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

FY11 NIAC Phase 1 Study
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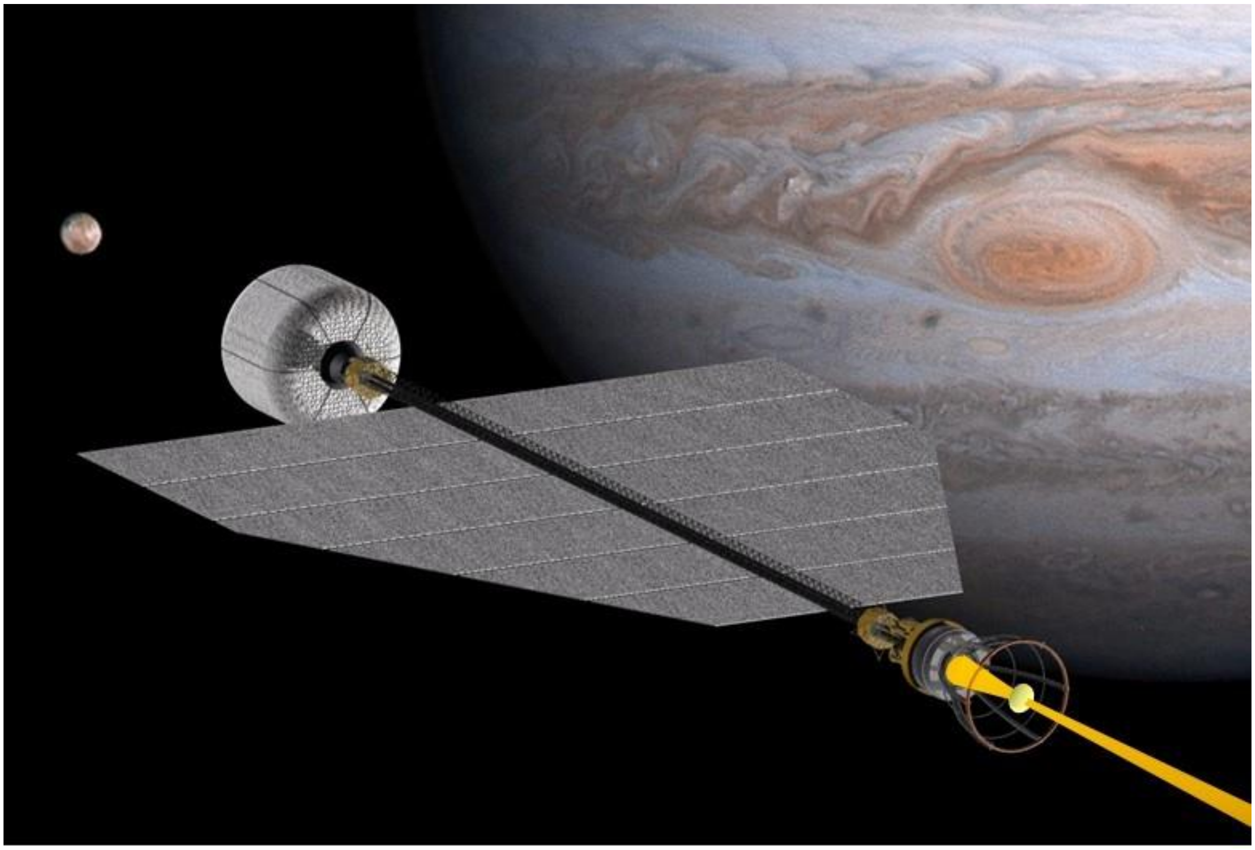

Acknowledgements

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

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Structural Analysis	Janie Miernik (MSFC)	
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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.

Part 1

1. Executive Summary

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 a real-world analog, we operate to the Moon by climbing aboard a Carnival Cruise Lines-like 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 that uses today's physical principles to produce 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.

Today's space Explorers could travel in Cruise Liner fashion using 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 the 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 Launch Vehicle. This Exploration Spacecraft would require the resupply 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, from the engine waste heat, 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.

[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 chemical propulsion, Nuclear Thermal or VASIMR 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.

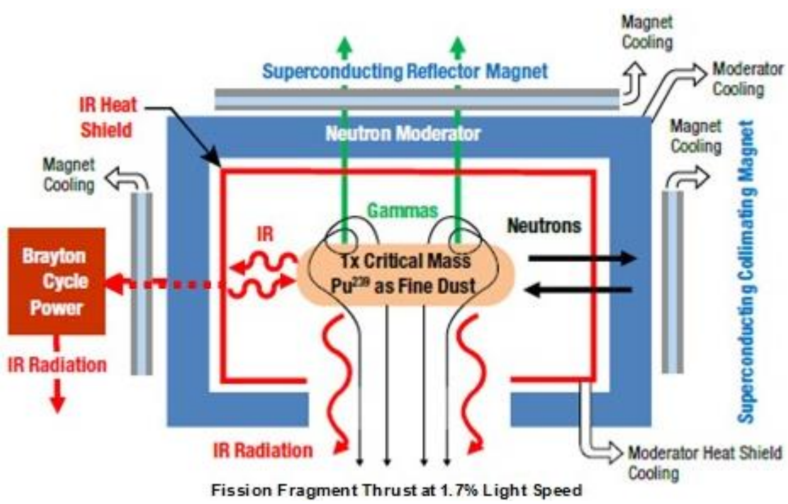
The remaining vehicle subsystems (reaction control, structures, thermal control, and Brayton cycle power generator) were resized to close the vehicle design. The payload of the HOPE vehicle, a manned Transhab module, had a mass of about 40 mT, contained an additional 4 mT of consumables and included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

[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.

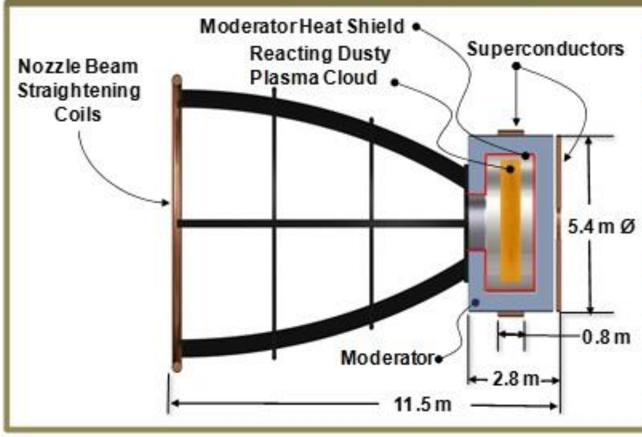


Unlike the fuel rods of a typical reactor, the FFRE reactor core consists of sub-micron sized fissioning dust grains that are suspended and trapped in an electric field. The amount of dust is only sufficient for a short period of critical operation and must be continuously replenished. The fission fragments 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 of light speed. 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 reflection off the heat shield wall and cooling of the first wall to space through very large radiators.

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 borehole 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.

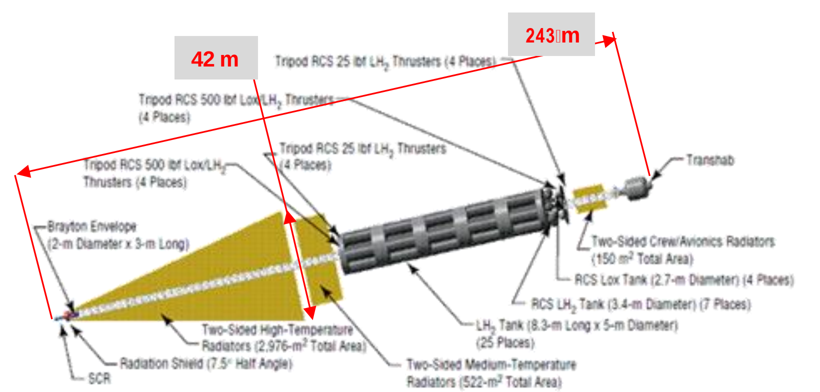
FFRE Physical Design Trades

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. 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



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 (m²)	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

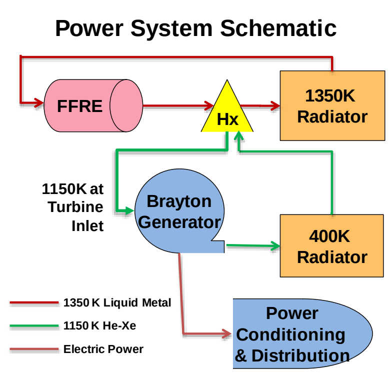
on the same HOPE mission since there was ample data available to make the necessary vehicle design adjustments and to provide detailed comparisons. The general summary of the concept vehicle configuration is provided above. The full report by the Advanced Concepts Office is included as Appendix B.

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, about 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.

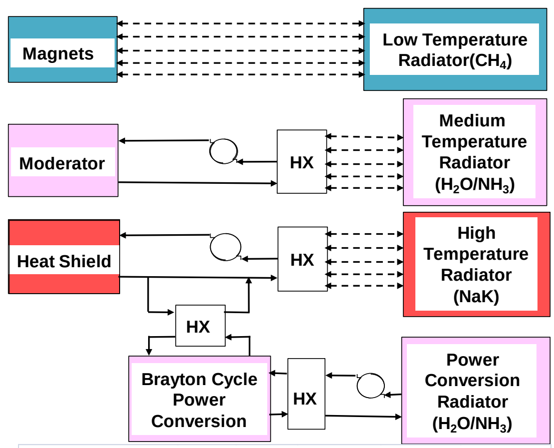
Subsystem Attributes: Brayton Cycle Power Conversion System. The power system configuration was duplicated from the HOPE NEP vehicle analysis, modified to provide about 100 kW of spacecraft power. The Brayton Cycle power system, shown in the schematic, provides 30 kW to the Payload Habitat, 50 kW to 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.



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-thrster 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: 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



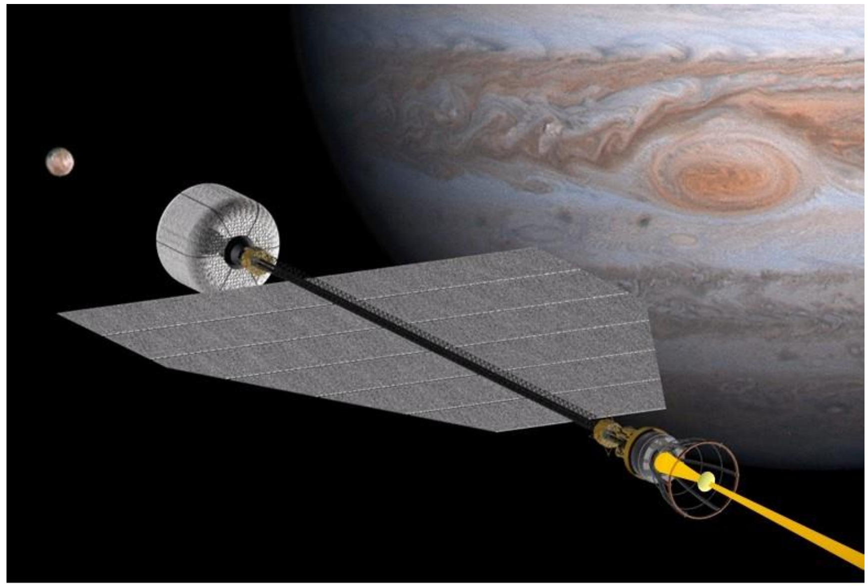
Thermal Control Subsystem

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

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.

