NIAC Spring Symposium

FFRE Powered Spacecraft

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What is NIAC ?

NASA Innovative Advanced Concepts

A program to support early studies of innovative, yet credible visionary concepts that could one day "change the possible" in aerospace

The FFRE

A FISSION FRAGMENT ROCKET ENGINE THAT:

Can free spacecraft from today's propulsion limitations

- Far less propellant than chemical or nuclear thermal.
- Far more efficient than nuclear electric.
- Far safer: charge reactor in space, radioactivity ejected.

Has highest exhaust velocity possible today

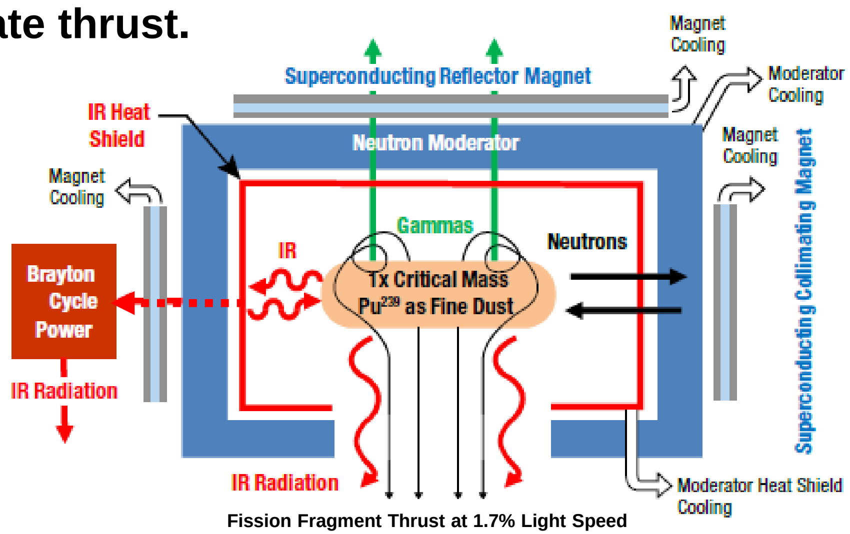
- 10s – 100s lbs of continuous thrust (years).
- Specific impulse above 500,000 s in practical design.

Spacecraft assessment study will reveal these attributes

- Faster travel.
- More payload.
- Nearly unlimited electrical power.
- Greater human safety (mission travel, maintenance).
- No need for vast propellant supply.
- Close-coupled nature of the FFRE & spacecraft.

Principles of FFRE

- Nanometer-sized, slightly critical Plutonium Carbide dust grains suspended and trapped in an electric field. The fission fragments, neutrons and gamma rays that result travel omni-directionally. The dust is radiatively cooled.
- A cooled, deuterated polyethylene moderator reflects sufficient neutrons to keep reacting dust critical through use of control rods.
- A cooled Carbon-Carbon heat shield reflects the dust infrared energy away from the moderator.
- Cooled low temperature superconducting magnets direct fission fragments out of the reactor. However, many fragments collide instead with reactor components and the reacting dust, creating heat.
- Electricity is generated from heat shield coolant using a Brayton Cycle power system
- The hole in the reactor allows escape of much of the heat. The escaping fission fragments, whose velocity is reduced by collisions from 3.4% to 1.7% light-speed, create thrust.



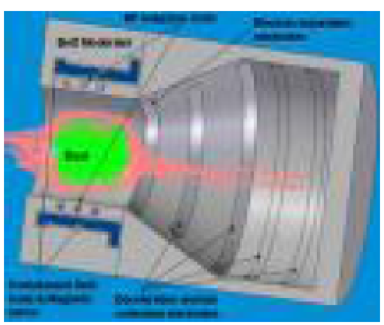
FFRE History

Original Spinning Brush FFRE

1986: George Chapline's "Spinning Brush" FFRE: Uranium coated carbon fiber permits half the fission fragments to escape, providing thrust. The other half heats up so fibers rotated out of reactor to cool.

Grassmere Dynamics Dusty Plasma Reactor

2003: Dr. Rob Sheldon levitated dust in stably trapped plasma by a quadrapole magnetic field with added levitating magnetic field divergence.



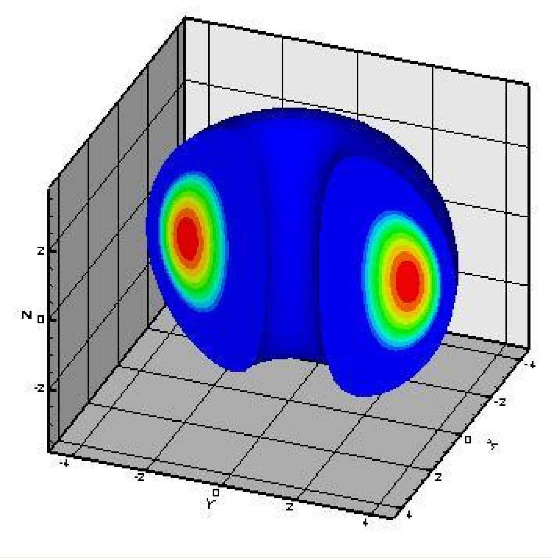
2005: Dr. Rod Clark creates "Dusty Plasma" FFRE: Fissioning uranium dust maximizes both fission fragment escape and radiative cooling, increasing efficiency and permitting reactor operation at Gigawatts of power.

