“BIMODAL” NUCLEAR THERMAL ROCKET (BNTR) PROPULSION FOR FUTURE HUMAN MARS EXPLORATION MISSIONS

Stan Borowski
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio

“Bimodal” Nuclear Thermal Rocket (BNTR) Propulsion for Future Human Mars Exploration Missions

presented by

Dr. Stanley K. Borowski
Space Transportation Office
NASA Glenn Research Center, Cleveland, OH
phone: (216) 977-7091,
e-mail: Stanley.K.Borowski@grc.nasa.gov

at the

2003 NASA Seal / Secondary Air System Workshop
Ohio Aerospace Institute (OAI)
November 5-6, 2003
Artificial Gravity “Bimodal” NTR Crew Transfer Vehicle (CTV) for Mars DRM 4.0 (1999)
The “Bimodal” NTR (BNTR) Integrated Space Propulsion & Power System
-- Smarter Systems Engineering --

- During short, high thrust propulsion phase, each BNTR produces ~340 MWt and ~15 klbf of thrust
- During long, power generation phase, each BNTR operates in “idle mode” producing just ~150 kWt
- A Brayton conversion unit on each BNTR produces up to 25 kW_e to enhance stage capabilities
Rover/NERVA* Program Summary (1959-1972)

• 20 Rocket/reactors designed, built and tested at cost of ~ $1.4 billion

• Engine sizes tested
  – 50-250 klbf

• H₂ exit temperatures achieved
  – 2,350-2,550 K (Graphite fuel)

• Iₚ capability
  – 825-850 sec (hot bleed cycle)

• Burn duration
  – 62 mins. (NRX-A6 -- single burn)
  – >4 hrs. (NRX-XE -- 28 burns)
    (accumulated)

• Engine thrust-to-weight
  – ~3 for 75 klbf NERVA

• "Open Air" testing at Nevada Test Site

*NERVA: Nuclear Engine for Rocket Vehicle Applications

NERVA program experimental engine (XE) demonstrated 28 startup/shutdown cycles during tests in 1969.
Nuclear Thermal Rocket (NTR) Propulsion

What’s New?

Then (Rover/NERVA: 1959–72)

- Engine sizes tested
  - 50–250 klbf

- \( \text{H}_2 \) exit temps achieved
  - 2,350–2,550K (Graphite)

- Isp capability
  - 825–850 sec (hot bleed)

- Engine thrust-to-weight
  - ~3 for 75 klbf NERVA

- Testing (Rover/NERVA)
  - “Open Air” exhaust at Nevada test site

Now

- “Current” focus is on smaller NTR sizes
  - 5–15 klbf (Code S science–humans)

- Higher temp. fuels being developed
  - 2,700K (Composite), 2,900K (Cermet) and ~3,100K (Ternary Carbides)

- Isp capability
  - 915–1005 sec (expander cycle)

- Advances in chemical rockets/materials
  - ~2–6 for small NTR designs

- Small NTR allows full power testing in
  - “Contained Test Facility” at INEL with “scrubbed” \( \text{H}_2 \) exhaust

Smaller, Higher Performance

Easier to test

Environmentally “Green”

For Public Acceptance

Then

Now

For Public Acceptance

Environmentally “Green”

1. Smaller, Higher Performance
2. Easier to test
3. Environmentally “Green”
4. For Public Acceptance

Then

- Engine sizes tested
  - 50–250 klbf

- \( \text{H}_2 \) exit temps achieved
  - 2,350–2,550K (Graphite)

- Isp capability
  - 825–850 sec (hot bleed)

- Engine thrust-to-weight
  - ~3 for 75 klbf NERVA

- Testing (Rover/NERVA)
  - “Open Air” exhaust at Nevada test site

Now

- “Current” focus is on smaller NTR sizes
  - 5–15 klbf (Code S science–humans)

- Higher temp. fuels being developed
  - 2,700K (Composite), 2,900K (Cermet) and ~3,100K (Ternary Carbides)

- Isp capability
  - 915–1005 sec (expander cycle)

- Advances in chemical rockets/materials
  - ~2–6 for small NTR designs

- Small NTR allows full power testing in
  - “Contained Test Facility” at INEL with “scrubbed” \( \text{H}_2 \) exhaust
Nuclear Thermal Rocket (NTR) Propulsion
-- Key Technology / Mission Features --

