SPACE TRAVEL IN THE NEXT MILLENIUM?

☐ How do we predict the future?

- We do so by examining the past
  - We predict the near future by examining the immediate past and extrapolate into the far future by studying the more distant past
- We also use a lot of imagination

☐ Constraint: In the use of our imagination, we are constrained to obey the "known" laws of physics
Ray of hope: The laws of physics are known to have been through many evolutionary and revolutionary changes. In fact, they are in a continuous state of flux.

Example: For many centuries physics was taught with the atom being exactly what the word means, **INDIVISIBLE**. Now, of course, atom is just a name and its splitting is history.

**GOALS FOR THE 21ST CENTURY**

- Expanded space travel and establishment of permanent manned outposts
- Lunar and Mars outposts represent the most immediate future in space travel and both have history from the very recent past
The Apollo program was successfully conducted with chemical propulsion.

- It was necessary to advance from the liquid oxygen/alcohol propellants of the V-2 to liquid oxygen/liquid hydrogen of the Saturn V upper stages in 15 years.
Trips to Mars were planned and vehicles were designed for landings and returns
- Unmanned 1984
- Manned 1988

Trade studies compared chemical cryogenics (O₂/H₂) with direct nuclear thermal propulsion using the NERVA engine

The following charts summarize the trades and vehicle designs conducted between 1965 and 1973.

HISTORY

Nuclear Engine
- KIWI - A (Los Alamos) 1957-1960
- KIWI - B (Los Alamos) 1961-1964
  - KIWI-B4E Aug 1964
    - 940 MW, 10-min, restart
- Phoebus (Los Alamos) 1965-1968
  - 4100 MW, 30-min
- NRX (Aerojet/Westinghouse) 1964-1967
- XE-1 (Aerojet/Westinghouse) 1969

Nuclear Stage
- Douglas Aircraft 1965-1969
  - Nuclear Flight Definition Study
    - Saturn derivative
    - Shuttle
  - Nuclear Stage System Definition Study
    - Propulsion module
  - Reusable Nuclear Shuttle (RNS)
    - Lunar
    - LEO-GEO
    - Earth – Mars
NERVA FLIGHT ENGINE CONFIGURATION

FULL SCALE MOCKUP OF NR-1 FLIGHT ENGINE, RATED AT 1500 MW, AND 75,000 LB THRUST
### Nuclear Rocket Reactor Testing

**LASL (LANL)**

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Date</th>
<th>Power Level (MW)</th>
<th>Run Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KiWi - A</td>
<td>July 1959</td>
<td>70</td>
<td>5</td>
</tr>
<tr>
<td>KiWi - A'</td>
<td>July 1960</td>
<td>85</td>
<td>6</td>
</tr>
<tr>
<td>KiWi - A3</td>
<td>Oct 1960</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>KiWi - B1A</td>
<td>Dec 1961</td>
<td>200</td>
<td>1</td>
</tr>
<tr>
<td>KiWi - B1B</td>
<td>Sept 1962</td>
<td>900</td>
<td>1</td>
</tr>
<tr>
<td>KiWi - B4A</td>
<td>Nov 1962</td>
<td>500</td>
<td>0</td>
</tr>
<tr>
<td>KiWi - B4D</td>
<td>May 1964</td>
<td>1020</td>
<td>1</td>
</tr>
<tr>
<td>KiWi - B4E</td>
<td>Aug 1964</td>
<td>940</td>
<td>10</td>
</tr>
<tr>
<td>TNT</td>
<td>Jan 1965</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Phoebus - 1A</td>
<td>June 1965</td>
<td>1090</td>
<td>11</td>
</tr>
<tr>
<td>Phoebus - 1B</td>
<td>Feb 1967</td>
<td>1500</td>
<td>30</td>
</tr>
<tr>
<td>Phoebus - 2A</td>
<td>June 1968</td>
<td>4100</td>
<td>13</td>
</tr>
<tr>
<td>Pee Wee - 1</td>
<td>Dec 1968</td>
<td>500</td>
<td>40</td>
</tr>
<tr>
<td>NF - 1</td>
<td>June 1972</td>
<td>434</td>
<td>108</td>
</tr>
</tbody>
</table>

