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

 jcavera@blueorigin.com

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 SRP (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:

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

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

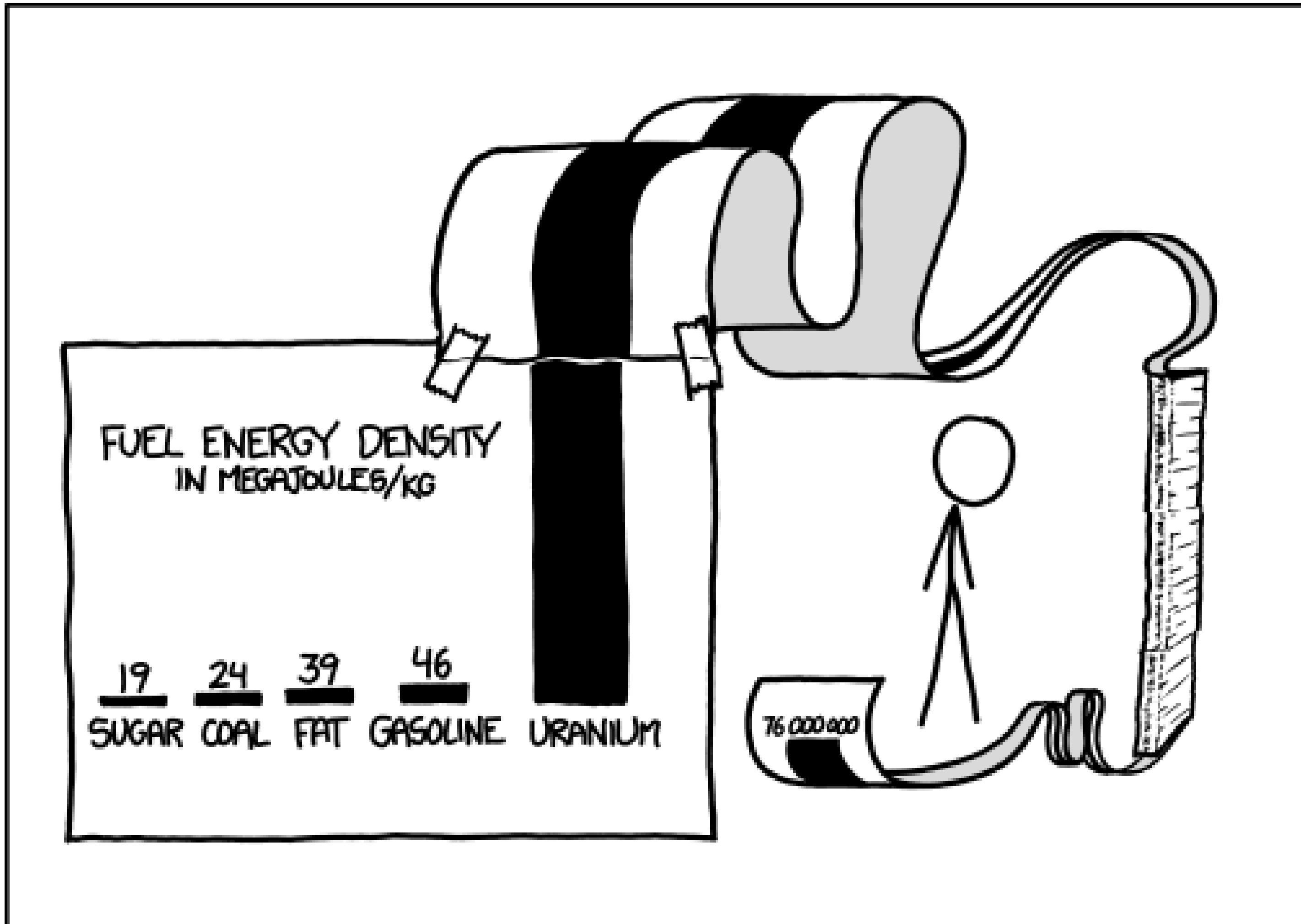
So if we want to go to five percent of light speed with a chemical rocket…

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

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*.

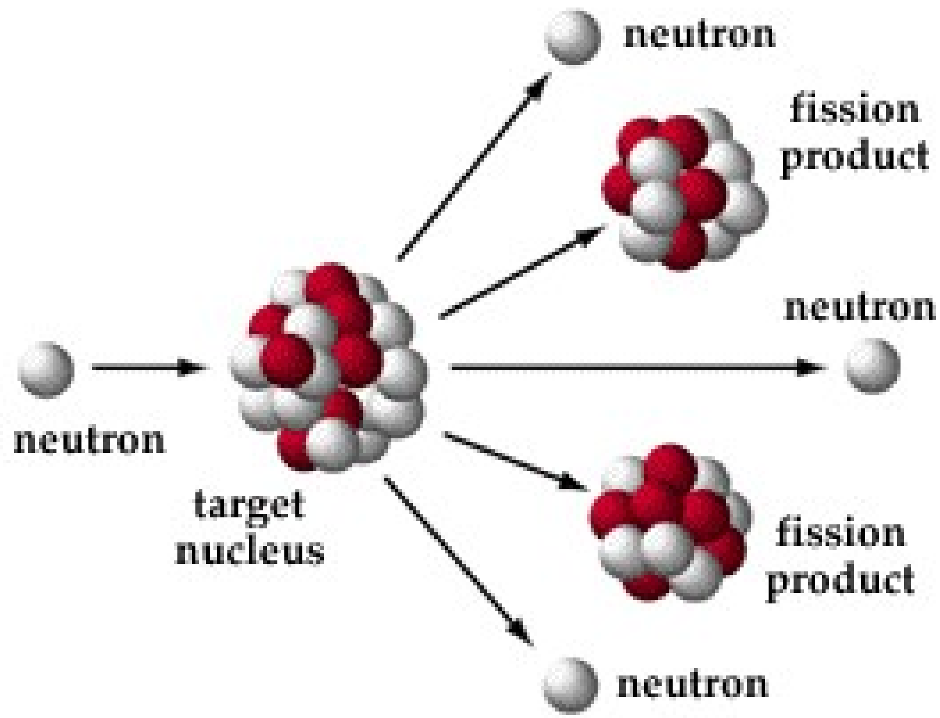
Nuclear fission 101

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…	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:

$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{92}Kr + {}^{141}Ba + 3n$

But a *lot* happens at the same time:

$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{236}U + \gamma$
$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{92}Kr + {}^{137}Te + 2n$
$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{90}Sr + {}^{144}Xe + 2n$
$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{87}Br + {}^{146}La + 3n$
$^{235}U + n \blacktriangleright {}^{236}U^* \blacktriangleright {}^{96}Rb + {}^{137}Cs + 3n$

...and then *those* decay…

$^{92}Kr \blacktriangleright n + {}^{91}Rb + \beta$
$^{92}Kr \blacktriangleright n + {}^{92}Rb^* \blacktriangleright 2n + \beta + {}^{91}Sr$

… and so on.

Standard reaction cycle:

$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{92}\text{Kr} + {}^{141}\text{Ba} + 3\text{n}$$

But a *lot* happens at the same time:

$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{236}\text{U} + \gamma$$
$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{92}\text{Kr} + {}^{137}\text{Te} + 2\text{n}$$
$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{90}\text{Sr} + {}^{144}\text{Xe} + 2\text{n}$$
$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{87}\text{Br} + {}^{146}\text{La} + 3\text{n}$$
$$^{235}\text{U} + \text{n} \blacktriangleright {}^{236}\text{U}^* \blacktriangleright {}^{96}\text{Rb} + {}^{137}\text{Cs} + 3\text{n}$$

Prompt
Neutrons

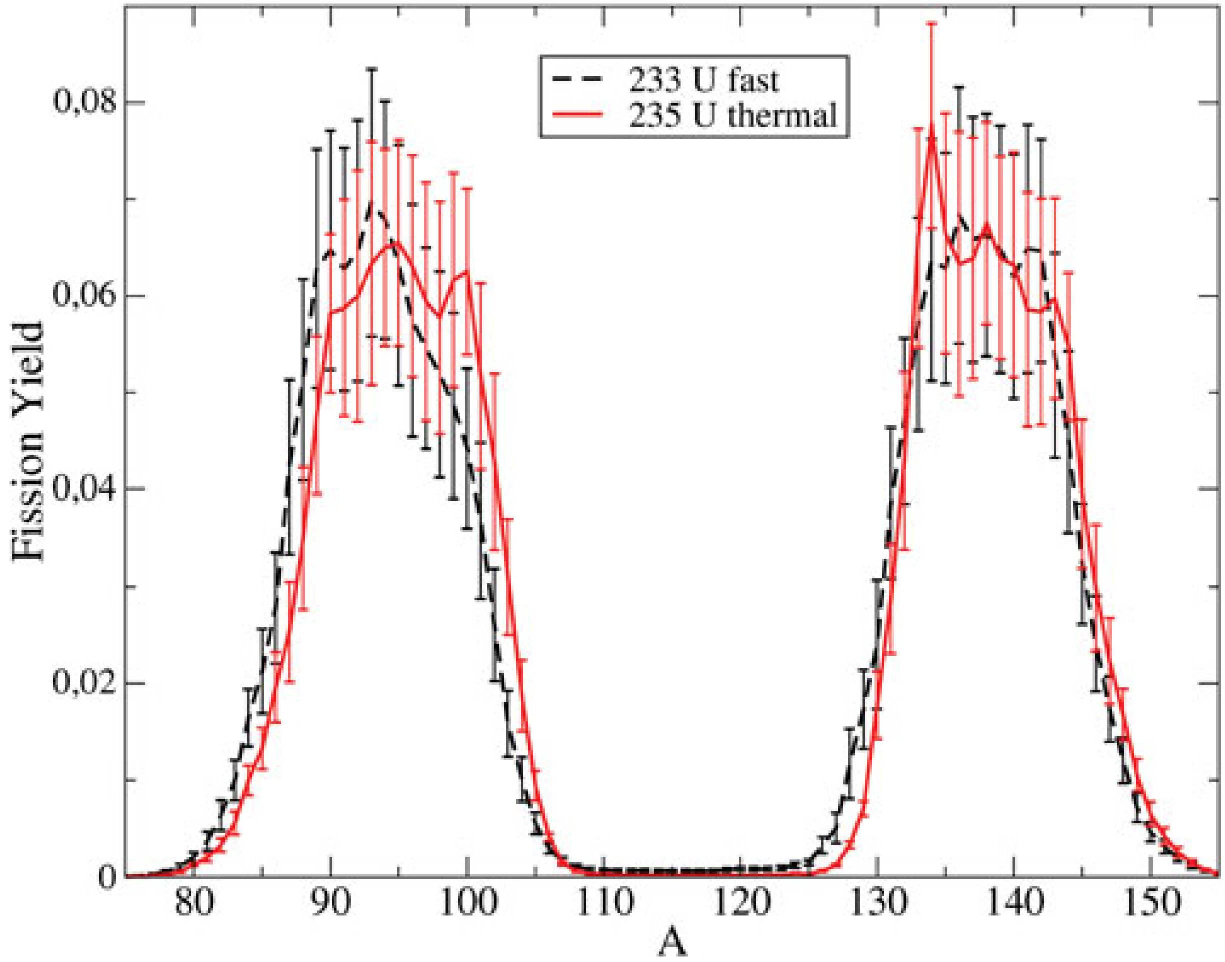
...and then *those* decay…

$$^{92}\text{Kr} \blacktriangleright \text{n} + {}^{91}\text{Rb} + \beta$$
$$^{92}\text{Kr} \blacktriangleright \text{n} + {}^{92}\text{Rb}^* \blacktriangleright 2\text{n} + \beta + {}^{91}\text{Sr}$$

