Positron Propelled and Powered Space Transport Vehicle for Planetary Missions

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- Dr. John Metzger – Consultant
- Mr. Kirby Meyer – Engineer
- Dr. Les Thode – Physicist
Mars Missions Require Large Payload Masses and Significant \( \Delta \)Vs to Reduce Radiation Exposure

- Studies* suggested payloads of 60,000 kg.
- Orbital mechanics suggest \( \Delta V = 3.7 \) km/sec for 6-month, one-way transit to Mars.
- Rocket equation:
  \[
  \Delta V = u_{eq} \ln \left( \frac{M_o}{M_b} \right) \approx I_{sp} g \cdot \ln \left( \frac{M_o}{M_b} \right)
  \]
- Assuming 40,000 kg for tank and engine, a chemical system to Mars could be 250,000 kg!
- Apollo payload \(~44,000\) kg. Result: Massively complex staged system, expensive.

Studies Suggested $I_{sp} > 1000$ sec to Reduce System Weights

- High $I_{sp}$, high thrust system limits propulsion types to:
  1. Nuclear-thermal (NERVA/Rover).
  2. Fusion (e.g. Daedalus).
  3. Antimatter.
  4. Combinations of above.

<table>
<thead>
<tr>
<th>Propulsion</th>
<th>$I_{sp}$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear-thermal</td>
<td>800-3000</td>
</tr>
<tr>
<td>Fusion</td>
<td>$10^4$ - $10^5$</td>
</tr>
<tr>
<td>Hybrid antimatter fusion</td>
<td>13,000</td>
</tr>
<tr>
<td>Direct positrons</td>
<td>$10^7$</td>
</tr>
</tbody>
</table>

- Nuclear-thermal, NASA GRC
- Daedalus ([http://www.aemann.pwp.blueyonder.co.uk/](http://www.aemann.pwp.blueyonder.co.uk/))
- ICAN Antiproton-Catalyzed Microfission/Fusion (ACMF), PSU.
- Direct positrons (Sänger) ([http://spectech.bravepages.com](http://spectech.bravepages.com))
Why Positrons?

- Antimatter has highest specific energy in existence.
- No residual radiation.
- Large amounts can be made available.
- Promising storage developments.**

- We estimate approximately 4 mg of positrons for a one-way trip to Mars with a system mass of 100,000 kg (e+ not used for powering payload).

<table>
<thead>
<tr>
<th>Propulsion Type</th>
<th>Specific Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td></td>
</tr>
<tr>
<td>LO₂/LH₂</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>400</td>
</tr>
<tr>
<td>Atomic H</td>
<td></td>
</tr>
<tr>
<td>Fission</td>
<td>8 \times 10^6</td>
</tr>
<tr>
<td>Fusion</td>
<td>3 \times 10^8</td>
</tr>
<tr>
<td>Antimatter</td>
<td>1.8 \times 10^{11}</td>
</tr>
</tbody>
</table>

**discussion restricted under provisions of AFRL contract #F08630-02-C-0018
Goal: Investigate Candidate Systems That Can Use Positrons

- Positron-electron annihilation create two, 511 keV gamma rays.
- Last positron concept developed by Eugen Sänger, 1935. Reflected gamma rays created thrust.
- There is presently no means to reflect gamma rays. They must be used to heat another propellant.
- Goal: delineate properties of positron-driven engine for fast access to Mars.

1. Solid Core.
2. Gas Core.
3. Other concepts.
Solid-Core Engine and Power Systems
Positron Solid-Core Energy Source

- Flexible for both propulsion & power
- Outstanding performance capability
  - High $I_{sp}$, ~1000 sec, propulsion.
  - High thrust, comparable to chemical & nuclear-thermal engines.
  - High specific mass systems (P/M or T/W).
- Not an operating or shutdown radiation source
  - No shielding required.
  - Does not need to be separated from Crew/Payload.
  - No shutdown cooling required.
- Simple operation
  - On-Off operation.
  - No complex control mechanisms.
  - No criticality requirements.
- Nearer-term than other hi-tech options.