### Nuclear Rocket Reactor/Engine Testing

**WESTINGHOUSE/AEROJET**

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Date</th>
<th>Power Level (MW)</th>
<th>Run Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRX - A2</td>
<td>Sept 1964</td>
<td>1100</td>
<td>5</td>
</tr>
<tr>
<td>NRX - A3</td>
<td>April 1965</td>
<td>1100</td>
<td>17</td>
</tr>
<tr>
<td>NRX - EST</td>
<td>March 1966</td>
<td>1100</td>
<td>28</td>
</tr>
<tr>
<td>NRX - A5</td>
<td>June 1966</td>
<td>1100</td>
<td>30</td>
</tr>
<tr>
<td>NRX - A6</td>
<td>Dec 1967</td>
<td>1100</td>
<td>60</td>
</tr>
<tr>
<td>XE</td>
<td>Mar 1969</td>
<td>1100</td>
<td>10</td>
</tr>
</tbody>
</table>
CLASS 3 MULTI-MODULE RNS

- Command and Control Module (6 ft)
- Integral Waffle
- Spray Nozzle Refill
- Propellant Modules* (240 ft)
- Inboard Transfer
- Propulsion Module (60 ft)

*Individual Modules
15 ft in Diameter by 60 ft Long

CLASS 1 SINGLE-MODULE HYBRID RNS

- Command and Control Module (6 ft)
- Forward Umbilical
- Slosh Baffle
- Integral Waffle Tunnel
- APS Nozzles Spray Nozzle Refill
- Propellant Module (103.4 ft)
- Propellant Feed System
- Thermal and Meteoroid Protection

NERVA
- Propulsion Module (60 ft)
NUCLEAR STAGE DESIGN/PROGRAM CONSIDERATIONS

- Structure
- Propulsion
  - Auxiliary
  - Nuclear
- Electrical
  - Power
  - Guidance/Navigation
  - Control
  - Communications
- Thermal Control
- Radiation Protection
  - Configuration
  - Shielding
- Propellant Control
  - Pressurization
  - Chilldown
NUCLEAR STAGE DESIGN/PROGRAM CONSIDERATIONS
(Continued)

- Weight/Mass Control
- Ground/Orbital Operations
  - Assembly
  - Maintenance
- Safety
- Reliability
- Manufacturing
- Test Plan
  - Component
  - Systems
  - Battleship
- Program Schedule
- Costs

1988 MARS LANDING PROFILE
MSFC MANNED MARS
SPACECRAFT CONCEPT

Forward Interstage
Crew Compartment
Aft Interstage
Logistic Vehicle Tunnel
MEM Interstage Separation Plane
Probes

Weight (lb)
Mission Module 82,903
Mars Excursion Module 95,290
Mars Probes 36,000
Venus Probes 4,000
Interstages 21,000

Total Spacecraft 239,190

PROPELLANT REQUIREMENTS – BASELINE MODE

RNS Number

<table>
<thead>
<tr>
<th>RNS Number</th>
<th>ΔV (1000 fps)</th>
<th>Wp (1000 lb)</th>
<th>A'Cool (1000 lb)</th>
<th>Wp (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.9</td>
<td>36</td>
<td>2.5</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>0.7</td>
<td>10.2</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>129.5</td>
<td>6.8</td>
<td>46</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>6.5</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0.9</td>
<td>4.6</td>
<td>102.8</td>
<td>5.7</td>
<td>36</td>
</tr>
<tr>
<td>0.4</td>
<td>11.0</td>
<td>242.7</td>
<td>11.0</td>
<td>33</td>
</tr>
<tr>
<td>6.3</td>
<td>4.6</td>
<td>208.5</td>
<td>10.0</td>
<td>73</td>
</tr>
</tbody>
</table>

