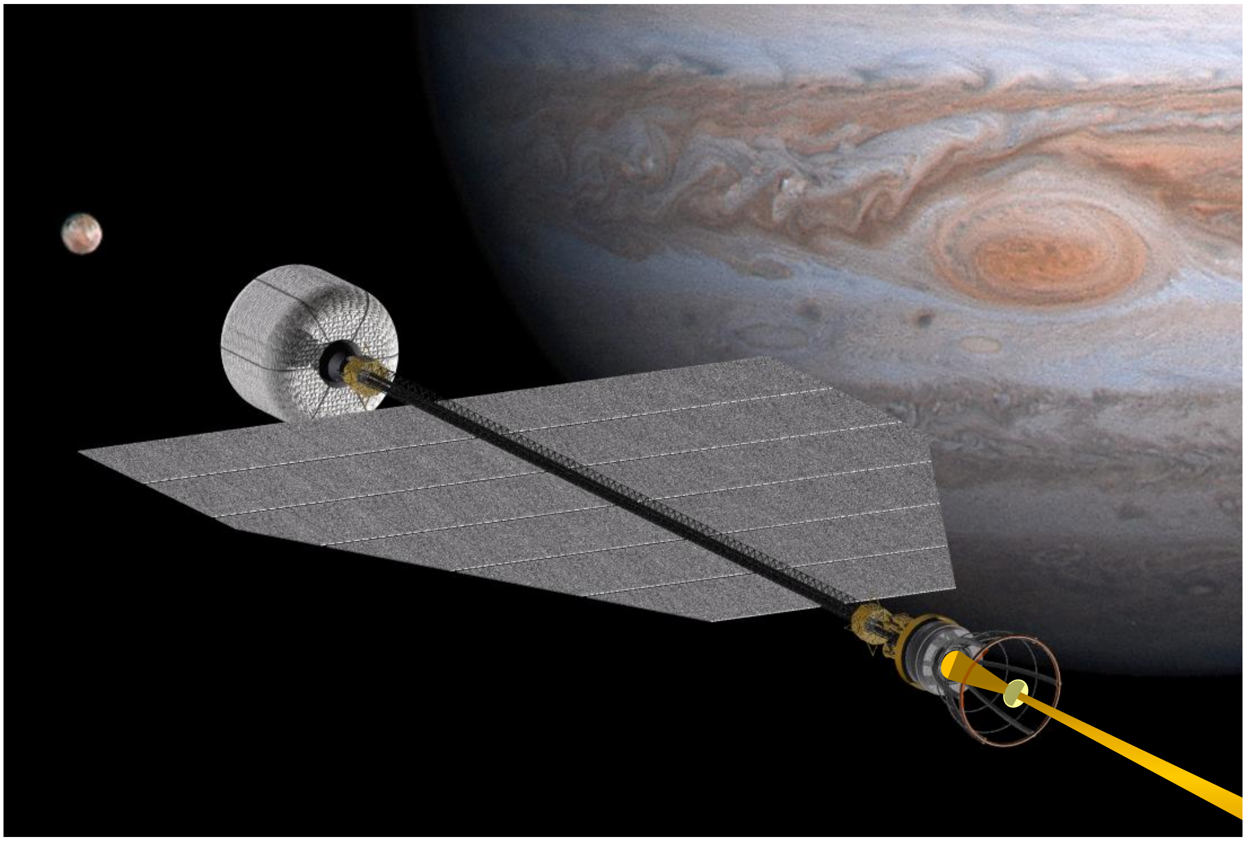
Final Report: Concept Assessment of a Fission Fragment Rocket Engine (FFRE) Propelled Spacecraft

FY11 NIAC Phase 1 Study
15 Aug, 2011 To 30 Sep, 2012

Robert Werka
Principal Investigator, MSFC EV-72

Rod Clark & Dr. Rob Sheldon
Grassmere Dynamics Co-Investigators

Tom Percy
SAIC Technical Support, Spacecraft



Acknowledgements

As the Principal Investigator, I wish to thank the team, and am sincerely grateful, for all the help, study, advice and review of this truly novel, game changing technology and its application to an otherwise ordinary spacecraft. The NIAC Program was instrumental in nurturing this effort and the opportunity to share our progress through forums could only have been done with the leadership of Dr. Jay Falker (HQ-UA000). The FFRE geniuses of Grassmere Dynamics who created this engine for the first time spent many hours, including their own time, in the complex effort to create, analyze, design, estimate performance and figure out how a real engine could be developed and tested. There were only two of these nuclear geniuses, Rod Clark and Dr. Rob Sheldon, but they did the work of an army. The Advanced Concepts Office hosted a team led by Tom Percy (ED-04) that created a "New Discovery" spacecraft in a matter of a few weeks by reusing old studies married to new ideas. I also need to thank Dr. Mike Houts (ZP31), Dr. Bill Emrich (ER24) and Harold Gerrish (ER20) for providing nuclear expert support and advice when we needed it most.

Team

Role	Name (Organization)
Customer/Principal Investigator	Bob Werka (MSFC)
Study Co-Leads	Tara Polsgrove (MSFC) Tom Percy (MSFC)
FFRE Engine Concept	Rod Clark (Grassmere) Rob Sheldon (Grassmere)
GR&A and Mass Summary	Dauphne Maples (MSFC)
Mission Analysis	Randy Hopkins (MSFC)
Power Systems	Leo Fabisinski (MSFC)
Thermal Analysis	Linda Hornsby (MSFC)
Structural Analysis	Janie Miernik (MSFC)
Configuration Design	Mike Baysinger (MSFC)

Dedication to Ms. Debra Clark

I would like to dedicate this study to the memory of a treasured compatriot, team member and the president of Grassmere Dynamics, Ms Debra Clark. Her sudden accidental death in September saddened us all and she will truly be missed.

1. Executive Summary


March 2012

AEROSPACE AMERICA

REAL ESTATE IN FREQUENCY SPACE

Viewpoint

The ephemeral ’advanced propulsion’

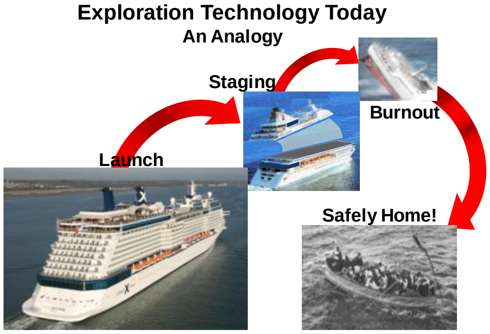
New technologies with the promise of more affordable, more efficient, and safer propulsion for space launch currently seem to be out of reach. That however, does not mean that we should stop searching

“. . . . All in all, the near-to-medium prospects for applying ‘advanced propulsion’ to create a new era of space exploration are not very good. “

by *Jerry Grey*
Editor-at-Large

24 AEROSPACE AMERICA/MARCH 2012

The March, 2012 issue of Aerospace America stated that “the near-to-medium prospects for applying ‘advanced propulsion’ to create a new era of space exploration are not very good”. In the current world, we operate to the Moon by climbing aboard a Carnival Cruise Lines vessel (Saturn 5), sail from the harbor (liftoff) shedding whole decks of the ship (staging) along the way and, having reached the return leg of the journey, sink the ship (burnout) and return home in a lifeboat (Apollo capsule). Clearly this is an illogical way to travel, but forced on Explorers by today’s propulsion technology. However, the article neglected to consider the one propulsion technology, using today’s physical principles that offer continuous, substantial thrust at a theoretical specific impulse of 1,000,000 sec. This engine unequivocally can create a new era of space exploration that changes the way spacecraft operate.



