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

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

presented by

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Artificial Gravity “Bimodal” NTR Crew Transfer Vehicle (CTV) for Mars DRM 4.0 (1999)
• During short, high thrust propulsion phase, each BNTR produces \(~340\, \text{MW}_t\) and \(~15\, \text{klbf}_t\) of thrust.
• During long, power generation phase, each BNTR operates in “idle mode” producing just \(~150\, \text{kW}_t\).
• A Brayton conversion unit on each BNTR produces up to \(25\, \text{kW}_e\) 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)

- Iₛₚ 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

- **H₂ 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” H₂ exhaust

**Easier to test**

**Smaller, Higher Performance**

**Environmentally “Green”**

**For Public Acceptance**
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$_{eng}$ ~3.1
- Each bimodal NTR produces 25 kW$_e$
- Utilizes proven Brayton technology
- Variable thrust & $I_{sp}$ optional with “LOX-afterburner” nozzle (LANTR)
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/W<sub>eng</sub> ~3.1)
- 50 kWe CBC w/Radiator
- 48.6t Capacity LH<sub>2</sub> Tank

Refrigeration System

“In-Line” Propellant Tank
(Tank Jettisoned)

- 43t Capacity LH<sub>2</sub> Tank
- Jettisonable Consumables (~6.9t)

Strongback Truss

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

- ECRV (~5.1t)

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

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

Crew Transfer from CTV to Hab Lander in Mars Orbit

CTV Rotation Provides Artificial Gravity to and from Mars

NTR Propulsive Capture at Mars

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
"Bimodal" NTR Crew Transfer Vehicle (CTV) in Artificial Gravity Mode
2014 “Bimodal” NTR Piloted Flight Profile
(210 Day Transit Out, 190 Day Return)

Earth @ Departure
Jan. 21, 2014

Mars @ Departure
Jan. 3, 2016

Return Inbound Trajectory

Earth @ Arrival
July 11, 2016
(190 days IB)

Mars @ Arrival
Aug. 19, 2014
(210 days OB)

Outbound Trajectory

Mars Stay Time: 502 days

Mars Perihelion:
January 22, 2013
December 10, 2014

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

NASA/CP—2004-21263/VOL1
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.)

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

![Diagram of NTR concept]

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<th>Life (hrs)</th>
<th>(T_{\text{ex}}) (°K)</th>
<th>(I_{\text{sp}}) (sec)</th>
<th>Tankage Fraction (%)</th>
<th>T/W_{\text{eng}} Ratio</th>
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*For 15 klf LANTR with chamber pressure = 2,000 psia and \(\varepsilon = 500\) to 1
“LOX-Augmented” Nuclear Thermal Rocket (LANTR)
“Afterburner” Nozzle Concept Demonstration

**LANTR Concept and Benefits:**
- "Afterburner" nozzle increases thrust by injecting & combusting GO\textsubscript{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\textsubscript{2} and O\textsubscript{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 O\textsubscript{2} consumption rate with nozzle length
- Thrust augmentation >50% measured

Baseline H/O Thrust: 2100 lbf at 1000 psia and MR = 1.5. With GO\textsubscript{2} injection into nozzle, measured thrust due to supersonic combustion is 3200 lbf (~52% thrust augmentation achieved at 50:1 and MR\textsubscript{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

- Docking Interface
- Saddle Truss
- Xenon Thruster Clusters
- 2 - 60 kW BRUs @ 50% power (enclosed)
- Electrical and Coolant Conduit Lines
- LH₂ Refrigeration System & Radiator
- Conical Radiator (~26 m²)
- Jettisonable LH₂ Tank
- LH₂ Tank
- Toroidal LOX Tank
- Saddle Truss-Mounted Radiator & Foldout Panels (~88 m²)
- Science Payload
- Conical Radiator (~26 m²)
- Science "Core" Stage

Top View

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

Docking Interface
- Saddle Truss
- Xenon Thruster Clusters
- 2 - 60 kW BRUs @ 50% power (enclosed)
- Electrical and Coolant Conduit Lines
- LH₂ Refrigeration System & Radiator
- Conical Radiator (~26 m²)
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- Toroidal LOX Tank
- Saddle Truss-Mounted Radiator & Foldout Panels (~88 m²)
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Significant Technology Development is Underway To Support Design Definition for Future "Bimodal" NTR Human Exploration Missions.