Delayed Neutrons

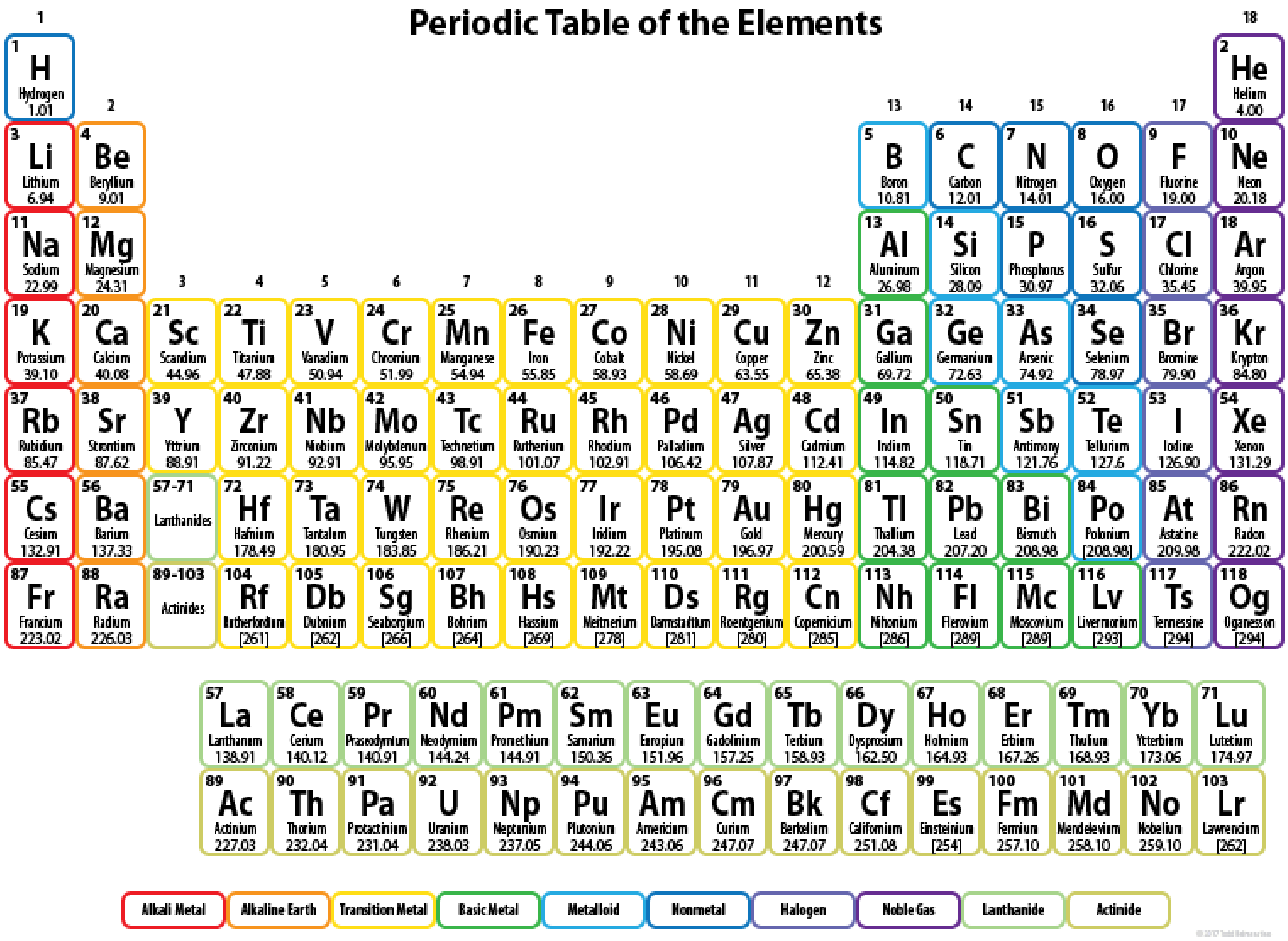
… and so on.

Reactions are a mess…

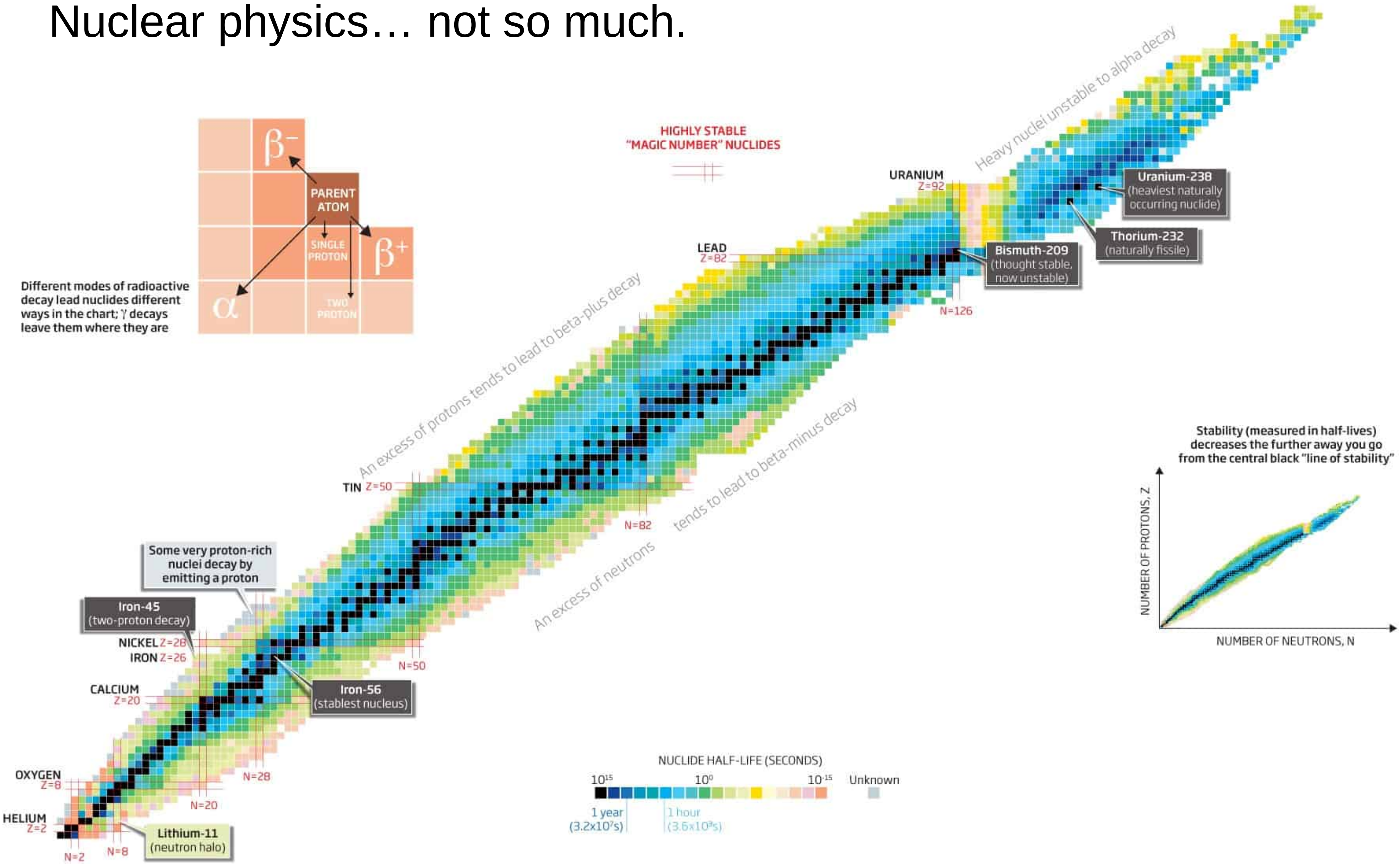


… but quantum mechanics runs on statistics

Chemistry is easy...



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 *lot* 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 = 2.4×10^{-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}H)
- Boron (^{10}B)
- Xenon (^{135}Xe)
- Samarium (^{149}Sm)
- Hafnium (^{176}Hf - ^{180}Hf)

Neutron "reflectors":

- Carbon (^{12}C)
- Beryllium (^{9}Be)
- Lead (^{204}Pb - ^{208}Pb)
- Tungsten (^{182}W - ^{184}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}U, ^{235}U) [cross section of ^{235}U is around 600 barns]
Plutonium (^{239}Pu, ^{241}Pu)

"Fertile" materials can be converted to something that is fissile:

Thorium (^{232}Th) [$^{232}Th + n$ ► ^{233}U, cross section ≈ 10 barns]
Uranium (^{234}U, ^{238}U)
Plutonium (^{236}Pu, ^{240}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.

$^{241}Am \blacktriangleright {}^{237}Np + \alpha + \gamma$

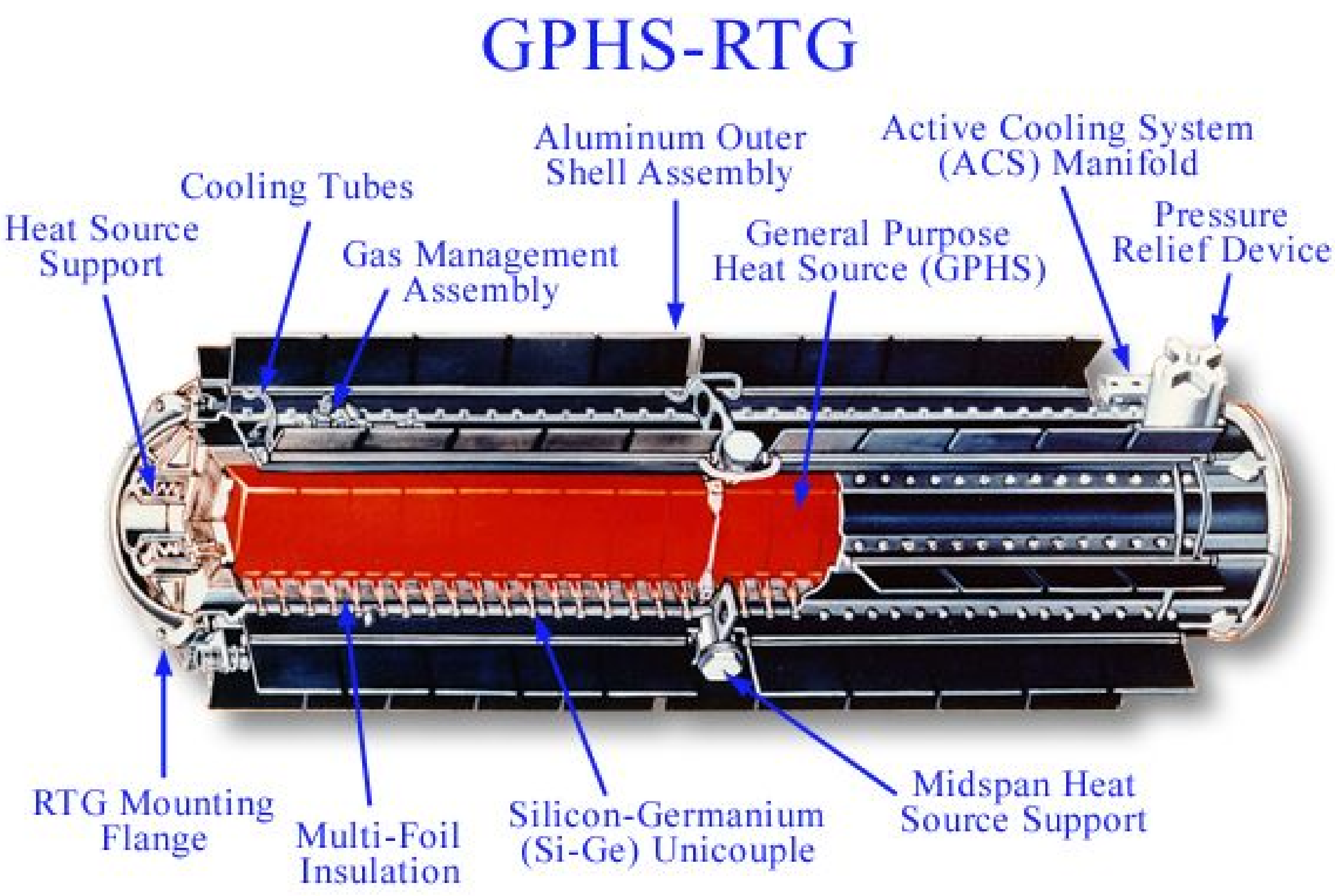
$^{9}Be + \alpha \blacktriangleright {}^{12}C + n + \gamma$

Americium and beryllium are often times pressed together in to a pellet as a “spark plug”

$^{241}Am \blacktriangleright 3n + A^* + B^* + \gamma$

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
MMRTG (Curiosity rover)	Pu-238	87.7	45	2000	110
GPHS-RTG (New Horizons mission)	Pu-238	87.7	58	4400	300
BES-5 Buk (Russian research reactor)	U-235	703,800,000	1000	100000	3000

Advantages:

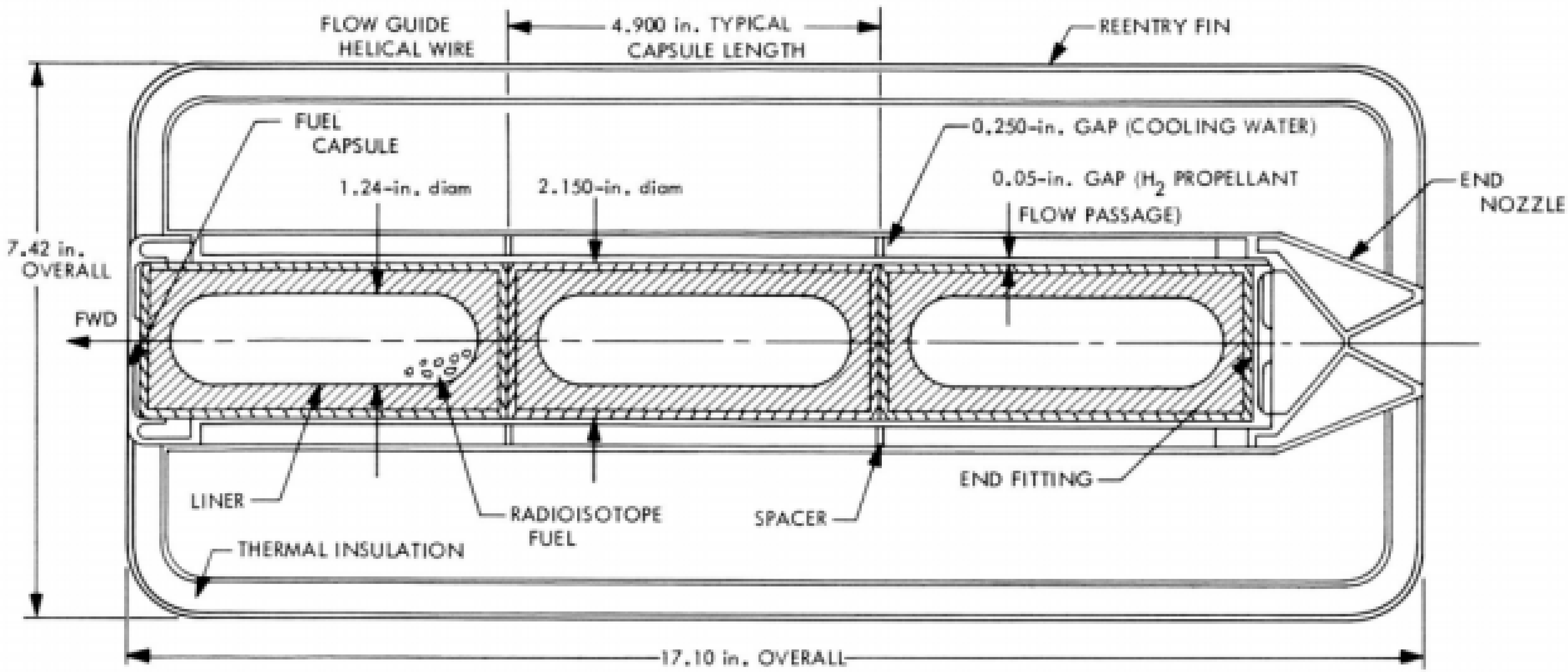
- Dead simple to build
- Nothing to control
- Can use any unstable isotope
- Predictable operation

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).



