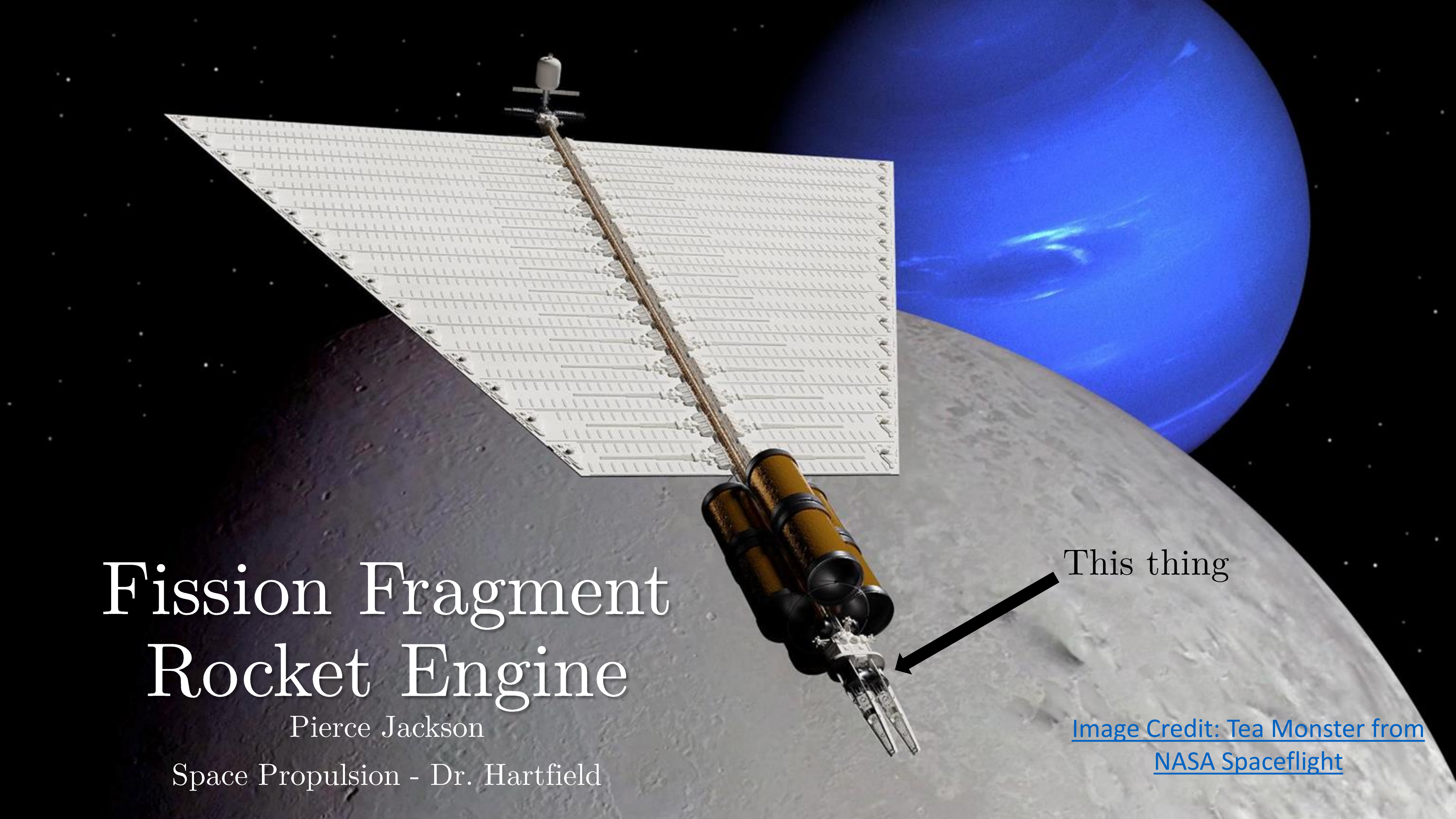
Fission Fragment Rocket Engine

Pierce Jackson

Space Propulsion - Dr. Hartfield



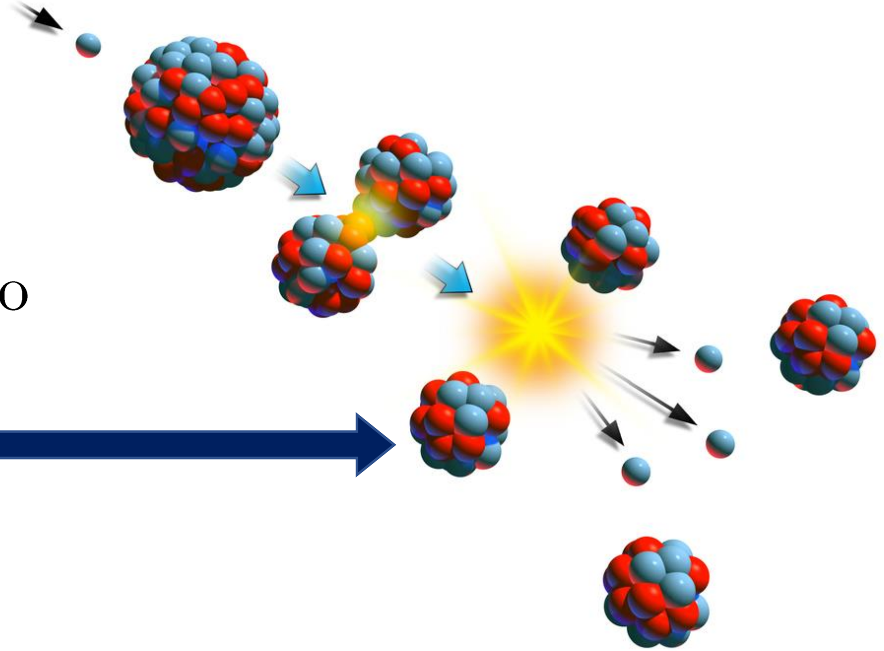
This thing

Image Credit: Tea Monster from NASA Spaceflight

Background

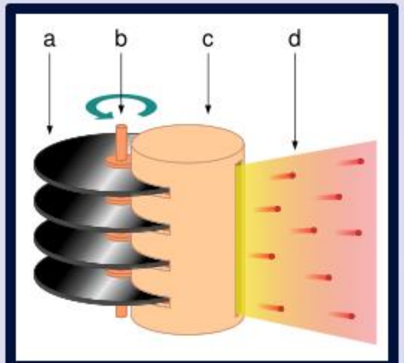
- Nuclear thermal propulsion
  - use the energy released from fission to heat and expel liquid hydrogen to produce thrust
- Nuclear electric propulsion
  - uses the energy released from fission to generate electricity and accelerate ions to produce thrust

- What if we cut out the middle-man (hydrogen, conversion to electricity) and "simply" use the fragments (or products) of the nuclear fission to produce thrust?
  - Just throw these guys out the back

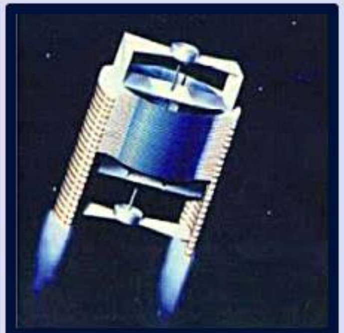


The Concept

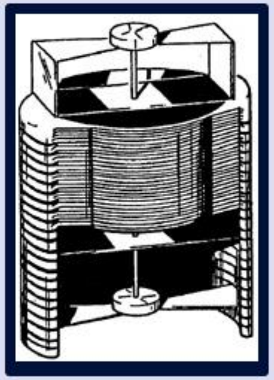
- Initially thought up by George Chapline of Lawrence Livermore National Laboratory
- Thin carbon filaments coated in micron thick fissile material
- When rotated through the core, nuclear material fissions
    - Fragments are expelled, guided by magnetic fields
- However, fragments that do not escape will heat up the carbon filaments and potentially cause them to melt
