Nuclear Propulsion for a Manned Mission to Mars

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Abstract

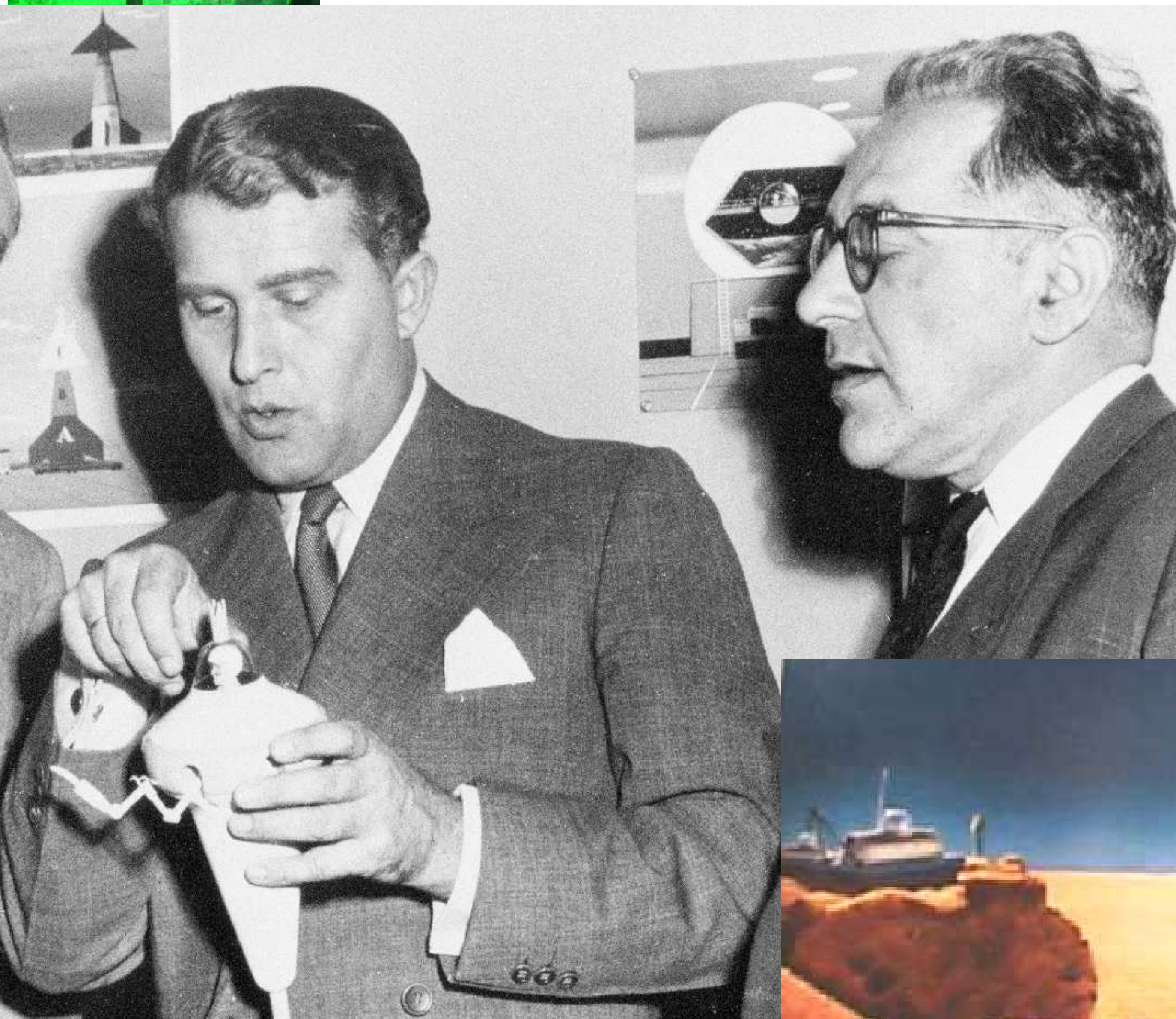
We discuss a novel dusty-plasma fission-fragment nuclear rocket that can provide both thrust and electricity for a mission to Mars, substantially improving over the 40+ year old NERVA. It is able to achieve higher power (~5GW) than NERVA (~1GW) through its innovative dusty core that cools very efficiently by radiation. It is able to achieve higher specific impulse (~100,000s) than NERVA (~800s) or DS1 (~10,000s) by emitting fission fragments at a few percent of the speed of light where the charged dust is confined by strong magnetic and electric fields, which also transfer the thrust. It uses modern neutron moderators that are about 100 times more effective and lighter weight than NERVA, for a "wet" mass of a few tons. It can produce electricity directly from the charged fission fragments at about 85% efficiency, with less thermal radiators than the corresponding Carnot process of "nuclear-electric". The environmental impact of radioactive exhaust for starting the rocket in low-earth orbit amounts to approximately one years worth of natural C14 production, depending on space weather. And finally, it uses proven HEU or Pu reactor fuel, which other than its processing as dust, is readily available. In conclusion, this technology may have broken through the twin barriers of cost and safety, permitting astronauts a speedy transport to and timely return from Mars.

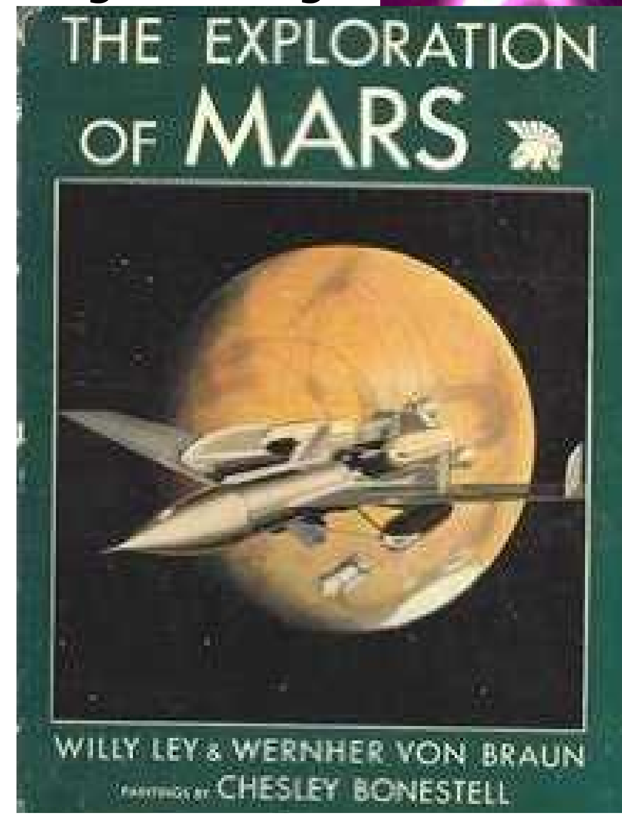
Outline

- The Dream of Mars
- The Necessity of Nuclear
  - Insufficiency of Chemical
  - Impotence of Ion Electric
  - Advantage of Nuclear
- The Nuclear Options
  - Propulsion
  - Power
  - Hybrid
- The Dusty-Plasma Fission-Fragment Rocket

I. The Dream of Mars

Werner vonBraun & Willy Ley





II. The Necessity of Nuclear

Tsiolkovsky Rocket Equation

$V_{exhaust} = I_{sp} * g$ [d/dt(MV) = 0]

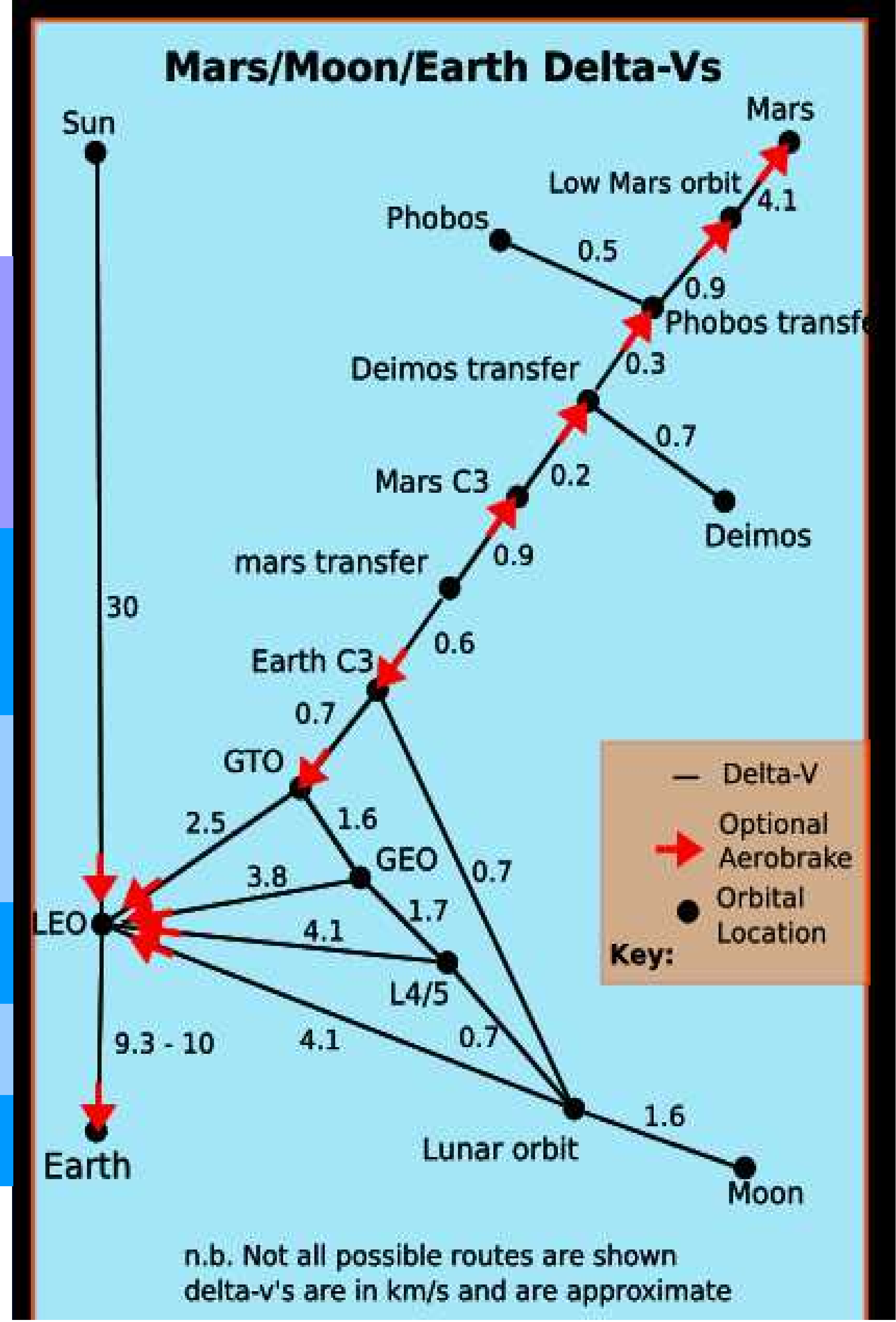
$dV = V_{exhaust} *$ log(final mass / initial mass)

Material	Isp	Limitation (more=better)
Solid fuel	200-250	fuel-starved
LH2/LOX	350-450	fuel-starved
Nuclear Thermal	825-925	efficiency-starved
Gas Core Nuclear	~2,000	efficiency-starved
MHD	< 5,000	energy-starved
Ion	< 10,000	energy-starved
Fission Fragment	~1,000,000	fuel-starved
Matter-Antimatter	~10,000,000	fuel-starved
Photons	30,000,000-∞	all-starved

Delta-V

Trip	w/o aero-brake	With aero-brake	Type of Trajec-tory
E → Mars	20.2	16.1	Hohmann
M → Earth	20.2	10.2	Hohmann
® trip	40.4	26.3	Hohmann
LEO-LMO	6.1	5.2	Hohmann
LEO-LMO	~231	~58	30 day

30-day computed w/o orbital dynamics



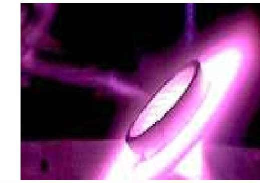
Mi / Mf Comparison

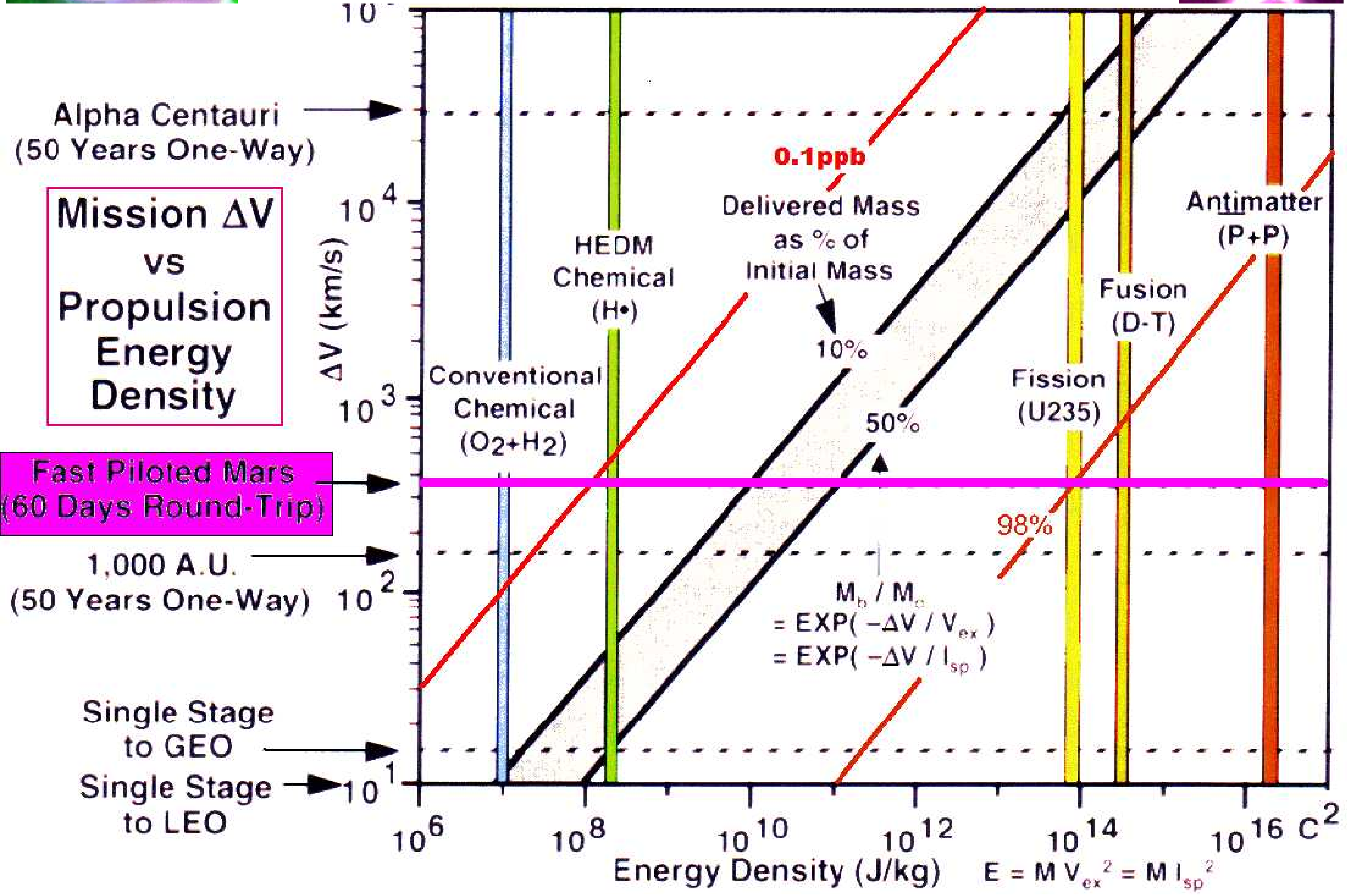
Mission Technique	Mars@1y Hohmann dV=40k/s	Mars@30d Linear dV=116	Grav.Lens 550au@10y	Oort Cloud .5ly@30y	α-Centauri 4ly@50y
LH2/LOX 450s	9518	e11	e41	e2222	e10666
NTR NERVA 820s	152	1341	e22	e524	e2535
Xe Ion 10ks	1.5	1.8	72	e43	e208
Fission Frag 1Ms	1.004	1.01	1.04	2.11	36
Fusion Frag 2Ms	1.002	1.003	1.02	1.65	11

Thrust/Power Requirements for 30d trip to Mars (dV=58km/s)

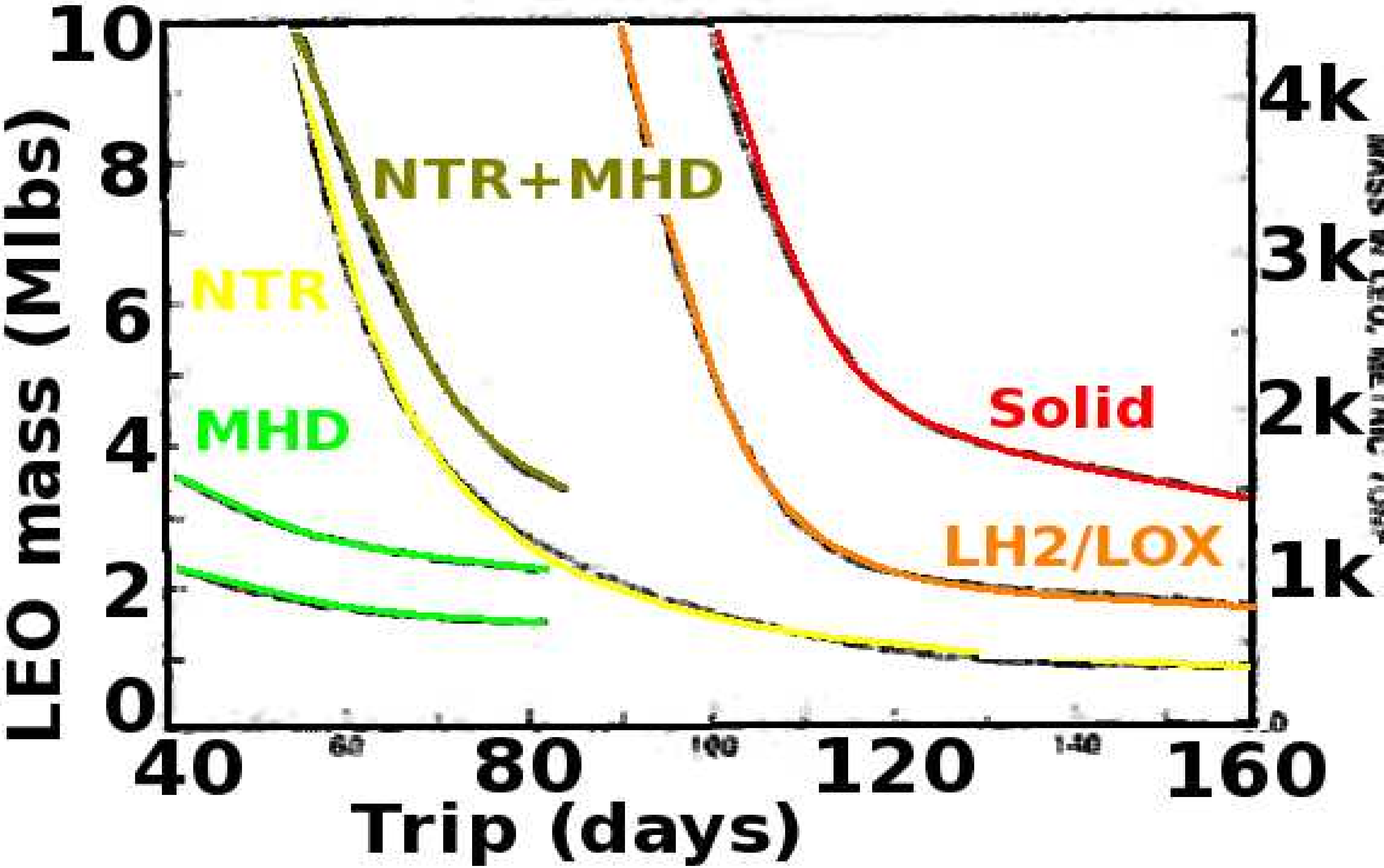
Rocket	Isp	Mf/Mi	<Force> Newtons 8T payld	mass flow kg/s	Kinetic Power MWatt	Total Power MWatt
LH2/LOX	450	500k	357M	81M	787	787
NERVA	870	886	4.8M	596k	19	19
Xe Ion	10k	1.8	1289	13.16	0.063	117 (~20 hoh)
Fission Fragment	1M	1.01	718	0.07	3.5	~20
Fusion Fragment	2M	1.003	716	0.04	7	~15