*ISP = 450 sec

Total Propellant Required = 1,097,800 lb
LAUNCH CONSIDERATIONS FOR MANNED MARS
CAPTURE AND LANDING MISSION (1988)

Class 1

- 4 stages, 1,097,800 lb LH₂
- Each stage weighs 69,245 lb dry
- Assume ALS 180,000 lb
- Mission requires 8 ALS launches
  - 4 launches of stage (70,000 lb) + 110,000 lb LH₂
  - 4 launches of 174,000 lb LH₂ (assume 6000-lb tank)

Class 3

- 4 stages (1 propulsion, 8 propellant, 1 command and control module)
  - Assume 1,335,000 lb LH₂
- Each stage weighs 85,000 lb dry
- Requires:
  - 4 launches for propulsion (30,475 lb) plus command and control module (4615 lb)
  - 32 launches for propellant module (40,075 lb) (containing 34,000 lb LH₂)
  - 6 launches 42,000 lb LH₂
- Total 42 launches (Space Shuttle/Titan IV)

NUCLEAR VERSUS CHEMICAL
PERFORMANCE COMPARISON
(SAME-STAGE TECHNOLOGY)

<table>
<thead>
<tr>
<th>Mission</th>
<th>OLV Booster</th>
<th>Number of Launches</th>
<th>Mission</th>
<th>Payload</th>
<th>OLV/ Booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture Orbits</td>
<td>Saturn V</td>
<td>Planet Flyby Missions-2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planetary Capture Missions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1977 Venus</td>
<td>Advanced Chemical</td>
<td>5</td>
<td>1977 triple planet</td>
<td>220,000 lb</td>
<td>S-IVC Advanced chemical</td>
</tr>
<tr>
<td>capture</td>
<td>Nuclear restart</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
<tr>
<td>1980 Venus</td>
<td>Advanced Chemical</td>
<td>5</td>
<td>1978 single planet</td>
<td>200,000 lb</td>
<td>S-IVC Advanced chemical</td>
</tr>
<tr>
<td>capture</td>
<td>Nuclear restart</td>
<td></td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
<tr>
<td>1982 Mars capture</td>
<td>Advanced Chemical</td>
<td>-</td>
<td>1976 dual planet powered</td>
<td>200,000 lb</td>
<td>S-IVC Advanced chemical</td>
</tr>
<tr>
<td></td>
<td>Nuclear restart</td>
<td>4</td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
<tr>
<td>1978 Mars capture</td>
<td>Advanced Chemical</td>
<td>8</td>
<td></td>
<td></td>
<td>S-IVC Advanced chemical</td>
</tr>
<tr>
<td></td>
<td>Nuclear restart</td>
<td>4</td>
<td></td>
<td></td>
<td>Nuclear Nuclear restart</td>
</tr>
</tbody>
</table>

* Requires two launches for payload
VISIONS OF THE FUTURE

- Deep space travel requires energy and delta velocity ($\Delta V$) in particular.
- Propulsion systems with $I_s > 1500$ sec are needed.

PROPULSION SYSTEM $\Delta V$ CAPABILITIES

- Chemical propulsion can barely achieve earth escape with a single-stage vehicle.
- Higher $I_s$ propulsion systems substantially increase payload delivery capabilities.
- New exotic propulsion systems need to be developed and made economical to produce, store and use.
SPECIFIC IMPULSES OF ROCKET FUELS