- Fragments ejected at speeds a few percent the speed of light
    - **Theoretical Isp > 1,000,000 sec ☺**
    - Low thrust ☹



*Fission-fragment propulsion as proposed by Dr. George Chapline. **a** fissionable filaments, **b** revolving disks, **c** reactor core, **d** fragments exhaust*



Fission fragment concept as proposed by Dr. George Chapline. The reactor consists of thin carbon filaments coated with nuclear fuel rotated at high speed through the core. Courtesy of LLNL (1986)



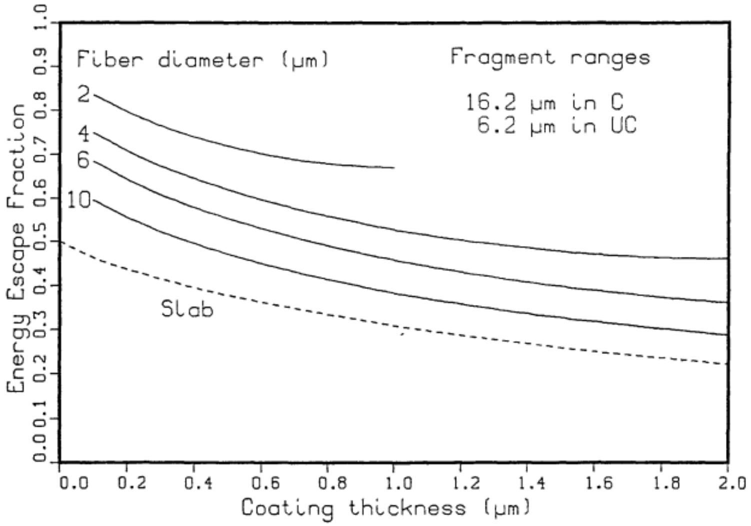


Figure 1. Fission fragment escape probability for uranium carbide coated graphite fibers.

The Dusty-Plasma Configuration

- Fragments produced from fission are much more likely to escape smaller particles
- So, grind fissile material into “dust” < 100 nm
- Suspend dust inside reactor core using electric fields
- Magnetic fields guide fragments out for thrust
  - Or into a chamber that decelerates fragments using electric fields, generating a high-voltage DC supply

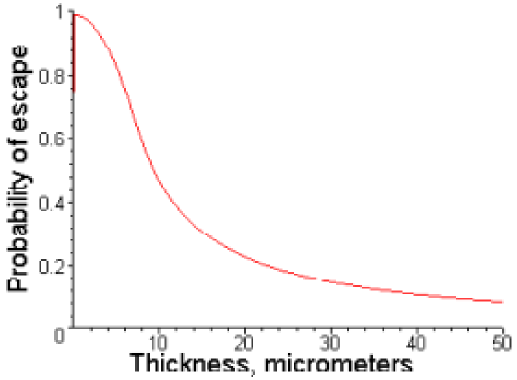


Figure 3. Fission fragment escape probability as a function of fuel particle size.