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.

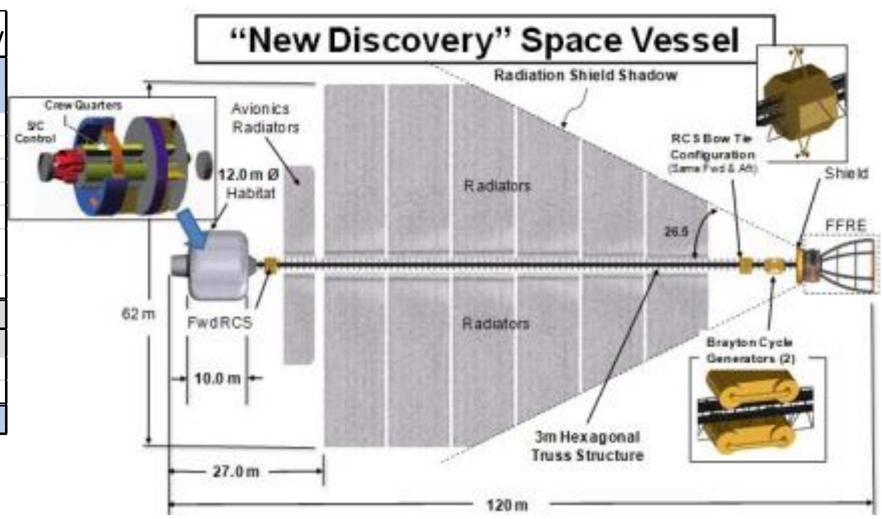
Spacecraft Attributes Summary. "New Discovery", the study spacecraft shown below, represents an entirely new approach to long duration space travel in both manned and unmanned versions. Yet this kind of vessel is the "stuff" of classic science fiction. The accompanying art on the next page shows "New 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 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.



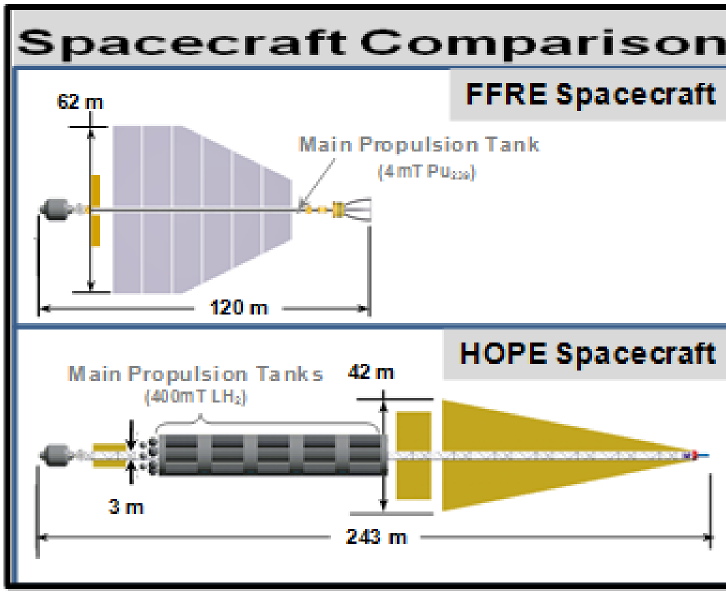
A mass summary of the "New Discovery" spacecraft subsystems (including the requisite MGA) is shown in the accompanying table. The FFRE-propelled spacecraft concept is distinctly different from the 2004 NEP HOPE concept used as the point of departure. Since only 4 mT of propellant consisting of Uranium 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. The next most massive subsystem is for thermal management, being over 64 mT. Future geometry changes to improve the FFRE efficiency will significantly reduce the engine cooling, the radiator area and mass required. Also, advanced radiator materials now in development at MFSC will reduce this mass further.

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 it consumes an insignificant propellant quantity, shortens "New Discovery" to a vessel of about ISS dimensions whereas the MPD engines make the HOPE vehicle the size of a



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

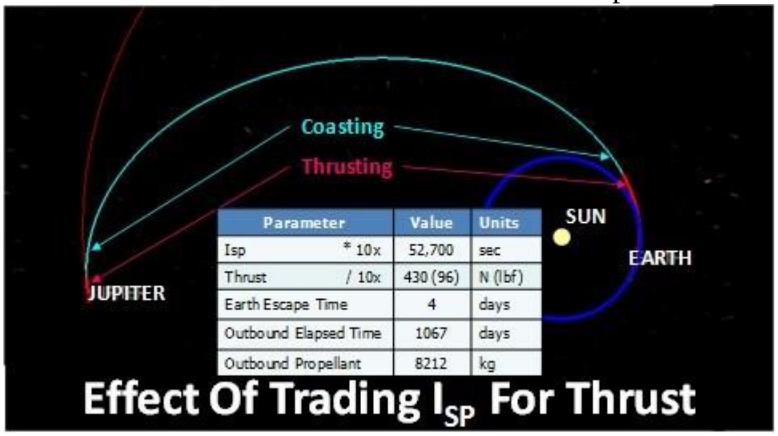
cruise liner. Further, the HOPE ship needs as much liquid hydrogen as resides in three SLS core stages. This hydrogen would have to be maintained in a cryogenic condition throughout the mission, a formidable task. These immense hydrogen tanks would be shed as the propellant is consumed during each mission burn. Consequently for another 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, as shown in the above figures. 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.

The "New Discovery" low acceleration requires 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 needed 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 Jupitercentric 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 16 years including a one year stay at Callisto.

Mission Analysis: Enhancing FFRE Performance. 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 and is discussed in Part 2. 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.

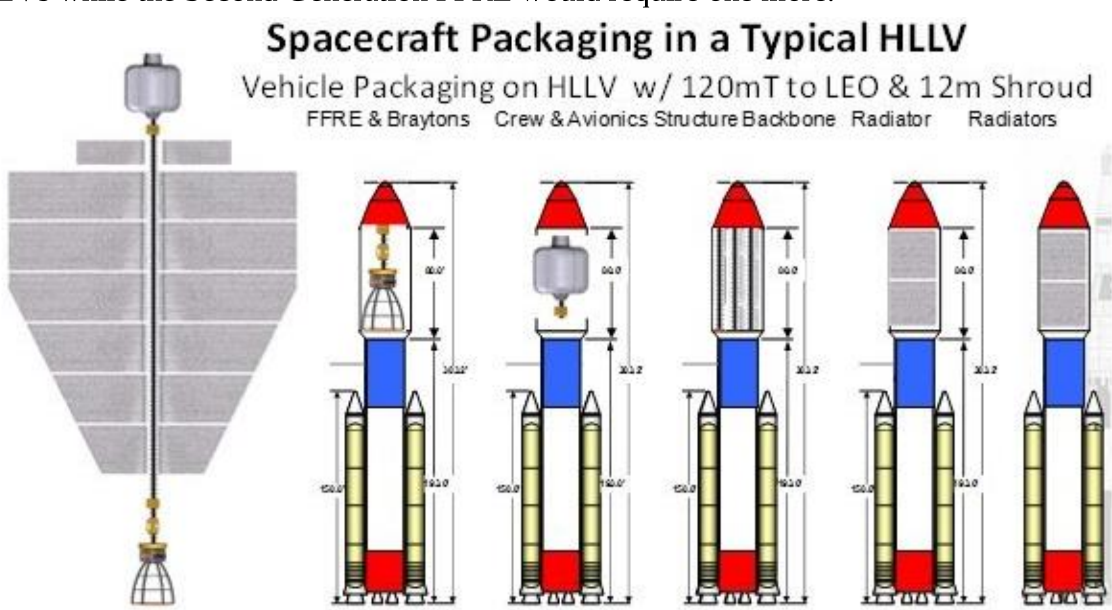
Creation of tons of fissionable fuel in nano-dust form is also a manufacturing issue. Current interest in nanotechnology has created a need for large scale industrial methods to fabricate nano-dust. Nano-particles are now being used in the manufacture of scratchproof eyeglasses, crack- resistant paints, 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 Analysis and 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 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.

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 efficient functioning of radiators and IR mirrors internal to the FFRE 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.

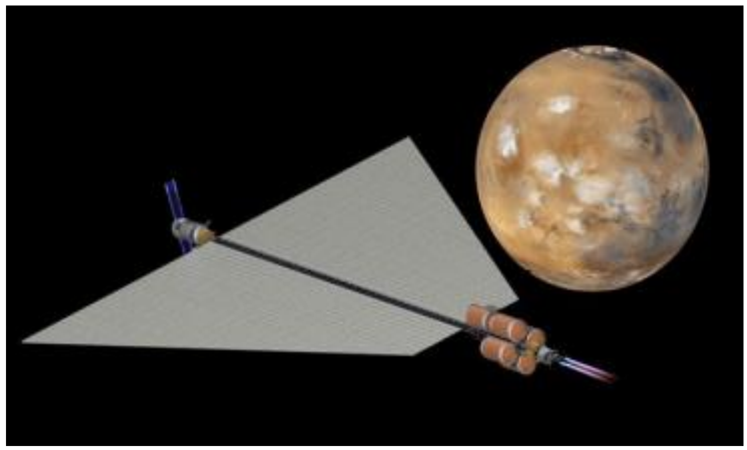
The release of radioactive ash caused by igniting the FFRE in Earth orbit has been posed as a serious environmental concern. However, these particles do not immediately fall to the Earth, since the Earth's magnetic field acts as a trap or a bottle for these self-ionizing species. The Van

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.

Part 2

1. Background

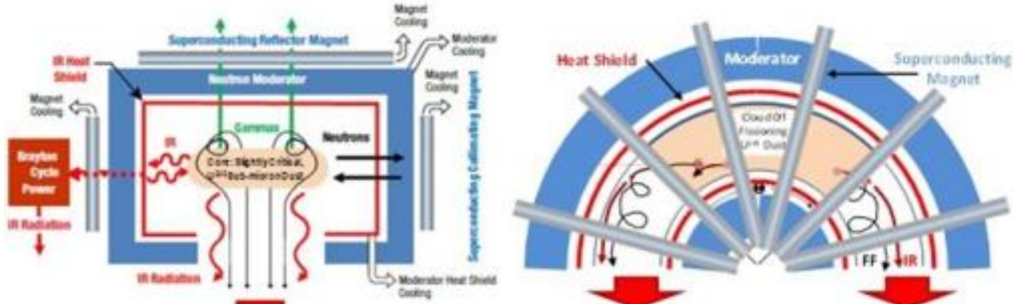
The study of fission fragment rocket engines (FFRE) that had been started in FY11 was continued by investigating the engine attributes whose performance was enhanced by introducing hydrogen into the exhaust beam to increase thrust. This resulted in a reduction in specific impulse. The study then integrated the resulting engine onto an in-space vehicle, analogous to that done in Part 1, and a mission flown to Mars for direct comparison to contemporary DRM 5 architectures. The results showed that a 1,000mT craft, carrying 170mT of Lander and Habitat, powered by a 1046lbf engine delivering 32,000 sec of impulse, could support a 290 day to Mars round trip, including a 60 day stay. This craft would be propulsively returned to Low Earth Orbit, to be refueled and replenished for future missions. For readers of vision, this innovation represents a practical solar system exploration class vessel that provides the same game-changing technology of 19th century Clipper ships for global commerce or 20th century commercial jet airliners. For readers who have scoffed at such previous claims as being fabricated science fiction, **their view would be grossly in error.**



This Study was money well spent in that this revolutionary engine was shown to provide a game-changing, exciting new way of swiftly and safely exploring our solar system, for which the Aerospace American author had wished. This variable thrust / specific impulse vehicle based on the Afterburner FFRE offers attributes better than those identified in Part 1 with far more confidence in the projections.

