Pulsed Fission Fusion (PuFF) Propulsion System

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PuFF enables robotic missions to the outer solar system and near interstellar space, and greatly enhances crewed missions in the inner solar system.

- The PuFF engine system provides a propulsive impulse operating on the principle of a pulsed two stage nuclear reaction combining Fission and Fusion processes triggered by the compression of a nuclear fuel target (containing small quantities of uranium/tritium) using an intense electrical pulse.

- Resultant charged particles, emitted by the impulse, are deflected by magnetic nozzle, also serving as an energy capture device to energize the primary power system capacitors for subsequent pulse.

- Concept focused on a single reusable vehicle design enabling a wide range of mission architectures. For example, Mars mission performance sufficient to carry Space Habitat, CEV, Lander, Surface Habitat & ISRU facility (120 mT payload).

PuFF enables missions throughout the solar system and beyond with a single, in-space, reusable engine design.

<table>
<thead>
<tr>
<th>PuFF</th>
<th></th>
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<tbody>
<tr>
<td>Isp</td>
<td>30,000 sec</td>
</tr>
<tr>
<td>Thrust</td>
<td>29,000 N</td>
</tr>
<tr>
<td>In-Space System Weight (Mars Mission)</td>
<td>240 Metric Tons</td>
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Fission and Fusion Energy Release
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- Mass Defect = Mass of free nucleons – mass of assembled nucleus
  - Nuclear force (residual strong force) stronger than electrostatic
- Nuclear Binding Energy
  - \( \frac{E}{A} = \frac{\Delta m}{A} c^2 \)
- Fusion
  - Energy release by combining nuclei
- Fission
  - Energy release by splitting nuclei

http://en.wikipedia.org/wiki/Nuclear_binding_energy
Fission/Fusion Reaction Space

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- **Fission**
  - Neutron
  - Fissile Nucleus (U-235)
  - Product Nuclei (KE - 169 MeV)
  - Neutrons (E ~ 2.2 MeV)

- **Fusion**
  - Deuterium
  - Helium

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http://www.mwit.ac.th/~physicslab/hbase/nucene/fisfrag.html#c1

http://www.propagation.gatech.edu/ECE6390/project/Fall2010/Projects/group10/MANTIS_2010_SatCom/MANTIS_2010_SatCom/PowerSys/default.html

http://fusionforenergy.europa.eu/understandingfusion/

http://en.wikipedia.org/wiki/Nuclear_fusion
Fission/Fusion Ignition Requirements

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• **Fission**
  - Criticality is a function of
    - fission cross section
    - Number density
    - And geometry
  - Neutrons must balance
    - Lost outside reactor
    - Absorbed through photon

  ![U-235 Fission Cross Section](http://t2.lanl.gov/nis/tour/sch002.html)

• **Fusion**
  - Breakeven is a function of
    - Fusion cross section
    - temperature distribution
    - density
  - Lawson Criterion
    \[ n_e \tau_E \geq \frac{12 k_B}{E_c} T \sigma \]  
    ![Lawson Criterion](http://en.wikipedia.org/wiki/Lawson_criterion)
PuFF utilizes a multistage nuclear process

• **Pre-reaction**
  - Lithium shell/cone is injected to bridge the power system anode to target holder.
  - 2 mega-amps (at 2 mega-volts) travels along the liquid lithium cone to target.
  - Lorentz force ($j \times B$) produced by the current/magnetic field compresses a hybrid target of uranium/Deuterium-Tritium (D-T), reaching criticality for the Uranium.

• **First Stage (Fission)**
  - Uranium criticality produces spontaneous fission reaction (heating)
  - Fission heats the D-T fuel creating fusion conditions (interaction cross-section)

• **Second Stage (Fission - Fusion Cascade)**
  - Fusion produces additional neutron which in turn ignite more fission
  - Additional fission reactions generate more heat, boosting fusion rate
  - Fission to D-T fusion cycle cascades until burnout.

• **Expansion**
  - Plasma produced during impulse expands outward against magnetic nozzle
  - Magnetic nozzle directs particles generating thrust & captures energy necessary to initiate the next pulse
  - Single target impulse event requires several microseconds; repeat up to 100 Hz
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Mars High Speed Mission

• Earth to Mars in 37 days
  • 0.6 Earth escape
  • 2.6 day TMI
  • 31.4 day coast
  • 0.8 day Mars deceleration
  • 2.1 day Mars capture

• Payload
  • 25 mT crew compartment
Interstellar Precursor Mission Analysis

- **Interstellar Space**
  - Termination shock in 5 years (pass Voyager I)
  - 275 AU in 10 years
  - Solar gravitational lens in 20 years
  - 1000 AU in 36 years

- **Burn profile**
  - 0.4 days Earth escape
  - 1.4 days deorbit
  - 48 day inbound coast
  - 2.5 day solar burnout
Historical timeline for basic R&D activities related to PUFF

- Charger-1, PuFF and LTD development provides a unique high power research and development capability for MSFC
- Limited funding from varied sources and partners – focused on small hardware evaluations
- Striving to maintain forward momentum
• Time invariant model
  • MCNP criticality runs
  • EOS to determine pressure, current reqt’s
Charger 1 Refurbishment – MITL Development

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Charger 1 Refurbishment – Mini-Marx Testing

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Linear Transformer Driver – Cavity and Stack Development

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- Metglas Ferrite Cores
- High Permittivity BaTiO$_3$ Capacitors
- High Voltage Fast Gas Switches
- LTD Cavity
- High Voltage Charge Lines
- Trigger Lines