"Nuclear Thermal Propulsion: Past, Present and a Look Ahead"

"Propelling Us to New Worlds"

presented by

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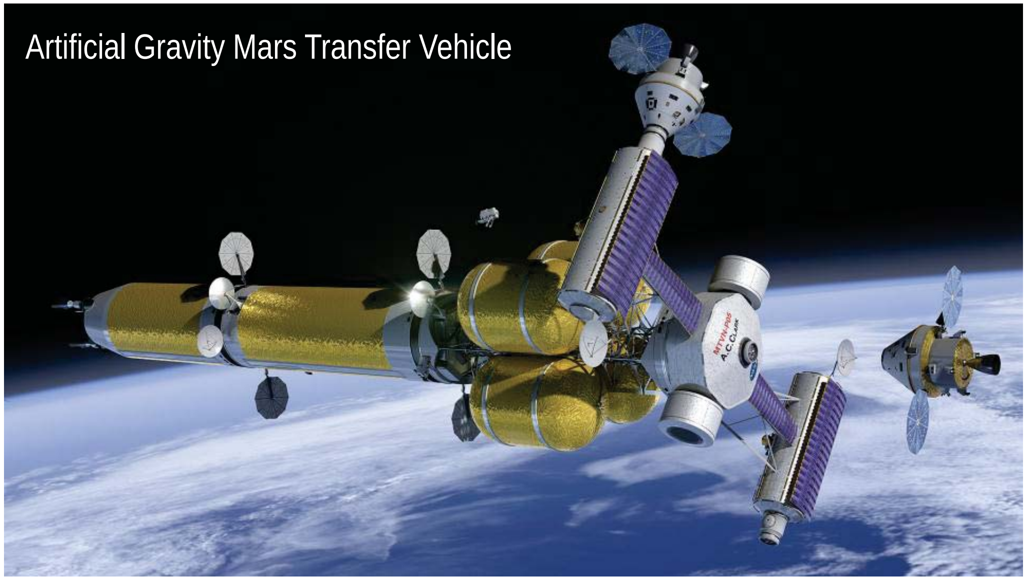
at the

Wernher von Braun Memorial Symposium
Advanced Propulsion Technologies Panel
Chan Auditorium, University of Alabama in Huntsville


Artificial Gravity Mars Transfer Vehicle


7-Day Round Trip Commercial Lunar Tourism Mission

Wednesday, October 29, 2014

Glenn Research Center
at Lewis Field

Nuclear Thermal Rocket (NTR) Concept Illustration (Expander Cycle, Dual LH_2 Turbopumps)

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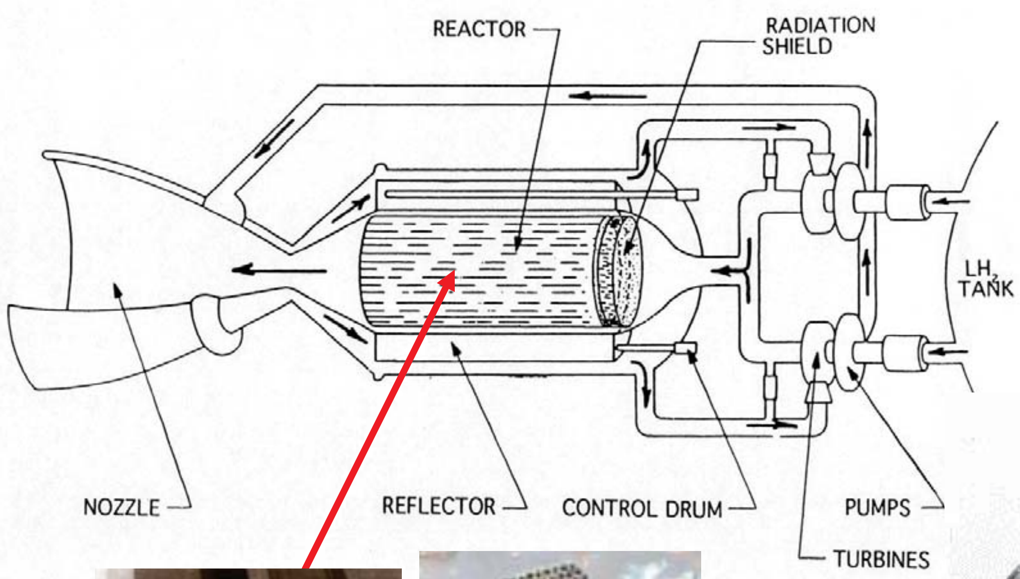
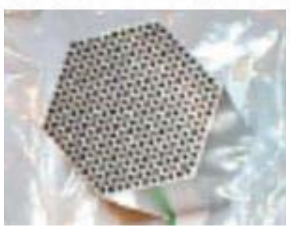
NTR*:** High thrust / high specific impulse (2 x LOX/LH_2 chemical) engine uses high power density fission reactor with enriched uranium fuel as thermal power source. Reactor heat is removed using H_2 propellant which is then exhausted to produce thrust. Conventional chemical engine LH_2 tanks, turbopumps, regenerative nozzles and radiation-cooled shirt extensions used -- ***"NTR is next evolutionary step in high performance liquid rocket engines"

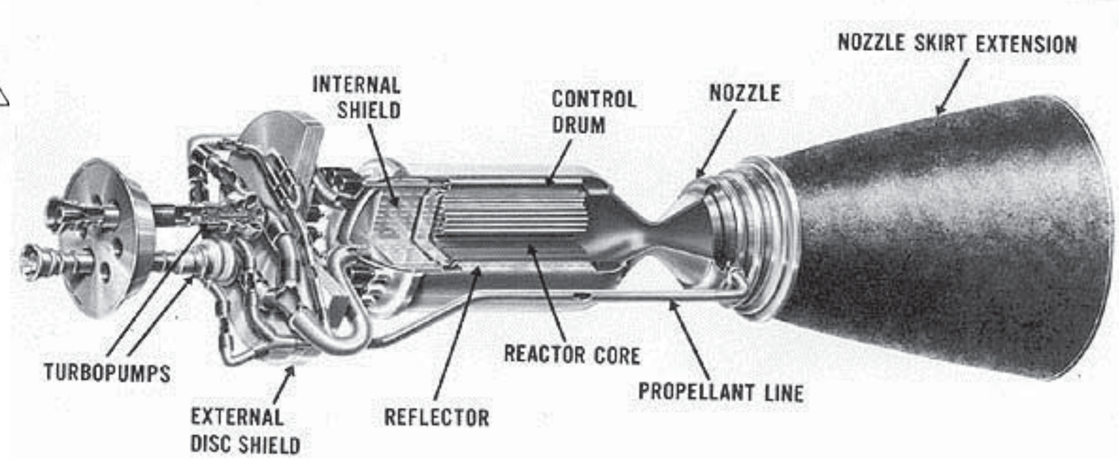


During his famous Moon-landing speech in May 1961, President John F. Kennedy also called for accelerated development of the NTR saying this technology "gives promise of some day providing a means of even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself."