2. Reestablishing an FFRE

At the end of Part 1, the FFRE had to be dramatically changed from the "Tuna Can" configuration on the left below to a "Half Torus" configuration shown on the right. The reason was that the geometry of the "Tuna Can" could not simultaneously support a small enough hole in the moderator to retain sufficient neutrons to keep the core critical



FFRE Design Change

and a large enough hole to enable the magnetics to direct the fission fragments out of the reactor.

While the new shape in Part 1 significantly increased the moderator weight, the thrust was doubled from two nozzles instead of one and the heavy superconducting mirror magnet and companion radiators could be reduced, leaving the vehicle acceleration unchanged. This was the engine configuration leading into Part 2.

Following the completion of the Part 1 study, there was recognition that the hastily completed Half-Torus engine design needed to be revisited and FF escape efficiency confirmed before the Part 2 Study modeling of the afterburner could proceed. The full engine analysis discussion can be found in Appendix A. As a result, two separate approaches, one Monte Carlo and one Global, investigated how FFs interacted with the dust and plasma in the core and escaped the engine. The Monte Carlo approach, SRIM, was a carryover from the Part 1 study and employed the philosophy that each FF could be tracked for each incremental time step from the fission event until either escape or being stopped in the core. This approach then employed a Monte Carlo simulation of a statistically significant number of fission events to extrapolate to full engine performance. The Global approach, FF-HEAT, computed the energy deposited by the fragments into the plasma. Once the units and coding errors were eliminated, the results from each model were sufficiently different and irreconcilable that outside assistance was required.

A tiebreaker code, Geant4, was provided by the MSFC ZP-12 organization under the leadership of Dr. Abdulnasser Barghouty. This industry-standard code, while computational intensive, is a platform for the generalized simulation of the passage of heavy ions through matter using Monte Carlo methods. The initial Part 1 Study Monte Carlo fast running code, once corrected, provided the best comparison to Geant4 and allowed the analysis to proceed into the investigation of FFRE performance and efficiency issues.

The first discovery was that the corrected Monte Carlo model now pushed the core density to provide FF escape down from 0.10 g/cc to 0.01 g/cc. When the problem first surfaced that the FF had insufficient energy remaining to escape the core, the proposed solution was to simply scale the FFRE to a larger size, since neutrons go as the volume, but friction goes as the diameter. Even when the reactor power was made very large, the friction remained close to 99%. More dismally, the thrust per GW of power remained close to 0.1 N/GW, a value far from the “ideal” FFRE value of 120N/GW. By changing the ratio of the dimensions of the torus, the efficiency could be raised to 2%, a not very encouraging number. By changing from a torus to a “spherical torus” (similar in shape to a Tokomak reactor), the efficiency could be raised to produce perhaps 5N/GW, again not very encouraging number.

Since geometry was not the solution to the thrust problem, choosing a fissile fuel with larger neutron cross section would lower the mass and density required to make the reactor critical. Uranium-235 with about 500 barns of cross section could be replaced with Plutonium-239 with 720 barns for a small improvement. Thrust developed based on this design provided about 97% thermal and 3% fission fragment thrust, for about 5N per GW-thermal. On the other hand, Americium-242m (Am^{242m}) with 7200 barns of cross section would provide nearly 40% fission fragment thrust with only 60% going into heat.

While several papers have suggested the feasibility of making this unique fuel, it is apparent that its primary purpose is as a trigger in nuclear bombs, so amounts of this fuel and its production are highly classified. Nevertheless, large stockpiles of Am^{242m} exist both in the US and in Europe. Am^{242m} naturally occurs in 0.4% of this material. Given the need based on this engine, it is conceivable that this fuel could be produced with sufficient re-processing and, perhaps enrichment. For the mission profiles studied, less than a metric ton is sufficient to reach Mars.

Since size would no longer be a constraint for criticality with this most energetic fuel (Am^{242m}), the smallest Half-Torus configuration that would still contain a sufficient amount of fuel for criticality was selected; it was a 1-meter minor radius, 2 meter major radius "spherical torus" surrounded by about 90 metric tons of oil-based C^{13}-D moderator.

The fission fragment-only thrust generated from this design was about 50N/GW. This is the same as the Part 1 Study of FY11. This configuration was shown in the previous study to be sufficient to enable travel to distant destinations on fission fragment thrust alone, but too slow to provide astronaut safety. To propel a space vessel of the size of the Part 1 Study (or even larger to accommodate more payload) far more swiftly, the thrust level had to be increased. Based on the FFRE, the reactor power would need to be increased by one or two orders of magnitude, clearly not a possibility. The objective of this study, then, was to show the ability to substantially increase this thrust level using an “afterburner”. This device mass-loads the fission fragment beam by injecting hydrogen into the exhaust stream after it exits the reactor.

4. Afterburner Configuration

The "afterburner" concept requires a magnetic nozzle for transferring the thrust of the hot plasma to the spacecraft structure without melting the supports. A magnetic nozzle is used to direct plasma flow, convert energy into thrust, and ensure efficient plasma detachment from the spacecraft while preventing the plasma from interacting with the nozzle structure. A magnetic nozzle is composed of multiple high-field strength circular magnets supported by a space frame structure. The converging nozzle section compresses the fission fragment beam to maximize its interaction with the injected hydrogen. The throat is where the hydrogen afterburner gas is injected and ionized by the intense beam of fission fragments. The expansion section must be sufficiently long to keep the hydrogen plasma contained during the energy exchange process. The cooled beam and heated hydrogen plasma then expand through the magnetic nozzle to generate thrust.

The amount of hydrogen introduced into the beam determines the final velocity of the mixed exhaust. Since the hydrogen is accelerating through collisional interactions, this amounts to a reduction in speed of the fission fragments, up to a factor of 100, from an exhaust velocity of 5,000,000 m/sec (I_{SP} = 500,000sec) to an exhaust velocity of 50,000 m/sec (I_{SP} = 5,000sec). Since the energy goes as velocity squared, this is a transfer of 99.99% of the energy from the fission fragments to the hydrogen gas, which is heated and ionized. The hot plasma then expands out of the nozzle at great speed. If hydrogen gas flow rate is increased, the fixed power of the fission fragment beam means the final temperature is lower, the exhaust velocity is lower, the mass flow is greater and the thrust is greater as well. Conversely, throttling the hydrogen gas raises the temperature and the final I_{SP} while reducing thrust.

The optimal exhaust velocity for any specific mission requires balancing I_{SP} and thrust, for a total mass of the vehicle. Rather than analyze the engine to a single exhaust velocity, a spread sheet was constructed by the Grassmere team in which the reactor power and final I_{SP} of the hydrogen gas were input variables so that the vehicle designers and mission planners of the Advanced Concepts Office could perform mission optimization studies for a Mars mission.

5. Afterburner Fission Fragment Rocket Engine Baseline

For this Part 2 Study, a human exploration to Mars was selected to better show an apples-to-apples comparison with the contemporary "DRM 5.0" architecture, Figure 5-1. In an AFFRE version of this mission, all elements will be delivered on one flight and it performs a propulsive capture back at Earth. A single Mars lander is assumed at a mass of 135 mT (compared to two 100 mT landers). The AFFRE spacecraft also enables significantly faster trip times to and from Mars. This reduced trip time results in lower consumable masses for the crew leading to a 35 mT deep space habitat (compared to a 41 mT habitat in DRA 5.0) and significantly reduced the health risks to the crew.

Figure 5-1. Mission Requirements

- **Human flight to Mars**
- **Based on Mars DRA 5.0 mission**
- **AFFRE delivers all systems to Mars in one trip**
- **Payload is 170 mT**
  - Deep Space Habitat (35 mT)
  - Mars Lander (135 mT)

Using the Grassmere engine spreadsheet and iterating on Mars round trip trajectories, the engine heat loading (Figure 5-2) and general radiator thermal requirements (Figure 5-3) could be determined. As shown in Figure 5-4, the reactor power was greatly increased from the Part 1 design. The mass flow is also higher, mostly resulting from the addition of the hydrogen. The thrust of the engine increased to over 1000 lbf and the specific impulse reduced to 32,000 seconds. This combination of thrust and specific impulse is still a

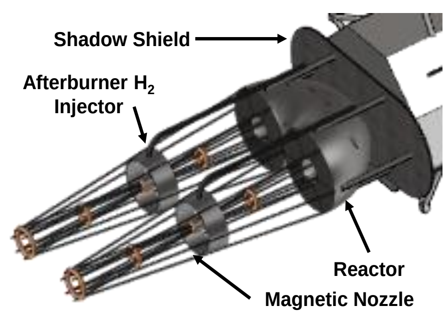
Figure 5-2 Power Allocation

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

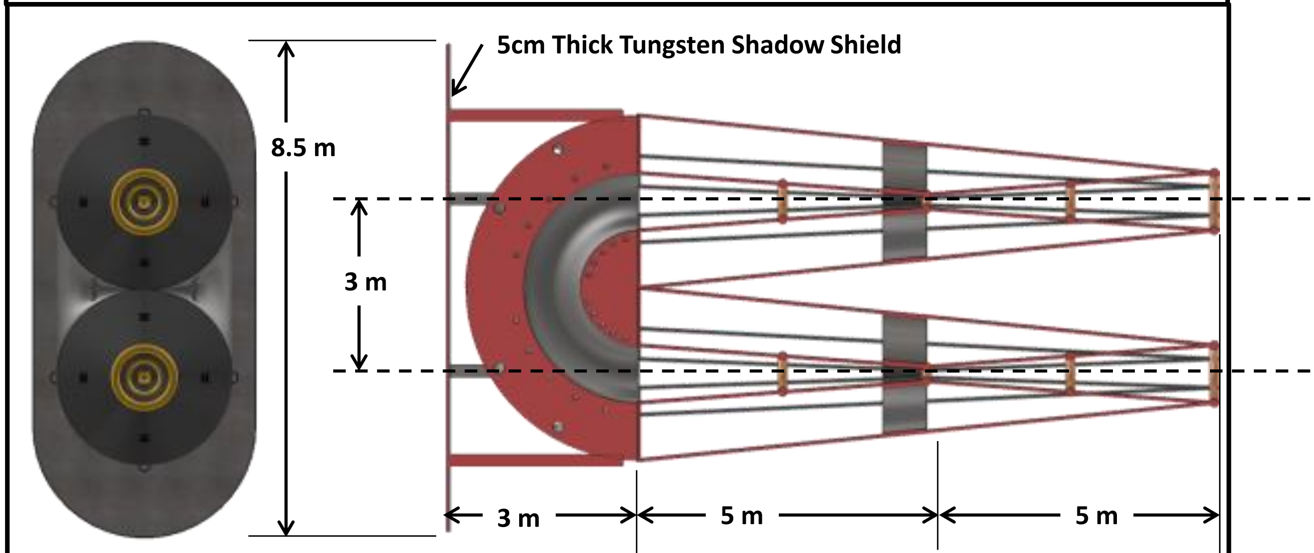


Reactor Power: **2.5GW**
Mass Flow: **FF** **3.1e-5kg/s**
H_2: **1.8e-2kg/s**
Total Thrust: **4651N**
1046lbf
Specific Impulse: **32,000sec**

game-changing improvement over propulsion systems of today or any under development or any future concepts with a reasonable chance of being brought to fruition.