Ideal Rockets



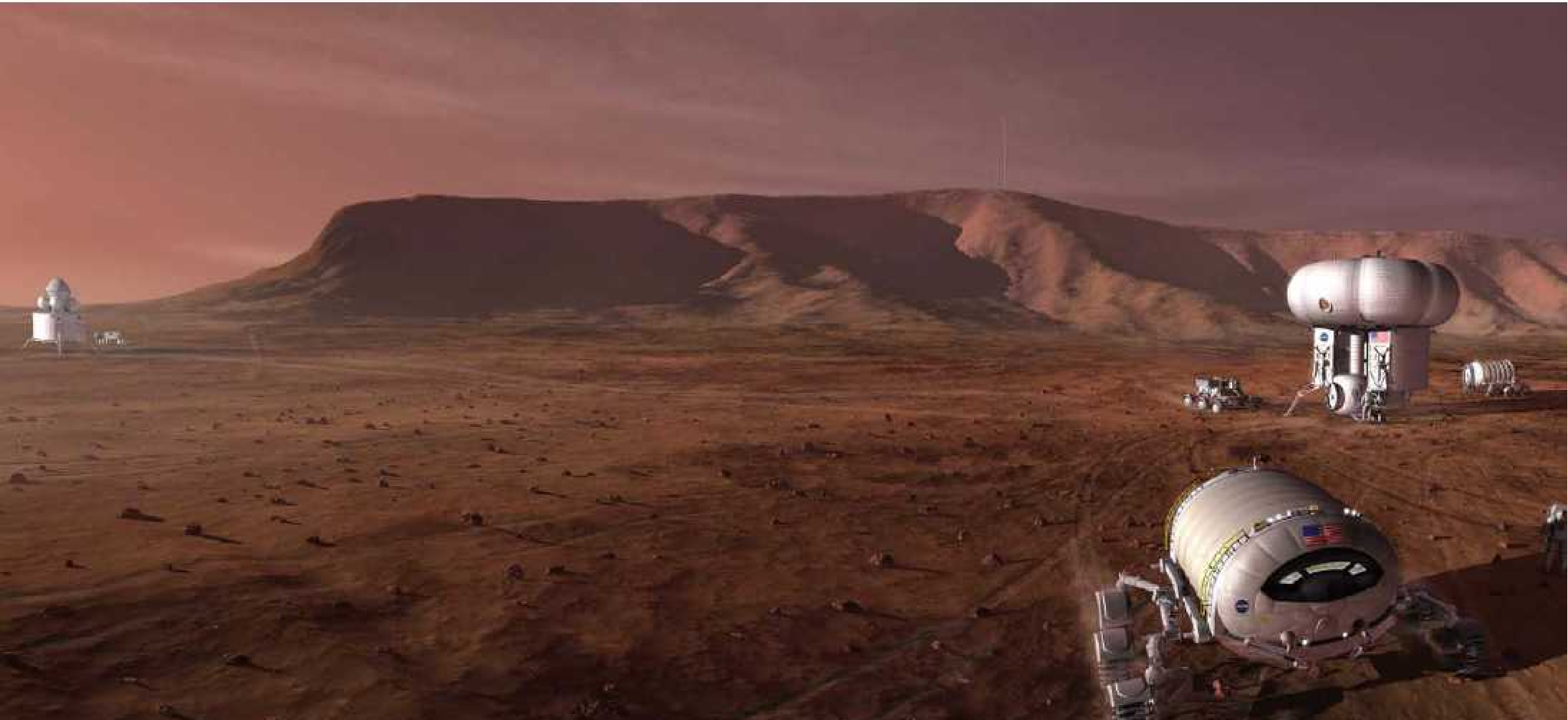


LEO Mass for Mars Missions



Human Exploration of Mars
Design Reference Architecture 5.0

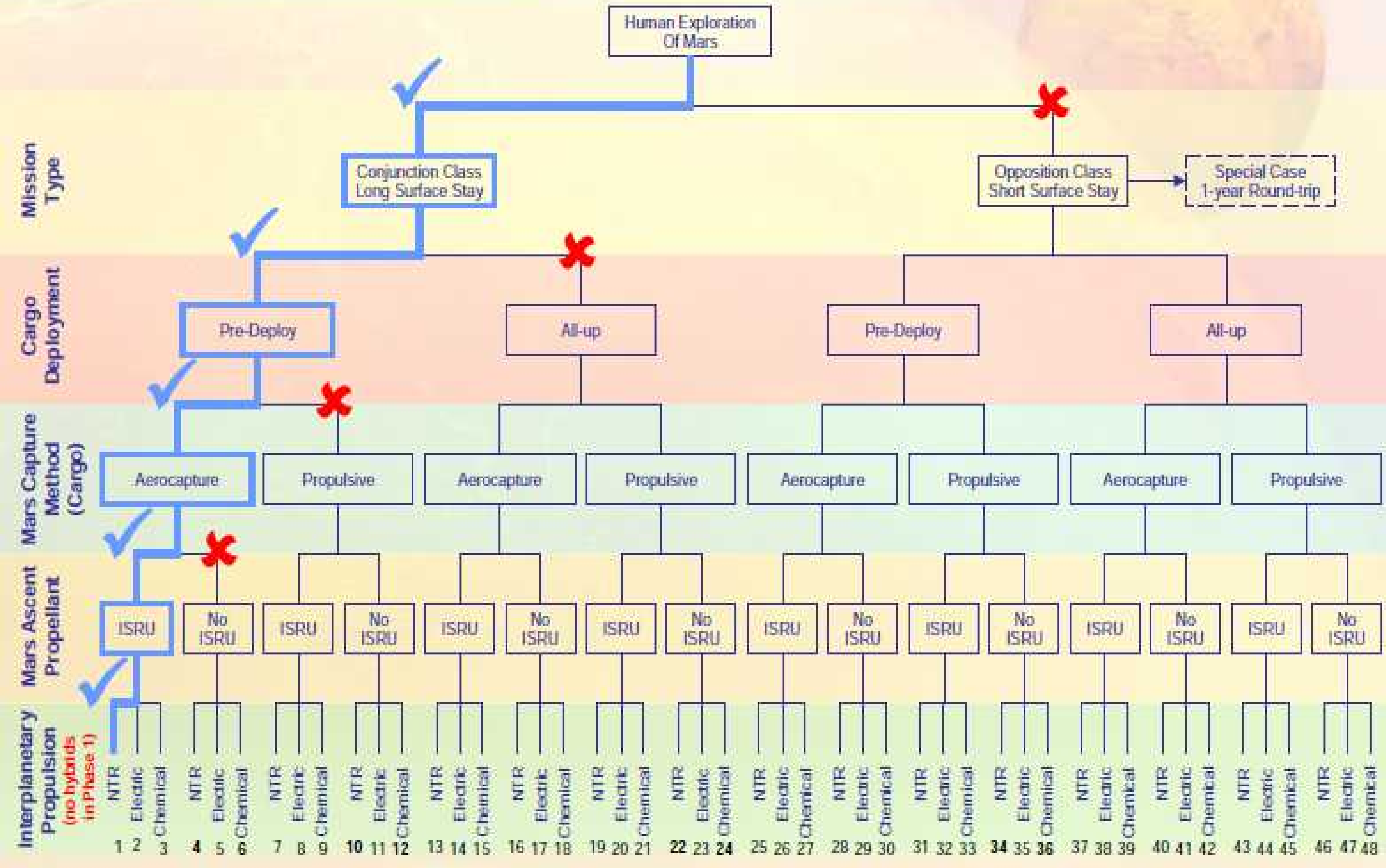
National Aeronautics
and Space Administration



Bret G. Drake
Lyndon B. Johnson Space Center

February 2009

Mars Design Reference Architecture 5.0
Top-level Trade Tree



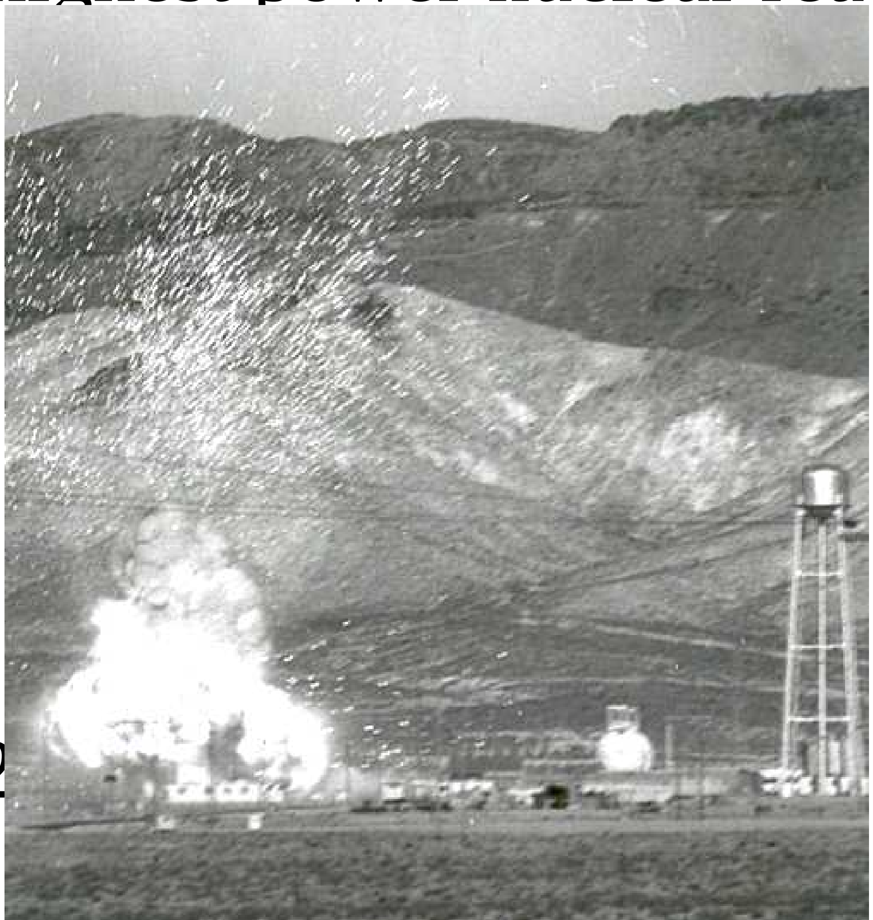
Human Exploration of Mars
Key Decisions and Tenets

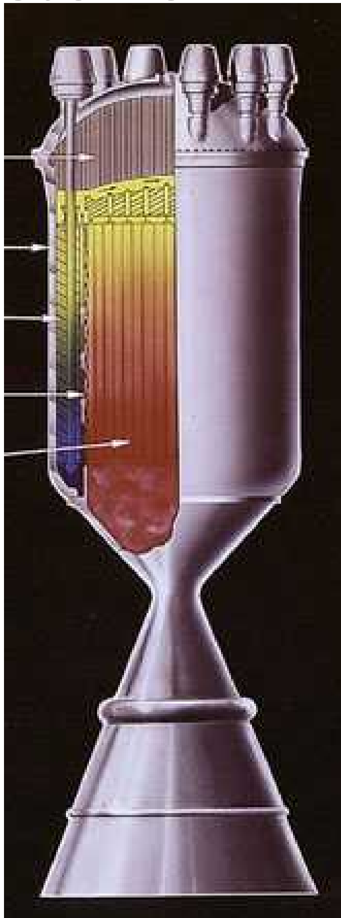
- Long surface stays with visits to multiple sites provides scientific diversity thus maximizing science return
- Mars systems pre-deployed to reduce mission mass and conduct system checkout prior to crew departure from Earth
- Enabling characteristics of human exploration of Mars:
  - Entry, Descent, and Landing of large payloads (40 t) – Dual use Ares V shroud
  - Robust Ares V launch campaign: 7+ launches on 30-day centers
  - Nuclear Thermal Rocket (NTR) propulsion preferred transportation option (retain chemical/aerobrake as backup)
  - ISRU : Production of ascent propellant (oxygen) and crew consumables from the atmosphere
  - Nuclear surface power : Enables In-Situ Resource Utilization (ISRU) while providing continuous robust power
  - Mobility at great distances (100's km) from the landing site enhances science return (diversity)
  - A rich "Mars like" lunar Program which demonstrates key system behavior, operability, repair, and time on systems is necessary
  - Operation and maintenance of systems for long durations (500-1200 days) with no logistics resupply

III. The Nuclear Options

NERVA nuclear thermal circa 1968

1.5GW Pu239 reactor cooled with GH2 run for >30 minutes, stopped and restarted without incident at Jackass Flats NV. One version made 4.08GW for 12 minutes. Held the record almost 30 years for the highest power nuclear reactor on Earth.





-Mass (dry) = 34 ton

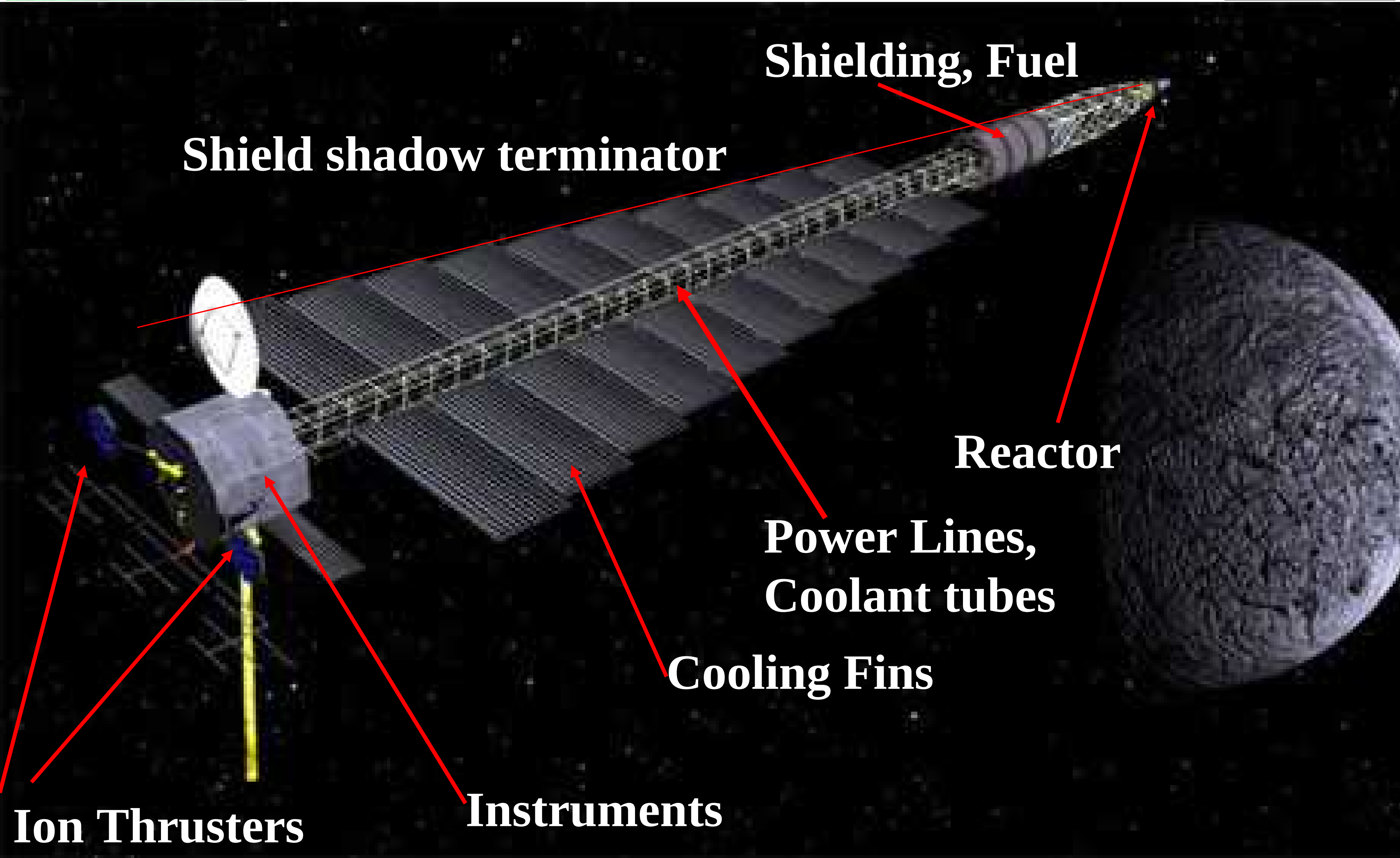
-Diameter = 10.5 m

-Thrust = 867 kN in vacuum

-ISP~820second @1.2GW

Could place men on Mars 1985. Cancelled in 1972

JPL Nuclear-Electric Concept



Hybrid Nuclear

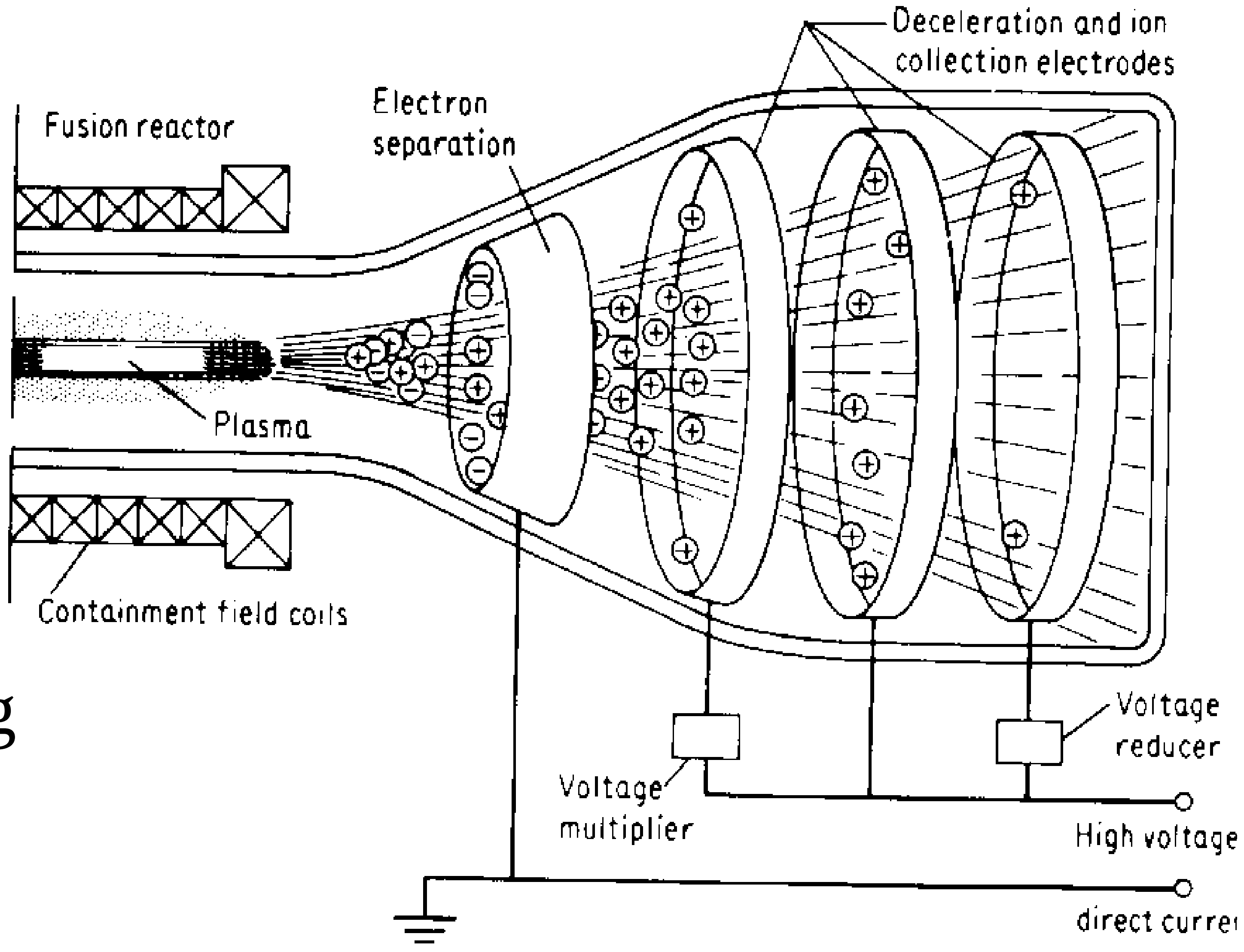
- If you need NTR to get to Mars, and you need electric power to stay on Mars, why not use that electric power in orbit to generate high Isp thrust, and save on fuel?
- Combining to two reactors also allows savings on weight, moving the baseline downwards. What could be the problem with that?
- Heat.
- Nuclear power plants use Carnot-cycle conversion of heat to electricity at about 40%, but efficiency is strongly dependent on the “cold” temperature: ==>(Ti – To)/Ti
  And space has only radiative cooling ==> σT^4

Nuclear-Electric Heat Problem

- Nuclear-Electric converts nuclear energy to heat, heat to electricity, then electricity to propulsion. The overall efficiency isn’t very high. There’s abundant nuclear power, so low efficiency can be tolerated, but now we also have much heat to remove, which in space can only be done with radiators.
- Estimates from 1987 were that radiators were as twice as heavy as the nuclear power plant itself—60T compared to 30T.

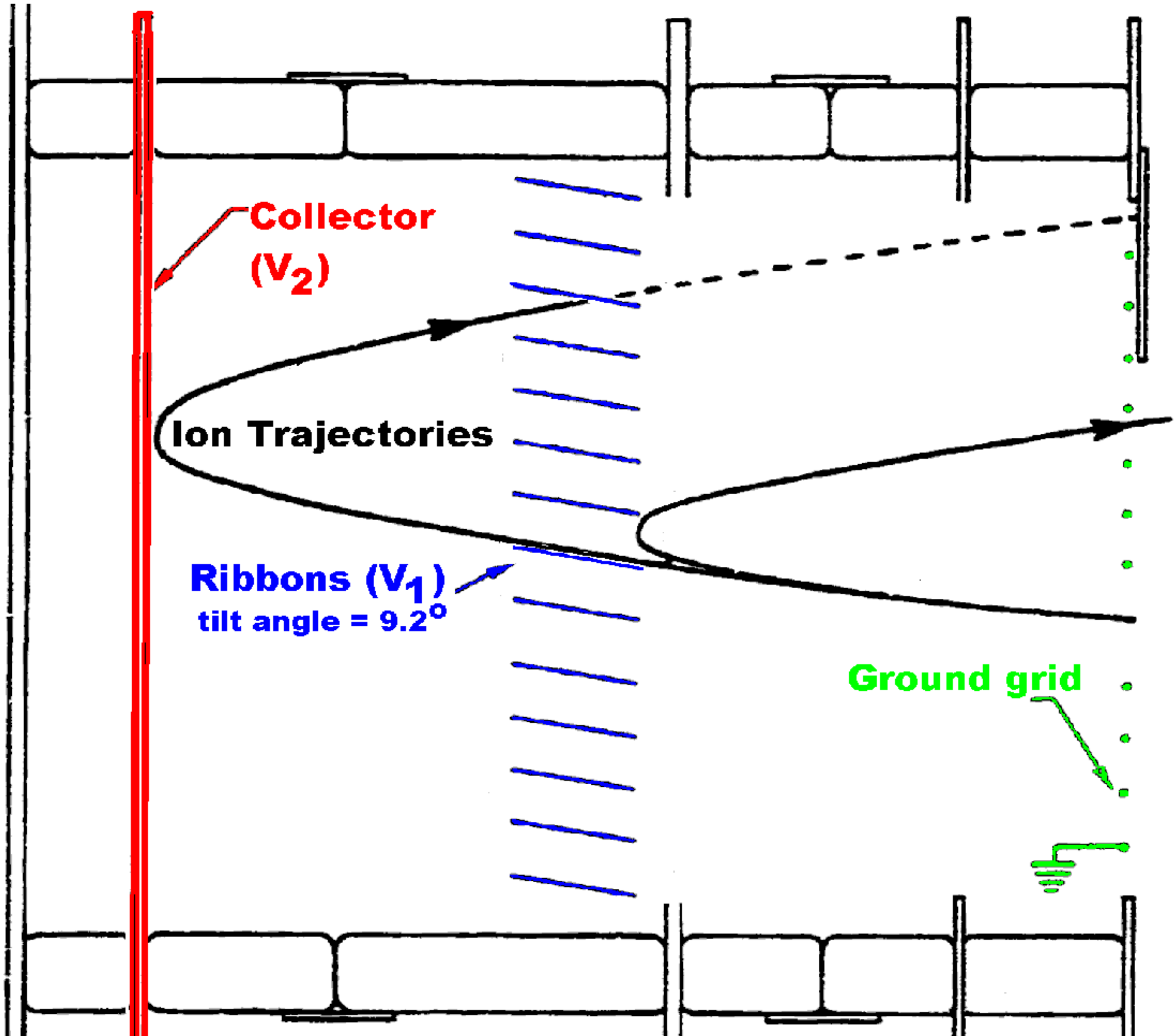
Direct Conversion
Fission Fragment-->Power

Fission Fragments have ~2MeV /nuc of energy and about 26 + charges. Rings are biassed at higher and higher + Voltage. Moving current uphill is like charging a battery. ~85%

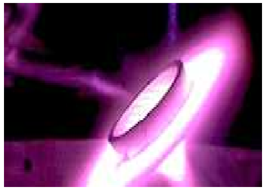


Venetian Blind Converter

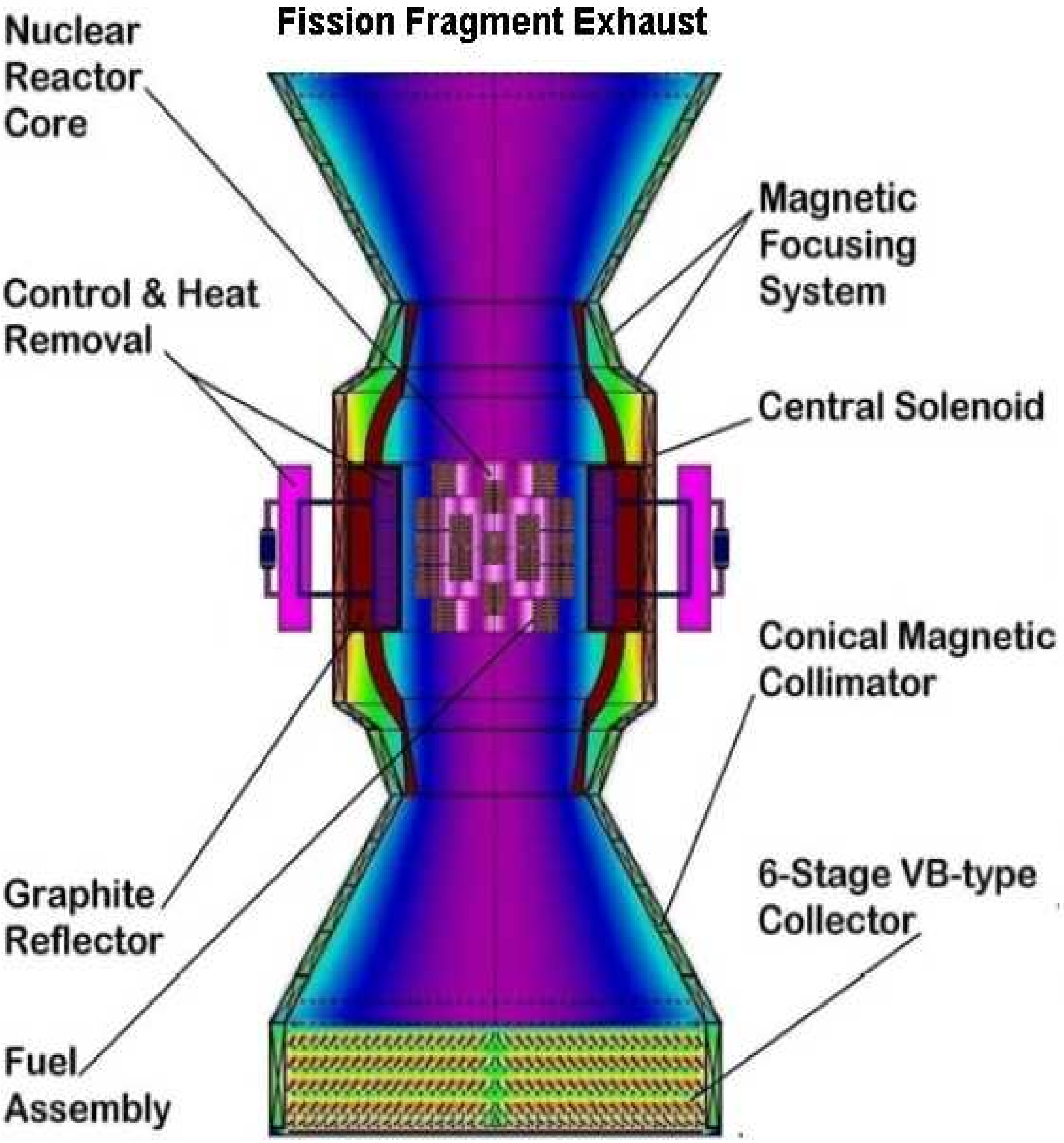
Collector shapes can be optimized for collecting “at rest” FF.



