On Becoming a Spacefaring Society

Chapter One: Nuclear Propulsion

If we are to become a true spacefaring society, we must abandon chemical rockets and focus our R&D on nuclear rockets.

Ejner Fulsang

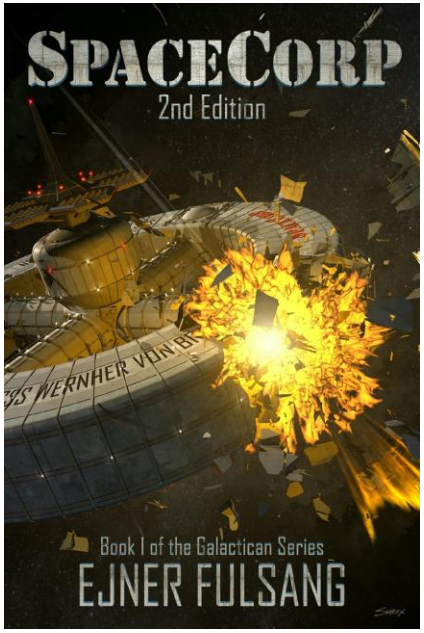
efulsang@Comcast.net

21JUL2017

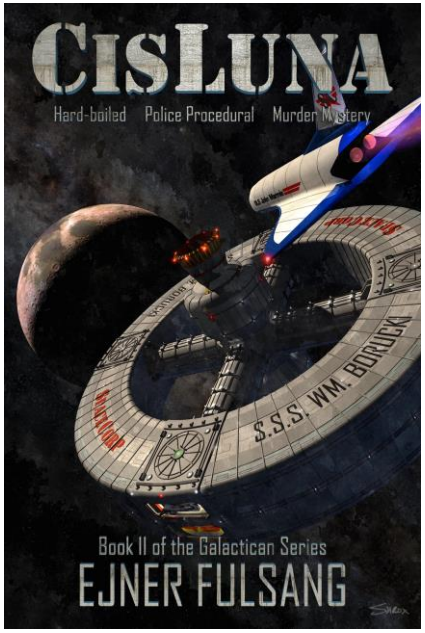
Books I, II, and III of The Galactican Series

<u>Hard</u> SciFi – everything in each book is scientifically and technologically <u>plausible</u>.

Each of the six planned books takes us an evolutionary step closer to becoming a true spacefaring society.



Amazon Jan 2017
2069-72
SpaceCorp occupies LEO with 1-km ring-shaped space stations. **Solid Core Nuclear Thermal Rockets (NTRs)**



Amazon Jul 2017
2085
SpaceCorp occupies Earth-Moon Lagrange Points plus surface colonies. **Gas Core <u>Closed</u> Cycle NTRs "Lightbulbs"**

Amazon Dec 2018
2101-02
SpaceCorp launches the *SIS John Carter* to Mars. **Gas Core <u>Open</u> Cycle NTRs**

Books IV, V, and VI of The Galactican Series

MainBelt	KuiperBelt	αCentauri
Book IV	Book V	Book VI
Amazon Mid-2019 **c 2175** SpaceCorp sets up permanent colony in the Main Belt Asteroids. **Gas Core Open Cycle NTRs**	**Amazon Late 2021** **c 2300** SpaceCorp launches mission into the Kuiper Belt. **Fusion Power Rockets**	**Amazon Mid-2023** **c 2400** SpaceCorp's first voyage to Alpha Centauri. **Beamed Core Antimatter Drive**

NOTE: SpaceCorp has no use for chemical rockets.

Konstantin Tsiolkovsky

The Party Pooper of Space Travel

(also the reason space travel is possible at all)

Tsiolkovsky's famous rocket equation:

Delta V_{max} = V_e x ln (Wet Mass / Dry Mass)

where:

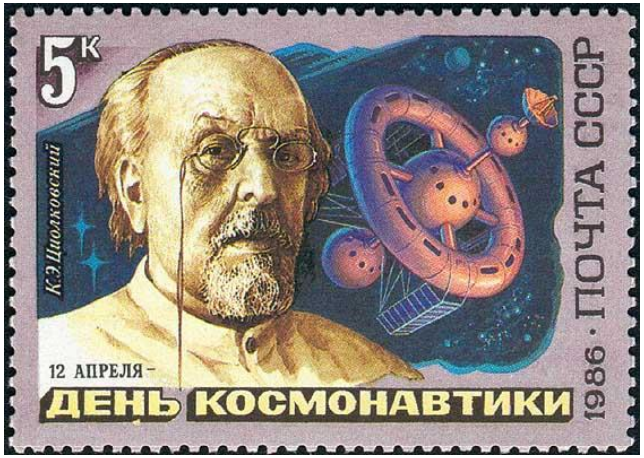
Delta-V_{max} is the rocket's maximum velocity,

V_e is the exhaust gas velocity

Wet Mass is the mass of the fueled rocket

Dry Mass is the mass of the unfueled rocket

Wet Mass / Dry Mass is called the Mass Ratio



Russian and Soviet rocket scientist
b 1857, d 1935

First, inevitably, the idea, the fantasy, the fairy tale. Then, scientific calculation. Ultimately, fulfillment crowns the dream.

—Konstantin Tsiolkovsky

http://www.projectrho.com/public_html/rocket/engines.php

What do we mean by Delta V_{max}?

Here we have an astronaut floating in space.
(He's the rocket ship and the payload.)

How fast is he going?

We don't know. We have no reference frame.

Let's ***assume*** his velocity ***V*** is zero.

NOTE: velocity is a vector with speed and direction.

If he doesn't do anything, he will continue to sit at **V = 0**, immobile, floating… forever.

Mass = 500 kg

He needs a rocket motor!

With a rocket motor he can "do something!" He can <u>change</u> his velocity… **<u>Delta</u> V**.

As long as he fires his rocket motor he will accelerate… until it runs out of fuel.

At that point he will be at **Delta V_{max}**.

Here we have two sophisticated NASA rocket motors from Home Depot*. One is empty. One is full of propellant.

Mass = 500 kg

Mass = 9500 kg

(Propellant is 9000 kg)

* Due to Congressional budget cuts

What do we mean by *Wet* Mass?

Mass = 500 kg

+

Mass = 9500 kg

=

***Wet* Mass**

Wet Mass = 10,000 kg

What do we mean by *Dry* Mass?

Mass = 500 kg

+

Mass = 500 kg

=

***Dry* Mass**

Dry Mass = 1000 kg

What do we mean by Mass Ratio?

Wet **Mass**

+

Dry **Mass**

Mass = 500 kg

+

Mass = 100 kg

$$= \frac{10{,}000}{1000} = 10$$

What is the astronaut's Delta V_{max}?

Assume for simplicity that exhaust gas velocity V_e is 1 km/sec.

Delta V_{max} = V_e x ln (Wet Mass / Dry Mass)

Delta V_{max} = 1 x ln (10) = 1 x 2.3 = 2.3 km/sec

Why do we use ln (Wet Mass / Dry Mass)?

Every time we pulse the rocket, we reduce the Wet Mass by shooting some propellant out the nozzle.

Meanwhile, Dry Mass remains constant.

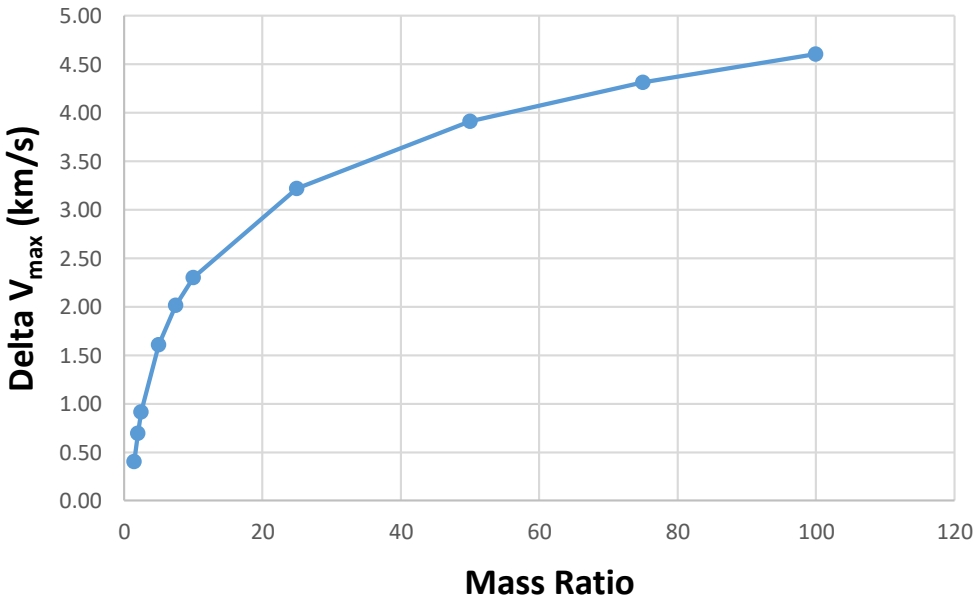
Mass Ratio degrades until Wet Mass = Dry Mass.

When you run out of propellant, your Mass Ratio = 1.

What if I want to go faster than 2.3 km/sec?

Holding V_e constant at 1.0 km/sec, I could increase the Mass Ratio by adding propellant. But this yields diminishing returns:

V_e (km/s)	Mass Ratio	Delta V_{max} (km/s)
1.0	1.5	0.41
	2	0.69
	2.5	0.92
	5	1.61
	7.5	2.01
	10	**2.30**
	25	3.22
	50	3.91
	75	4.32
	100	4.61



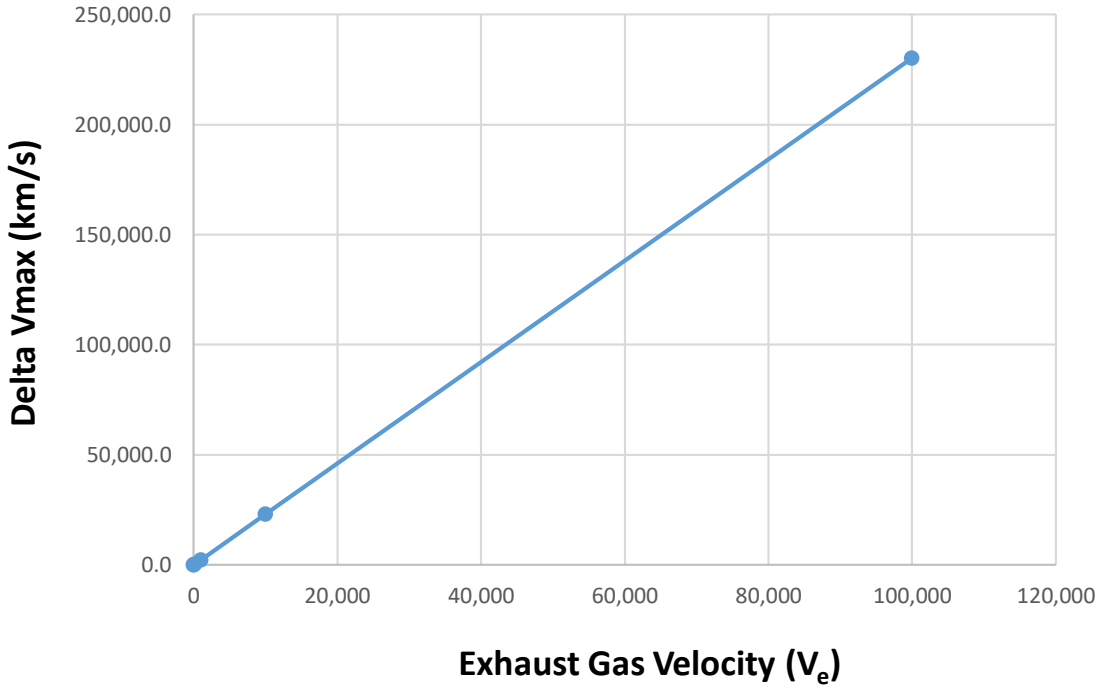
Takeaway Message:

If you start at the low end of the Mass Ratio scale, you get good returns for your fuel investment. But for Mass Ratios higher than 10, the payoff diminishes rapidly.

What if I want to go faster than 2.3 km/sec?

Holding the Mass Ratio constant at 10 while increasing the exhaust gas velocity V_e offers even returns:

V_e (km/s)	Delta V_{max} (km/s)
1	2.3
10	23.0
100	230.3
1,000	2,302.6
10,000	23,025.9
100,000	230,258.5



Takeaway Message:
Investing in rocket engine technology to increase V_e is worth every penny!

Some practical thoughts about Delta V

In theory, if you had a rocket that could achieve a Delta V_{max} of 100 km/sec, you could actually reach a velocity of 100 km/sec. BUT then you have the problem of slowing down. *Rocket ships don't have brakes*.

In practice, you would use a portion of your Delta V budget to accelerate to your cruise speed, and then when you get close to your objective, you would do a flip-and-burn maneuver to slow down enough for orbit insertion. Of course, then you have the problem of returning home. And ideally, you would want a minimum 30% margin in your Delta V budget.

So a typical round-trip mission profile would be as follows:

Total Delta V	100 (%)
Outbound Acceleration	17.5
Outbound Deceleration	17.5
Return Acceleration	17.5
Return Deceleration	17.5
Margin	30

How do chemical rockets fare with exhaust gas velocity?

Propulsion	Oxidizer/Fuel	V_e (km/sec)	Thrust (Mega-Newtons)
Space Shuttle SRB x2	PBAN-APCP	**2.6**	24
Saturn-V F-1 x5	LOX/Kerosene	**3.0**	38.7
SpaceX Merlin 1D x9	LOX/Kerosene	**2.6**	7.6
Space Shuttle RS-25 x3	LOX/LH2	**4.4**	5.4

The above rocket engines are weight lifters, designed to overcome atmospheric drag and earth's gravity to place heavy payloads in Low Earth Orbit.

NOTE: The highest possible V_e for chemical rockets comes from LOX/LH2.

That means the best Delta V_{max} you can hope for with a Mass Ratio of 10 is 44 km/sec.

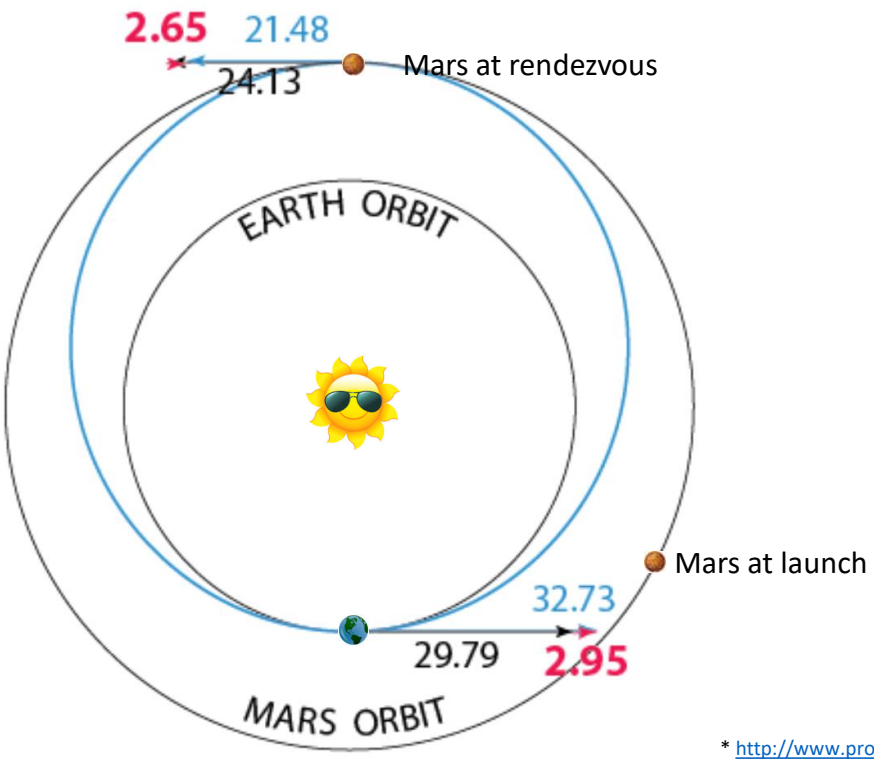
This in turn means your best outbound leg velocity is 7.7 km/sec.

Okay, you're stuck with a chemical rocket and you want to go to Mars anyway…

That would be economy class, aka the Hohmann Transfer Orbit*.

Why do we call it a 'transfer orbit?'

—Because we start out in Earth orbit (around the Sun) and we *transfer* to Mars orbit (around the Sun).



Assume for simplicity that Earth and Mars orbits are circular.

Earth orbits the Sun at a distance of 1 AU at 29.79 km/sec.

Mars orbits the Sun at a distance of 1.5 AU at 24.13 km/sec.

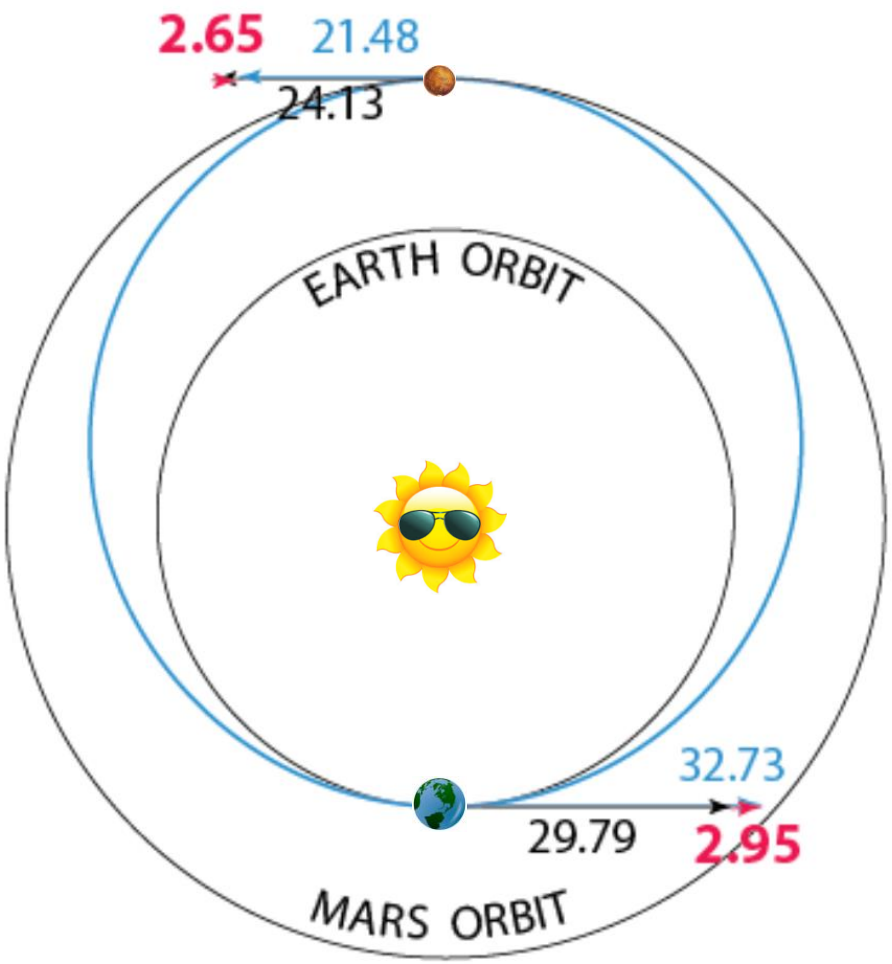
(The farther from the Sun you are the slower your orbital velocity.)