Grassmere Dynamics, LLC

The Company

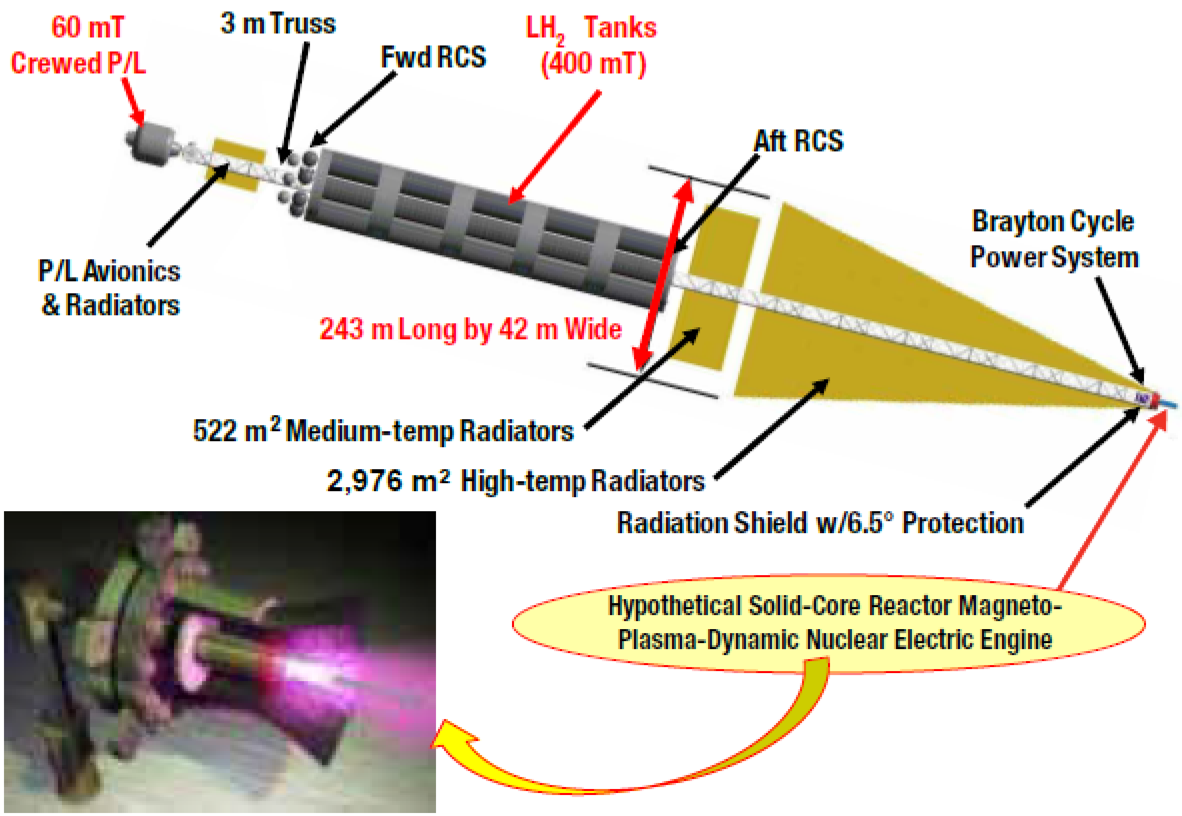
- **Engineering & Consulting**
- **40 Years Of Combined Experience In Engineering Design, Materials, Testing & Quality Assurance.**
- **Specialty Modeling Skills:**
  - Computational Fluid Dynamics (CFD)
  - Magneto Hydrodynamic Plasma (MHD)
  - Nuclear (Radiation, Reactor Design & Performance)
  - Optical

3D Simulation Of Tokomak Nuclear Fusion Reactor Magnetically Confined Plasma Using Grassmere Developed Code