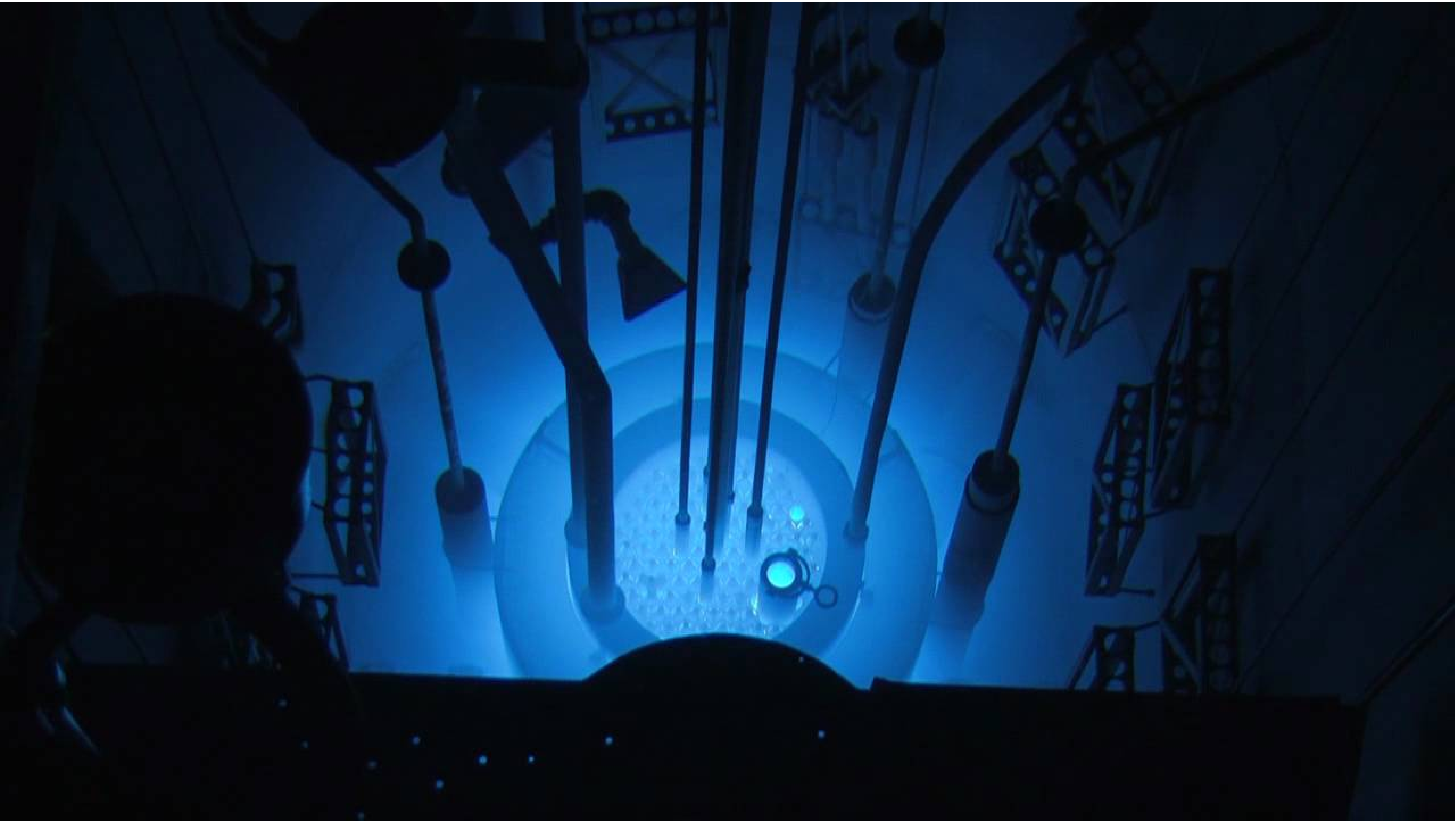
I_{sp} = 600-ish sec., Duration = 700 sec., Thrust = almost none

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 ≈ 0.5% ^{235}U (the rest is ^{238}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.

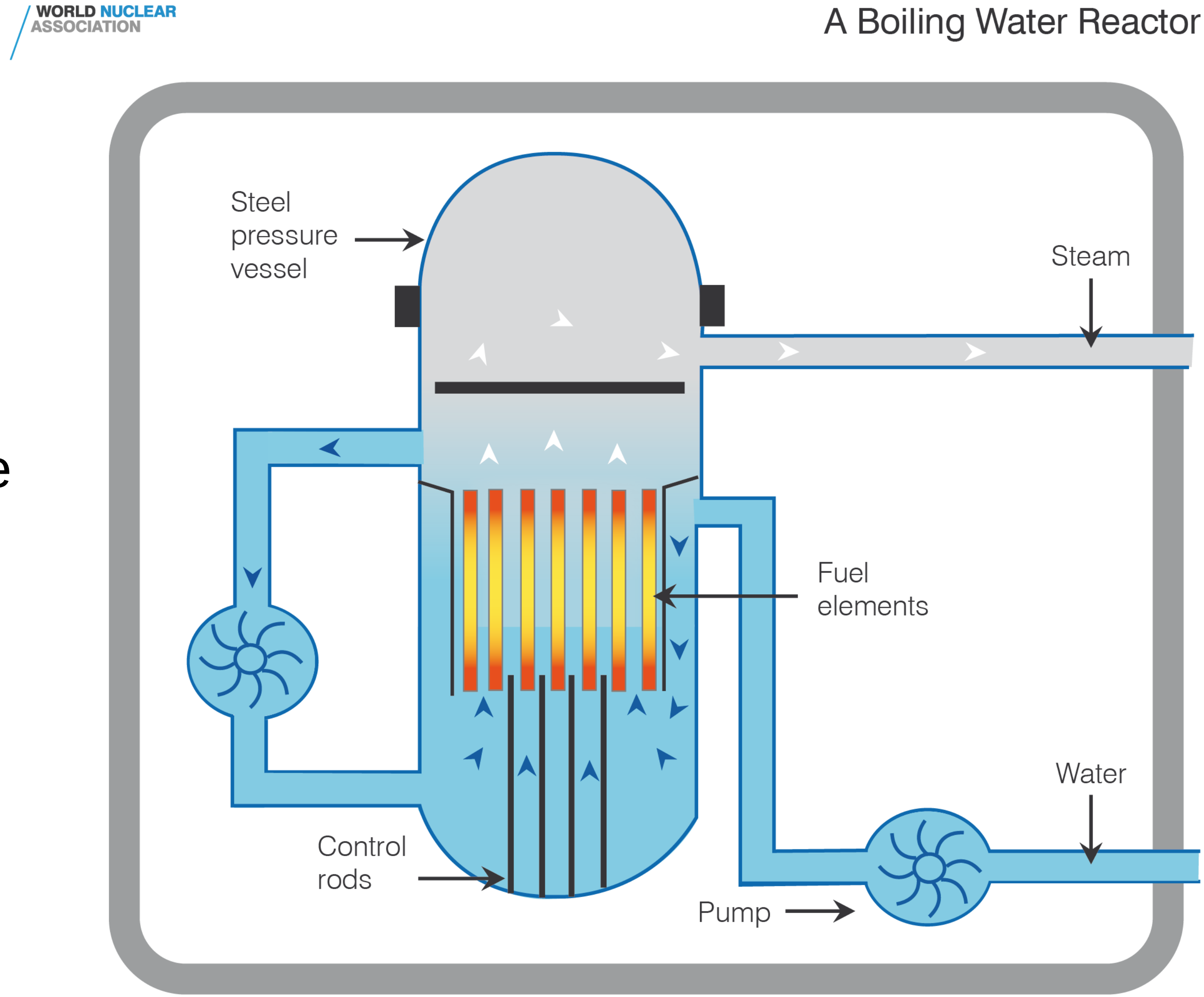
Jim Cavera
jcavera@blueorigin.com

A Boiling Water Reactor (BWR)

