Integrated Technology Plan
for the
Civil Space Program

FOCUSED TECHNOLOGY: NUCLEAR PROPULSION

Nuclear Thermal Propulsion

Nuclear Electric Propulsion

JUNE 27th, 1991
Washington, D.C.

OVERVIEW

Thomas J. Miller
Head, Nuclear Propulsion Office
NASA Lewis Research Center
FOCUSED TECHNOLOGY: NUCLEAR PROPULSION

SUMMARY

- IMPACT:
  - Nuclear Propulsion Enables and/or Enhances Space Exploration Missions

Nuclear Electric Propulsion (NEP)
- Enables: Robotic Science Missions
- Enhances: Lunar & Mars Cargo, & Mars Piloted Space Exploration

Nuclear Thermal Propulsion (NTP)
- Mars Piloted
- Lunar & Mars Cargo, Lunar Piloted & Robotic Science Space Exploration

- USER COORDINATION:
  - Exploration Studies Identify Nuclear Propulsion as a Key Technology
  - OAET/RZ - Provide Performance Predictions for NASA Studies
  - OSSA Study on NEP for Robotic Science Missions
  - DOE, DoD & NASA Included on Steering Committee (also Astronaut Office)

- TECHNICAL REVIEWS:
  - Interagency Design Review Teams will Periodically Review Technical Progress

- OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
  - High Priority Technology Areas Identified (some efforts initiated)
  - Budget Deliberations Continue
  - Single Multi Agency Plan Defined for FY92 Implementation

- MAJOR TECHNICAL/PROGRAMMATIC ISSUES:
  - Agency/Department Roles
  - Funding to Initiate Technical Efforts
  - Projected Budget Does Not Support Schedules

Nuclear Thermal Propulsion

PERFORMANCE OBJECTIVES

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>STATE-OF-THE ART</th>
<th>OBJECTIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>THRUST (lb)</td>
<td>75K (NERVA)</td>
<td>75K-125K/Engine</td>
</tr>
<tr>
<td>SPECIFIC IMPULSE (sec)</td>
<td>825</td>
<td>≥ 925</td>
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<tr>
<td>CHAMBER PRESSURE</td>
<td>450</td>
<td>500 - 1000</td>
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<tr>
<td>EXHAUST TEMP. (°C)</td>
<td>2200-2500</td>
<td>2,700 (w/ Approp. Safety &amp; Reliability Margins)</td>
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<tr>
<td>POWER (MW)</td>
<td>1100 (NERVA)</td>
<td>≥ 1,600</td>
</tr>
<tr>
<td>4,200 (PHOEBUS)</td>
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<tr>
<td>LIFETIME (Hrs)</td>
<td>1.0</td>
<td>4.5 (2 Mission req.)</td>
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<tr>
<td>Cumulative</td>
<td>1.5</td>
<td>5</td>
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<tr>
<td>REUSABILITY (No. Missions)</td>
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CHALLENGES

- High Temperature Fuel and Materials
- Hot Hydrogen Environment
- Test Facilities
- Safety
- Environmental Impact Compliance
- Concept Development

MISSION BENEFITS

- Short Transit Time Missions are Enabled
- Reduced IMLEO (~1/2 of Chemical)
- Crew Safety Enhanced
- Wider Launch Windows
- More Mars Opportunities
- High Thrust Available
- Aerobrake Not Required

PR12-2
Nuclear Electric Propulsion

**PERFORMANCE OBJECTIVES**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>STATE-OF-THE ART</th>
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<tbody>
<tr>
<td>POWER</td>
<td>SP-100</td>
<td>210.0</td>
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<tr>
<td>POWER LEVEL (MW)</td>
<td>0.1</td>
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<td>SPECIFIC MASS (Kg/KWe)</td>
<td>30</td>
<td>≤ 10</td>
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<td>PROPULSION</td>
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<td>SPECIFIC IMPULSE</td>
<td>2000-9000</td>
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<td>EFFICIENCY</td>
<td>0.7-0.8</td>
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<td>POWER LEVEL (MW)</td>
<td>0.01-0.03</td>
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<td>LIFETIME (hrs)</td>
<td>10,000</td>
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<td>PMAD EFFICIENCY</td>
<td>0.90</td>
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<td>SPECIFIC MASS (Kg/KWe)</td>
<td>4</td>
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<td>REJECTION TEMP. (*K)</td>
<td>400</td>
<td>600</td>
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**CHALLENGES**

