Large Depot to Service Manned Mars Missions

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Mission challenge

Goal:
Creating an infrastructure
1) capable of supporting a recursive manned mission to Mars
2) versatile to enhance robotic exploration of the outer solar system

Minimum requirements:
• 250 days roundtrip to Mars
• Permanence on Mars: 7 days
• Payload: Columbus-like module: 10 tons
Main criticalities

Criticalities:

- Extremely high $\Delta V$
- Strongly variable $\Delta V$

Worst case: $\Delta V \approx 47$ Km/s
Best case: $\Delta V \approx 28$ Km/s

(Hohmann round trip: $\Delta V \approx 12$ Km/s and TOF=520 days)
Adopted strategies

- Worst windows discarded
- In-space refueling: EML1 & ASO
- On orbit staging
- Modular structures
Vehicles

Diomede

Ares

Core

Icarus
Steady state configuration

- Assembling and re-configuration operations: → EML1
- Refueling operations: → EML1 and ASO
- Required vehicles for scheduling:
  → 4 Ares (TOF=4.6 years)
  → 1 Diomede (TOF=250 days)
  → 1 Core

Configuration aimed to guarantee human crew safety
Propulsive system

**Diomede**
- Fast transfer → High thrust required
- Large ΔV required → High efficient propulsion

<table>
<thead>
<tr>
<th>NTP propulsive system ANERVA[1]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant</td>
<td>LH2</td>
</tr>
<tr>
<td><strong>Specific impulse</strong></td>
<td><strong>1000 s</strong></td>
</tr>
<tr>
<td><strong>Thrust</strong></td>
<td><strong>220 kN</strong></td>
</tr>
<tr>
<td>Vehicle thrust-to-weight ratio</td>
<td>0.086</td>
</tr>
<tr>
<td>Reactor mass</td>
<td>1600 kg</td>
</tr>
<tr>
<td>Shield mass</td>
<td>3100 kg</td>
</tr>
<tr>
<td>Turbopump mass</td>
<td>90 kg</td>
</tr>
<tr>
<td>Total mass</td>
<td>7300 kg</td>
</tr>
</tbody>
</table>

**Nuclear vs cryogenic: worst case**

<table>
<thead>
<tr>
<th>Propulsive system</th>
<th>Total fuel mass (t)</th>
<th>N° of launches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear</td>
<td>≈600</td>
<td>28</td>
</tr>
<tr>
<td>Cryogenic</td>
<td>≈8600</td>
<td>304</td>
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</tbody>
</table>

**Ares**
- Continuous manoeuvres
- Huge mass transportation

<table>
<thead>
<tr>
<th>MPD propulsive system</th>
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<tbody>
<tr>
<td>Propellant</td>
<td>LH2</td>
</tr>
<tr>
<td><strong>Specific impulse</strong></td>
<td><strong>5000 s</strong></td>
</tr>
<tr>
<td><strong>Thrust</strong></td>
<td><strong>120 N (each)</strong></td>
</tr>
<tr>
<td>Number of thrusters</td>
<td>12</td>
</tr>
<tr>
<td>Thruster assembly mass</td>
<td>3200 kg</td>
</tr>
<tr>
<td>Power consumed</td>
<td>9.9 MW</td>
</tr>
</tbody>
</table>

[1] Dual-mode reactor and ANERVA: Project M3-a study for a manned Mars mission in 2031, Taraba et al
Structural design and sizing

Tank structure:
- Three sizes
- External layer: Carbon-Epoxy
- Core: Nomex
- Internal layer: Carbon-Epoxy

<table>
<thead>
<tr>
<th></th>
<th>D (m)</th>
<th>H (m)</th>
<th>LH2 mass (tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-40</td>
<td>8.0</td>
<td>11.4</td>
<td>35.0</td>
</tr>
<tr>
<td>T-13</td>
<td>5.0</td>
<td>8.7</td>
<td>11.4</td>
</tr>
<tr>
<td>T-8</td>
<td>4.4</td>
<td>6.8</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Truss structure:
- Truss member:
  - Boron/epoxy composite
  - Diameter: 40 cm
  - Thickness: 3 mm
- Launch configuration: 9 m + 12 m trusses

Static loads
- Maximum axial: 6.0 g
- Maximum lateral: 2.3 g

Frequency requirements
- Bending: 8 Hz
- Axial: 30 Hz

→ Structural requirements satisfied with a factor of safety of 2
Vehicles assembly and re-configuration
LH₂: Thermal control strategy

- **On ground sub-cooling technique**
  - Cryogenic hydrogen stored on ground at T=15k, P=1atm
- **MLI insulation**
  - Multiple MLI layers coverage (30 for small and 20 for big and medium tanks)
- **Thermal shield**
  - MLI layers shield (10 layers)

Small amount of LH₂ is extracted and expanded through a J-T valve, subtracting heat during evaporation.