Simple in design

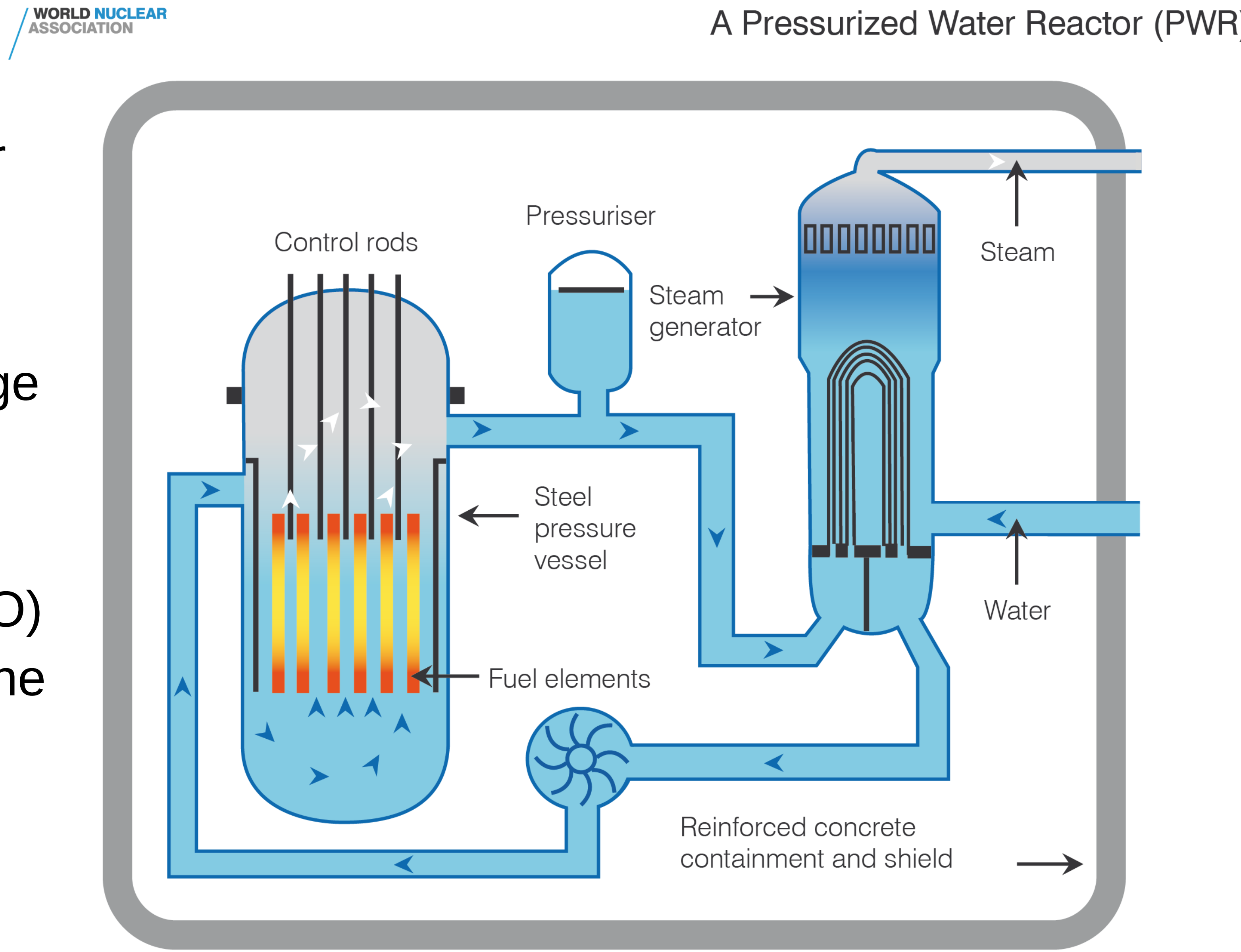
Steam directly drives a turbine

Most like a coffee percolator



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

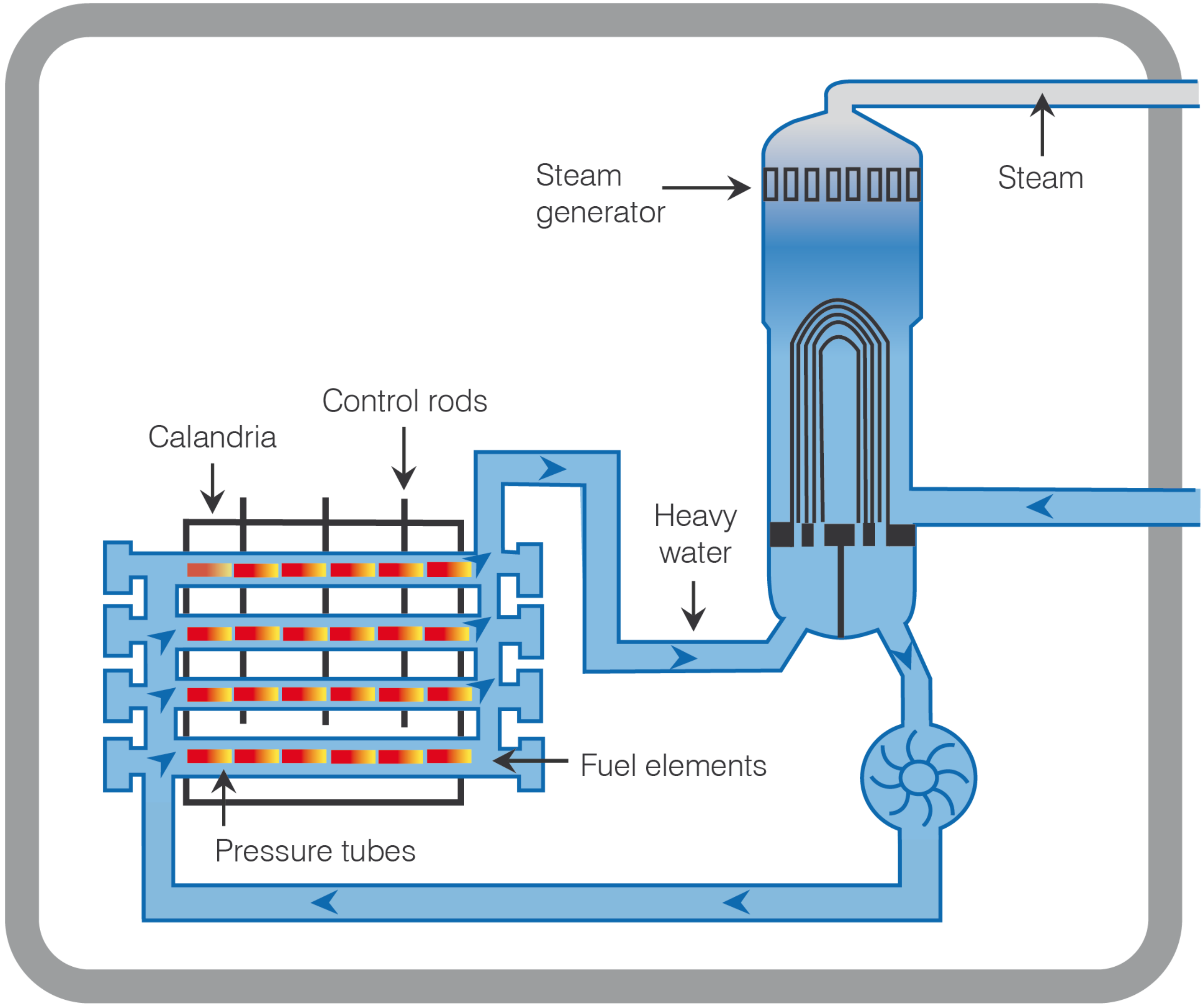
A "PHWR" uses heavy water (D_2O) to make use of the higher cross section to fast neutrons



WORLD NUCLEAR ASSOCIATION

A Pressurized Heavy Water Reactor (PHWR/Candu)

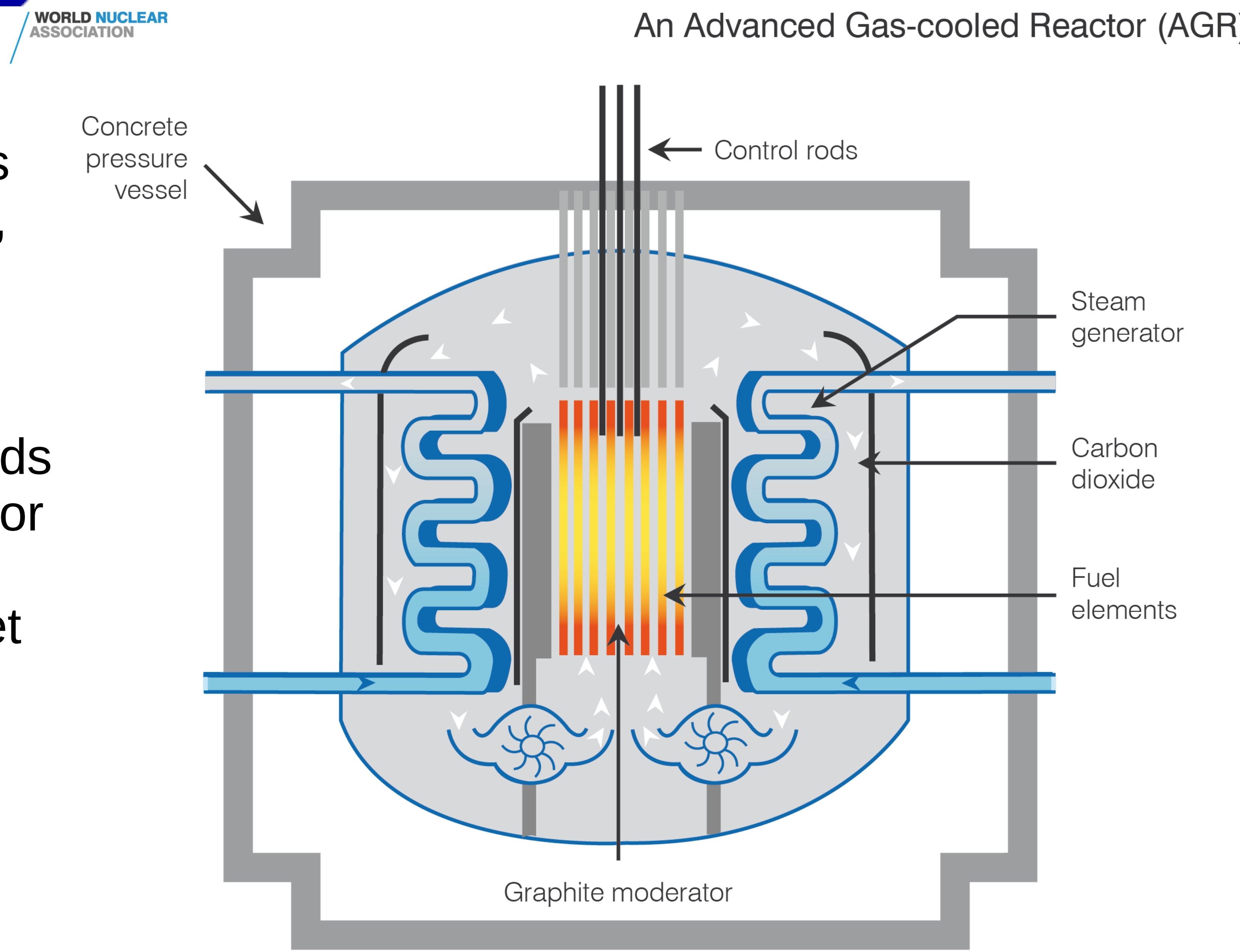
The CANDU design changes the PHWR geometry such that natural uranium can be used with no enrichment

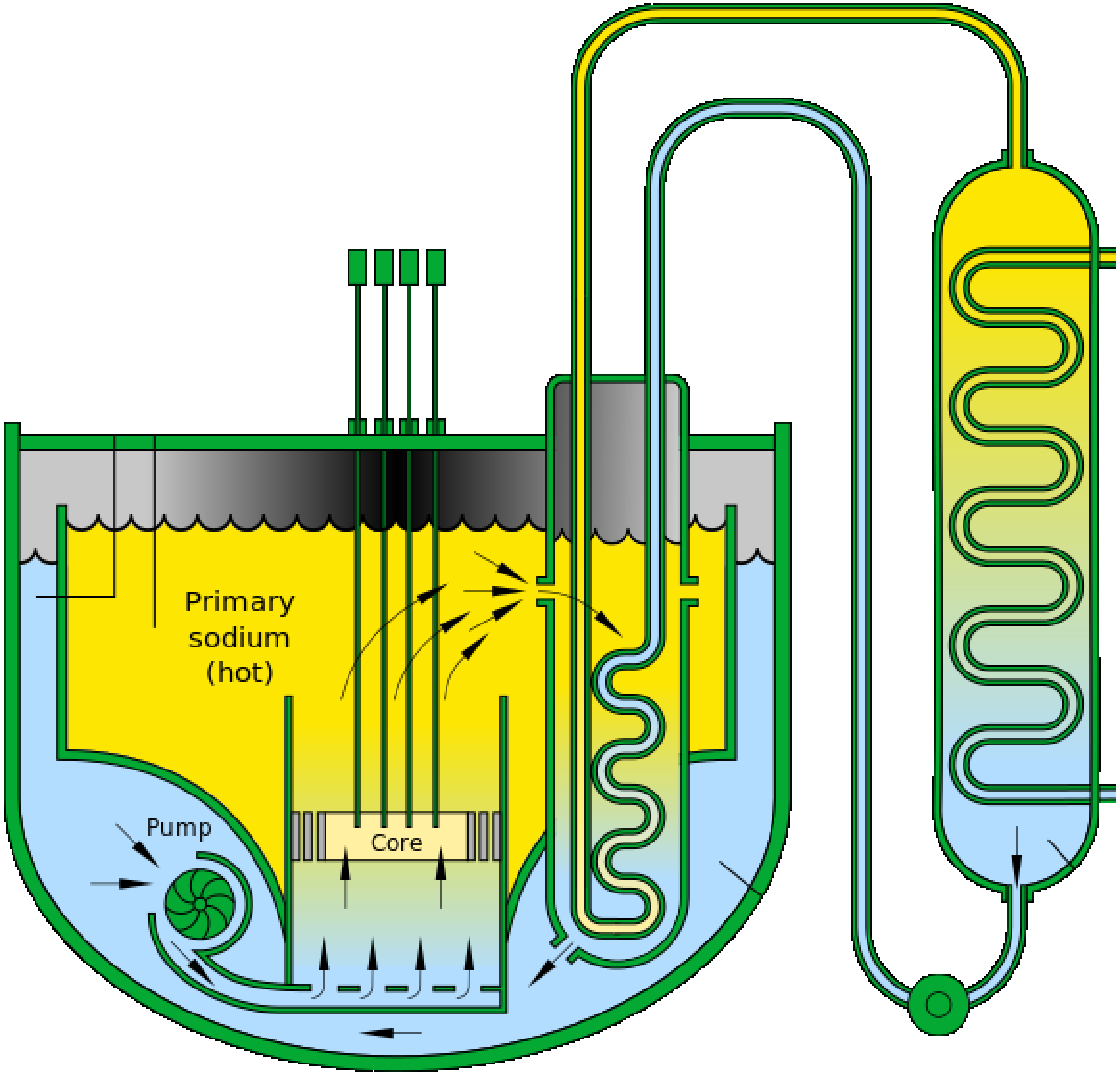


Gas cooled uses an inert gas (He, Ar, CO_2, etc.)

For a power generator, it needs a steam generator

For a rocket… jet the gas





Liquid metal reactors

Use a metal as a first-stage coolant and moderator

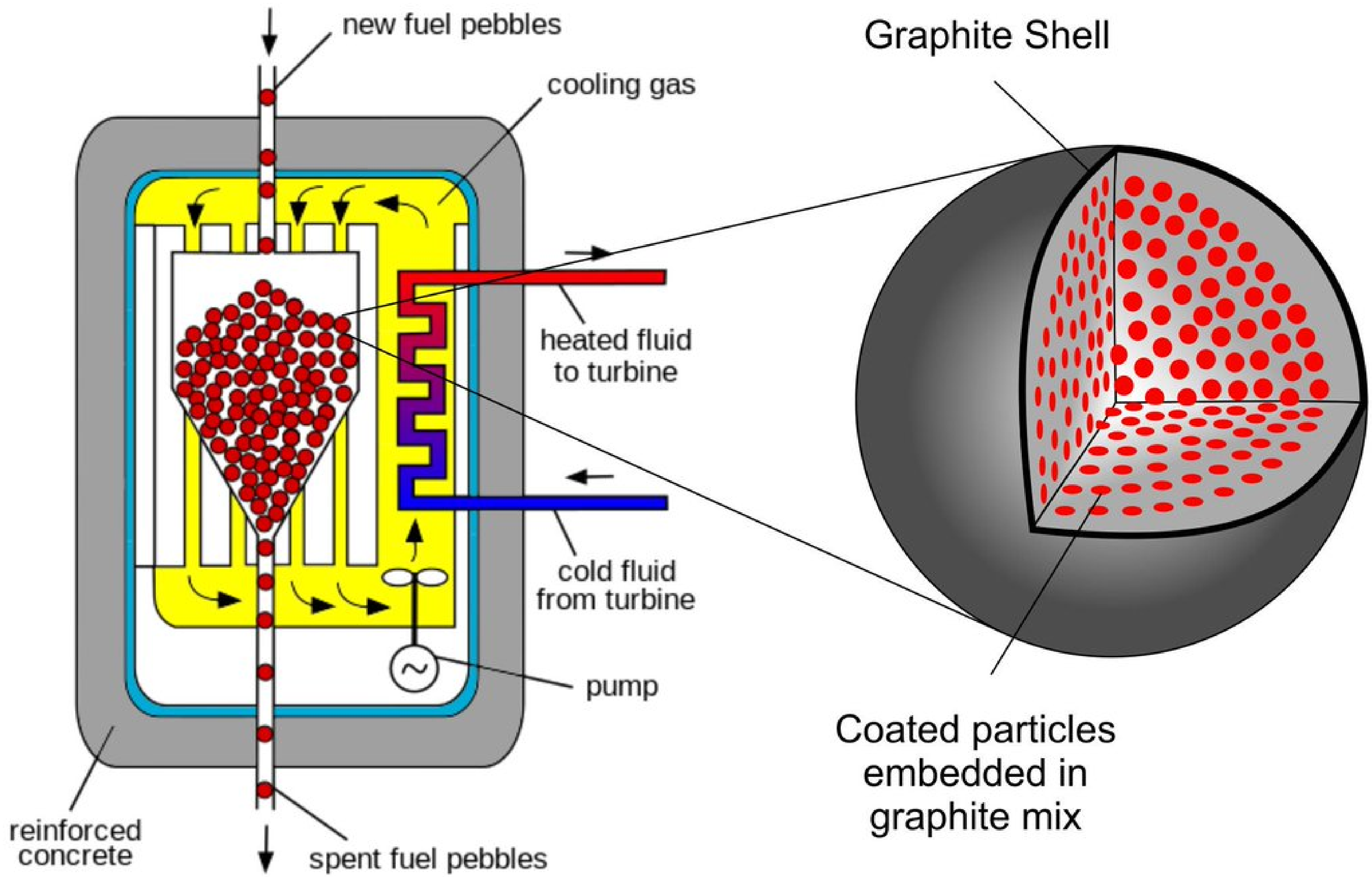
Sodium, lead, salt, and mercury have been tried