- Long Operational Lifetime
- High Temperature Reactors, Turbines, Radiators
- High Fuel Burn-up Reactor Fuels, Designs
- Efficient, High Temperature Power Conditioning
- High Efficiency, Long Life Thrusters
- Safety
- Environmental Impact Compliance
- Concept Development

**MISSION BENEFITS**

- Low Resupply Mass
- Availability of Onboard Power
- Reduced IMLEO Sensitivity w/Mission Opportunity
- Broad Launch Windows
- Commonality with Surface Nuclear Power
- Aerobrake Not Required

**TRANSPORTATION TECHNOLOGY**

**SPACE TRANSPORTATION**

**Nuclear Thermal Propulsion**

**OBJECTIVES**

**Programmatic**

Develop propulsion technologies capable of fulfilling requirements, such as performance, long life, and multiple starts, for future piloted and cargo missions to Mars and the Moon, and robotic precursor missions.

**Technical**

- Fuel Lifetime: 4.5 hrs (cyclic)
- Man-Rated: Autonomous Robotic Operation
- Ground Testing: Full System (TRL-6) by 2006

**SCHEDULE**

- 1992 Lab-Scale Demonstration of 2700K reactor fuel
- 1994 Complete conceptual designs of selected concepts for piloted Mars mission
- 1996 Nuclear Furnace Facility Complete
- 1998 Select NTR Concept(s) for Systems Testing
- 1999 Systems Facility Construction Complete
- 2002 First NTR Reactor Test Complete
- 2006 Full System Ground Testing Complete Verifying Technology Readiness Level 6 (TRL-6) for NTR

**RESOURCES**

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<tr>
<th>YEAR</th>
<th>NASA**</th>
<th>DOE*</th>
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<td>1991</td>
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<td>1992</td>
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<tr>
<td>1997</td>
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* DOE current estimate for both NTP & NEP
** NASA dollars do not include CoF

**PARTICIPANTS**

- Lewis Research Center
  Lead Center
  Participating Center
- Marshall Space Flight Center
- Johnson Space Center
  Supporting Center

- DOE Laboratories
  INEL, LANL, SNL, ORNL, ANL, BNL...
**NUCLEAR THERMAL PROPULSION ROADMAP/SCHEDULE**

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**FOCUSED R&T**
- Innovative Technology
  - Facilities
- NTP Technology
  - Concept Development & Systems Engineering
  - Safety, QA, Reliability, Environment

**R&T BASE**

| **TRANSPORTATION TECHNOLOGY** |
| **SPACE TRANSPORTATION** |

**OBJECTIVES**
- **Programmatic**
  - Develop propulsion technologies capable of fulfilling requirements, such as performance, long life, and multiple starts, for future piloted and cargo missions to Mars and the Moon, and robotic precursor missions.
- **Technical**
  - Power: > 10MWe
  - Specific Mass: < 10kg/kWe by 2006
  - Specific Mass: < 5 kg/kWe by TBD
  - Lifetime: 3-10 years

**SCHEDULE**
- 1993: Complete 500 kW electric propulsion testing facility and designs for high power (MW class) electric thrusters
- 1994: Complete candidate systems study for reactor power source, power conversion, power processing, thruster and control concepts
- 1997: Complete breadboard demo of megawatt class electric thruster technology
- 2000: Verify 1000 hours of life for 500 kW electric propulsion system
- 2005: Complete ground tests to verify megawatt class power/propulsion system
- 2006: Verify TRL-6 through flight test of 500 kW subscale NEP vehicle

**RESOURCES**
- DOE*: 1991 - $0.0, 1992 $144.0M, 1993 $55.0M, 1994 $095.0M, 1995 $145.0M, 1996 $190.0M, 1997 $210.0M

**PARTICIPANTS**
- Lewis Research Center
- Jet Propulsion Laboratory
- Johnson Space Center

**DOE Laboratories**
- INEL, LANL, SNL, ORNL, ANL, BNL...

**PR12-4**
## NUCLEAR ELECTRIC PROPULSION ROADMAP/SCHEDULE

### KEY ACTIVITIES

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<td>(Does Not Include CoP)</td>
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<td>$190.0 M</td>
<td>$210.0 M</td>
<td>(Includes Both NTP &amp; NEP)</td>
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**Program Management/Public Acceptance**

**FOCUSED R&T**

- Innovative Technology
  - Facilities
  - NEP Technology
  - Concept Development & Systems Engineering
  - Safety, QA, Reliability, Environment