NERVA-derived Composite Fuel



Ceramic Metal (Cermet) Fuel



NTP uses high temperature fuel, produces ~560 MWt (for ~25 klb_f engine) but operates for ≤ 80 minutes on a round trip mission to Mars (DRA 5.0)

"Heritage" Fuel Element – Tie Tube Arrangement for NERVA-derived NTR Engines

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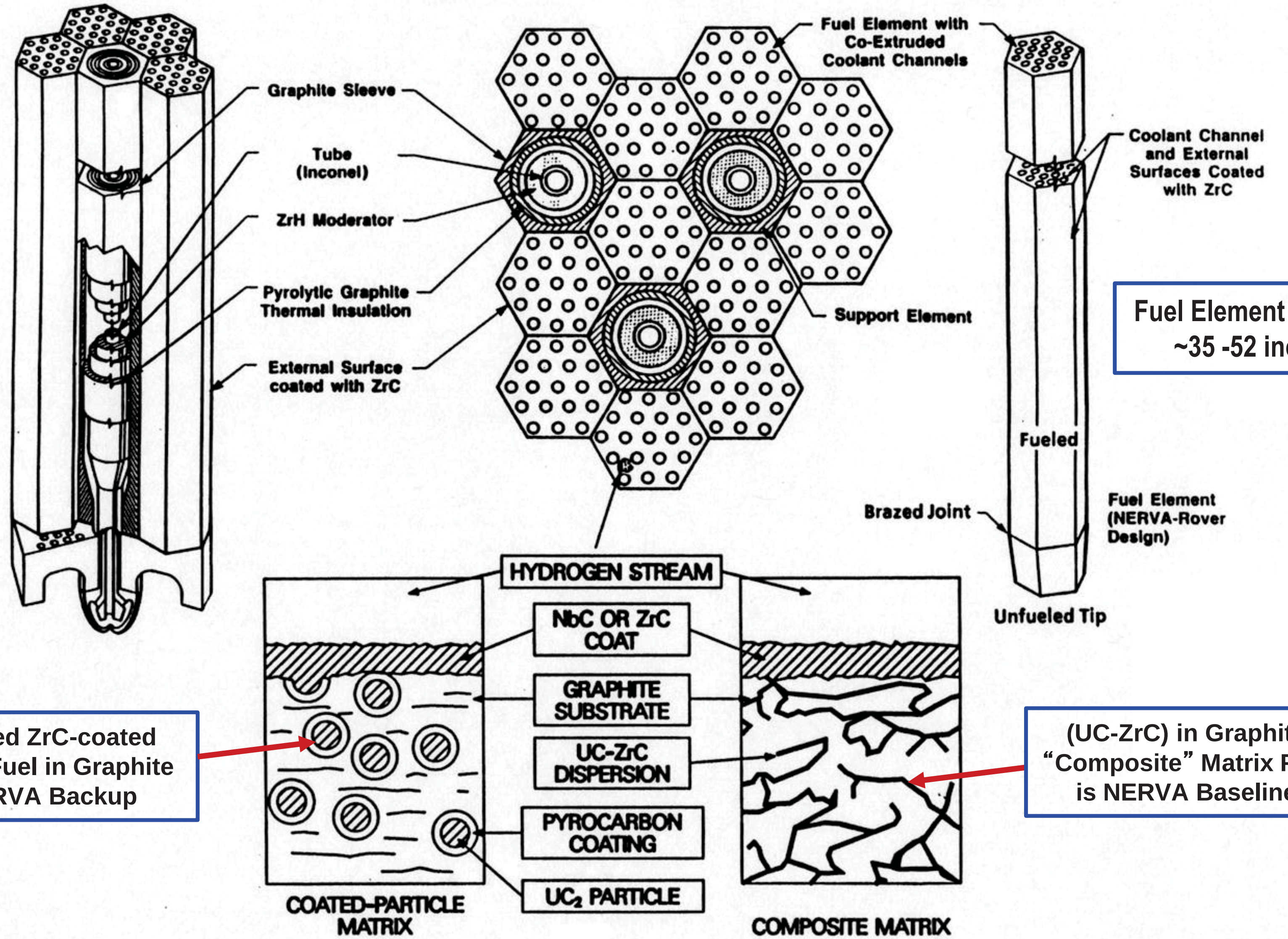


