EASTERHEGG 2019 BUN INTENDED

Nuclear Propulsion

from the somewhat reasonable to the utterly insane

By Paul Hayden

Source for background:
https://signs.cyber.cooking/eh19/

Rockets are tools to make you go faster. Orbits aren't characterized (just) by their position, but by the velocity they require.

The faster things go out the backside of a rocket, the more efficient the propellant can be used.

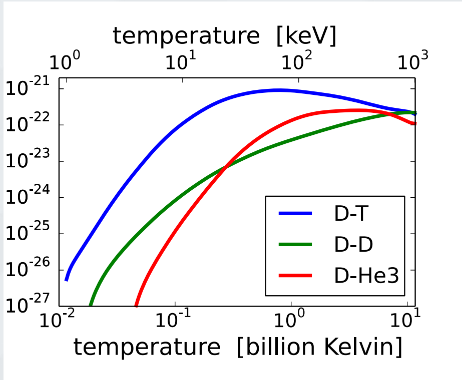
Generally speaking, the hotter the rocket burns and the lighter the particles expelled are, the faster they are expelled. $v \sim \sqrt{T/M}$

Efficiency of engines is measured in "specific impulse", or I_{Sp}, given in seconds, as it's roughly approximated as v_{exit} /(9.81 m/s²)

I_{Sp} of chemical rockets <500s

Fusion Challanges

- Keep temperature high
- Keep pressure up
- Can’t touch walls

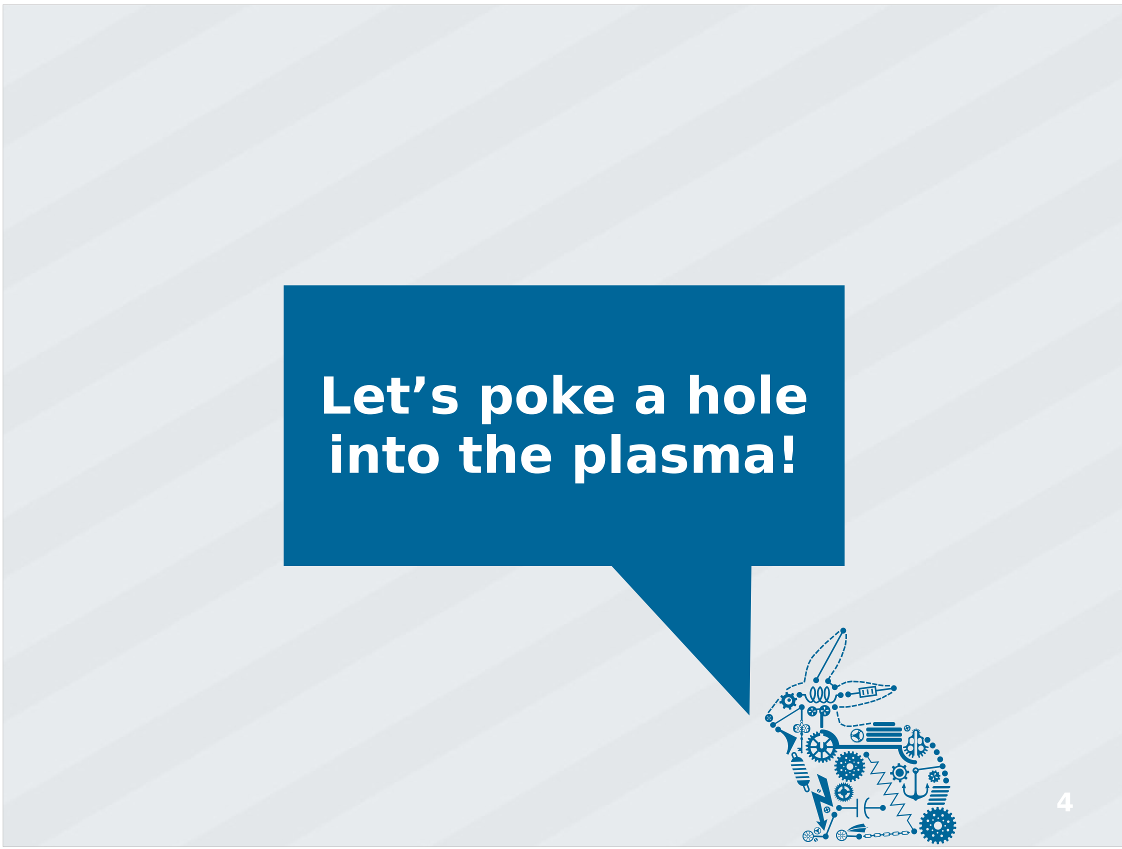


Fusion requires super high temperatures, reached only in a plasma.

Plasma is so hot it radiates in the hard X-Ray spectrum.

Since heat-flow is determined by temperature-difference, the plasma looses all its energy when touching a wall.

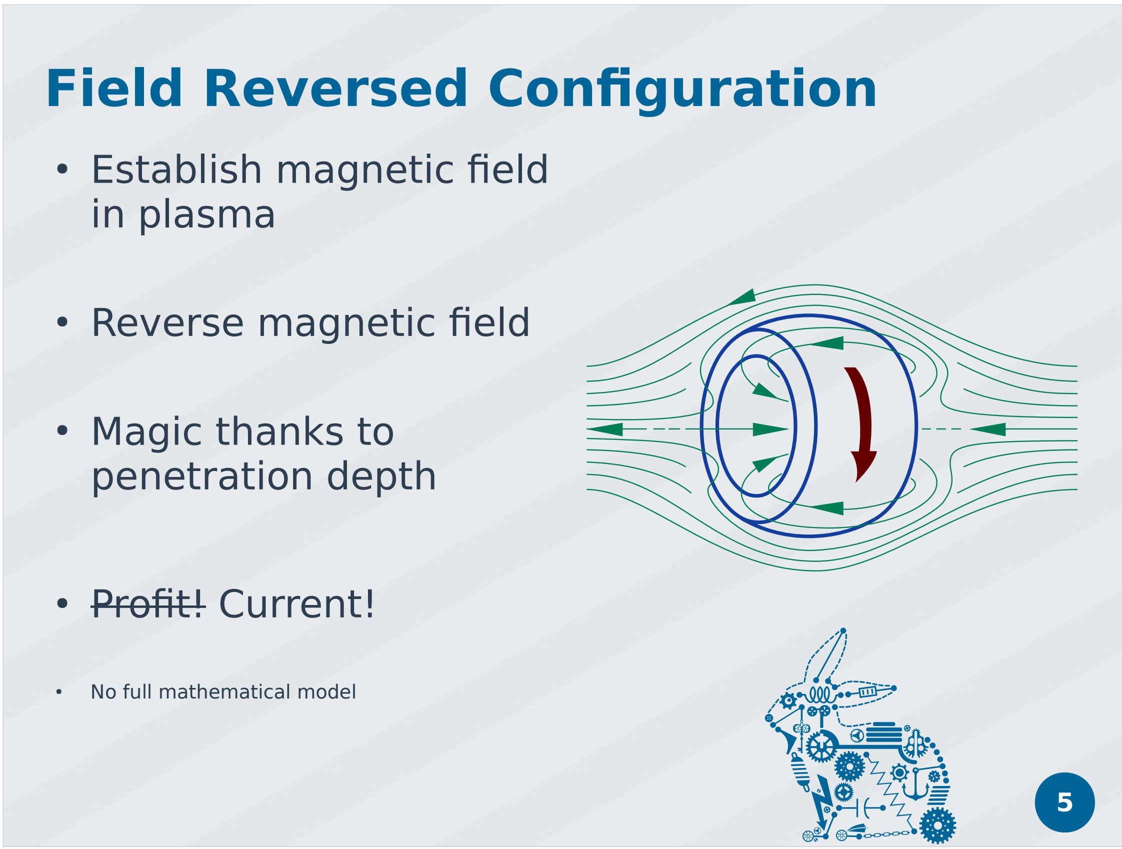
Different elements require different temperatures to fuse. Deuterium-Tritium is easiest, which is why hydrogen-bombs use it. Deuterium-Helium3 is doable, but difficult. Other processes, such as CNO-cycle, require even higher temperatures.