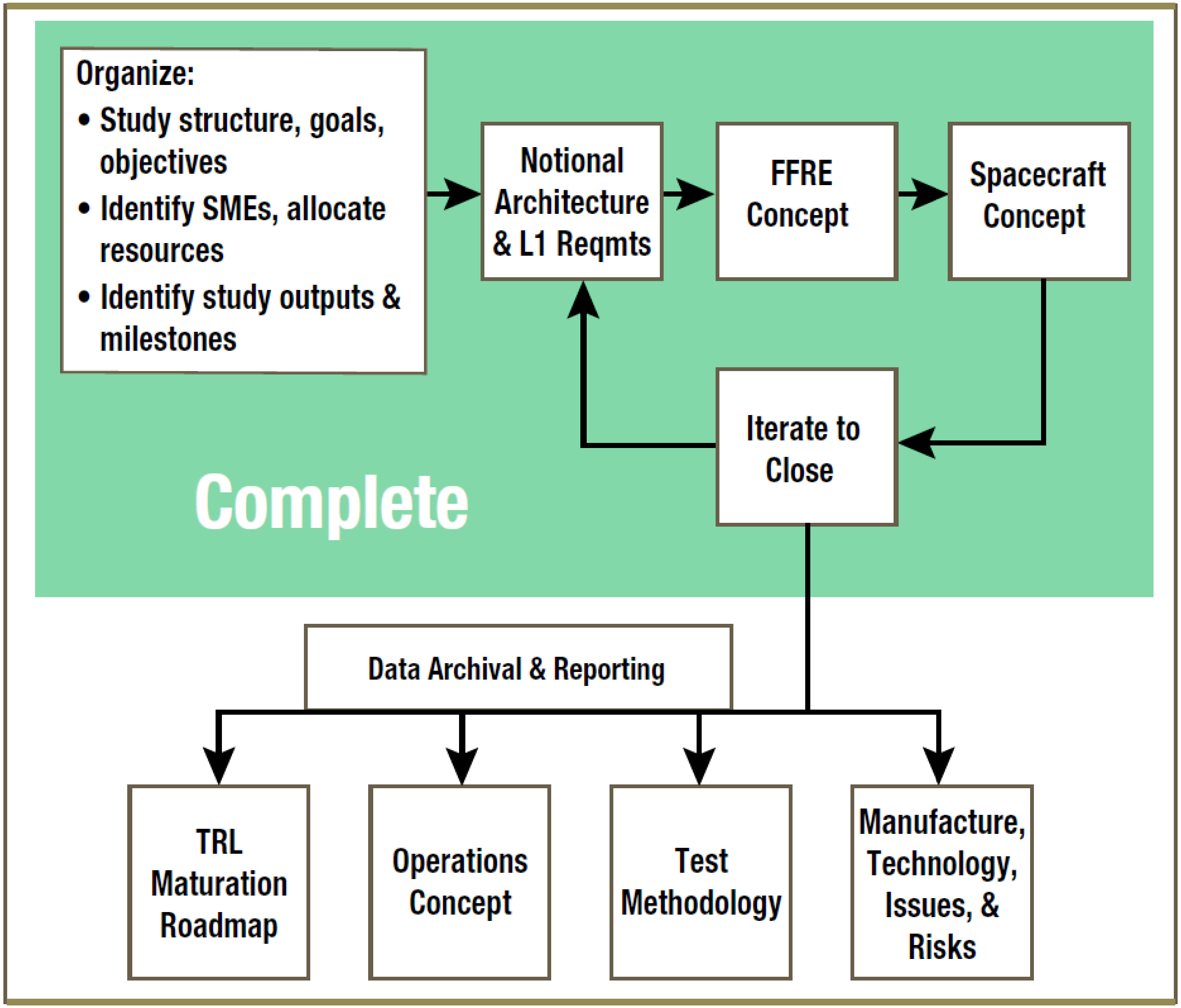


Study Groundrules

- Spacecraft and mission based on 2004 Human Outer Planet Exploration (HOPE) study
  - 60 mT crewed payload on roundtrip mission to Callisto
- Propulsion was hypothetical nuclear electric magneto-plasma-dynamic thrusters (6 NEMPD engines, 33 MW each, providing ~22-lb thrust at 8,000 s delivered I_{sp} using hydrogen as propellant)
  - 1 FFRE substituted for 6 NEMPD engines
- All impacted spacecraft subsystems to be redesigned