Positron-Powered Rocket Engine
Modified from Experienced Gained from the Space Nuclear Program (Rover); LA-10062-H, D.R. KoenigMay 1986
Positron Heater-Attenuator
The Energy Source of a Positron-Powered System

- Similar in arrangement to NERVA/Rover configuration
  - Hexagonal elements appropriately supported for structural & vibration considerations.
  - Flow channels orificed to preclude viscosity instability.
- Element configuration
  - Central channel for positron injection.
  - Propellant/coolant channels.
  - Materials tailored to ensure flat energy profile; i.e., flat exit propellant temperature profile.
- Element model
  - Concentric annular shells.
- Power & material temperature determine number & geometry of elements.
A thermal-fluids model for concept analysis

- Hot-bleed cycle.
- Determines temp., pressure, & enthalpy at every point indicated.
- Determines engine performance - thrust, $I_{sp}$, power, nozzle geometry.
- Determines e+ utilization (number and mass rates) and propellant utilization.
- Estimates turbopump requirements.
- Estimates $\Delta P$ thru heater-attenuator.
- Dependant upon geometry of attenuator-heater.

Model based on thermodynamic principals, energy balance and momentum balance.
Solid-Core Positron Rocket Results

- Analyzed two classes of rocket engines
  - Small engines - 72 kN (16k lb_f) thrust.
  - Large engines - 1000 kN (225k lb_f).
- Results base-lined to results from NERVA/Rover.
- Results of analysis comparable to NERVA / Rover published results.*
- Geometry optimized for material surface temperatures up to 3000 K.

Solid-Core Positron Rocket Results (continued)

Large engine (100 kN) results. Specific impulse graph matches that for small engine.
Closed Brayton Cycle (CBC) Model Using Positrons for Power Plant and/or Martian Surface

- A thermal-fluids model for concept analysis
  - Variable He-Xe mixtures and compressor/turbine pressure ratio.
  - Regeneration (allows for 2-stage w/reheat and inter-cooling).
  - Determines temp., pressure, & enthalpy at every point indicated.
  - Determines cycle performance - efficiency and back-work ratio.
  - Estimates radiator size, regenerator size and heater-attenuator material temperatures.
  - Determines e+ utilization (number and mass rates).
  - Estimates $\Delta P$ thru heater-attenuator.
  - Dependant upon geometry of attenuator-heater.

- Model based on thermodynamic principles, energy balance and momentum balance.
Solid-Core Positron CBC Results

- Results are for 100 kW\textsubscript{e} available system power.
  - Example: Efficiency of 25% means 400 kW of e+ power necessary for 100 kW output.
- Selection of pressure ratio is a trade-off of system mass and efficiency.
  - Efficiency decreases with pressure ratio.
  - Back-work ratio (BWR) increases.

Expect about 30% efficiency, 7 µg/hr
Solid-Core Positron CBC Results (continued)

- Some performance parameters are also dependent on He-Xe ratio (density and molecular weight)
  - Material temperature
  - Component sizes
- Optimal near He = 72%.
- Lower desired temperatures mean lighter materials such as titanium can be used.

• He has a larger specific heat than Xe (5.193 vs 0.159 kJ/kg-K.)
• Xe density is larger than He (1.23 vs 40.5 kg/m³).
Gas-Core Concept
Gas-Core Rocket Should Exceed the Solid-Core’s Performance and Meet Mars Mission Profile

- The theoretical maximum of e+ solid-core system Isp of 1150 sec.
- Mars mission spacecraft mass or TOF can be reduced if Isp is improved.
- Since solid-core system has proven similarities to nuclear-thermal rockets, the gas-core should meet 1150 sec.
- The gas-core should meet ~100 kN thrust requirements and have reasonable efficiency.
1-D and 2-D Cylindrical Simulations; Open-Cycle Gas-Core Concept may be of One or Two Species

- **Two species**

  - H₂
  - L₂Xe

- **Single-species**

  - LN₂ or Ne

Suggests low molecular weight for high Isp, but high density needed for gamma-ray attenuation
Attenuation Simulations Provided An Approximate Radius of Engine for Single Gas

Analytically:

\[ E_{\text{ABSORBED}} = E_0 (1 - \exp(-\mu \rho r)) \]

- Determined that efficiency would be too low with He or H2 (single gas/liquid) unless pressures exceeded material limits.
- Numerically used GEANT4 to get attenuation data for LN₂.
- Results show minimum of R=25 cm for >50% efficiency. Used R=40 cm (75%). Here, gamma ray source must be located at center.
Two Codes were Used – a 1-D Euler Equation solver and a 2-D CFD commercial package (ANSWER)

**SYSTEM CODE (in-house FORTRAN code)**
- Assumes laminar, inviscid flow.
- Solves throat geometry.
- Provides 1-D solution as input to CFD codes.