Rocket = hot pressure vessel.

Nozzle = hole in the pressure vessel.

Today’s “fusion reactors” aren’t up for the challenge.



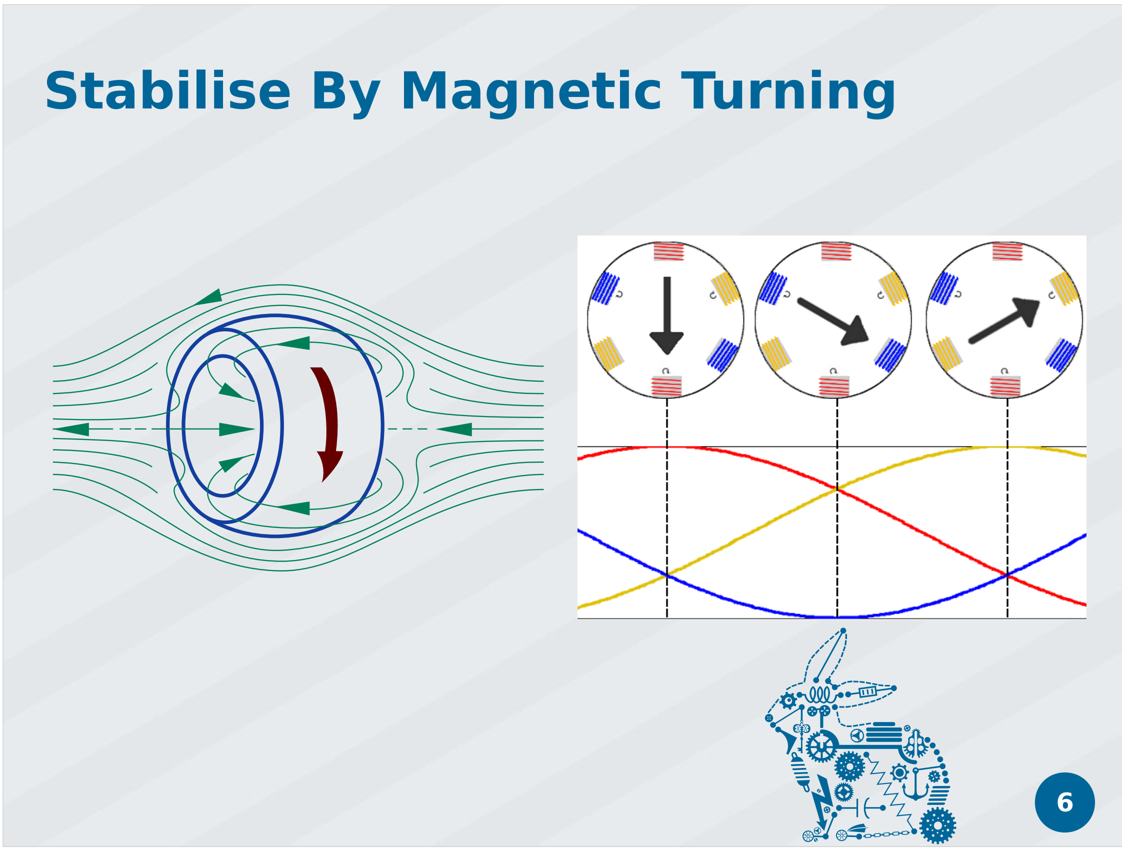
Donut-Plasma is stable for some time.

Have plasma with magnetic field in one direction (e.g. by igniting plasma <u>after</u> establishing magnetic field).

Quickly reverse magnetic field. Can’t penetrate through whole plasma, field outside reversed of magnetic field in center

Requires donut current. Once that current is lost (due to electric resistance), donut collapses

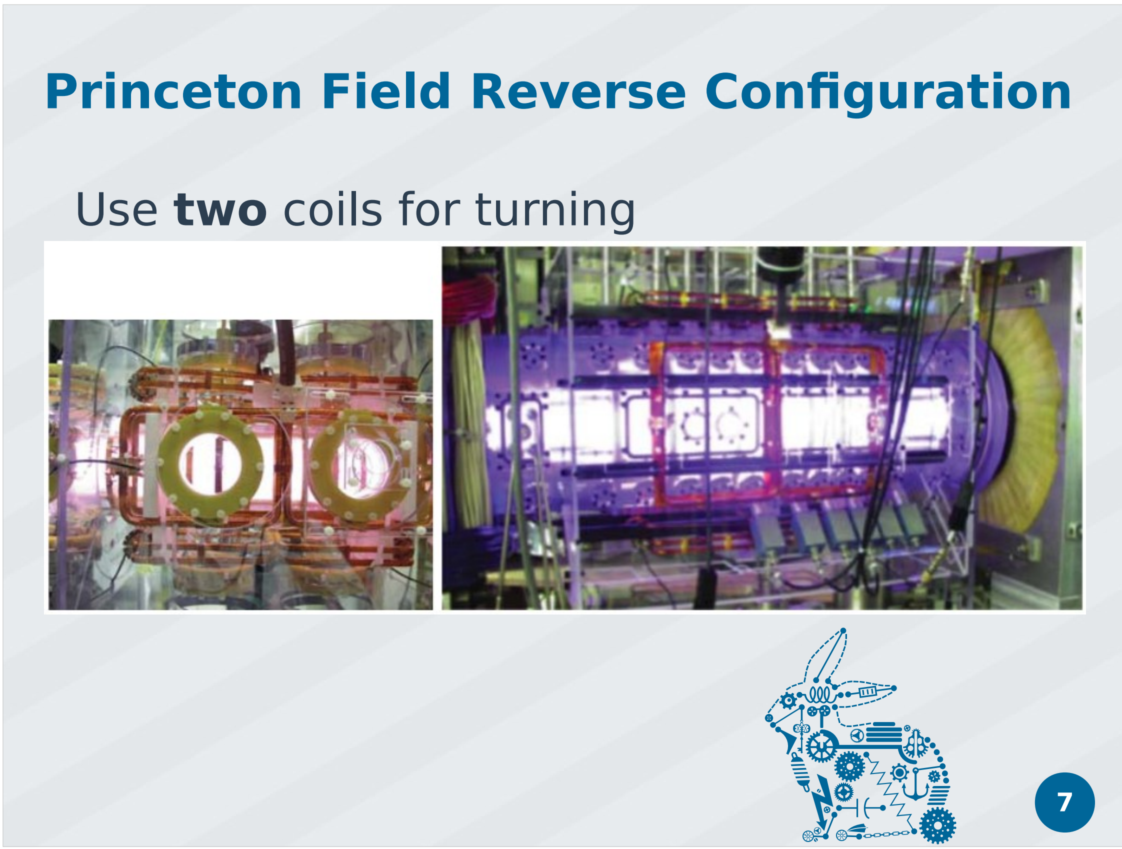
No full mathematical description, equations break down in 0-mag.-field-region



Kicking the current continuously should enable stabilizing current for longer time.