**R&T BASE**

### NUCLEAR PROPULSION PROJECT

#### PROJECT MANAGEMENT

- **Public Awareness**
- **Facilities**
- **Safety, QA, Reliability Environment**
- **Nuclear Propulsion Project**
- **Concert Development & Systems Engineering**
  - NTP Systems (NASA)
  - NEP Systems (NASA)
  - Nuclear Subsystem (DOE)
  - Nonnuclear Subsystem (NASA)
- **Innovative Technology**
- **Nuclear Electric Propulsion Technology**
- **Nuclear Thermal Propulsion Technology**
- **Consortiums**
  - Critical Experiments & Analysis
  - Concepts
- **Analytical Facilities**
- **Nuclear Facilities** (DOE)
- **Flight Safety**
- **Operational Safety**

### LEWIS RESEARCH CENTER

**PROJECT WORK BREAKDOWN STRUCTURE**
NUCLEAR THERMAL ROCKET (NTR) PROPULSION

Dr. Stanley K. Borowski
NASA Lewis Research Center

OUTLINE OF PRESENTATION

• RATIONALE FOR NASA DEVELOPMENT OF NTR PROPULSION
• NTR MISSION APPLICATIONS AND BENEFITS
  - LUNAR MISSION BENEFITS
  - MARS MISSION BENEFITS
• ROVER/NERVA PROGRAM ACCOMPLISHMENTS
• NTR TECHNOLOGY NEEDS
• TECHNOLOGY CHALLENGES/APPROACHES FOR RESOLUTION
• "STATE-OF-THE-ART" ASSESSMENT
• TECHNOLOGY PERFORMANCE OBJECTIVES
• SYNERGY WITH OTHER TECHNOLOGY AREAS
• SUMMARY
• SUPPLEMENTAL INFORMATION
**SOLID CORE NTR CONCEPT**
*(DUAL TURBOPUMPS, EXPANDER CYCLE)*

NTR: A SPACE PROPULSION DEVICE WHICH USES HEAT FROM A NUCLEAR FISSION REACTOR TO RAISE THE TEMPERATURE OF A PROPELLANT (LH₂) AND THEN EXPANDS IT THROUGH A NOZZLE TO PROVIDE THRUST.

**WHY IS NTR PROPULSION NECESSARY?**
- **SYNTHESIS GROUP OBSERVATIONS**

- SAFETY TO CREW GREATLY ENHANCED
  - SHORTER TRIP TIMES REDUCES RADIATION EXPOSURES AND PSYCHOLOGICAL STRESSES
  - FEWER MOVING PARTS AND ELEMENTS INCREASE RELIABILITY, REDUCE RISK
  - WIDER LAUNCH WINDOWS LEAVING EARTH AND FOR MARS RETURN
  - MORE OPPORTUNITIES TO GO TO MARS, ALL TWO YEAR INTERVALS FEASIBLE
  - LESS ASSEMBLY OF MARS SPACECRAFT NEEDED IN EARTH ORBIT

- REDUCED MISSION COSTS
  - MASS IN LOW EARTH ORBIT GREATLY REDUCED (ONE-THIRD TO ONE-HALF) WITH A CORRESPONDING REDUCTION IN MISSION COSTS
  - FLEXIBILITY IN SCHEDULES
NUCLEAR THERMAL ROCKET MISSION APPLICATIONS

- NTR TECHNOLOGY HAS A WIDE RANGE OF MISSION APPLICATIONS: PROBES, OTVs, CARGO AND PILOTED VEHICLES
- "1st GENERATION" NTR FLIGHT ENGINE CAN SATISFY ENTIRE SPECTRUM OF SEI MISSIONS - ADVANCED DESIGNS DESIRABLE BUT NOT REQUIRED FOR CURRENT MISSIONS OF INTEREST

LUNAR TRANSFER VEHICLES
- CARGO
  - SEP (MULTI - 100 kW_e - MW_e CLASS)
  - NEP (MW_e CLASS, α ≥ 15 kg/kW_e)
  - "DUAL MODE" SC/NTR (≤ 75 kbf & MULTI - 10 kW_e CLASS)
- PILOTED
  - SC/NTR (≤ 75 kbf)
  - "DUAL MODE" SC/NTR (≤ 75 kbf & MULTI - 10 kW_e CLASS)