Hybrid FF Rocket--NERI



- Coils at each end of the FF reactor control how much FF go into thrust, and how much into electricity.
- Operating the nuclear reactor at max efficiency, we can adjust thrust and electricity separately.



Heat: The hidden killer
Dust: the best protection

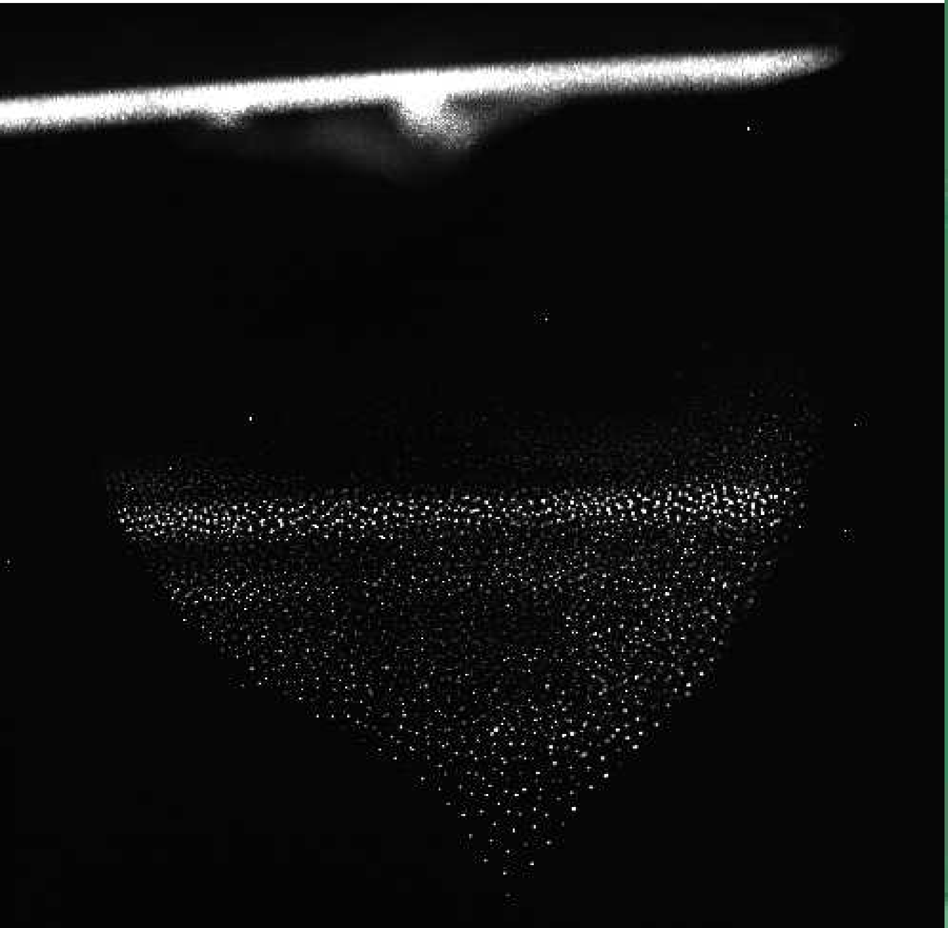
- So the problem with space nuclear propulsion is NOT raw power, but how to eliminate waste heat. The more efficiently we can generate thrust, the less waste heat produced.
- Can we have our cake and eat it too? Can we have a non-thermal nuclear propulsion minimizing waste heat?
- Yes. By making the fuel into dust.

IV. The Dusty Plasma Fission Fragment Rocket

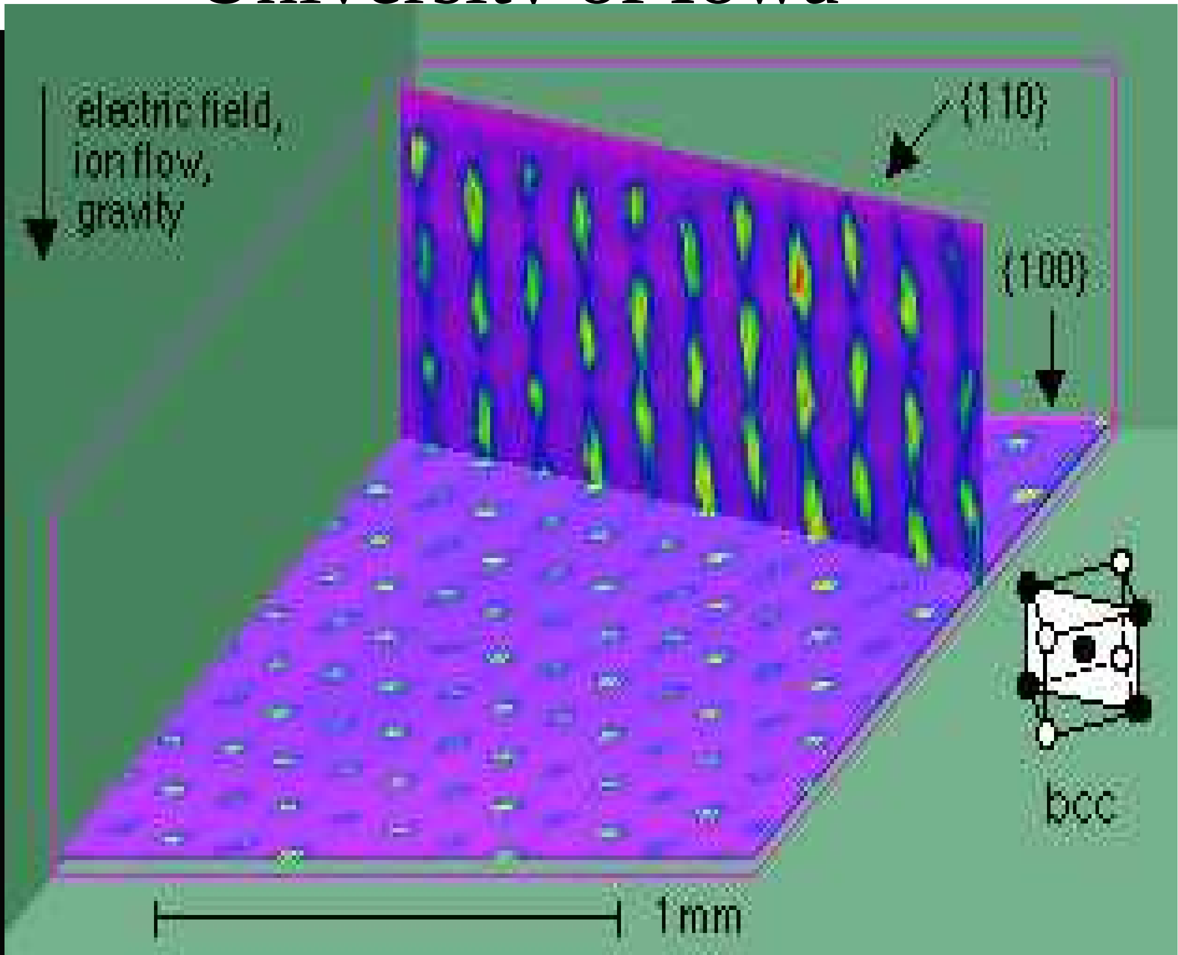
What is a dusty plasma?

Charged dust + plasma = a "plum pudding" Coulomb crystal, or as Cooper-pairs in BCS theory. Note surface tension & crystalline interaction.

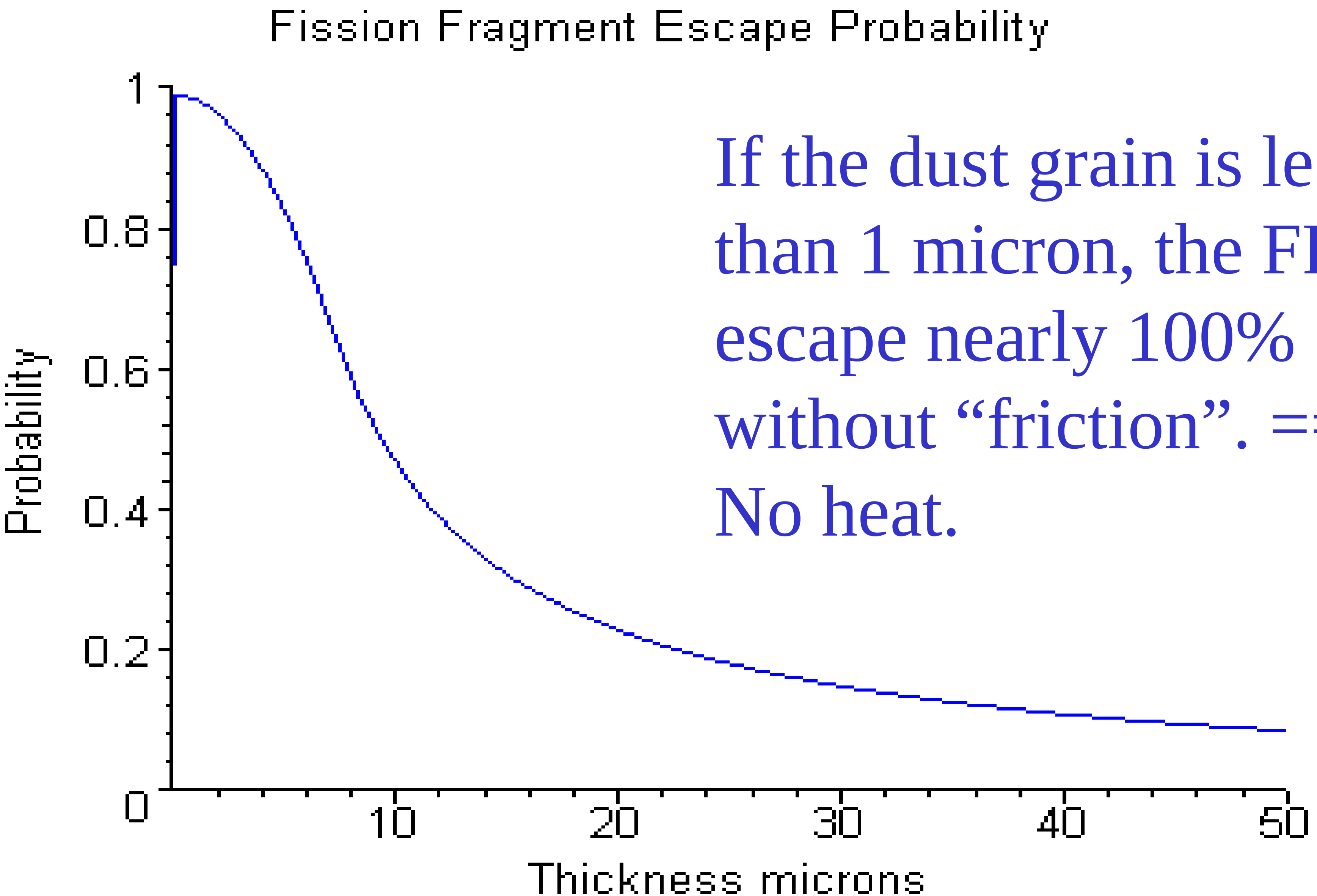
Auburn University



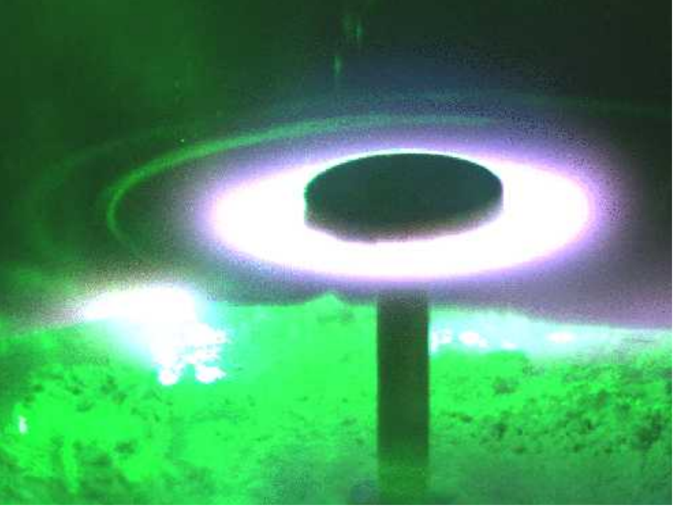
University of Iowa



Cool Dust

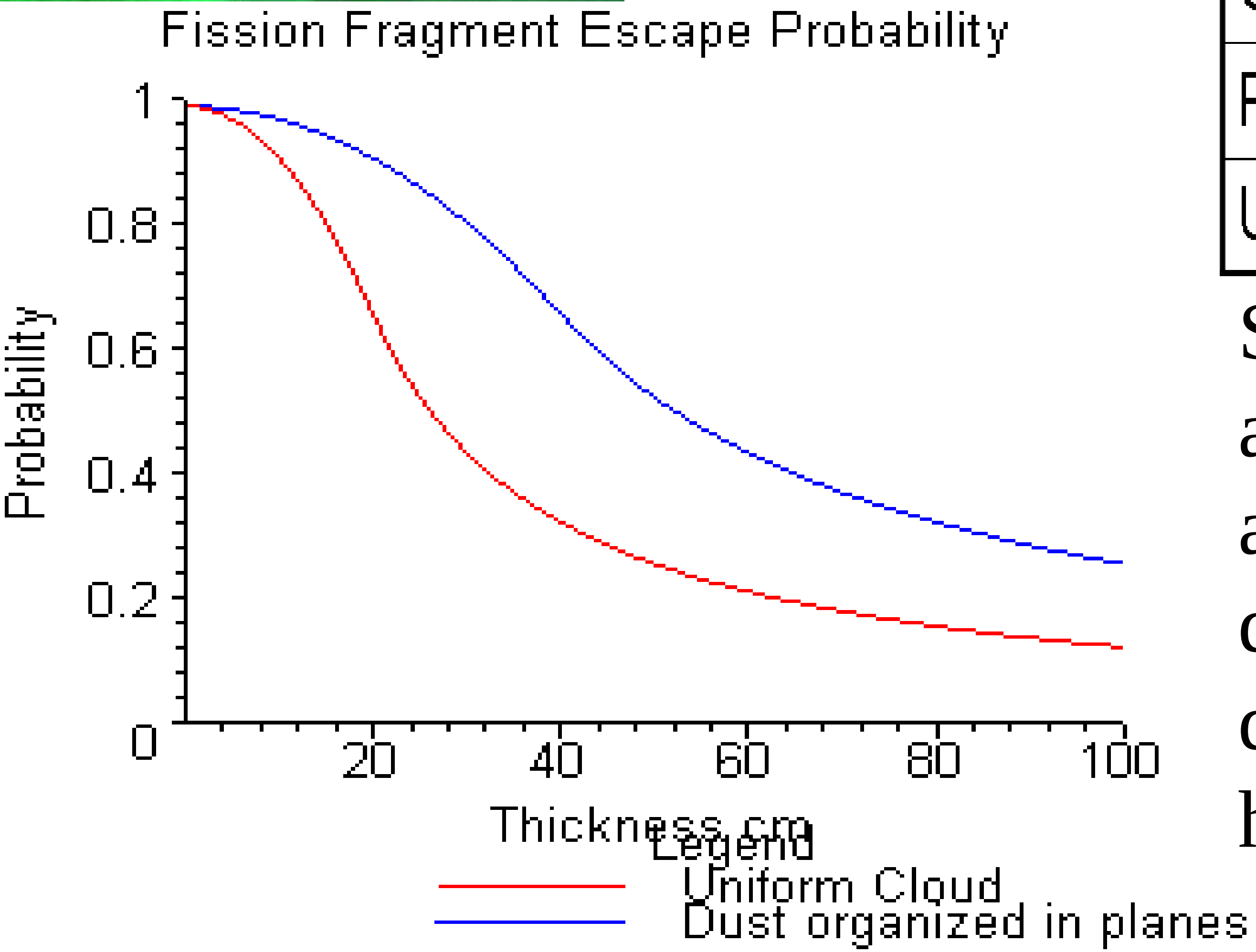


If the dust grain is less than 1 micron, the FF escape nearly 100% without “friction”. ==> No heat.



Can FF escape the Dust Cloud?

Am^{242m}	0.5 kg
Cm^{245}	1.1 kg
Pu^{239}	5.6 kg
U^{235}	11 kg



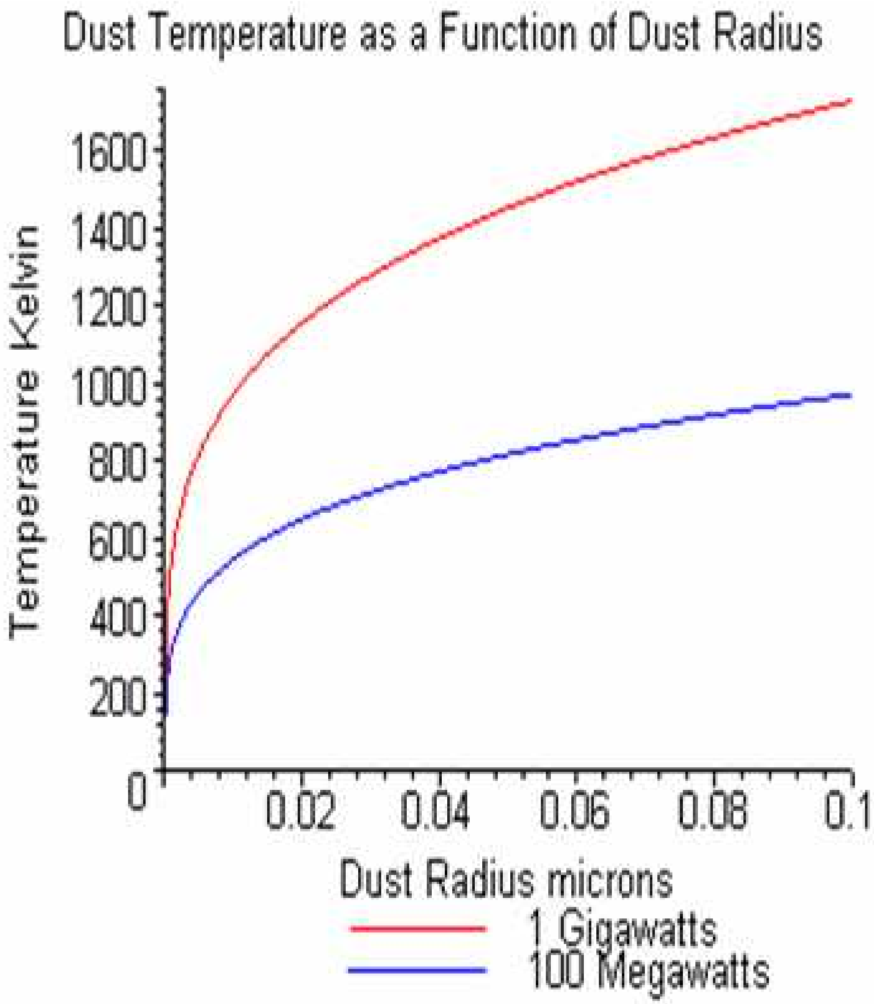
Since we need a total amount of U235 to achieve criticality, how do we collect enough dust grains without heating them?

Organization.