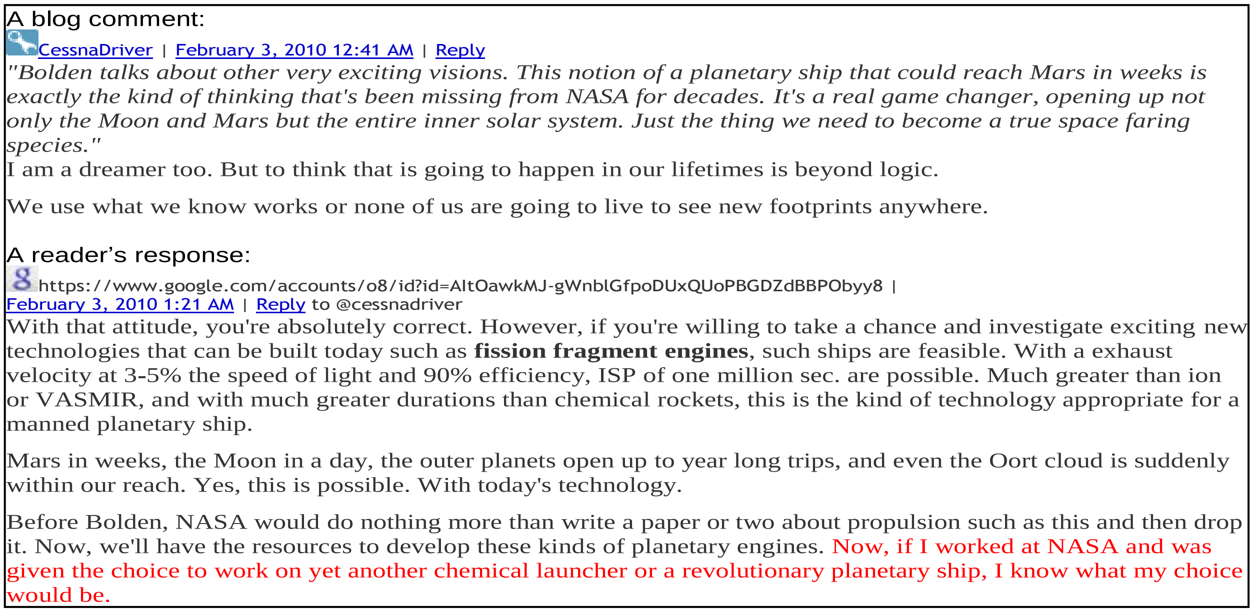
Why Would You Want To Explore Like This?

Today’s space Explorers could travel in Cruise Liner fashion using the technology not considered by Aerospace America, the novel Dusty Plasma Fission Fragment Rocket Engine (FFRE). This NIAC study addresses the FFRE as well as its impact on Exploration Spacecraft design and operation. It uses common physics of the relativistic speed of fission fragments to produce thrust. It radiatively cools the fissioning dusty core and magnetically controls the fragments direction to practically implement previously patented, but unworkable designs. The spacecraft hosting this engine is no more complex nor more massive than the International Space Station (ISS) and would employ the successful ISS technology for assembly and check-out. The elements can be lifted in “chunks” by a Heavy Lift Launcher. This Exploration Spacecraft would require the resupply of small amounts of nuclear fuel for each journey and would be an in-space asset for decades just as any Cruise Liner on Earth.

This study has synthesized versions of the FFRE, integrated one concept onto a host spacecraft designed for manned travel to Jupiter’s moon, Callisto, and assessed that round trip journey. This engine, although unoptimized, produced 10 lbf of thrust at a delivered specific impulse of 527,000 sec for the entire 15 year mission while providing enormous amounts of electrical power to the spacecraft. A payload of 60 mT, included in the 300 mT vehicle, was carried to Callisto and back; the propellant tanks holding the 4 mT of fuel were not jettisoned in the process. The study concluded that the engine and spacecraft are within today’s technology, could be built, tested, launched on several SLS (or similar) launchers, integrated, checked out, moved to an in-space base such as at a Lagrange point and operated for decades.

2. Introduction

The Constellation Program and the Exploration dreams were being terminated in February of 2010. NASA Administrator Bolden held a news conference that outlined *"the Administration's fiscal year 2011 budget request as the agency's road map for a new era of innovation and discovery".* I read readers' comments about this article at a website devoted to tracking NASA activities (nasawatch.com). I found two comments that astounded me as a professional propulsion person. I have highlighted key text in red for emphasis:



A blog comment:

CessnaDriver | February 3, 2010 12:41 AM | Reply

"Bolden talks about other very exciting visions. This notion of a planetary ship that could reach Mars in weeks is exactly the kind of thinking that's been missing from NASA for decades. It's a real game changer, opening up not only the Moon and Mars but the entire inner solar system. Just the thing we need to become a true space faring species."

I am a dreamer too. But to think that is going to happen in our lifetimes is beyond logic.

We use what we know works or none of us are going to live to see new footprints anywhere.

A reader's response:

https://www.google.com/accounts/o8/id?id=AItOawkMJ-gWnblGfpoDUxQUoPBGDZdBBPObyy8 |
February 3, 2010 1:21 AM | Reply to @cessnadriver

With that attitude, you're absolutely correct. However, if you're willing to take a chance and investigate exciting new technologies that can be built today such as **fission fragment engines**, such ships are feasible. With a exhaust velocity at 3-5% the speed of light and 90% efficiency, ISP of one million sec. are possible. Much greater than ion or VASMIR, and with much greater durations than chemical rockets, this is the kind of technology appropriate for a manned planetary ship.

Mars in weeks, the Moon in a day, the outer planets open up to year long trips, and even the Oort cloud is suddenly within our reach. Yes, this is possible. With today's technology.

Before Bolden, NASA would do nothing more than write a paper or two about propulsion such as this and then drop it. Now, we'll have the resources to develop these kinds of planetary engines. Now, if I worked at NASA and was given the choice to work on yet another chemical launcher or a revolutionary planetary ship, I know what my choice would be.

I chose to investigate. Clueless about fission fragment engines, I "Googled" the subject and discovered the physics was straightforward and a natural occurrence of any fission event. The idea had been patented in 1986 and a 2005 paper[1] had been written by Huntsville nuclear contractors that claimed an affiliation with MSFC. This paper, devoid of design details, postulated the same game changing-to-spaceflight paradigm claimed by the blogger. Contacting these contractors and their NASA supervisor eventually led to a proposal that resulted in a Marshall Center Innovation Fund award to study the basic physics of fission fragment engines. Collaboration with these contractors resulted in a successful NIAC Phase 1 award, reported here.

This NIAC study had the goals of creating a FFRE design from which functional and physical attributes could be assessed, a spacecraft created whose attributes could be defined, and a typical mission evaluated. In addition, various assessments were projected:

- Manufacture of the nuclear fuel, storage on the spacecraft and delivery to the engine
- FFRE Technology issues and risks
- How engine testing might be accomplished
- How the engine might be operated
- FFRE Technology Readiness Level and ideas on a TRL Maturation Roadmap
- Spacecraft technology issues, risks, environmental concerns and HLV requirements.

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[1] Dusty Plasma Based Fission Fragment Nuclear Reactor, R. Clark and R. Sheldon, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference, July 10-13, 2005.

All the aforementioned groundbreaking areas were to be completed for the bargain price of $120,000 within a 12 month window. Many of the assessments have received sparse attention due to other (non-NIAC) priorities. However, significant progress was made in the key areas of model development and the understanding of the interdependence of engine geometry and the resulting performance, as well as spacecraft attributes. By the March 2012 "NIAC Spring Symposium" held in Pasadena, sufficient detail was generated to conclude that a spacecraft propelled by even the least robust FFRE enabled an architecture that departed from today's norms and was exactly like the game-changing vision of journeys to distant worlds in a vessel of a "Space Navy[2]" that is being advocated by Dr. Paul Spudis. This spacecraft, a Space Navy vessel constructed like ISS, becomes a permanent round-trip in-space asset. For each mission, there is no need for resupply of vast quantities of propellants and expendable tanks as is the case for VASIMR, Nuclear Thermal or chemical propulsion systems, only the resupply of consumables.

3. Study Requirements

Distribution of the study budget restricted primary study focus to financing development of the initial engine concept and predicting its attributes. This meant only a small amount of the budget was available for assessments and for design of the spacecraft to host the engine. Fortunately, cost savings were possible because the Advanced Concepts Office of MSFC had already studied other planetary missions using futuristic engine concepts. The requirements of their 2003 Human Outer Planets Exploration study[3] formed the basis for the requirements for this study.

The overarching requirement of the HOPE study, adopted likewise for this study, was to launch a crewed vehicle from the Earth-Moon Lagrange Point 1 (L1), travel to an outer solar system destination, conduct research and exploration, and then return safely to L1. The destination chosen was the Jovian moon Callisto, selected because of the balance of scientific interest, vehicle design challenge severity, and the level of hazard to human operations posed by the local environment. The mission roundtrip duration was for less than 2000 days, of which the destination stay-time was 120 days. The mission date was planned for after January, 2040.