Fuel Element Length: ~35 -52 inches

Improved ZrC-coated Particle Fuel in Graphite is NERVA Backup

(UC-ZrC) in Graphite "Composite" Matrix Fuel is NERVA Baseline

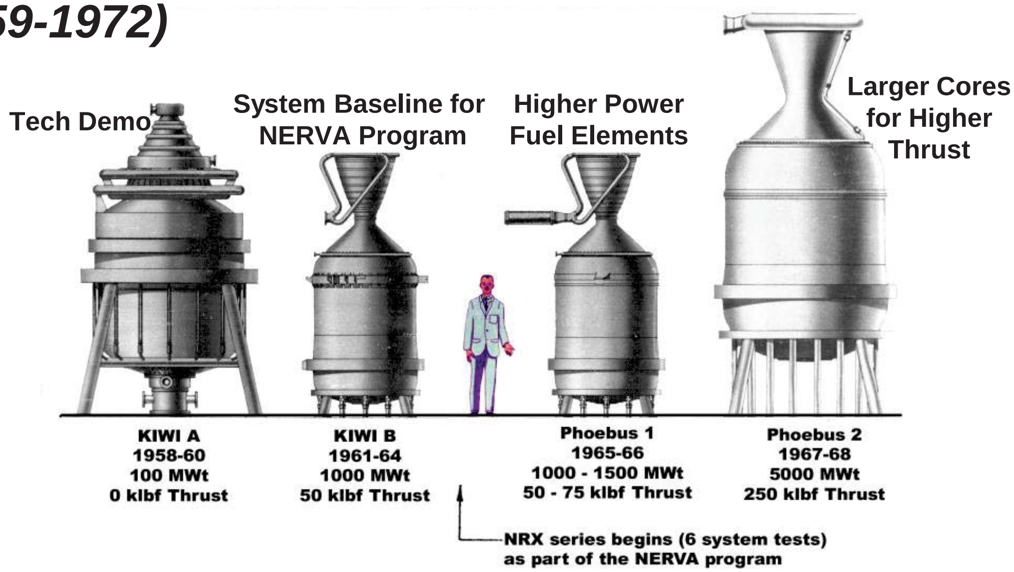
Rover / NERVA Program Summary*

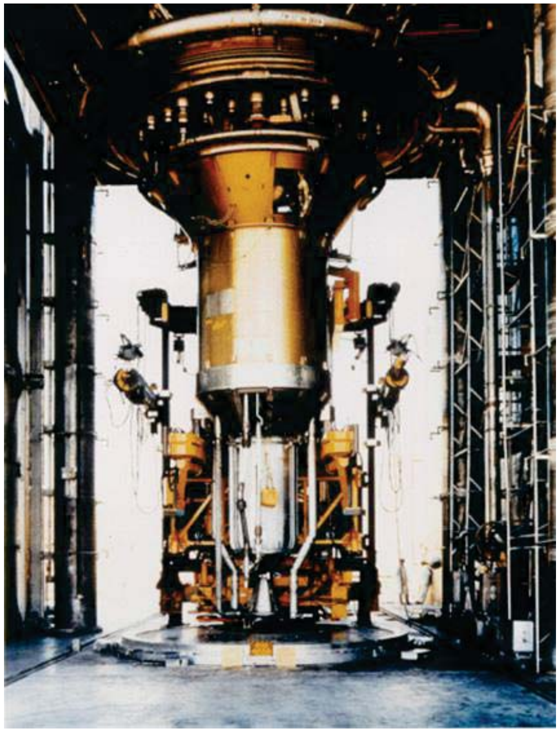
(1959-1972)

The smallest engine tested, the 25 klb$_f$ "Pewee" engine, is sufficient for human Mars missions when used in a clustered arrangement of 3 – 4 engines

- **20 NTR / reactors designed, built and tested at the Nevada Test Site – "All the requirements for a human mission to Mars were demonstrated"**
- **Engine sizes tested**
  - 25, 50, 75 and 250 klb$_f$
- **H_2 exit temperatures achieved**
  - 2,350-2,550 K (in 25 klb$_f$ Pewee)
- **I_{sp} capability**
  - 825-850 sec ("hot bleed cycle" tested on NERVA-XE)
  - 850-875 sec ("expander cycle" chosen for NERVA flight engine)
- **Burn duration**
  - ~ 62 min (50 klb$_f$ NRX-A6 - single burn)
  - ~ 2 hrs (50 klb$_f$ NRX-XE: 27 restarts / accumulated burn time)

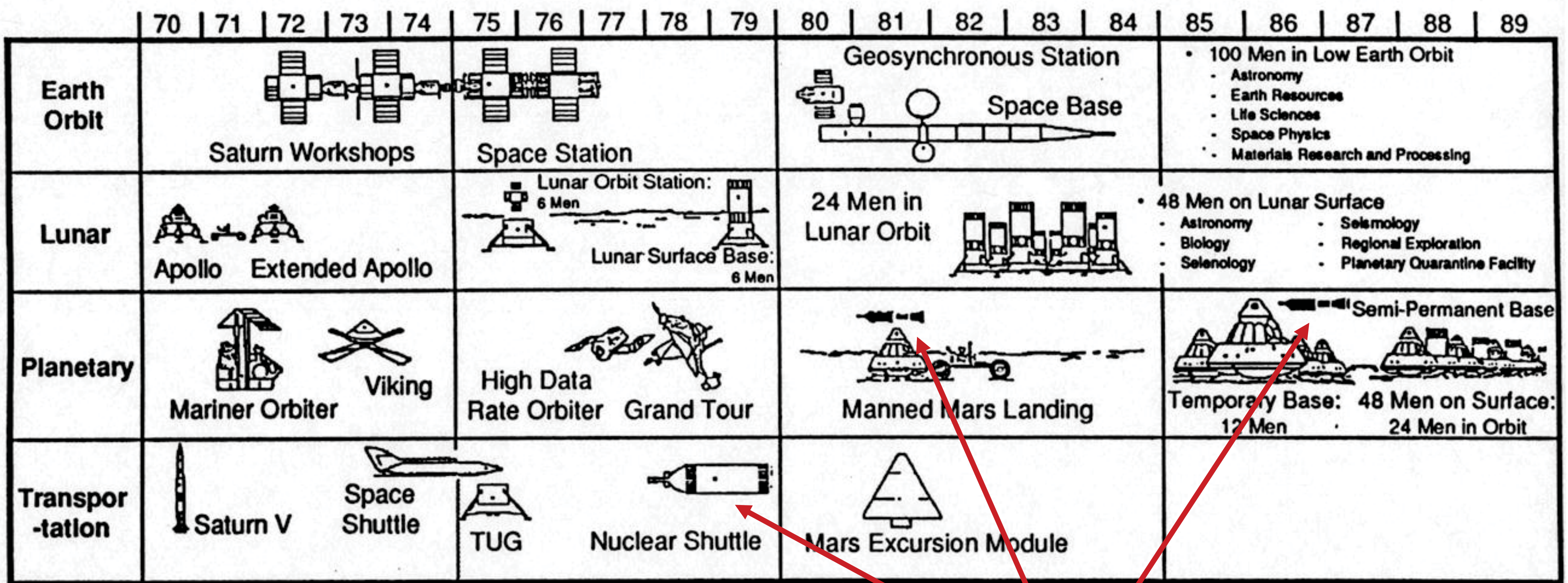
*** NERVA: Nuclear Engine for Rocket Vehicle Applications***





The NERVA Experimental Engine (XE) demonstrated 28 start-up / shut-down cycles during tests in 1969.

Wernher von Braun's Integrated Space Plan for NASA (1970 - 1990) Utilized Nuclear Thermal Propulsion



Presented to President Nixon's Space Task Group and Senate Committee on Aeronautics and Space Science on August 4 and 5, 1969.