Figure 5-5 shows the engine dimensioned. The moderator can be seen in the side view. The holes in the moderator notionally indicate the placement of the magnetic coils and control drums required to control the nuclear reaction and the dusty plasma core. The nozzle assembly is constructed using carbon-carbon tubes to allow for the reflected IR radiation to escape with minimal impact to the nozzle assembly. The structure supports four magnetic beryllium rings of varying sizes. The nozzle converges to a 20 cm nozzle diameter. The four magnetic rings help to direct the fission

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

Figure 5-6. Afterburner Feed System

- **Existing components to provide pumping and injection**
  - Injectors and pumps selected based on the 0.0179 kg/s LH2 flow rate
  - Redundant pumps support extended duration operations

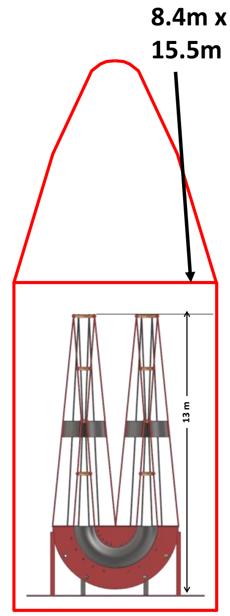
- **LH_2 Piston Pump developed by XCOR**
- **Successfully demonstrated LH_2 pumping**
- **Mass and power estimated from industry sources**

- **Hydrogen injectors from Astrium-developed 300N LOx/LH_2 thruster**
- **LH_2 flow rate 0.011 – 0.016 kg/s meets flow requirements of the AFFRE system**

fragments into a sufficiently narrow cross section to promote full engagement with the injected hydrogen and convert that hydrogen to a plasma which is then directed through an expansion over the last 5m of nozzle length.

To size the hydrogen feed system (Figure 5-6), existing technology was selected because the flow rate for the liquid hydrogen is extremely low. There is a piston pump currently under design at XCOR for use on the ULA Integrated Vehicle Fluids concept that provides approximately the AFFRE flow rate and has been demonstrated in a lab environment. Multiple pumps provide redundancy. The afterburner injectors were taken from an Astrium-developed 300N LOx/LH_2 thruster system. This throttleable, pressure-fed injector has the flow rate range required for each nozzle of the AFFRE design.

Figure 5-7. AFFRE in SLS Blk2 Shroud



This engine can be transported to orbit in 2 SLS-like flights (Figure 5-7). The engine's outer dimensions are 8.5 m diameter by less= than 20m long which places it within the dynamic envelope of a SLS launch vehicle 10m payload fairing. The engine can be tested fully on the ground before launch and all nuclear fuel removed from the engine by being vaporized at engine shutdown, allowing for a low risk flight of the engine hardware. Since the moderator is over 90mT of specialized hydrocarbon oil, the engine can be drained and launched empty. Once on-orbit, the oil can be added from a separate SLS launch and the nuclear fuel added after the engine is successfully checked out.

6. Vehicle Synthesis

A short summary of the vehicle Groundrules and Assumptions follows that was used to guide the synthesis of the concept vehicle. A complete discussion is found in Appendix B.

1.0 Structure Groundrules & Assumptions

- Primary structure: meets NASA-STD-5001-A
- Truss Spine: 2219 Aluminum tubing
- Critical load case: 0.005g axial acceleration
- Factors of safety for metallic materials
  - FS_u=1.4
  - FS_y=1.0
- Stability requirement: no global instability below Ultimate Load
- Secondary structure: assumed as10% of primary structure mass
- Truss Joints and fittings: assumed as 50% of truss mass
- AFFRE structural radiation protection: Carbon-Carbon composite.
- Shadow Shielding structural radiation protection: 22.5° half angle

2.0 Propulsion Groundrules & Assumptions

Category	Value
Nozzle Field Coil (2)	Copper coil with supporting Carbon-Carbon structure
Magnetic Focusing System	Super-conducting Magnet
	7 - 7.5 Tesla
	Operating Temperature - 140 K
Core Moderator	Configuration - Half-torus + a meter extension
	Material - Carbon 13 D
	Operating Temperature - 590 K
Core Moderator Shell	Material - Carbon-Carbon
	Thickness - 5 cm
Core Moderator Heat Shield	Configuration - Half-torus (+ 1 meter extension)
	Material - Carbon-Carbon
	Operating Temperature - 1000 - 1200 K
Total Magnet Power	Power Req'd - 100 W
Nozzle Power	Power Req'd - 101,000 W
Electrostatic Collector	Power Req'd - 100 W
Dust Injector	Power Req'd - 50 W
Reactor Critial Fuel Load	110 g
Dust Density	1×10^{-5} g/cm^3
Dust Temperature	2200 K
Thermal Management	Liquid metal active cooling
Shadow Shielding	Z-Pinch style: LiH, B_4C, Tungstern
Engine Structure Material	Carbon-Carbon
Hydrogen Feed System	scaled from known LH2 engine components
Thrust	1046 lbf (4651 N)
Specific Impulse	32,000 seconds

3.0 Power Groundrules & Assumptions

- **Comparable to HOPE NEP Crewed Vehicle**
- **Power to Habitat: (15) 20A circuits.**
- **Each Thermal Pump: 1250 W.**
- **Closed Brayton Cycle Generator**
  - 60k RPM shaft
  - 2 MPa Manifold Pressure
  - Turbine Inlet Temp 1150K
  - Radiator Rejection Temp 400K
- **Cabling**
  - Switched Power (to thermal pumps): 200m, 2% loss
  - Habitat Power: 200m, 5% loss
  - Pump Power: 25m, 2% loss

4.0 Avionics Groundrules & Assumptions

- **AFFRE space vessel controls flight of the stack**
  - Independent of other elements (Habitat and payloads)
  - The Habitat has command override capability
  - All elements provide health & status instrumentation
- **Guidance, Navigation, and Control (GN&C)**
  - Maneuvers and attitude control use RCS (No reaction wheels or CMGs)
  - A tender vehicle will be used for attitude control during assembly and startup
  - No AR&D capability will be included on any FFRE element
  - An Assembly vehicle will perform all assembly and docking operations
- **Communications**
  - Single HGA system for navigation and data link to the DSN
  - Single MGA system used in LEO for link to NEN and TDRSS
  - LGA system on each element for assembly support and backup
  - Video monitoring cameras on each element

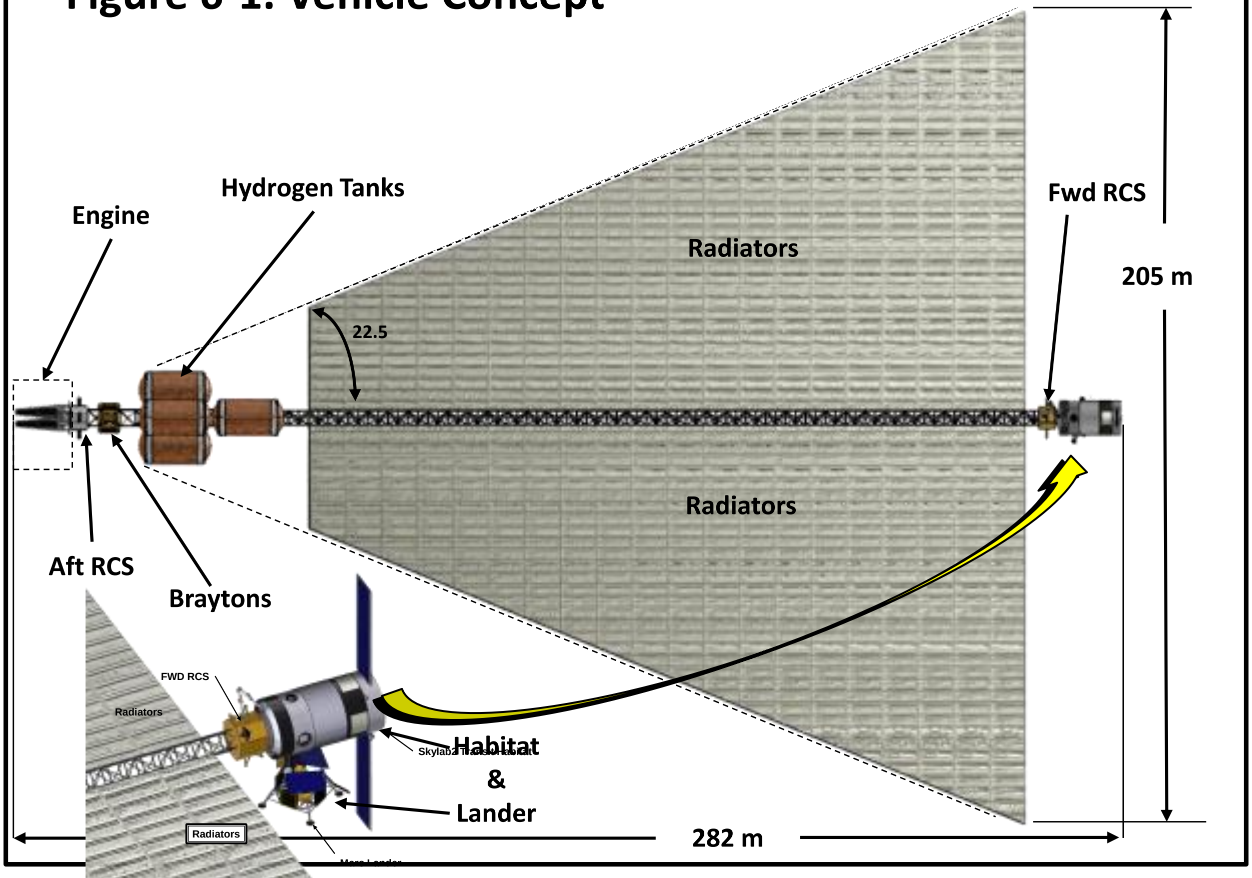
Thermal Groundrules & Assumptions

Category	Value
Crew Thermal	Not sized for this study (borrowed from HOPE)
Avionics	MLI, heaters, thermostats, radiators, heat pipes, pumps, heat exchangers, etc. to maintain spacecraft subsystem components within acceptable temperature ranges
Liquid Hydrogen Storage	Passive management (24 hours in LEO), active management (ZBO sized for LEO environments)
Environments	LH2 propellant management and boil off estimates based on vehicle environments at 407 km earth orbit, GG orientation.
Radiators	Radiators assumed to be double sided, deployed, and to have 0 deg. K view.
Low-Temp Radiator	140 K - 2 Sided - Areal Density 3.7 kg/m2
Medium Temp Radiator	590 K - 2 Sided - Areal Density is 4 kg/m2
High Temp Radiator	1200 K - 2 Sided - Areal Density is 5 kg/m2
Brayton Power System Radiator	400 K - 2 Sided - Areal Density is 4 kg/m2

This study started with the mission Groundrules of human exploration to Mars using the contemporary Mars DRM 5.0 as adjusted for the capability of a one vehicle architecture provided by an AFFRE. This was combined with the FY11 NIAC FFRE-propelled vehicle (itself a revised product of a 1990's Human Outer Planets Exploration (HOPE) vehicle) and the Grassmere Dynamics spreadsheet of AFFRE performance to begin the engine-to-vehicle-to-mission iteration until the synthesis closed.