- The low-density and small particle sizes of the dusty plasma allows for sufficient radiative cooling of fuel

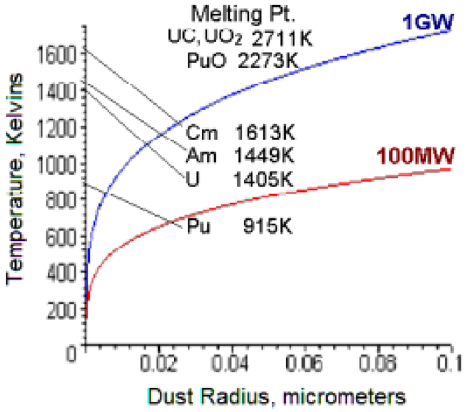
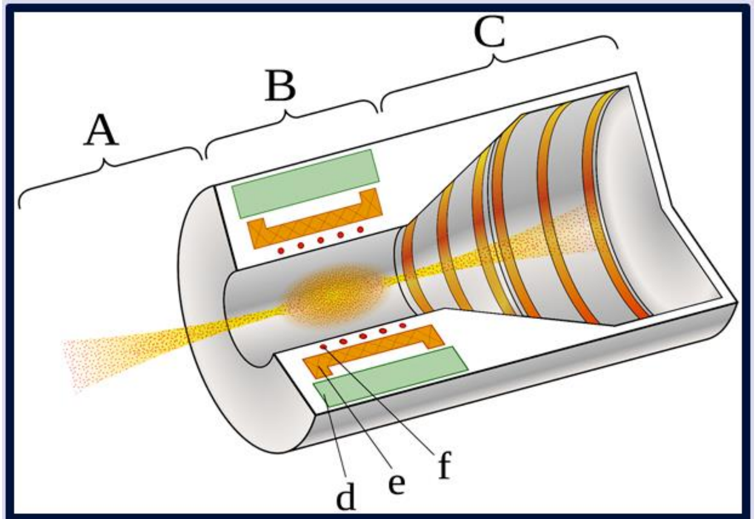


Figure 5. Equilibrium fuel particle temperature as a function of particle size.



Dusty plasma bed reactor by Rodney Clark and Robert Sheldon

A.	fission fragments ejected for propulsion
B.	reactor
C.	fission fragments decelerated for power generation
d.	moderator (BeO or LiH)
e.	containment field generator
f.	RF induction coil

Generation I Design

- Initially plutonium and uranium fuels were considered… changed in next iteration
- Inside of core covered in a mirror-heat shield that reflects 95% of thermal energy
- Neutron moderator slows down fast neutrons and redirects them back to the core to be captured; this maintains criticality
    - Beryllium oxide was considered, but it is heavy. So, Lithium hydride is favorable

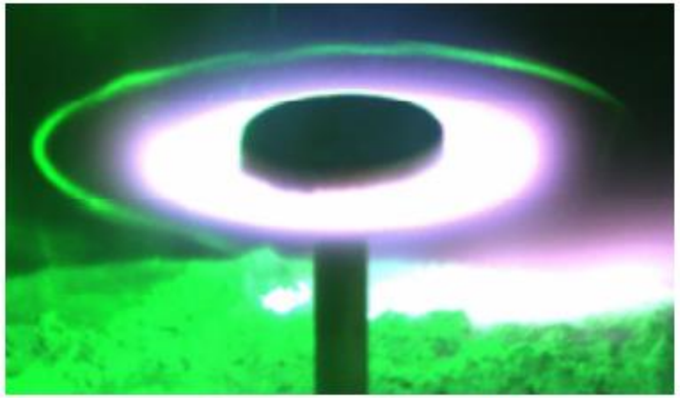
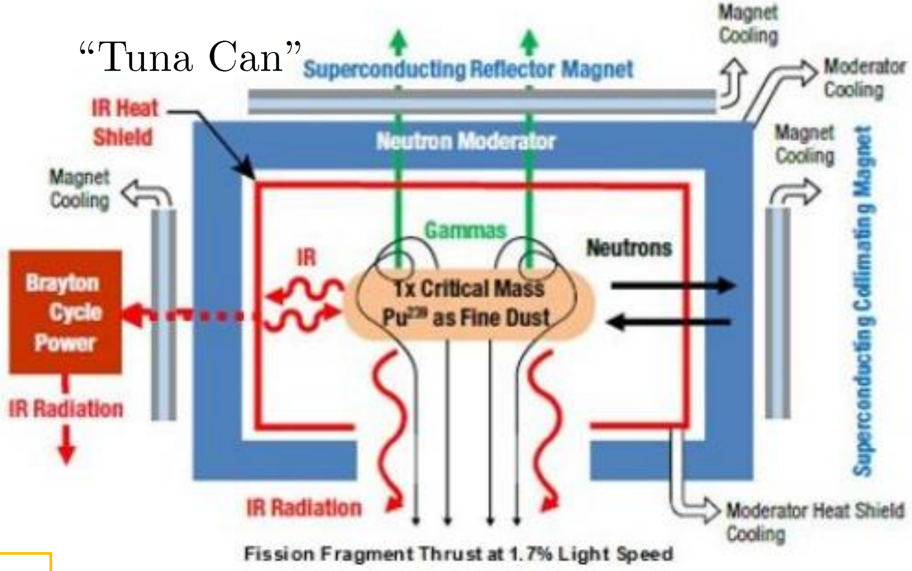
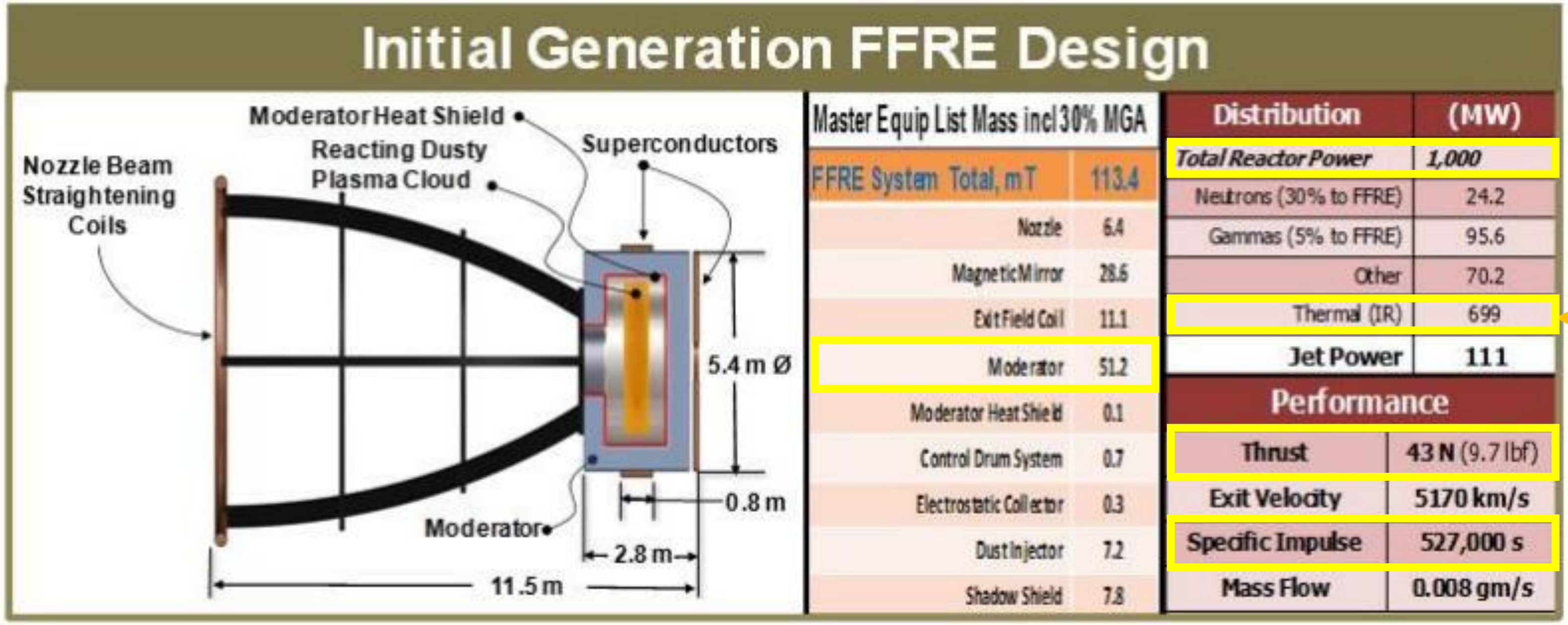