Thermal Management

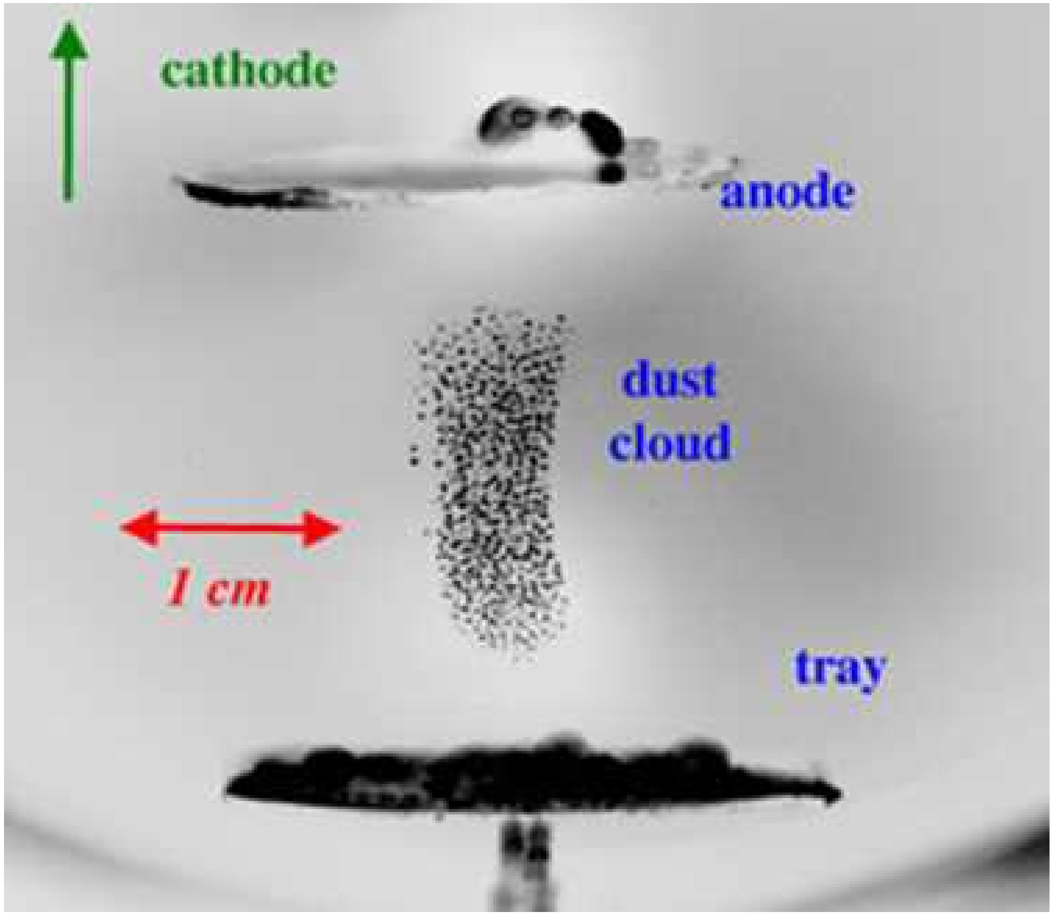
- 1 Gigawatt Reactor
- 46% Energy deposited into dust
- Thermal radiation provides adequate cooling for sufficiently small dust particle

Compound	Melting Point
Am	1449 K
U	1405.3 K
UO2	2711 K
UC	2711 K
Cm	1613 K
Pu	915.5 K
PuO	2273 K

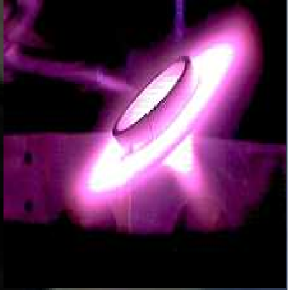


Nuclear Fuel suspended as dust

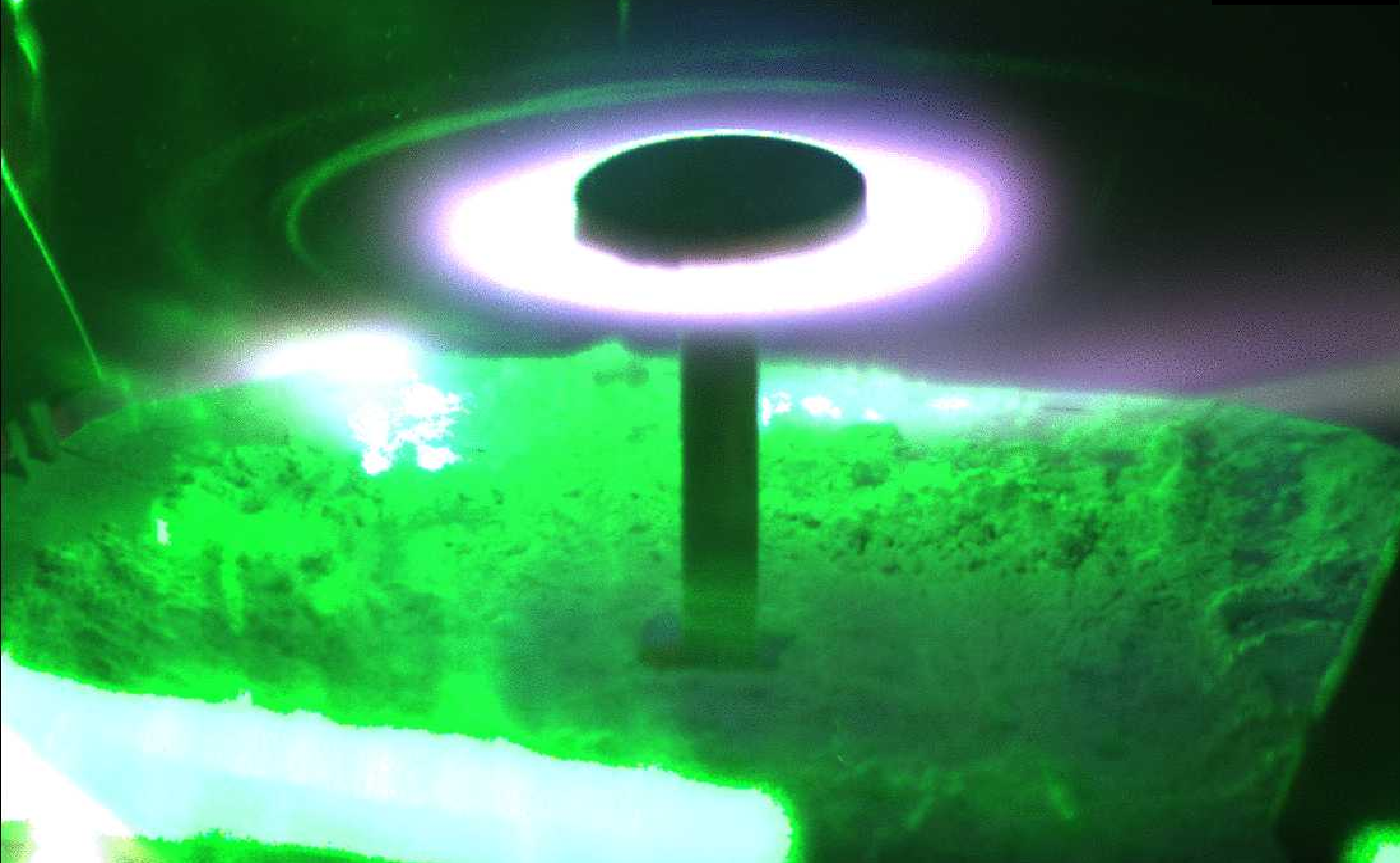
- Can the dust be suspended while the rocket is accelerating?
- Yes, 1g is typically no problem for labs.
- Will B-field change the dusty-plasma dynamics?
- Yes, but not much.

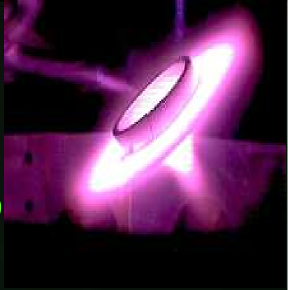


Terrella Lab (NSSTC)



Levitated Dusty Plasma w/Magnets

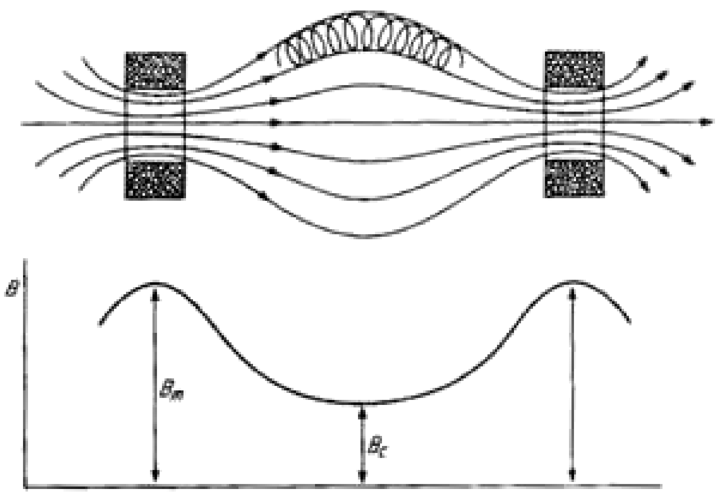


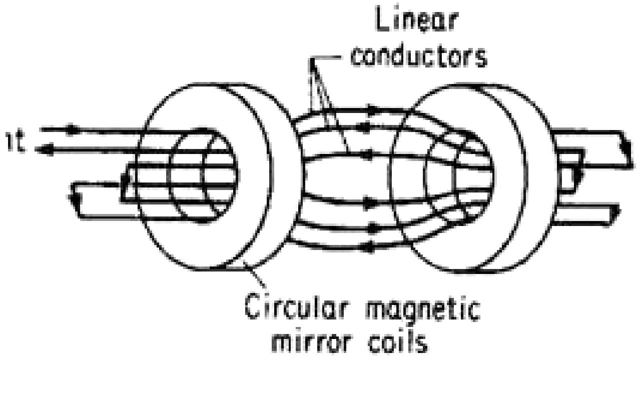


The Dust Trap

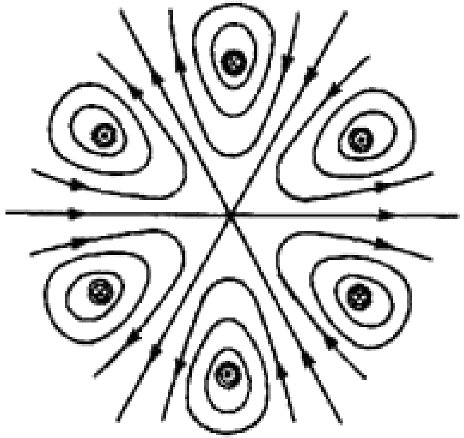
- Arc discharge on 3μ SiO_2 dust grains charges them negative. Probable charge state on dust is –10,000 e/grain.
- They are trapped in a positive space-charge region adjacent to ring current. The RC is formed by -400V DC glow discharge on NIB magnet, streaming electrons ionize the air, maintain the RC. Phase-space mismatch of streaming electrons and trapped ions produces the space charge. Highly anisotropic B-field contributes as well.

Can a reasonable B-field confine FF?





(a)



(b)

Particle	Atomic Weight A	Energy/amu	Effective Charge	Magnetic Field Required
Heavy Fragment	140	.5 Mev/amu	22	.63 Tesla-meter
Light Fragment	95	1 Mev/amu	22	.60 tesla-meter
alpha from Thorium	4	1.42 Mev/amu	2	.33 tesla-meter

$$Br := 14.\frac{A\sqrt{E}}{Zeff}$$

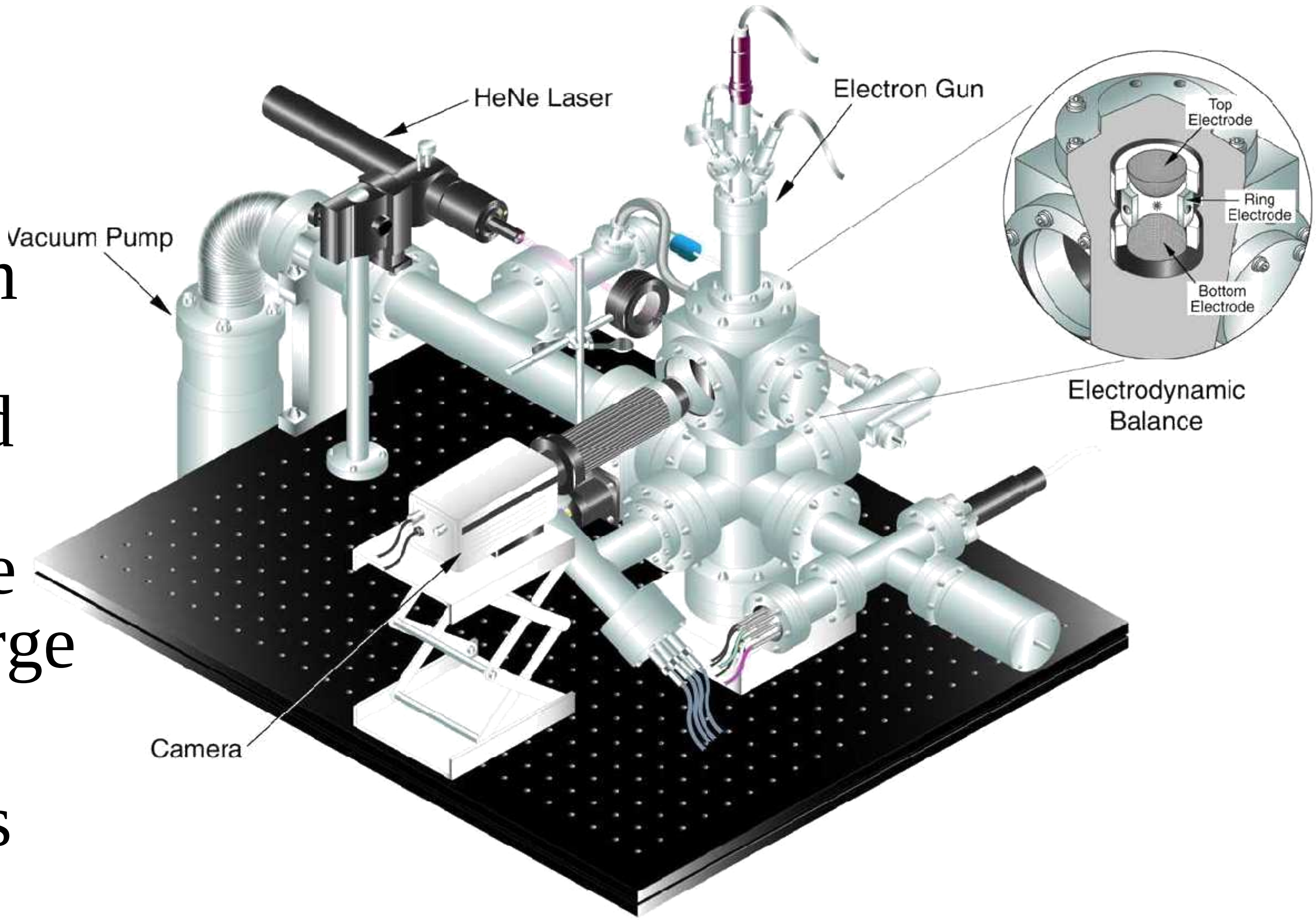
Toroidal Multipole Magnetic Trap

More on confinement

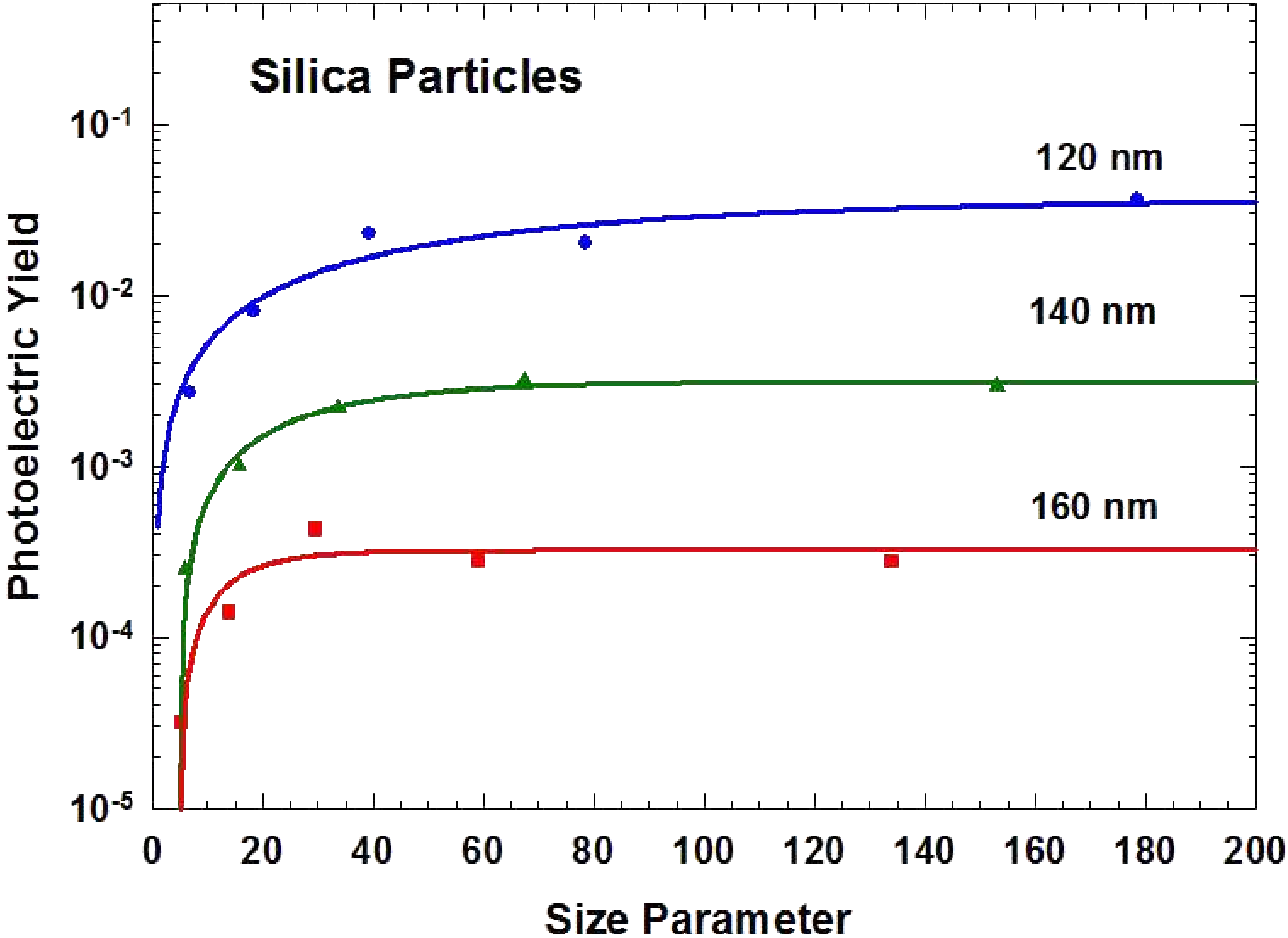
- B=0.6 T over 1-meter bore is an awesome energy density = pressure. If we could do that we'd be flying a fusion reactor! Instead, we use a multipole magnet toroid, such that the field strength drops as $|R - R_0|^{-N}$, with N>2, from the wall.
  - This has a magnetic gradient near the wall, producing a strong mirror force, "insulating" the wall from fission fragments.
  - By Liouville's theorem, n/B=constant, so fission fragment density peaks at the wall, low in the dusty plasma center. E.g, one pass through dust.
- Because the escaping fragments are positive, → net negative charge in the dust cloud. An ambipolar electric field (=some fraction of MeV) develops at edge as well, confining the fragments.
  - Proper treatment will require full kinetic simulations.

Discharging Dust

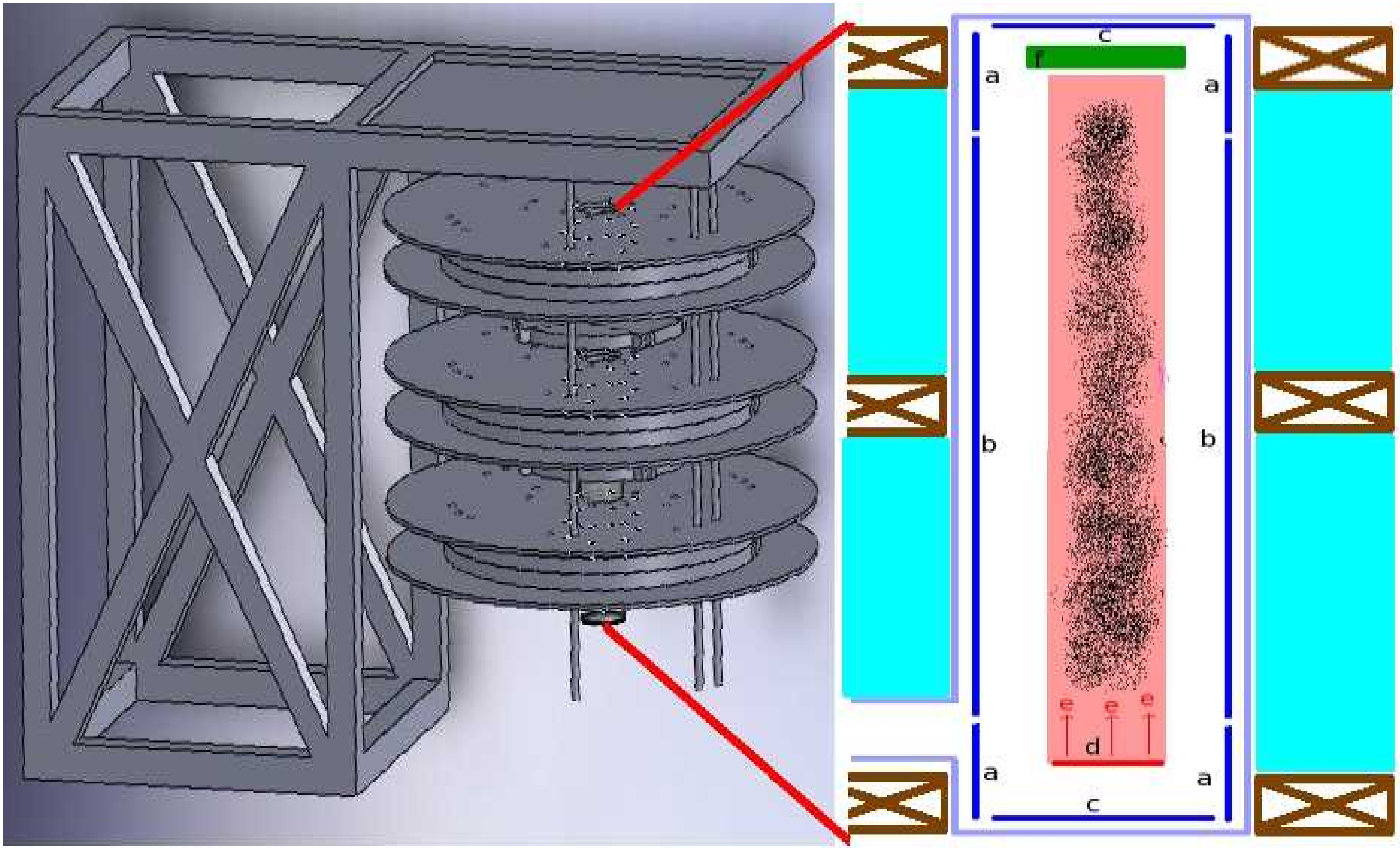
- Won’t negatively charged dust discharge from thermionic emission? And won’t 100nm dust have huge corona discharge current?
- Yes, but not as much as one might think.