Essentially, this wobbles the donut circularly

Problem: If a single loop is used as in a motor, the confinement breaks. It requires TWO loops to push and pull the donut.

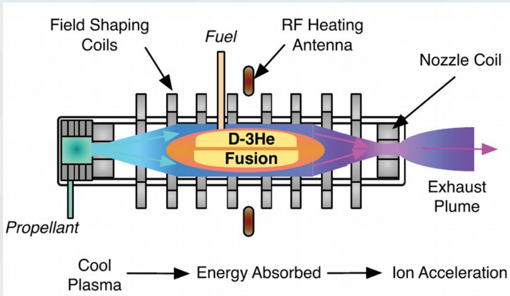


Princeton managed to build confined helium plasma, up to about 30ms now.

They also wrote the first simulation of the zero-magnetic-field region, using their own fortran-implementation to solve for zero-mag.-field-position.

PFRC Claims

- ^{3}He fusion
- Low neutron production
- 1-10 MW reactor
- Heat source for propulsion plasma



Proposed to use confinement for fusion rocket:

Use fusion to heat up bypass plasma

To keep neutron-load on magnets low, use He3-D fusion. Problem: Requires higher temperatures! Advantage: Neutron would take away ~ 4/5th of fusion-energy, impact walls. Proton on the other hand remains confined, heating the plasma, keeping neutron-load on walls low.

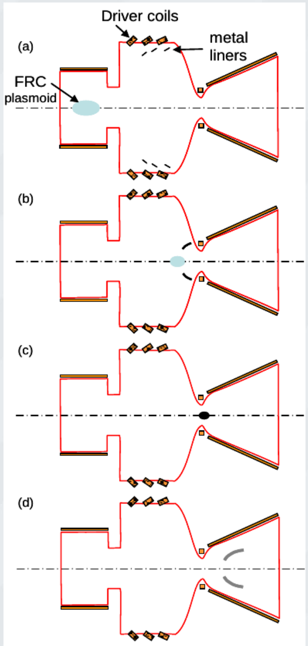
Low neutron-load means thin neutron-shields means less mass.

Claim to be able to build 1-10 MW reactor at 10T.

… if they manage, I want one!

Magneto Inertial Fusion

- Accelerate 3 metal bands towards plasma-ball
- Increasing magnetic flux compresses plasma
- Start fusion by compression-wave



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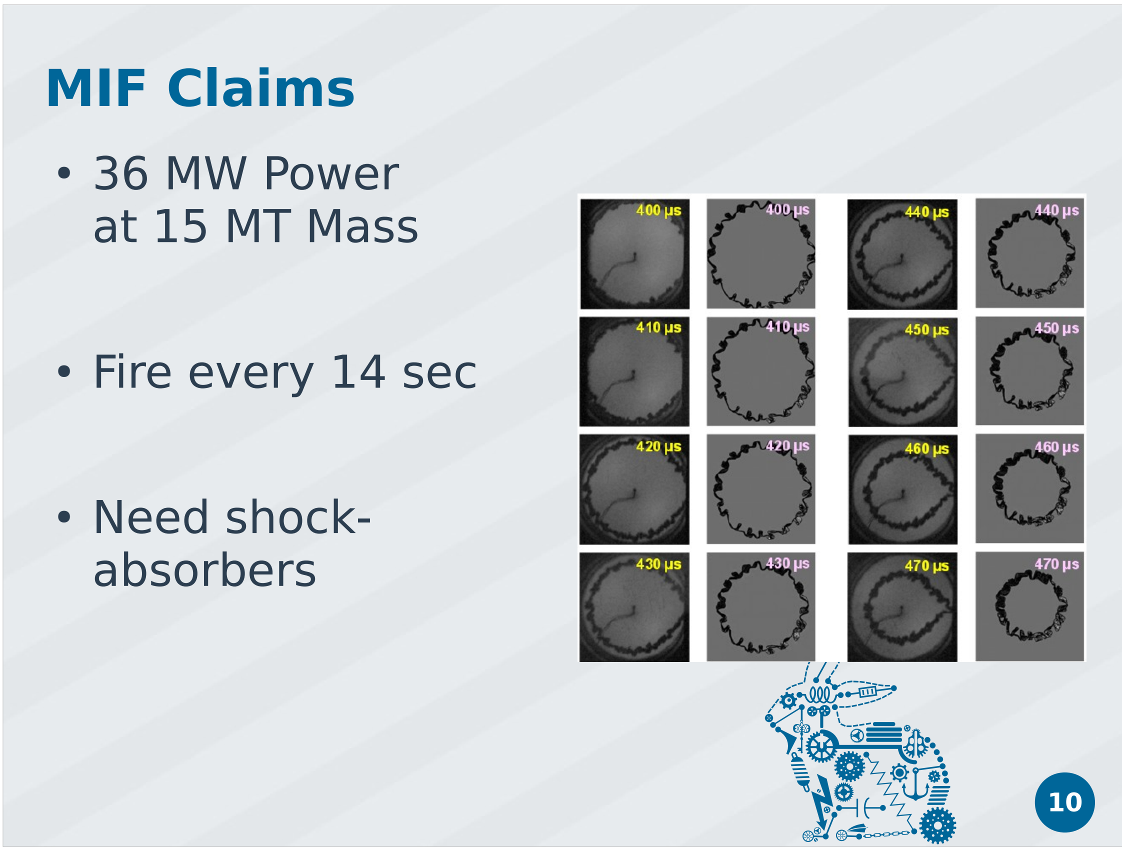
NASA themselves is developing to fuse plasma-donuts by quickly increasing applied magnetic field

They induce high currents by quickly changing magnetic field applied to 3 metal loops. Induced current + field propel rings inwards.

As loops grow closer, induced current is aprox. constant, so magnetic field inside grows rapidly.