NERVA NTR Stage Envisioned for Moon / Mars Mission Applications

von Braun envisioned NTPS being a "workhorse" space asset for delivering cargo and crew to the Moon first to support lunar base construction, then to send human missions to Mars

Sampling of NTR Lunar / Mars Transfer Vehicle Concepts Developed by GRC (~1989 - 2009)

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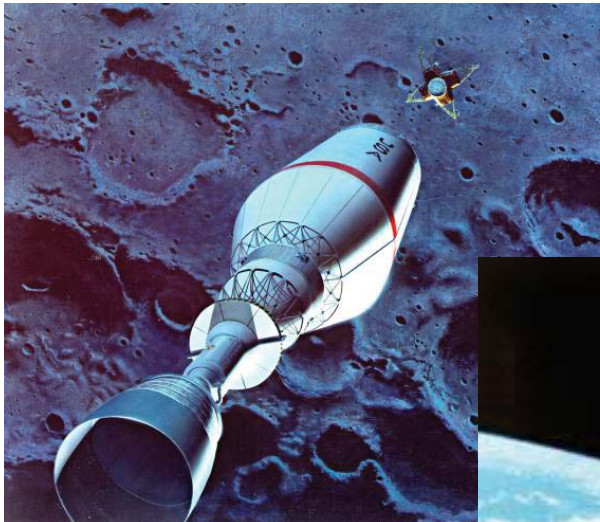
Design Transition from Single Large NTR to Clustered Smaller Engines



“Reusable” Lunar Transfer Vehicle using Single 75 klb_f NTR Engine – SEI (1990 - 91)

Expendable TLI Stage for “First Lunar Outpost” Mission uses 3 - 25 klb_f NTR Engines – “Fast Track Study” (1992)

Reusable “Modular” Crewed MTV uses Single 75 klb_f NTR Engine – SEI (1990 - 91)

“Artificial Gravity” Crewed MTV uses 3 - 15 klb_f / 25 kW_e “Bimodal NTR Engines – Mars DRM 4.0 (1999)

“Zero-Gravity” Crewed MTV uses 3 - 25 klb_f NTR Engines & PVA Auxiliary Power – Mars DRA 5.0 (2009)

Key NASA / DOE NTP Task Activities: FY' 11-14

- **Task 1 - Mission Analysis, Stage / Vehicle System Characterization & Engine Requirements Definition**
  - Define requirements & system characteristics (engine, stage, and vehicle) for future human exploration missions (Moon, NEAs, Mars) to guide concept design and development of future ground and flight technology demonstration efforts
- **Task 2 - NTP Fuels & Coatings Assessment and Technology Development**
  - Recapture, mature and select from two primary fuel forms identified by NASA and DOE – NERVA graphite "composite" and UO_2 in tungsten ceramic metal (cermet) fuel. Fabricate and test partial then full length fuel elements (FEs)
- **Task 3 - Engine Conceptual Design & Analysis, Model Development**
  - Develop concept designs for small (~5-10 klb_f) NTR engines that are scalable to full size (25 klb_f) engines using "heritage" NERVA and Cermet FE designs and state-of-the-art NASA and DOE engine and MCNP neutronics models
- **Task 4 - Demonstration of Affordable Ground Testing**
  - Develop and demonstrate innovative approaches for NTP ground testing like the SAFE concept that requires modest supporting infrastructure and offers the potential for reduced development costs
- **Task 5 - Formulation of Affordable & Sustainable NTP Development Strategy**
  - Develop a joint NASA / DOE program plan and formulate a development strategy that allows an affordable and sustainable NTP program

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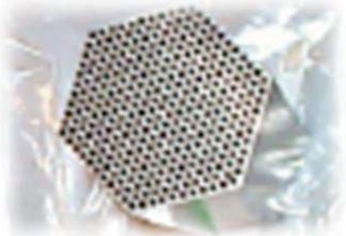
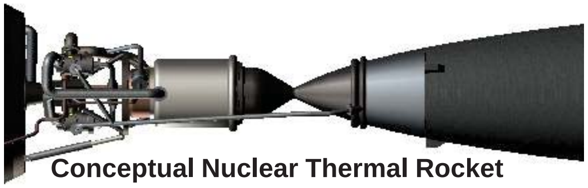
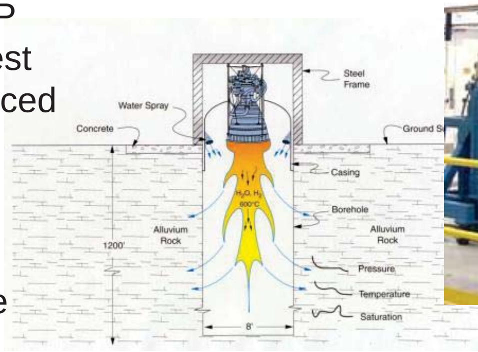
"Zero-Gravity" Crewed Mars Transfer Vehicle with 3 - 25 klbf NTR Engines - Mars DRA 5.0 (2009)


Demo Composite NERVA Fuel Elements


Demo Cermet Fuel Element


Conceptual Nuclear Thermal Rocket



Idealized configuration of the Surface Active Filtration of Exhaust (SAFE) testing concept


NTR Element Environmental Simulator (NTREES)

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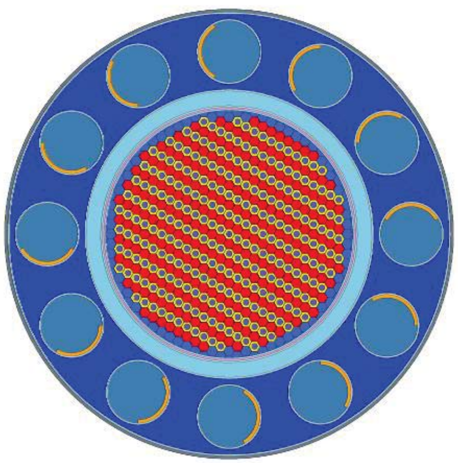
Oak Ridge National Laboratory

Idaho National Laboratory

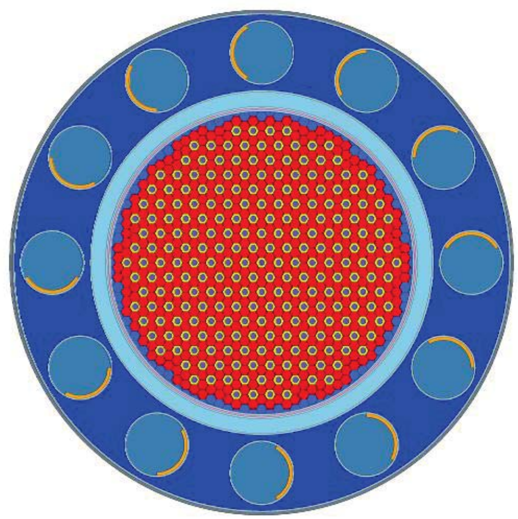
Development of a Common Scalable Fuel Element for Ground Testing and Flight Validation

- During the Rover program, a common fuel element / tie tube design was developed and used in the design of the 50 klbf Kiwi-B4E (1964), 75 klbf Phoebus-1B (1967), 250 klbf Phoebus-2A (June 1968), then back down to the 25 klbf Pewee engine (Nov-Dec 1968)