The FFRE study maintained compatibility with the HOPE MagnetoPlasmaDynamic-propelled (MPD) vehicle concept as much as possible. The spacecraft was assumed to be launched in major sections using multiple heavy lift launch vehicles, assembled in space and transported to its base at L1. The six-pack of hypothetical HOPE MPD engines and supporting subsystems were replaced with one FFRE and its supporting subsystems.

The remaining vehicle subsystems (reaction control, structures, thermal control, Brayton cycle power generator) were resized to close the vehicle design. The payload of the HOPE vehicle, a manned Transhab module, had a mass of about 40 mT, contained an additional 4 mT of consumables and included about 2 mT of cooling radiators. A mass growth allowance (MGA) applied to all mass estimates, including the payload, was 30 percent.

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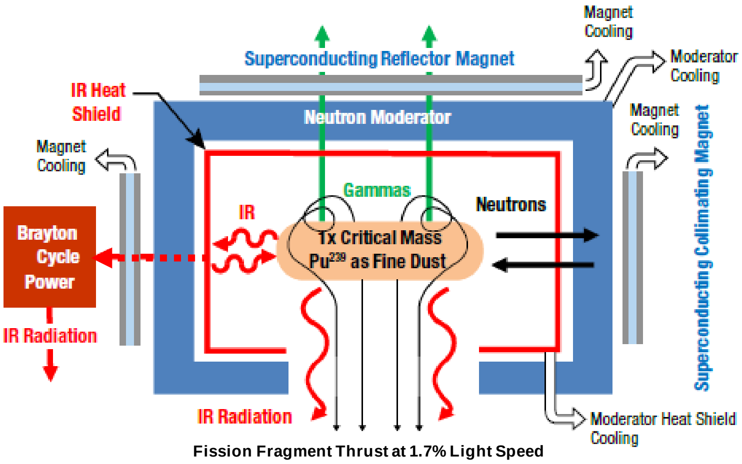
[2] Let's Argue About The Right Things, P. Spudis, Air & Space Magazine, September 17, 2011.

[3] Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets, R. Adams, R. Alexander et. al., NASA/TP—2003–212691, NASA/MSFC, November 2003.

4. Design: The Generalized FFRE Concept

The products of fission reactions are normally trapped inside a reactor, producing heat that is converted to electricity. This electricity, stepping through the inefficiencies, is used to produce thrust (in VASIMR or a Hall thruster, for example). The design of a FFRE, instead, allows these same heavy fission products to escape from the reactor, traveling at up to 5% of light speed. Theoretically, heavy fission products traveling at up to 5% of light speed produce thrust at a specific impulse of one million seconds (over 200 times better than electric engines). The efficiency of a FFRE, as measured by the quantity of fission fragments that escape as a beam rather than remain inside the reactor and produce waste heat, in this study was about 11%.

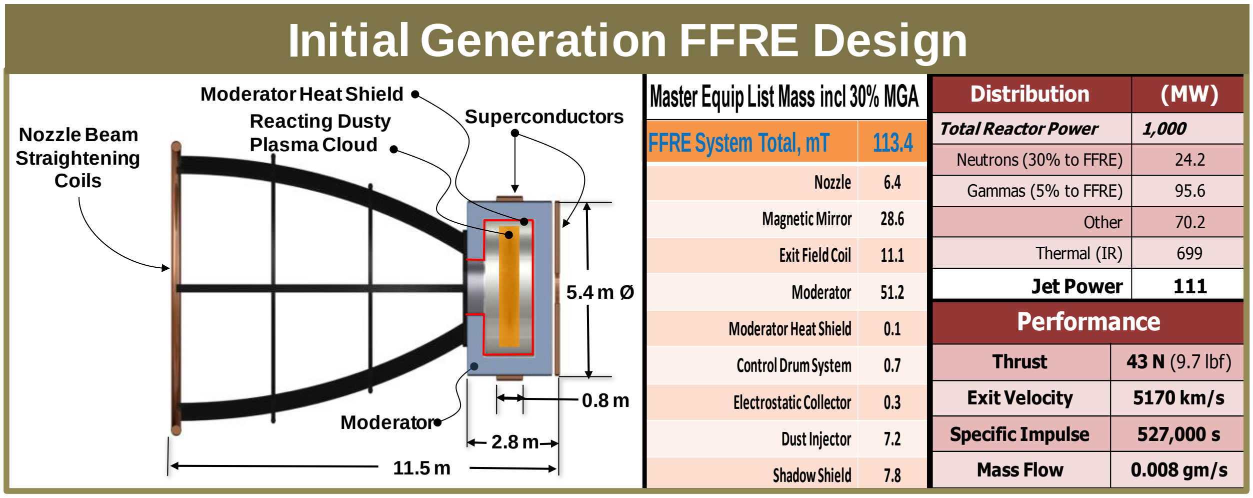
A conventional nuclear reactor contains large fuel rods that last for years containing a fissionable element (Uranium 235 for example) that is bound in a metal matrix, clad with a coating, and surrounded with coolant that wicks off the heat and converts this heat to electricity. The radioactive fission fragments collide with other atoms in the rod, accumulating and causing the fuel element to eventually "poison" (halt) the fuel fissions. To overcome this poisoning effect, the core needs an excess of nuclear material beyond that required for criticality. Nonetheless, these highly radioactive fuel rods must be eventually replaced in order to continue operation.



Unlike the fuel rods of a typical reactor, the FFRE reactor core consists of sub-micron sized fissioning dust grains that are suspended and trapped in an electric field. The amount of dust is only sufficient for a short period of critical operation and must be continuously replenished. The fission fragments that remain in the core collide with dust grains. These collisions, along with the thermal energy released by the fission events, create intense heat in the dust. Since there is no core cooling flow, the power of the FFRE is limited to the temperature at which the dust is able to radiatively cool without vaporizing. The cavity in which the dust resides is open to the vacuum environment; the loads on the engine are thermal, not pressure. Surrounding the dusty core is a mirror finish heat shield that reflects 95% of the thermal energy. The residual heat is wicked to a radiator and the heat rejected to space. The moderator maintains criticality of the core by converting fast fission event neutrons into slower speed thermal neutrons ("cooling") and reflecting them back into the core. This moderator also needs a radiator to maintain its operating temperature. A hole in the moderator allows a fraction of the fission fragments to escape as directed by surrounding intense magnetic fields. The performance and attributes of the FFRE depend significantly on the geometric shape.

Design: The "Initial Generation" FFRE

The following discussion, supported by Appendix A data, relates to the "Initial Generation" FFRE. This configuration resembles a tuna can in which resides a thin, disc-shaped cloud of fissioning dust. The overall dimensions are 5.7 m in diameter and less than 3.0 m in height. The moderator has a bore hole in the base 2 m in diameter for fission fragment escape through a magnetic nozzle. The physical geometry and performance parameters are displayed below.



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

The sub-micron sized dust, composed of Uranium Dioxide, melts at over 3000 Kelvins and enables operating the FFRE at a power of approximately 1000 MW thermal. Fission fragments that travel forward, rather than aft, are reflected by the superconducting mirror magnet and pass twice through the core on their way to escape. This "double jeopardy" reduces the fraction that escapes and reduces the average exhaust velocity to about 1.7 percent. This FFRE configuration was estimated to produce almost 10 lbf of thrust at a delivered specific impulse of 527,000 seconds. As a result, Uranium consumption is approximately one ounce every hour. Of the 1000MW produced, about 700 MW of power is dumped to space as IR radiation directly and to space through very large radiators on the spacecraft.