Pick a point opposite the Sun from Earth—that will be your rendezvous point.

Wait for Mars to be ahead of Earth by 44.3 degrees—that will be your launch window, happens every 26 months.

* http://www.projectrho.com/public_html/rocket/mission.php
http://www.projectrho.com/public_html/rocket/mission.php#id--Hohmann_Transfer_Orbits

Okay, so you want to go to Mars…



Initiate your launch from LEO, about 1000 km above Earth.

Your burn will be enough to give you a 2.95 km/sec Delta V. After you reach that velocity shut down your engines and cruise.

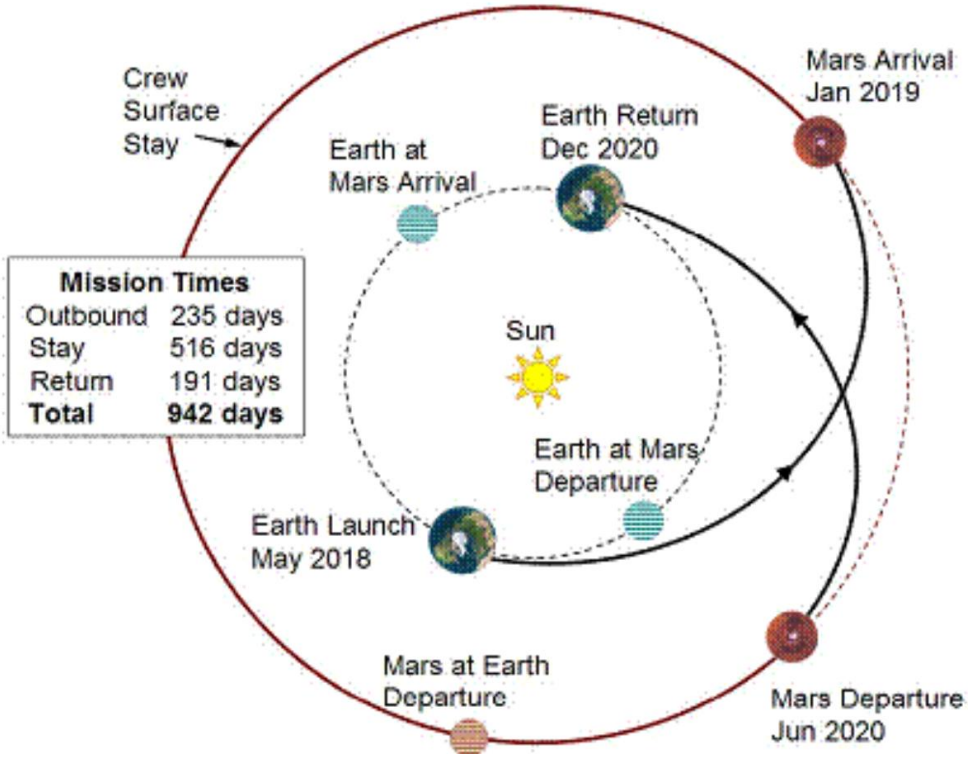
This will put you in an elliptical transfer orbit that is barely big enough to nick Mars' orbit 2.5 AU away.

As you approach Mars, your velocity will gradually degrade until you are only traveling 21.5 km/sec.

If you do nothing else you will continue down the backside of the ellipse picking up speed as you go until you are back at your launch point traveling 33 km/sec again. BUT Earth won't be there.

We don't want that, so we gun the engine when we reach Mars to add an extra 2.65 km/sec to our velocity to match Mars' orbital velocity. This is sometimes called a circularization burn.

Okay, so you want to go to Mars…



But we're not quite done since we want to avoid crashing into Mars. For that we do an Orbit Insertion Burn to the tune of 3 km/sec which puts us in a stable Mars orbit at 500 km altitude.

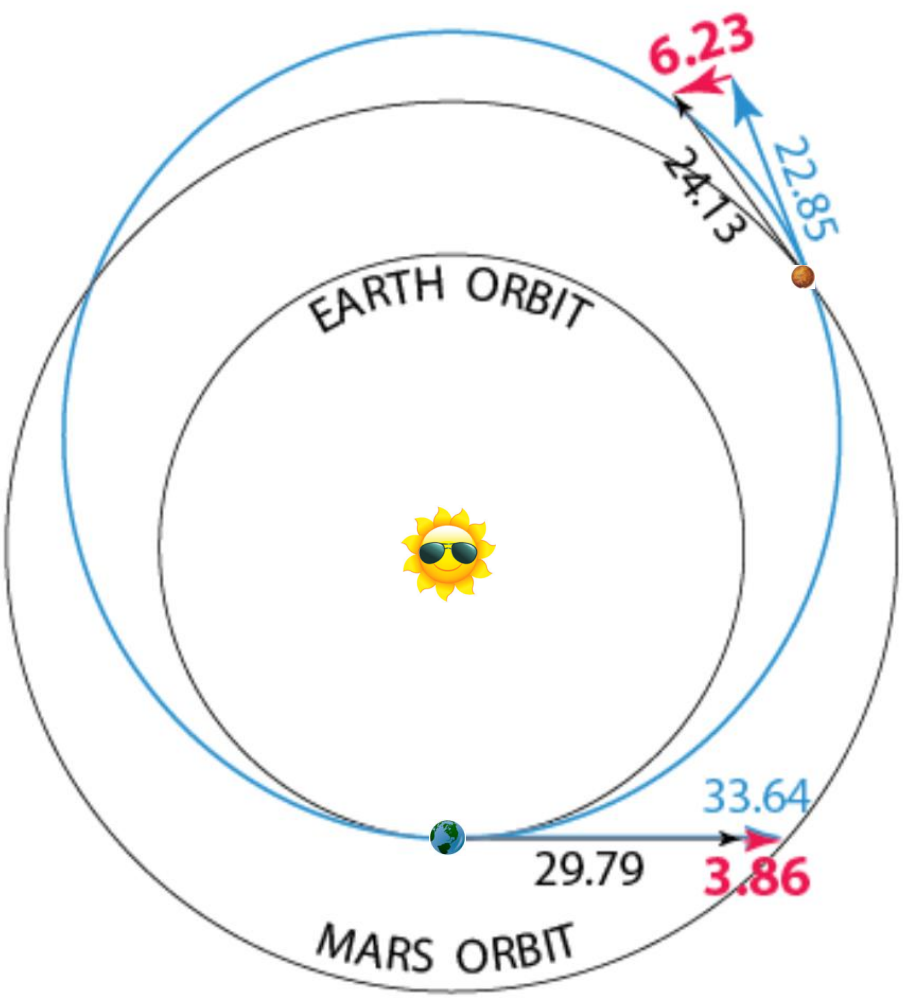
Altogether, your Hohmann transfer to Mars will cost you 9 km/sec of Delta V and will require 235 days travel time.

Getting home is roughly the same except that you have to wait for planetary alignment before you light your rockets. That will be 516 days. Hopefully, you brought a book. The return leg is a little faster requiring only 191 days.

Altogether, you'll need 942 days. That's a long time for vital equipment not to break, for crew not to get sick or injured, to not run out of essential stores (food, water, oxygen), and to not get cooked in interplanetary radiation (25 rems/year).

https://www.quora.com/Why-is-it-important-that-on-the-launching-day-of-the-Mars-rover-the-two-planets-should-be-close-to-each-other

What if we want to get to Mars quicker?



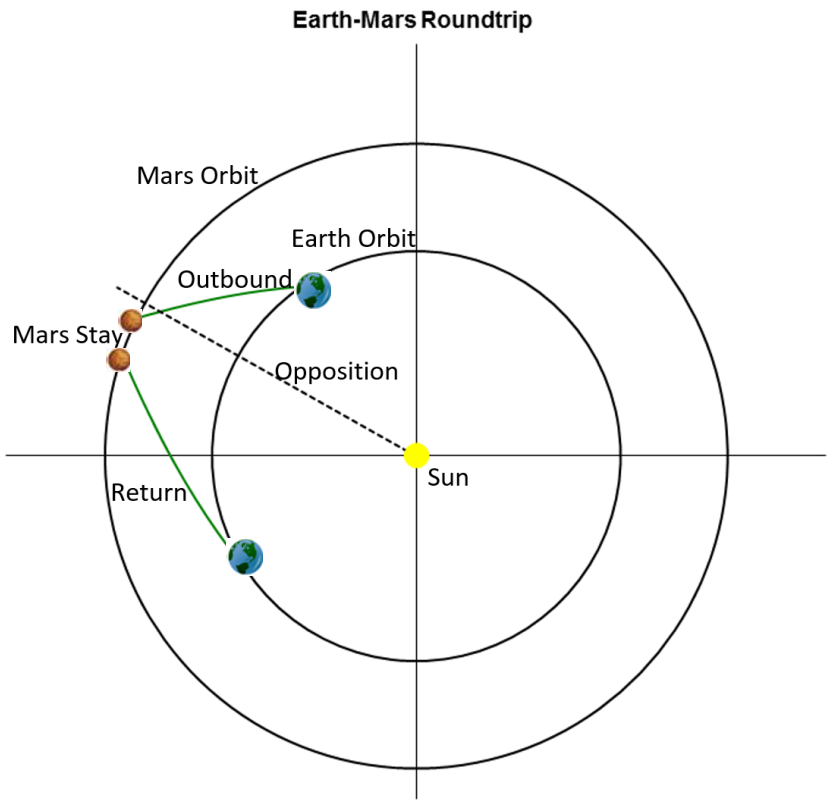
The Hohmann Transfer Orbit is a minimum sized ellipse that will just nick Mars' orbit. So why not try a bigger ellipse?

We initiate our elliptical transfer with a Delta V of 3.86 km/sec, but as we get close to Mars we have to do a much more aggressive braking burn of 6.23 km/sec.

What if we want to get to Mars even quicker still?

We could abandon elliptical transfers altogether and go for a hyperbolic transfer.

This one is a 93-day round trip with 17-day stay at Mars.

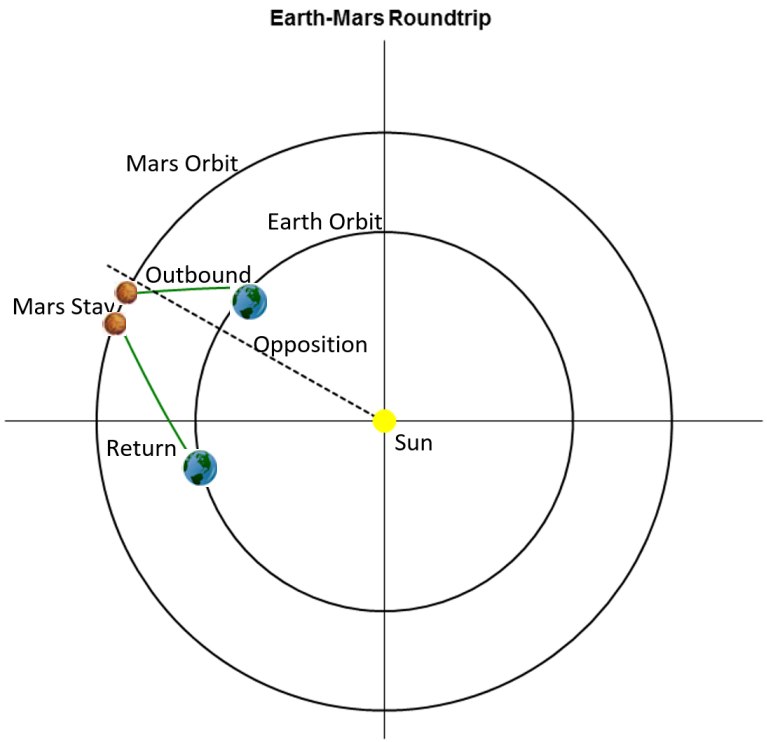


	Case 6
Earth Departure Delta V (km/s)	25.5
Earth Departure Flight Path Angle (deg)	30
Outbound Orbit Type	Hyperbola
True Anomaly at Earth (deg)	51.89
True Anomaly at Mars (deg)	81.45
Mars Arrival Delta V (km/s)	29.31
Total Outbound Delta V (km/s)	54.81
Delta True Anomaly (deg)	29.55
Outbound Transfer Time (days)	33.29
Mars Departure Delta V (km/s)	32.5
Mars Departure Flight Path Angle (deg)	-42.13
Return Orbit Type	Hyperbola
True Anomaly at Mars (deg)	-61.00
True Anomaly at Earth (deg)	-7.61
Earth Arrival Delta V (km/s)	22.77
Total Return Delta V (km/s)	55.27
Delta True Anomaly (deg)	53.39
Return Transfer Time (days)	43.07
Stay Time on Mars (days)	16.64
Total Delta V (km/s)	110.07
Total Round Trip Time (days)	93.00
Earth Departure Relative to Opposition (days)	-26.23
Mars Arrival Relative to Opposition (days)	7.06
Mars Departure Relative to Opposition (days)	23.71
Earth Arrival Relative to Opposition (days)	66.83

110 km/sec becomes 143 km/sec with 30% margin.

What if we want to get to Mars even quicker still?

An even more aggressive hyperbolic transfer with a 64-day round trip with 12-day stay at Mars.

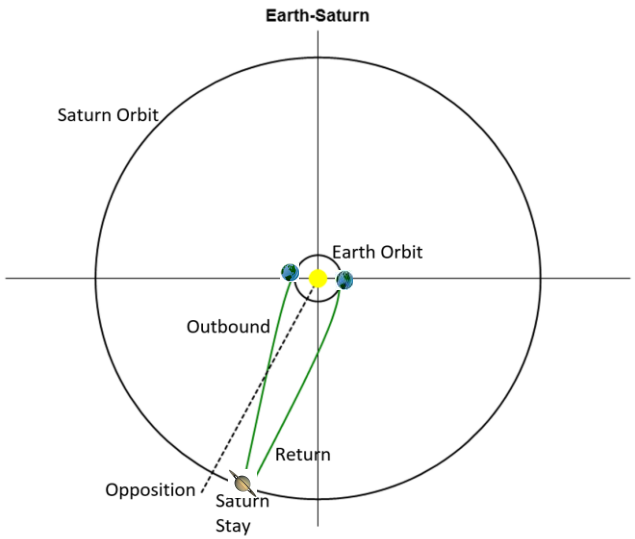


	Case 2
Earth Departure Delta V (km/s)	40
Earth Departure Flight Path Angle (deg)	45
Outbound Orbit Type	Hyperbola
True Anomaly at Earth (deg)	67.47
True Anomaly at Mars (deg)	86.23
Mars Arrival Delta V (km/s)	42.09
Total Outbound Delta V (km/s)	82.09
Delta True Anomaly (deg)	18.76
Outbound Transfer Time (days)	22.07
Mars Departure Delta V (km/s)	40
Mars Departure Flight Path Angle (deg)	-46.19
Return Orbit Type	Hyperbola
True Anomaly at Mars (deg)	-61.64
True Anomaly at Earth (deg)	-23.51
Earth Arrival Delta V (km/s)	31.04
Total Return Delta V (km/s)	71.04
Delta True Anomaly (deg)	38.13
Return Transfer Time (days)	30.06
Stay Time on Mars (days)	11.94
Total Delta V (km/s)	153.13
Total Round Trip Time (days)	64.08
Earth Departure Relative to Opposition (days)	-15.59
Mars Arrival Relative to Opposition (days)	6.48
Mars Departure Relative to Opposition (days)	18.43
Earth Arrival Relative to Opposition (days)	48.53

153 km/sec becomes 199 km/sec with 30% margin.

What if we want to visit the moons of Saturn?

Saturn is 10 AU from the Sun. A Hohmann Transfer to Saturn normally takes 10 years. This one takes 922 days <u>roundtrip</u> with 92 stay time at Saturn.



	Case 2
Earth Departure Delta V (km/s)	30.5
Earth Departure Flight Path Angle (deg)	0
Outbound Orbit Type	Hyperbola
True Anomaly at Earth (deg)	0
True Anomaly at Saturn (deg)	100.62
Saturn Arrival Delta V (km/s)	44.91
Total Outbound Delta V (km/s)	75.41
Delta True Anomaly (deg)	100.62
Outbound Transfer Time (days)	347.82
Saturn Departure Delta V (km/s)	30
Saturn Departure Flight Path Angle (deg)	-80.51
Return Orbit Type	Hyperbola
True Anomaly at Saturn (deg)	-115.03
True Anomaly at Earth (deg)	-29.58
Earth Arrival Delta V (km/s)	23.76
Total Return Delta V (km/s)	53.76
Delta True Anomaly (deg)	85.44
Return Transfer Time (days)	482.45
Stay Time on Saturn (days)	92.15
Total Delta V (km/s)	129.18
Total Round Trip Time (days)	922.42
Earth Departure Relative to Opposition (days)	-93.45
Saturn Arrival Relative to Opposition (days)	254.37
Saturn Departure Relative to Opposition (days)	346.59
Earth Arrival Relative to Opposition (days)	829.62

Saturn orbits the Sun at 9.69 km/s

129 km/sec becomes 168 km/sec with 30% margin.

Summarizing Total ΔV and Roundtrip Travel Times

	Outbound ΔV (km/s)	Outbound Transfer (days)	Stay Time (days)	Return ΔV (km/s)	Return Transfer (days)	Total ΔV (km/s) with 30% margin	Total Time (days)
Earth to Mars (Hohmann)	9	235	516	9	191	**23.4**	**942**
Earth to Mars (153-day)	32.6	70	13	32.6	70	**84.8**	**153**
Earth to Mars (93-day)	55	33	17	55	43	**143.0**	**93**
Earth to Mars (64-day)	82	22	12	71	30	**198.9**	**64**
Earth to Saturn (Hohmann)	9.9	1456	112	9.9	1184	**25.8**	**2,752**
Earth to Saturn (922-day)	75.4	347.8	92.2	53.8	482.5	**167.9**	**922.4**

(Assumes launching from and returning to LEO)

With the Hohmann Elliptical Transfers we need about 23 or 26 km/s, but it's going to be a long trip.

With the hyperbolic transfers we need about 200 or 168 km/s, but you can drastically shave the duration compared to ellipticals.

So can we get 26 km/s with a chemical rocket?

		Delta V_{max} by Mass Ratio				
Propellant	V_e (km/s)	10	20	30	50	100
LOX/LH2	4.9	11.3	14.7	16.7	19.2	22.6
LOX/RP-1	3.5	8.1	10.5	11.9	13.7	16.1

Not likely.

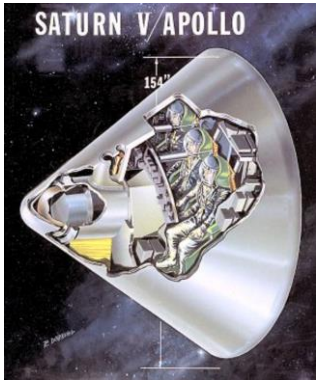
At least not with a single stage rocket.