As shown in Figure 6-1 below, the result produced a huge, powerful vehicle dominated by the enormous radiators required to reject the heat produced by the inefficient AFFRE.

Figure 6-1. Vehicle Concept



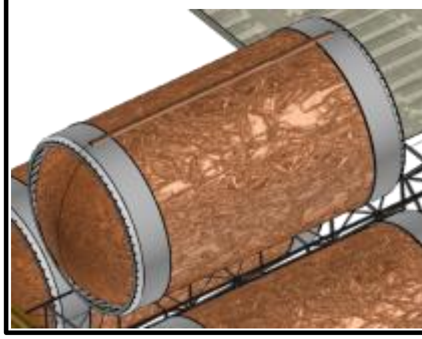
Most forward is the payload, a 135mT lander and a 35mT habitat/vehicle control center with its avionics radiators. This is followed by the forward reaction control system (RCS) located on the central spine of the vehicle. The spine is a square aluminum truss structure that supports the multiple radiators required to cool the AFFRE components. Within the spine are located the crash-proofed storage containers containing the Americium nuclear fuel which is suspended in a boric acid solution that acts as a neutron poison to keep the fuel inert until needed. Next in line are the propellant tanks storing liquid hydrogen under Zero Boiloff conditions, followed by the Brayton cycle electrical power generators, the aft RCS, the radiation shadow shield and lastly, the AFFRE. The following discussion briefly covers each major subsystem of the vehicle followed by analysis of a Mars round trip mission. For a more complete discussion, Appendix B covers in detail the vehicle study.

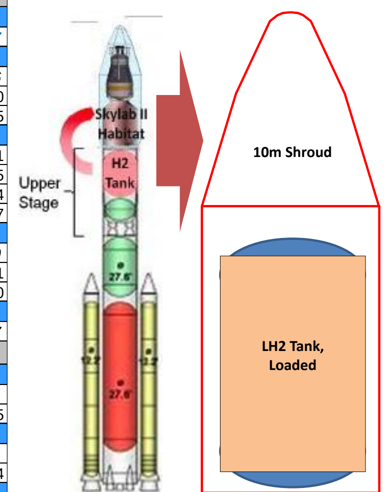
Propulsion: While the engine description has been covered in Section 5, the remainder of the propulsion system needs review. The hydrogen tanks used in this concept, Figure 6-2, were directly derived from a previous Mars mission study using traditional nuclear thermal propulsion. Each tank was sized to maximize the use of the SLS 10 meter payload shroud and each launch of a hydrogen tank is volume constrained, rather than mass. The vehicle has room for 8 hydrogen tanks; only 5 are required for the current mission. The tanks support zero boil-off hydrogen storage with the use of 20K cryo-coolers and take advantage of the massive amount of available electrical power.

Figure 6-2. Hydrogen Tanks

- Tanks derived from "Cryogenic Nuclear Propulsion Stage" Study employing Zero Boil-Off (ZBO)
- Tanks resized for AFFRE
  - Tanks sized to maximize hydrogen delivered by SLS Block 2
  - ZBO equipment and non load-bearing structures sized to AFFRE needs

Individual Tank Mass Summary			Mass (kg)
1.0	Structures		10,097
	1.1	*Primary Structure*	*10,097*
2.0	Propulsion (MPS)		364
	2.1	Pressurization System	*296*
	2.2	Valves	90
	2.3	Ducting	205
3.0	Power		364
	3.1	Avionics PDU	21
	3.2	Heaters, C&DH, Power Reg PDU	45
	3.3	Battery	64
	3.4	Harnesses	7
4.0	Avionics		689
	4.1	Cmd & Data Handling (C&DH)	*589*
	4.2	Communications	41
	4.3	Vehicle Systems, Heaters, Misc	60
5.0	Structures		2457
	5.1	Cryo Fluid Management	*2,457*
Dry Mass			13,743
6.0	Non-Propellant Fluids		35
	6.1	*MPS*	*35*
		6.1.2 Hydrogen Boiloff	35
7.0	Useable Propellant		68,684
	7.1	*MPS*	*68,684*
		7.1.1 Cryogenic Hydrogen	68,684
Total Mass Per Tank			82,642



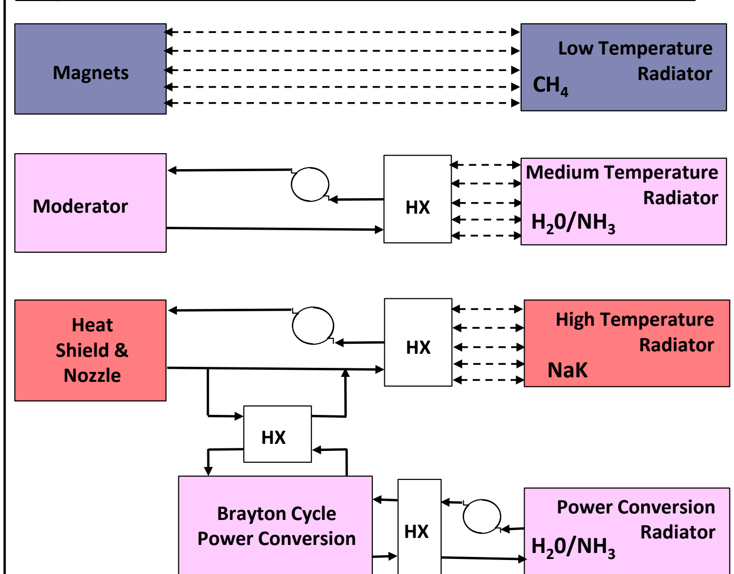


The other tankage needed for the AFFRE is for the Americium fuel. There are nine 4000kg tanks each containing 80kg of Americium dust suspended in a concentrated boric acid solution that acts as a neutron poison to prevent the fuel from going critical. The tanks are heavily crash-protected so that all can be safely launched to orbit. Once in orbit, the tanks can be transferred into the truss structure where connections to the nuclear fuel pumps provide delivery to the engine. Upon injection into the engine, the boric acid is flash evaporated, leaving behind the Americium dust to maintain reactor criticality.

A radiation shadow shield doubles as the thrust structure of the AFFRE. While neutron flux is moderated, the gamma ray radiation will escape the engine. To protect the rest of the spacecraft, including the crew, a shadow shield of 5 cm tungsten reduces the gamma ray flux. The shape outlines the engine base to maintain a 22.5° shadow cone for the radiators and crew systems forward of the engine. This shield is actively cooled using the medium temperature radiator loop.

Thermal Control: There are four thermal control systems for the FFRE vehicle as shown in Figure 6-3. A low temperature radiator system for the superconductor magnet system, a

Figure 6-23. Thermal Control Schematic



medium temperature radiator system for the moderator, a high temperature radiator to cool the moderator heat shield and nozzle, and a second medium temperature radiator for the Brayton power conversion system for heat rejection.

The low temperature system utilizes methane heat pipes where the evaporator end is in contact with the magnet system and the condenser portion is incorporated into the radiator. Loop heat pipes were selected based on their ability to transfer heat over relatively long distances. These heat pipes are self-pumping and do not require a pump in the system. All other thermal control loops incorporate a pump, heat exchanger, piping, and valves due to the significantly larger amount of heat to be transferred. The thermal control system components are estimated at 15% of the radiator panels.

Figure 6-4 details operating temperatures, areal densities, and calculated radiator size and mass for each of the radiator systems used for the AFFRE design. Analyses performed to size the radiators assumed the panels had a perfect view to space and were at a constant average temp-erature. The infrared emissivity was assumed to be 0.95. The areal densities assume heat pipe radiators of composite panels. Carbon fiber radiator technology is being advanced and would result in a lower unit weight.

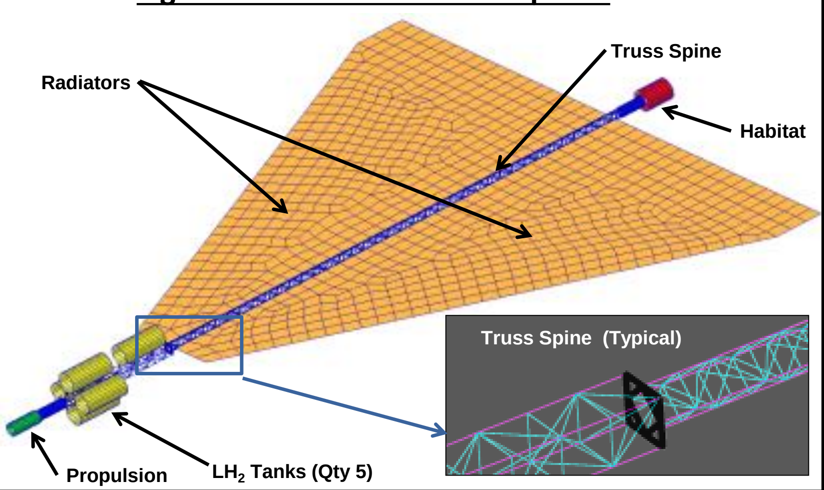
Figure 6-4. Radiator Analysis Results

- Heat pipe radiators: Lightweight composite, double sided, 0K view to space
- Radiator mass includes deployment mechanism
- Pumps, plumbing, and heat pipes: 15% of radiator panel mass
- Areal density taken from NASA/TP-2003-212691, , "Conceptual Design of In-Space Vehicles for Human Exploration of the Outer Planets"

Radiator System	Operating Temp (K)	Areal Density (kg/m²)	Radiating Area (m²)	Heat Rejection (MWatt)	Radiator Size (m²)	Radiator Mass (kg)
Low Temperature Loop (Magnets)	140	3.7	19333	0.40	9667	71535
Medium Temperature Loop (Moderator)	590	4.0	22614	147.6	11307	90455
High Temperature Loop (Heat Shield & Nozzle)	1200	5.0	2707	302.3	1353	13534
Brayton Cycle Cooling Loop	400	4.0	928	1.28	464	3714

Structure: The primary structure shown in Figure 6-5 was analyzed using MSC Nastran with the finite element models developed using MSC Patran. The 3D Truss Spine structure was modeled with linear CBAR elements. Multi-point constraints were used to connect subsystem components representing Propulsion, Thermal Radiators, Avionics, Power, LH_2 Tanks, and payload. The fuel tanks, propulsion system, and habitat were modeled using CBAR elements, rigid in stiffness and attached to the spine structure using multi-point constraint elements. All truss spine members were assumed to have the same

Figure 6-5. FEA Model Description



diameter and wall thickness for simplicity of analysis. The Truss Spine structure was developed using ProE CAD models.