A moderator reflects sufficient neutrons to keep reacting dust critical. The reaction rate is adjusted by conventional control rods embedded in the moderator. The reactor "neutronics" must balance a dust density with a moderator geometry that sustains core criticality while providing a bore hole size that allows for sufficient fission fragment escape. The moderator is protected from the core thermal radiation by an actively cooled Carbon-Carbon heat shield and additionally is cooled by active pumped cooling flow. This coolant flow is first passed through a Brayton power conversion system to extract electrical power for general spacecraft use. Mass of the moderator subsystem is about 52mT including 30 percent Mass Growth Allowance (MGA)

The fission fragments emanate from their fission sites in all directions. These must be turned to escape through the hole in the moderator. Despite their relativistic speed, the trajectories of the fission fragments can be controlled through the use of high field strength magnets. These electromagnets are made of materials called high-temperature superconductors that require active cooling flow and large radiators to maintain their performance in the presence of the fissioning core environment. At the forward end of the engine in the "Initial Generation" configuration is a mirror magnet that reflects the fission fragments back through the core toward the hole in the moderator. This magnet is the second heaviest engine component, weighing almost 30 mT including MGA. Surrounding the moderator cylindrical surface is the collimating magnet that deflects the remaining fragments toward the same hole. This magnet weighs over 10 mT.

The beam of fission fragments is electrically charged, relativistic, radioactive grit. The beam must be carefully managed since contact would result in near-instantaneous erosion of any material. As a result, a nozzle is employed to magnetically keep the beam straight and to electrically neutralize the charge of the fragments so that no contact with the spacecraft occurs. This structure, nearly 30 feet tall, is estimated to weigh over 6 mT.

FFRE Physics

This section can be found in Appendix A.

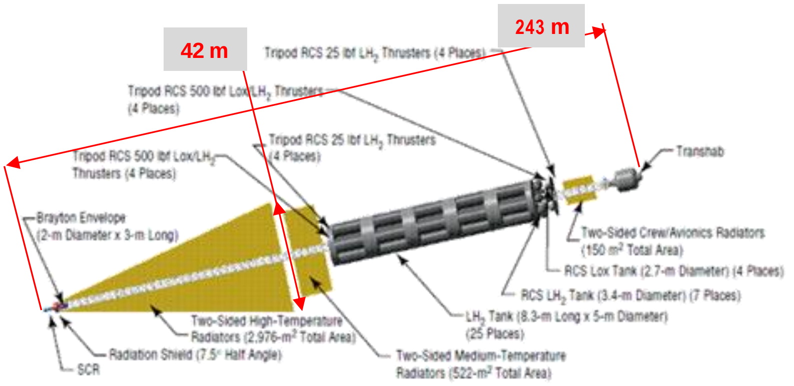
FFRE Physical Design Trades

This section can be found in Appendix A.

5. Design: Spacecraft Concept

Spacecraft Legacy

The NIAC study profited from a direct comparison of design and performance to those of previously conducted studies. The Revolutionary Aerospace Systems Concepts (RASC) program of 2003 provided high performance space vehicles intended for Human Outer Planet Exploration missions (HOPE, see reference 3). The destination chosen for the HOPE study was a manned round trip to Callisto with 60 mT (including 30% mass margin) of round trip payload.



HOPE MPD-Propelled Spacecraft For Callisto Mission

	HOPE
Total Mass (mT)	890
Dry Mass (mT)	460
Overall Length (m)	243
Overall Span (m)	42
Total Radiator Area (m^2)	3,498
Total Power (MW)	34
Jet Power (MW)	22
Thrust (lbf)	126.00
Specific Impulse (s)	8,000
Outbound Trip Time (days)	833
Return Trip Time (days)	693
Total Mission Duration (days)	1,658
Total Mission Duration (years)	4.5

Such high payload mass, revolutionary human exploration concepts employed various hypothetical propulsion technologies including a variety of nuclear electric propulsion such as the MagnetoPlasmaDynamic (MPD) nuclear electric engine. For the purposes of the NIAC study, the team elected to compare a FFRE-propelled version of the MPD-propelled spacecraft on the same HOPE mission since there was ample data available to make the necessary vehicle design adjustments and to provide detailed comparisons. The general summary of the concept vehicle configuration is provided above. The full report by the Advanced Concepts Office is included as Appendix B.

As a result of using the large Initial Generation FFRE for propulsion and its waste heat for electrical power, the HOPE spacecraft was extensively modified. Subsystems of the HOPE vehicle that were retained include the Transhab-like crew/payload section, the avionics and its radiators, the 3 m cross section structural truss spine and the pair of Brayton-cycle electrical power generation system units. Subsystems modified include the reaction control system (converted from LOx/LH_2 to hypergolic propellants, the high temperature and the medium temperature radiators (replaced with three separate temperature radiators) and the nuclear radiation shield (expanded in size for the larger FFRE reactor). Subsystems discarded include the 400 mT of liquid hydrogen and the propellant tanks (replaced with small containers holding the nuclear fuel dust in liquid suspension), the nuclear power reactor and the MPD engines (both replaced by the single FFRE). Using the same Ground Rules and Assumptions as the HOPE study, the new spacecraft was iteratively resized and the trajectory flown until the design closed.

Subsystem Attributes: Payload (Crew Habitat and Avionics)

The payload components of the manned HOPE vehicle consist of a Transhab module, spacecraft avionics and radiators for crew and electronics waste heat. These components are responsible for providing a habitable environment on the vehicle. The inflatable Transhab, approximately the “floor space” of a 4000 sq. ft. 4-story house, forms the main living quarters for the six crewmembers. This module, approximately 12 m in diameter and 10 m in length with an airlock at the forward end, has a mass (including 30 percent MGA) of about 52mT and contains an additional 6 mT of consumables.

Subsystem Attributes: Structure

The structure is composed of a simple 2024 aluminum hexagonal truss weighing about 125 kg per meter and spanning about 92 m. This lightweight structure is only feasible for the in-space environment and the low acceleration delivered by the FFRE. Secondary structure was estimated at 10 percent of the component masses attached. The radiation “shadow shield” is sited just ahead of the FFRE and forms 26.5^0 radiation-free shadow for the radiators.

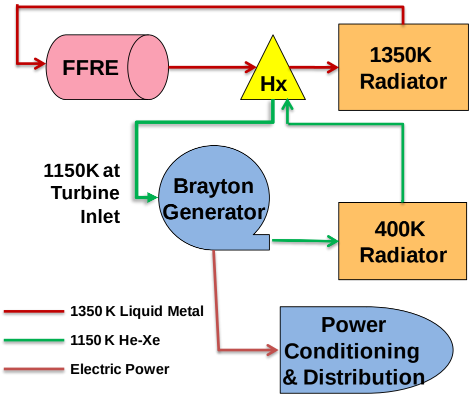
Subsystem Attributes: Reaction Control Subsystem

There are two sets of conventional hydrazine mono-propellant Reaction Control Subsystem (RCS) pods, each with redundant thrusters. There is one set of 4-thruster pods located just aft of the avionics/crew radiators and the other set is located just forward of the shadow shield. Using mono-propellant increases the RCS propellant required, but decreases the complexity significantly. Since the freezing point is high, heaters are continuously required to keep the hydrazine a liquid. The large moment arm between the RCS groups minimizes the required thrust. The RCS mass is slightly more than 4 mT including MGA.

Subsystem Attributes: Brayton Cycle Power Conversion System

The power system configuration was duplicated from the HOPE NEP vehicle analysis, modified to provide about 100 kW of spacecraft power. The Brayton Cycle power system, shown in the schematic, provides 30 kW to the Payload Habitat, 50 kW to run the cooling pumps, and an additional 20 kW (including reserves) for the FFRE, RCS, and communications. These power units have been designed for reliability and low weight rather than maximum efficiency. Gaseous Helium-Xenon mixture picks up waste heat in a heat exchanger to drive the power units. Total subsystem mass for the power units, power conditioning, instrumentation controls, and cabling is about 1.4 mT including MGA.