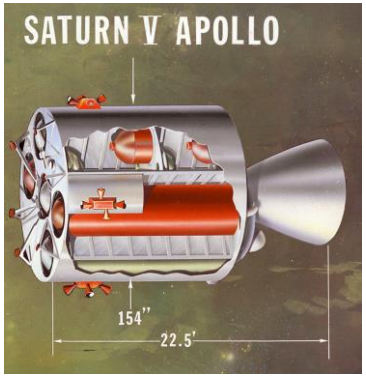
(Yes, we send chemical rockets to Mars all the time—we just don't bring them home.)

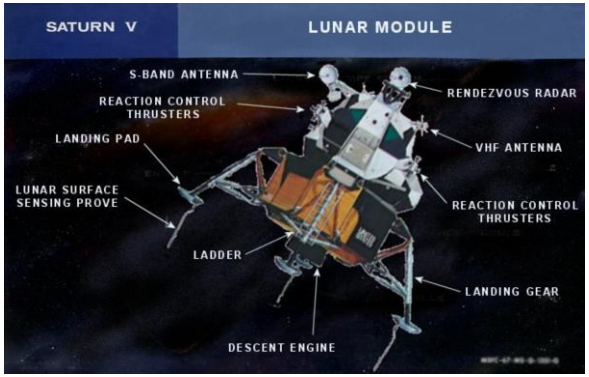
So let's look at a multi-stage rocket—the Saturn V that was used on the Apollo mission.

Saturn V Rocket	Stages			
	1st (5 F-1s)	2nd (5 J-2s)	3rd (1 J-2)	Payload
	LOX/RP-1	LOX/LH2	LOX/LH2	
Wet Mass	2,909,200.0	496,200.0	123,000.0	118000
Dry Mass	183,600.0	40,100.0	13,500.0	
Stack Total				
Wet Mass	3,646,400.0	737,200.0	241,000.0	
Dry Mass	355,200.0	171,600.0	131,500.0	
Mass Ratio	10.3	4.3	1.8	
Ve (km/s)	3.5	4.9	4.9	
ΔVmax (km/s)	**8.2**	**7.1**	**3.0**	
Total ΔV (km/s)	**18.3**			

(The Apollo spacecraft was 118,000 kg.)



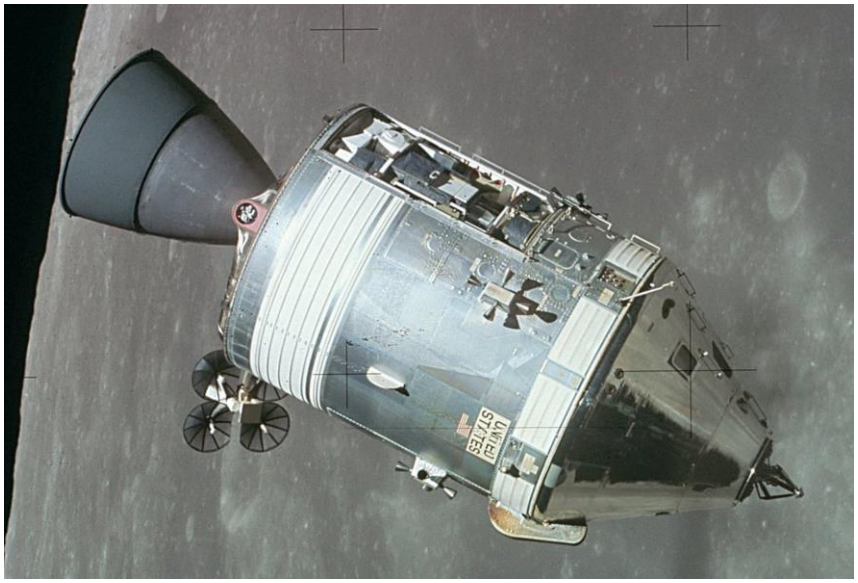




So let's look at a multi-stage rocket—the Saturn V that was used on the Apollo mission.

Things to keep in mind about the Apollo mission:

- **Apollo launched from Earth which adds an extra 10 km/s to your Delta V budget in order to get to LEO.**
- **Carried a "fourth stage" in the Command and Service Module**
  - **Aerojet AJ10-137 engine**
    - **Aerozine 50 fuel (3201 kg) and Nitrogen tetroxide oxidizer (5118 kg)**
    - **Hypergolic, corrosive, and carcinogenic**
    - **91 kN thrust**
  - **Roles:**
    - **Placing Apollo spacecraft into and out of lunar orbit**
    - **Mid-course corrections between Earth and Moon**
    - **Retrorocket for Earth return deorbit**



Wet Mass: 28,800 kg
Dry Mass: 11,900 kg
Mass Ratio: 2.4

V_e = 3.35 km/s

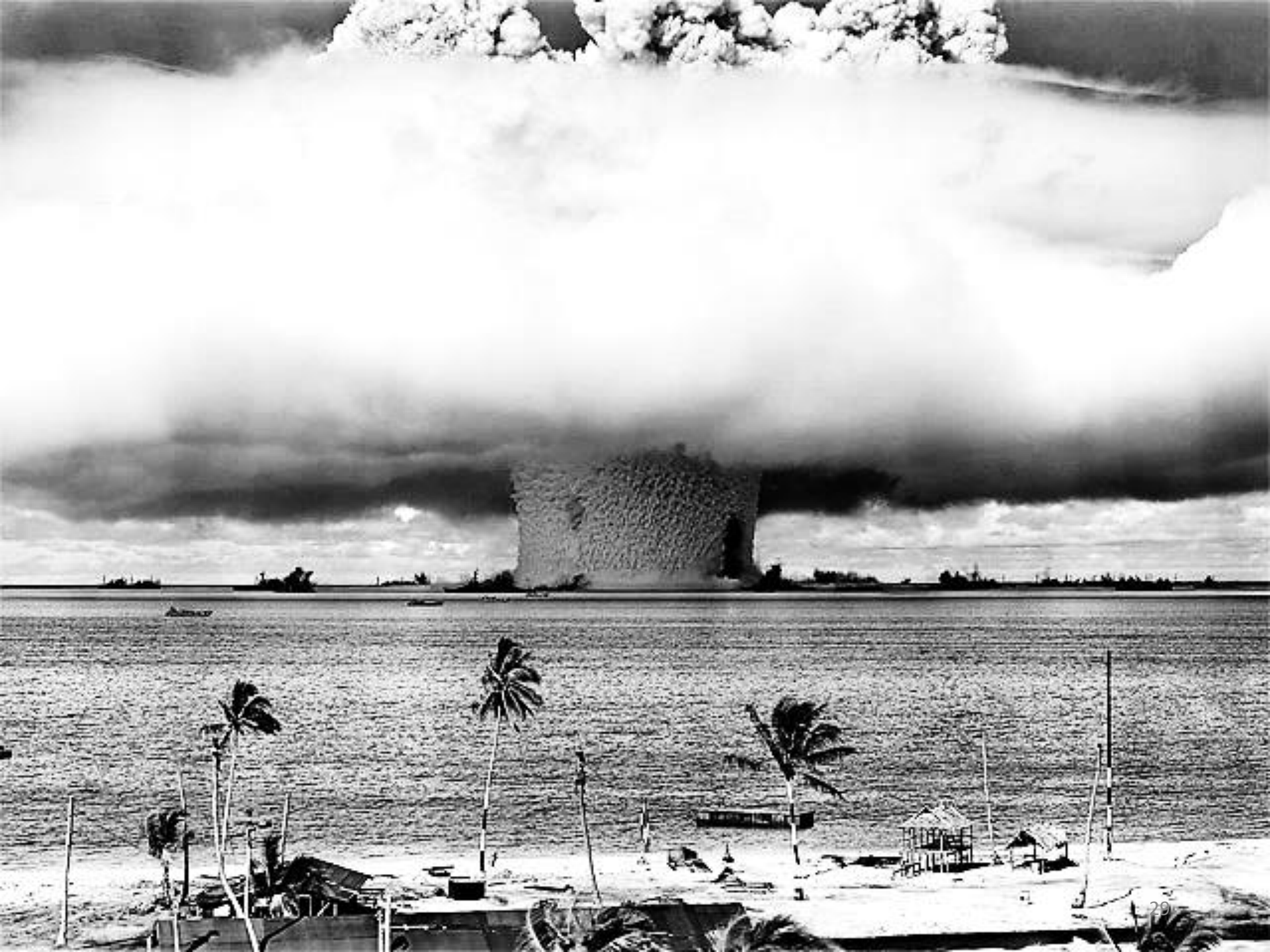
Delta V_{max} = 2.93 km/s

If we add this 3 km/s to the 18 we got from the first three stages, Mars begins to look possible.

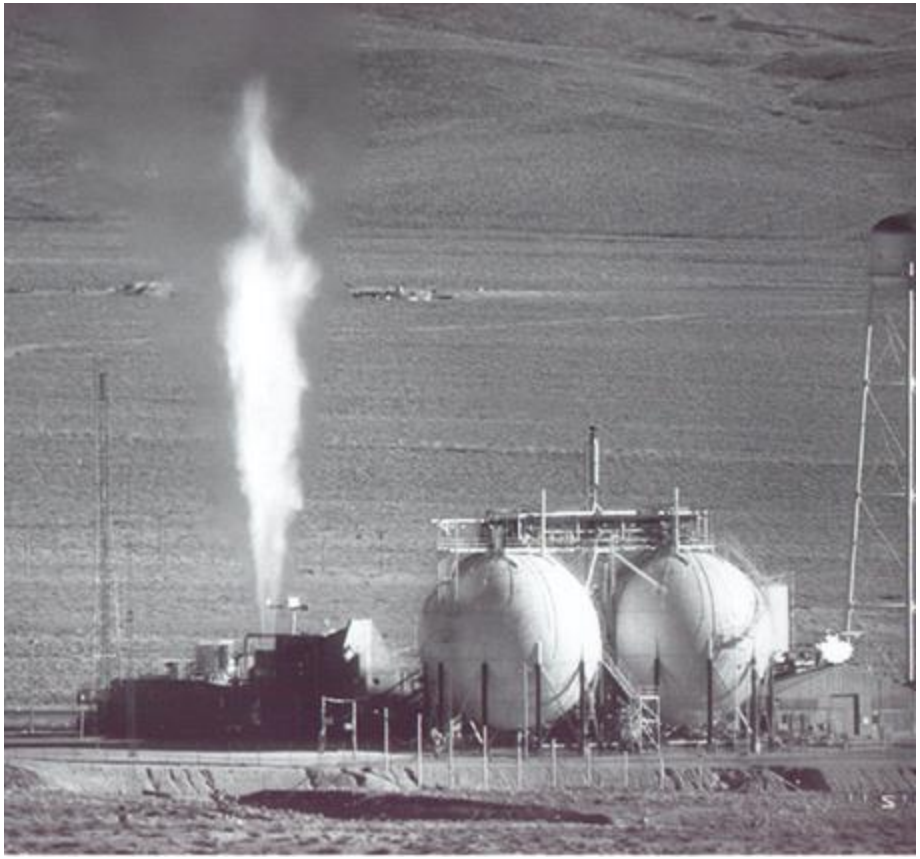
If chemical rockets can only take us beyond the moon slowly, what about the nuclear option?

Yes, that would be bomb-grade (93% enriched) fissile U-235 flying around in space.

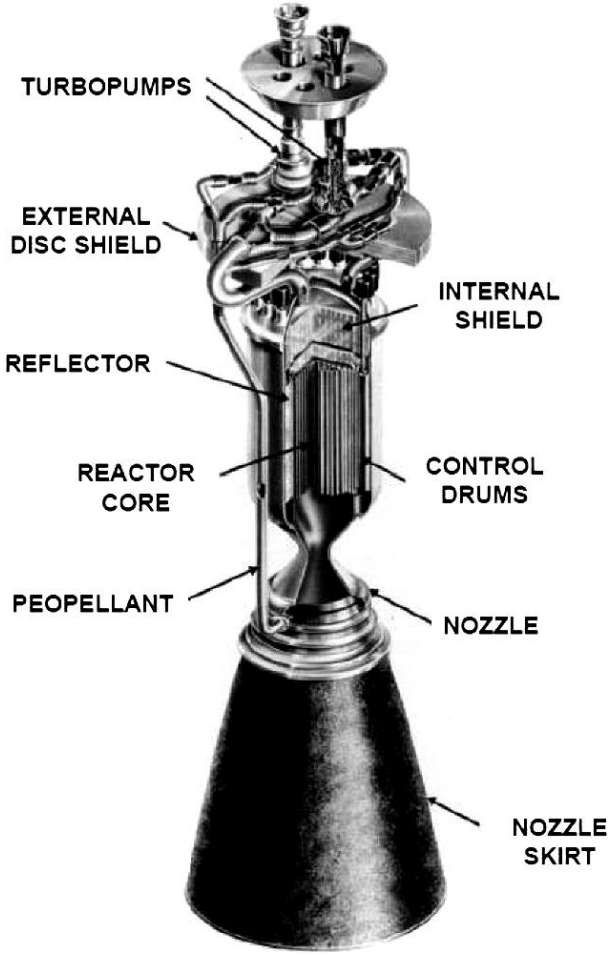
I know what you're thinking…



Actually, I was thinking about something more like this…



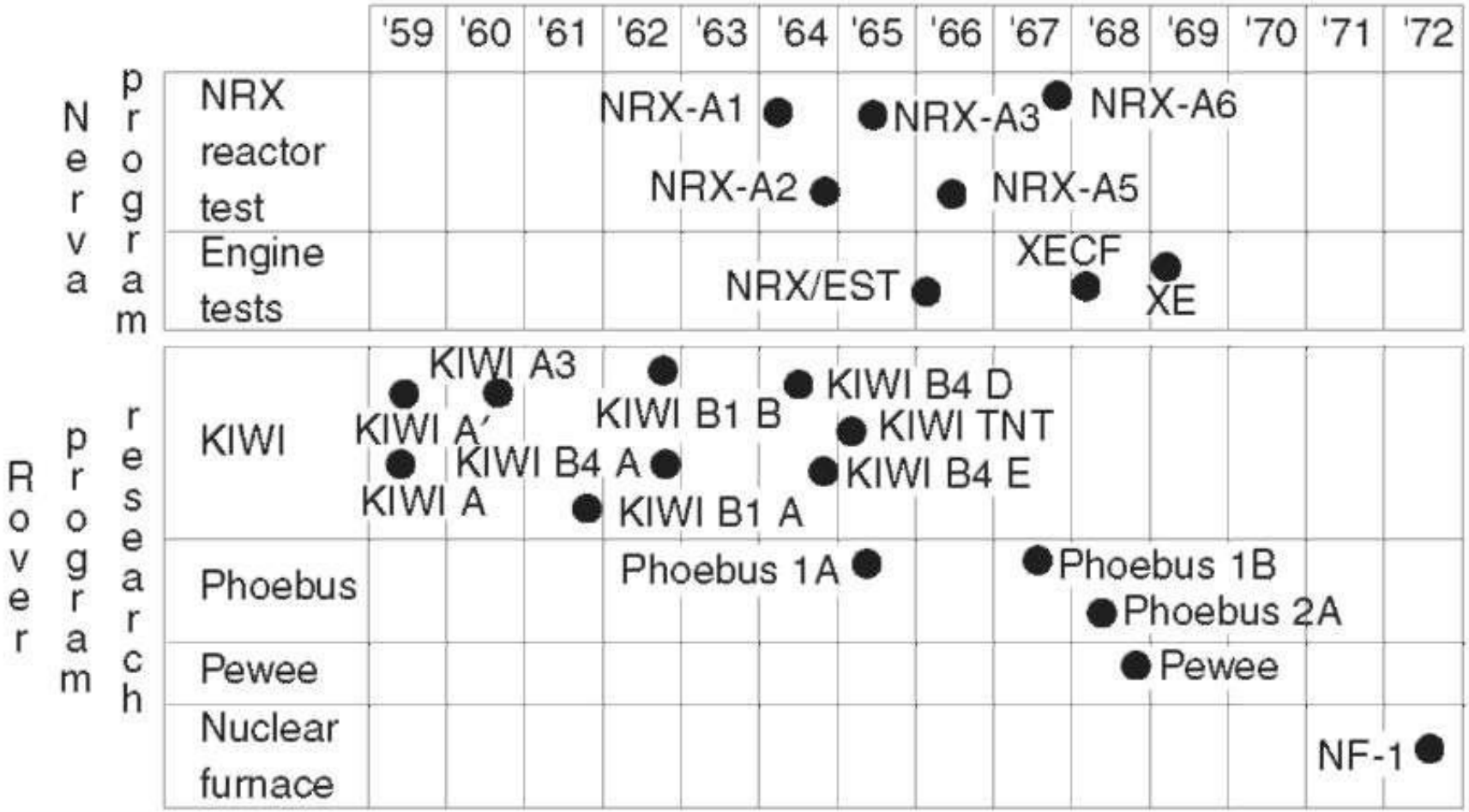
NASA's Nuclear Engine for Rocket Vehicle Application (NERVA) program at the Nuclear Rocket Development Station (NRDS), Jackass Flats, Nevada 1962-69.



This is a nuclear thermal rocket. It does <u>not</u> have a detonator.

No detonator, no boom.

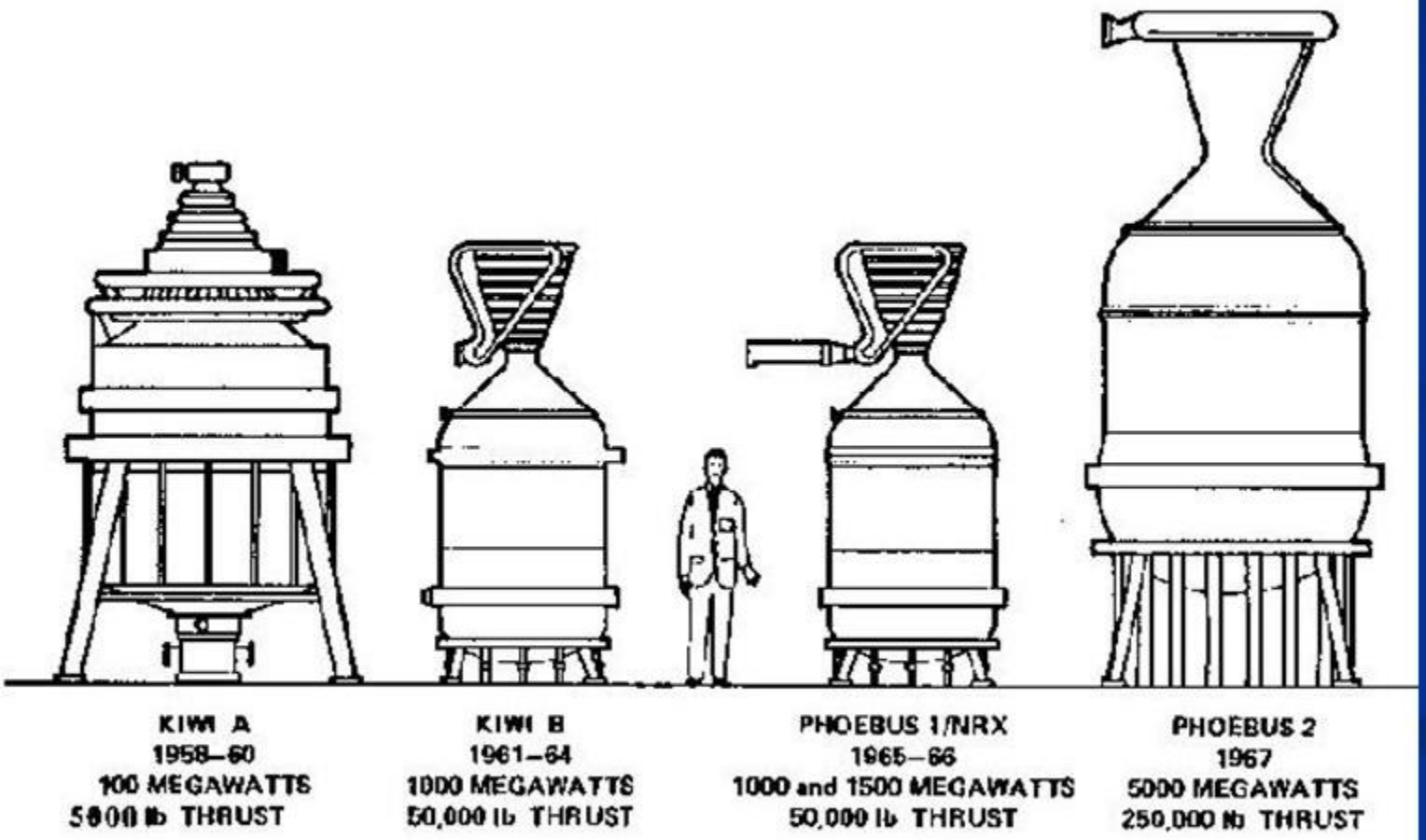
NERVA and Rover were active Nuclear Thermal Rocket (NTR) Programs sponsored by NASA during the 50s and 60s.



http://what-when-how.com/space-science-and-technology/nuclear-rockets-and-ramjets/

A number of solid core NTRs were developed.