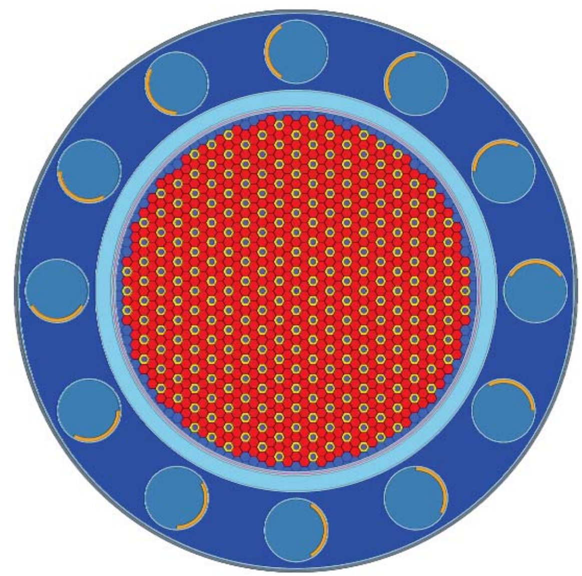
- NASA and DOE are using this same approach: design, build, ground then flight test a small engine using a common fuel element that is scalable to a larger 25 klbf thrust engine needed for human missions



7.4-klb_f low thrust engine



16.4-klb_f SNRE



25-klb_f "Pewee-class" engine (Radial growth option / sparse pattern)

Ref: B. Schnitzler, et al., "Lower Thrust Engine Options Based on the Small Nuclear Rocket Engine Design", AIAA-2011-5846 paper presented at the 47th Joint Propulsion Conference, San Diego, CA

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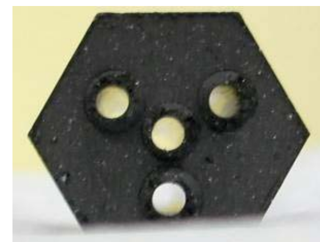
NERVA Graphite - Composite Fuel Elements with Protective ZrC Coating are Being Produced Now at ORNL for NCPS Project

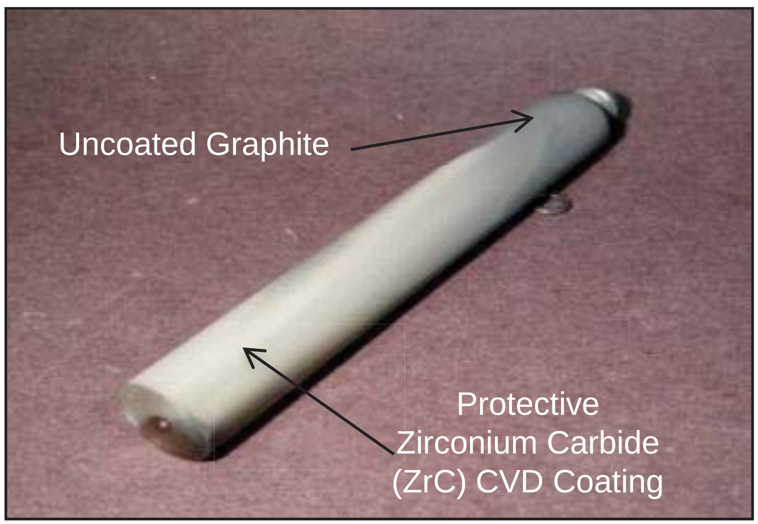
Oak Ridge National Laboratory

Above: 19 and 4-hole NERVA fuel element extrusion dies;
Left: Graphite extruder with vent lines installed for DU capability

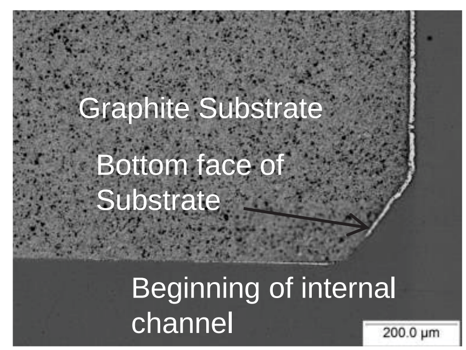


Above and Left: Extrusion samples using carbon-matrix/Ha blend 0.75” across flats, 0.125” coolant channels

Right: Layoff base / Graphite insert



Above: Test Piece highlighting ZrC Coating
Right: Coating primarily on external surface



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Fiscal Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027

Key Milestones

Fuels Selection

ATP

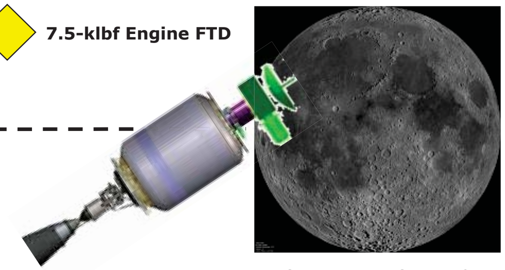
Start

End

GTD Engine Tests

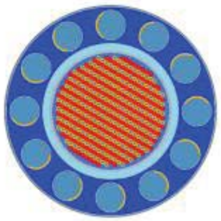
7.5-klbf Engine FTD

Notional



Small NTP Stage for Lunar Flyby Mission

Foundational Technology Development



SOTA Reactor Core & Engine Modeling

System Concepts & Requirements Definition / Planning / Engine Modeling & Analysis

In-House & Contractor System Concept Definition, Design, and Analysis

Initial GTD Design

Initial FTD Design

Initial 25-klbf GTD / FTD Designs

Reference Concept & Initial Requirements

NTP Technology Development and Demonstrations

Fuel Element Fab, Testing, Validation and Production; Irradiation Testing / PIE; Other Tech Development

Primary / Secondary Fuels Selection

Advanced NTP Tech Dev Includes Fuels & Bimodal Concepts

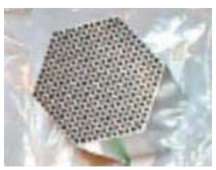
Hot H2 Testing in NTREES & DOE Reactor Irradiation Tests

NERVA “Composite” Fuel

NTP Test Facilities Development

Borehole Demo Testing

GTF Plan'g/Prel Des



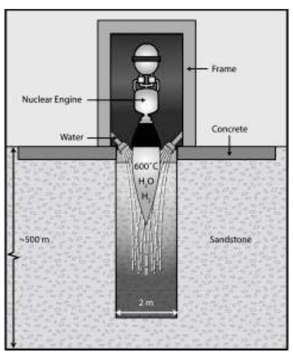
“Cermet” Fuel

“Fuel-Rich” Engine

Potential Demos / Mars Flights
2029-30 - Lunar/EM-L2 Flights
2031-33 - Mars Cargo Flights
2033-35 - Mars Crewed Flights

Fuel Element Irradiation Testing in ATR at INL

Ground & Flight Technology Demonstrators



Affordable SAFE Ground Testing at the Nevada Test Site (NTS)