MARS TRANSFER VEHICLES
- CARGO
  - SEP/NEP (≥ 5 MW_e, α ≤ 15 kg/kW_e)
  - SC/NTR (≥ 75 kbf)
  - "DUAL MODE" SC/NTR (≤ 75 kbf & 10's kW_e-MW_e)
- PILOTED
  - NEP/SEP (≥ 75 MW_e, α ≤ 10 kbf)
  - SC/NTR (≥ 75 kbf)
  - "DUAL MODE" SC/NTR (≤ 75 kbf & 10's kW_e-MW_e FOR EP)
  - COMBINED HIGH & LOW THRUST CONCEPTS
  - "QUICK PILOTED TRIPS" (≤ 1 YEAR)
    - SC/NTR (SPLIT/SPRINT MISSIONS)
    - "DUAL MODE" SC/NTR + MMWe EP
    - GC/NTR
    - "SUPER" NEP (10's MW_e, α < 10 kg/kW_e)

RATIONAL FOR NASA DEVELOPMENT OF NTR PROPULSION

- THE ROVER/NERVA PROGRAMS ESTABLISHED A SIGNIFICANT DATA BASE ON SC/NTRs
  - 1.4 B$ INVESTMENT IN 1960-1970 TIME FRAME EQUIVALENT TO >9.5 B$ TODAY
- THE SC/NTR CONCEPT HAS BEEN SUCCESSFULLY GROUND TESTED (TO TRL 6) AT THE POWER AND THRUST LEVELS, AND HYDROGEN EXHAUST TEMPERATURES/EQUIVALENT SPECIFIC IMPULSES SUFFICIENT TO PERFORM A 434 DAY 2016 MARS MISSION IN "REUSE" MODE i.e., WITH PROPULSIVE RETURN OF ENTIRE VEHICLE TO LEO
  - A STATE-OF-THE-ART GRAPHITE CORE NTR (AT 1000 psi, ε = 500:1) OPERATING AT 2360 kW 850 s HAS IMLEO = 725 t, 102 t LIGHTER THAN REFERENCE CHEM/AB VEHICLE WITH ECV RETURN TO EARTH
- NTR CAN PROVIDE REDUCTIONS IN TRANSIT TIMES ACROSS THE 15 YEAR CYCLE. MAGNITUDE WILL DEPEND ON TRAJECTORY TYPE, PARTICULAR OPPORTUNITY, MISSION MODE, AND IN-PLACE INFRASTRUCTURE
  - WITH MODEST TECHNOLOGY ADVANCES BEYOND '72 VINTAGE NERVA (COMPOSITE FUEL DELIVERING 925 s), A 1 YEAR ROUND-TRIP MARS MISSION (2016) IS POSSIBLE, IN SPLIT/SPRINT MODE, WITH ACCEPTABLE TOTAL IMLEO (<1000 t) FOR BOTH PILOTED AND CARGO VEHICLES
- NTR TECHNOLOGY OFFERS POTENTIAL FOR SIGNIFICANT EVOLUTIONARY GROWTH
  - SOLID CORE: GRAPHITE (2500 K) — COMPOSITE (2700 K) — CARBIDES (>3000 K)
  - SOLID CORE — LIQUID CORE — GAS CORE

PR12-8
## PERFORMANCE CHARACTERISTICS OF NTR SYSTEMS

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<thead>
<tr>
<th>PARAMETER</th>
<th>GOODNESS</th>
<th>IMPORTANCE</th>
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<tbody>
<tr>
<td>SPECIFIC IMPULSE (SECONDS)</td>
<td>MODERATE → HIGH</td>
<td>IMPROVED FUEL EFFICIENCY</td>
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<tr>
<td>SPECIFIC MASS (RECIPIROCAL OF SPECIFIC POWER, kg/kW)</td>
<td>LOW</td>
<td>ENGINE HAS GOOD POWER PRODUCING CAPABILITY</td>
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<tr>
<td>ENGINE THRUST/WEIGHT</td>
<td>MODERATE → HIGH</td>
<td>OPERATIONAL FLEXIBILITY</td>
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LUNAR NTR APPLICATIONS
WHY NTR FOR LUNAR MISSIONS?