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)

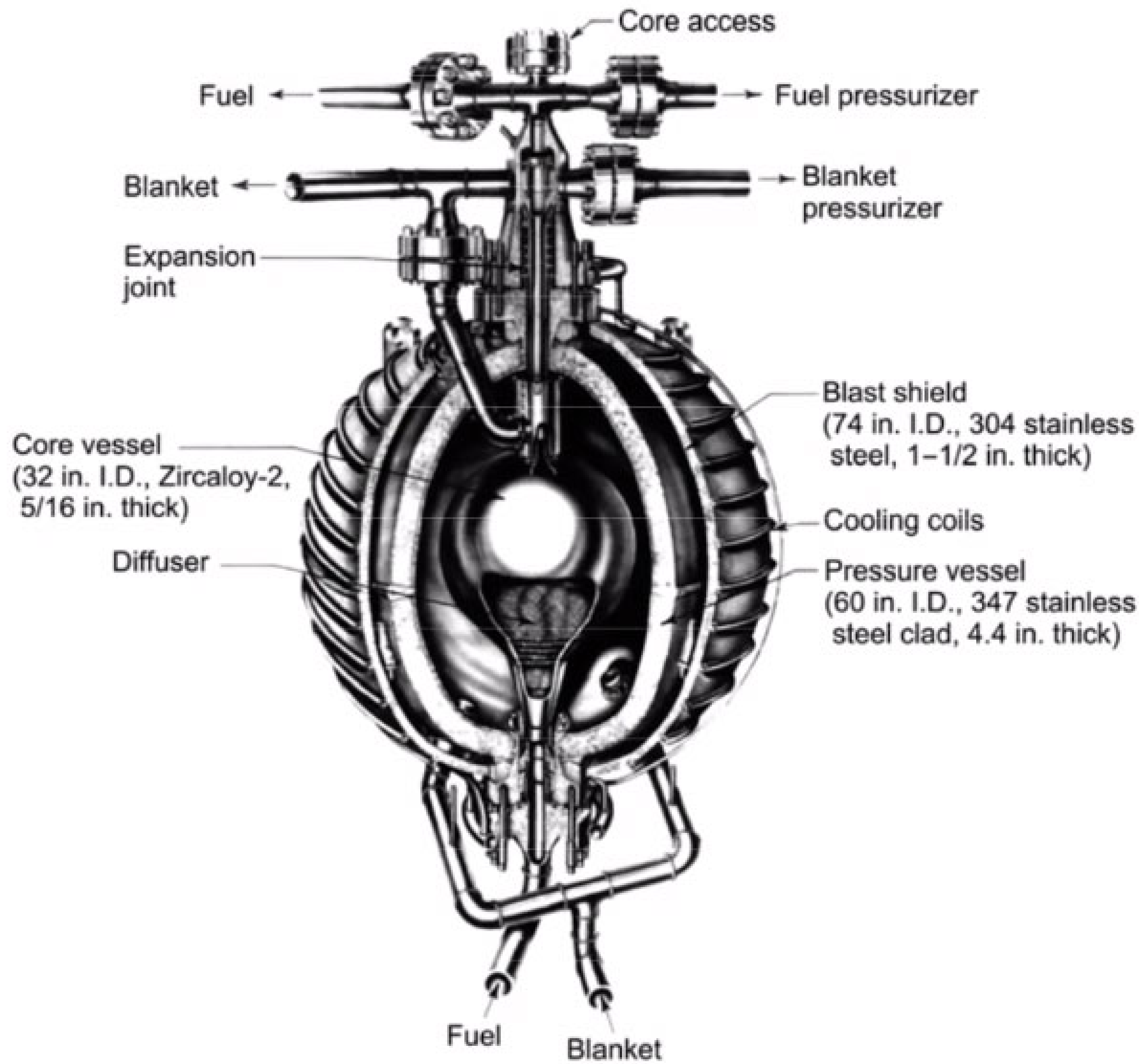


Aqueous core reactor

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

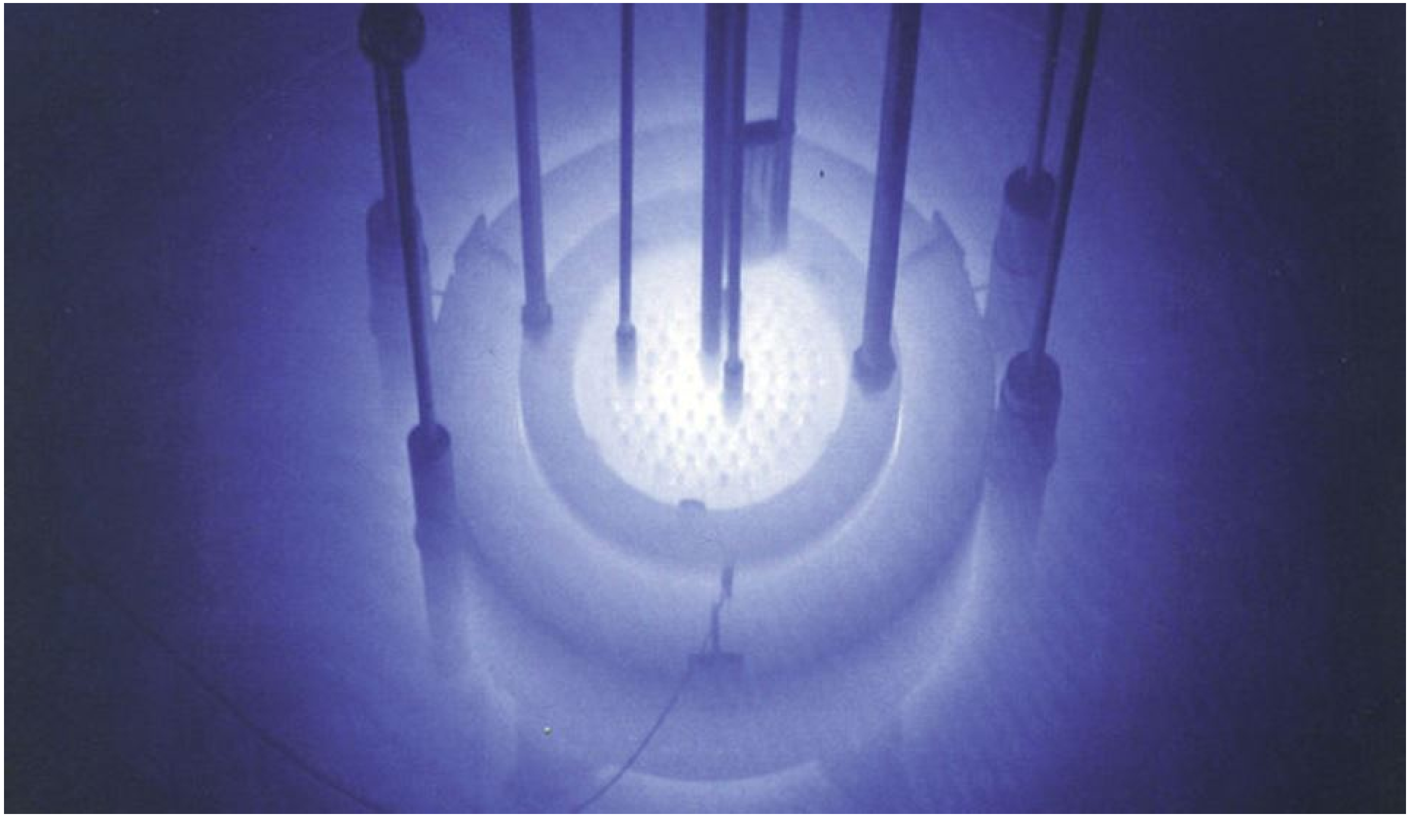


TRIGA

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

Reactivity (n) can be around “weapon” levels

Offers an intriguing possibility for propulsion



jcavera@blueorigin.com

Going from terrestrial power reactors to propulsion systems

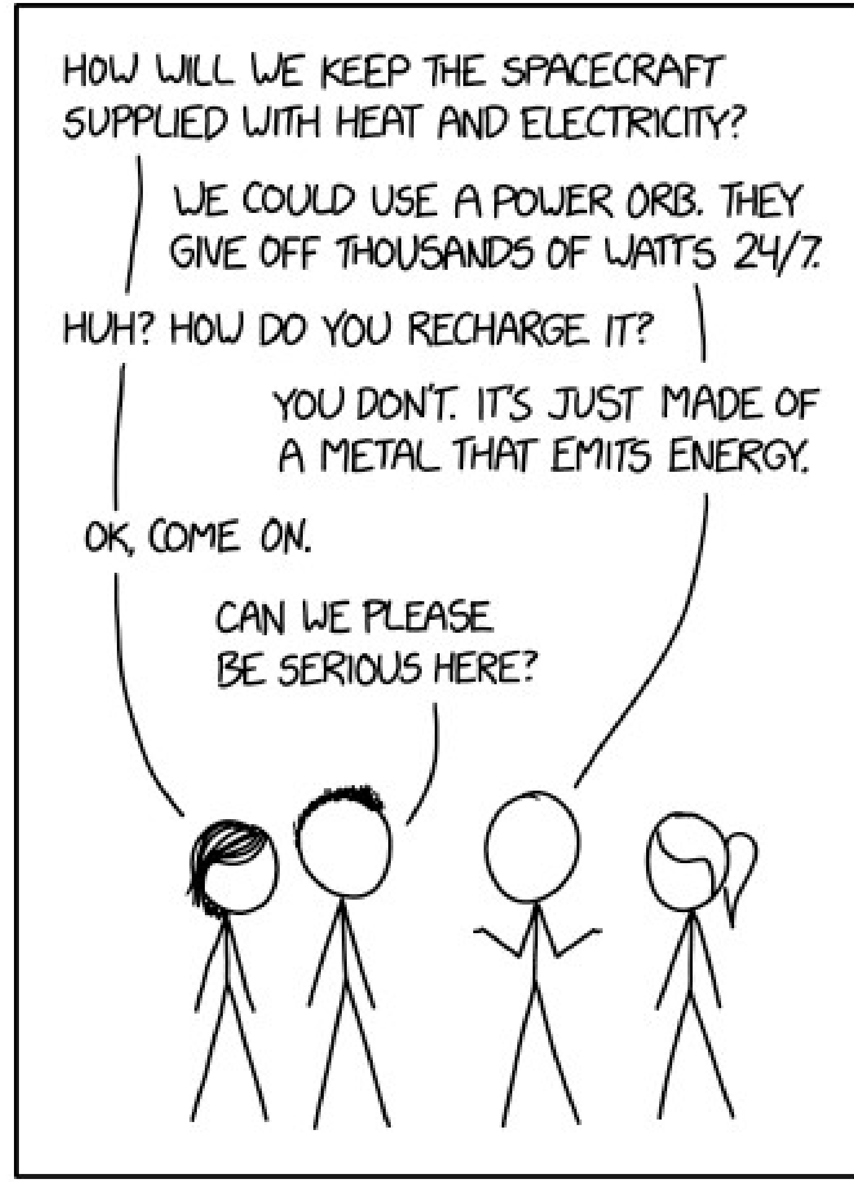
1) Start by getting rid of the coolant

2) And as much shielding as possible

3) Add a big tank of cryogenic hyrodgen

4) Run the hydrogen through the core

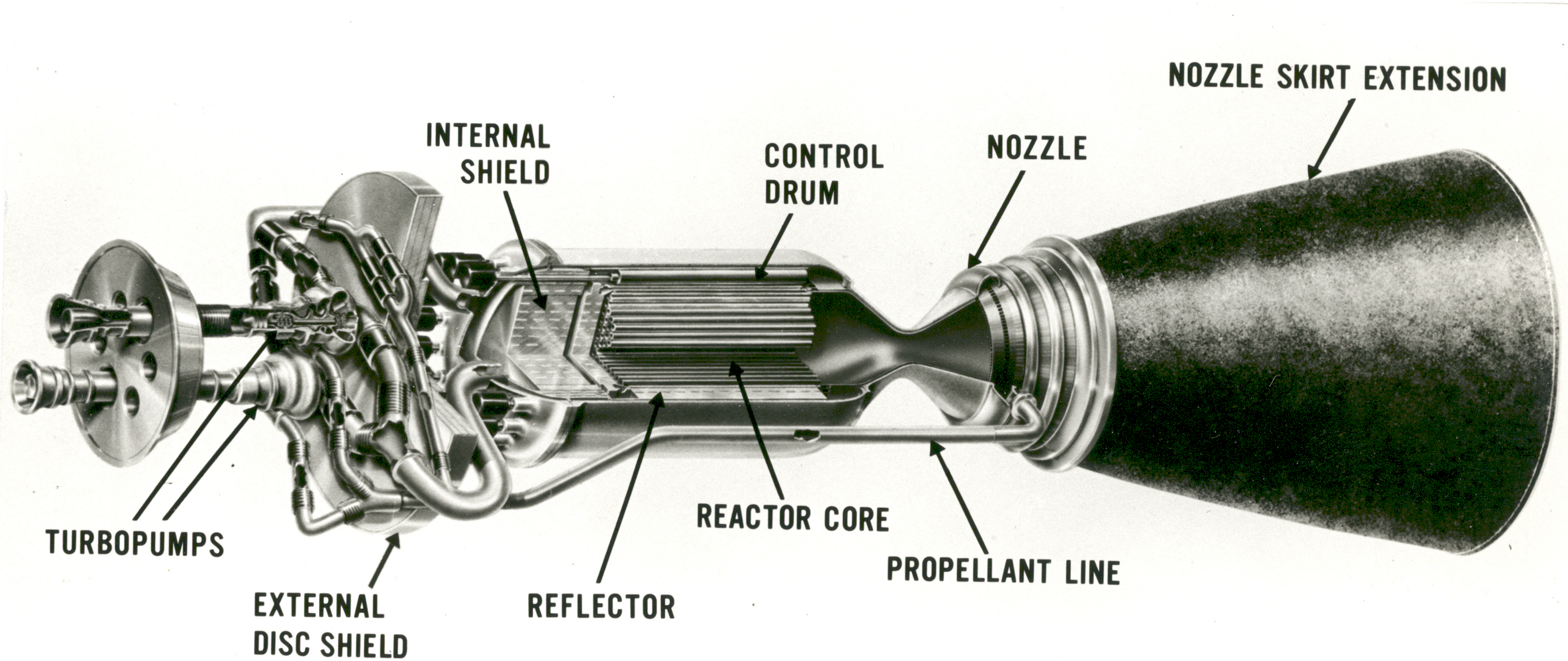
5) And jet it out the back



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...



The reactors in the previous table are the only (publicly) known nuclear thermal propulsion systems that have ever been built and tested.

Kiwi B1: Notable for its use of gaseous hydrogen as its coolant/propellant. It was the precursor to the rest of the Kiwi B test articles, all of which used liquid hydrogen and were designed for gigawatt power levels. It was postulated that there would be some neutronic and thermodynamic issues with using liquid hydrogen in a fully-controlled core (the A-series had only rudimentary controls for killing the chain reaction). These concerns did not materialize, and the rest of the Kiwi B's had good runs with the cryogenic working fluid.

Kiwi-TNT (not on the chart): This was a test of the survivability of the engine in the event of an accident involving a chemical booster stage. Essentially a copy of Kiwi B4E, the TNT model was brought up to power and then detonated (well away from anyone) by pulling out the controls and rapidly bringing the reactivity up to about six dollars, until the pressure vessel burst. Note that the explosion was mechanical in nature – the reactivity was not high enough for an actual nuclear detonation.

The Phoebus series were the first test articles designed for deep throttling and restarts (both hot and cold). They also made good use of instrumentation and closed-loop control such that the reactivity (and thus, core temperature) could be safely automated. The Phoebus series also brought to light some corrosion issues in the fuel rods.

The Phoebus 2A test article was the most powerful nuclear engine ever built. It had a design margin of five gigawatts and had a measured thrust of 1.11 MN (about 250,000 lbs.) at 80% power, beating its design estimate by ten percent.

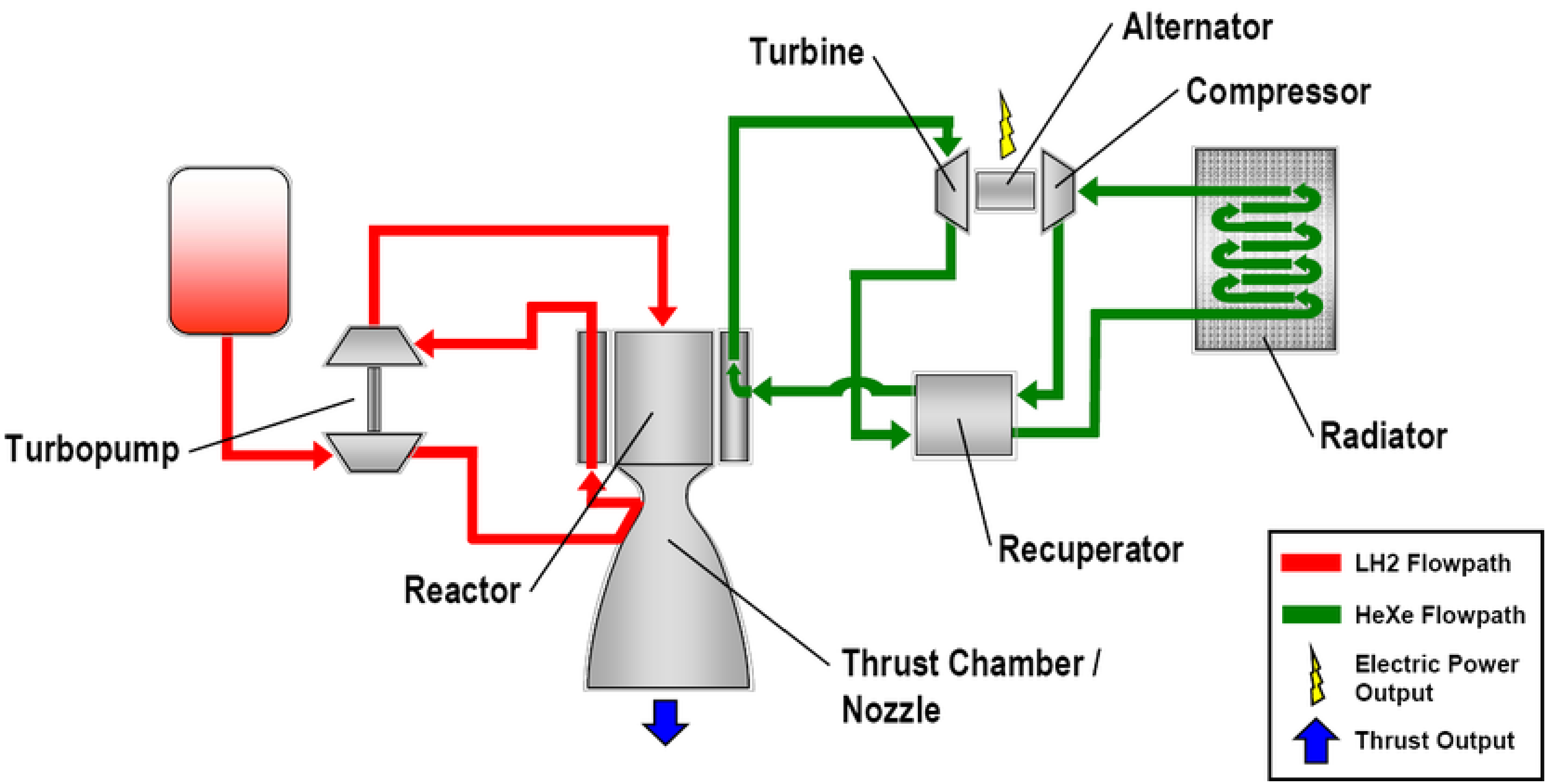