Photoelectrons vs. size

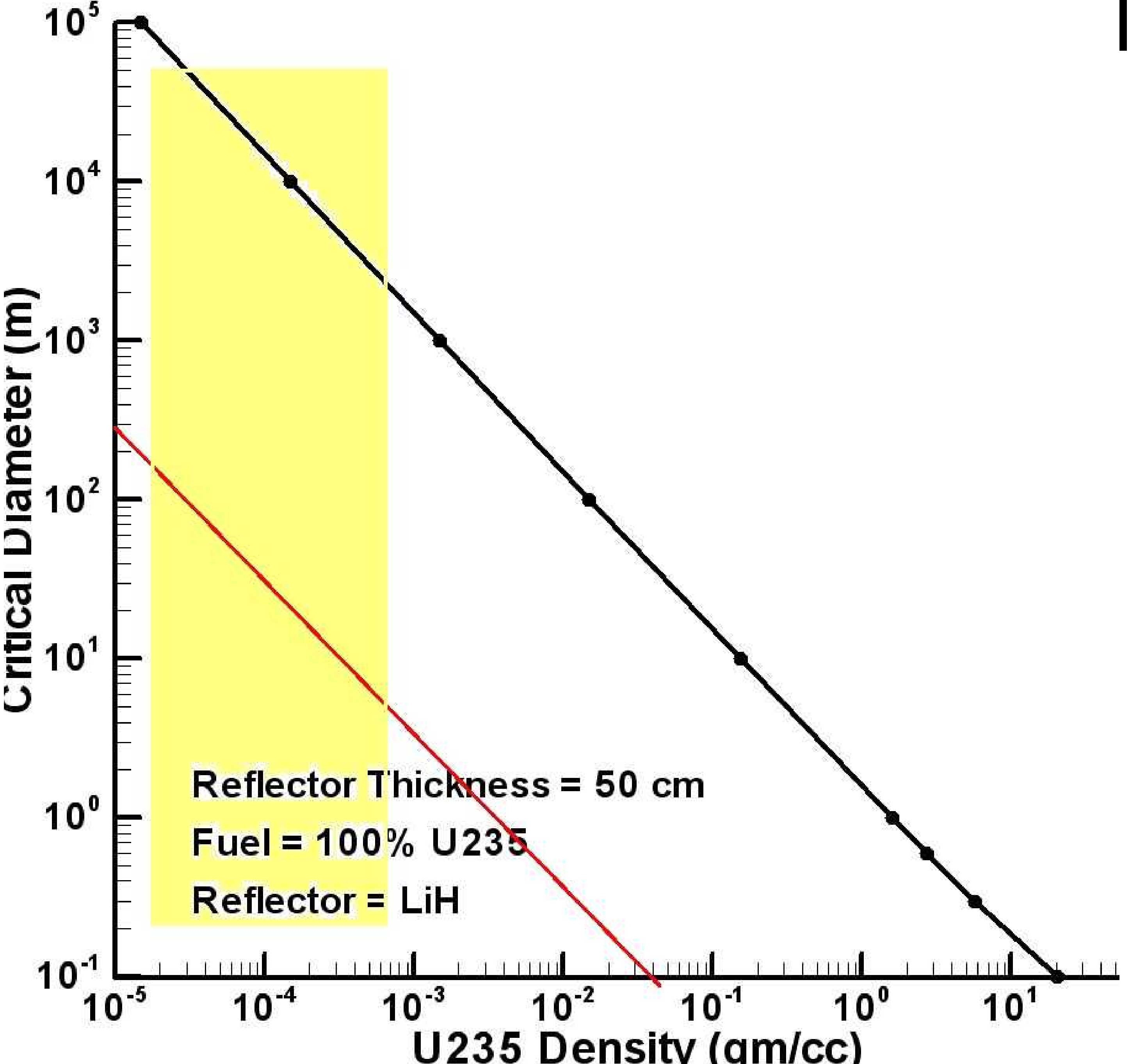


Lab Dust Cloud Test



Size of Critical Cloud

Black line is U235 with LiH moderator. Red line is Pu239 with C13-D moderator.



Nuclear Pollution?

- Since radioactive fission fragments are emitted from the rocket, how dangerous is this for the Earth?
- From the two missions analyzed, we calculated how long each rocket is withing 10 Re of the earth, and how much fuel is burned during this time.
  - 30 day mission to Mars 240 g U235 ~ 1 mole
  - 550 AU mission = 720 g U235 = 3 moles
  - 0.5 Lightyr mission=3.7 kg U235 = 15 moles
- We modelled the transport through the radiation belts, ionosphere & stratosphere and decay lifetimes of 60 decay products. Short-halflife products decay before reaching the surface of earth. Long-halflife products produce almost no radioactivity. We list radioactive products that make it to Earth from 1 mole U235, both by number and curies.

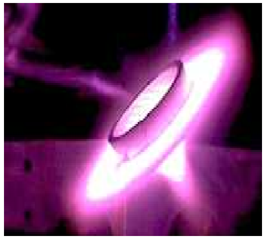
Modelled Pollution from 1mole U235/P239

- By moles (total radioactivity ~10% of U235)
  - Rb87 .1 = 0.1 uCu
  - Sr90 .2 = 180 Cu
  - Cs135 .3 = 0.4 mCu
  - Cs137 .3 = 360 Cu
  - Nd144 .05 = 1 pCu
- By Curies fast diff slow diffusion
  - Sr90 180 180
  - Ru108* 20 11
  - Cs137 360 360
  - Ce144 190 77
  - Pm147* 230 93

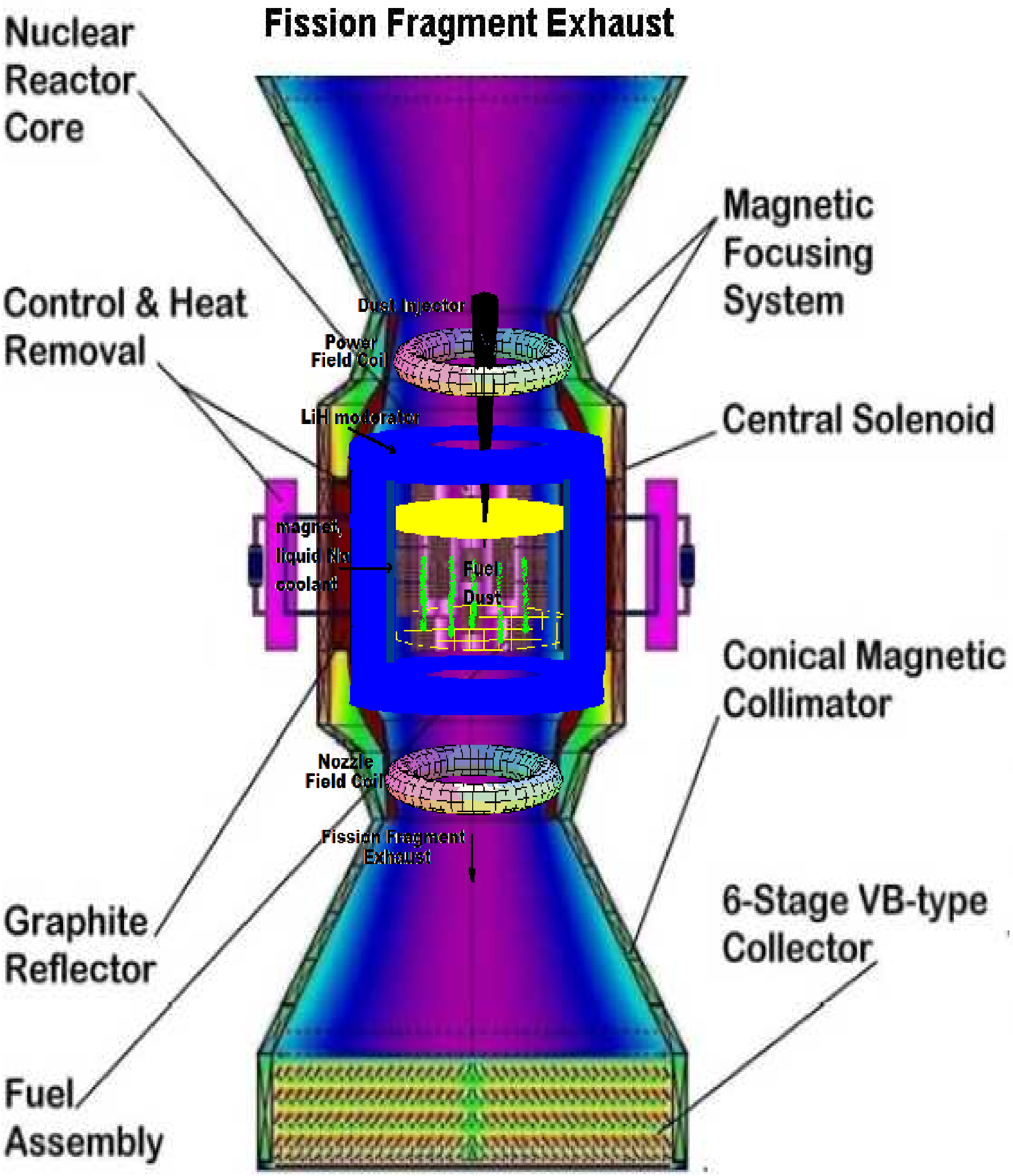
Cosmic Ray production

C14 = 266 Cu/yr

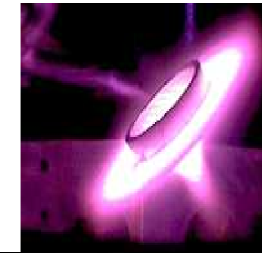
Concept

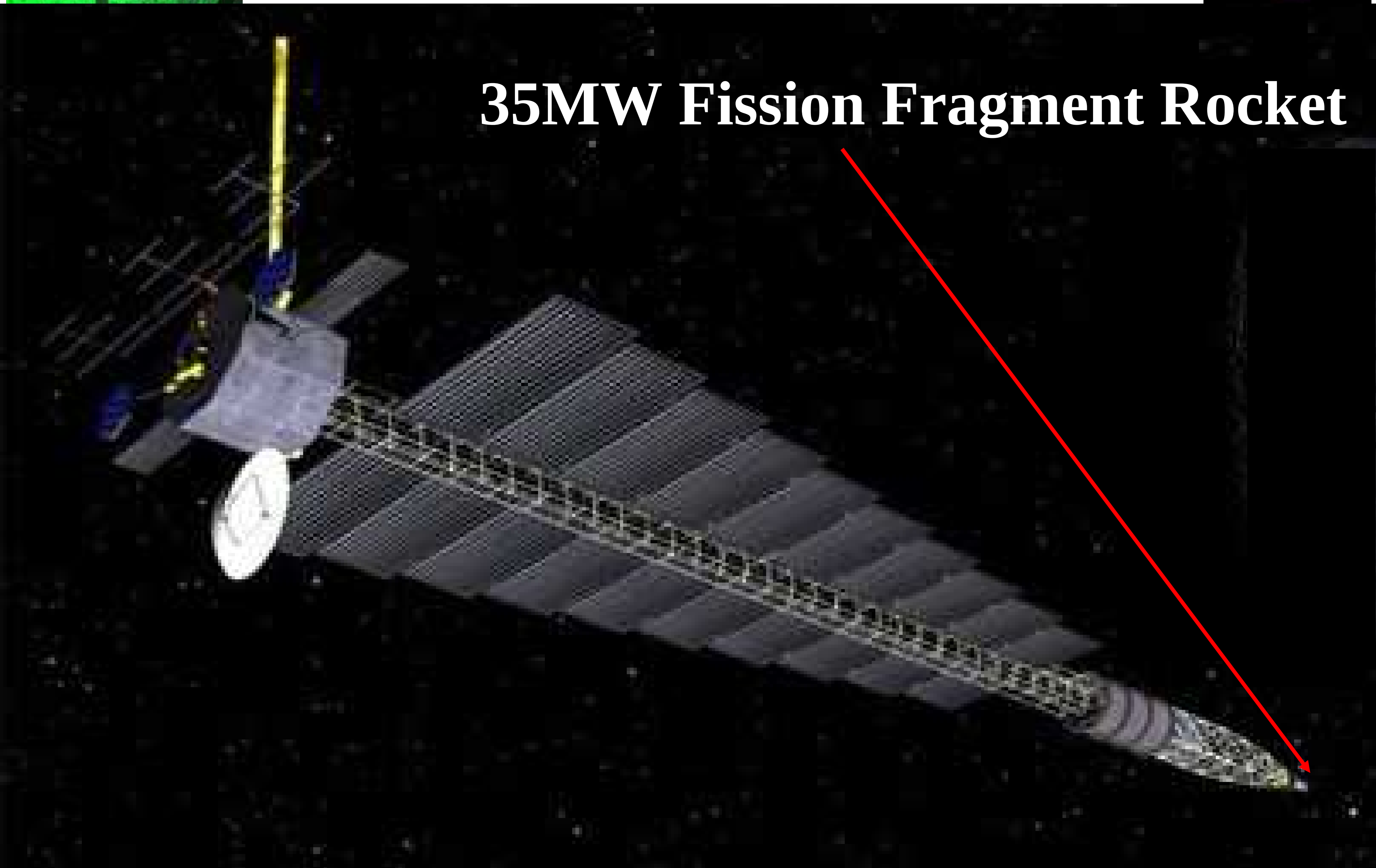


- Field coils on the end control thrust & power
- Pu239 dust
- Moderator is lightweight C13D
- Multipole permanent magnets on sides contain fragments



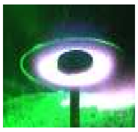
Mars Mission Concept





Conclusions

- The 2009 Design Reference Architecture 5.0 chose a “slow” mission to Mars because there really was no alternative. This led to an enormous program of life support for several years, artificial gravity, and massive LEO launch costs.
- A viable hybrid nuclear rocket that lowers the weight and cost, enables a fast visit which increases safety, is both more likely to be funded, and more likely to succeed.
- At about 20 MW, this design is a very conservative nuclear power design, and easy to implement.
- The hurdle at this time is scientific, “can a dusty plasma rocket actually work at 20MW?”



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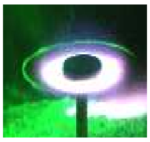
This is jointly the work of nuclear engineer Rod Clark, with contributions by dusty plasma physicist Rob Sheldon.



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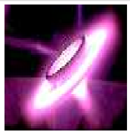

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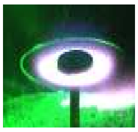
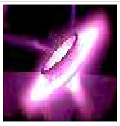
Abstract as circulated by e-mail

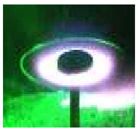


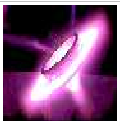
Outline



- The Dream of Mars
- The Necessity of Nuclear
  - Insufficiency of Chemical
  - Impotence of Ion Electric
  - Advantage of Nuclear
- The Nuclear Options
  - Propulsion
  - Power
  - Hybrid
- The Dusty-Plasma Fission-Fragment Rocket

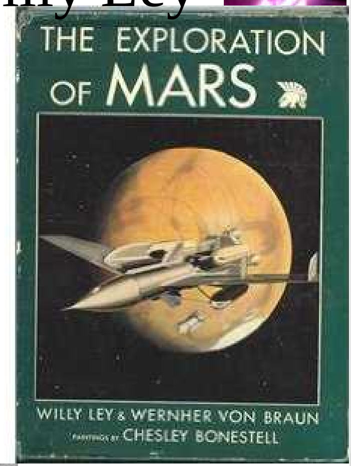
We first want to show the necessity of nuclear, then the various issues with nuclear, closing with the advantages of an advanced nuclear rocket.





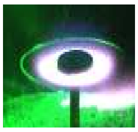
I. The Dream of Mars

Werner vonBraun & Willy Ley

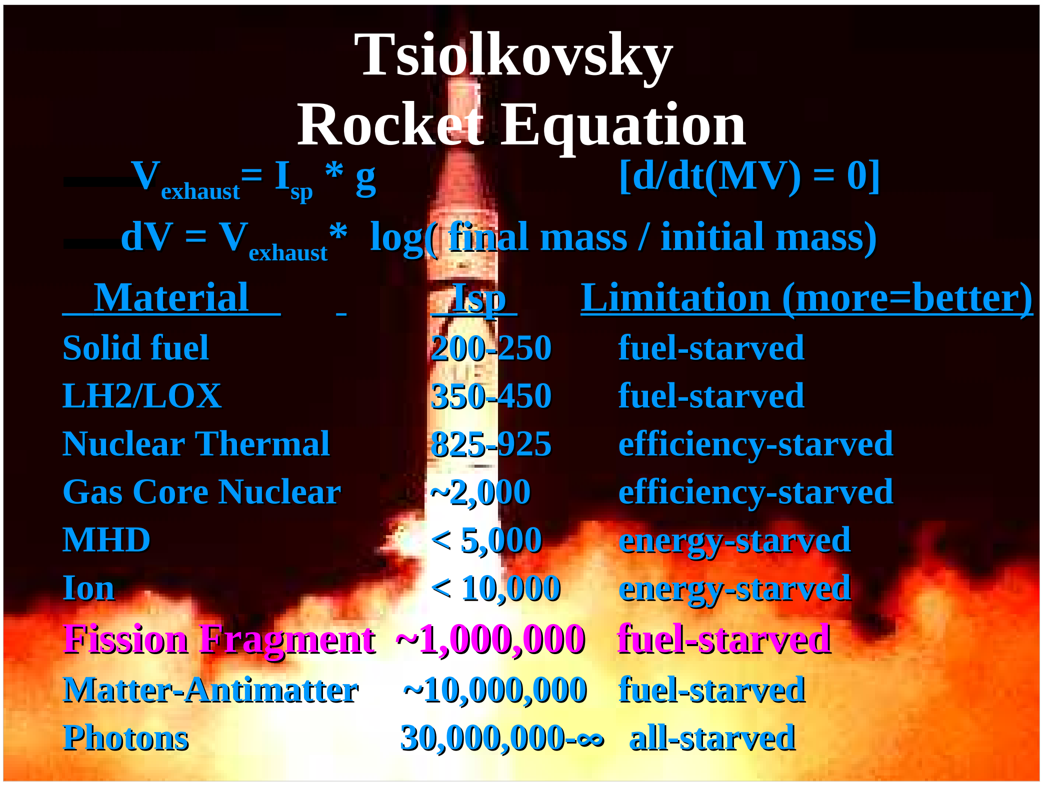


Werner Von Braun did not start out intending to go to the Moon. He started out intending to go to Mars. He wrote a paper in 1947 which Chesley Bonestell and Willy Ley used in their 1949 Book, “The Conquest of Space”. Later they all collaborated on a 1956 book, “The Exploration of Mars”. It was this book that I studied so hard in 1968 when I really thought the colonization of the Moon was around the corner. And it was the ideas in this book, that caused Von Braun to give a lecture in 1972 about a nuclear thermal mission to Mars in 1984. It was highly detailed and realistic. Unfortunately, it was also the last time it was realistic, because the NERVA nuclear thermal rocket program was terminated the next year.

As we attempt to show next, there is no realistic manned mission to Mars that doesn't involve nuclear power.



II. The Necessity of Nuclear



At the risk of boring everyone, the rocket equation comes from conservation of momentum, d/dt(MV) = 0, and then integrating the equation in the frame of the rocket:

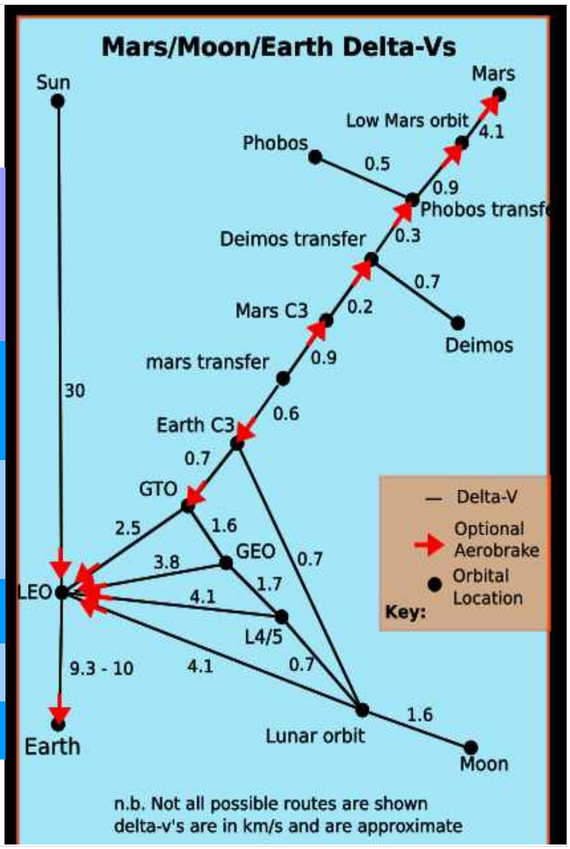
Delta-V/V_exhaust = ln(Mf/Mi).

For obscure reasons, rocket scientists give V_exhaust in units of Velocity/surface_g = (m/s) / (m/s^2) = seconds. Various V_exhaust speeds are given for different types of rockets. The last column asks what limits the thrust of the rocket. Fuel-starved suggests that more fuel will increase the thrust. Efficiency-starved means that fuel is abundant, but the system is running near maximum temperature allowed by current materials. Higher efficiency would increase thrust. Energy-starved suggests that propellant is separate from the energy source, and the limitation lies with the energy source.

Delta-V

Trip	w/o aero-brake	With aero-brake	Type of Trajec-tory
E → Mars	20.2	16.1	Hohmann
M → Earth	20.2	10.2	Hohmann
® trip	40.4	26.3	Hohmann
LEO-LMO	6.1	5.2	Hohmann
LEO-LMO	~231	~58	30 day

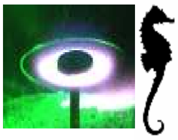
30-day computed w/o orbital dynamics



The other peculiarity of rocket science, is that it doesn't use the usual units of energy to calculate cost. Instead it uses "delta-v". For the cognoscenti, this is because the rocket problem is a vector problem, so we cannot generate a scalar potential like energy to describe the cost to go from point A to point B. Momentum, however, is a vector, though the mass is constantly changing, and thus "delta-V" became the accepted way to describe the "cost".

Then in acceptable units we can compute the cost to go from Earth to Mars, showing the various solutions. The lowest cost method is the "Hohmann transfer" elliptical orbit, which "matches" the speed of the transfer orbit to the destination speed, so that no extraneous maneuvers need be performed on arrival. In contrast the direct or hyperbolic orbit has excess velocity that has to be shed on arrival. We can also distinguish these two approaches by the time it takes, with Hohmann orbits taking some 120 days or so, and hyperbolic orbits much less, in our example, 30 days.

Since we won't be operating a nuclear rocket in the atmosphere of Earth or Mars, it may be more appropriate to compare the delta-V for Low-Earth-Orbit (LEO) to Low-Mars Orbit (LMO) which is roughly 5 km/s for 120 days, or 50 km/s for 30 days. This factor of ten in cost means that short, fast trips to Mars taking less than a year, cannot be accomplished with current technology as we show next.



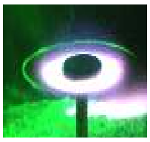
Mi / Mf Comparison

Mission Technique	Mars@1y Hohmann dV=40k/s	Mars@30d Linear dV=116	Grav.Lens 550au@10y	Oort Cloud .5ly@30y	α-Centauri 4ly@50y
LH2/LOX 450s	9518	e11	e41	e2222	e10666
NTR NERVA 820s	152	1341	e22	e524	e2535
Xe Ion 10ks	1.5	1.8	72	e43	e208
Fission Frag 1Ms	1.004	1.01	1.04	2.11	36
Fusion Frag 2Ms	1.002	1.003	1.02	1.65	11

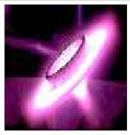
Having found Isp and delta-V for various technologies and missions, we can combine them in the rocket equation to see how much fuel it will take to accomplish the mission. Mi/Mf is the the ratio of the rocket mass wet to the rocket mass dry. Anything over a factor of 10 is going to be difficult, and anything over 1000 is well-nigh impossible.

Clearly, solid-fuel rockets are not in the running. Cryogenic rockets might barely make it to Mars on a Hohmann orbit, barely. But Von Braun didn't suggest we should go to Mars that way, he suggested a nuclear thermal rocket. We can see from this chart that Hohmann to Mars using Nuclear Thermal is difficult but not impossible, but a 30 day trip is nearly impossible. This tradeoff will show up in all the NASA planning since 1972, as we will see later.

But the surprise is that Xe ion engines make a 30 day trip to Mars seem trivial, as well as the even higher performance fission and fusion fragment rockets. But we have flown several Xe ion engines: DS-1, Dawn are two interplanetary missions, whereas many geostationary satellites use them for station keeping. Why are these not suggested for a Mars mission?