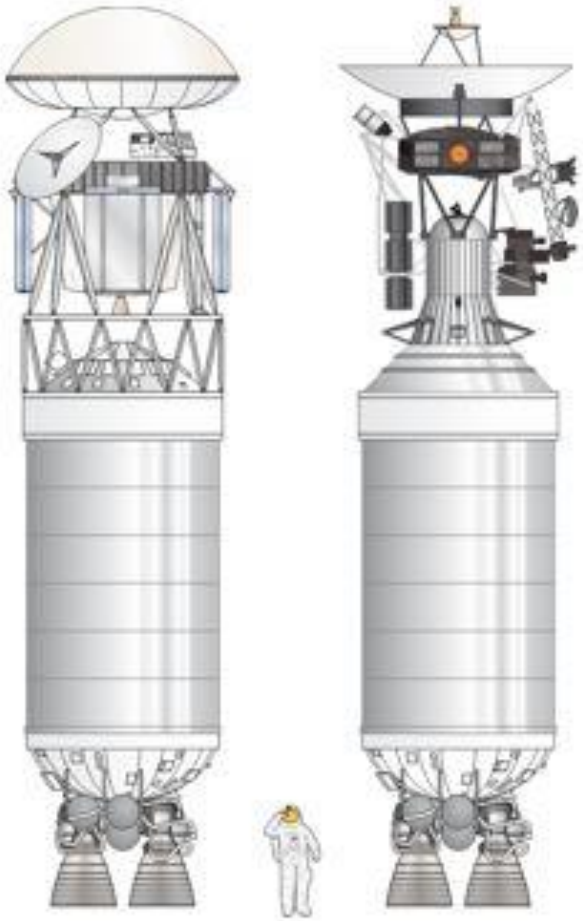
Nuclear propulsion – Nerva program (1957-1972)



Source: S. V. Gunn, (1989) "Development of Nuclear Rocket Technology", AIAA paper 89-2386

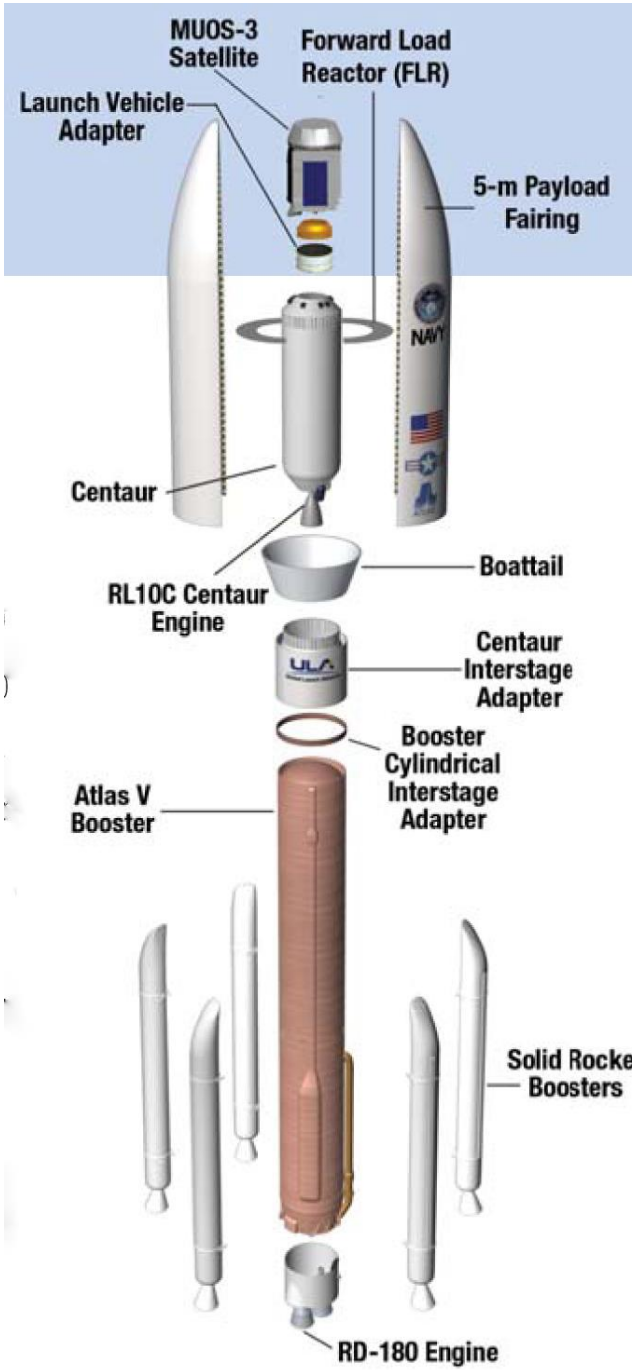
There were plans at one time to mount a NERVA rocket to a Centaur Upper Stage. Project advanced to TRL-7 (launch-ready).

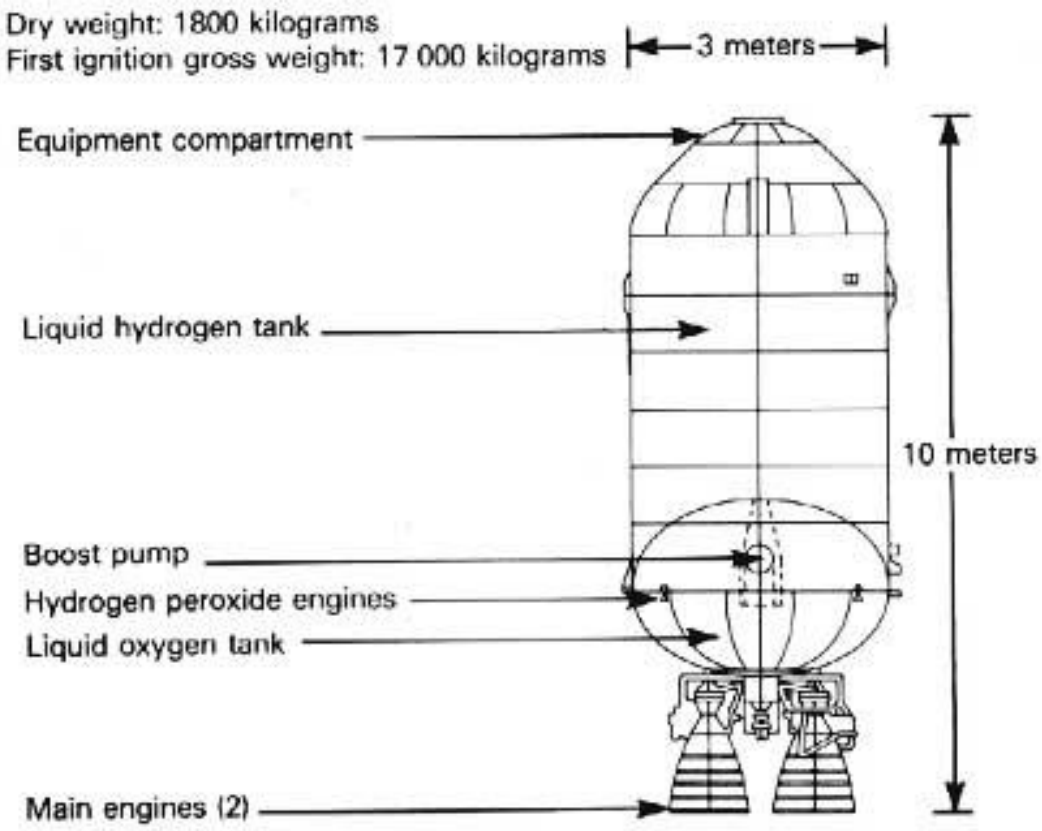
General Dynamics Centaur Upper Stage with conventional LOX/LH2 RL-10 engines



Viking and Voyageur spacecraft mounted atop Centaur Upper Stages

Centaur cont.





The Centaur has been a real workhorse with 242 launches as of April 2017. Most of them end up in graveyard orbits when they're done.

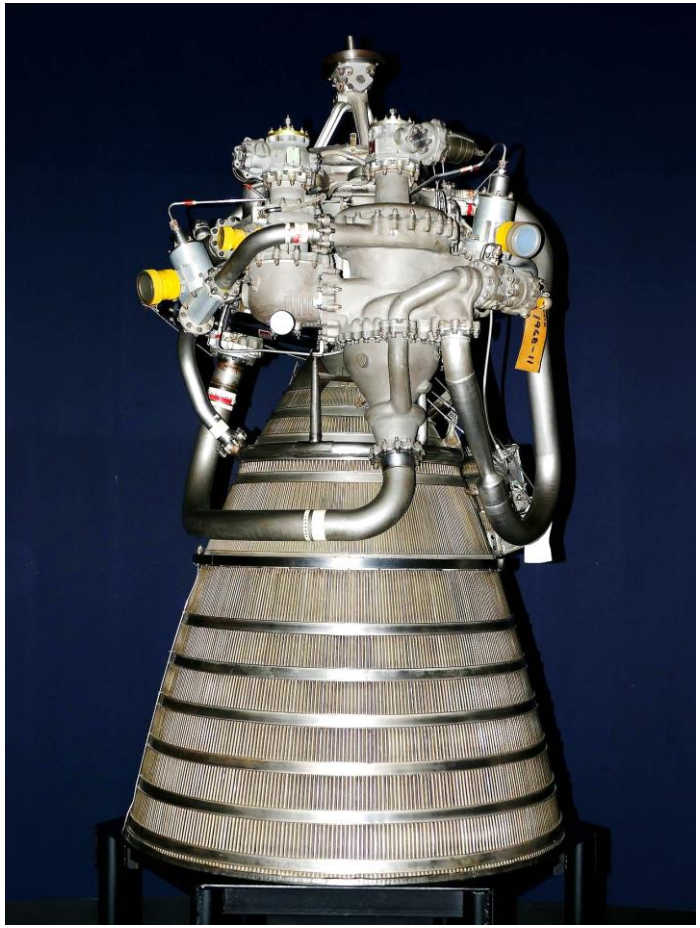
Centaur cont.

Centaur was the first upper stage to use LOX/LH2

- Twin RL-10 engines
- V_e = 4.4 km/s (same for all LOX/LH2 engines)
- Mass Fraction = 9.46*
- **Delta V_{max} = 9.9 km/s**

* Subject to payload mass

9.9 km/s is pretty good given that you are already in LEO when you light it off.



RL-10 Engine

Centaur: Chemical vs. Nuclear Option

Chemical Rockets (Twin RL-10s)

For the chemical Centaur (calculated)
LOX: 17,821 kg (86%)
LH2: 3,009 kg (14%)
Total LOX/LH2: 20,830 kg

Wet Mass of Centaur: 23,292 kg
Dry Mass of Centaur: 2,462 kg
Mass Ratio: 9.4
V_e of RL-10: 4.4 km/s

Dry mass of 2 RL-10s: 554 kg

Thrust (2x): 110,000 N

Delta V_{max}: 9.9 km/s

Nuclear Rocket (single Pewee-class)

For the nuclear Centaur (calculated)
LOX: 0 kg
LH2: 20,830 kg (100% propellant)
Total LH2: 20,830 kg

Wet Mass of Centaur: 25,978 kg
Dry Mass of Centaur: 5,148 kg
Mass Ratio: 5.0
V_e of Pewee: 9.2 km/s

Dry mass of Pewee: 3,240 kg

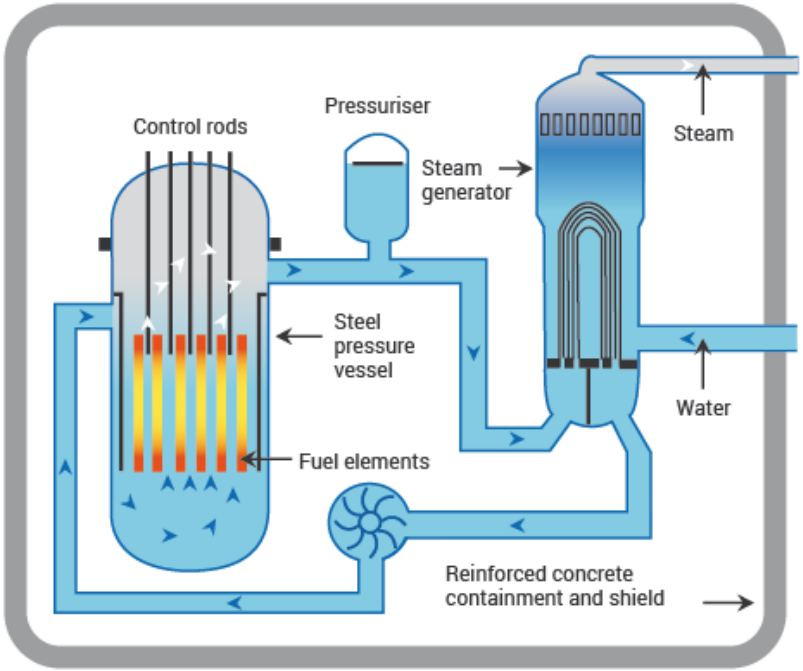
Thrust (1x): 111,200 N

Delta V_{max}: 14.9 km/s

Let's take a look under the hood of a Nuclear Thermal Rocket

For starters, all NERVA program rockets were solid core based on fission.

In principle, they work pretty much like nuclear reactors in power plants.

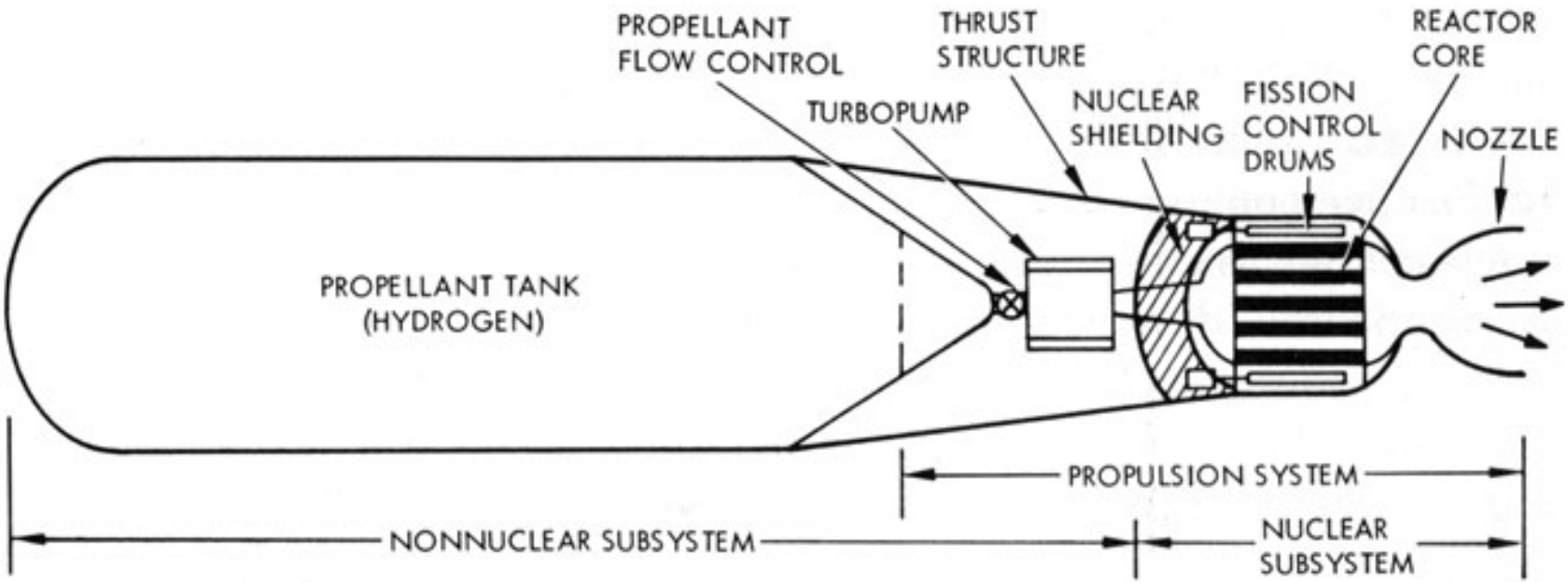


They use uranium enriched to a higher percentage of ^{235}U than ^{238}U than is found in nature.

- Natural uranium has 0.72% ^{235}U.
- Commercial reactors use 3-4% ^{235}U.
- Weapons grade is anything over 85%.
- Solid core NTRs use 93%.
- Nuclear subs use up to 96%.