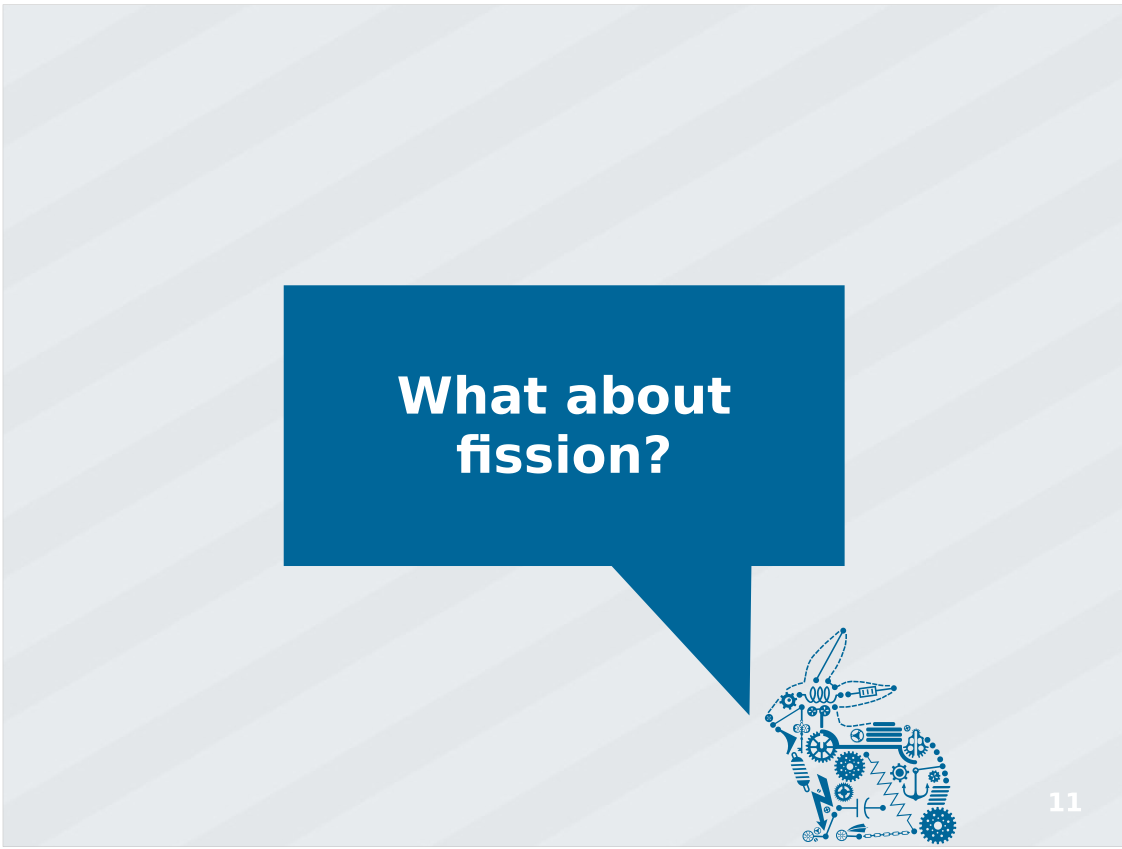
High magnetic field results in high pressure, causes fusion, metal rings vaporise and can be accelerated backwards.



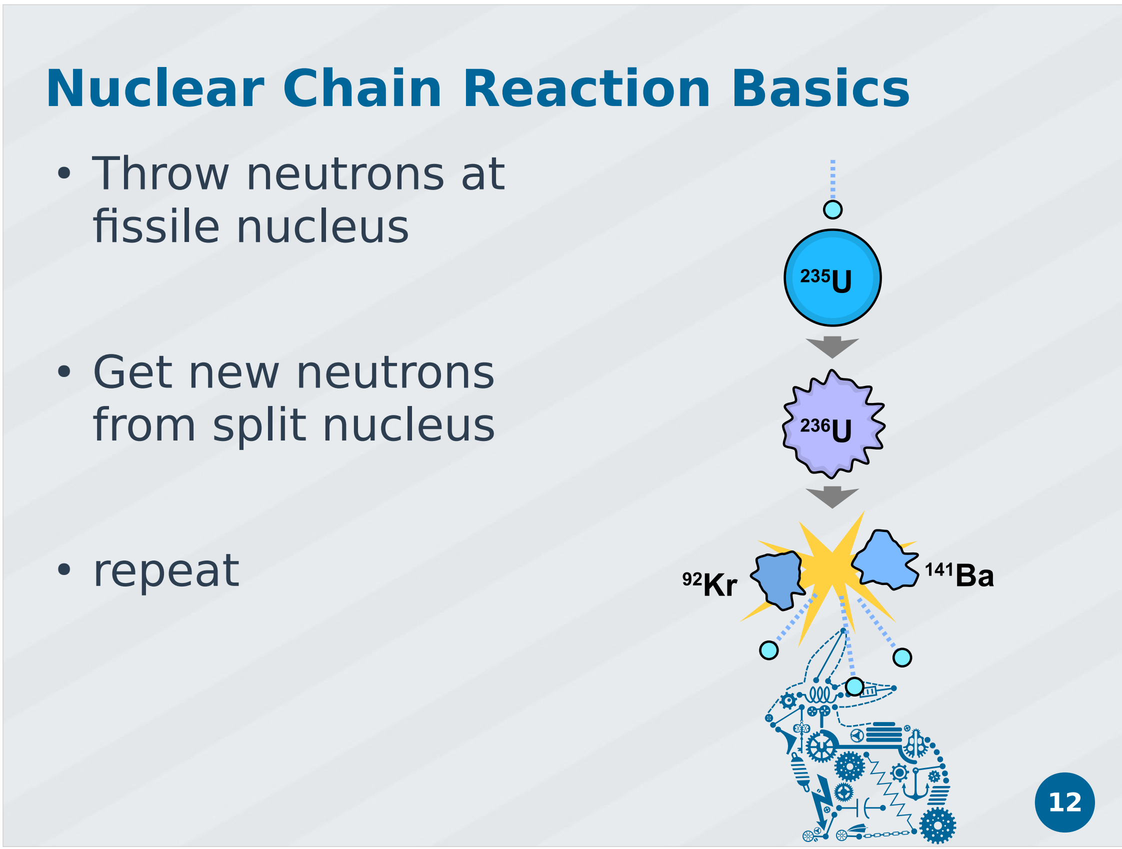
Toy model: about 36MW from a 15MT engine, Princeton can do a lot better.

Low power due to long dead-times of ~14 sec to refill metal loops.

Essentially singular detonations, so a shock absorber between engine and ship is required.



Fusion is hard to implement. What can we do with nuclear fission?



General principle: hit fissile material with a neutron

Material splits in two, releasing neutrons

Neutrons do more fission

that’s all we need to know to build nuclear bombs.

Energy-budget: ~95% of immediate energy is released as kinetic energy of fission fragments, ~5% is released as kinetic energy of neutrons, <1% is released as x-rays.

Project Orion

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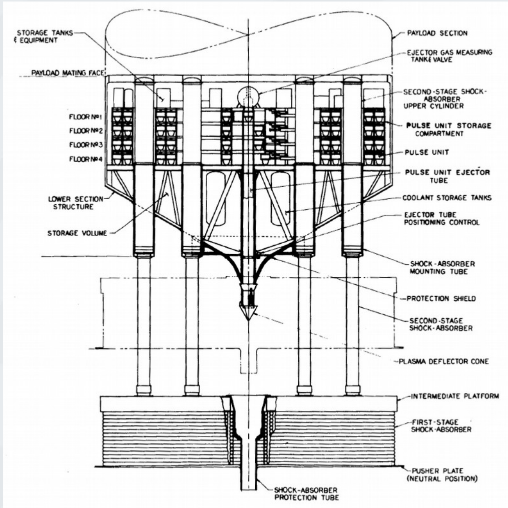
Riding a nuclear blast

Riding Nuclear Bombs

- Very well tested technology
- Up to 3% speed of light
- Just 1 radiation death per launch!



Ultra simple design (maybe use shape-charge bombs)

Throw nuclear bomb behind ship
Detonate
Capture shockwave (of vaporised metal)

requires pusher plate and shock-absorbers, but no complex mechanic behind shock-absorbers

Isp of 10 ks – 100 ks

If used in atmosphere, just 1 rad. Death / launch!

