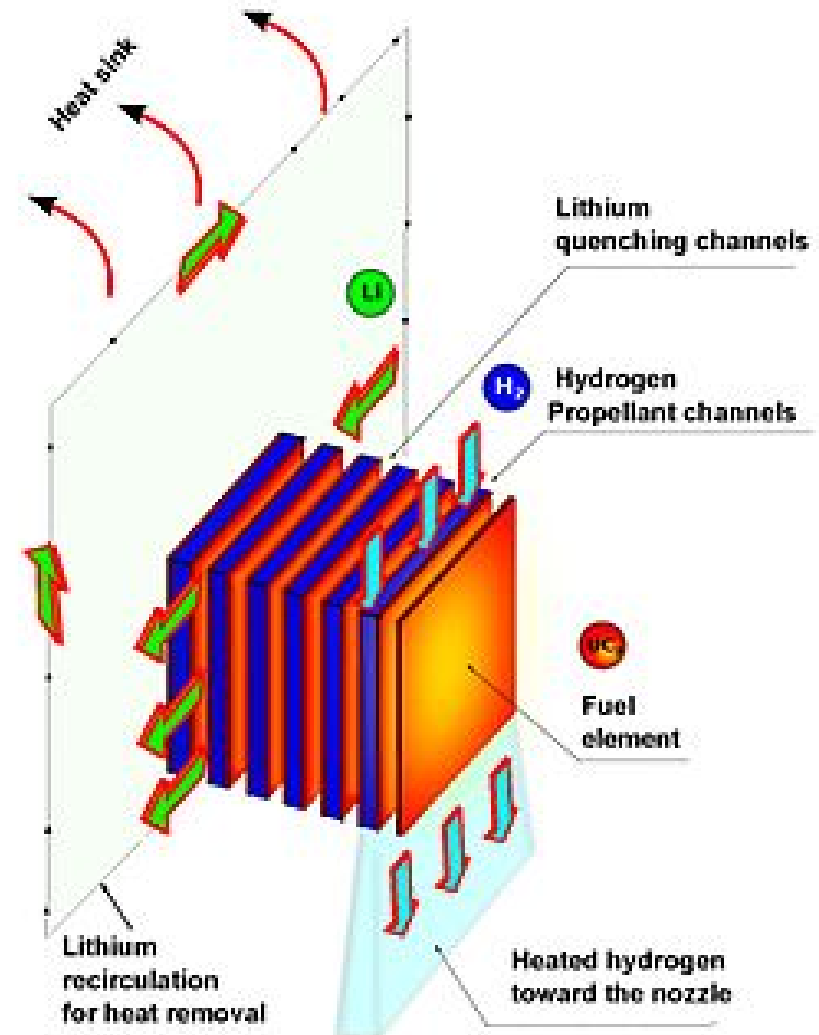
All of the previously mentioned concepts (barring Orion) are heat engines and can only get more efficient by turning up the temperature. So let's ditch the whole heat engine idea.

Remember TRIGA reactors? Every time they pulse, they generate as many prompt neutrons as a nuclear bomb.

These neutrons can be captured by a propellant with a high cross-section.

That propellant can then gain more energy than would be allowed by standard heat transfer. In theory, the propellant can be much hotter than the reactor core.

$I_{sp}$  around 1,000,000 seconds?





While we're discussing that, why bothering transferring energy at all? A fission fragment rocket simply jets the high-energy particles themselves.

On the upside,  $I_{sp}$  can be up to 1,500,000 seconds.

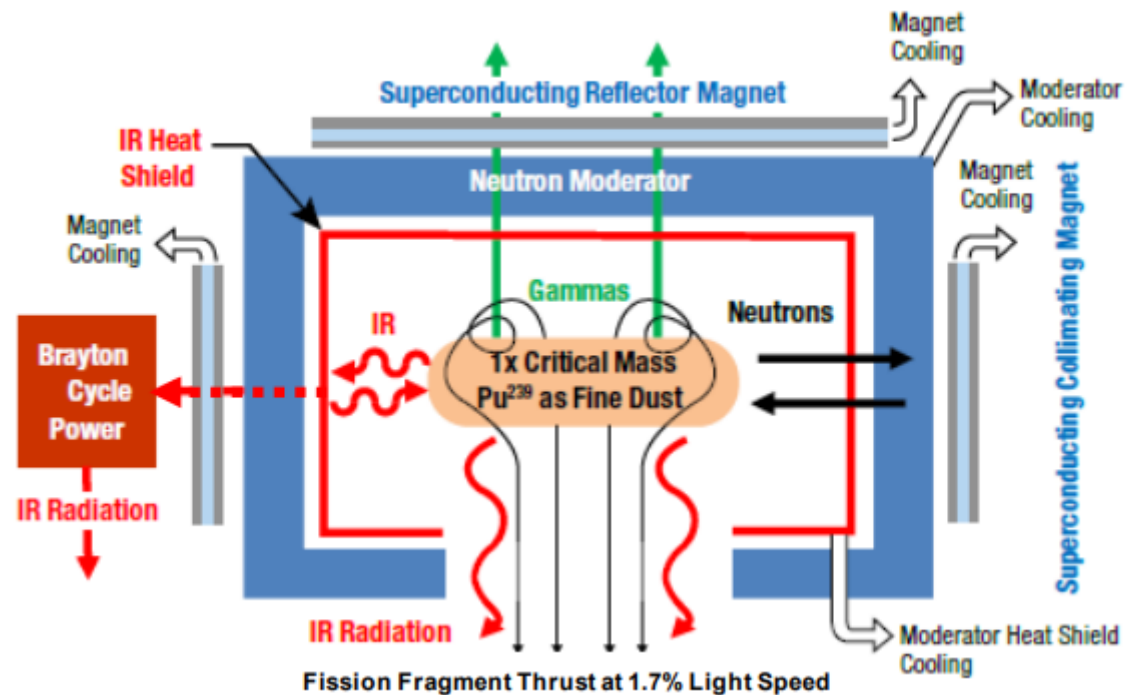
On the downside, thrust is best measured in units of "hummingbirds"\*.