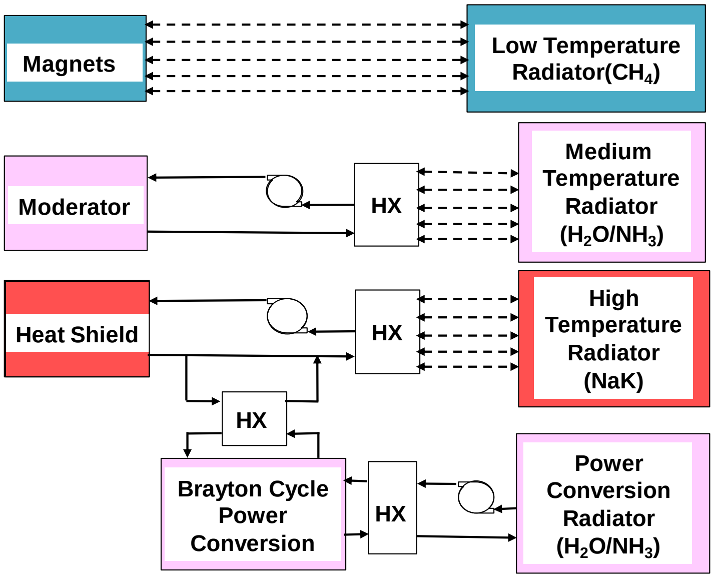
Power System Schematic



Subsystem Attributes: Thermal Management

The payload (crew habitat and spacecraft avionics) thermal management system configuration was directly imported without change from the HOPE NEP vehicle analysis. The FFRE thermal management system configuration was based on the HOPE NEP vehicle analysis, but modified to provide the dissipation of about 700 MW of FFRE waste heat and to power the Brayton Cycle electrical power subsystem. The FFRE thermal management system, a dominant part of the spacecraft, is shown in the schematic.

Thermal Control Schematic



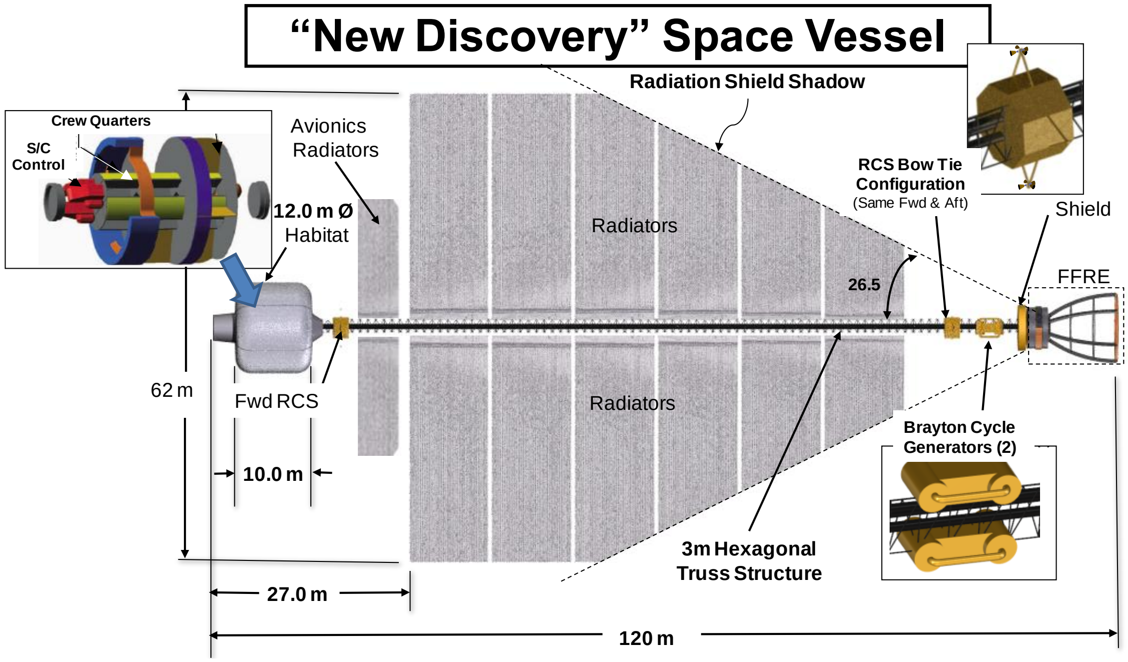
Four double sided, radiator systems constructed of composite materials keep this FFRE design within its thermal limits by rejecting over 700 MW to space. These radiators total over 56000 ft^2 and would be folded to fit within a Heavy Lift Launch Vehicle payload shroud. The masses, including MGA, are shown in the accompanying table and total a massive 64 mT including MGA.

Thermal Control Subsystem

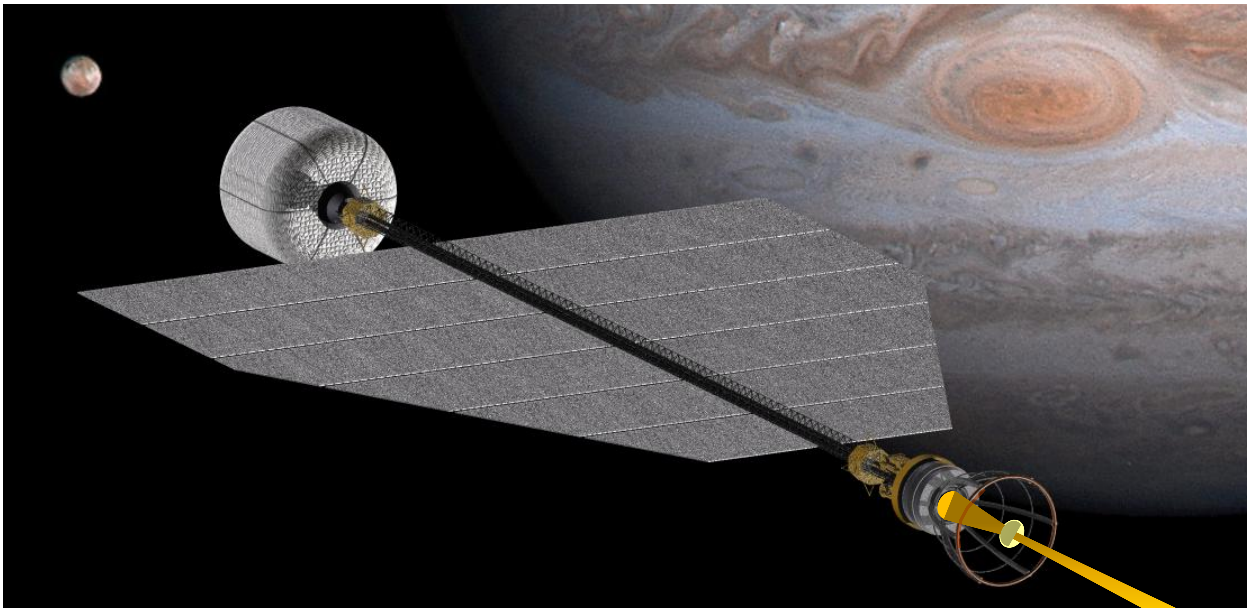
Radiator System	Ops Temp (K)	Heat Reject (MW)	Radiator Size (m^2)	Radiator Mass (mT)	Element Mass (Inc MGA) (mT)
Low Temperature Loop (Magnets)	120	0.05	2247	16.6	22.9
Medium Temp Loop (Moderator)	500	6	896	7.2	10.7
High Temperature Loop (Heat Shield)	1350	699	1954	19.5	29.2
Brayton Cycle Cooling Loop	400	0.3	109	0.9	1.4

The “Low Temperature” radiator keeps the engine’s magnets under the 120 Kelvins superconducting maximum temperature. A double sided surface area of 2250 m^2 rejects 50kW of acquired heat using liquid methane as the transport mechanism. The “Medium Temperature” radiator operates at 500 Kelvins to maintain the moderator as a solid. Its double sided surface area of 900 m^2 rejects 6 MW of thermal energy that “leaks” past the core thermal shield using an ammonia mixture for thermal transport. The “High Temperature” radiator operates at 1350 Kelvins and has the challenging requirement to reject 700 MW of thermal energy that emanates from the fissioning core. Nearly 2000 m^2 of double sided radiator surface is needed and the transport medium is a sodium-potassium molten salt. Lastly, the “Power Conversion” radiator taps off the “High Temperature” loop that, through a heat exchanger, powers the Brayton Cycle electrical generators. This system rejects only 0.3 MW of thermal energy, an insignificant percentage of the high temperature loop heat. About 100 m^2 of double sided radiator surface is needed and the transport medium is the same ammonia mixture as the “Medium Temperature” loop.