Where Do Neutrons Come From

- Fission releases few *prompt neutrons* — ~10^{-15} sec. control constant
- Fission products decay, release *delayed neutrons* — ~10^{-2} sec. control constant
- Delay required to control reactors
- No delay → bomb

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Control-systems need some time to react.

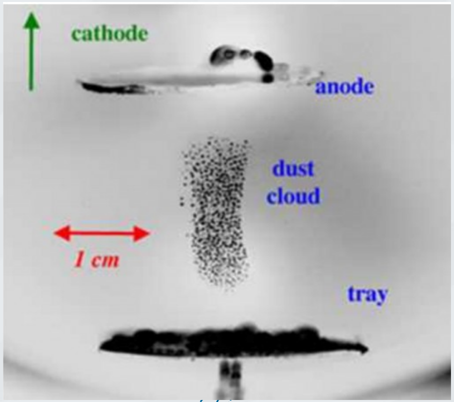
Neutrons from fission itself react too quickly, reactor could go off the rails (explode or shut down) before any system might intervene.

Delayed neutrons provide additional time. They come from fission fragments when they decay.

Without delayed neutrons, there is no way to control a reactor. That’s called prompt-critical and is how a nuclear bomb works.

Nuclear Dust Drive

- Keep tiny particles in magnetic field
- Fission fragments leave particles
- Direct particles outwards w. magnets



Use tiny dust particles because of two reasons:

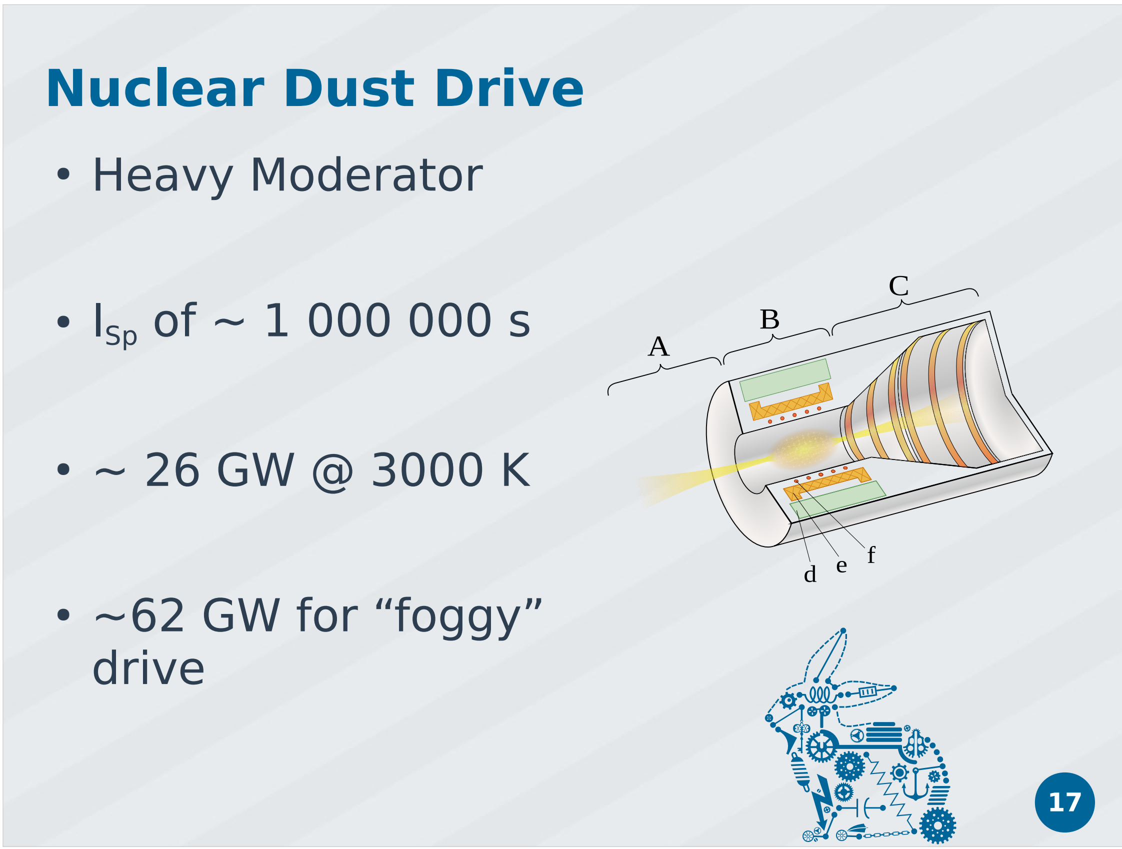
High surface => lots of radiation!

Fission Fragments are so small that they leave the particle with >99% chance

Fragments get 95% of fission-energy, which can then be used for thrust.

Particles may be held in a magnetic bottle, since the fission process constantly charges them.

Loosing fission fragments means loosing delayed neutrons. Bummer.

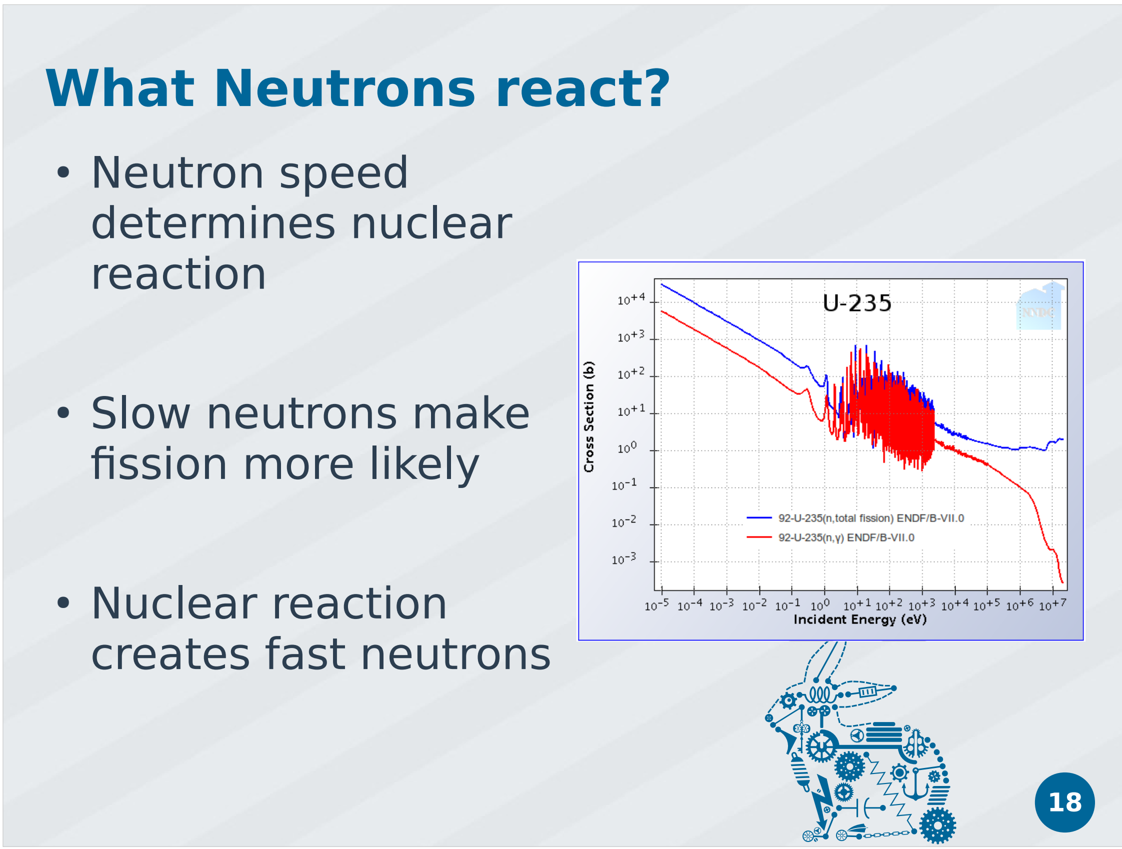


B: actual drive
A: plume
C: decelleration generator

Fission fragments gain energy directly from fission, so they are super fast. Directing them outwards allows for extremely high I_{Sp}, since exit speed isn't directly dependent on temperature anymore.