Sub-cooled-region:
T=15k P=1atm
Boiling point
T=20.29k P=1atm

Permanence time (EML1) results:
- Big tank 5.65 years
- Medium tank 3.74 years
- Small tank 3.4 years

1371 W/m²

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<table>
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<tbody>
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<td>Big tank</td>
<td>5.65 years</td>
</tr>
<tr>
<td>Medium tank</td>
<td>3.74 years</td>
</tr>
<tr>
<td>Small tank</td>
<td>3.4 years</td>
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Nuclear Power generation for ARES

Requirements
• 9.9 MW to feed MPD thrusters
• Total mass less than 40 tons

Solution
• Nuclear Power generation
• Dynamic power conversion
• Brayton cycle
• He/Xe as working fluid

Results
• Total mass of 39.9 tons
• Radiator area 1000 m²
• Turbine inlet temp. 1600 K
• Brayton cycle efficiency 31%
• Oversizing margin 12%
ADCS: large structures of variable size control strategy

CMGs
- 4 (Tetrahedron configuration) for each piece of beam
- Incremental configuration: control authority augments when Diomede/Ares size increases

Thrusters
- 8 thruster clusters (UDMH-N₂O₂) placed at main beam tips
- Aimed for demanding maneuvers and desaturations

<table>
<thead>
<tr>
<th>N0. of CMGs</th>
<th>M_{act} (kg)</th>
<th>P_{req} (W)</th>
<th>τ_{max} (Nm)</th>
<th>H_s (Nms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>54</td>
<td>30</td>
<td>51</td>
<td>971</td>
</tr>
<tr>
<td>Quadruplet</td>
<td>216</td>
<td>120</td>
<td>64</td>
<td>1295</td>
</tr>
</tbody>
</table>
GNC: Rendezvous & Docking phase

- **Multiple sensors systems**: working at different distances for autonomous RV/D operations:
  - Visual sensors
    - CAMVIS: visible camera
    - CAMIR: Infra-red camera
  - LIDAR: Laser imaging aperture and ranging
  - Optical sensor (proximity)
    - VDM: Vide-meters
    - TGM: Tele-goniometers

- Computational requirements estimated by analogy with military rocket guidance software
- Guidance algorithm by iterative comparison of 10 images in ±1°

<table>
<thead>
<tr>
<th>Estimated SW size</th>
<th>MIPS</th>
<th>MFLOPS</th>
<th>RAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

**SW’s accuracy and reliability enhanced by the usage of markers**

*Wookey, Cathy; Nicholson, Bruce, “A/RD imaging processing” (1996)*
## TMTC Phases and Link Budget

<table>
<thead>
<tr>
<th>Phases</th>
<th>Event</th>
<th>Data rate (kbps)</th>
<th>Antenna type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Launch</td>
<td>-</td>
<td></td>
<td>Launcher antenna</td>
</tr>
<tr>
<td>2. Post Launch and Cruise</td>
<td>1. ICARUS-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>a) Near earth</td>
<td>10</td>
<td>LGA</td>
</tr>
<tr>
<td></td>
<td>b) Far earth</td>
<td>10</td>
<td>MGA</td>
</tr>
<tr>
<td></td>
<td>2. ARES</td>
<td>25</td>
<td>HGA</td>
</tr>
<tr>
<td>3. Orbit Insertion</td>
<td>ARES Orbit Insertion</td>
<td>25</td>
<td>HGA</td>
</tr>
<tr>
<td>4. Orbital motion</td>
<td>ARES Orbit (ASO)</td>
<td>25</td>
<td>HGA</td>
</tr>
<tr>
<td>5. Docking</td>
<td>a) ICARUS-CORE (EML1)</td>
<td>44</td>
<td>HGA</td>
</tr>
<tr>
<td></td>
<td>b) CORE-ARES (EML1)</td>
<td>44</td>
<td>HGA</td>
</tr>
<tr>
<td></td>
<td>c) CORE-DIOMEDE (EML1)</td>
<td>44</td>
<td>HGA</td>
</tr>
<tr>
<td></td>
<td>d) ARES-DIOMEDE (ASO)</td>
<td>80</td>
<td>HGA</td>
</tr>
</tbody>
</table>

- Modulation and coding – QPSK
- Downlink – BER of $10^{-6}$
- Antenna Efficiency - 0.7
- Line Losses – 2dB
- Implementation Losses - 3dB

**X band**

### Link Budget

<table>
<thead>
<tr>
<th>LINK</th>
<th>Pt dBW</th>
<th>$G_Tx$ dB</th>
<th>$G_Rx$ dB</th>
<th>EIRP dBW</th>
<th>$L_{TOT}$ dB</th>
<th>$E_b/N_0$ dB</th>
<th>Margin dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICARUS-DSN</td>
<td>13.01</td>
<td>16.8</td>
<td>46</td>
<td>29</td>
<td>22</td>
<td>14.62</td>
<td>4.03</td>
</tr>
<tr>
<td>CORE-DSN</td>
<td>13.01</td>
<td>40</td>
<td>65</td>
<td>51</td>
<td>22</td>
<td>47.32</td>
<td>33.33</td>
</tr>
<tr>
<td>ARES-DSN</td>
<td>14.77</td>
<td>41.2</td>
<td>65</td>
<td>53.95</td>
<td>24</td>
<td>26.68</td>
<td>12.68</td>
</tr>
</tbody>
</table>
Conclusions

1. **Cycling and recursive configuration** capable to support many fast round trip to Mars

2. **Versatile and modular design** to support robotic program to explore Solar System and beyond

3. **Permanent structure in EML1** useful for many other different purposes

A feasible solution can be achieved in few decades
Thank you for your attention!