*Project Forecast II
Propulsion Technologies

Antimatter (PT-42*)
1000 to 7 sec

Nuclear Matter (PT-02*)
800 to 6330 sec

Molecular Matter (PT-01*)
600 to 3150 sec

250 to 500 sec

FUSION PROPULSION SYSTEMS

V.S. Maloukas, McDonnell Douglas

MAY 1989

McDonnell Douglas Space Systems Company

McDONNELL DOUGLAS
## SPACE TRANSFER VEHICLE COMPARATIVE DESIGN DATA

**LEO - GEO - LEO Mission, $M_{pl} = 36,000$ kg ; $Del \ V = 9$ km/s;**

**Burn Time = 3675s (Constant)**

<table>
<thead>
<tr>
<th></th>
<th>Chemical Cryogenic, 6 FL - 10's</th>
<th>Nuclear, 4 Alpha 2's</th>
<th>Fusion, $Me=12$ (is)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rocket Engine</strong></td>
<td>400</td>
<td>278</td>
<td>208</td>
</tr>
<tr>
<td><strong>Thrust</strong></td>
<td>450</td>
<td>880</td>
<td>2500</td>
</tr>
<tr>
<td><strong>Specific Impulse</strong></td>
<td>(s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mass Breakdown</strong></td>
<td>333,291</td>
<td>134,548</td>
<td>34,685</td>
</tr>
<tr>
<td><strong>Propellants</strong></td>
<td>(kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>51,275</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>(LH₂)</strong></td>
<td>282,015</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Oxidizer</strong></td>
<td>(LOX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Propellant Tank</strong></td>
<td>970</td>
<td>1,937</td>
<td>499</td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
<td>8,156</td>
<td>10,849</td>
<td>2,797</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pressurization</strong></td>
<td>1,374</td>
<td>1,828</td>
<td>471</td>
</tr>
<tr>
<td><strong>Helium System</strong></td>
<td>792</td>
<td>10,270</td>
<td>30,000</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>3,411</td>
<td>4,538</td>
<td>1,170</td>
</tr>
<tr>
<td><strong>Miscellaneous</strong></td>
<td>383,024</td>
<td>198,033</td>
<td>105,123</td>
</tr>
<tr>
<td><strong>Total Vehicle Mass</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The initial vehicle mass serves as the key criterion of optimization
- The higher specific impulse of the fusion system results in lower propellant and vehicle mass for the specified mission and payload
FISSION AND FUSION ROTV COMPARISON

TOTAL VEHICLE MASS vs. RETURNED PAYLOAD FROM GEO

Assumes Each Vehicle Has Delivered a 36,000 kg Payload to GEO

---

MDC-GA FUSION SPACE TRANSFER

VEHICLE SIZING DATA

Mission: Transfer 36,000 kg to Geosynchronous Orbit (GEO)

Return Vehicle Empty and with Original Payload

Engine: GA Fusion Engine

Is = 1500 s, Thrust = 100 kN, Mass = 12 (Is)

<table>
<thead>
<tr>
<th>Mass Breakdown</th>
<th>LEO-GEO Empty Return</th>
<th>LEO-GEO Return Payload</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellant (kg)</td>
<td>27,910</td>
<td>57,597</td>
</tr>
<tr>
<td>Propellant tank</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total volume (m³)</td>
<td>402</td>
<td>829</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>2,251</td>
<td>4,644</td>
</tr>
<tr>
<td>Pressurization (kg)</td>
<td>379</td>
<td>783</td>
</tr>
<tr>
<td>Engine (kg)</td>
<td>18,000</td>
<td>18,000</td>
</tr>
<tr>
<td>Miscellaneous (kg)</td>
<td>941</td>
<td>1,942</td>
</tr>
<tr>
<td>Total Vehicle Mass (kg)</td>
<td>98,070</td>
<td>118,967</td>
</tr>
</tbody>
</table>
Problems and promises

- Production: USAF has priced a production facility at BNL for $10^{15}$ p/yr at approximately $14$ million (1989)

- Containment: Antiprotons have been stored for long periods at CERN and preliminary designs for transportable storage bottles have been proposed

- Antimatter use holds great promises for applications in
  - Medicine: Diagnosis and eradication of tumors
  - Materials: Location and cure of flaws, processing of composites, etc.