Assuming solid uranium particles, reactor may produce 26GW.

Allowing particles to melt enables 62GW reactor with "foggy" plasma, but there is little to no experience with that type of plasma.



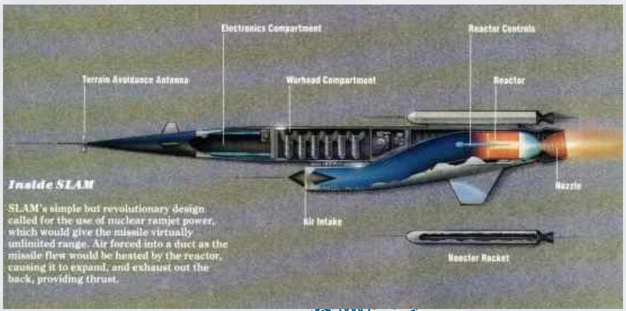
Weather a neutron causes fission is up to chance! More likely for SLOW neutrons!

Nuclear processes (weather fission itself or fragment decay) create very fast neutrons

→ To keep fission going, neutrons need to be slowed down. That’s what a moderator does.

Project Pluto

- Transport nuclear bombs using a nuclear reactor



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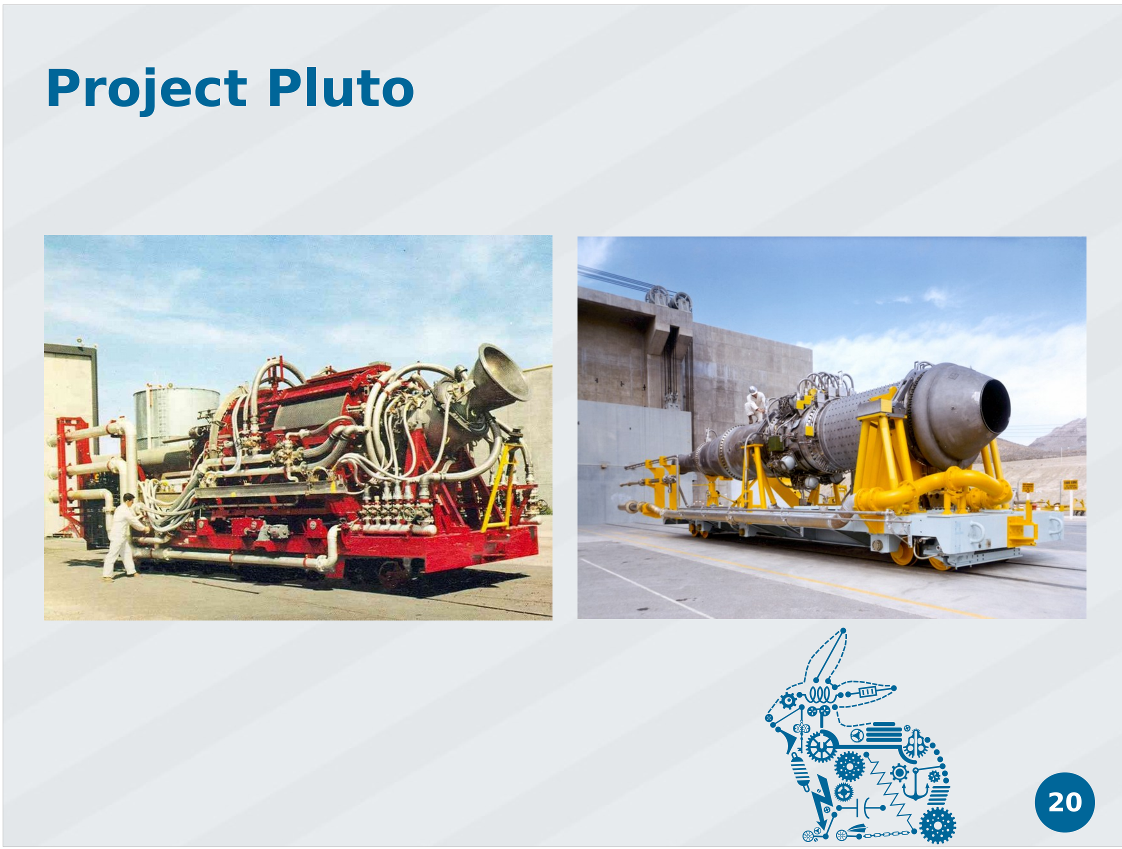
Build long range low altitude vehicle to avoid radar (Supersonic Low Altitude Missile

Carry nuclear bombs to russia

“No moving parts” (except reactor control)



They were called Tory reactors
The one on the right ran for about 5 minutes.

Reactor built from graphite + uranium.
Graphite = moderator.

Actuators were glowing red hot. Needed to operate in this state.

Project Pluto

- No radiation shielding
- Operate reactor near auto ignition temperature
- No pilot

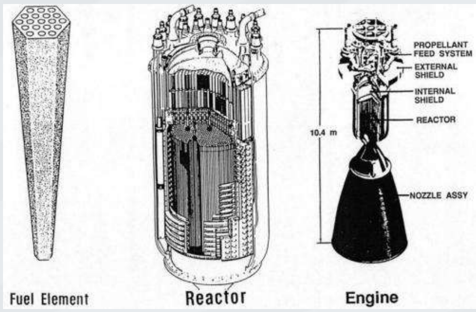
Pic: A point about workplace safety

Reactor built from graphite + uranium. Graphite = moderator.

Heating air to 2300°C, 150° below auto ignition of base plate

High radiation → no pilot! Developed automatic flight system

Project Rover



Upper pic: “Copernicus” ship to constantly cruise between mars and earth.

Lower pic, left to right:
1.5m long fuel element (19 holes through it)
Reactor, hydrogen inlet on top
Full engine assembly

Put liquid hydrogen through reactor to heat up to 2600°C

Elements porous carbon-matrix /w UO2, coated w. carbides (niobium, later zirconium - carbide)

Left: Kiwi testing, hydrogen ignited to mitigate explosion risk

Right: Phoebus, 4GW reactor, most powerful single reactor built at the time (probably wrong, actually “Peewee”, but source claimed it to be.)

Problem: 22K on one end, >2000K on other end of fuel element. Fuel was constantly eroded away. “Flight ready”: loosing 17kg of reactor every 2h of use.