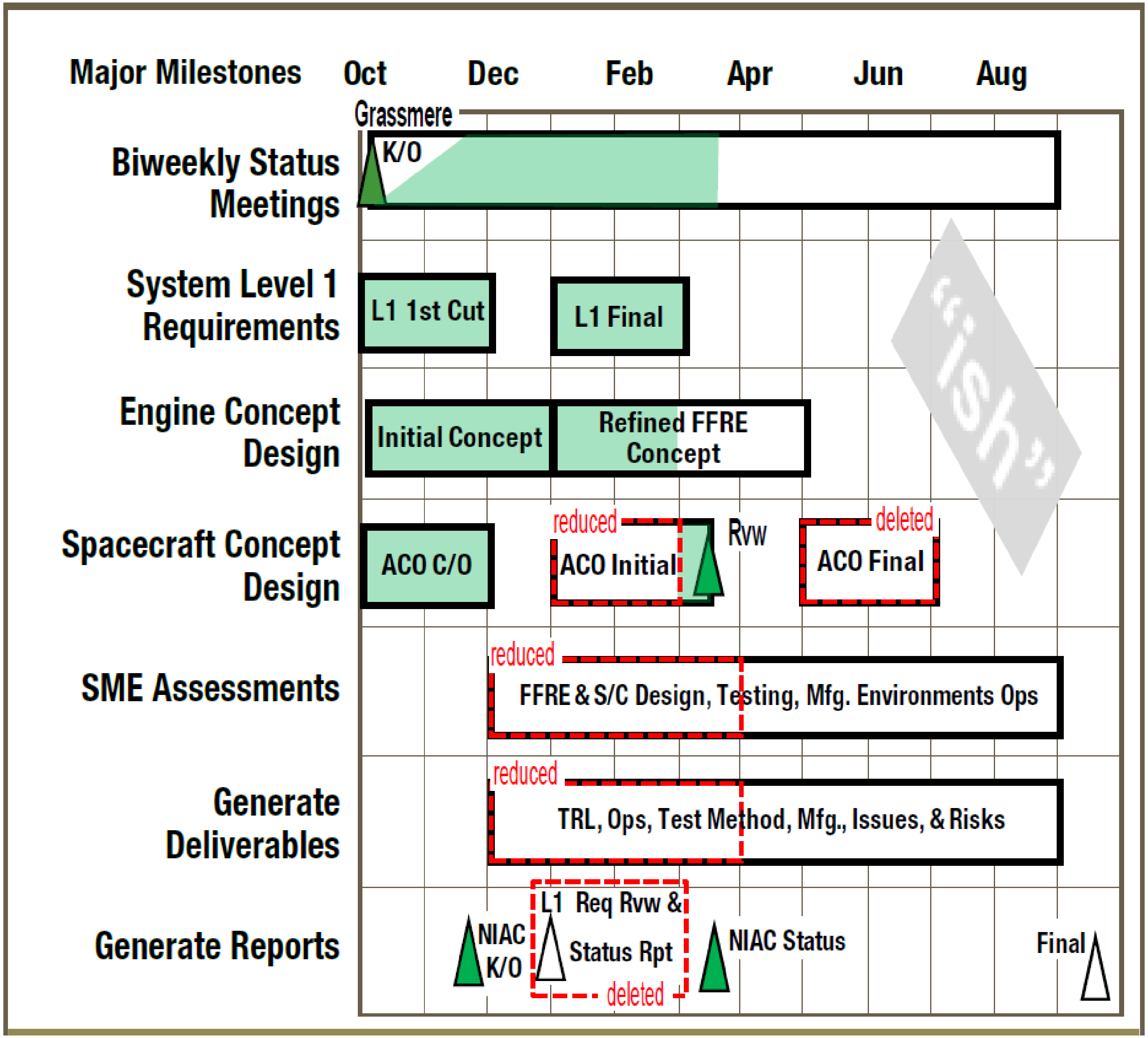


Study Plan



Organize:
• Study structure, goals, objectives
• Identify SMEs, allocate resources
• Identify study outputs & milestones
Notional Architecture & L1 Reqmts
FFRE Concept
Spacecraft Concept
Iterate to Close
Complete
Data Archival & Reporting
TRL Maturation Roadmap
Operations Concept
Test Methodology
Manufacture, Technology, Issues, & Risks