Figure 8. Magnetically confined dusty plasma cloud.

“Tuna Can”





Initial Generation FFRE Design

Master Equip List Mass incl 30% MGA	
FFRE System Total, mT	113.4
Nozzle	6.4
Magnetic Mirror	28.6
Exit Field Coil	11.1
Moderator	51.2
Moderator Heat Shield	0.1
Control Drum System	0.7
Electrostatic Collector	0.3
Dust Injector	7.2
Shadow Shield	7.8

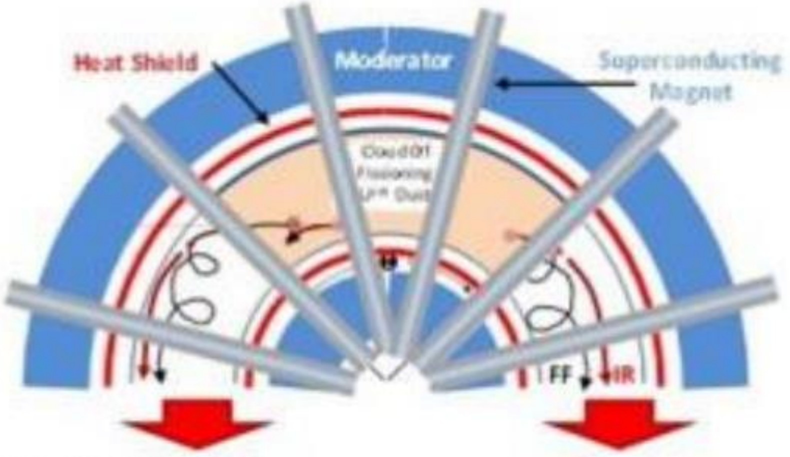
Distribution	(MW)
Total Reactor Power	*1,000*
Neutrons (30% to FFRE)	24.2
Gammas (5% to FFRE)	95.6
Other	70.2
Thermal (IR)	699
Jet Power	**111**

Performance	
Thrust	43 N (9.7 lbf)
Exit Velocity	5170 km/s
Specific Impulse	527,000 s
Mass Flow	0.008 gm/s

Lots of power radiated to space as heat; large radiators needed

Generation II Design & Afterburner

- The “tuna can” design ‘could not simultaneously support a small enough hole in the moderator to retain sufficient neutrons to keep the core critical and a large enough hole to enable the magnetics to direct the fission fragments out of the reactor.’
- Thrust was still small; Consider a different fuel
    - Uranium-235: 500 barns, 98% of fragments to thermal, 2% to thrust
    - Plutonium-239: 720 barns, 97% of fragments to thermal, 3% to thrust
    - <u>Americium-242m: 7200 barns, 60% to thermal, 40% to thrust</u>