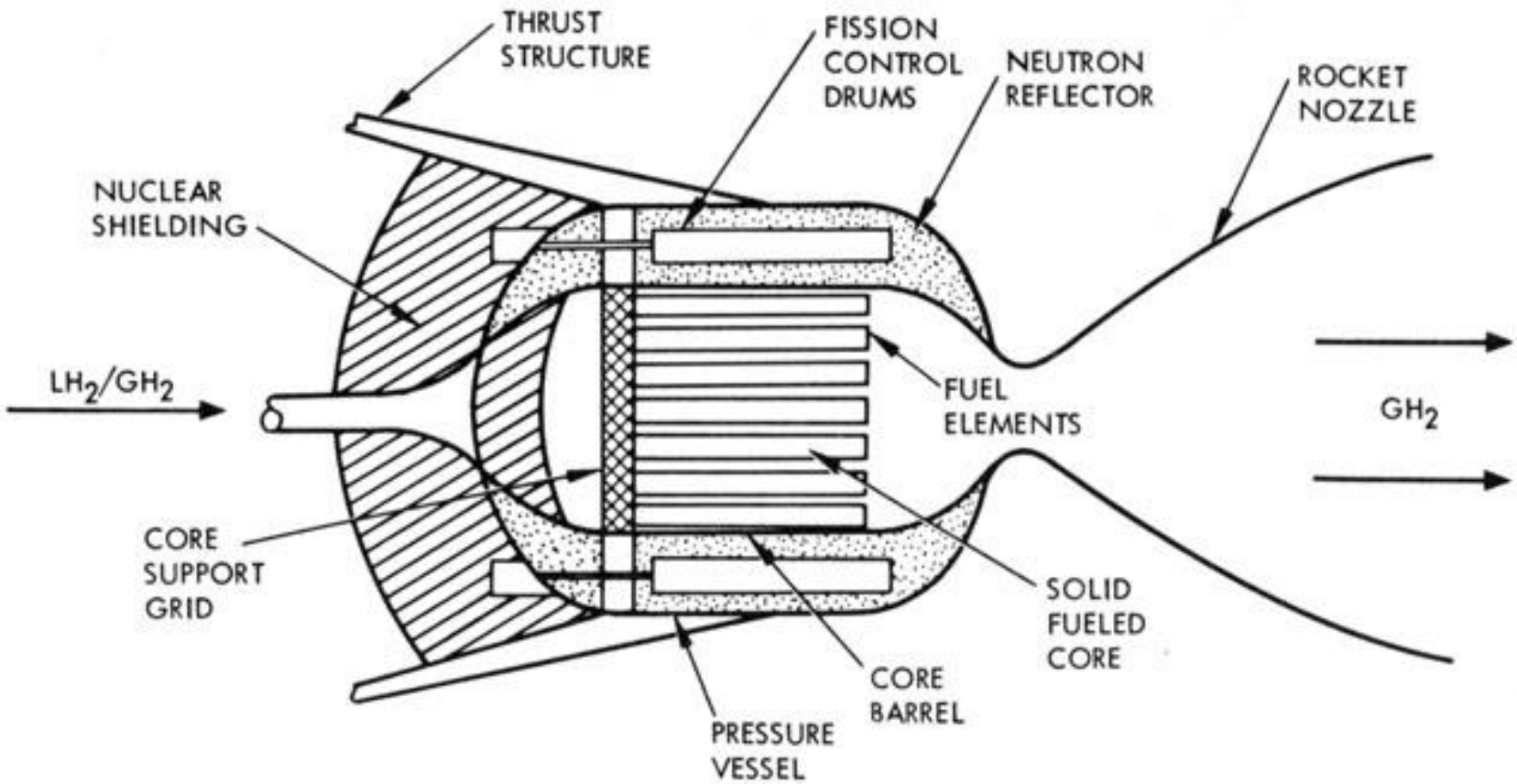
Solid core fuel elements in a submarine are embedded in metal-zirconium alloy. They sit in a water bath and undergo fission when in close contact with one another. Control rods are lowered to provide separation, stopping fission.

Now let's compare a nuclear rocket



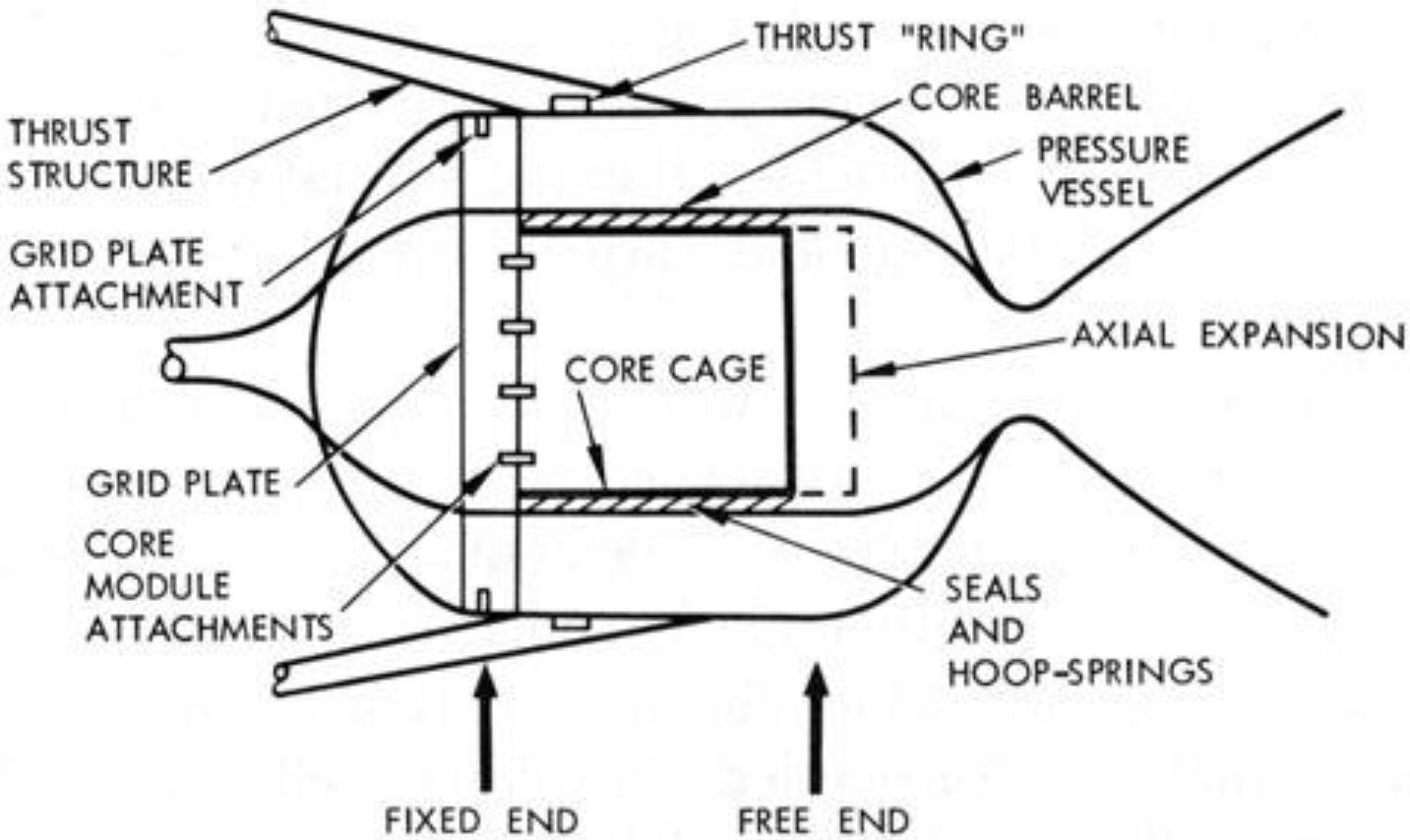
NOTE: It has a substantial LH2 propellant tank, but no LOX oxidizer tank.

Nuclear rocket engine details…



Nuclear rocket engine details…

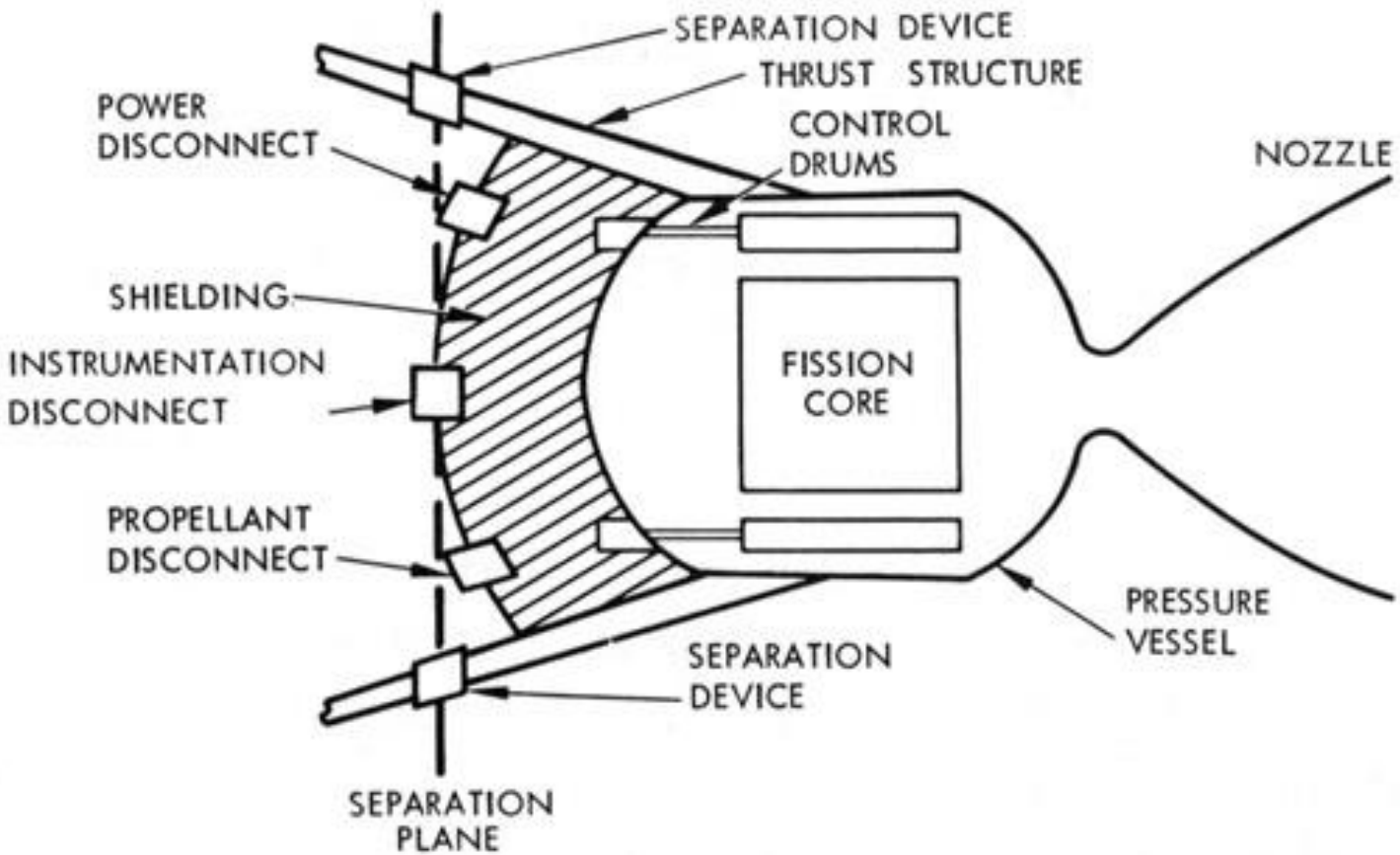
Here the Fission Core is contained within the core cage where the fuel rods are separated by control material to prevent fission.



Nuclear rocket engine details…

Here the Fission Core is extended beyond the core cage where the fuel rods can undergo fission. When they get hot (~2750 K), LH2 propellant is passed through the rocket chamber where it becomes superheated from contact with the fuel rods. This makes it exhaust out the nozzle at high V_e (~9 km/s**)**.

Max V_e is limited by core temperature.



Nuclear rocket take-away messages

Nuclear rockets use bomb-grade uranium but they have no detonators, hence they are not bombs.

The Navy uses even more enriched Uranium fuel than proposed for nuclear rockets and they've never had a nuclear accident.

"We have never had an accident or release of radioactivity which has had an adverse effect on human health or the environment,"

—Lukas McMichael, Public Affairs Officer for Naval Reactors

Nixon cancelled the NERVA program in 1972.

He also cancelled the last three Apollo missions:

- Apollo 18 — Copernicus Crater (Feb 1972)
- Apollo 19 — Hadley Rille (Jul 1972)
- Apollo 20 — Tycho Crater (Dec 1972)

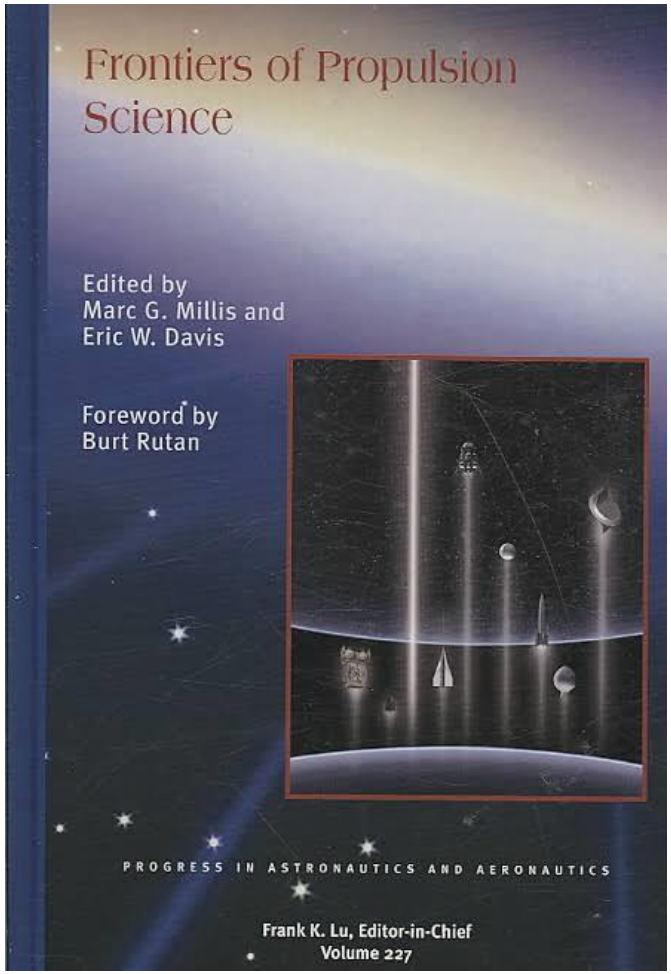
Ostensibly, this was to pay for Vietnam.

What Nixon did to the space program was his *second* most egregious sin. His <u>worst</u> sin was lowering the national speed limit to 55 mph in 1974, the year I got my brand new Pontiac Firebird Formula 400.

If Nixon hadn't cancelled NERVA, where might our research have led?

The following propulsion concepts were all sponsored by NASA, typically under the NASA Institute for Advanced Concepts (NIAC) program from 1998-2007 and NASA's Breakthrough Propulsion Physics Project (1996-2002) at NASA Glenn Research Center.

As such, they are all considered plausible advanced concepts, and hence fair game for writers of hard SciFi (that would be me) and board game designers of the same persuasion (e.g., John Butterfield, designer of the *SpaceCorp,* GMT Games due out 2017).



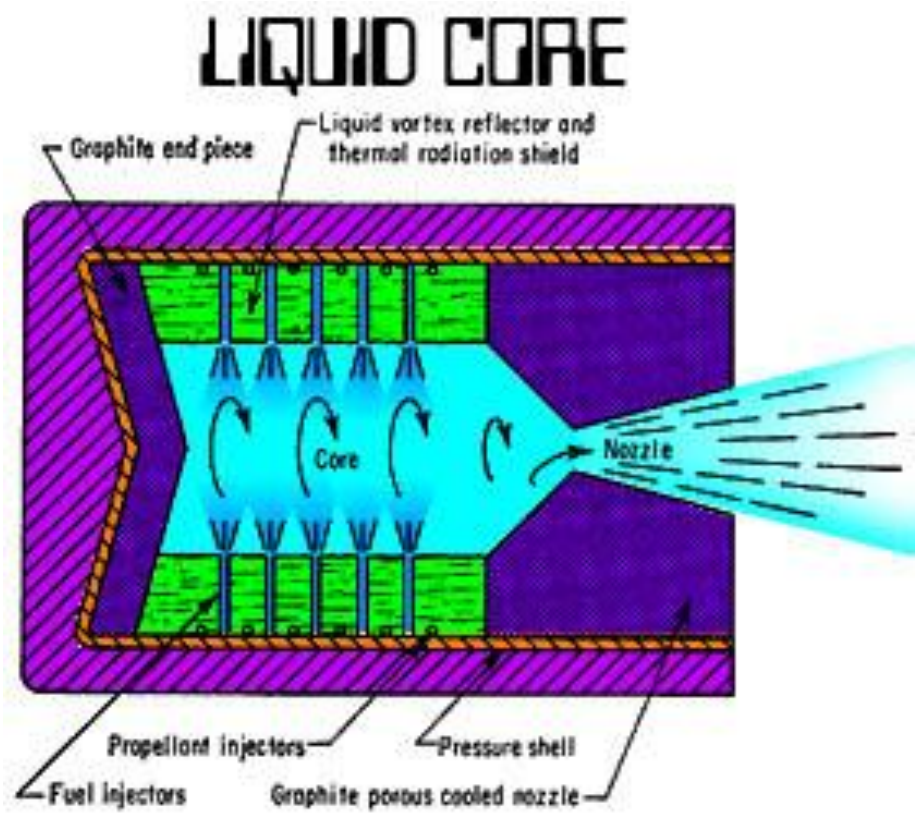
https://en.wikipedia.org/wiki/Breakthrough_Propulsion_Physics_Program
https://boardgamegeek.com/boardgame/214029/spacecorp

More advanced nuclear propulsion concepts

NERVA and Rover produced solid core nuclear rockets limited to V_e of 9.2 km/s and a Delta V_{max} of 14.9 km/s (on our Centaur testbed).

There are also liquid core NTRs.

- Nominal core temperature **5250 K** vs 2750 K for a solid core
- **V_e** **16 km/s**
- **Delta V_{max}** **25.75 km/s**
- Work by bubbling LH2 through a molten fissionable core, e.g., tungsten, osmium, rhenium, tantalum.
- Problems:
  - Keeping the liquid contained inside the rocket chamber
  - Start-up and shut-down complicated



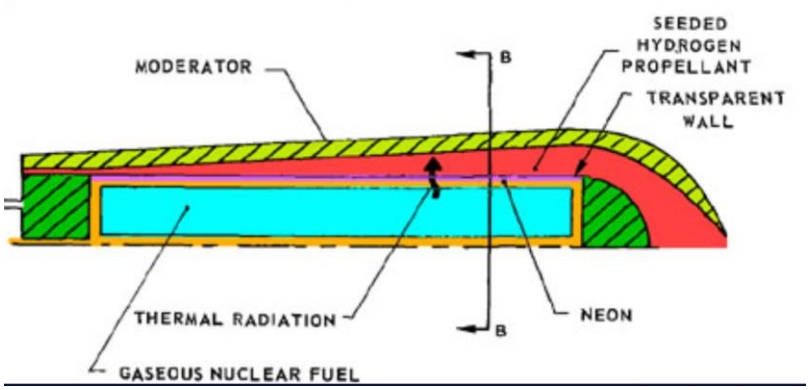
http://www.projectrho.com/public_html/rocket/enginelist.php#ntrliquid

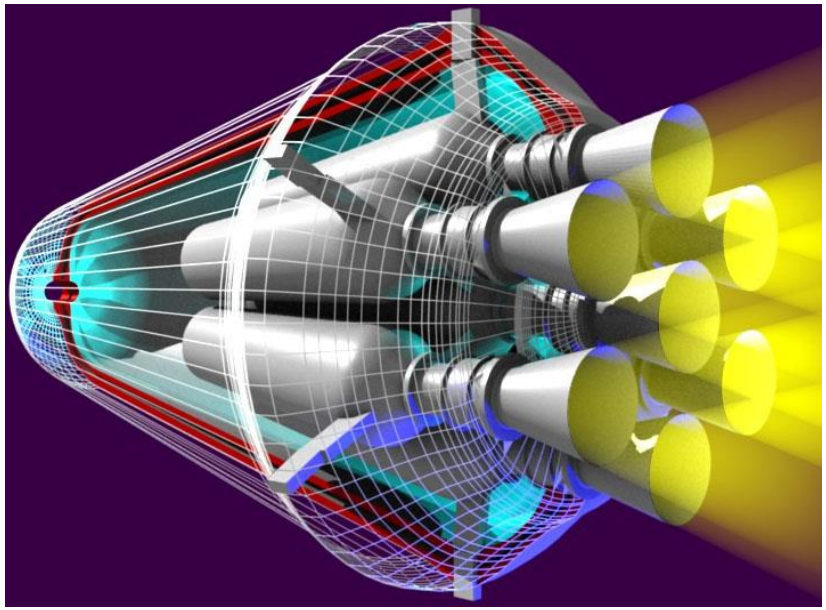
More advanced concepts

NERVA and Rover produced solid core nuclear rockets limited to V_e of 9.2 km/s and a Delta V_{max} of 14.9 km/s (on our Centaur testbed).