Ground Test Facility (GTF)

Prel. & Final Design | Construction & Asset Installation | Check -out

Test Articles for Ground & Flight

CDR GTA

CDR FTA

Detailed Design | Fabrication & Subsys. Assembly | Subsys. Test / Engine Assem. | GTA1 | GTA2

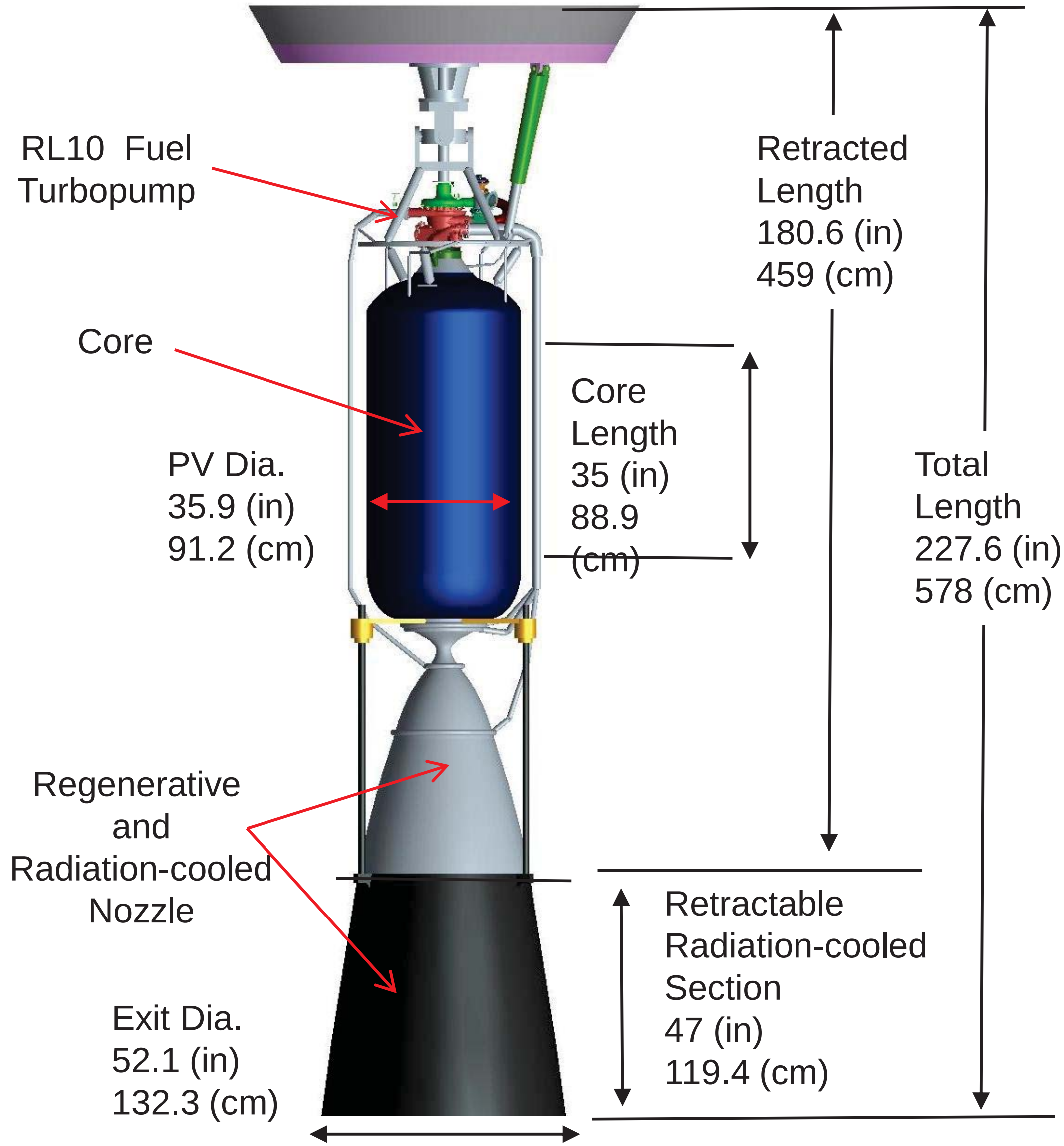
Detailed Design | Fabrication & Subsys. Assembly | Subsys. Test / Engine Assem. | FTA

GTD	Ground Tech Demo
GTA1	Ground Test Article 1
GTA2	Ground Test Article 2
FTA	Flight Test Article
FTD	Flight Tech Demo

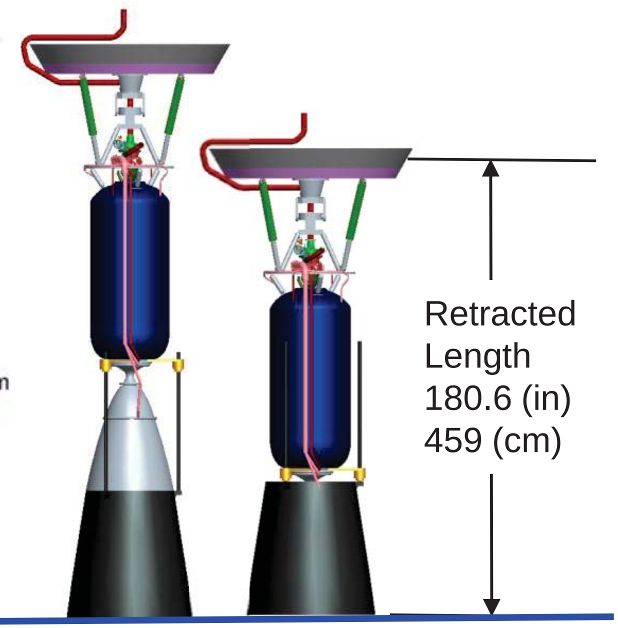
NTR Element Environmental Simulator (NTREES)

Small NERVA-derived 7.42 klb$_f$ NTR Engine Layout and Dimensions

Aerojet Rocketdyne has been working with GRC to define a small, low thrust NTR scalable to higher thrust engines



LO2/LH2 RL10B-2 Tvac 24,750-lbf



2025 Small NTPS FTD Mission: “Single-Burn Lunar Flyby”

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- ELV launches Small NTPS (SNTPS) to LEO (407 km)
- 3 – Day LEO to Moon Transit
- Lunar Gravity Assist and disposal

SNTPS FTD Launch on Delta 4 M (5,4)

DCSS delivers SNTPS to LEO

Earthrise Final Farewell Pictures

Single-Burn TLI sends SNTPS to the Moon

Lunar Gravity Assist sends SNTPS into Deep Space

- IMLEO ~12.72 t
- F ~7.42 klb_f, I_{sp} ~900s, F/W_{eng} ~1.87
- LH_2 mass ~5.07 t
- Stage dry mass ~7.40 t
- PL ~250 kg
- Burn time ~20.9 mins