Schedule

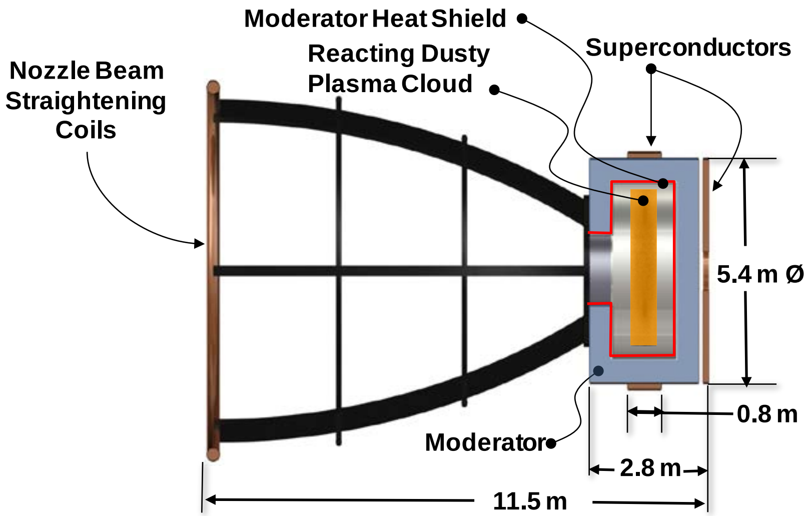

Major Milestones
Oct
Dec
Feb
Apr
Jun
Aug
Grassmere
K/O
Biweekly Status Meetings
System Level 1 Requirements
L1 1st Cut
L1 Final
Engine Concept Design
Initial Concept
Refined FFRE Concept
Spacecraft Concept Design
ACO C/O
reduced
ACO Initial
Rvw
deleted
ACO Final
"ish"
SME Assessments
reduced
FFRE & S/C Design, Testing, Mfg. Environments Ops
Generate Deliverables
reduced
TRL, Ops, Test Method, Mfg., Issues, & Risks
Generate Reports
NIAC K/O
L1 Req Rvw & Status Rpt
deleted
NIAC Status
Final

Forward Work

- Finalize FFRE design, identify potential improvements
- Peer review of FFRE design & technology
- Develop draft FFRE test methodology
- Develop draft FFRE & spacecraft concept of operation
- Identify key issues and risks of FFRE
- Develop preliminary FFRE TRL maturation roadmap
- Document in final report
- Refine FFRE through additional studies & experiments

FFRE Design Status

Base 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

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**

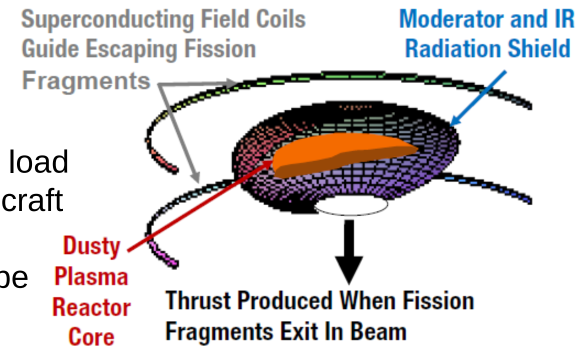
Performance	
Thrust	**43 N** (9.7 lbf)
Exit Velocity	**5170 km/s**
Specific Impulse	**527,000 s**
Mass Flow	**0.008 gm/s**

Revised FFRE Designs

Generation 1

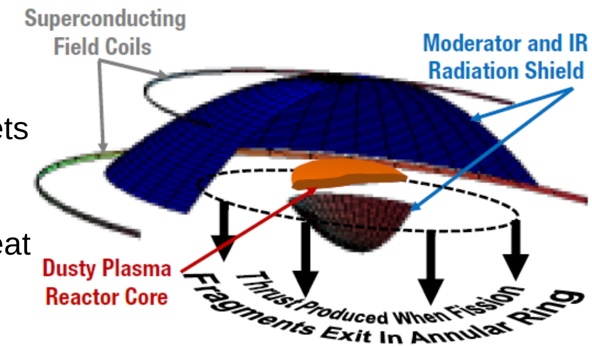
Attributes:
- ❑ Ellipsoid Moderator
- ❑ Ring Magnets

Assessment:
- ❑ Reduced heat load so less Spacecraft radiator mass
- ❑ Complex Shape Moderator
- ❑ Thrust & I_{sp} unchanged