Thrust/Power Requirements for 30d trip to Mars (dV=58km/s)

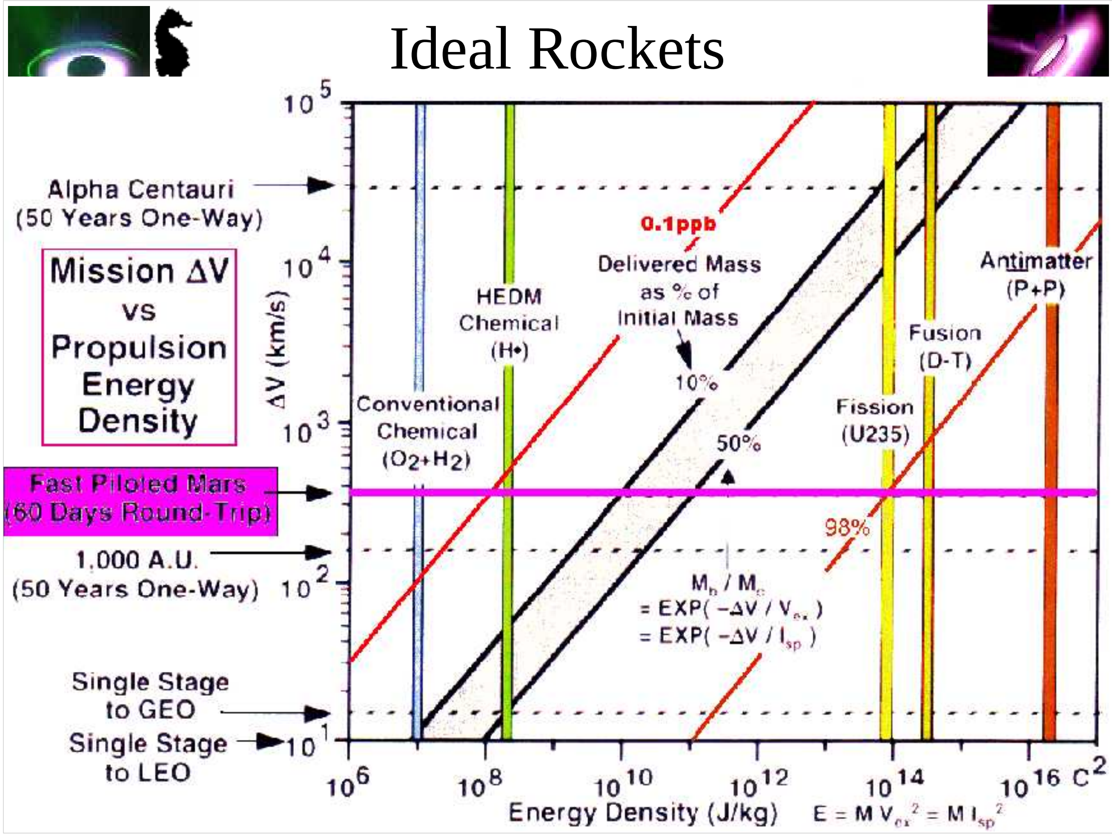


Rocket	Isp	Mf/Mi	<Force> Newtons 8T payld	mass flow kg/s	Kinetic Power MWatt	Total Power MWatt
LH2/LOX	450	500k	357M	81M	787	787
NERVA	870	886	4.8M	596k	19	19
Xe Ion	10k	1.8	1289	13.16	0.063	117 (~20 hoh)
Fission Fragment	1M	1.01	718	0.07	3.5	~20
Fusion Fragment	2M	1.003	716	0.04	7	~15

If you remember from the earlier slide, some propulsion systems are limited by fuel, others by efficiency, and still others by energy. The rocket equation tells us which systems are starved for fuel (because the mass ratio is very large, and thus requires a lot of fuel). Xe ion engines, for all their excellent properties in the rocket equation, have abundant fuel (mass ratios low) but are starved for energy and are additionally starved for efficiency.

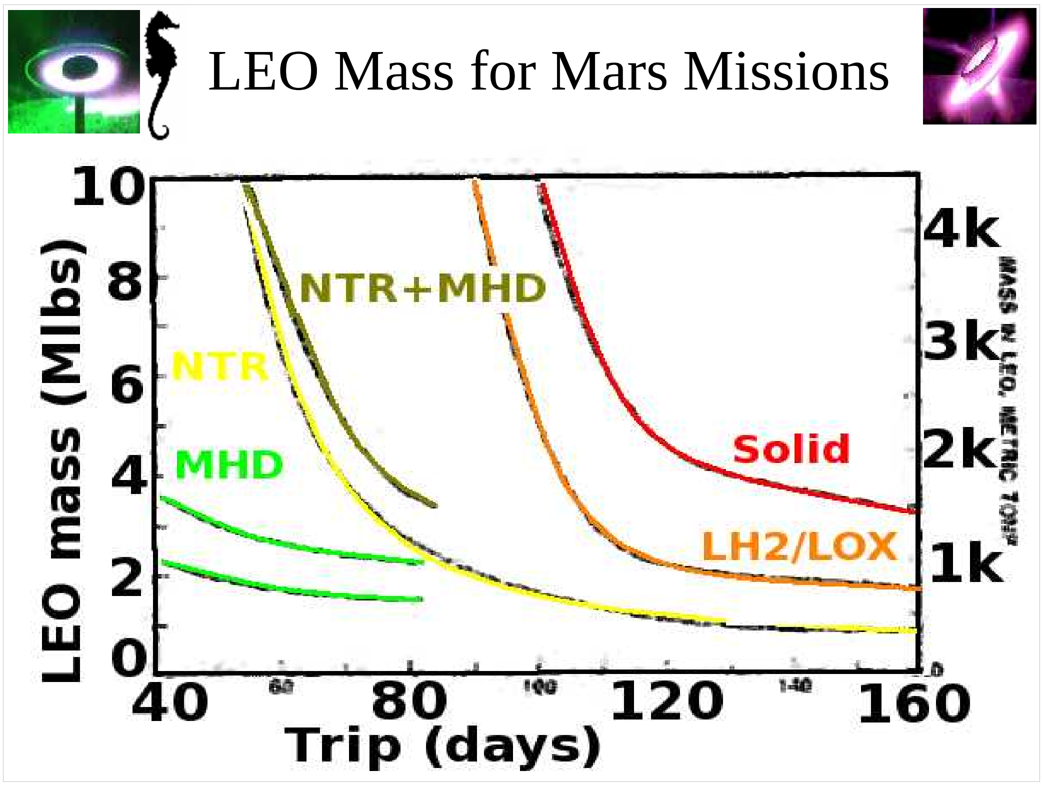
That is, if we pick a number for the dry rocket mass (in this slide = 8 Tons), then the rocket equation tells us the wet rocket mass, and the delta-V divided by the time gives us the average acceleration. Then wet mass * acceleration = initial force = dm * V_exhaust. So we calculate the delta-m, and then ½ delta-m (V_exhaust)^2 gives the kinetic power.

So far, Xe ion looks like a real winner. A few kWatts of kinetic power is consumed. But hiding in this great idea are two hidden killers. The fuel starts out as bottled Xe gas, but the rocket accelerates Xe ions. Converting gas to ions consumes 1000 more energy than accelerating it down the nozzle! When this “ionization” energy is added to the energy cost, suddenly Xe ion takes 117 MW. The second killer is hiding in this calculation, because that's 117 MW of electrical energy, which has to be converted from some energy storage, probably nuclear, which occurs at an efficiency of 40% in nuclear power plants, but more likely 25% in space, so real power is more like 400MW where 75% has to be dissipated as heat. Radiators for “nuclear-electric” as this combination is called, can easily be 3-5x heavier than the nuclear reactor itself. If you are going to have to fly a 400MW reactor anyway, it might be better to find a more efficient nuclear propulsion method. That's where fission fragment starts to look attractive.



If all the energy density in the fuel were converted 100% into kinetic energy (x-axis) then we can calculate a theoretical V_exhaust (or ISP) for the technology. The y-axis shows the delta-V from 10-100,000 km/s of various missions. Diagonal lines calculate isocontours of ln(Mf/Mi) at various values. Chemical propellants don't get much better than LH2/LOX shown as the vertical blue stripe. Unobtainium chemical propellants (green), such as metastable hydrogen or helium, would provide a factor 20 more ISP. Then six orders of magnitude better are the fission energy density (yellow), followed by a hypothetical fusion engine (orange). Fusion shows a higher energy density not because the nuclear binding energy is so much higher, but because the mass of the exhaust is so much less. Finally another 2 orders of magnitude up is anti-matter propulsion (red). Finally on the far right, is the maximum V_exhaust possible, the speed of light. Typical operational rockets fall in the shaded diagonal band in the middle. Note that a fast mission to Mars using nuclear is capable of 98% payload, whereas a chemical rocket to Mars in the same amount of time has a <0.1ppb payload. (Of course, multi-stage rockets effectively enhance the V_exhaust, but not by enough to matter for a fast trip to Mars.)

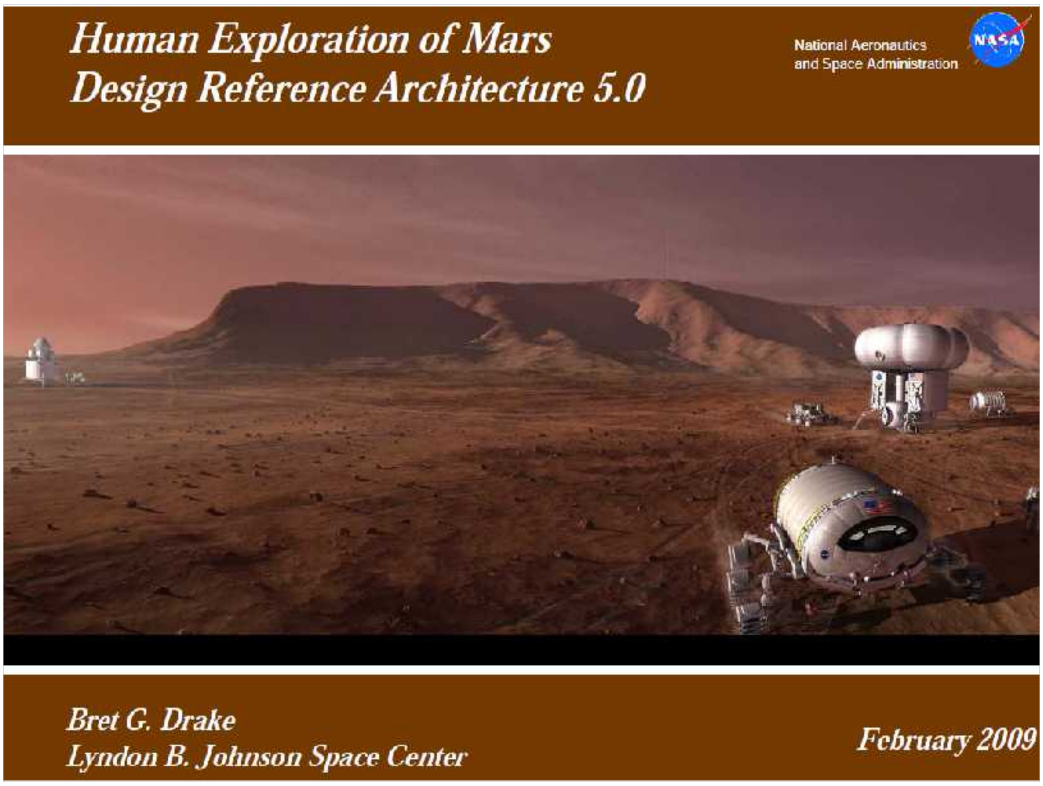
Note that the two magnitudes of missing fuels between green and yellow vertical stripes unfortunately lands smack in the middle of fast missions to Mars. That means that we can't creep up on a Mars mission, it is clearly nuclear or nothing. This is as close to a binary decision tree as we will find.



This plot comes from a 1987 conference “Case for Mars III”, in which the author replotted the above log-log plots in terms of a linear plot of LEO Mass and mission travel time. To shorten the mission time requires a higher delta-V, and higher delta-V requires higher mass ratios. Thus we get a curve that exponentially decreases down to some “dry rocket mass” baseline. Using some reasonable assumptions, those baselines can be estimated for various technologies, and the LEO fueled “wet mass” rocket can be plotted for given trip time.

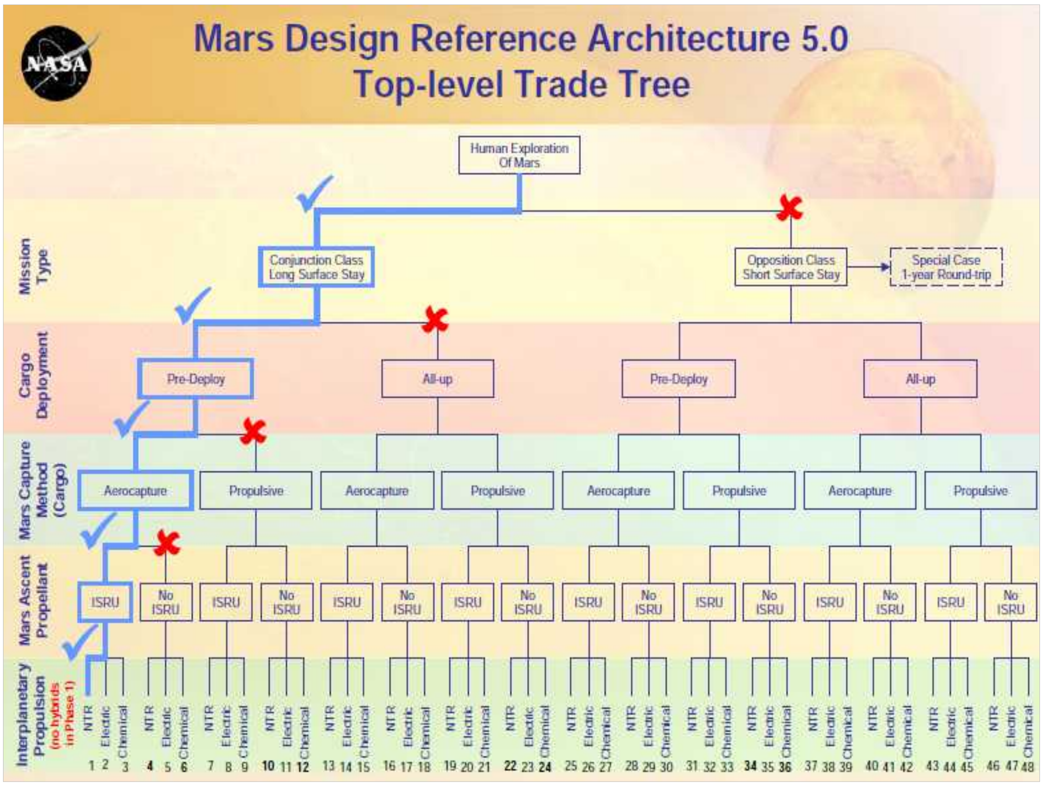
Hohmann orbits become possible at 120 days, which is also where solid (Isp=250s) and LOX (450s) rockets start to hit the exponential in the rocket equation. NTR (900s) hits the wall at about 80 days, and adding in a MHD stage (5000s) to provide some interplanetary thrust merely raises the baseline without noticeably changing the “wall”. Only when we go to a purely MHD rocket (presumably nuclear-electric) does the wall recede to about 30 days. However notice that the baseline dry weight is increased for nuclear-electric, possibly even above the LH2-LOX dry engine weight as a result of both the reactor and the radiators.

Well all this was a conference 23 years ago, what improvements have occurred since then?



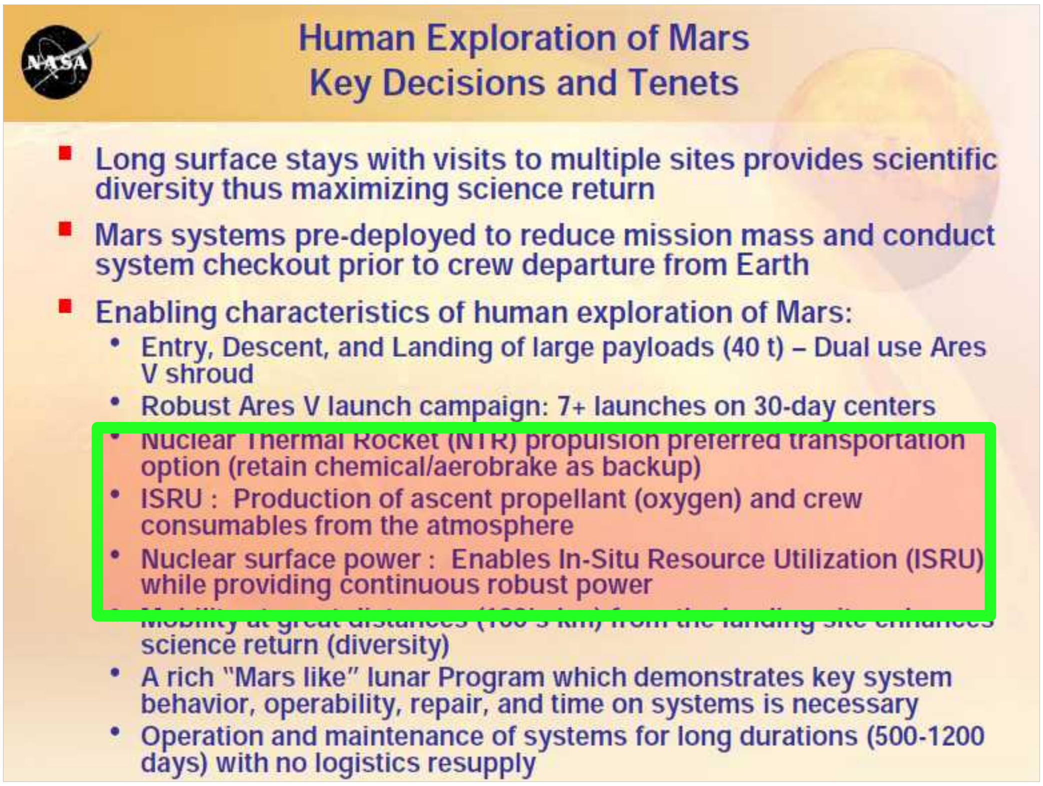
This is the official 5th version of the Manned Mars Mission as culmination of 8 years of study, as well as the 38 years since Von Braun first presented the idea. What has changed?

Well, the graphics for sure.



The plan even includes a decision tree, showing all the options that were discussed in the intervening 38 years, and lo-and-behold we are back to Von Braun's original design: Nuclear Thermal Rocket taking a Hohmann orbit to Mars.

Why are all the red X's eliminating some exciting options? Because we don't have the technology to go any faster. If we could get to Mars in 30 days, it would be an order of magnitude cheaper to go. But we don't have the technology, just as Von Braun didn't have the technology in 1972.



What is the required technology for this Hohmann orbit NTR-powered trip to Mars?

The report has a handy summary slide. The first two red bullets aren't drivers, they are rationalizations for decisions forced by the third red bullet, which has 8 sub-bullets.

#1 and #2 merely restate that our principle LEO lifter will be the Ares V. This is not really an enabling technology, since we could do it with Shuttle launches, but a political decision to put all our eggs in the Ares V basket.

#3 is the recognition that Von Braun was right, we need NTR to get to Mars

#4 is the refinement stressed by Robert Zubrin, that we should make use of Martian material for the return trip to save money, material, and time. It is enabling in the sense that it lowers the cost substantially. However, it necessitates bullet #5.

#5 is the recognition that long surface stays, as well as bullet #4 will require a nuclear power source on the planet's surface. Despite abundant sunlight, the technology of solar panels isn't quite up to the reliability and power demands of a manned colony.

#6 isn't an enabling technology, its a scientific wish list.

#7 and #8 are, again, not enabling technology but enabling politics, since even more massive military maneuvers (such as D-Day) have been executed without practice. NASA doesn't actually need to practice Mars missions to fly one, (presumably simulations can be substituted) but it does need to convince the public/Congress that it is capable of a Mars mission, which is what this bullet is all about.

Therefore the enabling technologies are really 3, 4, and 5= Nuclear Thermal Rocket, ISRU, and Nuclear power plant for ISRU. Nuclear, nuclear and Nuclear.

III. The Nuclear Options

NERVA nuclear thermal circa 1968

1.5GW Pu239 reactor cooled with GH2 run for >30 minutes, stopped and restarted without incident at Jackass Flats NV. One version made 4.08GW for 12 minutes. Held the record almost 30 years for the h ctor on Earth.

-Mass (dry) = 34 ton

-Diameter = 10.5 m

-Thrust = 867 kN in vacuum

-ISP~820second @1.2GW

Could place men on Mars 1985. Cancelled in 1972

NERVA was a nuclear thermal rocket being developed for NASA through the 1960’s. It consisted of a nuclear core cooled by gaseous Hydrogen. It’s ISP was limited by the need to keep the core below 2700K. The photograph shows destructive safety testing going on at the Nevada test range.

(Was that molten Pu they are spraying all over the desert?)

JPL Nuclear-Electric Concept

This proposed mission “JIMO” to Jupiter intended to use a nuclear power source for electricity, and then use the electricity for a high-ISP (~10,000 V) electric Xe ion propulsion. Very little Xe propellant is needed, but the conversion of nuclear to heat to electric to propellant is inefficient, generating much heat. This heat requires cooling by massive radiators. (Remember those nuclear power plant cooling towers?)

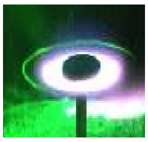
Hybrid Nuclear

- If you need NTR to get to Mars, and you need electric power to stay on Mars, why not use that electric power in orbit to generate high Isp thrust, and save on fuel?
- Combining to two reactors also allows savings on weight, moving the baseline downwards. What could be the problem with that?
- Heat.
- Nuclear power plants use Carnot-cycle conversion of heat to electricity at about 40%, but efficiency is strongly dependent on the “cold” temperature: ==>(Ti – To)/Ti And space has only radiative cooling ==> σT^4

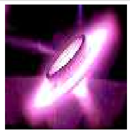
Since the Baseline 5.0 mission has NTR toward Mars, and nuclear-electric on Mars, it would be a cost and weight savings if the same nuclear reactor were used for both. The idea that nuclear reactors can supply thrust as well as electricity is called “hybrid” nuclear.

The disadvantage is that NTR doesn't need radiators, but nuclear-electric does. If we build a hybrid nuclear reactor, it would seem to require massive radiators that diminish the NTR efficiency. Furthermore, radiators work better the hotter they are (by the Stephan-Boltzmann Law), whereas Carnot-cycle converters from nuclear-thermal to electricity work better the colder the radiators are. The bigger the radiators are, the colder they run, but also the more massive they become. More mass means less efficient NTR thrust (less acceleration). These two properties force an unhappy compromise: any hybrid nuclear system will run less efficiently than two single-purpose nuclear reactors in order to accomplish two, mutually exclusive requirements.

Is there a better way? Yes.



Nuclear-Electric Heat Problem

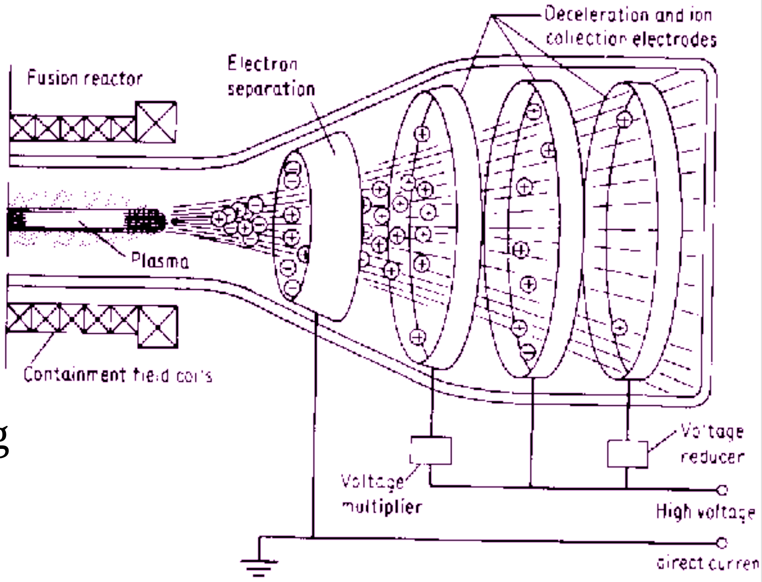


- Nuclear-Electric converts nuclear energy to heat, heat to electricity, then electricity to propulsion. The overall efficiency isn't very high. There's abundant nuclear power, so low efficiency can be tolerated, but now we also have much heat to remove, which in space can only be done with radiators.
- Estimates from 1987 were that radiators were as twice as heavy as the nuclear power plant itself—60T compared to 30T.