The Pewee reactor was a test bed for fuel element designs and not for producing insane amounts of power. As such, a number of element configurations and materials were tried, in order to best optimize burn-up fraction, neutronic configuration, and minimize fuel rod corrosion. The basic fuel rod geometry was the same as in the Kiwi series, but with different cladding (molybdenum, niobium-carbide, zirconium-carbide, etc.) and different levels of enrichment (from around ten- to about sixty-percent).

The NF-1 reactor was a continuation of Pewee, but with different moderation and cooling schemes as well. In particular, water was used as a moderator and coolant, and then run through a heat exchanger to simulate a bi-modal (power-generating as well as thrust-generating) engine.

The NRX series of test articles were designed as flight-engines (without actually flying). In this final series, every effort was made to minimize mass and maximize the level of automation. The XE was the final flight design and was a true hot-bleed-cycle engine with fully automatic controls. In its testing, it went through twenty-four separate starts and re-starts, many of them from cold conditions. Because it was the only design ever truly considered a “flight engine”, it’s the only one that has a good measurement of the thrust-to-weight ratio. The XE test article (sans fuel) massed a hair over 40,000 pounds for a TWR of about 6.75.

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".



As an example of a tri-modal engine, Pratt and Whitney, Aerojet, and NASA performed a design study of an engine called "Triton" (for obvious reasons). This was meant to be an actual flight article, but sadly, never made if off the drawing board. The specifications were impressive enough. In "normal" NTR mode, specific impulse was calculated to be between 900 and 1000 seconds, with a thrust-to-weight ratio of about 3.6 (thrust of about 22 kN). In LANTR (LOX-Augmented Nuclear Thermal Rocket) mode, specific impulse would drop to around 600, but thrust-to-weight would jump to around 10 (thrust of about 330 kN). Power generation in both cases was projected to be around 100 kilowatts.

The Triton design made use of a cermet fuel rather than the traditional fuel rods as in the Rover and NERVA programs. Unlike standard uranium oxide rods, cermet fuels (a ceramic-metal matrix made from uranium and zirconium) are fast-spectrum reactive. Thus no moderator is needed, further saving weight and simplifying the core design.

jcavera@blueorigin.com

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

Isp ≈ 50,000 sec.

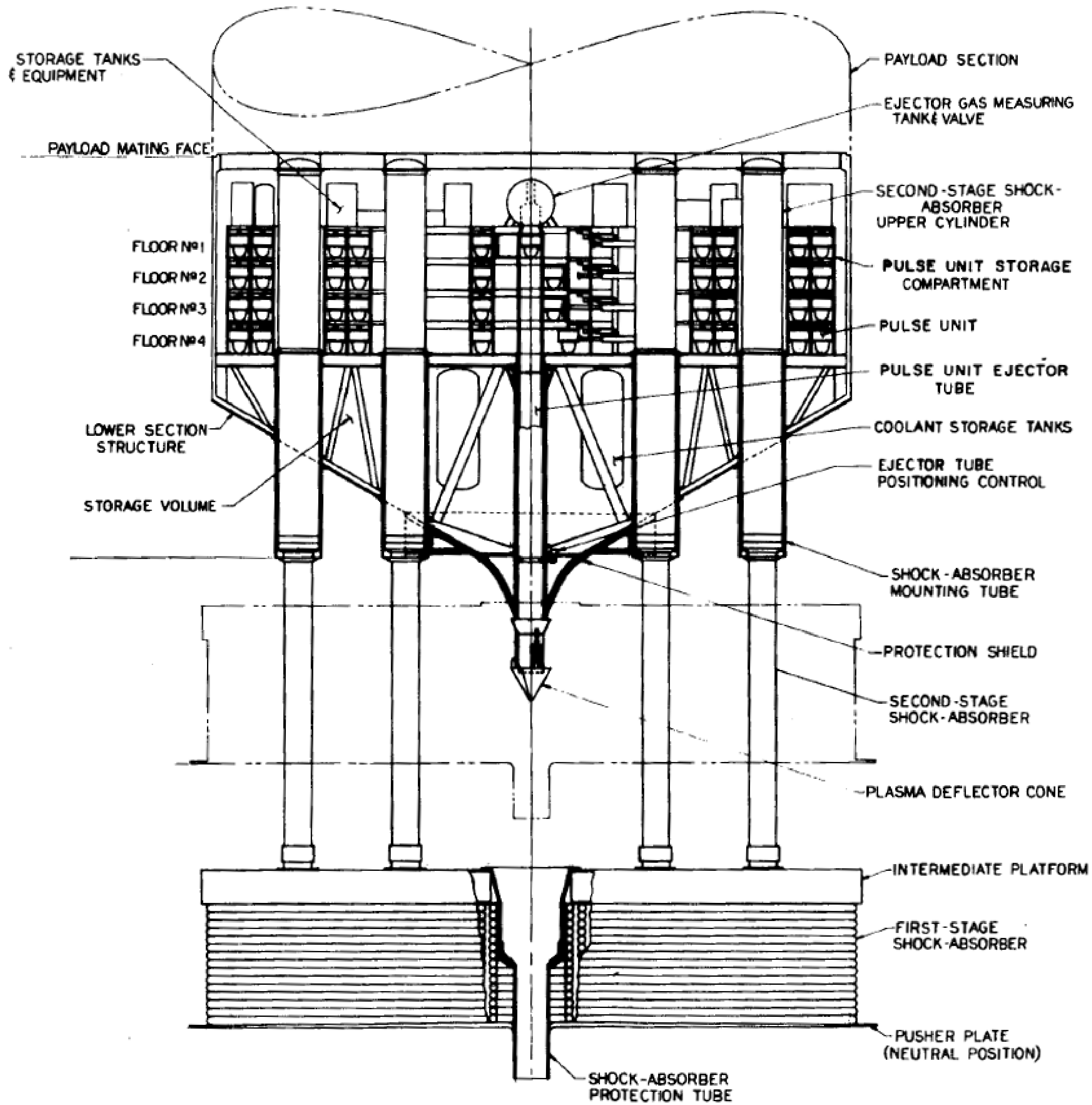
Thrust ≈ mega-newtons

Vehicle mass ≈ 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.