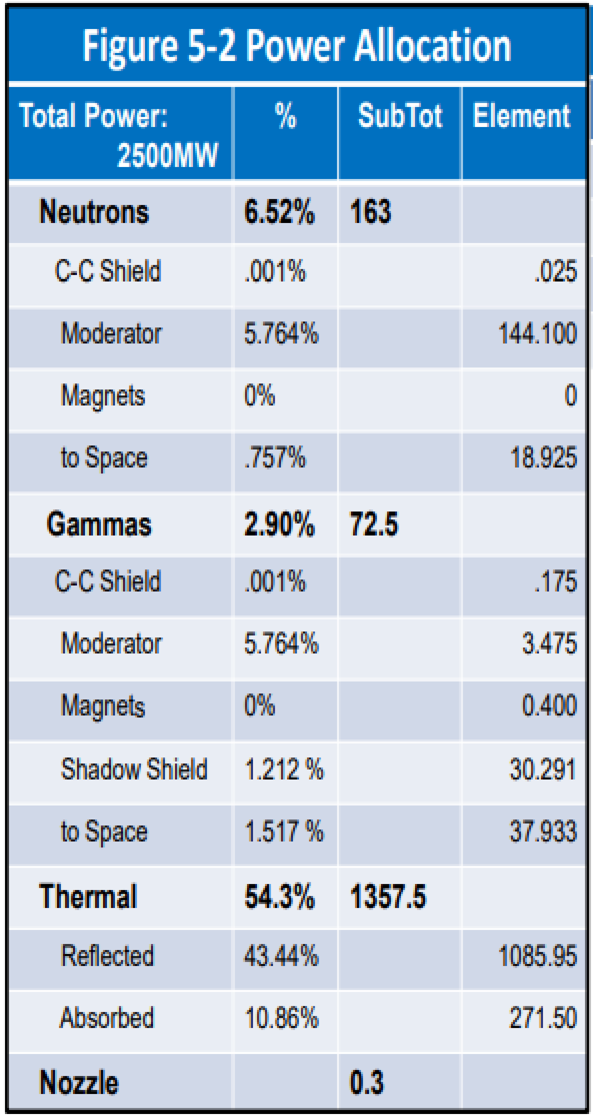


Figure 5-2 Power Allocation

Total Power: 2500MW	%	SubTot	Element
Neutrons	**6.52%**	**163**	
C-C Shield	.001%		.025
Moderator	5.764%		144.100
Magnets	0%		0
to Space	.757%		18.925
Gammas	**2.90%**	**72.5**	
C-C Shield	.001%		.175
Moderator	5.764%		3.475
Magnets	0%		0.400
Shadow Shield	1.212 %		30.291
to Space	1.517 %		37.933
Thermal	**54.3%**	**1357.5**	
Reflected	43.44%		1085.95
Absorbed	10.86%		271.50
Nozzle		**0.3**	

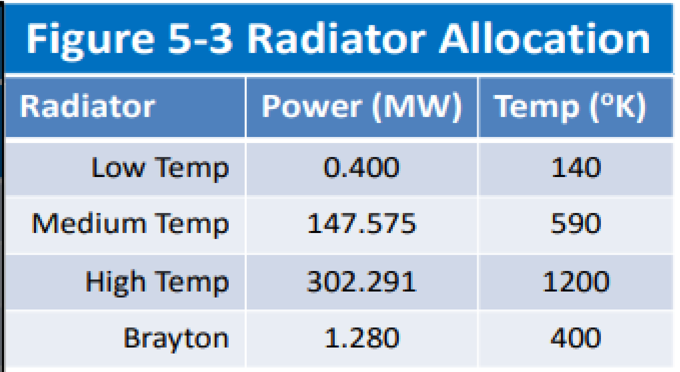


Figure 5-3 Radiator Allocation

Radiator	Power (MW)	Temp (°K)
Low Temp	0.400	140
Medium Temp	147.575	590
High Temp	302.291	1200
Brayton	1.280	400

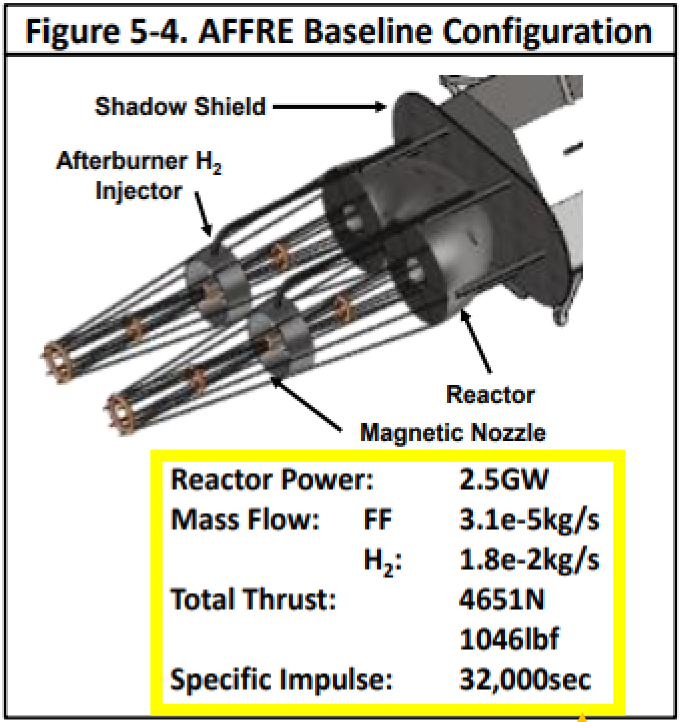
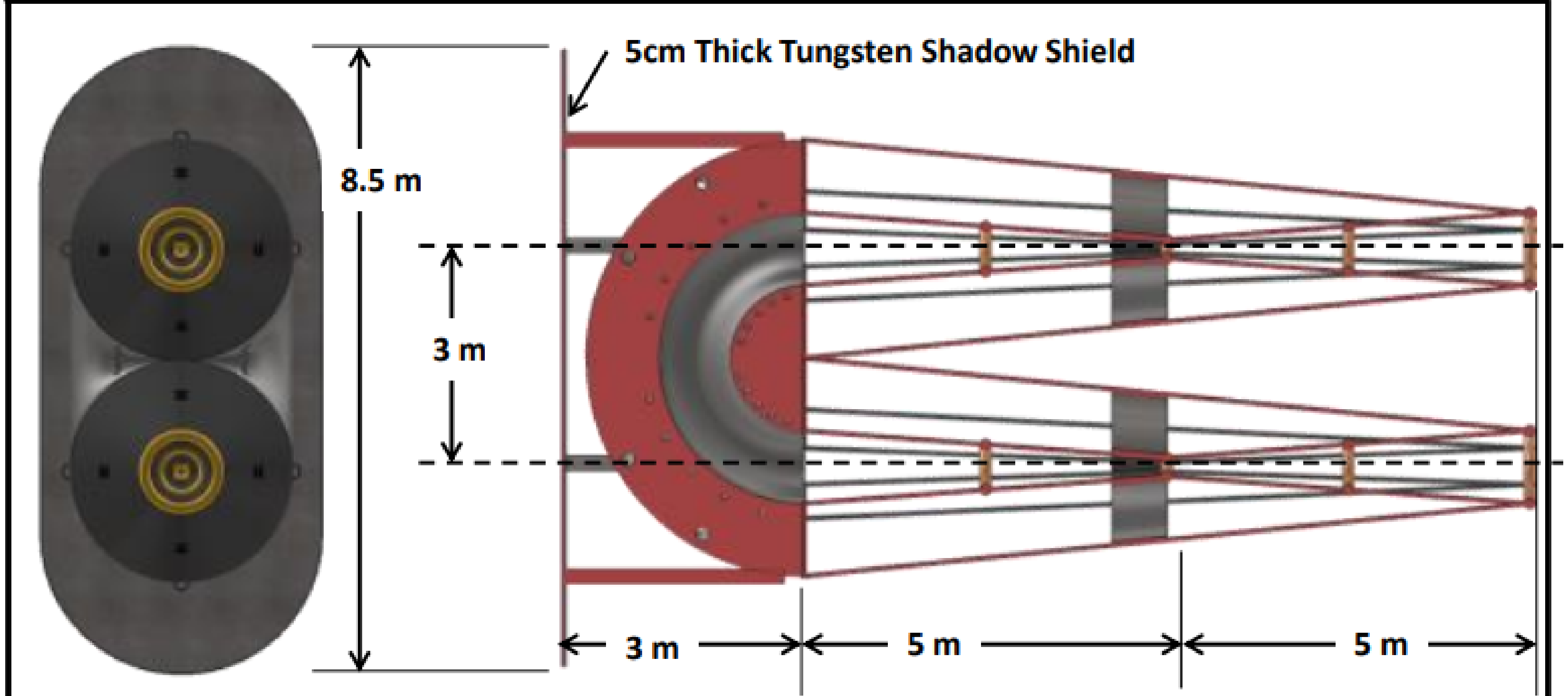