There are also gas core NTRs, e.g., the nuclear lightbulb, a closed cycle concept.

- Closed cycle means the nuclear fuel (Uranium hexafluoride or hex) remains contained in the rocket body.
- Nominal core temperature **8333 K**
- **V_e** **30 km/s**
- **Delta V_{max}** **48.3 km/s**





A cluster of seven nuclear lightbulbs on a Liberty Ship.

Works like a light bulb in a closed chamber. Nuclear fuel is contained in a quartz 'lightbulb.' LH2 is passed around it, becomes superheated and exits the nozzle.

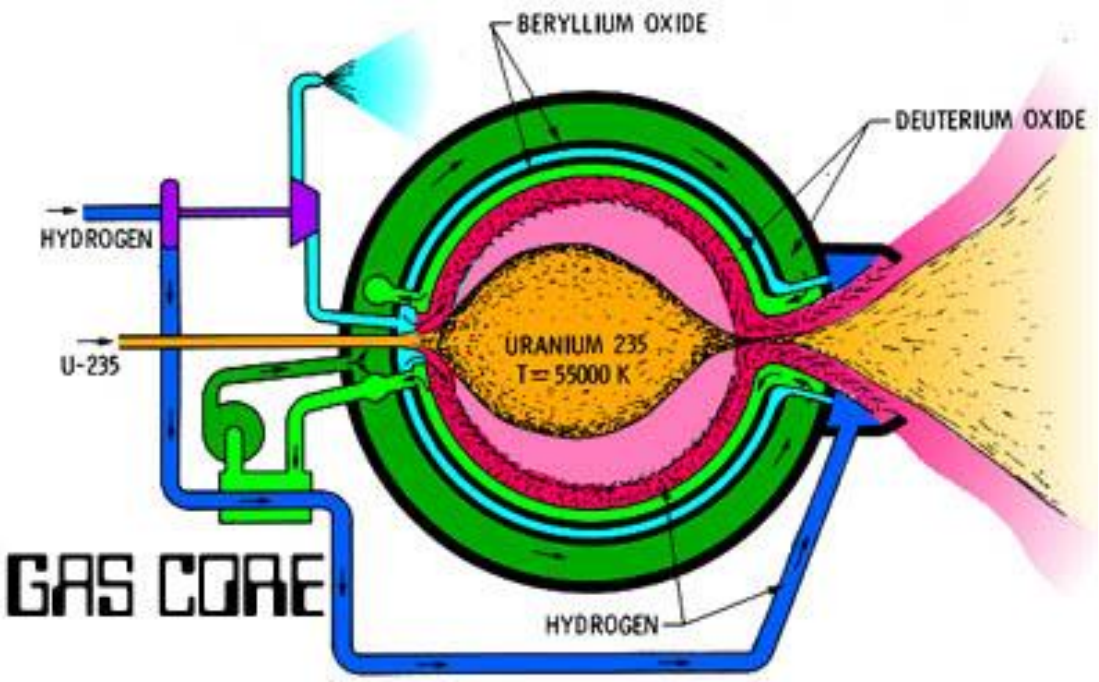
http://www.projectrho.com/public_html/rocket/enginelist.php#id--Nuclear_Thermal--Gas_Core--Closed_Cycle

More advanced concepts

NERVA and Rover produced solid core nuclear rockets limited to V_e of 9.2 km/s and a Delta V_{max} of 14.9 km/s (on our Centaur testbed).

There are also gas core NTRs, e.g., an open cycle concept.

- Open cycle means the nuclear fuel, uranium hexafluoride or hex, is allowed to escape out the nozzle with the LH2—very radioactive.
- Nominal core temperature **55,000 K**
- **V_e** **98 km/s**
- **Delta V_{max}** **157.7 km/s**



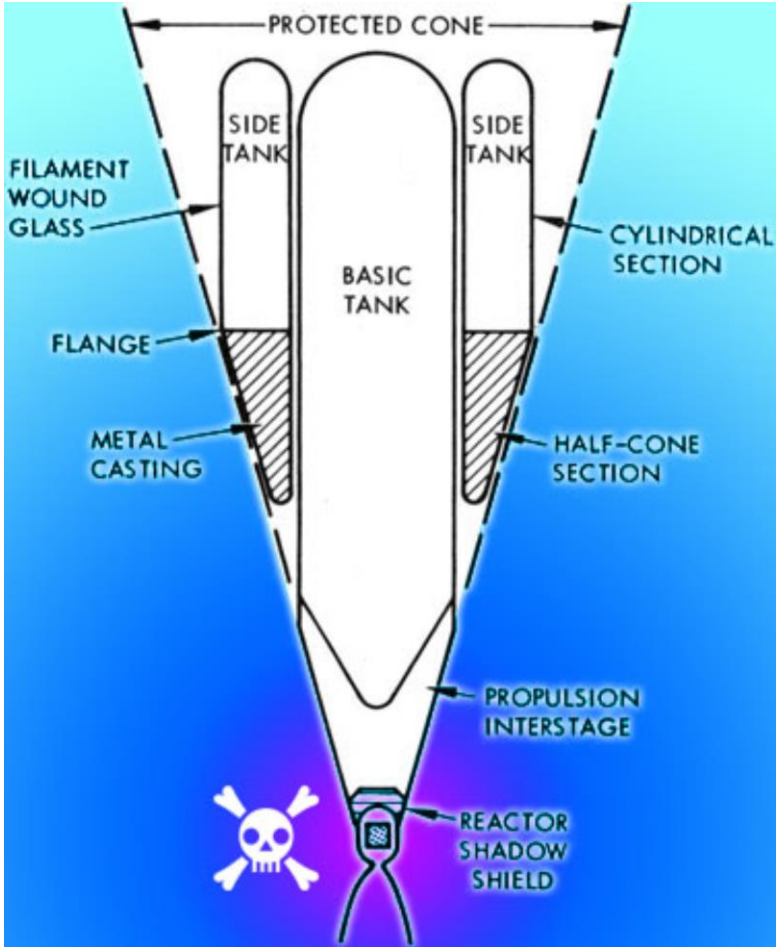
http://www.projectrho.com/public_html/rocket/enginelist.php#id--Nuclear_Thermal--Gas_Core--Open_Cycle

Gamma radiation is a problem with all nuclear thermal rockets. Radioactive fuel is only a problem with open cycle rockets.

We protect against gamma radiation with shadow shields.

In Space Propulsion Analysis and Design they give the specs on a typical shadow shield. Starting at the atomic engine, the gamma rays and neutrons first encounter 18 centimeters of beryllium *(which acts as a neutron reflector)*, followed by 2 centimeters of tungsten *(mainly a gamma-ray shield but also does a good job on neutrons)*, and finally 5 centimeters of lithium hydroxide (To stop the remaining neutrons. Hydrogen slows down the neutrons and lithium absorbs them.). This attenuates the gamma flux to a value of 0.00105, and neutron flux to 4.0e-9. This has a **mass of 3,500 kilograms per square meter of shadow shield** *(ouch!)*.

The thing about gamma radiation is that, being a photon, once it pops out the nozzle it's gone at the speed of light.

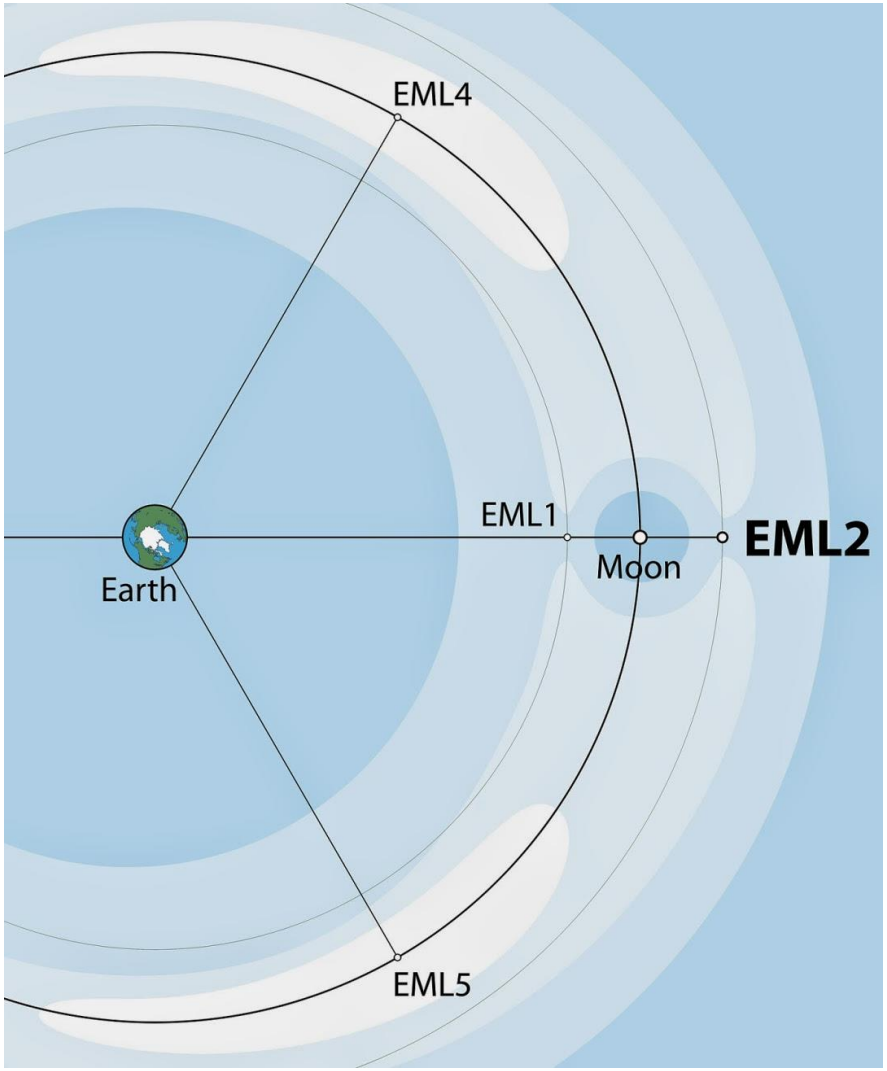


From Nuclear Space Propulsion by Holmes F. Crouch

http://www.projectrho.com/public_html/rocket/radiation.php

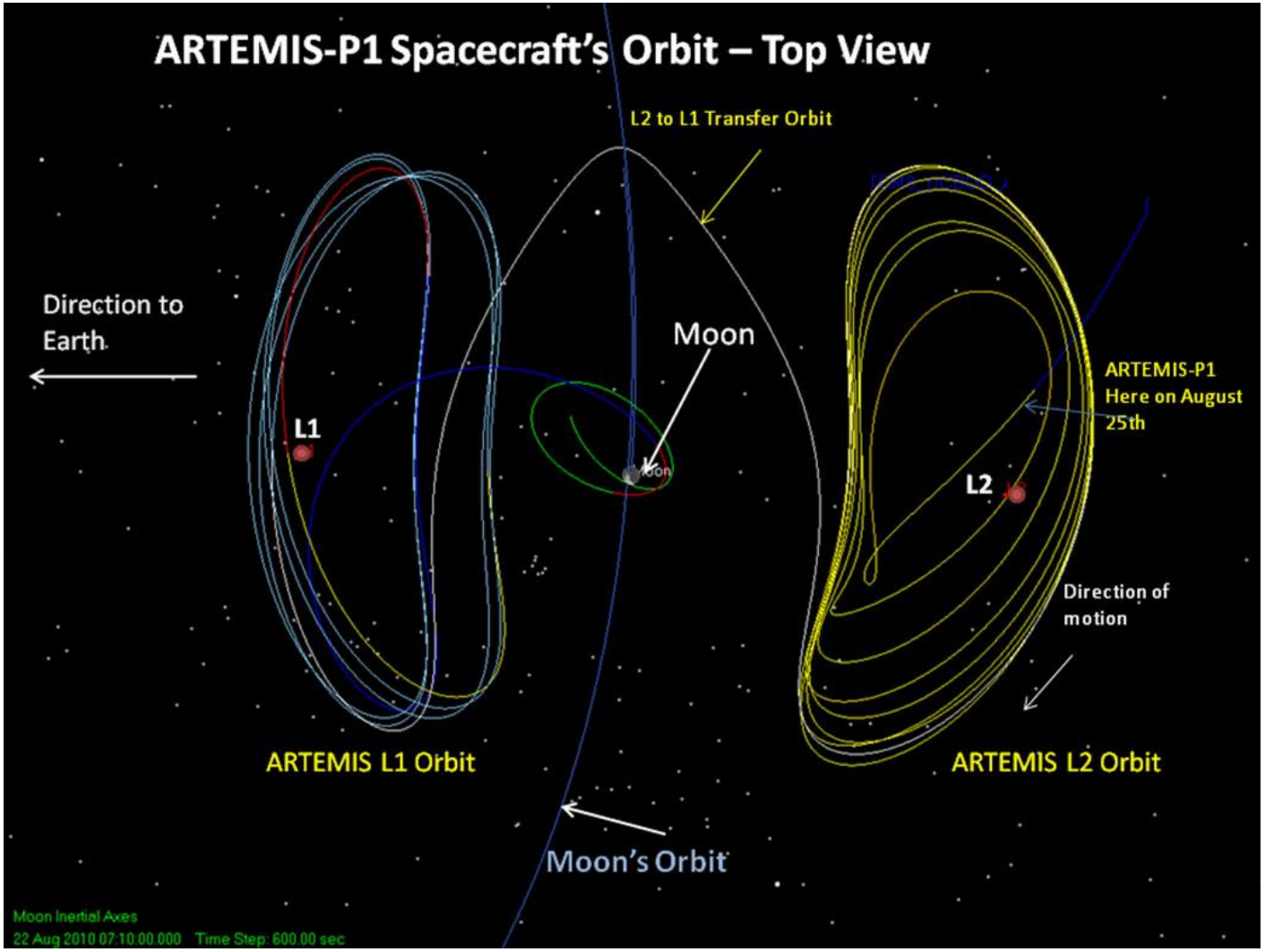
Launch etiquette is the best way to protect against hex.

EML1 is the location of CisLuna's colony of 12 space stations. Interplanetary rocket construction is done there. Launching is done after the space ships are towed into place at EML2, 110,000 km away. Even then the tugboats start the launch by getting the ship underway at maybe 2 km/s. A day of coasting at that speed would put you about 300,000 km away from EML1. At that point you could start your closed cycle lightbulbs to boost your Delta V to 20 km/s. A day or so of that speed will get you a couple of million km from EML1. By then it should be safe to fire the gas core open cycles bringing you up to your interplanetary intercept cruise speed of up to 40 km/s.



http://hopsblog-hop.blogspot.com/search?updated-max=2015-06-08T21:34:00-07:00&max-results=7&start=21&by-date=false

EML1 and EML2 support orbiting space stations in a Lissajous orbit.



https://space.stackexchange.com/questions/4050/is-there-a-lot-of-space-trash-at-the-earth-moon-lagrange-points

Technology beyond Nuclear Thermal Rockets

Chemical based rockets do convert mass to energy but at such low rates it does not even register. Best V_e is 4.4 km/s.

Fission based rockets convert mass to energy at about 1%.

- Best V_e is 9.2 km/s for solid core,
- Best V_e is 16 km/s for liquid core,
- Best V_e is 30 km/s for gas core closed cycle, and
- Best V_e is 98 km/s for gas core open cycle.

Fusion based rockets convert mass to energy at about 3%.

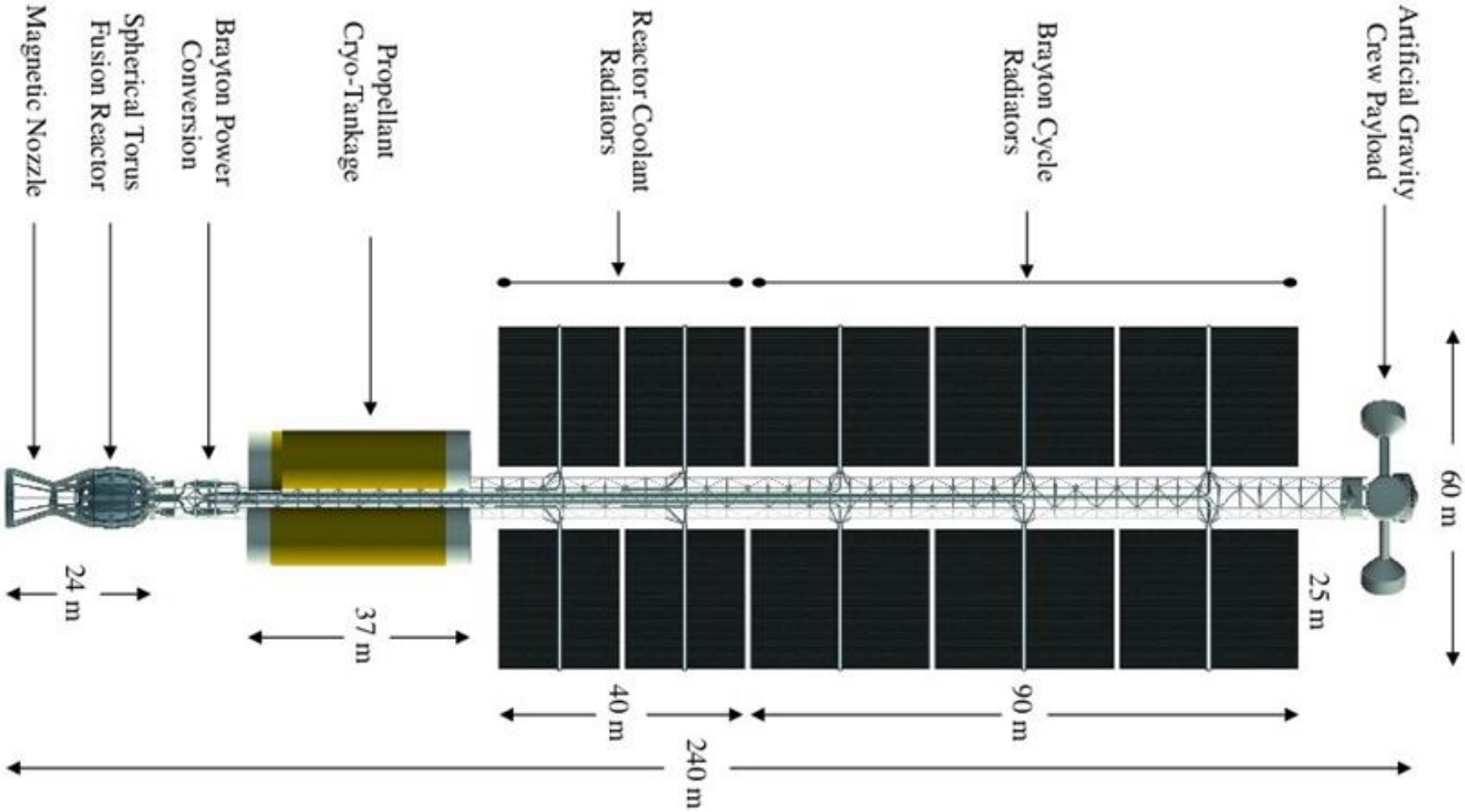
- Best V_e is 7,840 km/s using ^{3}He-D
- 49 kN thrust in pure fusion mode
- **Most practical/complete design to date is Discovery II with V_e = 347 km/s**
- **Capable of 223 km/s Delta V_{max}**
- (BTW: 223 km/s is 0.07% of c)

Antimatter based rockets convert mass to energy at 100%.