- NTR engines have negligible radioactivity at launch / simplifies handling and stage processing activities at KSC
  - < 10 Curies / 3 NTR Mars stage vs ~400,000 Curies in Cassini’s 3 RTGs
- High thrust / Isp NTR uses same technologies as chemical rockets
- Short burn durations (~25-50 mins) and rapid LEO departure
- Less propellant mass than all chemical implies fewer ETO launches
- NTR engines can be configured for both propulsive thrust and electric power generation -- “bimodal” operation
- Fewest mission elements and much simpler space operations
- Engine size aimed at maximizing mission versatility
  -- robotic science, Moon, Mars and NEA missions
- NTR technology is evolvable to reusability and “in-situ” resource utilization (e.g., LANTR -- NTR with LOX “afterburner” nozzle)
“Bimodal” NTR Cargo & Crew Transfer Vehicles for 1999 Mars Design Reference Mission (DRM) 4.0

6 - “80 t” SDHLVs plus Shuttle for Crew & TransHab Delivery

2011 Cargo Mission 1
Habitat Lander
IMLEO= 131.0 t

Optional “In-Line” LH₂ Tank (if needed)

2011 Cargo Mission 2
Cargo Lander
IMLEO= 133.7 t

2014 Piloted Mission
Artificial Gravity
Crew Transfer Vehicle
IMLEO= 166.4 t
Modular “Bimodal” NTR Transfer Vehicle Design for Mars Cargo and Piloted Missions

**Bimodal NTR:** High thrust, high $I_{sp}$ propulsion system utilizing fissioning $U^{235}$ produces thermal energy for propellant heating and electric power generation enhancing vehicle capability.

**Vehicle Characteristics**
- Versatile design
- “Bimodal” stage produces 50 kW$_{e}$
- Power supports active refrigeration of LH$_2$
- Innovative “saddle” truss design allows easy jettisoning of “in-line” LH$_2$ tank & contingency consumables
- Vehicle rotation ($\omega$ 4-6 rpm) can provide Mars gravity to crew outbound and near Earth gravity inbound (available option)
- Propulsive Mars capture and departure on piloted mission
- Fewest mission elements, simple space ops & reduced crew risk
- Bimodal NTR vehicles easily adapted to Moon & NEA missions

**Engine Characteristics**
- Three 15 klb$_{f}$ engines, $T/W_{eng} \approx 3.1$
- Each bimodal NTR produces 25 kW$_{e}$
- Utilizes proven Brayton technology
- Variable thrust & $I_{sp}$ optional with “LOX-afterburner” nozzle (LANTR)

**TransHab**

**Piloted Transfer Vehicle**
Mars DRM 4.0: “Bimodal” NTR Crew Transfer Vehicle (CTV) with Inflatable “TransHab” Module & Artificial Gravity Capability

“Bimodal” NTR Core Stage w/Refrigeration
( Sized for Delivery by “Shuttle-Derived” HLV )

3 x 15 klbf BNTRs
(F/Weng ~3.1)

50 kWe CBC w/Radiator

Refrigeration System

48.6t Capacity LH₂ Tank

“In-Line” Propellant Tank
( Tank Jettisoned )

43t Capacity LH₂ Tank

Strongback Truss

Jettisonable Consumables (~6.9t)

Shuttle Launched
“TransHab” Module
( Payload ~21.1t )

IMLEO: ~166.4 t
“Bimodal” Crew Transfer Vehicle
Earth Orbit Assembly Sequence

1: Rendezvous
Two “80 t” SDHLV payloads rendezvous and dock prior to Shuttle rendezvous.

ECRV retrieved by SRMS.

2: Assembly
ECRV checked out for crew use.
SRMS used to attach packaged TransHab to CTV.

3: Final CTV Configuration
ECRV transfers crew from Shuttle to CTV. Crew inflates TransHab, deploys flooring and partitions, and checks out CTV systems.
“Artificial Gravity” BNTR Mars Crew Transfer Vehicle (CTV) Mission Scenario

CTV Flies by Earth

Crew Re-entry

Trans-Mars Injection, Empty In-Line Tank Jettisoned

2 Magnums used for CTV Assembly
1 STS used for Crew & TransHab Delivery

Crew Ascends & Docks with CTV, Contingency Consumables left in Mars Orbit, Trans-Earth Injection

Crew Transfer from CTV to Hab Lander in Mars Orbit

NTR Propulsive Capture at Mars

CTV Rotation Provides Artificial Gravity to and from Mars
“Bimodal” NTR Crew Transfer Vehicle (CTV) in Artificial Gravity Mode
2014 “Bimodal” NTR Piloted Flight Profile
(210 Day Transit Out, 190 Day Return)

Earth/Mars Synodic Period:
The proper alignment with Mars occurs every 2.13 yrs allowing the “opening” of the TMI window.