The NTPS with In-Line LH_2 Tank Allows Reusable Lunar Cargo Delivery Missions (Max Lift to LEO ~70 t)

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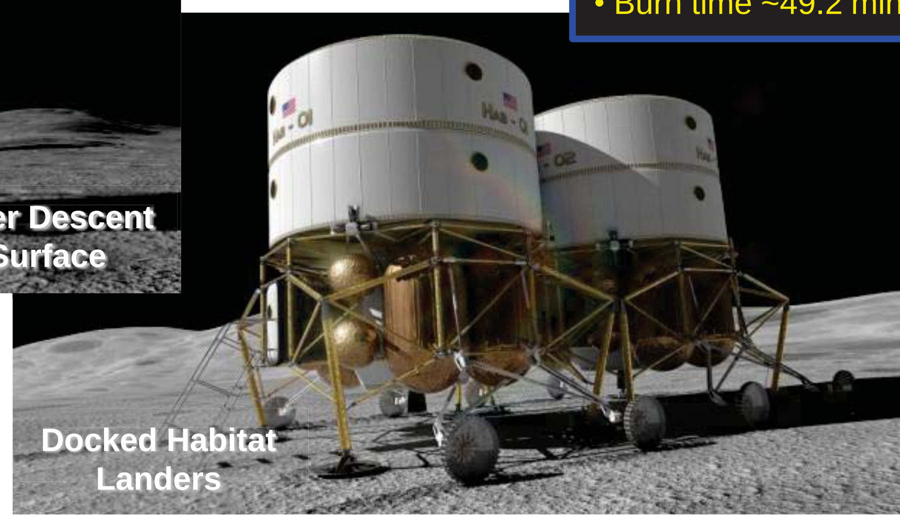
NTP Cargo Delivery Mission – 3 – Day LEO to LLO Transit and Habitat Lander Deployment

Lunar Cargo Delivery:
- IMLEO ~186.7 t
- NTPS ~70 t
- In-Line LH_2 Tank ~52.6 t
- Habitat Lander ~61.1 t
- PL Adaptor ~3 t
- Burn time ~49.2 mins



NTP Cargo Mission Return – 3 – Day Transit from LLO to 24–hr Elliptical Earth Orbit (EEO)

Reusable Crewed Lunar Landing Mission Uses NTPS and In-Line LH_2 Tank (Max Lift to LEO ~70 t)

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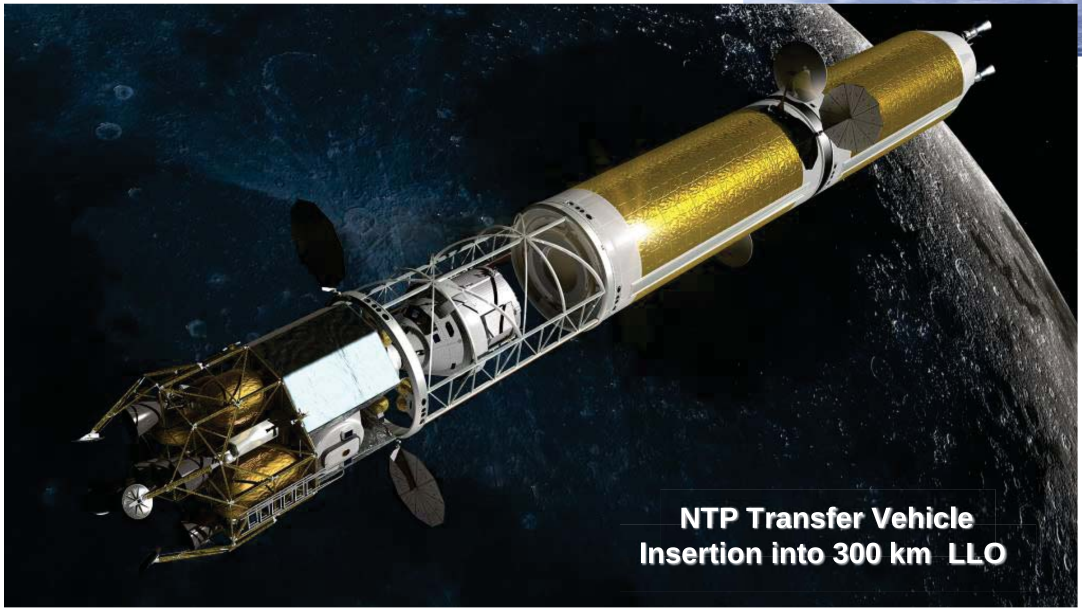
Crewed Lunar Landing Mission – 3 – Day LEO to LLO Transit



Crewed Lunar Landing:
- IMLEO ~188.6 t
- NTPS ~70 t
- In-Line LH_2 Tank ~63.3 t
- LDAV and PL ~34.5 t
- Truss and RCS ~6.4 t
- MPCV, 4-Crew ~14.4 t
- Burn time ~55 mins

Only 27 Humans Have Seen the Far Side of the Moon Up Close and Personal

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Lunar Orbital Tourism: What's Possible?