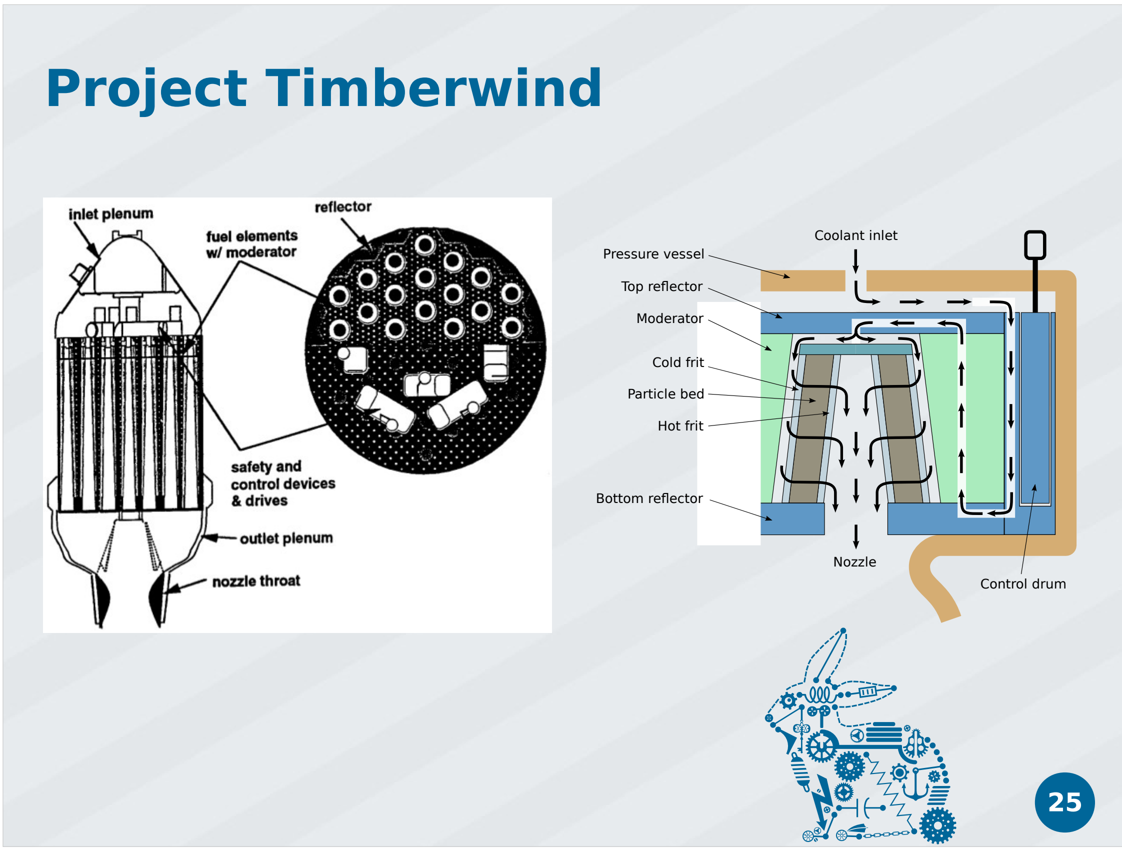
Kiwi TNT

- Prompt critical Kiwi

Someone asked: What could go wrong?
Someone answered: can get prompt critical
They tried that.

Bright spots: nuclear reactor

Waited 3 weeks, told army to clean it up as “excercise”



Many concepts of other reactor types existed, this one was tried and audited afterwards.

Used pebbles: 2mm spheres filled with uranium. No thermal stresses. Uranium may get liquid inside spheres. Fission-Fragments would enter Hydrogen-stream.

Pump hydrogen through pebbles

Control: rotating drum on the side, shows moderator or neutron-catcher.

“Fail safe”: could get critical even if one control-drum was stuck in “off”-position

Project Timberwind - aftermath

Introduction. In 1987, the Strategic Defense Initiative Organization (SDIO) began research and development on a nuclear propulsion system for a rocket that would intercept hostile ballistic missiles. The project was protected under a special access program named TIMBER WIND. Between FYs 1987 and 1991, SDIO budgeted approximately $139 million for the program.

- Improvement on neutron shielding (Boron Aluminum Titanium Hydride)

Use: missile interception. Rockets explode when intercepting missiles. Would spread nuclear engine everywhere.

Neutron shielding is generally a good moderator + neutron absrober. They improved on existing technology. Better BATH-salts. Ha-Ha.

Slowing Down Neutrons

- Elastic scattering with other nuclei
- Similar mass allows maximum energy transfer

  → Hydrogen ideal moderator

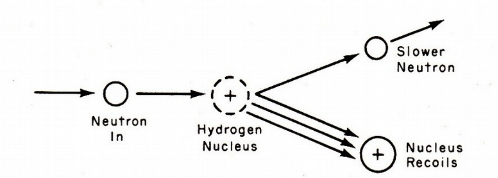
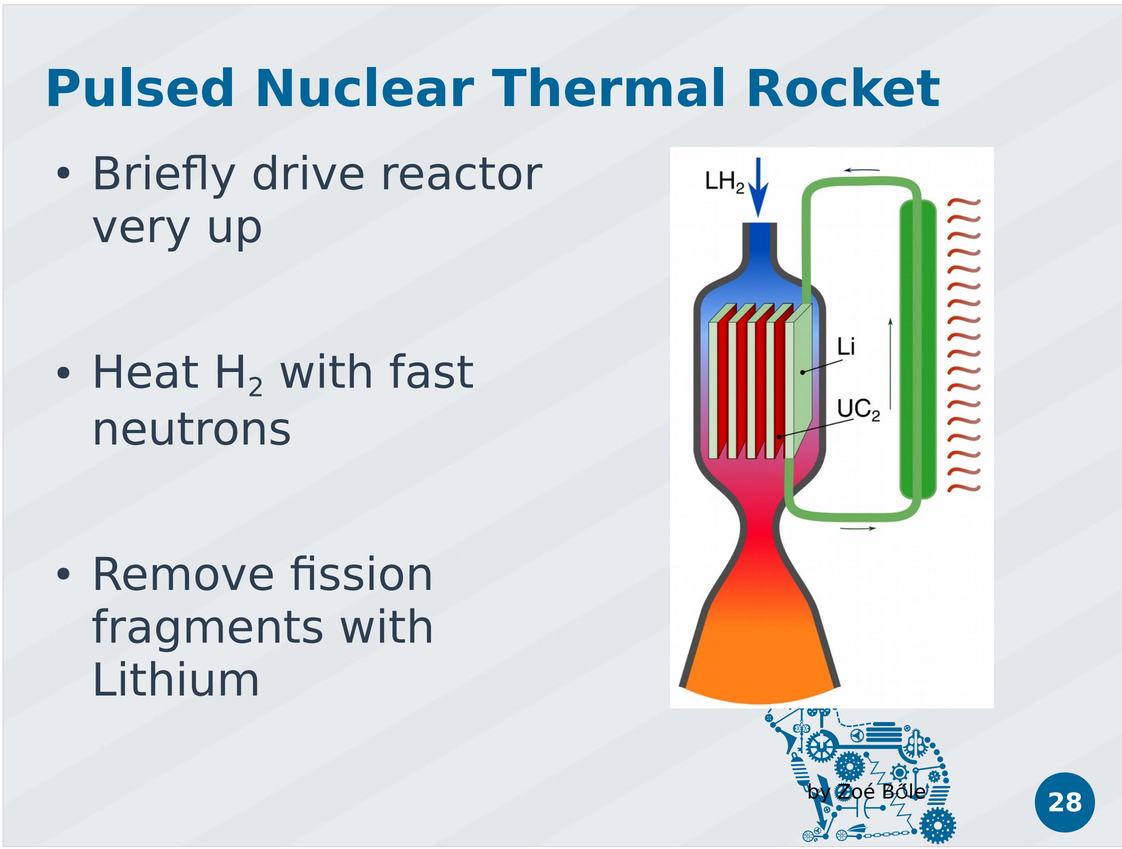


Fig. 6—Elastic scattering.