Mars Perihelion: January 22, 2013
December 10, 2014

2014 “Bimodal” NTR Piloted Flight Profile
(210 Day Transit Out, 190 Day Return)
Human Mars Mission Architecture Mass Comparison
(Shown at 80 t steps)

- TMI Stage
- MOC/TEI Stage
- Chemical Descent Stages
- Aerobrake/Descent Shells
- Payload (Surface, Habs, etc.)

IMLEO (t)

Bimodal NTR  SEP/Chem  Chem TMI

ISS @ Assembly Complete (470 t)
"LOX-Augmented" NTR (LANTR) Concept--
Operational Features and Characteristics--

<table>
<thead>
<tr>
<th>Life (hrs)</th>
<th>i_sp (sec)</th>
<th>T_ex (°K)</th>
<th>Tankage Fraction (%)</th>
<th>T/Weng Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5</td>
<td>2,900</td>
<td>35</td>
<td>3.0*</td>
</tr>
<tr>
<td>1.0</td>
<td>10</td>
<td>2,800</td>
<td>35</td>
<td>4.8</td>
</tr>
<tr>
<td>3.0</td>
<td>35</td>
<td>2,600</td>
<td>35</td>
<td>8.2</td>
</tr>
<tr>
<td>5.0</td>
<td>576</td>
<td>2,600</td>
<td>35</td>
<td>11.0</td>
</tr>
<tr>
<td>7.0</td>
<td>514</td>
<td>2,600</td>
<td>35</td>
<td>13.1</td>
</tr>
</tbody>
</table>

*For 15 kib, LANT with chamber pressure = 2,000 psia and e = 500 to 1
“LOX-Augmented” Nuclear Thermal Rocket (LANTR)  
“Afterburner” Nozzle Concept Demonstration

LANTR Concept and Benefits:
- “Afterburner” nozzle increases thrust by injecting & combusting GO$_2$ downstream of the NTR throat
- Enables NTR with variable thrust and Isp capability by varying the nozzle O/H mixture ratio (MR)
- Operation at modest MRs (<1.0) helps increase bulk propellant density for packaging in smaller volume launch vehicles
- LANTR’s bipropellant operation enables smaller, faster Moon / Mars vehicles when using extraterrestrial sources of H$_2$ and O$_2$

LANTR Test Program Objectives: (Aerojet & GRC)
- Measure thrust augmentation from oxygen injection and supersonic combustion using small, fuel-rich H/O engine with two different area ratio nozzles (@ 25:1 and 50:1) as “non-nuclear” NTR simulator.
- Use results to calibrate reactive CFD assessment of bimodal LANTR engine

Status: LANTR afterburner nozzle demonstrated
- Oxygen injection into hot supersonic flow
- Supersonic combustion in the nozzle
- Elevated nozzle pressures measured
- Benign nozzle wall environment observed
- Increase O2 consumption rate with nozzle length
- Thrust augmentation >50% measured

Baseline H/O Thrust: 2100 lbf at 1000 psia and MR = 1.5. With GO$_2$ injection into nozzle, measured thrust due to supersonic combustion is 3200 lbf (~52% thrust augmentation achieved at 50:1 and MR$_L$~3.0)
Fully Reusable NTR-Powered Transfer Vehicle  
“The Key to Affordable Lunar Transportation”

Ref: Borowski, NASA/TM 106739
Robotic Science “Hybrid” BNTEP Vehicle

Elevation View

- 2 - 60 kW_e BRUs @ 50% power (enclosed)
- 5 klbf BNTR
- Electrical and Coolant Conduit Lines
- Docking Interface
- Saddle Truss
- LH₂ Refrigeration System & Radiator
- “Jettisonable” In-Line LH₂ Tank
- Xenon Ion Thruster Clusters

Top View

- “Core” Stage LH₂ Tank
- Toroidal LOX Tank
- Saddle Truss-Mounted Radiator & Foldout Panels (~88 m²)
- Conical Radiator (~26 m²)
- LiH / W Shield
- Science Payload

~17 m ~17 m
Significant Technology Development is Underway
To Support Design Definition for Future
“Bimodal” NTR Human Exploration Missions