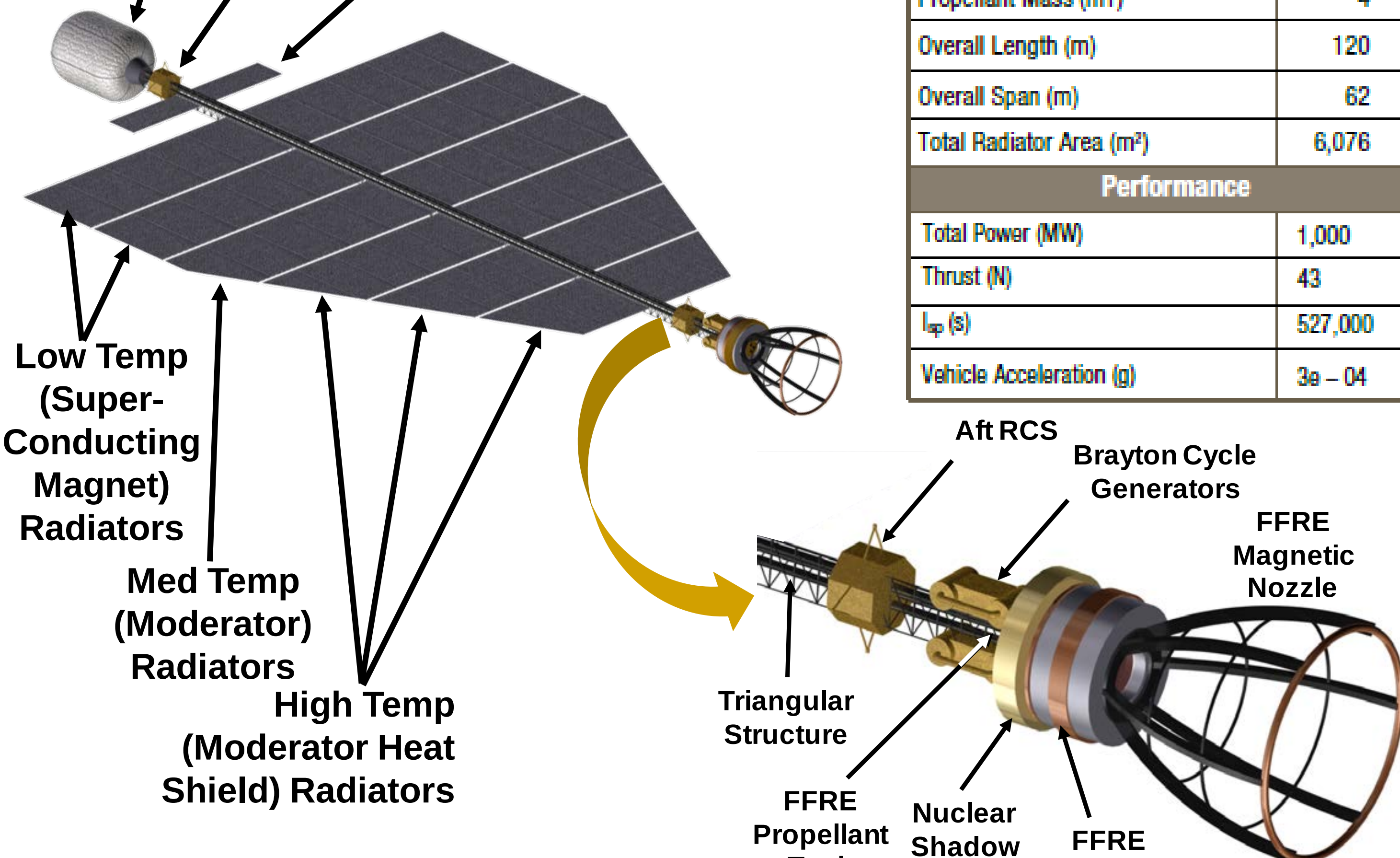
Generation 2

Attributes:
- ❑ Dual Paraboloid Moderator
- ❑ Ring Magnets



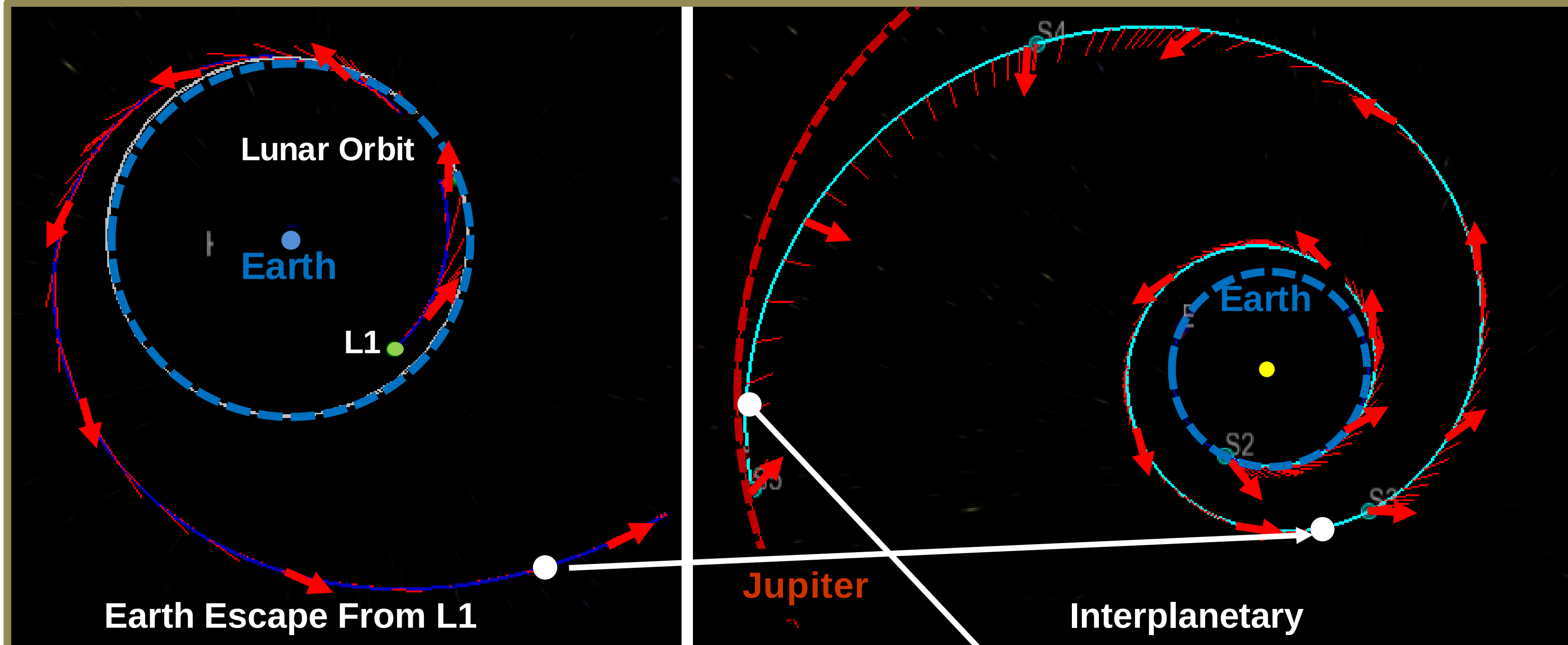
Assessment:
- ❑ Reduced heat load so less Spacecraft radiator mass
- ❑ Complex shape moderator, difficult to support & cool, weighs more
- ❑ Thrust: 2X (86 N, 19 lbf)
- ❑ I_{sp} unchanged (527,000 s)