Subsystem loads were applied using multiple RBE3 multi-point constraint elements to simulate inertial loading from the subsystem components. The radiators were meshed using CQUAD4 elements and are shown in Figure 6-5 as illustration of size. They were not considered part of the structural model and were not attached to the Spine structure but separately constrained. The habitat size and mass were derived using information from a previous Skylab II feasibility study.

The model loads were applied using FORCE cards which simulate inertial acceleration. One load condition was analyzed, the axial thrust of 1046lbf. It was recognized that this may not be the design driving load condition, but there were insufficient resources to conduct a comprehensive study. The driving design factor for this analysis was stability. Model stresses were extremely low and did not size any structure. The first buckling mode was a classic 1st order beam buckling model with simply constrained end points. The first buckling eigenvalue was 9.89, which is much higher than the required 1.4 Global Stability value.

Additional mass estimation included secondary mass percentage of 10% (since the structure is almost 100% Truss members) and an estimate of 50% of the Truss Spine mass added to account for Truss Joints and Fittings. A Mass Growth Allowance of 30% was assumed because of the low fidelity description of loads.

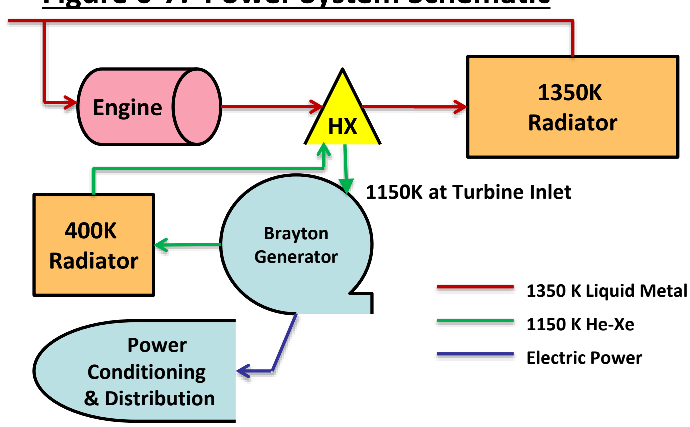
Power: The previously mentioned HOPE NEP study had a similar vehicle that was used in this study as the benchmark. The habitat requires only 25kW power. The AFFRE requires 26kW to operate while the AFFRE magnetic nozzles require 75kW. The thermal control system consumes 106kW.

Figure 6-6. Power Sizing

Load	Required Power
Habitat	25 kW
Active Thermal Control	106 kW
AFFRE & Nozzles	101 kW
Avionics	10 kW
Design Margin (24%)	58 kW
Total Required (3 Brayton Generators)	***300 kW***
Total Available (2 spare units)	***500 kW***

The Closed Brayton Cycle (CBC) generators were taken as-is from the NASA Human Outer Planets Exploration study. The study used a high fidelity design tool to design a number of 100kW power plants with different parameters to determine which had the lowest system mass. Brayton cycle generators are not as efficient in general as Rankine generators, but they are lighter per unit power generated, and were selected for this study.

Figure 6-7. Power System Schematic

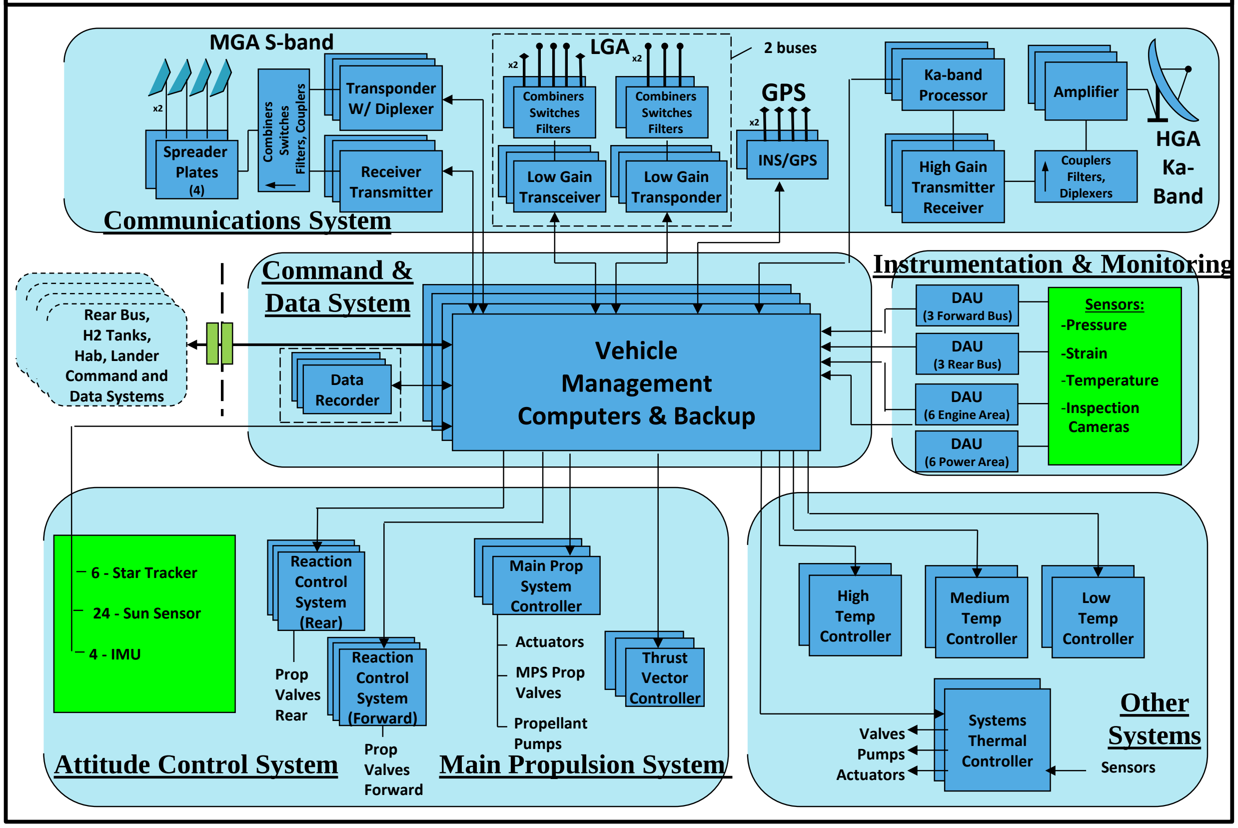


This schematic of Figure 6-7 illustrates the power conversion process. The

AFFRE heats liquid metal to transport the heat to the 1350K high temperature radiators. A heat exchanger is used to heat He-Xe gas to power the Brayton engine. The Brayton generator converts the thermal power to electricity and delivers He-Xe at 400K to the low temperature radiators. The power produced is managed by the PMAD system. Although three Brayton units are required, five are carried for fault tolerance.

Avionics: This avionics diagram shown in Figure 6-8 is for the spacecraft bus, and does not include the avionics for the Zero Boil-Off subsystem required for the hydrogen tanks.

Figure 6-8. Avionics Schematic



A data bus link is shown to the left that interfaces with the hydrogen tanks avionics, along with the Habitat and lander. The top section is the communication section with the Ka-band High Gain Antenna (HGA) system, S-band medium Gain Antenna (MGA) system, and multiple Low Gain Antenna (LGA) systems to be installed on each element. The vehicle would have a LGA and instrumentation on both the forward and rear buses. Instrumentation for the engine area and power generation area would also be provided. The attitude control and Main Propulsion system avionics is shown in the lower left. The Reaction Control System equipment would be located in the forward and rear spacecraft buses with the RCS thrusters. The Main Propulsion System equipment would be located in the engine area, and might need additional radiation shielding not accounted for in the avionics mass. The star trackers and IMUs would be located in the forward bus. Data from the sun sensors would be broadcast throughout the spacecraft and radiators for approximate pointing knowledge. The thermal control system, shown in the lower right of the diagram, consists of the high, medium, and low temperature controllers, along with the Brayton and vehicle thermal controllers.

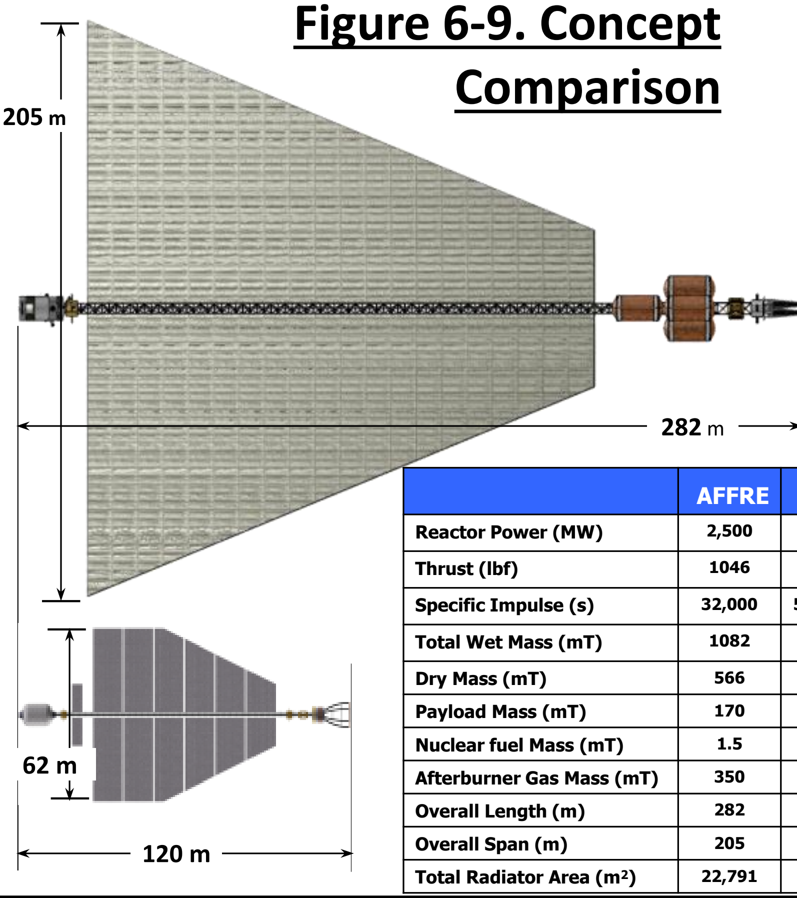
The vehicle would be in control of the flight of the stack independent of payload elements, particularly the Habitat, landers, and payloads. The Habitat would have command override capability. All elements would provide health and status instrumentation to the AFFRE vehicle.

For Guidance, Navigation, and Control (GN&C), maneuvers and attitude control would be accomplished using the Reaction Control System (RCS). No reaction wheels or Control Moment Gyros would be used. An Assembly vehicle would perform all assembly and docking operations for the construction of the stack, as well as maintaining orientation during assembly and providing power prior to startup. No Automated Rendezvous & Docking (AR&D) capability would be included on any spacecraft component except for payloads which would have active AR&D systems for maneuvering and docking.

Communications would consist of three different systems. The single HGA system would be used for navigation and data link to the Deep Space Network. The single MGA system would be used in LEO for link to TDRSS. A LGA system on each element would be used for assembly support and backup of the wired link between elements and ground. Video monitoring cameras would be included on each element.

