NIAC Spring Symposium

FFRE Powered Spacecraft

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Robert Werka
MSFC EV72
FY11 NIAC Fellow

What is NIAC?

NASA Innovative Advanced Concepts

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

A FISSION FRAGMENT ROCKET ENGINE THAT:

Can free spacecraft from today’s propulsion limitations
- Far less propellant than chemical or nuclear thermal.
- Far more efficient than nuclear electric.
- Far safer: charge reactor in space, radioactivity ejected.

Has highest exhaust velocity possible today
- 10s – 100s lbs of continuous thrust (years).
- Specific impulse above 500,000 s in practical design.

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

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

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

**Grassmere Dynamics Dusty Plasma Reactor**
2003: Dr. Rob Sheldon levitated dust in stably trapped plasma by a quadrapole magnetic field with added levitating magnetic field divergence.

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

The Company

- Engineering & Consulting
- Specialty Modeling Skills:
  - Computational Fluid Dynamics (CFD)
  - Magneto Hydrodynamic Plasma (MHD)
  - Nuclear (Radiation, Reactor Design & Performance)
  - Optical

3D Simulation Of Tokomak Nuclear Fusion Reactor Magnetically Confined Plasma Using Grassmere Developed Code
Spacecraft and mission based on 2004 Human Outer Planet Exploration (HOPE) study

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

Organize:
- Study structure, goals, objectives
- Identify SMEs, allocate resources
- Identify study outputs & milestones

Notional Architecture & L1 Reqmts
FFRE Concept
Spacecraft Concept
Iterate to Close

Data Archival & Reporting
- TRL Maturation Roadmap
- Operations Concept
- Test Methodology
- Manufacture, Technology, Issues, & Risks

Complete
Forward Work

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

- **Nozzle Beam Straightening Coils**
- **Moderator Heat Shield**
- **Reacting Dusty Plasma Cloud**
- **Superconductors**

- **Dimensions:**
  - 11.5 m
  - 2.8 m
  - 5.4 m Ø

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

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**Master Equip List Mass incl 30% MGA**

<table>
<thead>
<tr>
<th>FFRE System Total, mT</th>
<th>113.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle</td>
<td>6.4</td>
</tr>
<tr>
<td>Magnetic Mirror</td>
<td>28.6</td>
</tr>
<tr>
<td>Exit Field Coil</td>
<td>11.1</td>
</tr>
<tr>
<td>Moderator</td>
<td>51.2</td>
</tr>
<tr>
<td>Moderator Heat Shield</td>
<td>0.1</td>
</tr>
<tr>
<td>Control Drum System</td>
<td>0.7</td>
</tr>
<tr>
<td>Electrostatic Collector</td>
<td>0.3</td>
</tr>
<tr>
<td>Dust Injector</td>
<td>7.2</td>
</tr>
<tr>
<td>Shadow Shield</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**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**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Thrust</td>
<td>43 N</td>
</tr>
<tr>
<td>(9.7 lbf)</td>
<td></td>
</tr>
<tr>
<td>Exit Velocity</td>
<td>5170 km/s</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>527,000 s</td>
</tr>
<tr>
<td>Mass Flow</td>
<td>0.008 gm/s</td>
</tr>
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**Revised FFRE Designs**

**Generation 1**
- **Attributes:**
  - Ellipsoid Moderator
  - Ring Magnets

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

**Generation 2**
- **Attributes:**
  - Dual Paraboloid Moderator
  - Ring Magnets

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

**Vehicle**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Payload (Crew/Science Equip.) (mT)</td>
<td>60</td>
</tr>
<tr>
<td>Total Mass (mT)</td>
<td>303</td>
</tr>
<tr>
<td>Dry Mass (mT)</td>
<td>295</td>
</tr>
<tr>
<td>Propellant Mass (mT)</td>
<td>4</td>
</tr>
<tr>
<td>Overall Length (m)</td>
<td>120</td>
</tr>
<tr>
<td>Overall Span (m)</td>
<td>62</td>
</tr>
<tr>
<td>Total Radiator Area (m²)</td>
<td>6,076</td>
</tr>
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</table>

**Performance**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Power (MW)</td>
<td>1,000</td>
</tr>
<tr>
<td>Thrust (N)</td>
<td>43</td>
</tr>
<tr>
<td>$I_{sp}$ (s)</td>
<td>527,000</td>
</tr>
<tr>
<td>Vehicle Acceleration (g)</td>
<td>$3 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- **FFRE** Proellant Tank
- **Nuclear Shadow Shield**
- **Triangular Structure**
- **FFRE Magnetic Nozzle**
- **Aft RCS** Brayton Cycle Generators
- **Fwd RCS**
- **60 mT Crew Habitat & Exploration Equipment**
- **Payload Avionics Radiators**
- **Low Temp (Super-Conducting Magnet) Radiators**
- **Med Temp (Moderator) Radiators**
- **High Temp (Moderator Heat Shield) Radiators**
Spacecraft Performance
(First FFRE / Spacecraft Assessment)

Initial FFRE Propelled Spacecraft Mission Performance
1st Generation FFRE: 43 N Thrust 527,000s $\mu_\text{sp}$
Spacecraft is acceleration limited

<table>
<thead>
<tr>
<th>Outbound Trajectory Results</th>
<th>Segment Time (Days)</th>
<th>Thrust Time (Days)</th>
<th>CUM Nuclear Prop (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Spiral — Out</td>
<td>55</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Interplanetary</td>
<td>2,106</td>
<td>2,161</td>
<td>1,553</td>
</tr>
<tr>
<td>Jupiter Spiral — In</td>
<td>503</td>
<td>2,665</td>
<td>1,915</td>
</tr>
</tbody>
</table>

Stay Time at Callisto: ~330 Days

Total Elapsed Mission Time: 5,850 Days (16.0 Years)
Total Nuclear Fuel Used: 4 mT
Effect on Mission Of 2nd Generation FFRE Design

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

**Spacecraft**
- Assumed no change (conservative)

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

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

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

**Spacecraft**
- Added “propellant” and tankage

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

What Is Learned So Far

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

THERE’S MUCH WORK TO DO.