Spacecraft Attributes Summary



“New Discovery”, the study spacecraft shown above, represents an entirely new approach to long duration space travel in both manned and unmanned versions. Yet this kind of vessel is the “stuff” of classic science fiction. The accompanying art on the next page shows “New Discovery” decelerating into the Callisto/Jupiter system. This vessel is unchanged from when it left Earth and is unchanged upon its return to its Earth/Moon L-1 base; no pieces would be scattered across the solar system. There is no reason to crowd the crew into lifeboats to return to base. For the entire mission, there is an abundance of electrical power that allows use for astronaut comfort and for interplanetary radiation environment safety. “New Discovery” provides the profound game-changing architecture sought by the NIAC objectives and is vitally needed if long distance Exploration is to be real rather than be science fiction.

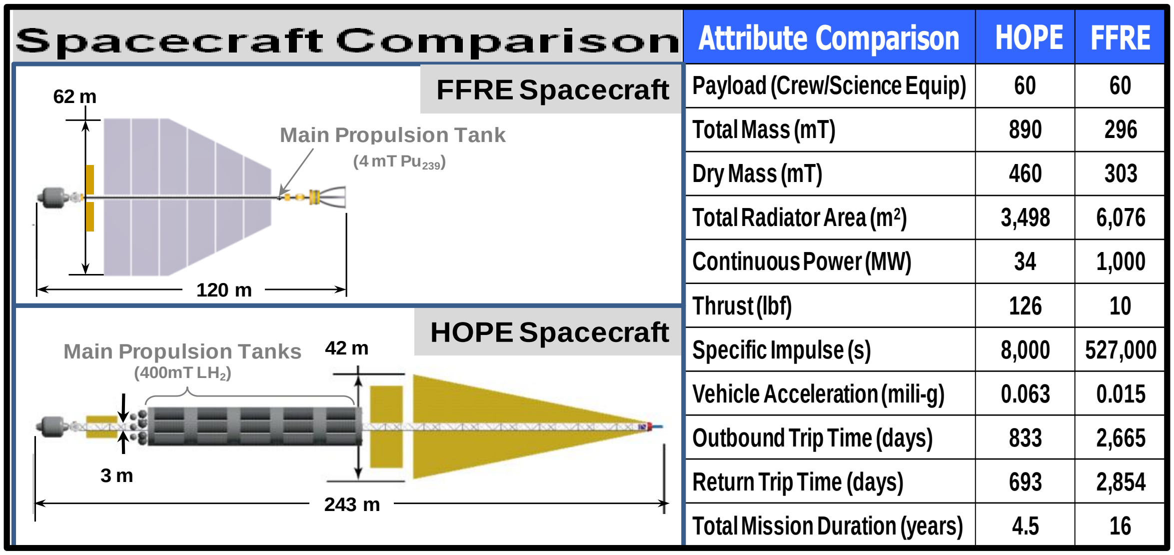


A mass summary of the "New Discovery" spacecraft subsystems (including the requisite MGA) is shown in the accompanying table. The FFRE-propelled spacecraft concept is distinctly different from the 2004 NEP HOPE concept used as the point of departure. Since only 4 mT of propellant consisting of Uranium Dioxide dust is required instead of the 400 mT of liquid hydrogen, the spacecraft mass drops dramatically from the HOPE Study design to only slightly more than 300 mT. Despite the thrust reduction of the FFRE with respect to the hypothetical MPD engines, the vehicle acceleration is less impacted due to the substantial reduction in vehicle mass. Besides the engine, the next most massive subsystem is the thermal management, being over 64 mT. Geometry changes to the FFRE in the future will significantly reduce the engine cooling requirements and reduce the radiator area and mass required. Additionally, the use of advanced radiator materials now in development at MFSC will reduce this mass as well.

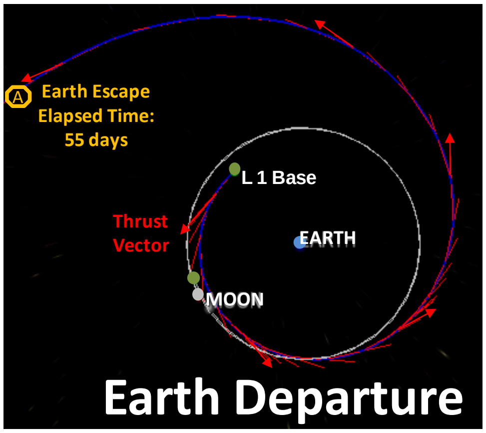
FFRE-Propelled Spacecraft Mass Summary

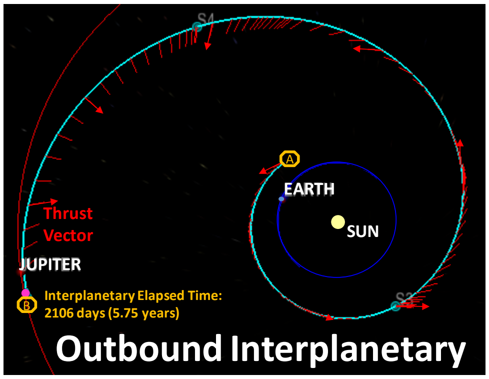
Master Equipment List	Mass incl MGA (mT)
1. Reaction Control Subsystem	**0.9**
2. FFRE (Engine, Nozzle, Shield)	**113.4**
3. Structure	**56.4**
4. Thermal Control Subsystem	**64.1**
5. Power Subsystem	**1.4**
6.1Payload (Crew Habitat, Avionics, Communications)	**58.0**
6.2Payload (Radiators)	**1.7**
Inert Mass Total	***295.9***
7. Propellant Mass Total	***7.2***
7.1. RCS Hydrazine	**3.2**
7.2. Nuclear Fuel	**4.0**
Spacecraft Wet Mass Total	***303.1***

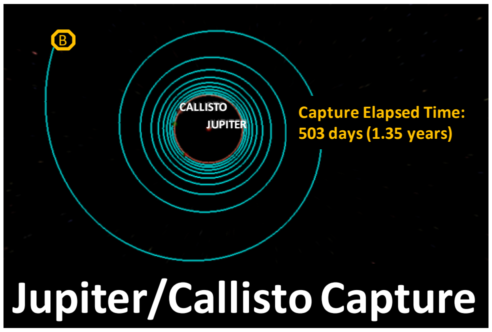
The physical comparison, shown in the figure on the next page, reveals the significant impact the opposing engine technologies have on vehicle configuration. The FFRE, with a specific impulse so great that an insignificant propellant quantity is consumed, shortens "New Discovery" to a vessel of about ISS dimensions whereas the MPD engines make the HOPE vehicle the size of a cruise liner. Further, the HOPE ship needs as much liquid hydrogen as resides in three SLS core



Attribute Comparison	HOPE	FFRE
Payload (Crew/Science Equip)	60	60
Total Mass (mT)	890	296
Dry Mass (mT)	460	303
Total Radiator Area (m²)	3,498	6,076
Continuous Power (MW)	34	1,000
Thrust (lbf)	126	10
Specific Impulse (s)	8,000	527,000
Vehicle Acceleration (mili-g)	0.063	0.015
Outbound Trip Time (days)	833	2,665
Return Trip Time (days)	693	2,854
Total Mission Duration (years)	4.5	16







stages. This hydrogen would have to be maintained in a cryogenic condition throughout the mission, a formidable task. These immense hydrogen tanks would be shed as the propellant is consumed during each engine burn. Consequently for a subsequent mission, at least five Heavy Lift flights would be needed just for replenishment of the needed hydrogen and for new tanks.

Mission Analysis

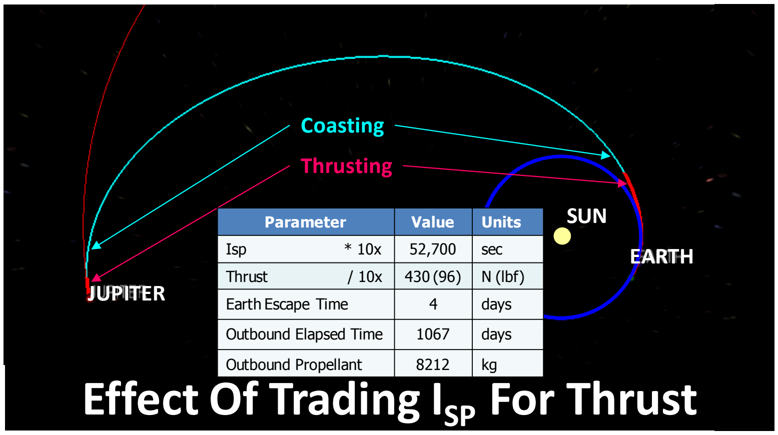
The most striking observation from the previous figure comparing attributes is that the current FFRE spacecraft has useable, although low, acceleration due to the high specific impulse but low thrust of the FFRE. The result is that the FFRE burns for the entire mission and the flight takes 3.5 times as long when compared to the hypothetical HOPE NEP.