- Best V_e is 100,000 km/s.
- 10,000 MN thrust
- Capable of 0.5 c Delta V_{max} (minimum velocity for interstellar voyages)

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Let's check out the Discovery II fusion rocket

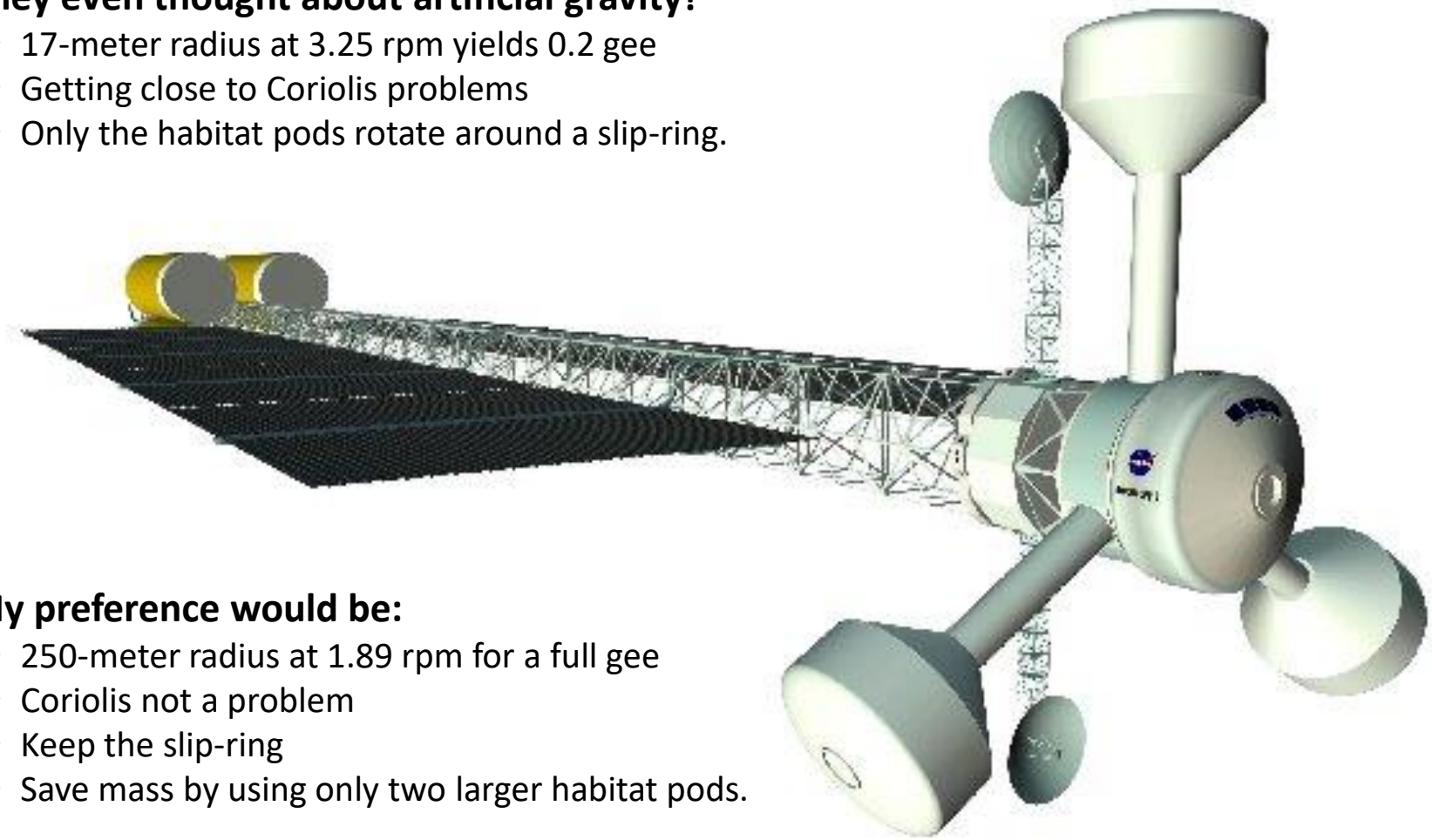


http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket

They even thought about artificial gravity!

- 17-meter radius at 3.25 rpm yields 0.2 gee
- Getting close to Coriolis problems
- Only the habitat pods rotate around a slip-ring.

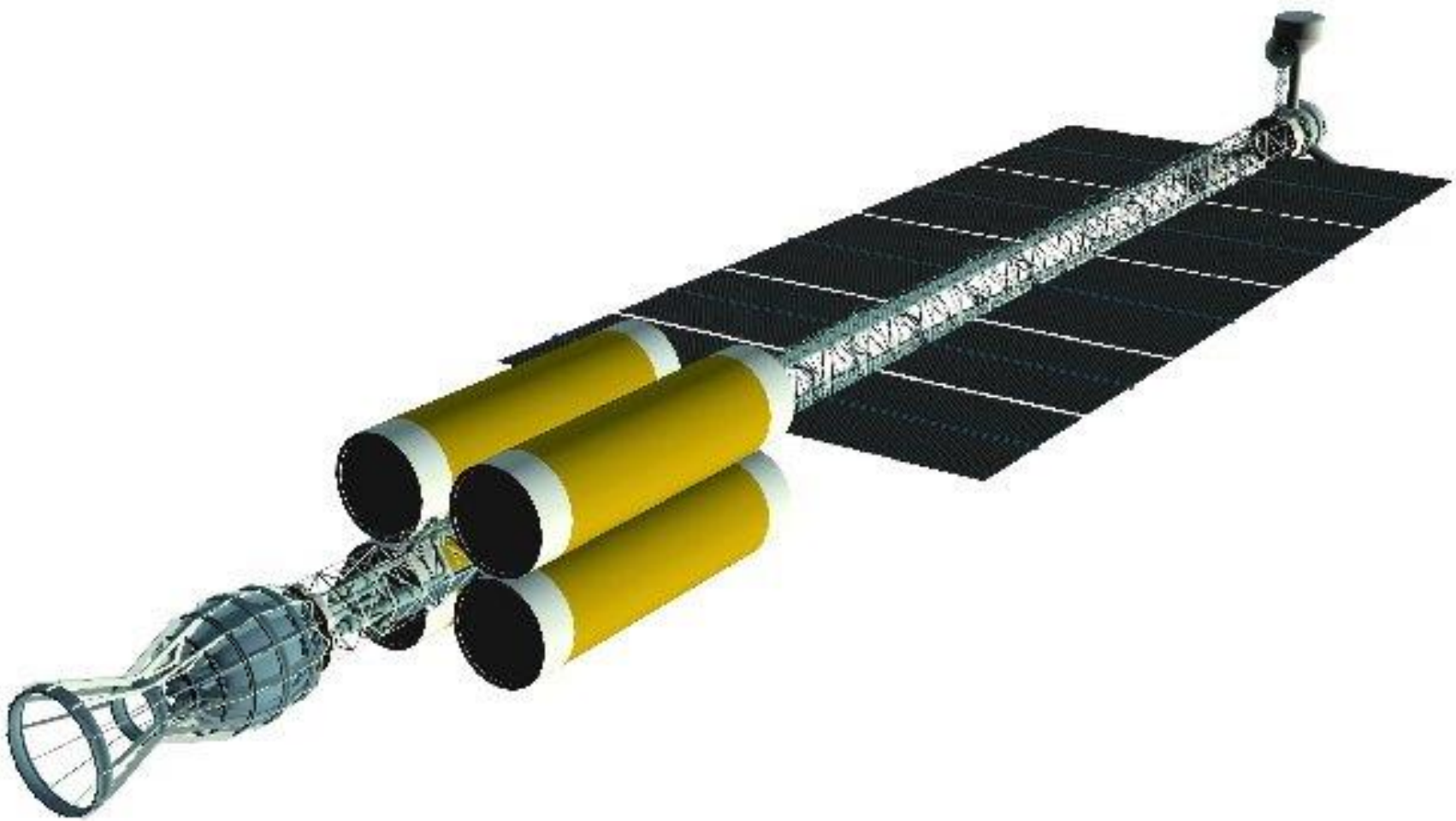


My preference would be:

- 250-meter radius at 1.89 rpm for a full gee
- Coriolis not a problem
- Keep the slip-ring
- Save mass by using only two larger habitat pods.

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket



http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

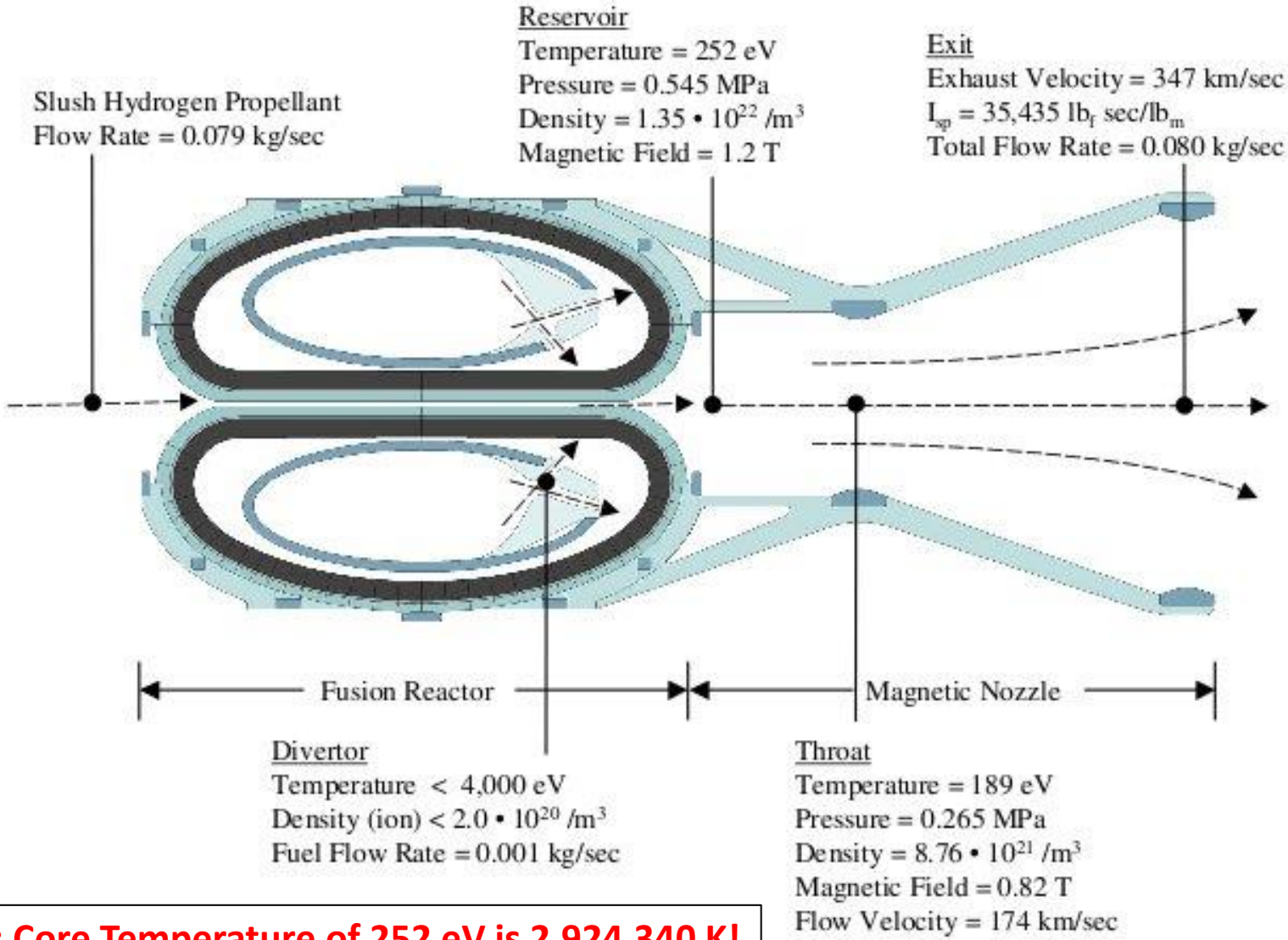
Discovery II fusion rocket

The business end of the fusion rocket

Note the open matrix nozzle. It's a magnetic nozzle, necessary because the exhaust gas temperature is too hot for a normal nozzle.

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket



Note: Core Temperature of 252 eV is 2,924,340 K!

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket

Discovery II	
ΔV	223,000 m/s
Specific Power	3.5 kW/kg (3,540 W/kg)
Thrust Power	3.1 gigaWatts
Propulsion	Helium^3-Deuterium Fusion
Specific Impulse	35,435 s
Exhaust Velocity	347,000 m/s
Wet Mass	1,690,000 kg
Dry Mass	883,000 kg
Mass Ratio	1.9
Mass Flow	0.080 kg/s
Thrust	18,000 newtons
Initial Acceleration	1.68 milli-g
Payload	172,000 kg
Length	240 m
Diameter	60 m wide

http://hdl.handle.net/2060/20050160960

Realizing "*2001: A Space Odyssey*": Piloted Spherical Torus Nuclear Fusion Propulsion, Craig H. Williams et al. March 2005. Goal was to produce a practical fusion-powered spacecraft based on the Discovery from the movie, *2001: A Space Odyssey*.

Engine Mass:	316,000 kg
^{3}He-D Fuel Mass:	11,000 kg
LH2 Propellant Mass:	861,000 kg
Exhaust Velocity:	**347 km/s**
Mass Ratio:	**1.9**

Applying Tsiolkovsky's equation we get:

Delta V_{max} = 223 km/s

Or doubling the Mass Ratio to 3.8 we get:

Delta V_{max} = 463 km/s

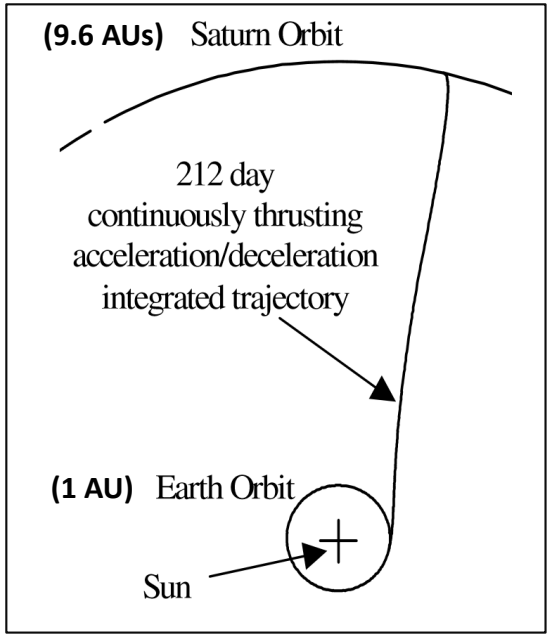
Or increasing the Mass Ratio to 10.0 we get:

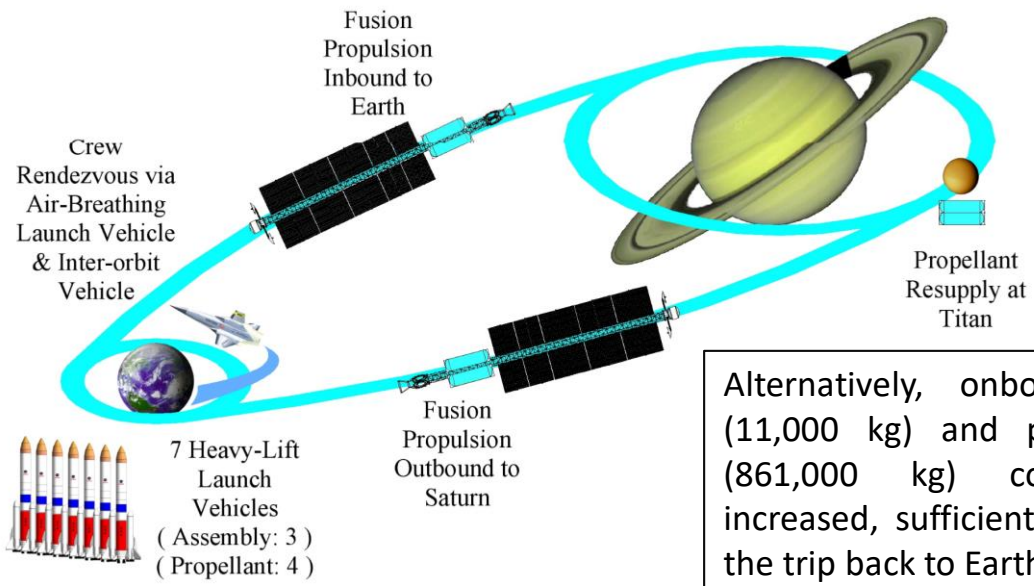
Delta V_{max} = 798 km/s

NOTE: This rocket is designed for a <u>continuous burn</u> for the duration of the mission. You <u>don't</u> burn to accelerate to cruise velocity, shut down and coast, then burn to decelerate for orbit insertion.

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket





Alternatively, onboard fuel (11,000 kg) and propellant (861,000 kg) could be increased, sufficient to cover the trip back to Earth.

"The normally thought of conics of minimum energy trajectories followed by today's chemical systems degenerate into nearly straight line, radial transfers at these high acceleration levels with continuous thrust."