The inefficiency of nuclear-electric, suggested a concept whereby fission fragments are directly used for generating electricity, with much less sensitivity to radiator temperatures (permitting much higher radiator T, much better for Stephan-Boltzmann, much smaller radiators, less mass) and independently, much less heat per watt generated.

Direct Conversion
Fission Fragment-->Power

Fission Fragments have ~2MeV /nuc of energy and about 26 + charges. Rings are biassed at higher and higher + Voltage. Moving current uphill is like charging a battery. ~85%



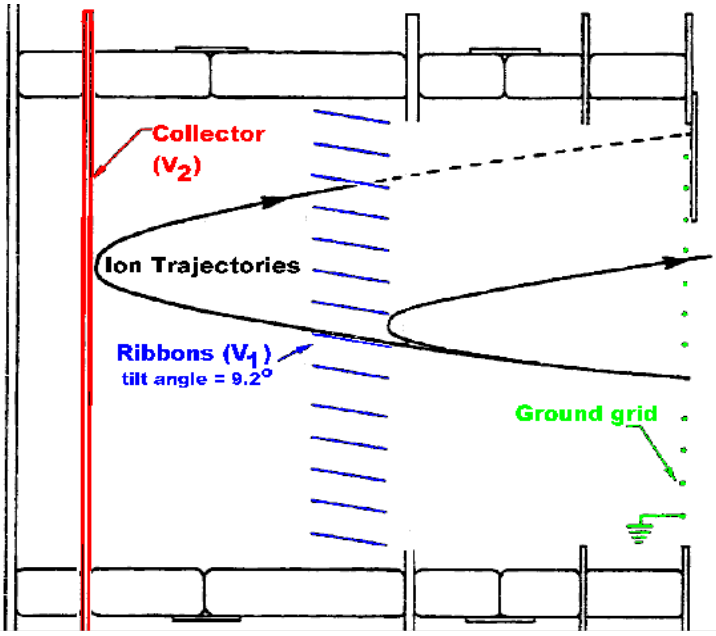
For a plasma or fission fragment reactor, the energy is located in the motion of charged particles. If these charged particles are directed onto a collection plate they can carry a current, and if the plate is repelling the charged particles, then the "uphill" current is a dynamo, converting kinetic energy into electric potential energy. In the case of a fission fragment nuclear reactor with about 2MeV/nucleon and 26+ charges, the collection plates are biassed around 2MV positive. This produces a very high voltage (MV) low current electric system, which can be down-converted (for example, with a transformer) to more useful high current, low voltage system.

This becomes a direct conversion of nuclear power into electricity without ever passing through a heat cycle. This means the conversion efficiency approaches 95% compared to a typical Carnot cycle heat engine (steam turbine, Rankine cycle etc.) used in nuclear power plants around 40%. This means that 60% of the nuclear energy in a power plant is being expelled as heat!

Of course, both a steam-turbine nuclear power plant and a dusty-plasma direct converter do not convert very much of the energy in the neutrons and gamma rays, so both are only converting the 85% of the total nuclear energy that appears in the charged particles. The importance for space, is not only the higher efficiency of the direct conversion, but the reduced heat load, which means less radiator mass.

Venetian Blind Converter

Collector shapes can be optimized for collecting “at rest” FF.



The positively biassed rings which produce an “uphill” electric potential also cause the charged particles to spread out and makes it hard to direct them. This is like playing putt-putt golf and trying to get the golf ball into the cup at the top of a volcano.

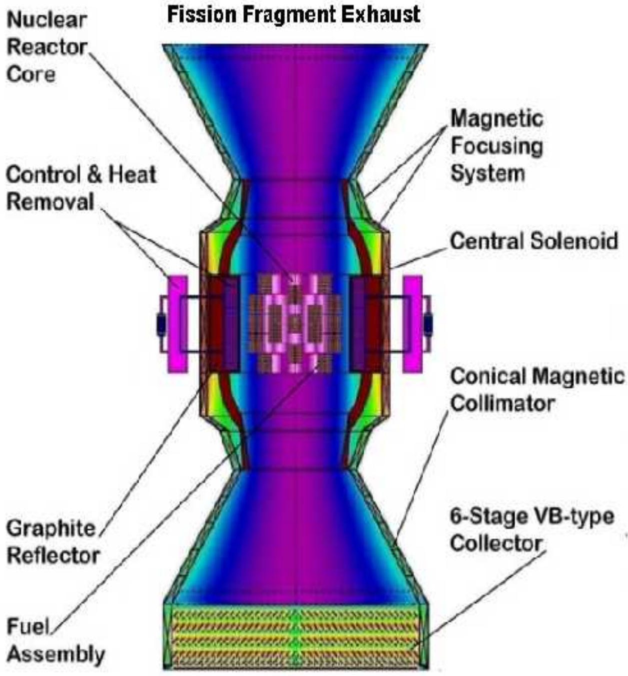
One answer to controlling the trajectory of the charged particles is to use a “venetian blind” collector which is shown here schematically.

The point isn't that we need a high-tech collector, but that there are solutions to controlling the trajectory of the charged particles while collecting most of their energy and converting it to current.

Hybrid FF Rocket--NERI

Coils at each end of the FF reactor control how much FF go into thrust, and how much into electricity.

Operating the nuclear reactor at max efficiency, we can adjust thrust and electricity separately.



The second advantage of direct conversion is that it can be configured simultaneously with the rocket thrust. In this diagram, we show a dusty plasma reactor surrounded by two coils and two nozzles. One nozzle provides thrust, and the other sends the charged particles onto a venetian blind direct-conversion collector. By changing the strength of the current in the upper and lower coils, the ratio of particles sent out as thrust or electricity can be smoothly adjusted from all to nothing.

This permits one nuclear reactor to provide both thrust and electricity with very low waste heat. It is a truly hybrid nuclear reactor.

Heat: The hidden killer
Dust: the best protection

- So the problem with space nuclear propulsion is NOT raw power, but how to eliminate waste heat. The more efficiently we can generate thrust, the less waste heat produced.
- Can we have our cake and eat it too? Can we have a non-thermal nuclear propulsion minimizing waste heat?
- Yes. By making the fuel into dust.

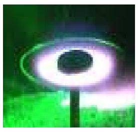
Direct conversion addresses the heat problem in getting electricity from nuclear-electric, but it has not explained why the nuclear reactor itself doesn't overheat. In nuclear thermal, the flowing hydrogen gas keeps the uranium core cool. In nuclear-electric a closed loop cooling fluid transfers the heat to a heat engine (say, steam turbine). Why keeps a fission fragment nuclear reactor from overheating?

The problem is that any gas or liquid that cools the core will also slow down the fission fragments, destroying the very thing we need for thrust and direct conversion. Since a vacuum is the best medium for allowing fission fragments to escape, the only heat rejection method is radiation.

By dividing the fuel into very small particles, <1 micron, the surface to volume ratio of the fuel can be made very large, allowing efficient radiative cooling of the fuel.

This has a second benefit of permitting the fission fragment to escape the fuel with minimal "friction" loss to the fuel, so that the fuel heats up less, and the heat is more effectively radiated.

Therefore the cure for "China Syndrome" is to make the nuclear core into dust. In the next section we discuss whether this is possible, and what simple models tell us about the properties of a dusty plasma fission fragment nuclear rocket. Ultimately though, it will take an experiment to prove its capabilities.

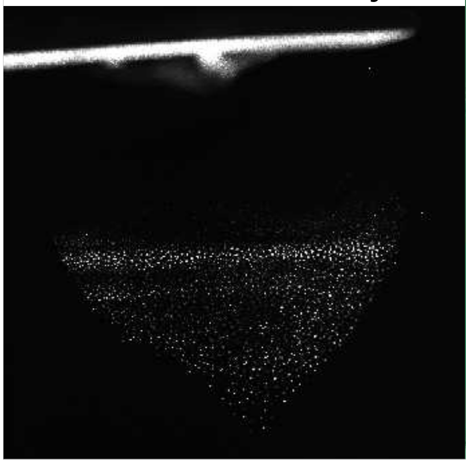


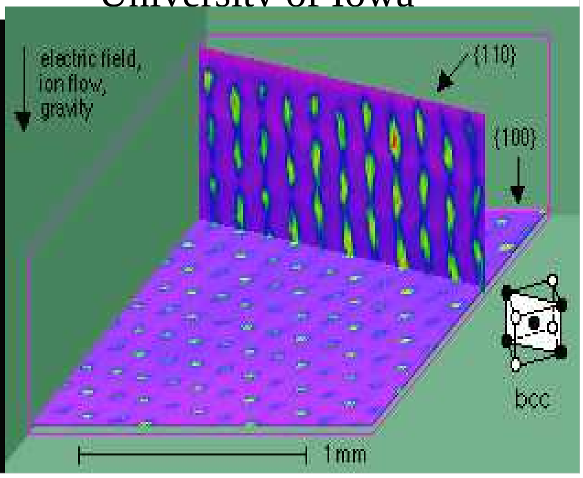
IV. The Dusty Plasma Fission Fragment Rocket

What is a dusty plasma?

Charged dust + plasma = a “plum pudding” Coulomb crystal, or as Cooper-pairs in BCS theory. Note surface tension & crystalline interaction.

Auburn University University of Iowa





Problem #1. The dust is in a vacuum, and so what keeps it from collapsing on the bottom of the reactor like dust-bunnies under the bed?

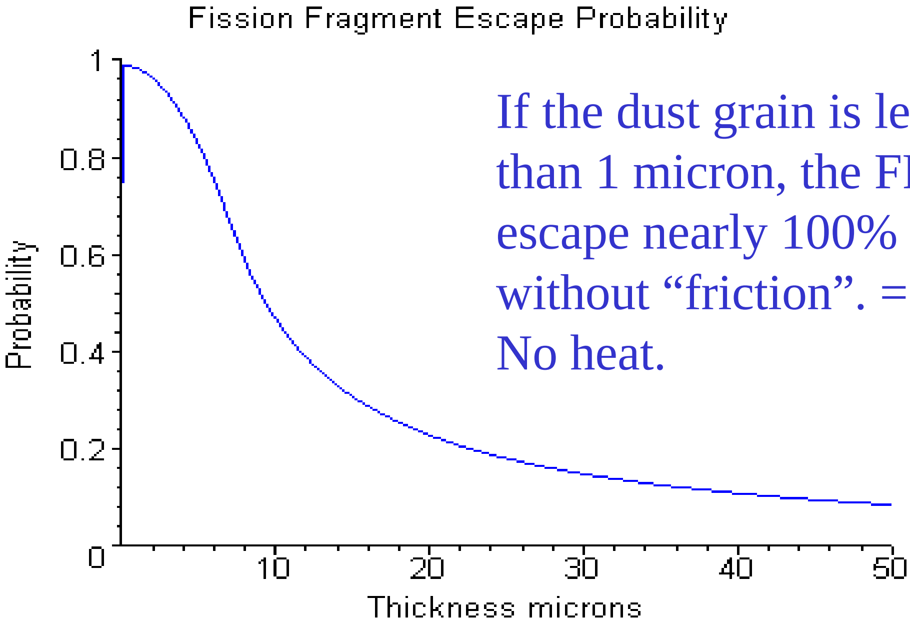
Electrostatic charge. If all the dust is charged negative, for example, it will repel other dust. A collection of charged dust is called a “dusty plasma” and has been an area of intense research over the past 20 years. Since dusty plasma is a new material its properties are still being explored. What we know right now is that micron sized charged dust with intervening (oppositely charged) plasma forms a stable macroscopic structure where “surface tension” forces hold the dust clouds together.

On the left is a “droplet” of dusty plasma suspended from a cathode. Not shown is an anode below the dusty plasma droplet. Together they provide a levitating vertical electric field, and the current in the ~100 mTorr plasma provides a confining magnetic field as well. Videos of the droplet show a significant “churning” or internal heating of the dust grains.

On the right is a much “colder” dusty plasma formed in a high density Q-machine plasma with much stronger magnetic fields. The dust grains do not move, and instead are “crystallized” in a lattice.

In both cases, the dust grains are far enough apart to be useful in a “dusty plasma” nuclear core.

Cool Dust



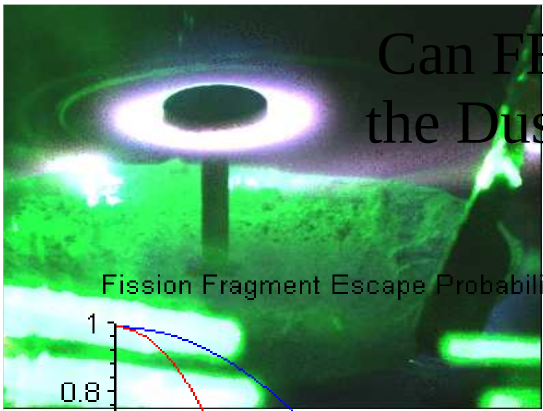
If the dust grain is less than 1 micron, the FF escape nearly 100% without “friction”. ==> No heat.

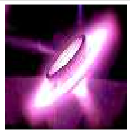
Using simple scattering theory/simulation for charged particles in matter (SRIM), we can calculate the probability of fission fragments escaping from a spherical fuel grain. We see that even at 2 microns, 95% of the fragments escape, and that below 1 micron the dust is virtually transparent to fission fragments.

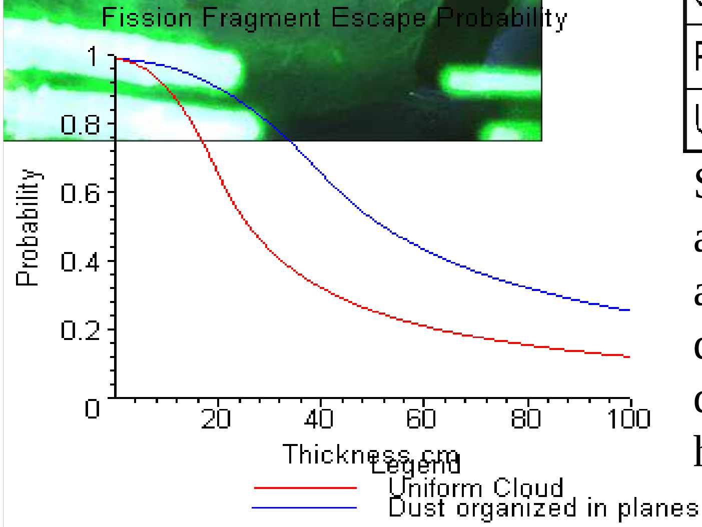
Therefore <1 micron dust fragments will solve the problem of generating internal heat.

But that leads to a 2^{nd} problem. What volume will it take to hold enough dust to achieve critical mass? That is, what is the density?

Can FF escape the Dust Cloud?







Am^{242m}	0.5 kg
Cm^{245}	1.1 kg
Pu^{239}	5.6 kg
U^{235}	11 kg

Since we need a total amount of U235 to achieve criticality, how do we collect enough dust grains without heating them?

Organization.

The critical mass of four fissioning isotopes is listed, requiring the suspension of large dust clouds. Choosing Pu239 as an easily obtained fuel, we simulate (MCNPX) a nuclear reactor with C13-D polyethylene moderator, and achieve critical mass at 5.6kg. Note that the critical mass is relatively independent of density, since the neutrons do not scatter in the fuel no matter what its density.

This means that the volume is strictly dependent only on the isotope and the density. If we assume the high particle densities observed in plasma etching machines, we have 10^8 /cc of particles 2 micron diameter. This is a volume filling fraction of 0.042% =4.2e-4, so that given 17gm/cc for Pu density, a critical mass of 5.6 kg ==> 0.784 m^3==> 57cm radius sphere.

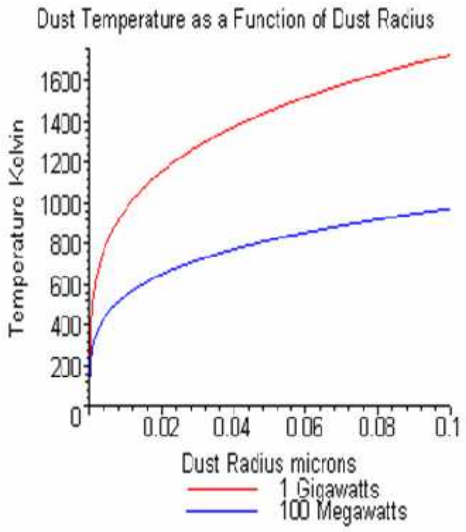
If we put this in a cylinder we have roughly a 1m x 1m cylinder, or 0.75 x 2m chamber. On average, the fission fragments have about 60 cm of dust to traverse, which on this chart, gives only a 20% probability of escaping.

This reduces the fission fragment escape probability, but we can still recover better performance if the dust is clumped or structured. Non-uniform magnetic fields also can improve the escape probability. The blue curve shows dust in sheets, the red curve shows isotropic dust, with escape probability as a function of dust cloud thickness.

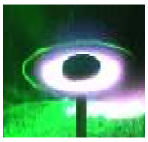
Thermal Management

- 1 Gigawatt Reactor
- 46% Energy deposited into dust
- Thermal radiation provides adequate cooling for sufficiently small dust particle

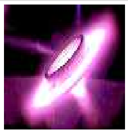
Compound	Melting Point
Am	1449 K
U	1405.3 K
UO2	2711 K
UC	2711 K
Cm	1613 K
Pu	915.5 K
PuO	2273 K



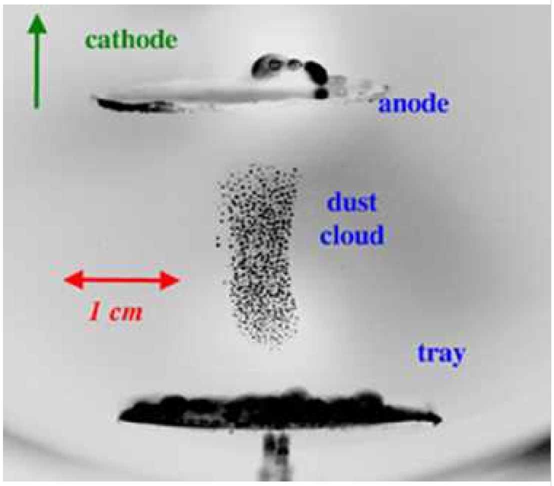
Given a 46% escape probability from a 50cm cloud, we can estimate the equilibrium temperature of a dust grain that is simultaneously being heated by fission fragments, and radiatively cooling. For 1 GW reactor, a 0.1 micron dust grain heats up to 1700 degrees. This is above the melting point of most metals, but well within the melting point of their oxides. The inner walls of the chamber will come into thermal equilibrium with the dust, but in addition, they will absorb the 10% gamma rays coming from the fission. Active cooling will be needed to keep the walls colder than the dust. Nevertheless, this is a much easier problem than conventional reactors where 100% of the heat appears in the reactor.



Nuclear Fuel suspended as dust



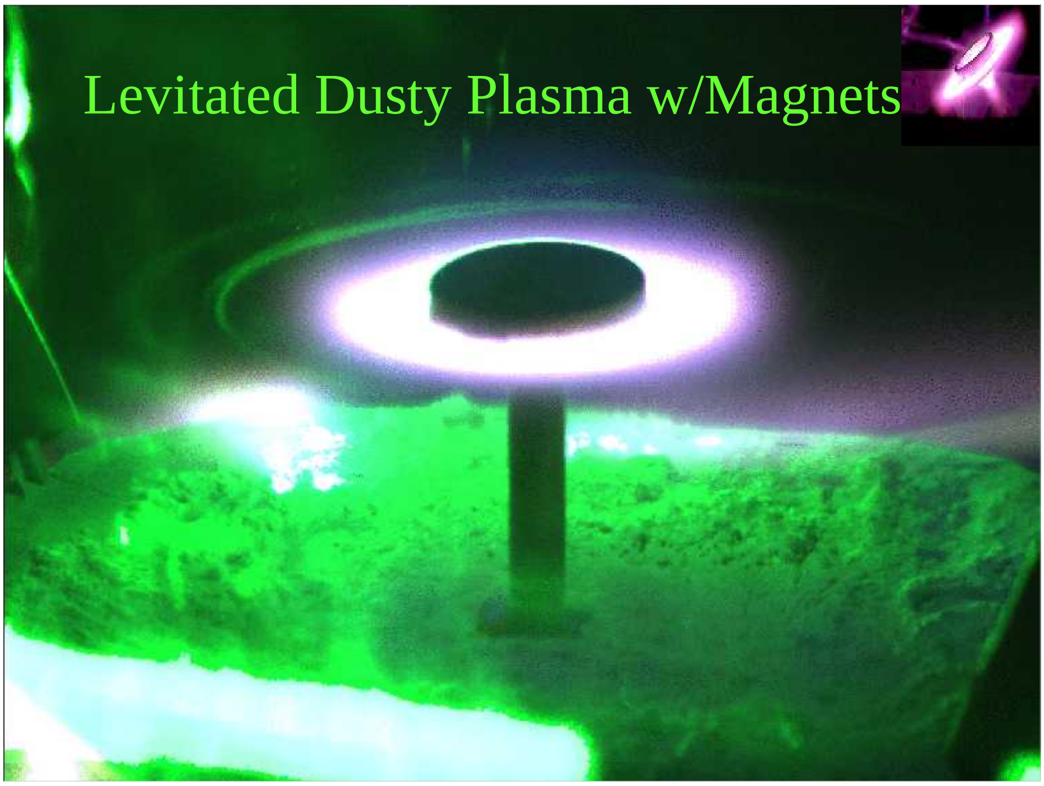
- Can the dust be suspended while the rocket is accelerating?
- Yes, 1g is typically no problem for labs.
- Will B-field change the dusty-plasma dynamics?
- Yes, but not much.



Can the dust be suspended while accelerating? Most certainly, it works in the lab with an acceleration of 1g. This figure shows a vertical dust column supported by an electrostatic field (and parallel current passing through the plasma).

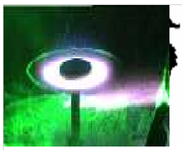
Will B-fields change the dust physics? Not much, as the next experiment shows. The key point is that the magnetic field suppresses the large parallel currents, while still maintaining the vertical electrostatic fields.

Dusty plasma in the NSSTC terrella lab. Bell jar, oil-roughing pump, purple DC-glow discharge plasma around a 1T NIB magnet, illuminated with green 532nm laser.



NIB 1cm magnet on alumina standoff with –400V applied to Ni coating in a pressure ~100 mTorr air (or nitrogen) the electron emission generates a glow discharge plasma trapped in the equatorial plane of the magnet. Tray of 3micron SiO_2 dust in a tray below the magnet is biassed + to generate arcs that charge the dust and explosively launch dust, which collects at the equatorial plane. A green laser is mechanically scanned (rotating mirror) to illuminate the dust trapped at the equator.