Neutrons slow down by hitting other matter and transfer momentum. Moderators transfer a lot of kinetic energy to material.

Newton-cradle/Billiard: equal weight = ball stands still.
Light ball vs. heavy ball: light ball is essentially reflected, loosing very little energy.

Transferring momentum means moderating neutrons heats the moderator!



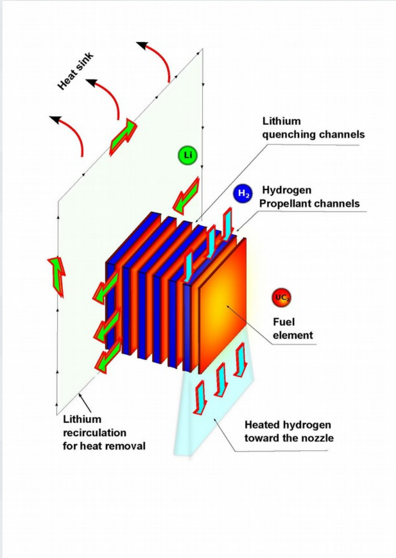
General theory: use lithium to cool reactor, use liquid hydrogen as moderator. Heat hydrogen with neutrons, not hot reactor.

Rapidly increase neutron flux (and fissions)
Fast neutrons heat moderator due to elastic scattering

Rapidly drive down moderator
Lithium cools reactor
Lithium removes fission fragments to disable delayed heating (and delayed neutrons)

Pulsed Nuclear Thermal Rocket

- Require prompt critical bursts of ~10 kHz
- Lithium provides cooling
- Lithium needs cooling



Square core to enable good cooling + good moderator-flux

Lithium needs to be cooled (through radiation) before cycling back through reactor.

Require 1-10kHz to operate efficiently. Essentially a volume in constant thermal shock.

Pulsed NTR Challenges

- Requires 10 kHz capable neutron-blinds
- Fission fragments need to be removed – along with 95% of thermal energy

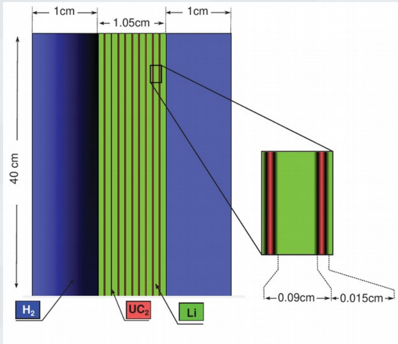


FIG. 7: Reference unit cell.

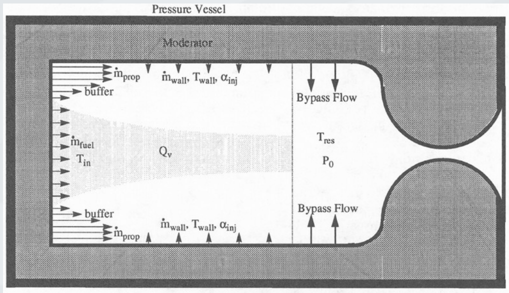
Requires 10kHz moderator-control-succession (maybe fast turning cylinders?)

Fission fragments removal removes 95% of energy as heat of lithium, need to be disposed from lithium (accumulate in lithium in long-running operations).

Super small!!!
Super thin uranium carbide planes! Loosing fuel would result in loosing liquid lithium + reaction with hydrogen.

Open Cycle Gas Core Rocket

- Boil uranium fuel in reactor
- Keep off the walls with boiling H_2
- Expel H_2 with as little fuel as possible



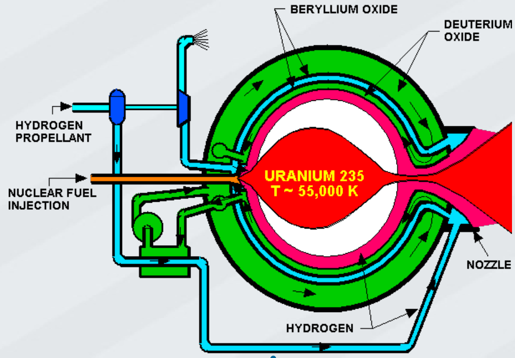
Give up to keep reactor solid, boil uranium. Nuclear reactions happen in gaseous ractor.

Walls would melt if uranium gas touches them. Keep them cool by pumping liquid hydrogen through walls, thereby cooling them and pushing gaseous uranium off walls.

Keep loss of uranium at a minimum by injecting bypass-hydrogen downstream

Open Cycle Gas Core Rocket

- Require ~ 1000 bar
- Fuel has ~2 min. to burn, propellant ~2 sec. to heat
- H_2 dissociates at ~52 000 K



Have to push hard to keep gaseous uranium contained (pressure)

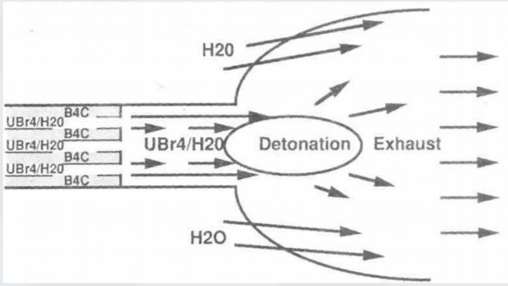
Fuel has about 2 minutes to react

Glows ultra violet, above dissociation-energy of H2

3GW power (less than solid fuel!)
ISP of 3000 s
Thrust of 120 kN

Nuclear Salt Water Rocket

- Uranium salts dissolved in water
- Stored in boron-tubes
- Needs constant flow (of ~ 66 m/s)



Mix fuel and moderator. Burn up continuously.

Mixture super critical on its own. Need to store in boron-tubes (boron absorbes neutrons)

Prompt critical reaction inside tube (=nuclear bomb inside tube) destroys tube

Thermal neutrons flow with water. Neutron flux rises exponentially. Use water flow to have maximum neutron flow after pipe-exit

Nuclear Salt Water Rocket

- **6 x 60 cm tube**
- I_{sp} = 6700 s
- F = 13 MN
- P = 871 GW
- 196 kg/s
- p = 11 500 bar

- **RS-25 (Shuttle)**
- I_{sp} = 452 s
- F = 2.23 MN
- P = 10 GW
- 1400 kg/s
- p = 206 bar

Quick comparison: nice ISP, nice thrust, nice power
Look at that pressure!!!

Believe In Riding Nuclear Bombs!

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Thanks for your attention!

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