Spacecraft Concept Overview



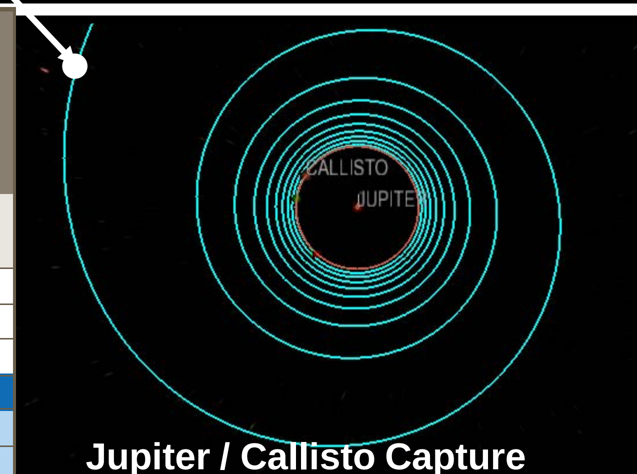
Vehicle	
Payload (Crew/Science Equip.) (mT)	60
Total Mass (mT)	303
Dry Mass (mT)	295
Propellant Mass (mT)	4
Overall Length (m)	120
Overall Span (m)	62
Total Radiator Area (m^2)	6,076
Performance	
Total Power (MW)	1,000
Thrust (N)	43
I_{sp} (s)	527,000
Vehicle Acceleration (g)	3e – 04

Spacecraft Performance
(First FFRE / Spacecraft Assessment)



Intitial FFRE Propelled Spacecraft Mission Performance
1st Generation FFRE: 43 N Thrust 527.000s I_{sp}
Spacecraft is acceleration limited

Outbound Trajectory Results	Segment Time (Days)	Thrust Time (Days)	CUM Nuclear Prop (Kg)
Earth Spiral — Out	55	55	40
Interplanetary	2,106	2,161	1,553
Jupiter Spiral — In	503	2,665	1,915
Stay Time at Callisto: ~330 Days			
Total Elapsed Mission Time	5,850 Days (16.0 Years)		
Total Nuclear Fuel Used	4 mT		



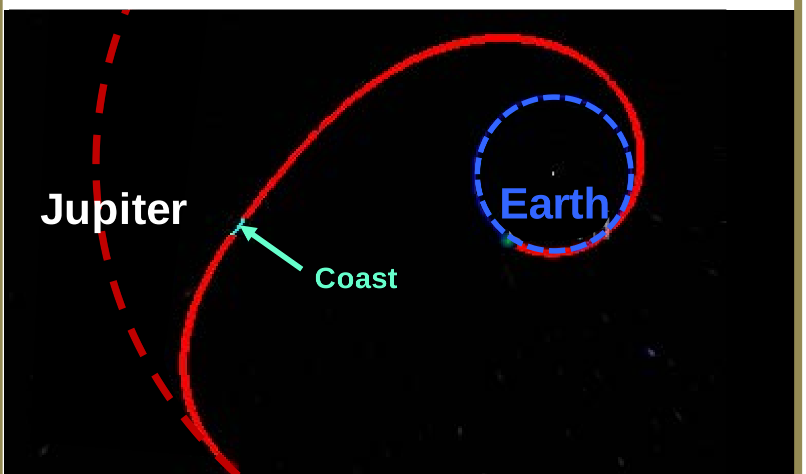
Performance Trades

Effect on Mission Of 2nd Generation FFRE Design

FFRE
- ❑ Thrust: 2X (86N)
- ❑ I_{sp}: 527,000s

Spacecraft
- ❑ Assumed no change (conservative)