A roughly 10 V vertical potential is sufficient to trap the dust, but only where the magnetic field is vertical, which occurs at the equatorial plane.

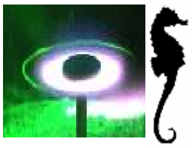


The Dust Trap

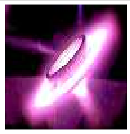
- Arc discharge on 3μ SiO_2 dust grains charges them negative. Probable charge state on dust is –10,000 e/grain.
- They are trapped in a positive space-charge region adjacent to ring current. The RC is formed by -400V DC glow discharge on NIB magnet, streaming electrons ionize the air, maintain the RC. Phase-space mismatch of streaming electrons and trapped ions produces the space charge. Highly anisotropic B-field contributes as well.

There is some confusion that the magnetic field is trapping the dust. This can be easily disproven by calculating the gyroradius of the dust (many kilometers, even if the field were uniform.) Rather, the charged dust is trapped electrostatically in the potential well that preferentially forms at the equator of the magnet due to pitchangle differences of electrons and ions.

So the B-field traps the plasma, the plasma traps the dust.



Can a reasonable B-field confine FF?



Particle	Atomic Weight A	Energy/amu	Effective Charge	Magnetic Field Required
Heavy Fragment	140	.5 Mev/amu	22	.63 Tesla-meter
Light Fragment	95	1 Mev/amu	22	.60 tesla-meter
alpha from Thorium	4	1.42 Mev/amu	2	.33 tesla-meter

$$Br := 14.\frac{A\sqrt{E}}{Zeff}$$

The electric field is not sufficient to trap the fission fragments. That is, a potential well of about 100V is sufficient to hold the dust, but the fission fragments have a electric kinetic energy of about 2 MV.

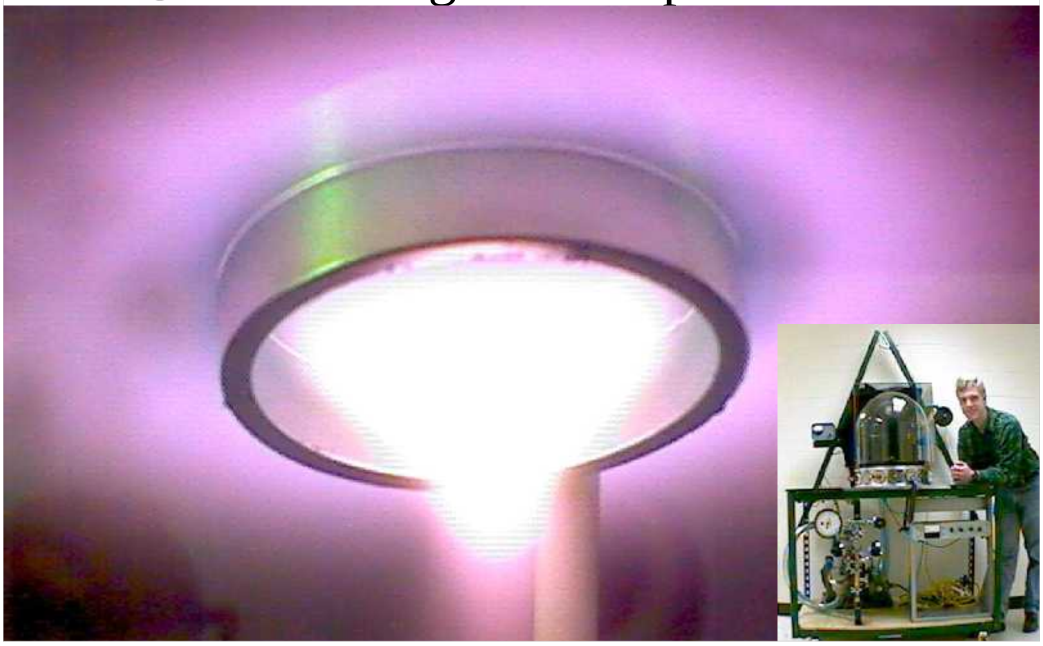
However, the magnetic field needs to be strong enough to confine the fission fragments to the reactor, and direct them either toward the direct conversion surface or the nozzle of the rocket. This looks to be a rather large magnetic field.

The rigidity of fission fragments is given by the equation on the right, which gives 0.6 Tesla-meters for the gyroradius. To keep a fission fragment inside the reactor (diameter 1m) will require a field of 0.6 Teslas. This is a large field, and in the laboratory, can be supplied by superconducting magnets.

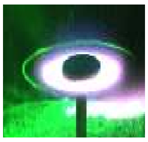
However in space, it is disadvantageous to be using such large fields, which will add a great deal of mass to the system. The key observation is that the field need not be uniform, merely strong near the edges of the reactor so as to keep the fission fragments confined. That is, we can use field coils to generate a basic magnetic bottle geometry, supplemented by both wires and permanent magnets around the perimeter. The advantage of a multipole field, is that the magnetic strength need only be large at the wall, not in the center of the reactor.

Has this been done before? Absolutely, and the “polywell” electrostatic fusion device is using this approach for magnetic fusion. We did it with permanent magnets in an undergraduate lab...

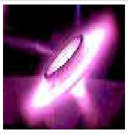
Toroidal Multipole Magnetic Trap



We show such confinement is possible by the simple laboratory experiment involving a toroidal magnetic field producing an electron bombardment plasma (-400V) in a 100 mTorr nitrogen atmosphere. The glow outside the toroid is what is expected for a “ring current” around a dipole field. The high density plasma inside the toroid was unexpected, but very similar to the fission fragment geometry. Note that plasma density contours do not follow magnetic field lines, demonstrating a quasi-static electric field with some components parallel to B. The inset shows one of the two undergraduates who built and conducted the experiment.

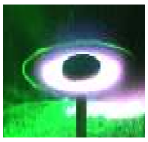


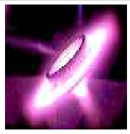
More on confinement .



- B=0.6 T over 1-meter bore is an awesome energy density = pressure. If we could do that we'd be flying a fusion reactor! Instead, we use a multipole magnet toroid, such that the field strength drops as $|R - R_0|^{-N}$, with N>2, from the wall.
  - This has a magnetic gradient near the wall, producing a strong mirror force, "insulating" the wall from fission fragments.
  - By Liouville's theorem, n/B=constant, so fission fragment density peaks at the wall, low in the dusty plasma center. E.g, one pass through dust.
- Because the escaping fragments are positive, → net negative charge in the dust cloud. An ambipolar electric field (=some fraction of MeV) develops at edge as well, confining the fragments.
  - Proper treatment will require full kinetic simulations.

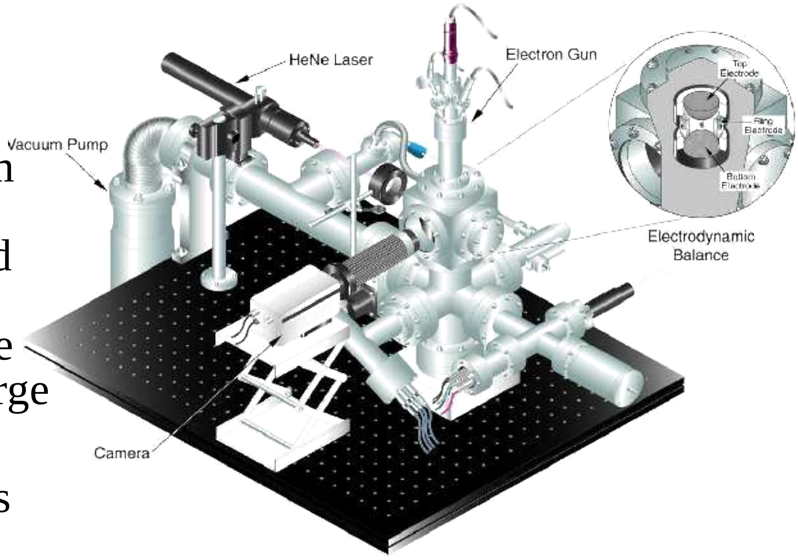
By analytic arguments, we expect that a multipole field will produce both a large repelling mirror force at the walls, as well as a decrease in fission fragment interaction with the dust. A consequence of containing the high energy plasma is an ambipolar electric field due to the high speed fission fragments and the low speed charged dust. This electric field is also contributing to the confinement of the fission fragments. Clearly though, full multi-fluid kinetic computer models will be needed to find the equilibrium plasma voltages and particle trajectories in this complex environment.



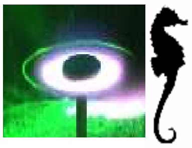


Discharging Dust

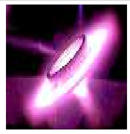
- Won't negatively charged dust discharge from thermionic emission? And won't 100nm dust have huge corona discharge current?
- Yes, but not as much as one might think.

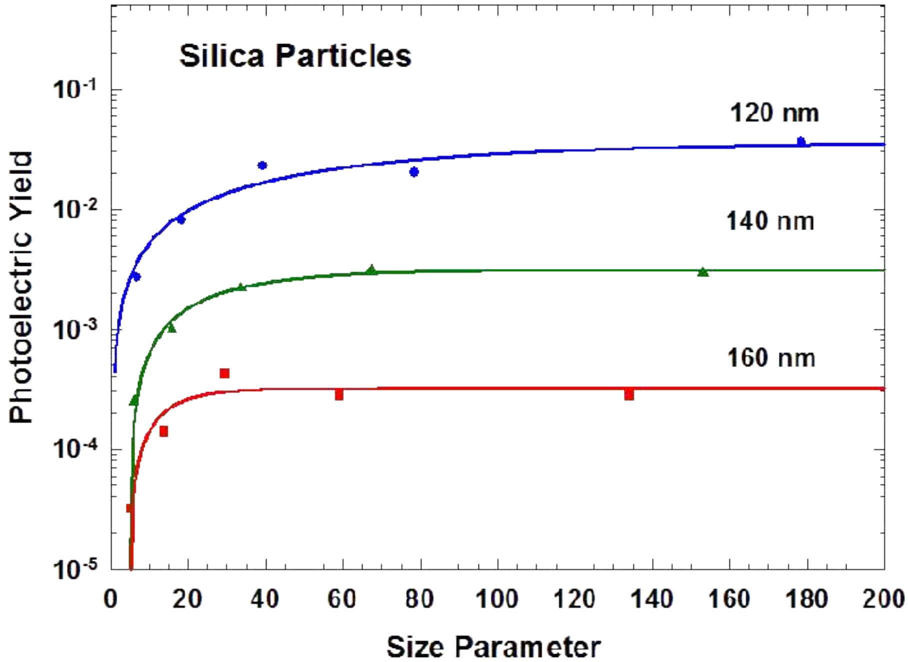


Will the negatively charged dust emit electrons and become neutralized at these temperatures and conditions? The Dusty Plasma Lab at MSFC addresses the physics of photoemission from single dust grains under VUV irradiation (which is equivalent to a much hotter temperature than that of the reactor).



Photoelectrons vs. size



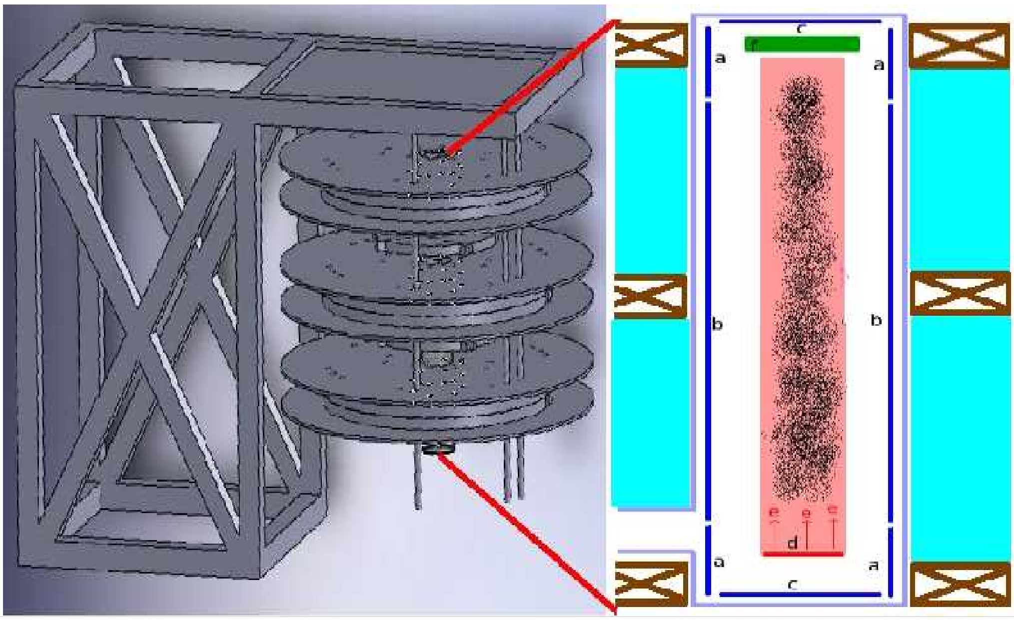


Experiments in the Dusty Plasmas Lab show that small < micron sized grains do not discharge as rapidly as simple theories had predicted. This is very helpful because not only will there be large electric fields in the nuclear reactor, but they will be very hot, with the principle discharge mechanism expected to be photoemission.

Silicates are similar to the ceramic fuel materials potentially used in the reactor, and show similar properties as carbonaceous grains, despite having bulk conductivities orders of magnitude lower than carbon. This appears to be a size (not bulk) effect.

(References are Mian Abbas work published in the literature.)

Lab Dust Cloud Test



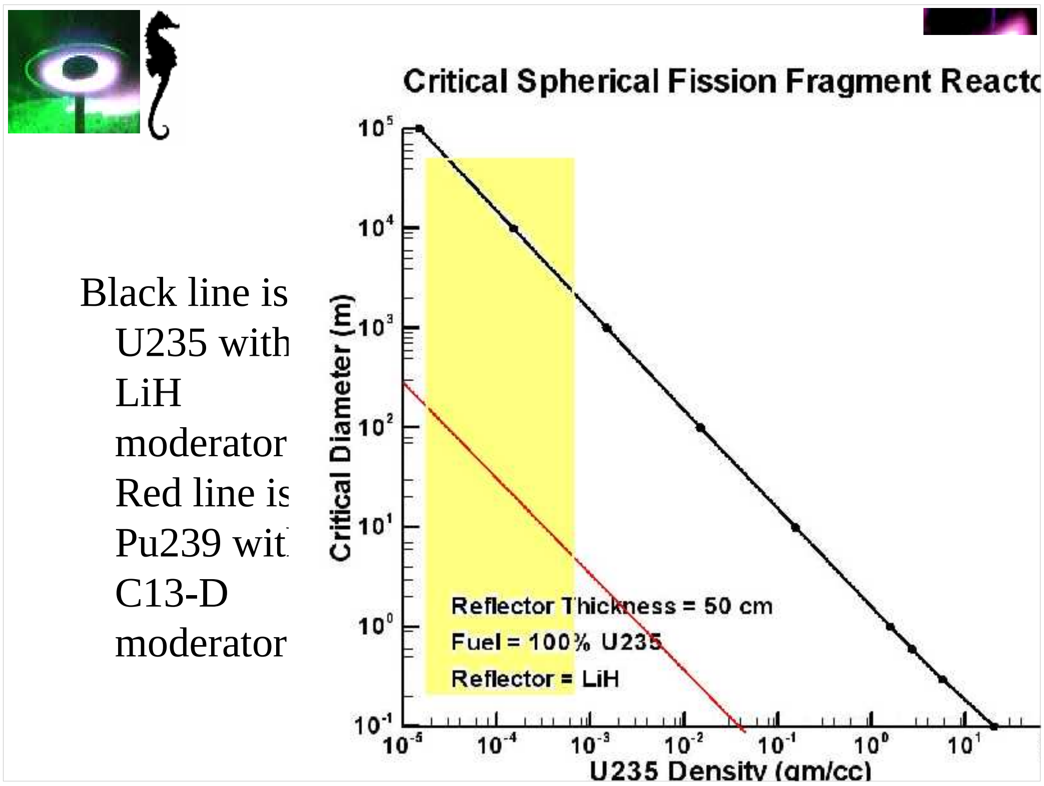
The acid test of whether a dusty plasma can maintain its integrity while heating and fissioning is a laboratory test.

We designed a glass ampule that is 3” in diameter and about 12” long. It is mounted in a water-cooled copper magnet to provide the 0.1 T of field and can be placed adjacent to a test reactor so as to intercept enough neutron flux to begin fissioning.

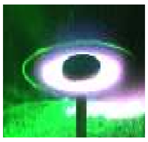
The red line is a LiO electron emitter for creating a plasma at low pressure hydrogen gas.

The blue lines are InO electrodes placed around the glass ampule to study the electric field suspension of the dust.

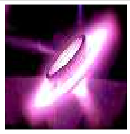
The green bar is a solid state silicon detector for the fission fragments, which can be binned by location. By adjusting the magnetic field we can study the interrelation between fission fragment confinement, dusty plasma suspension and neutron density.



I've taken this plot from another simulation, so I can't verify the curves, but it is my understanding that the yellow band is the typical dust density, whereas the amount of fuel required to go critical are the diagonal lines. This calculation is for Uranium, which has about twice the critical mass as Pu239, but in any case, a diameter of a few meters is the sort of size expected for a dust reactor.



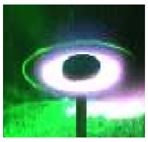
Nuclear Pollution?



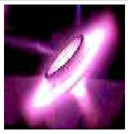
- Since radioactive fission fragments are emitted from the rocket, how dangerous is this for the Earth?
- From the two missions analyzed, we calculated how long each rocket is withing 10 Re of the earth, and how much fuel is burned during this time.
  - 30 day mission to Mars 240 g U235 ~ 1 mole
  - 550 AU mission = 720 g U235 = 3 moles
  - 0.5 Lightyr mission=3.7 kg U235 = 15 moles
- We modelled the transport through the radiation belts, ionosphere & stratosphere and decay lifetimes of 60 decay products. Short-halflife products decay before reaching the surface of earth. Long-halflife products produce almost no radioactivity. We list radioactive products that make it to Earth from 1 mole U235, both by number and curies.

How much Earth pollution is caused by firing up this rocket in Earth orbit?

The charged fission fragments are captured by the Earth’s magnetic field, and slowly diffuse toward the Earth while they are also radioactively decaying. Short-halflife isotopes never make it. We calculated that a Mars mission uses about 1 mole, a 550AU mission uses 3 moles, and an Oort cloud mission deposits 15moles in the magnetosphere. A simple model was used to estimate the diffusion rate in magnetosphere, the settling rate in the stratosphere, to estimate the amount deposited in the troposphere (and washed out by rain).




Modelled Pollution from 1mole U235/P239



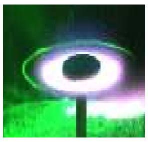
- By moles (total radioactivity ~10% of U235)
  - Rb87 .1 = 0.1 uCu
  - Sr90 .2 = 180 Cu
  - Cs135 .3 = 0.4 mCu
  - Cs137 .3 = 360 Cu
  - Nd144 .05 = 1 pCu
- By Curies fast diff slow diffusion
  - Sr90 180 180
  - Ru108* 20 11
  - Cs137 360 360
  - Ce144 190 77
  - Pm147* 230 93

Cosmic Ray production
C14 = 266 Cu/yr

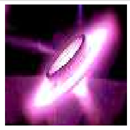
Listed by moles of radioactive material, Rb87 and Cs135 are big contributors, but when their long-halflife is calculated, they have almost no effect.

Listed by Curies of radioactivity, several short-halflife isotopes are found to be important, Ru108, Ce144, Pm147. If we use a “fast” transport rate in the magnetosphere of 1 Re/day at L=6, then these species contribute, but a slower more typical 0.1 Re/day resulted in a great diminution of these species. As expected, the two bad isotopes are Sr90 and Cs137, both with intermediate halflife ~30 years.

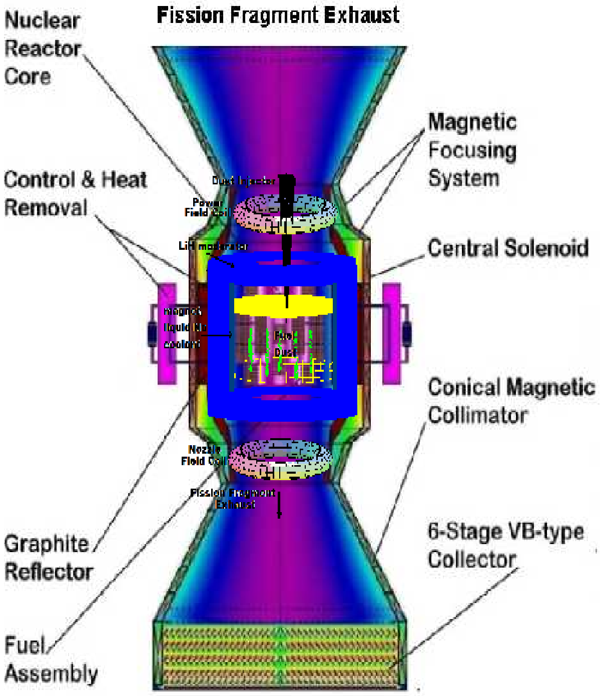
In comparison, cosmic ray production of C14 deposit 266 Cu/yr, so the 1mole mission contributes about 2 times the natural yearly amount, hardly above background.



Concept

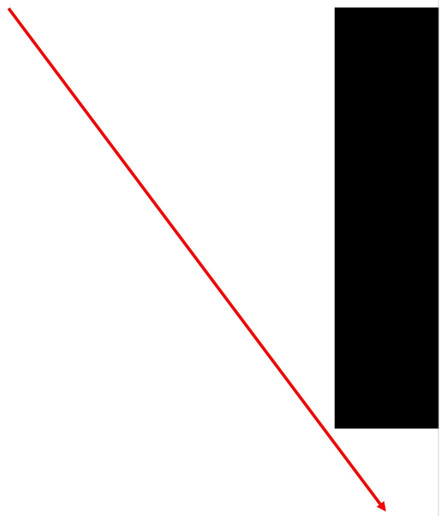


- Field coils on the end control thrust & power
- Pu239 dust
- Moderator is lightweight C13D
- Multipole permanent magnets on sides contain fragments

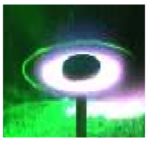


The refined schematic then, has some 30 cm of moderator surrounding a 1-m diameter chamber. The inner wall has both a liquid Na active cooling system, and a layer of permanent magnets to reduce power requirements and provide for a "cold start". The dust injector is moving milligrams per second of dust into the system. As dust is "burned" its diameter shrinks and charge state changes, permitting a natural sorting of fresh and spent fuel. Further modelling is needed to understand the final destiny of spent fuel, whether it is vaporized, expelled, or settles to the "floor".

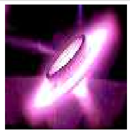
Mars Mission Concept



So what does the mission look like? A lot like NEP, but with a more powerful rocket pushing the satellite.



Conclusions



- The 2009 Design Reference Architecture 5.0 chose a “slow” mission to Mars because there really was no alternative. This led to an enormous program of life support for several years, artificial gravity, and massive LEO launch costs.
- A viable hybrid nuclear rocket that lowers the weight and cost, enables a fast visit which increases safety, is both more likely to be funded, and more likely to succeed.
- At about 20 MW, this design is a very conservative nuclear power design, and easy to implement.
- The hurdle at this time is scientific, “can a dusty plasma rocket actually work at 20MW?”

In conclusion, high delta-V missions are enabled by this technology, and it is not the stuff of science fiction.