Figure 5-4. AFFRE Baseline Configuration

Reactor Power:		**2.5GW**
Mass Flow:	**FF**	**3.1e-5kg/s**
	H_2:	**1.8e-2kg/s**
Total Thrust:		**4651N** **1046lbf**
Specific Impulse:		**32,000sec**

Afterburner: Inject liquid hydrogen into the beam-flow of fission fragments. Trade Isp (particle velocity) for increased thrust (mass movement)

Figure 5-5. AFFRE General Arrangement



	Fission Fragment MEL	Qty	Unit Mass (kg)	Basic Mass (kg)	MGA (%)	MGA (kg)	Predicted Mass (kg)
2.0	Propulsion			222709	21%	46198	268907
2.1	Moderator	1	70260	70260	30%	21078	91338
2.2	Core Heat Shield	1	8000	8000	30%	2400	10400
2.4	Core Superconducting Magnet Assembly	1	31062	31062	30%	9319	40381
2.5	Engine Structure	1	7026	7026	30%	2108	9134
2.6	Nozzle Structure	2	2073	4147	30%	1244	5391
2.7	Nozzle Magnet Assembly	2	2250	4500	30%	1350	5850
2.8	Dust Injector	1	2000	2000	30%	600	2600
2.9	Shadow Shielding	1	25000	25000	30%	7500	32500
2.10	Control Drums	1	500	500	30%	150	650
2.11	Hydrogen Pumps	10	50	500	30%	150	650
2.12	Hydrogen Feed/Injector Assembly	2	500	1000	30%	300	1300
2.13	Tanks	5	13743	68714	0%	0	68714

AFFRE	
Engine	AFFRE
Engine Mass (reactor)	107,000 kg
Engine Mass (mod oil)	91,000 kg
Engine Mass (total)	268,961 kg
Reactor Power	2.5 GW
Thrust	4,651 N
Thrust Power	730 MW
Specific Impulse	32,000 sec
Exhaust Velocity	313,900 m/s
Mass Flow (FF)	3.12×10^{-5} kg/s
Mass Flow (Hydrogen)	0.0179 kg/s
Mass Flow (Total)	0.018 kg/s
T/W	0.002

Shifting Gears		
Engine	**Isp**	**Thrust**
FFRE	527,000 sec	43 Newtons
AFFRE	32,000 sec	4,651 Newtons

Mission Analysis

- Engine (Dry mass) and moderator oil can be launched on separate Starship flights
  - They chose SLS because this was in 2012 and Starship didn't exist yet.
- Rest of the spacecraft launched and constructed in LEO
- To Mars & back in under 300 days
- Deep-space missions are possible.