212-Day Saturn Rendezvous Mission

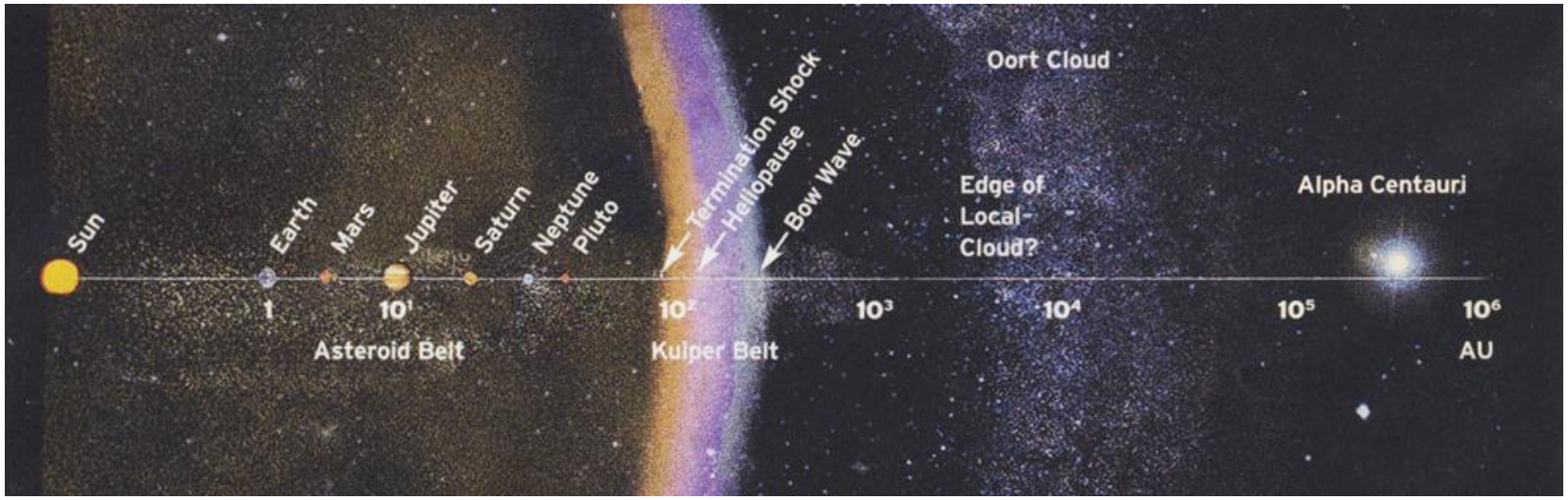
It would be constructed, launched, and recovered in LEO using 7 heavy-lift launch vehicles. (3 Assembly; 4 Propellant) 6-person crew arrives by shuttle. Propellant flow-rate is reduced to 0.045 kg/s to cover the longer transit time. Gas Core Open Cycle fission rocket would need 347 days for the outbound leg.

http://www.projectrho.com/public_html/rocket/enginelist.php#he3dfusion
http://www.projectrho.com/public_html/rocket/realdesignsfusion.php#discovery2

Discovery II fusion rocket

Fusion power is the future of space travel within the Solar System!

The Limits of Fusion Rocketry



Alpha Centauri, our nearest star, is 4.3 ly away, or 276,174 AUs. Neptune is 30 AUs away, making AC 9205 times farther away than Neptune. Getting to Neptune in a reasonable amount of time, does not equate to getting to AC in a reasonable amount of time.

For the sake of the argument, I define a reasonable transit time to AC as 1 year of acceleration, 8 years of coasting, and 1 year of deceleration. Hence, a starship capable of 0.5 c is called for.

Discovery II (even if augmented to a Mass Ratio of 10) would need over 9000 years to reach AC. A Fusion Max drive (V_e = 7840 km/s, Max Delta V = 3159 km/s or ~1% c) would require over 400 years.

Antimatter is the minimum technology capable of reaching 0.5 c.

Air & Space Magazine

Technology beyond Nuclear Thermal Rockets

Chemical based rockets do convert mass to energy but at such low rates it does not even register. Best V_e is 4.4 km/s.

Fission based rockets convert mass to energy at about 1%.

- Best V_e is 9.2 km/s for solid core,
- Best V_e is 16 km/s for liquid core,
- Best V_e is 30 km/s for gas core closed cycle, and
- Best V_e is 98 km/s for gas core open cycle.

Fusion based rockets convert mass to energy at about 3%.

- Best V_e is 7,840 km/s using ^{3}He-D
- 49 kN thrust in pure fusion mode
- **Most practical/complete design to date is Discovery II with V_e = 347 km/s**
- **Capable of 223 km/s Delta V_{max}**
- (BTW: 223 km/s is 0.07% of c)

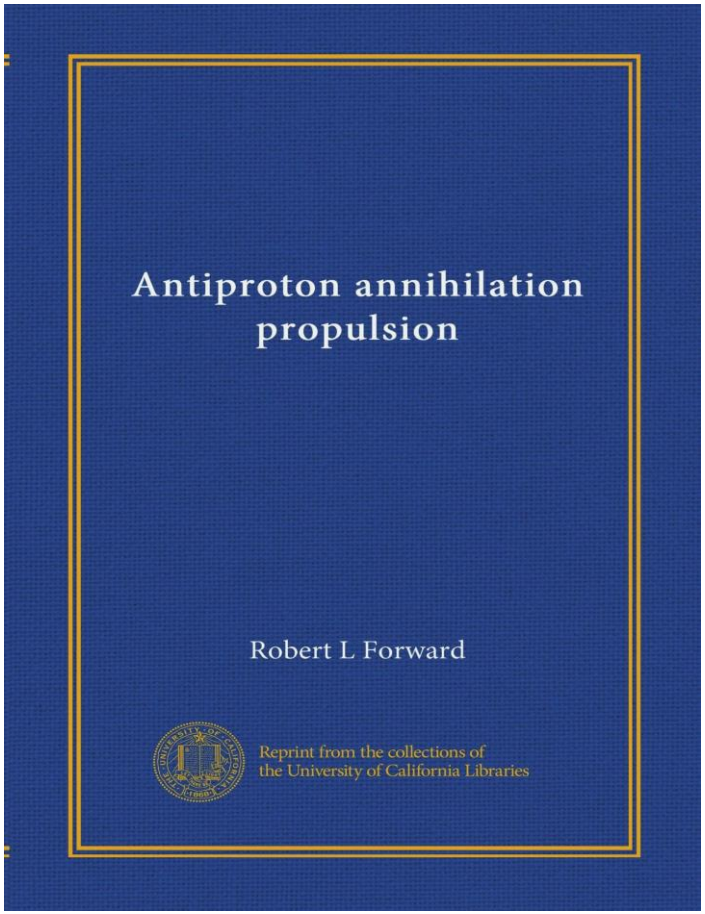
Antimatter based rockets convert mass to energy at 100%.

- Best V_e is 100,000 km/s.
- 10,000 MN thrust
- Capable of 0.5 c Delta V_{max} (minimum velocity for interstellar voyages)

http://www.projectrho.com/public_html/rocket/enginelist.php#ambeam
https://web.archive.org/web/20060601234257/http://www.aiaa.org/Participate/Uploads/2003-4676.pdf

Let's check out the Frisbee Beamed Core Antimatter Starship.

First introduced by physicist and SciFi writer Robert L. Forward in "Antiproton Annihilation Propulsion" in September 1985 as a final report for the Air Force Rocket Propulsion Lab.



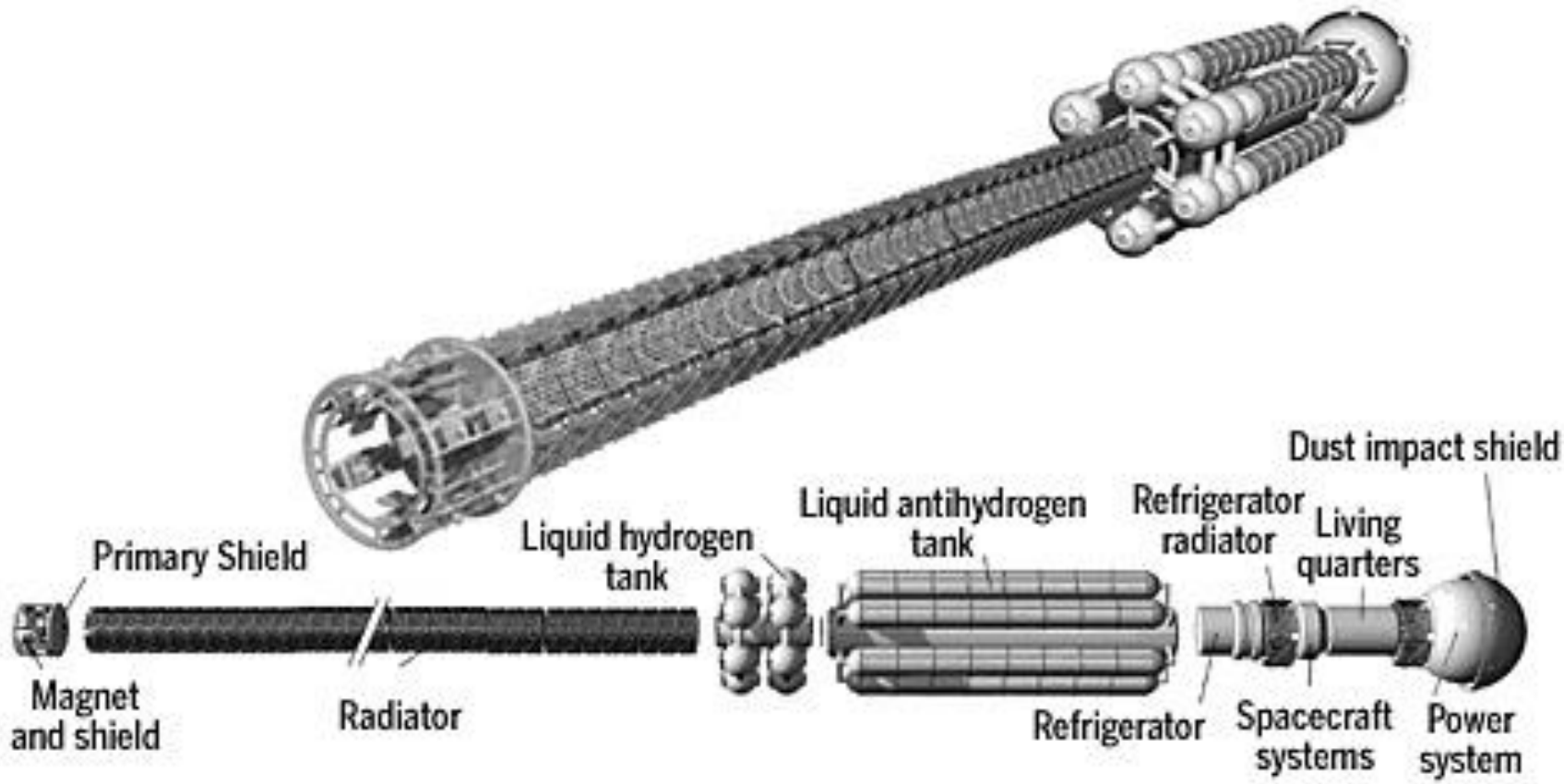
The concept was later expanded by Robert H. Frisbee of JPL in his 2003 paper "How to Build an Antimatter Rocket for Interstellar Missions." The Frisbee variant was good for V_e = 0.333 c which in turn yielded a Delta V_{max} of 0.25 c.

Roman L. Keane and Wei-Ming Zhang in 2012 expanded on Frisbee's concept with some simulation research on the magnetic nozzle design. The result was V_e = 0.69 c which in turn yielded a Delta V_{max} of 0.48 c.

'c' is the speed of light, 299,792,458 m/s.

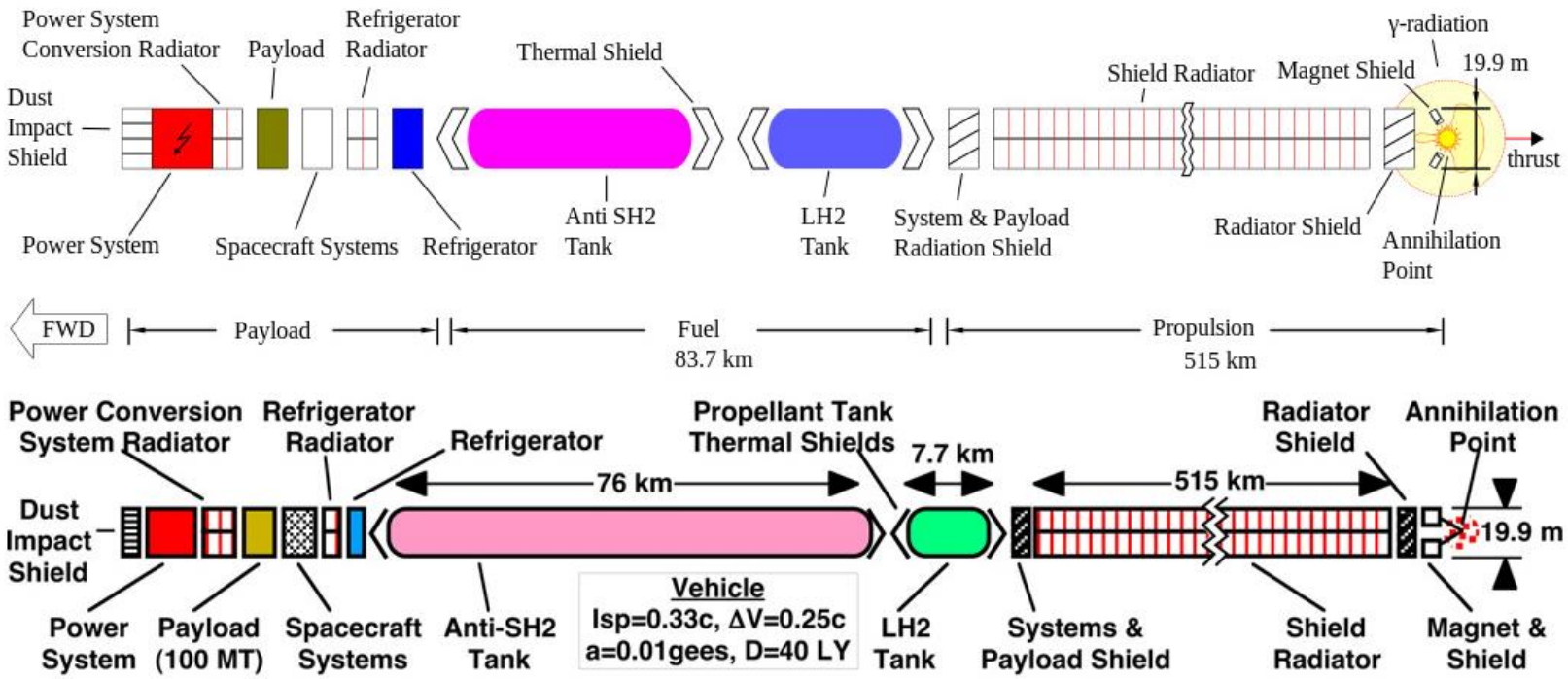
http://www.projectrho.com/public_html/rocket/enginelist.php#ambeam
https://web.archive.org/web/20060601234257/http://www.aiaa.org/Participate/Uploads/2003-4676.pdf
https://arxiv.org/pdf/1205.2281

Frisbee Beamed Core Antimatter Starship



http://www.projectrho.com/public_html/rocket/enginelist.php#ambeam
https://web.archive.org/web/20060601234257/http://www.aiaa.org/Participate/Uploads/2003-4676.pdf

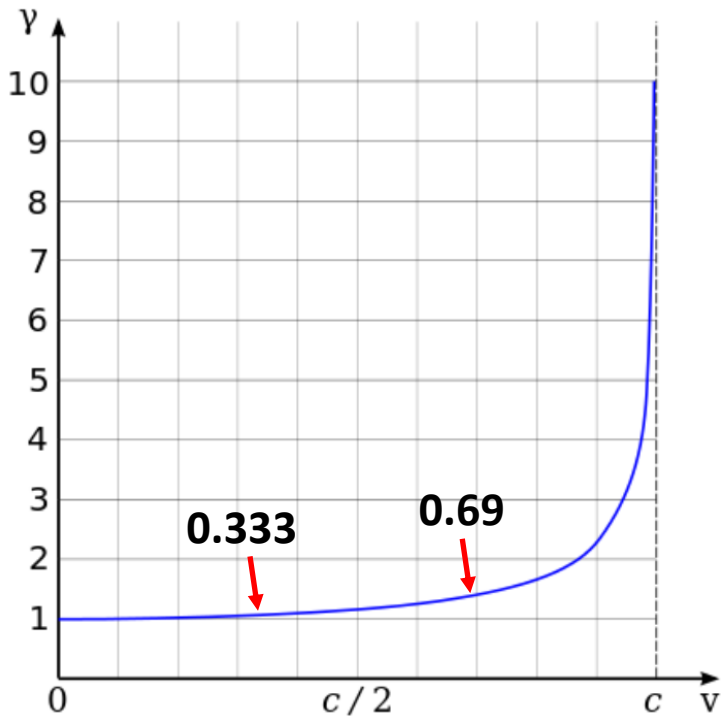
Frisbee Beamed Core Antimatter Starship



Note: Overall length is 700 km due to ginormous gamma radiation and the need for 500 km of heat radiators!!!

http://www.projectrho.com/public_html/rocket/enginelist.php#ambeam
https://web.archive.org/web/20060601234257/http://www.aiaa.org/Participate/Uploads/2003-4676.pdf

When we start measuring V_e in c, we need a new rocket equation.



Lorentz Factors as a function of c

At 0.69 c we are starting to hit the knee in the Gamma Curve.

The world as we know it—time, length, mass, etc.—changes as velocity approaches c. These changes are reflected in the Lorentz Factor, γ.

- Frisbee's rocket had a V_e of 0.333 c, giving it a Lorentz Factor of about 1.06—not very significant.
- Keane & Zhang's rocket had a V_e of 0.69 c, giving it a Lorentz Factor of about 1.4—significant.

https://en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation#Special_relativity
https://en.wikipedia.org/wiki/Lorentz_factor

When we start measuring V_e in c, we need a new rocket equation.

$$\Delta v = v_{\mathrm{e}} \ln \frac{m_0}{m_f}$$

Classical Rocket Equation

$$\Delta v = c \cdot \tanh\left(\frac{v_e}{c} \ln \frac{m_0}{m_1}\right)$$

Relativistic Rocket Equation

	Frisbee	Keane & Zhang
V_e (c)	0.33	0.69
Mass Ratio	2.15	2.15
LN(MR)	0.77	0.77
Classical V_{max} (c)	**0.26**	**0.53**
γ	**1.06**	**1.40**
Relativistic V_{max} (c)	**0.25**	**0.48**

'tanh' is the hyperbolic tangent. It's on your iPhone scientific calculator.

https://en.wikipedia.org/wiki/Tsiolkovsky_rocket_equation#Special_relativity
https://en.wikipedia.org/wiki/Lorentz_factor

Conclusion

You may have heard of the Kardashev Scale used to measure an alien society's level of technological advancement. It's based on energy utilization:

Type I—Uses all the energy available on the planet
Type II—Uses all the energy available from the host star
Type III—Uses all the energy available from the host galaxy

I propose the Propulsion Scale as a more practical measure of an alien society's technological advancement:

Type 0—Has yet to make it to space

Type 1—Chemical Propulsion—Uses chemical rockets; routine travel inside local stellar system using Hohmann Elliptical Transfers

Type 2—Fission Propulsion—Uses fission rockets; routine travel inside local stellar system using hyperbolic transfers

Type 3—Fusion Propulsion—Uses fusion rockets; routine travel beyond local stellar system, e.g., Kuiper Belt, Oort Cloud, using hyperbolic transfers

Type 4—Antimatter Propulsion—Uses antimatter rockets; routine travel to nearby stars; have begun initial migration to stars within 100 ly

Type 5—Faster Than Light Propulsion—Uses technology similar to the Alcubierre Warp Drive to achieve speeds up to Warp 10; migration beyond 100 ly

https://www.pinterest.com/pin/359443613992276568/