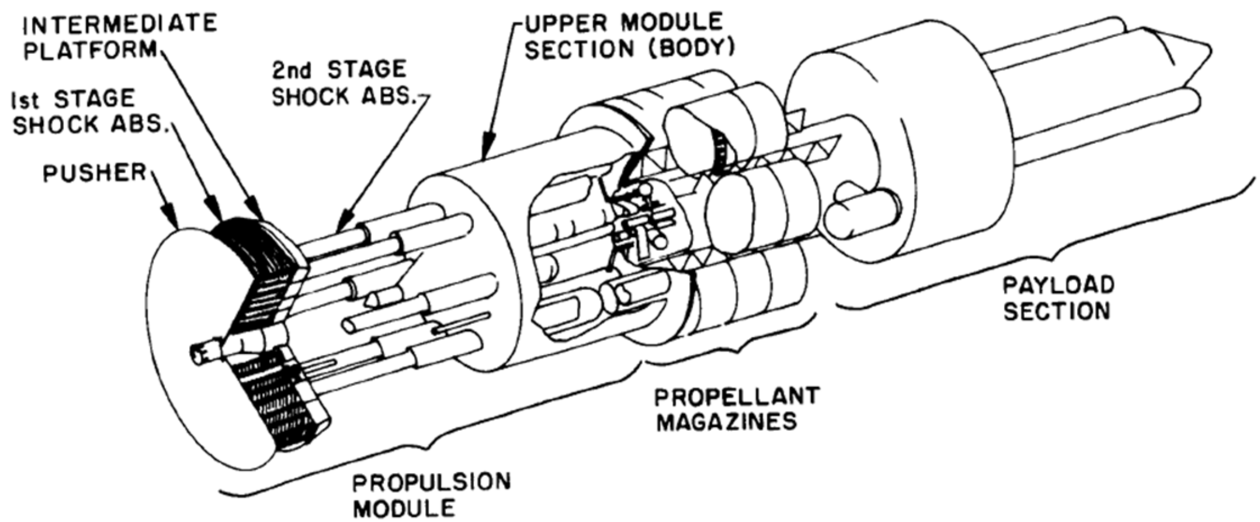
Orion takeaways...

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.

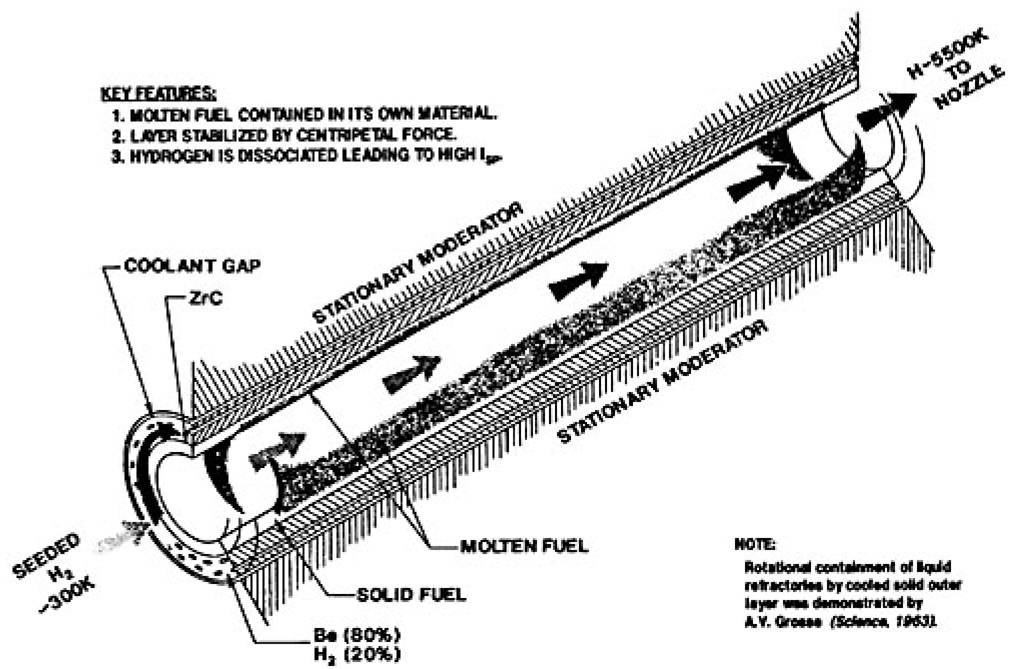
3) Getting off the ground would be disastrous, but in-space? Maybe so.

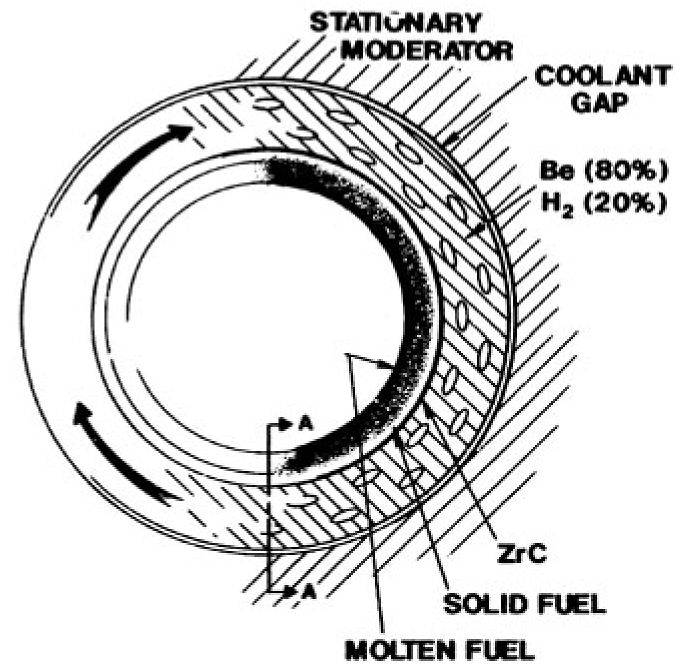
4) Turn fission to fusion, the bombs to pellets, and we may have something.



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)

jcavera@blueorigin.com

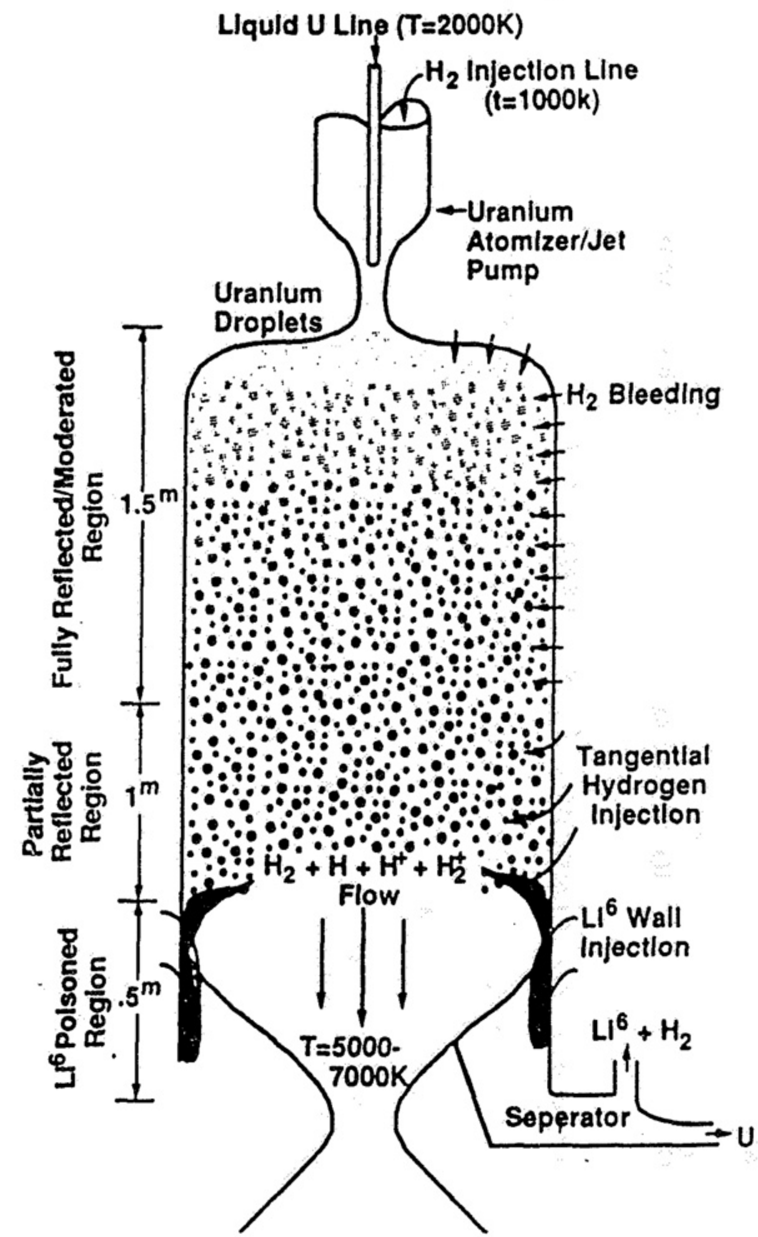
Liquid core can give an I_{sp} of about 1500 sec. But why stop there?

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

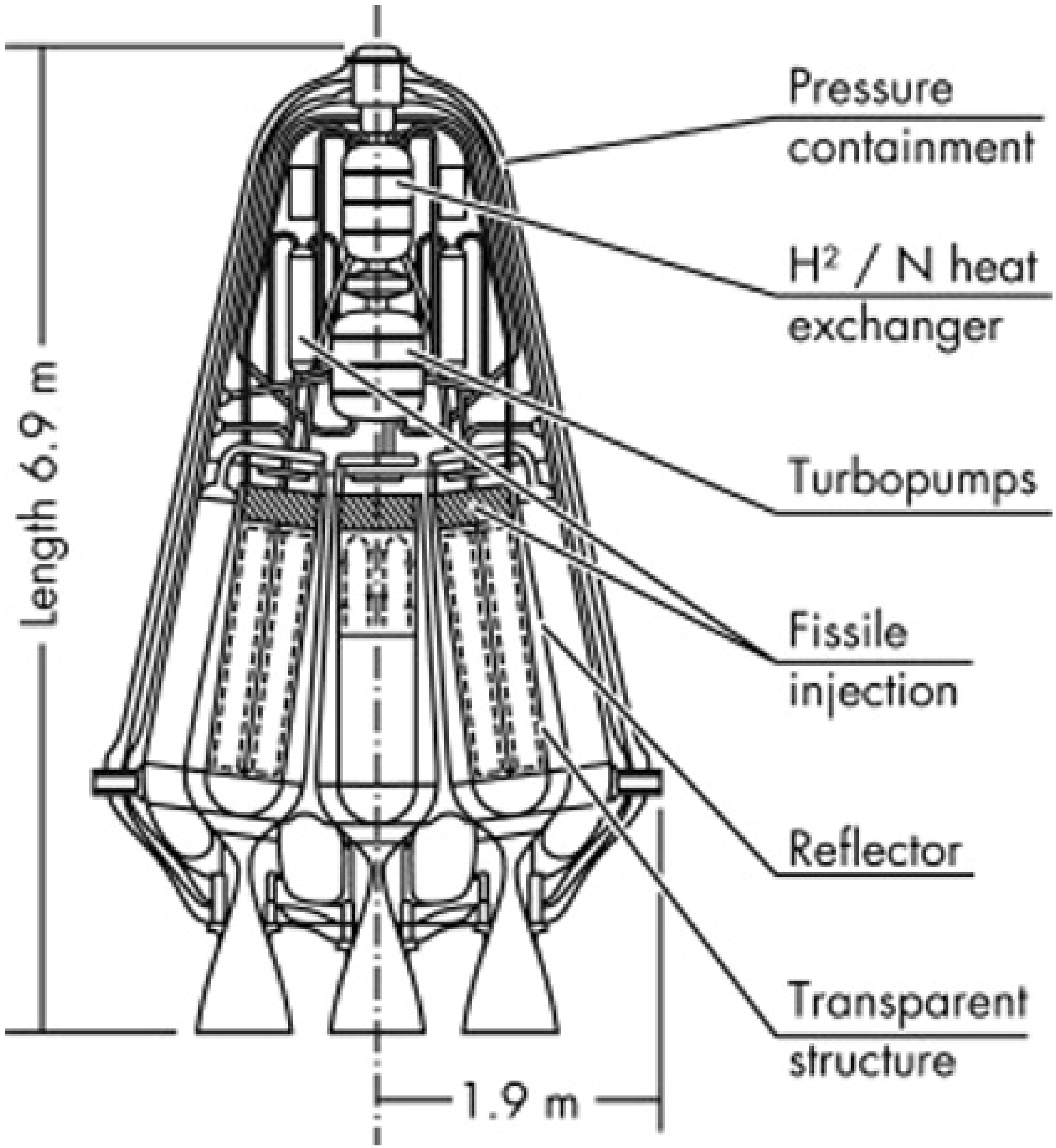
Enriched uranium hexafloride is contained in a quartz bulb