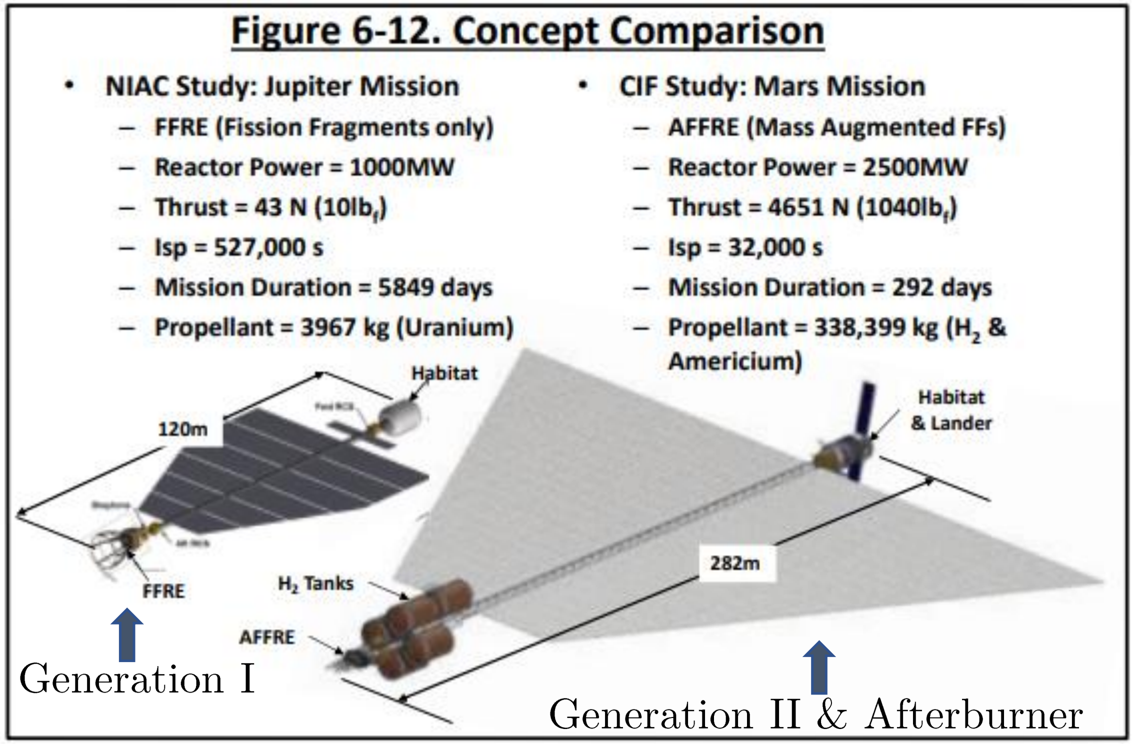
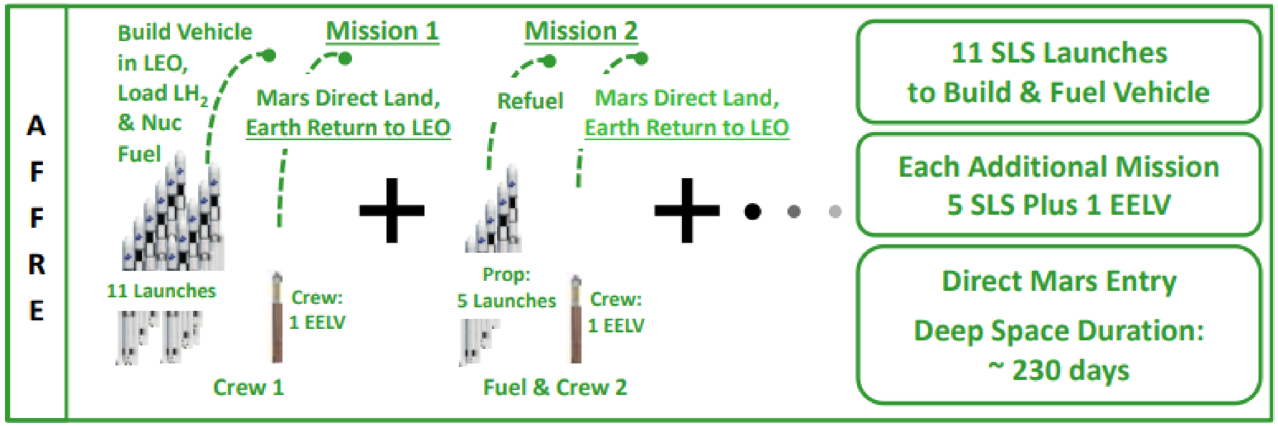


Figure 6-12. Concept Comparison

- NIAC Study: Jupiter Mission
  - FFRE (Fission Fragments only)
  - Reactor Power = 1000MW
  - Thrust = 43 N (10lb$_f$)
  - Isp = 527,000 s
  - Mission Duration = 5849 days
  - Propellant = 3967 kg (Uranium)
- CIF Study: Mars Mission
  - AFFRE (Mass Augmented FFs)
  - Reactor Power = 2500MW
  - Thrust = 4651 N (1040lb$_f$)
  - Isp = 32,000 s
  - Mission Duration = 292 days
  - Propellant = 338,399 kg (H_2 & Americium)