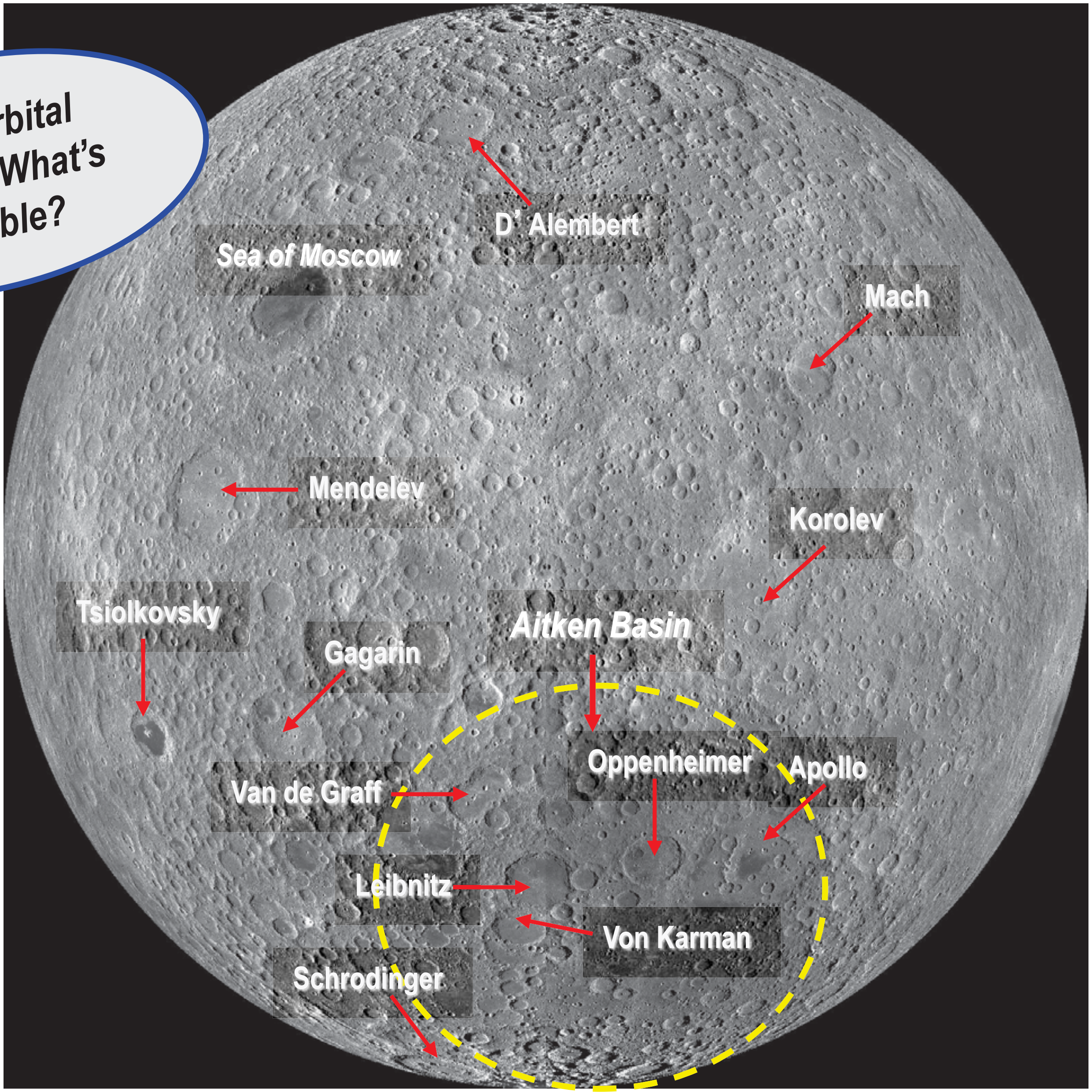

Image from Lunar Reconnaissance Orbiter's Wide Angle Camera

NTR
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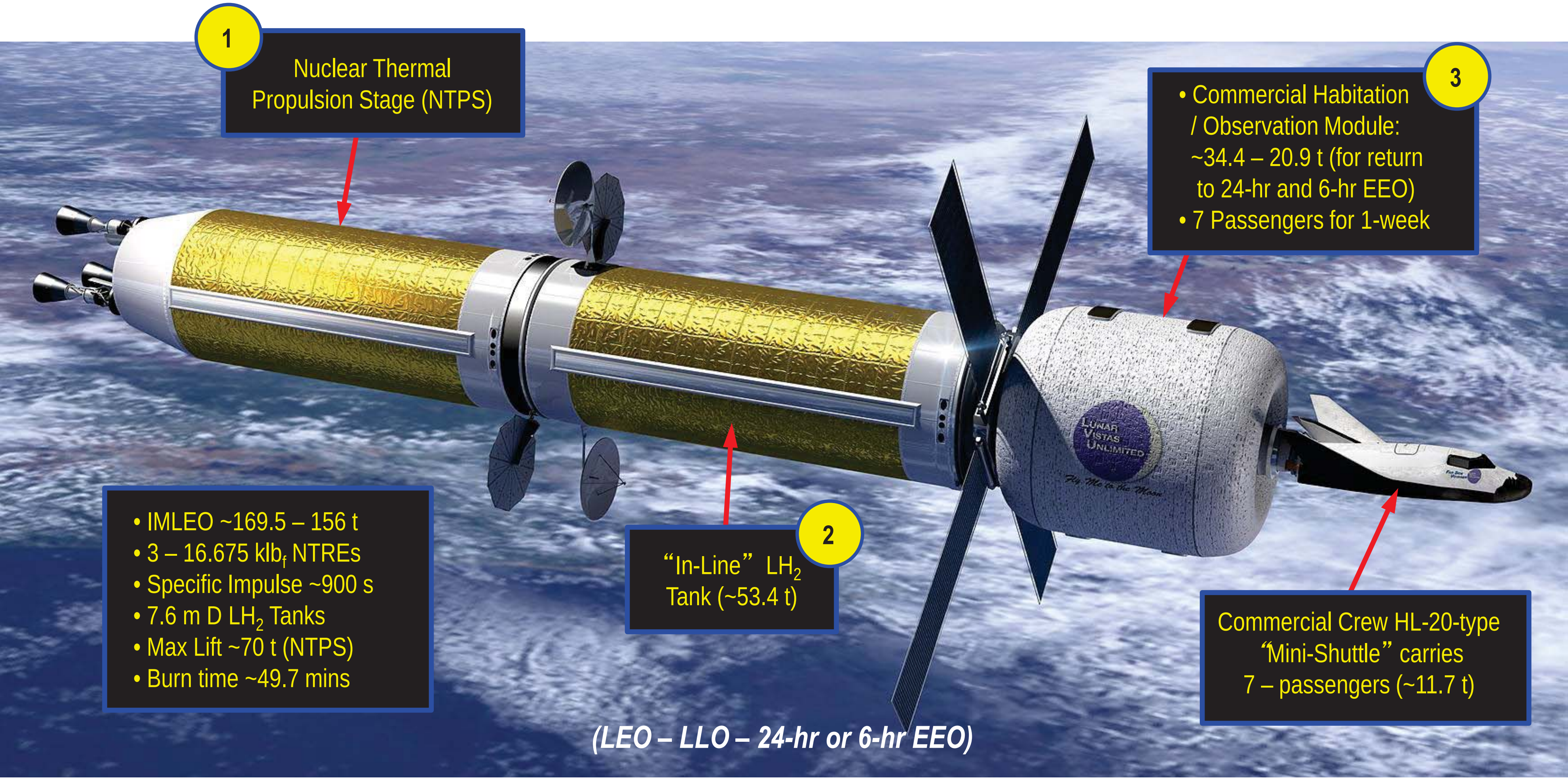
Week-long Orbital "Tourism" Missions to the Moon Using NTP
(Includes 3-day Transits to and from the Moon with 1-day in Orbit)



Orbital Tourism Missions Could Utilize a Reusable NTP Lunar Transportation System plus Commercial Crew Launch, Habitation, and Refueling Services

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