To simplify the analysis, the trajectory was segmented based on which was the "primary gravitational attractor": Earth, Sun, or Jupiter. Once the Earth escape velocity was achieved at waypoint "A" for example, the trajectory computation was shifted from an Earth-centered system to a Sun-centered one.

In the accompanying figures, the "New Discovery" low acceleration results in taking 55 days to achieve Earth escape velocity starting from a base at Earth-Moon Lagrange Point 1. For the interplanetary phase, over 2100 days were required to reach the orbit of Jupiter. The FFRE thrusts the entire time to maintain the 0.015 milli-g acceleration with about 25% of the trajectory spent braking into the Jupiter orbit. This nearly 6 year flight phase did not consider planetary flybys for boosting velocity. Once in the Jupiter environment at waypoint “B”, the computation was again shifted, this time to a Jupiter-centric analysis. Over 500 days were required to settle into the orbit of Callisto. The return journey is a mirror-image of the outbound journey, totaling about 16years including a one year stay at Callisto.

Mission Analysis – Enhancing The FFRE

Increasing thrust by 10 times at the expense of a reduction by a factor of 10 in specific impulse brings about an interesting tradeoff between the mission duration and the propellant expended. An “afterburner”, the physical implementation of this thrust increase, injects an inert gas into the FFRE exhaust beam. This concept is proposed for a future NIAC study. The figure shows one example of how the afterburner engine would be used in which thrusting is terminated early so that the deceleration needed to match the Jupiter orbit is minimized. This means that an Earth Departure requires 4 days rather than 55 days and introduces a long coast period. The result is that the mission duration nearly matches that of the hypothetical HOPE NEP mission using only 16.5 mT of propellant (vice 400 mT of LH_2 for HOPE). Of the fuel used, about 0.25 mT would be the expensive nuclear fuel. This represents only a five percent increase in vehicle size mass. If the same mission was optimized instead for minimum mission time, the vehicle would be accelerating roughly half the way and decelerating into Jovian orbit the other half. With the afterburner engine attributes the same, this would result in Jupiter missions on the order of a year and a half each way and a total round trip propellant expenditure of about 90 mT, including less than 1 mT of nuclear fuel.



Parameter		Value	Units
Isp	* 10x	52,700	sec
Thrust	/ 10x	430 (96)	N (lbf)
Earth Escape Time		4	days
Outbound Elapsed Time		1067	days
Outbound Propellant		8212	kg

Effect Of Trading I_{SP} For Thrust

6. Manufacturing Issues

The mechanical structure of the FFRE reactor has some features in common with a tokomak fusion reactor. Both the tokomak and the FFRE operate in a vacuum. The tokomak reactor is designed for operation on earth so the pressure vessel must maintain a vacuum against the external atmospheric pressure. On the other hand, the FFRE reactor core also maintains a vacuum. Being only operated in space, the FFRE structural design is simplified since the only significant structural loads are surviving launch to orbit environment.

The FFRE uses magnetic fields for plasma containment, as does the tokomak fusion reactor. Like a tokomak, the FFRE low density plasma is contained by magnetic fields which are designed to isolate the plasma from the core first wall to minimize the heat transfer to it. The tokomak magnetic field is challenged to contain the plasma long enough to allow the fusion reaction to occur. Unlike the tokomak reactor, the FFRE uses a much simpler design in which magnetic fields are designed to leak and allow the fission fragment plasma to escape the reactor at the exit nozzle. In both reactors, the mechanical structure of the magnets must be strong enough to resist the plasma pressure. The magnetic field strength needed in a FFRE, about 1 Tesla, is less than a tokomak so the structural and cooling requirements are much less.

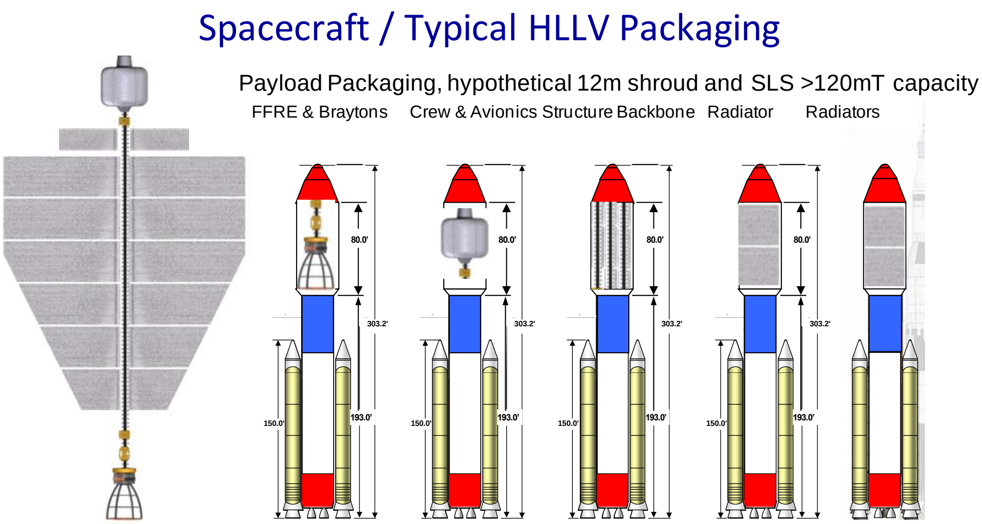
Creation of tons of fissionable fuel in nano-dust form is also a manufacturing issue. Current interest in nanotechnology has created a need for large scale industrial methods to fabricate nano-dust. Nano-particles are now being used in the manufacture of scratchproof eyeglasses, crack- resistant paints, transparent sunscreens, anti-graffiti coatings for walls, stain-repellent fabrics, self-cleaning windows, powder metallurgy and ceramic coatings for solar cells. Methods exist to support the routine production of hundreds of tons of nano-particles annually. The method of choice depends on the particular chemistry of the desired nano-particle. Two basic methods are commonly used: cryomilling and chemical precipitation. Cryomilling is a variation of mechanical milling by combining cryogenic temperatures with conventional mechanical milling. The extremely low milling temperature suppresses recovery and recrystallization, leading to finer grain structures and more rapid grain refinement. By chilling the material significantly, even elastic and soft materials become embrittled and grindable. In chemical precipitation, a chemical reaction among the gas or liquid reactants forms a solid precipitate. This solid precipitates out like ice crystals in snow. By properly timing the reaction, the size of the particles can be controlled.

7. FFRE Technology

This section can be found in Appendix A.

8. Spacecraft Technology Issues

The spacecraft has two principal technology risk areas that involve spacecraft assembly and FFRE/Spacecraft integration. The “New Discovery” class space vessel is of a size similar, but simpler in form, to the International Space Station (ISS). Lift to space and assembly of the ISS elements was hampered and protracted by the limited 25 mT payload capacity of the Space Shuttle. Using a HLLV such as the SLS greatly simplifies the assembly to a few launches. The adjacent figure shows