Mission
- ❑ ~8 years round trip
- ❑ Spiral out and in times halved
- ❑ Small coast period in interplanetary flight
- ❑ Propellant: ~4 mT nuclear

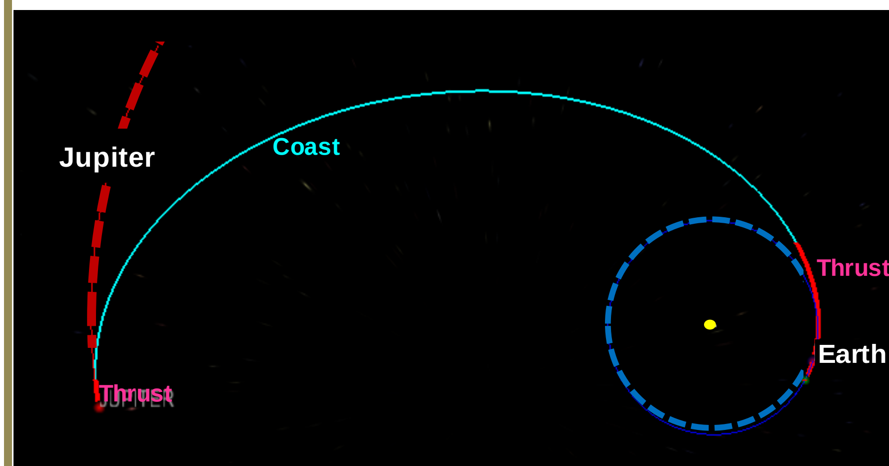


Effect on Mission Of Adding an "Afterburner" to FFRE Design

FFRE
- ❑ Fission fragments accelerate an inert gas added to nozzle via friction, adding thrust & decreasing specific impulse
- ❑ Thrust: 430N, I_{sp}: 52,700s (notional)

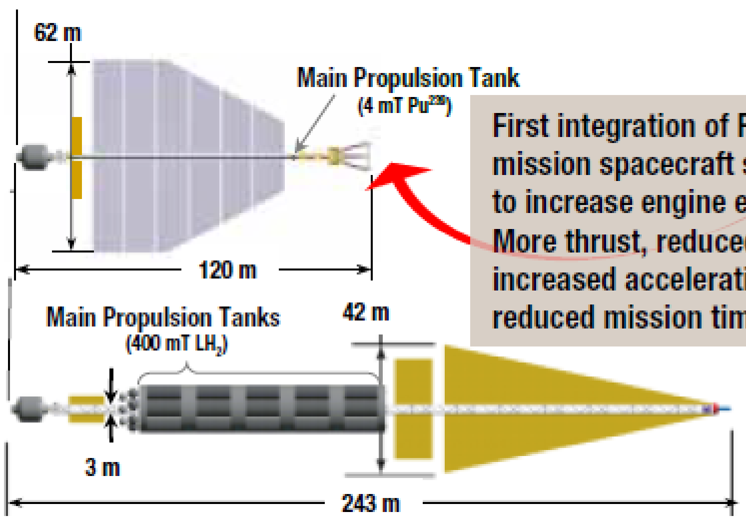
Spacecraft
- ❑ Added "propellant" and tankage

Mission
- ❑ ~6 years round trip
- ❑ From Earth: 4 days, Into Jupiter: 40 days
- ❑ Interplanetary Coast: 950days
- ❑ Propellant: 0.3mT nuclear, 22mT gas



Spacecraft Comparison

Vehicle	HOPE	FFRE
Payload (Crew/Science Equip) (mT)	60	60
Total Mass (mT)	890	303
Dry Mass (mT)	460	295
Propellant Mass (mT)	400	4
Overall Length (m)	243	120
Overall Span (m)	42	62
Total Radiator Area (m^2)	3498	6,076
Performance	**HOPE**	**FFRE**
Total Power (MW)	34	1,000
Thrust (lbf)	126	9.7
I_{sp} (s)	8,000	527,000
Vehicle Acceleration (g)	14e-4	3e-4
Outbound Trip Time (days)	833	2,665
Return Trip Time (days)	693	2,854
Total Mission (years)	HOPE 4.5yrs?	8-16 yrs



First integration of FFRE & mission spacecraft shows need to increase engine efficiency: More thrust, reduced mass, increased acceleration, & reduced mission time.

What Is Learned So Far

- ❑ A FFRE is credible – ordinary engineering, ordinary physics. NO MIRACLES.
- ❑ A FFRE-propelled spacecraft is game changing to travel in space. A spacecraft with a heavy payload can depart for and return from many solar system destinations. NO REASSEMBLY REQUIRED.
- ❑ Our first constructs of a FFRE are grossly inefficient. We are like a Ford Model T engine. Only a few ways of improving performance of the FFRE and spacecraft have been considered.

THERE'S MUCH WORK TO DO.