- This synergism should be explored and pursued
FAR FUTURE PROPULSION SCHEMES

- Matter/antimatter
  - Antimatter safely stored will deliver its energy, via beam technology, to a flowing propellant. Rates of energy delivery and propellant flowrate to control the level of the thrust to any desired level

- Teleportation "Beam me up, Scotty"
  - Matter destructuring (i.e., breakdown into particles), and restructuring to be first perfected on inanimate objects. Transportation to be done by beam technology

FAR FUTURE PROPULSION SCHEMES (CONT)

- Antigravity
  - Gravity waves will be fully characterized (Why not?)
  - Each celestial body sends out waves whose amplitude and frequency are directly related to its mass and size
  - The net gravity field at any point in space is the result of the gravity wave interference pattern
  - Super sensors and supercomputers analyze this wave pattern and identify its basic components
  - An "antigravity wave generator" will then generate waves of precisely the same amplitude and frequency but of opposite phase. Thus, by causing an exact destructive interference, it will precisely cancel out the gravity field
  - A suitable propulsion system can then accelerate the vehicle to very high velocities with a rather low force and low energy expenditure
(a) The dashed line is a sawtooth "wave" commonly encountered in electronics. The Fourier series for this function is

\[ y(t) = \frac{1}{\pi} \sin \omega t - \frac{1}{2\pi} \sin 2\omega t - \frac{1}{3\pi} \sin 3\omega t - \cdots \]

The solid line is the sum of the first six terms of this series and can be seen to approximate the sawtooth quite closely.

(b) Here we show the first six terms of the Fourier series which, when added together, yield the solid curve in (a).

Result: No Wave
SCIENCE FICTION?

Yes!

- Science fiction of one time period is science fact of some later time

- Let us consider the following

BUCK ROGERS IN THE 25th CENTURY
"STAR TREK"
SCIENCE FICTION 1966

- 23rd CENTURY STARSHIP ENTERPRISE POWERED BY AN ANTIMATTER REACTION CHAMBER CAN REACH SPEEDS UP TO WARP 8

SCIENCE FACT 2016?
(50 YEARS LATER)
- WILL THE 23rd CENTURY HAVE ARRIVED?
- WILL STARSHIP ENTERPRISE AND STARBASE 12 HAVE BECOME REALITIES?

"PIONEERING THE SPACE FRONTIER"
CAN WE DO IT?

- Recent history tells us: Yes!
- We went from Sputnik 1 to Apollo 11 in less than 12 years
- From the basic university lab atom splitting experiment (Berlin, Dec 1938) to Hiroshima and Nagasaki (Aug 1945) in 6.5 years
- We need a strong resolve, commitment of resources, and dedication
- We should not be afraid of risk and failure
Some of the greatest advances and discoveries resulted from some apparent "failure" and setback

Example: The negative results of the Michelson-Morley experiment resulted in the Theory of Relativity, $E = MC^2$ etc.

The space exploration initiative, some times called "The Bush Push", will present us with unparalleled challenges and it will undoubtedly lead to even greater developments and discoveries

Go For It!

HISTORIC SCIENTIFIC MILESTONES

- 1905: $E = MC^2$
- 1938/39: Uranium Nucleus Split/Einstein writes to FDR
- 1945: Alamogordo – Hiroshima – Nagasaki (40 years later)
  - Notes: – Pressing need (WWII)
    – Manhattan Project, $$$, etc.
- 1955: – Antiproton is discovered
  – Antimatter becomes fact
- 1994: – Trapping and storage of antiprotons achieved
- 1995: ?? ?? (40 years later)

SHOULD WE BE DOING SOMETHING?
FAMOUS PRONOUNCEMENTS

- "Heavier than air flying machines are impossible"
  Lord Kelvin, President, Royal Society, 1895

- "Everything that can be invented has already been invented"
  Charles H. Duell, Director of U.S. Patent Office, 1899

- "There is no likelihood man can ever tap the power of the atom"
  Robert A. Millikan, Nobel Prize in Physics, 1923

- "Who the hell wants to hear actors talk"