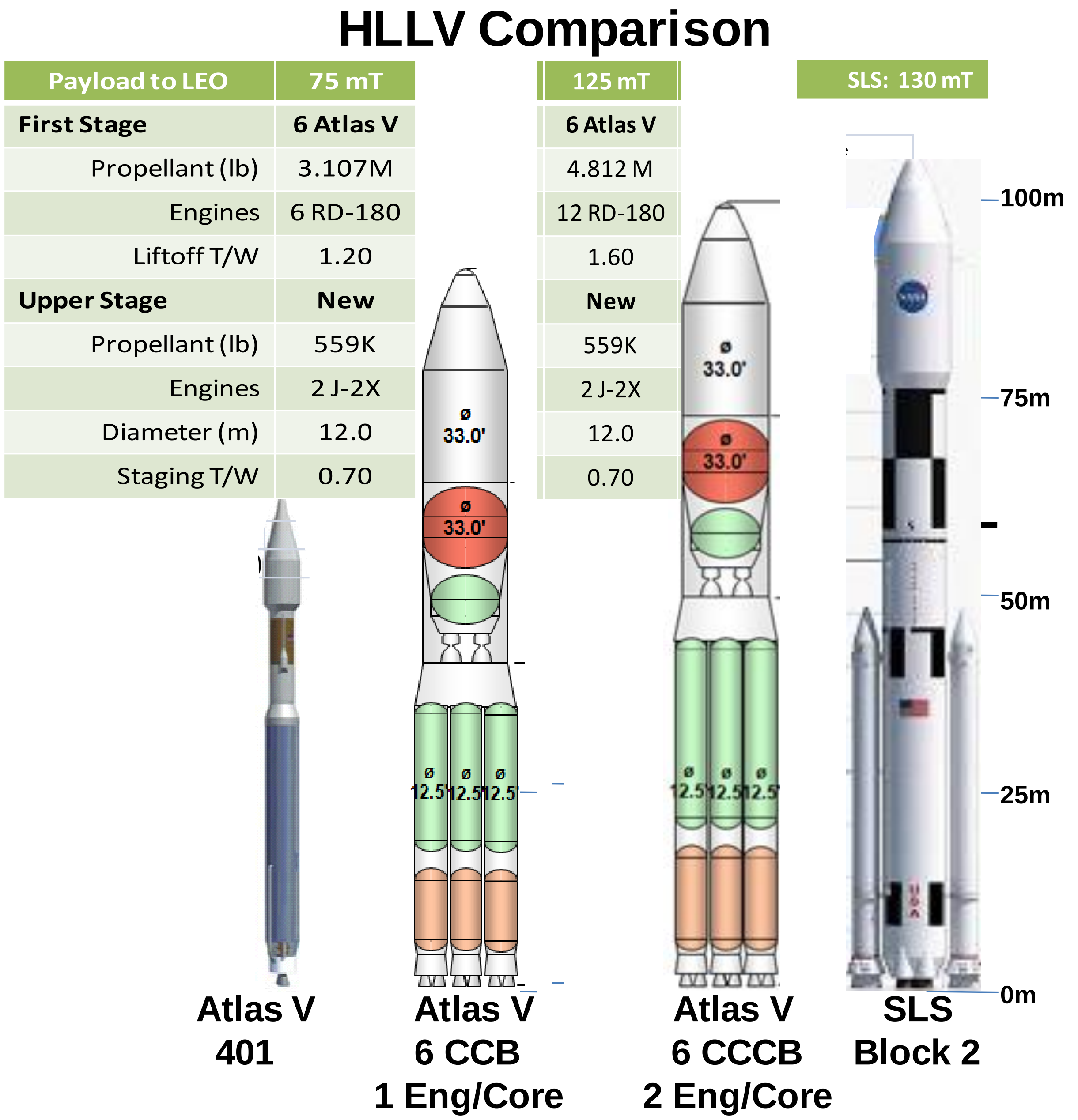


that the Initial Generation FFRE could be lofted on 5 SLS Block 2-like HLLVs while the Second Generation FFRE would require one more.

The future of the “New Discovery” space vessel is not linked to SLS, however. A quick review of available, existing launch vehicles reveals that a two stage vehicle composed of a six-pack of Atlas V common Core Boosters can be clustered in a fashion similar to the early Saturn 1C that would provide, with a cryogenic upper stage like that of SLS Block 2, over 75 mT. By replacing each first stage engine package with a pair of RD-180 engines (or a new engine of similar performance), the same configuration delivers over 125 mT to LEO. The advantages of this approach include the minimization of development cost, the cost sharing of fixed assets (facilities and production personnel) with other users of Atlas, and the ability to flexibly procure launch vehicles. It is especially important to provide from one launch every five years to multiple launches each year. A comparison with the SLS Block 2 HLLV is shown in the figure on the subsequent page.


Saturn I. Von Braun launch vehicle known as 'Cluster's Last Stand' - 8 Redstone tanks around a Jupiter tank core, powered by eight Jupiter engines. Jupiter, Redstone & H-1 engines were in production at that time.

The other spacecraft issue concerns integration of the space vessel and the FFRE from the individual launch packages. The lessons learned from ISS will well serve the integration of the various launches. These launch packages, although more massive than ISS, are generally less complex and have fewer interfaces. Only the radiator components represent complex assembly tasks due to the need to unfold each and to complete the fluid connections. Since the engine is checked out on the ground before launch and is a self contained system, its integration consists of making the connections for radiator fluid, electrical, instrumentation and the nuclear fuel feed. Starting the FFRE that has been discussed previously brings electrical power to the space vessel for early integration checkout. The FFRE would remain in idle mode with the magnets off to preclude contamination of the local environment during this time.



HLLV Comparison

Payload to LEO	75 mT	125 mT
First Stage	**6 Atlas V**	**6 Atlas V**
Propellant (lb)	3.107M	4.812 M
Engines	6 RD-180	12 RD-180
Liftoff T/W	1.20	1.60
Upper Stage	**New**	**New**
Propellant (lb)	559K	559K
Engines	2 J-2X	2 J-2X
Diameter (m)	12.0	12.0
Staging T/W	0.70	0.70

SLS: 130 mT

9. Environmental Issues

The greatest challenge of the FFRE has nothing to do with radiation; the challenge has to do with handling the enormous power generated by the engine without melting the components. The only escape for all this energy in the vacuum of space is thermal radiation so that the proper functioning of radiators and IR mirrors becomes a crucial operational hazard.

The FFRE creates far less of an environmental issue than a NTR or a space nuclear reactor needed for fusion propulsion. This is true even though the FFRE waste products are fission fragments. In a conventional fission reactor, the fission fragments are trapped in the reactor fuel rods and constitute a neutron poison which must be counteracted with an excess quantity of fuel. Initially when the reactor is fueled, the excess reactivity is countered by boron control rods. As the fuel is consumed and the fission event neutron poisons accumulate, the control rods are gradually removed from the reactor core to overcome their neutron poisoning effect. Near the end of the operational life, the control rods are completely removed and the fission event poisons alone cause the nuclear chain reaction to stop. The fuel rods and the fission event neutron poisons they contain must then be removed and new fuel rods inserted. The removed fuel rods are highly radioactive as they contain most of the fission event waste accumulated over the period of operation.

In contrast, the FFRE fission fragments are continuously expelled from the core at high velocity and leave the vicinity of the reactor. Although the FFRE exhaust is radioactive, it is rapidly (at more than 1% of light speed) leaves the solar system. Also, the flow rate of fission fragments is only ounces per hour (mg/sec), so there is never a significant accumulation of fission fragments that would cause a local safety hazard. Unlike a conventional power reactor or NTR, the FFRE core needs only to contain a minimum mass of fuel to remain critical at any given time since the neutron poisons typically created by the fission events are continuously removed from the core by the fission fragment process of producing thrust. When the reactor is shut down, there are negligible radioactive fission fragments left in the core because the magnetic fields have kept the fission fragments away from the walls. This means crew EVA and maintenance operations around the reactor can be initiated soon after the reactor is shut down.

The release of radioactive ash caused by igniting the FFRE in Earth orbit has been posed as a serious environmental concern. However, these particles do not immediately fall to the Earth, since the Earth's magnetic field acts as a trap or a bottle for these self-ionizing species. The Van Allen radiation belts are an example of naturally-occurring radiation—principally from neutrons sputtered off the upper atmosphere by cosmic rays—that are likewise trapped by the magnetic fields. By modeling the diffusion of these radioactive species based on the Van Allen belt 40-year dataset, it is possible to conclude that a FFRE at 1000 km altitude will deposit radioactive ash in the radiation belts that will take over a year to arrive in the stratosphere. By that time, most of the highly-radioactive species will have long since decayed, leaving mostly ^{137}Cesium and ^{90}Strontium as the only contributors to stratospheric radiation. The amount of these two radioactive species emitted by a 1000 MW FFRE burning for several hours on its way out of Earth orbit is comparable to amount of radioactive ^{14}Carbon generated by cosmic rays in one year. That is to say, it is measurable, but hardly dangerous. Even this minimal amount could be reduced to essentially zero, if a space base outside the Earth's magnetic field were established, for example around L-1. Here, firing the FFRE would send the ash into a trajectory that would leave the solar system rather than be magnetically trapped in Earth orbit.