Integrated Vehicle: Figure 6-9 shows the comparison between the spacecraft concept developed under the Part 1 study and the Part 2 study concept. The Part 1 study vehicle was sized for a Jupiter mission using a low-thrust, high-Isp engine design using a 1000MW reactor. The mission duration was 15 years round-trip; the propellant load on this spacecraft was very low due to its 527,000sec specific impulse. The Part 2 study spacecraft was sized for a shorter Mars mission. The changes to the engine design have resulted in a significant increase in reactor power to 2500MW to provide more thrust but at a significant decrease in specific impulse. This results in a much higher propellant load, although the nuclear fuel required is much less than in the Part 1 study.

Figure 6-9. Concept Comparison



	AFFRE	FFRE
Reactor Power (MW)	2,500	1,000
Thrust (lbf)	1046	10
Specific Impulse (s)	32,000	527,000
Total Wet Mass (mT)	1082	303
Dry Mass (mT)	566	295
Payload Mass (mT)	170	60
Nuclear fuel Mass (mT)	1.5	8.0
Afterburner Gas Mass (mT)	350	0
Overall Length (m)	282	120
Overall Span (m)	205	62
Total Radiator Area (m^2)	22,791	6,076

As shown in Figure 6-10, the vehicle size has dramatically grown for three reasons: 1) the payload is increased by a factor of three; 2) the reactor power was increased by a factor of 2.5; and 3) the specific impulse reduction by a factor of 16 results in a considerable fuel load, but a shorter mission time. The Part 1 study vehicle, of about ISS size and mass, was within the capability of a SLS-like heavy launcher to deliver the subassemblies for on-orbit assembly in five lifts. But the starting point for any mission had to be L1 or beyond due to the low FFRE thrust. The Part 2 study vessel, in contrast, is about the size of a nuclear aircraft carrier with most of this expanse due to its massive radiators. These radiator systems connected to truss structures are very much like those of the ISS, allowing on-orbit assembly, integration and checkout using the same ISS-learned methodology. As a result, this massive space vessel can be packaged into subassemblies for 11 SLS-like heavy launcher flights. Also, the substantially greater thrust provides a vehicle acceleration that permits mission initiation from Low Earth Orbit rather than L-1, handily reducing the logistics of mission preparation.

Figure 6-10. Vehicle Size Comparison

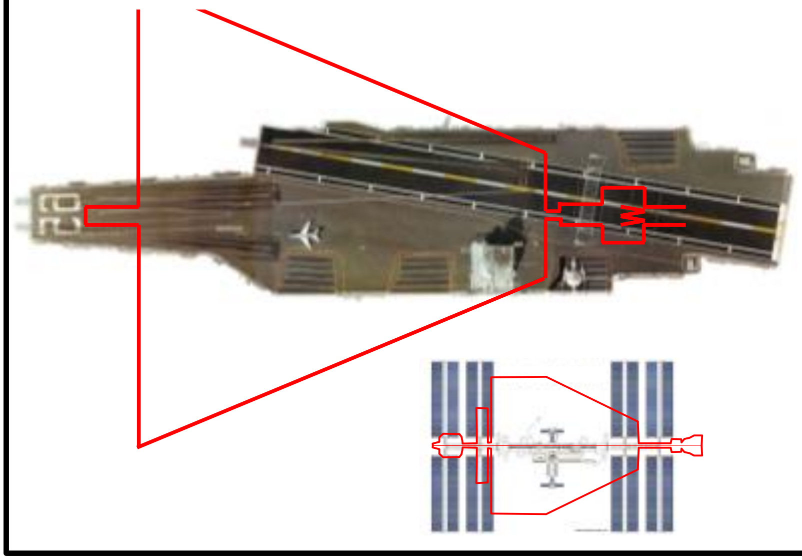


Figure 6-11 summarizes the Part 2 study vehicle basic mass of 927,704 kg (927mT) and the Mars Mission mass of 1,081,518 kg (1082mT). The dry mass includes the reaction control system, main propulsion consisting of AFFRE, hydrogen tanks with zero boil-off equipment, and truss structure, thermal, and power. The vehicle dry mass also includes the non-propellant fluids and payload. The total vehicle mass includes, in most cases, a 30% factor for mass growth allowance (MGA).

Figure 6-11. Vehicle Mass Summary

AFFRE MEL		Basic Mass (kg)	MGA (%)	Predicted Mass (kg)
1.0	Attitude Control System (ACS)	711	30%	925
2.0	Propulsion	222709	21%	268907
3.0	Structures	4538	30%	5899
4.0	Thermal	216137	30%	280816
5.0	Power	4777	30%	6200
6.0	Avionics	2411	29%	3118
Dry Mass		451283	25%	565865
7.0	Non-Propellant Fluids	54		54
8.0	Payload	130769	30%	170000
9.0	Propellant	345599		345599
Total Vehicle Mass		927704		1081518

The key trade that determined the vehicle size and performance required finding the "sweet spot" of reactor power. The Grassmere engine model allowed the paramertization of engines to produce sizing relationships for the vehicle dry mass as a function of reactor power. The reactor power affects the total thermal energy rejection which, in turn, impacts the area and mass of the radiators. The radiator area drives the mass of the primary structure of the vehicle by affecting its overall length. A relationship of thrust and dry mass as a function of reactor power was developed to support the mission analysis. As the power was reduced, thrust and mass were reduced resulting in longer spiral times for Earth and Mars proximity operations and more propellant consumed. With decreasing reactor power, the propellant load increased at a faster rate than the dry mass decreased. Consequently, a reactor power of 2500MW was determined (for the set of design assumptions) to be the cross over point and established the design point power level for this study.

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)**

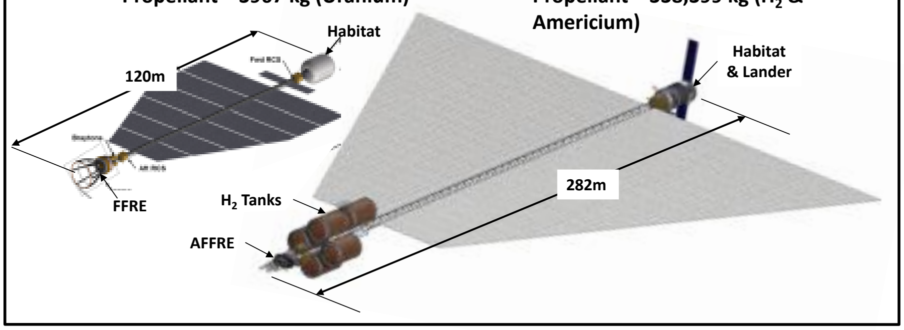
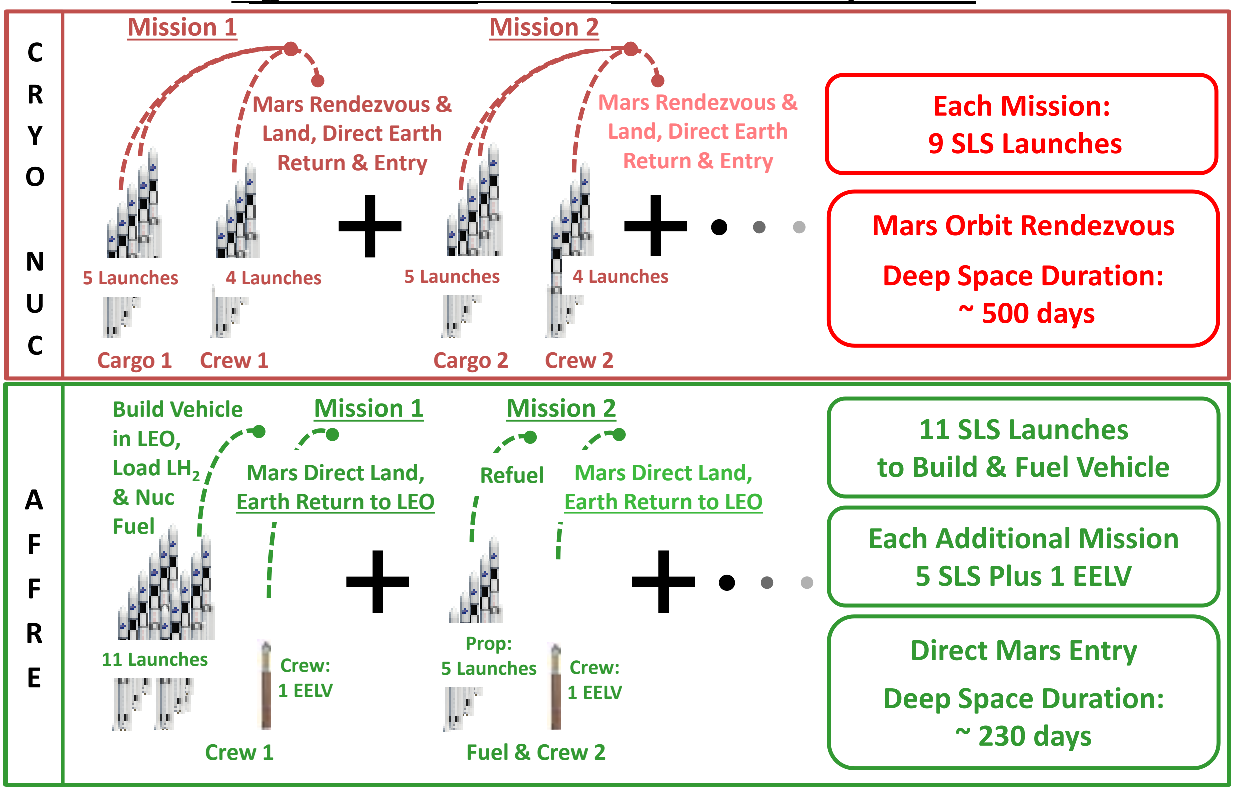


Figure 6-12 provides another side by side comparison of the two concepts in terms of mass and physical size. The four major drivers behind the mass increase are the heavier payload, the heavier engine, the mass of the radiator system and the need for additional propellant. The engine mass has increased due to the new geometric configuration that ensures the escape of fission fragments from the reactor and interaction with the hydrogen. This half torus configuration requires significantly more moderator material and additional superconducting magnets. The vehicle size is a direct result of the need for larger radiators. This increase is due to the distribution of the heat flux from the reactor and the 2.5 factor increase in power level. However, the current engine is significantly more efficient at converting heat energy to thrust which leads to a reduction in the heat rejection requirement from 700 MW to 450 MW. In the current design, a significantly higher percentage of that heat flux reaches the superconducting magnets, which must be maintained at a low temperature. This leads to a larger overall radiator area which increases both the thermal subsystem attributes and the length of the overall vehicle as well. The additional propellant needed, consisting of hydrogen tanks with the vital Zero Boil-off equipment, are required to compensate for the lower, but more efficiently matched to the mission, engine specific impulse.

The AFFRE Mars reusable space vessel compares favorably with conventional Mars mission "throwaway" architectures with significant benefits as shown in Figure 6-13. A rough estimate of as few as 11 SLS-like launches would create a fully fueled AFFRE-propelled reusable space vessel and one EELV-like launch would be required to provide the crew. This is about 2 more launches than envisioned for a Cryogenic Nuclear Thermal Propulsion-based mission but one or two less launches for a Chemical Propulsion-based Mars mission. The real savings occur for future missions. Rather than building and launching a new set of mission vehicles, a 9 to 12 SLS launch undertaking, only 5 SLS launches of hydrogen and nuclear fuel and one EELV-like crew launch are all that is required to ready the AFFRE-powered space vessel for the mission.