**ANSWER (commercial FORTRAN, JAVA code)**
- Can handle laminar, turbulent, viscous flow.
- Provides 2-D cylindrical solution.
- Includes wall effects, annular flow vortices.

**Validation**

- Flow is highly turbulent but inviscid since N₂ has low viscosity.
- Tests show turbulent solution behaves laminar-like w/o diffuser at inlet, so ANSWER solution should match favorably to System Code.
Typical Mesh Generated by System Code is Directly Used in ANSWER (Single-species)

Constant Heating region

From system code

ANSWER Solution
Results Using For Mars Mission (~300 MW) Show High Thrust, Low Specific Impulse with Constant Heat Density

- Values are shown for nozzle expansion ratio = 30.
- Reducing flow rate < 100 kg/sec (T = 100 kN) may provide >1000 sec Isp.
- But up to this point, we assumed a constant heat source. Now we address a point source with dependence of mass density:

\[ E_{\text{ABSORBED}} = E_0 \left(1 - \exp(-\mu \rho(r)r)\right) \]
Validation of 1-D Results in 2-D CFD Code. Mass Density Interface Moves Upstream.

Single species (LN2)
“High” Isp (> 200 sec) only occurs with poor efficiency (Pa/P₀ < 10%)

Single-fluid concept may be infeasible since high density region moves away from energy source.
Two-Fluid Concept Variations

- **Vortex Configuration**
  - Will not work because evidence shows heating changes density profiles, causing vortex to destabilize.

- **Flow-thru Configuration**
  - May behave similar to single-fluid if Xe mass flow rate is significant, reducing $I_{sp}$.
  - Work in progress.

- **Cartridge Configuration**
  - $e^+$ encased with Pb annihilate, creating plasma.
  - Lower energy photons heat H2.
  - Early studies show excellent promise with $I_{sp} = 2600$ sec, with Pb/H2 flow ratio 5:1.
  - Have to examine effects of varying mass density in system, transport to walls, pulsed behavior.
Other Concepts
Solid Ablation Concept as a Realistic Sänger Rocket Keeps High Density Close to Positron Source

- Concept: 21st century Sanger rocket, where solid ablation material replaces unrealistic photon reflector.
- Small prompt radiation in direction of spacecraft still makes system attractive.
- Intrinsic 50% efficiency must be compared against valid gas-core concepts.
Task: Find Optimal Ablation Material and Geometry for 511 keV Gamma Rays

- Minimize penetration depth to increase local energy density at surface for ablation.
- 511 keV gamma rays have long attenuation length.
- Encase e+ cartridges with lead. Lead plasma radiating at lower eV ablates solid propellant such as SiC.* Has similarity to gas-core cartridge concept.

Phase II Prospectus

- **Solid Core Work:**
  - A transport design/analysis effort to determine a system that will allow relatively flat radial and axial power profile.
  - Use of codes such as GEANT for attenuation studies. Material identification.
  - CFD analysis for the propulsion engine.
  - Efficiency studies of an integrated power plant with engine.
  - Experimentally design and analyze an electrically-heated heater attenuator w/ gas flow for comparison against code.

- **Gas-Core Work:**
  - Investigate pulsed behavior of cartridge scheme.
  - Examine wall temperature effects.

- **Ablative Sänger Concept:**
  - Study penetration depth of gamma rays and derive ablation material(s).
  - Investigate non-impulsive mission scenarios.
Conclusions

- Positron-based engines are “thick”.
  - “Thick” means gamma rays travel further to interact with propellant.
- Solid-Core engine will work.
  - More detailed studies required.
- Gas-core concept
  - High density gas must be kept close to high-energy gamma rays.
  - Means of reducing energies of photons to allow low-Z, high $I_{sp}$ propellant should be investigated.
- Ablative Sänger engine promising based on previous work at Penn State.