Generation I

Generation II & Afterburner



A F F R E

Build Vehicle in LEO, Load LH_2, & Nuc Fuel

11 Launches

Mission 1

Mars Direct Land, Earth Return to LEO

Crew: 1 EELV

Crew 1

\+

Mission 2

Refuel

Mars Direct Land, Earth Return to LEO

Prop: 5 Launches

Crew: 1 EELV

Fuel & Crew 2

\+ • • •

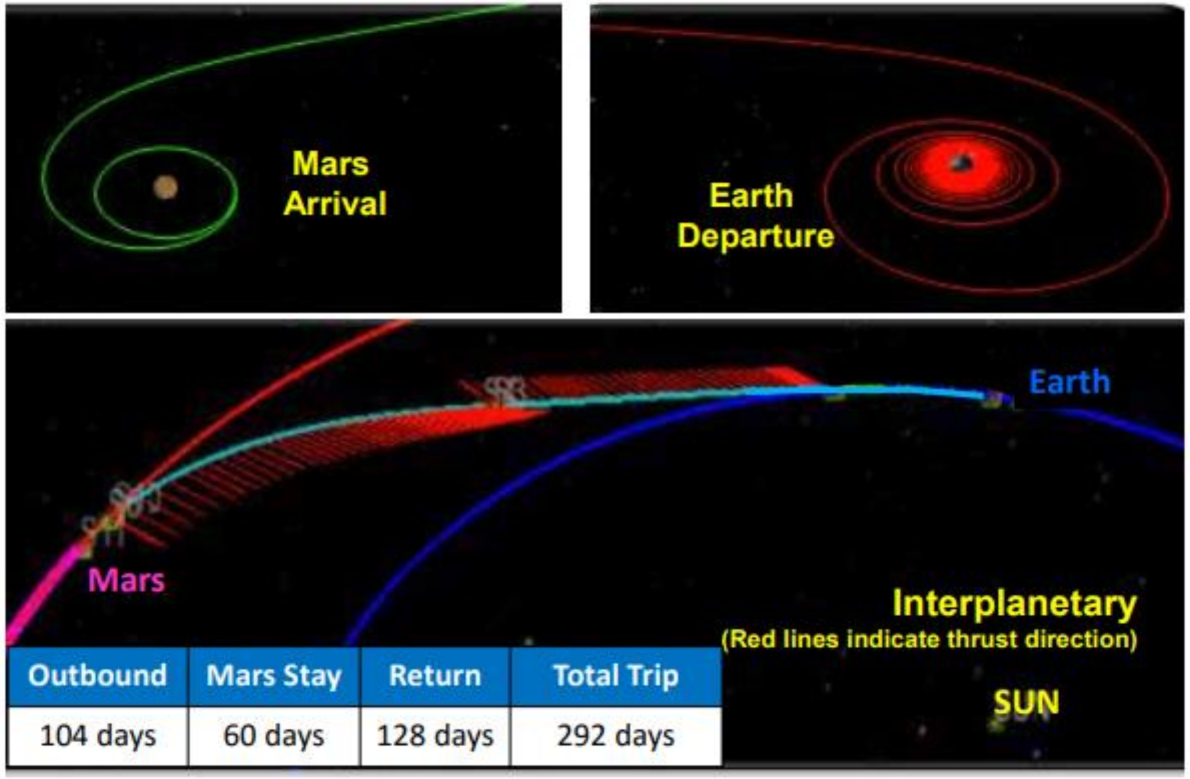
11 SLS Launches to Build & Fuel Vehicle

Each Additional Mission 5 SLS Plus 1 EELV

Direct Mars Entry

Deep Space Duration: ~ 230 days

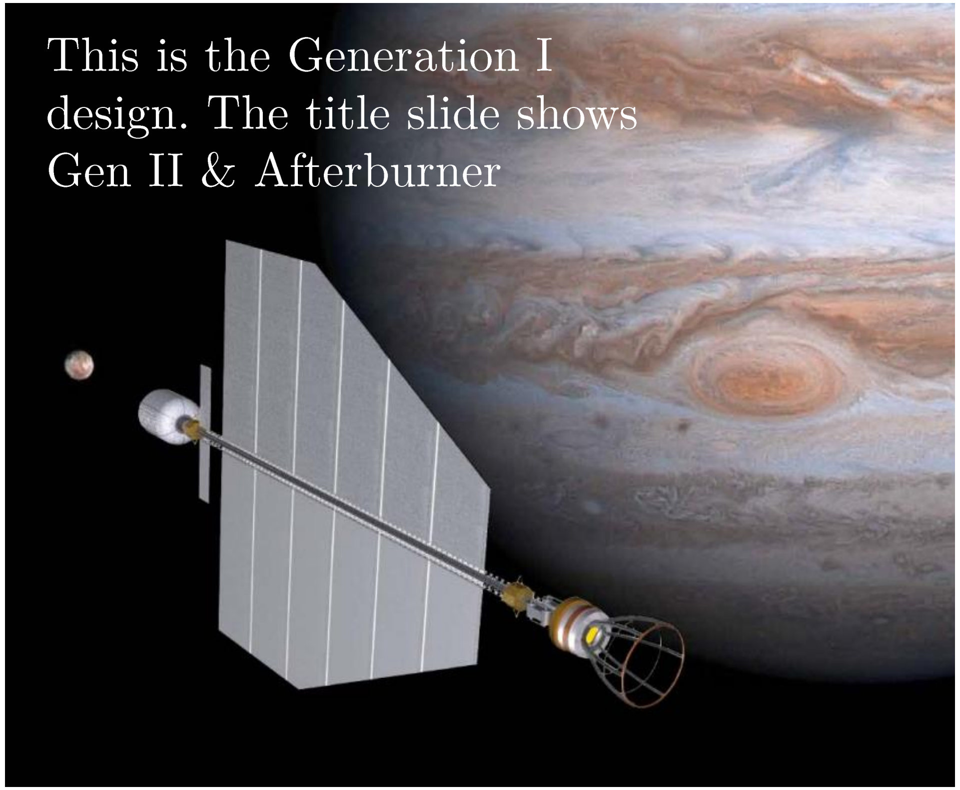
Figure 7-1. AFFRE Mars Architecture-



Outbound	Mars Stay	Return	Total Trip
104 days	60 days	128 days	292 days

Conclusions

1. Fission fragment rocket engines directly expel the products of nuclear fission to produce extremely high Isp, but low thrust
2. This type of engine can simultaneously generate more than enough electricity to supply a spacecraft for long durations
3. The dusty-plasma self cools; meltdown unlikely
4. An "afterburner" configuration (AFFRE) lowers Isp, but increases thrust
5. While this engine has not been funded or created yet, **no new physics or materials** are required for its development
6. Once a spacecraft is constructed in LEO, the vehicle is useable for decades; journey to and from destinations in-tact
7. This engine can likely be further optimized



This is the Generation I design. The title slide shows Gen II & Afterburner