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

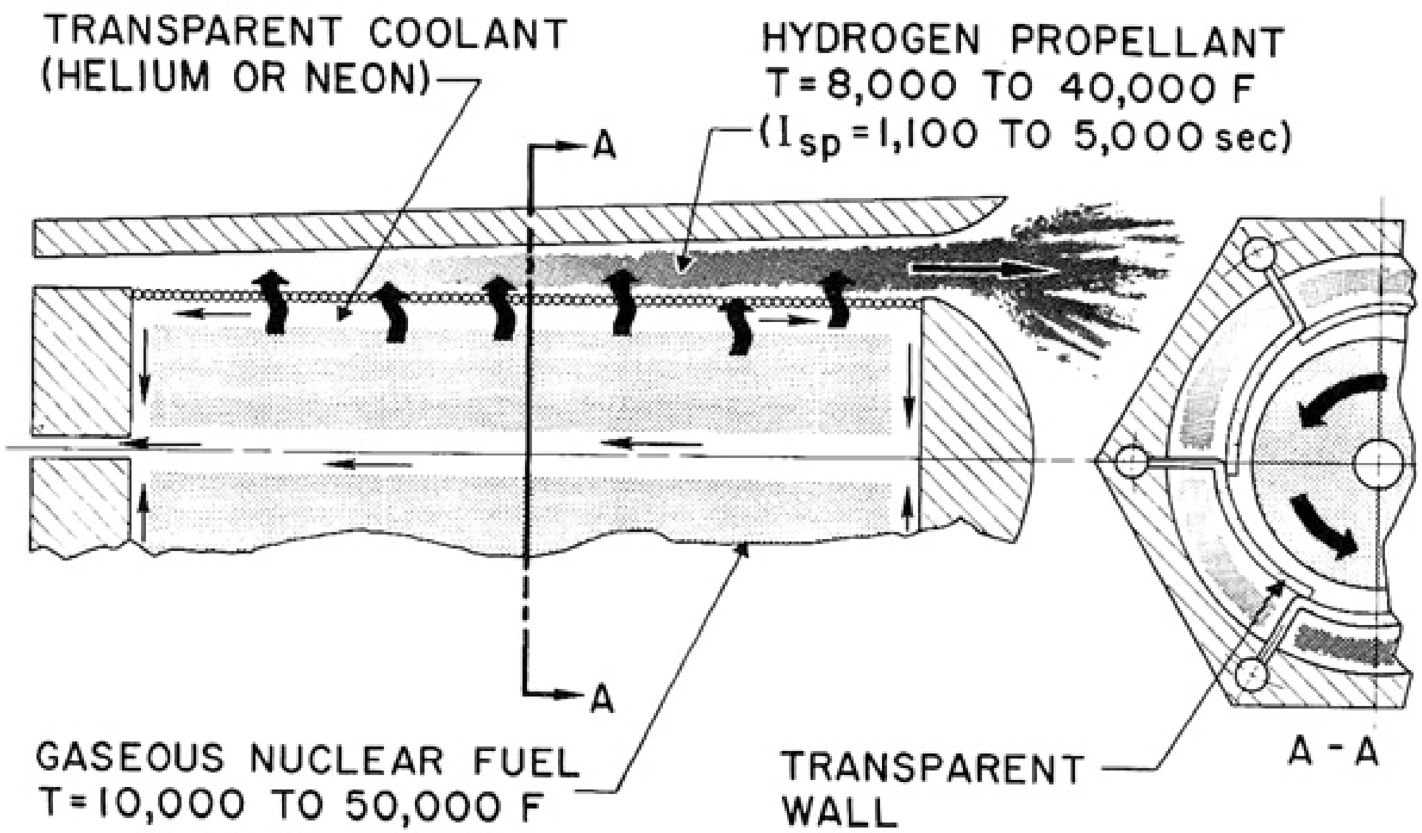
I_{sp} up to 5000 sec.

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.

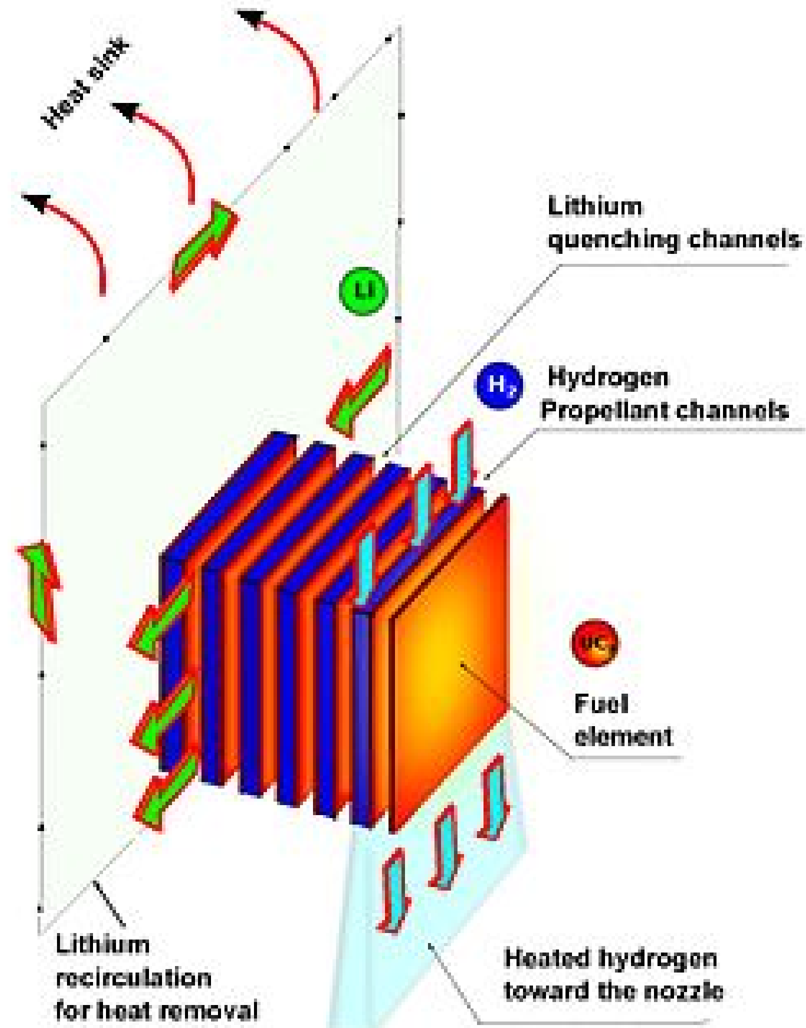
All of the previously mentioned concepts (barring Orion) are heat engines and can only get more efficient by turning up the temperature. So let's ditch the whole heat engine idea.

Remember TRIGA reactors? Every time they pulse, the 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?



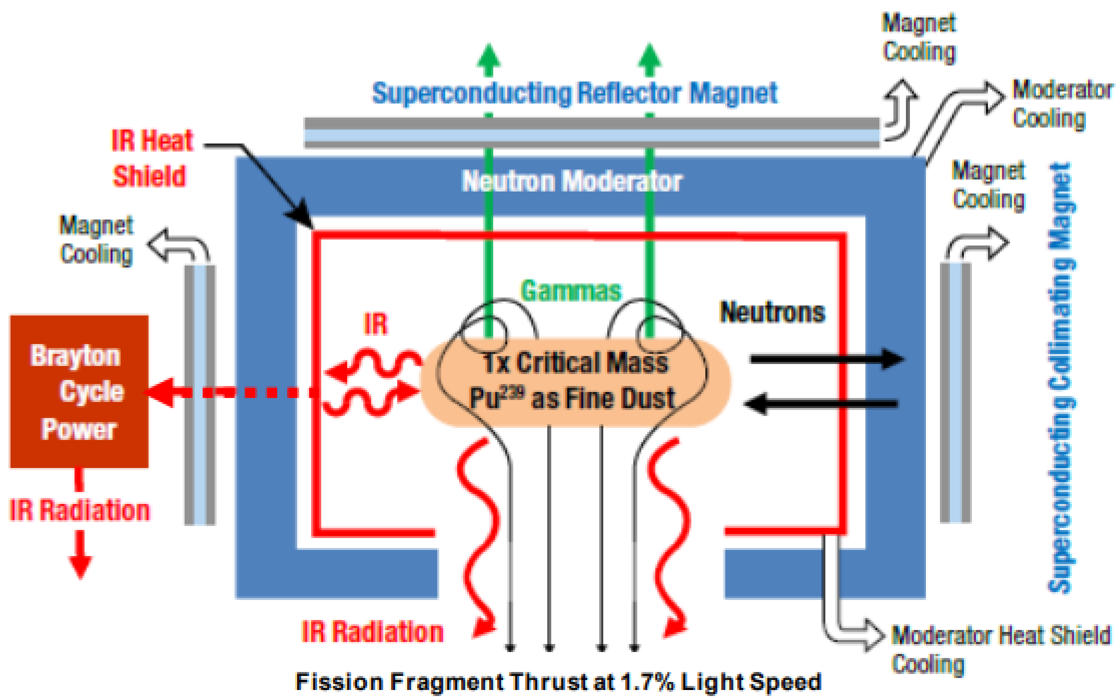
While we're discussing that, why bothering transferring energy at all? A fission fragment rocket simply jets the high-energy particles themselves.

On the upside, Isp 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):

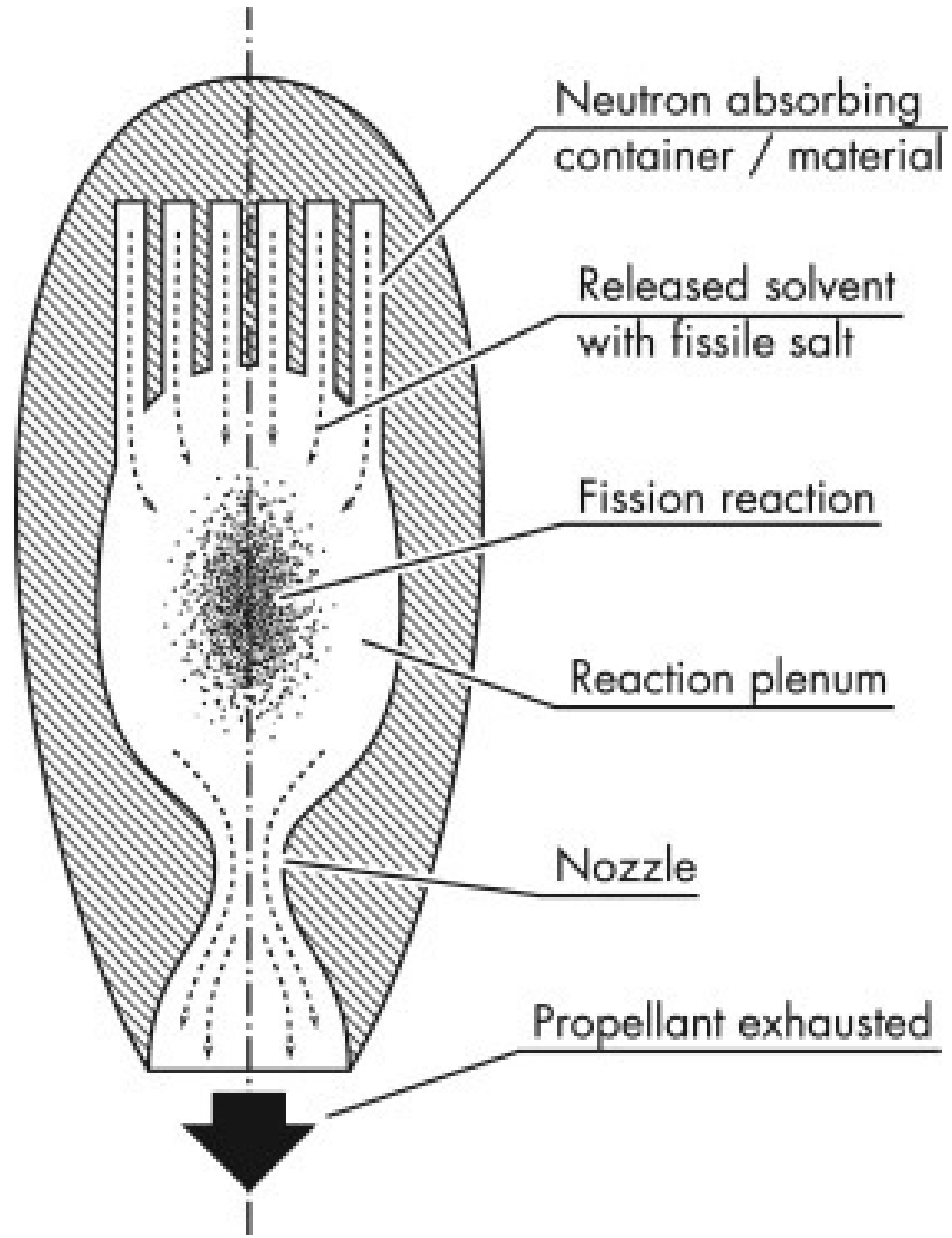
Thrust = 15,000,000 N

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?