The AFFRE also offers the advantage of a single stack trip to Mars rather than splitting the trip into multiple separate stacks that need to journey separately to Mars, including some needing to rendezvous in Mars orbit before descending. Unlike traditional Mars architectures that stage away elements during the mission, the entire AFFRE spacecraft returns to be propulsively braked into Earth orbit for refueling, replenishment, and reuse. Finally, the AFFRE spacecraft also provides more than a 50% reduction in the deep-space transit time for the crew, saving consumables, reducing mission risk and greatly reducing the crew's exposure to the deep space radiation environment.

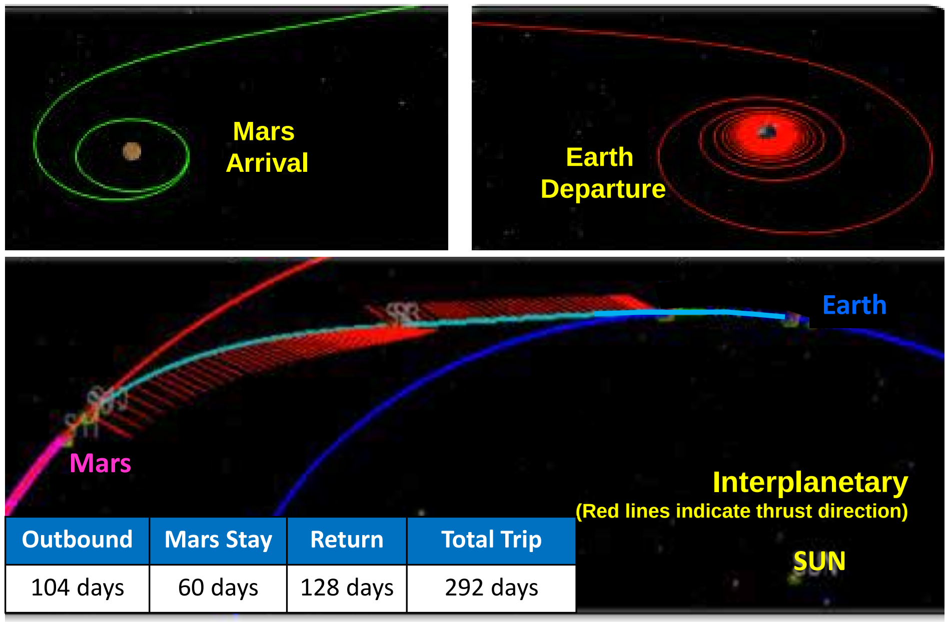
Figure 6-13. Mars Architecture Comparison



7. Mission Analysis

For this Part 2 study, the mission chosen to enable direct comparison with other architectures was the human Mars exploration mission. The mission is based on the Mars DRA 5.0 with some very significant differences based on the respective vehicle capabilities. In the DRA 5.0 approach, two cargo missions are flown to Mars followed by a crew flight. The crew must rendezvous with a pre-deployed lander in Mars orbit and descent to the surface where they rendezvous with a pre-deployed surface infrastructure that includes a habitat, surface power system, and in-situ produced propellant required for Earth return ascent. The contemporary duration of a Mars DRA 5.0 mission requires 1000 days, including a 500 day stay at Mars and two transfer legs that total approximately 500 days in deep space.

Figure 7-1. AFFRE Mars Architecture-



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

In an AFFRE version of this mission, all elements will be delivered on one AFFRE spacecraft flight. First, the AFFRE vehicle needs to be launched in pieces, assembled, integrated, checked out, and fueled in LEO. All elements for the mission travel to Mars on one stack. A single Mars lander is assumed at a mass of 135 mT as compared to two 100 mT landers in DRA 5.0. Figure 7-1 shows the overall mission timeline from LEO to the return to LEO for crew transfer back to Earth. The AFFRE spacecraft also enables significantly faster trip times to and from Mars. This reduced trip time results in lower consumable masses for the crew leading to a 35 mT deep space habitat (compared to a 41 mT habitat in DRA 5.0) and significantly reduced the health risks to the crew. It is important to note that the engine performance of this vehicle also allows for a propulsive capture back into LEO, where it can be refueled and replenished in space for multiple missions. While the Mars mission was used as a sizing case, there are many other missions that would benefit from the performance of this spacecraft. Unfortunately, there was not time to explore any other missions.

8. Seeing a Path Forward

Three years of study leads this PI to make the following conclusions that apply to Fission Fragment Rocket Engines, the variants, and about the vehicles that result from incorporating this technology. What is remarkable is that these conclusions have withstood the ups and downs and ups again of this analytical adventure:

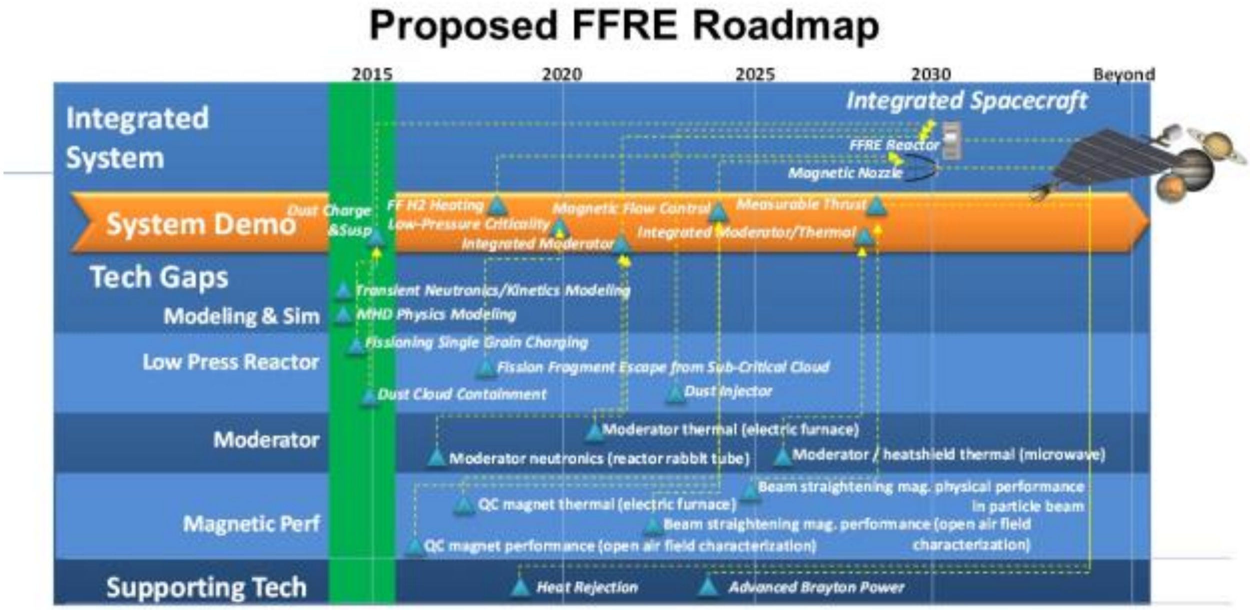
- FFs when turned loose are useful in producing thrust. This concept has proven robust to analysis and peer review
- FFREs use today's materials and todays physics – are not dependent on "HOPE" or= pulsed fusion physics.
- FFREs are not yet efficient. However, this inefficiency allows for production of unimaginable amounts of electrical power. This inefficiency also means they need LOTS of radiators. They also need lots of moderator material, making the reactor heavy. Large size vehicles result from the large reactor mass and radiator mass. But these radiators and moderators and power generators are less complex than those of ISS since power comes from a reactor rather than solar wings.

- FFREs, despite their size and mass, fit within SLS lift capability & envelope (if the moderator is drained). Large FFRE-propelled vehicles are launchable in pieces on SLS just like ISS was lifted by the Space Shuttle.
- This application of nuclear technology far safer than conventional NTR:
  - the AFFRE reactor self-cools so there is no core meltdown
  - full scale terrestrial testing possible due to small efflux per pound of thrust
  - exhaust radioactivity passes the orbit of Neptune within 200days
  - launch is unfueled which avoids making the payload a launch hazard or a launch preparation target for terrorists
  - residual radiation in the engine is small, it is flushed in the shutdown exhaust
  - nuclear fuel can be brought to orbit in crashproof containers
- Afterburner FFRE allows for mission flexibility by tailoring thrust and impulse to the mission. Alternate missions deserve detailed study also
- Once in LEO, the vehicle is useable for decades - to journey to many destinations AND TO RETURN INTACT
- Huge payloads can be carried on single vehicle, which simplifies mission architectures
- Provides NASA and international community with a chance to collectively work on a meaningful, enduring vehicle that opens up the Solar System to exploration

In summary, the AFFRE technology provides several significant benefits over any traditional propulsion system. Its combination of thrust and specific impulse enables short trip times to Mars on relatively low propellant loads. The reusability of the spacecraft is an appealing feature that can transform the way we think about interplanetary travel. However, the technologies required to make such a spacecraft a reality present some challenges and must be developed further before this spacecraft design can be refined.

Suggestions for near term future work include investigating more fission fragment-based engine alternatives. Higher efficiency systems that will support a reduction in required reactor power and commensurate radiator size would be interesting. Also of interest would be engine versions that reduce the heat flux into low-temperature components. Refined mission parametric analyses will also reveal more uses for the vehicle and help inform the design path for the engine to maximize its usefulness, both for Mars and for other solar system destinations. Lastly, it is time to begin in earnest doing the necessary nuclear critical (system) experiments that demonstrate that this technology is ready to enter mainstream development; the first simple experiment is underway in FY13 at Oak Ridge. These “system” experiments are not expensive and would make major strides in demonstrating concept credibility.

A first cut at a development roadmap is summarized on the next page. While the dates are “out of date”, the activities identified need only to demonstrate the engineering development of well-understood physical principles of Fission Fragments. This is not to diminish the challenging engineering solutions needed to the thermal and radiation environments of the FFRE, but no “new physics” development is required.


Proposed FFRE Roadmap
2015
2020
2025
2030
Beyond
Integrated System
Integrated Spacecraft
FFRE Reactor
Magnetic Nozzle
System Demo
Dust Charge &Susp
FF H2 Heating
Low-Pressure Criticality
Integrated Moderator
Magnetic Flow Control
Integrated Moderator/Thermal
Measurable Thrust
Tech Gaps
Modeling & Sim
Transient Neutronics/Kinetics Modeling
MHD Physics Modeling
Low Press Reactor
Fissioning Single Grain Charging
Fission Fragment Escape from Sub-Critical Cloud
Dust Cloud Containment
Dust Injector
Moderator
Moderator thermal (electric furnace)
Moderator neutronics (reactor rabbit tube)
Moderator / heatshield thermal (microwave)
Magnetic Perf
Beam straightening mag. physical performance in particle beam
QC magnet thermal (electric furnace)
Beam straightening mag. performance (open air field characterization)
QC magnet performance (open air field characterization)
Supporting Tech
Heat Rejection
Advanced Brayton Power