A more-or-less realistic design (detailed in a 2011 NIAC study) came up with:

Thrust = 43 N

Engine mass = 113 t

$I_{sp} = 500,000$  sec.



\* Fun fact: 1 hummingbird can generate about 50 mN of thrust



Now we come to the scariest of the nuclear rockets. This one is from Robert Zubrin and is dedicated to all of those people who really like the idea of Orion but don't think that it's quite "explodey" enough.

Ladies and gentlemen, the nuclear salt water rocket.

- 1) Dissolve highly-enriched uranium salts in water
- 2) Contain this in hollow rods made of something that absorbs neutrons
- 3) Use a series of pistons to evacuate all of those rods in to a chamber
- 4) When the "streams cross" they go prompt-super-critical pretty much instantly and will continue to do so until you're out of fuel

Essentially, this is a megaton-class nuclear weapon  
that just NEVER. STOPS. EXPLODING.



Statistics (when using weapons-grade uranium, because... why the hell not):

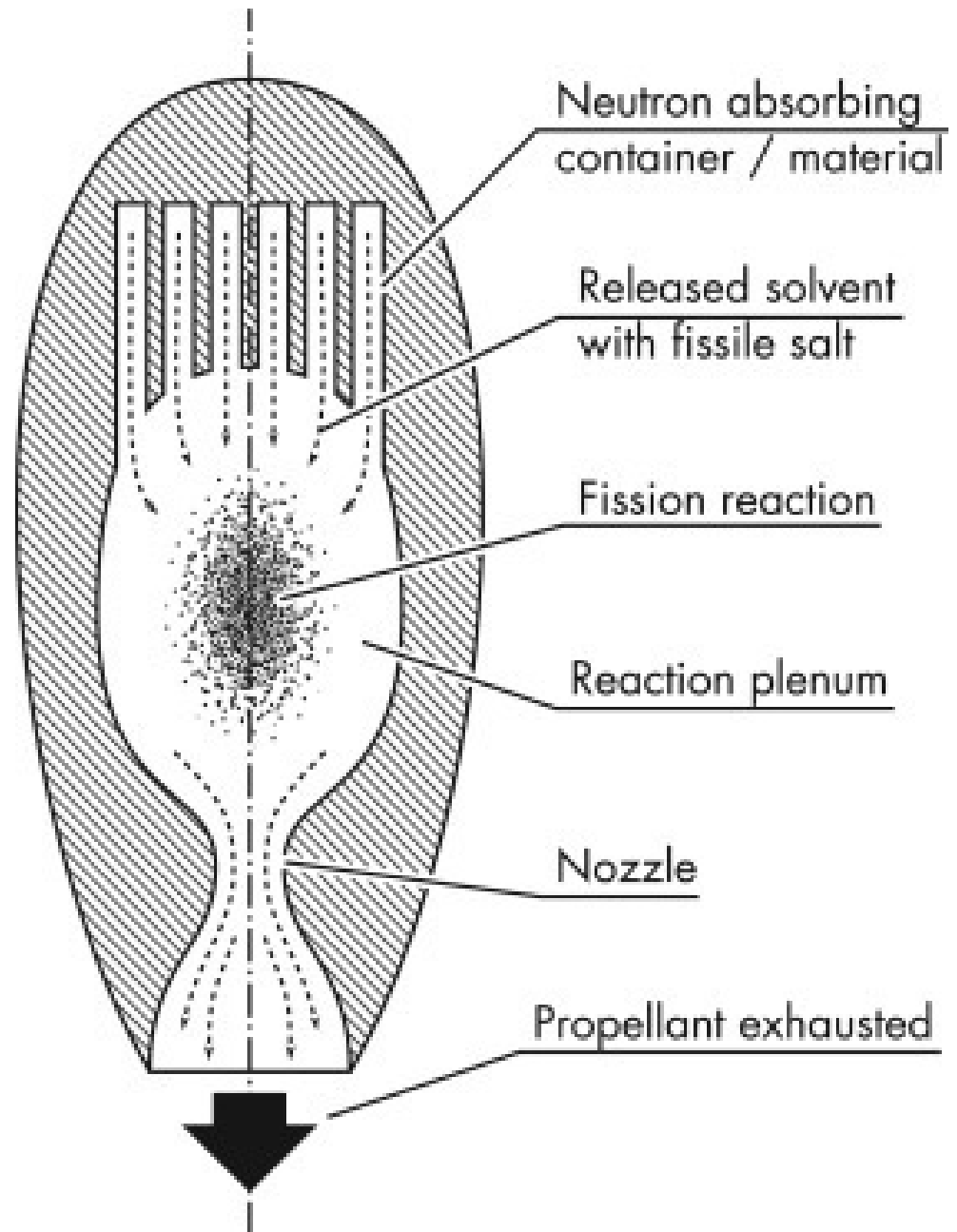
Thrust = 15,000,000 N

$I_{sp} = 500,000$  sec

Chamber temperature and pressure are both roughly equal to “You’ve got to be f\*cking kidding me”

But hey... you want an Epstein drive? Merry frikken’ Christmas.

I sort of feel like we need a heavy metal soundtrack to go with this.





# Questions?