- Potential Performance Benefits
  - High Isp and T/W allows both piloted and cargo missions
  - Enables single stage, fully reusable lunar transfer vehicle
  - Enables more demanding mission profiles (e.g., "courier" and polar orbit missions with significant plane change)
  - Reduces IMLEO/fewer Earth to orbit launches

- Early Operations Experience
  - NTR vehicle assembly
  - Refueling, rendezvous, and docking in radiation environment
  - Disposal of "end-of-life" engines

- Technology Test Bed and "Dress Rehearsal" for Mars
  - Interplanetary mission "in miniature" requiring major impulsive maneuvers and multiple engine restarts
  - Reduced performance requirements: \( \Delta V \), flight time/thrust time
  - Operations in "nearby" space environment
  - "Free Return" trajectory available without penalty
Nuclear Thermal Propulsion Vehicle
Opposition/Swingby Mission Mass Statement

NERVA: 
- \( Isp = 925 \text{ s} \)
- \( T/W_{eng} = 4.0 \)

ADV. NTR: 
- \( Isp = 1050 \text{ s} \)
- \( T/W_{eng} = 20.0 \)

Crew of 4, 30-day stay;
Inbound Venus swingby;
Elliptic parking orbit
at Mars, 250 km x 24 hrs;
Apsidal rotation
penalty optimized;
25 t. surface cargo;
925 lsp;
Reusable return

2016 opposition with Venus swingby 434 day mission time

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<tr>
<th>Element</th>
<th>NERVA</th>
<th>Advanced NTR</th>
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<tbody>
<tr>
<td>MEV decelerator</td>
<td>7000</td>
<td>7000</td>
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<td>MEV ascent stage</td>
<td>22464</td>
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<td>MEV descent stage</td>
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<td>MEV surface cargo</td>
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<td>MEV total</td>
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<td>MTV crew hab module 'dry'</td>
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<td>MTV consumables &amp; resupply</td>
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<td>MTV science</td>
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<td>MTV crew habitation system tot</td>
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<td>MTV frame, struts &amp; RCS inert wt</td>
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<td>Reactor/engine weight</td>
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<td>Radiation shadow shield weight</td>
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<td>EOC propellant (( dV = 1799 \text{ m/s} ))</td>
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<td>TMI propellant (( dV = 4105 \text{ m/s} ))</td>
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<td>ECV</td>
<td>7000</td>
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<td>Cargo to Mars orbit only</td>
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IMLEO | 622380 | 477495 |

*PARAMETERS ARE ACTUALLY FOR COMPOSITE FUEL NERVA DERIVATIVE ENGINE SYSTEM

PR12-11
NTR MARS PERFORMANCE
THRUST/WEIGHT AND ISP VARIATIONS
MULTI PERIGEE EARTH ESCAPE BURN

RELATIVE IMLEO (% CH/AB)

OPTIMUM THRUST (WITHIN 25 KLB)
4.5 MT SHEILDING HELD CONSTANT
NTR PROPULSIVE AT MARS
ECCV RETURN ONLY

ISP • 850
Tex (°K) 2500

ISP • 925
ISP • 1000
ISP • 1100
ISP • 1250

ENGINE THRUST/WEIGHT

NTR TECHNOLOGY

- PAST ACCOMPLISHMENTS
- "STATE-OF-THE-ART" PROJECTIONS
- TECHNOLOGY CHALLENGES AND NEEDS
ROVER/NERVA PROGRAM

SUMMARY


• DEMONSTRATED PERFORMANCE

<table>
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<tr>
<th>POWER (MWt)</th>
<th>THRUST (kbf)</th>
<th>FUEL TEMPS. (K)</th>
<th>EQUIV. SPECIFIC IMPULSE(S)</th>
<th>BURN ENDURANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1100 (NRX SERIES)</td>
<td>-55 (NRX SERIES)</td>
<td>-2750/2550 (PEWEE)</td>
<td>-850 (PEWEE)</td>
<td>1-2 HOURS</td>
</tr>
<tr>
<td>-4100 (PHOEBUS -2A)</td>
<td>-210 (PHOEBUS -2A)</td>
<td>-</td>
<td>-</td>
<td>62 MINUTES AT 1125 MWt (SINGLE BURN)</td>
</tr>
<tr>
<td>-</td>
<td></td>
<td>28 AUTO START-UPS/SHUTDOWNS WITH XE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

• БROAD AND DEEP DATABASE ACHIEVED/USED IN PRELIMINARY NERVA "FLIGHT ENGINE" DESIGN (1972)

• ANTICIPATED PERFORMANCE

<table>
<thead>
<tr>
<th>BURN ENDURANCE</th>
<th>SPECIFIC IMPULSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>-10 HOURS (DEMONSTRATED IN ELECTRIC FURNACE TESTS AT WESTINGHOUSE)</td>
<td>UP TO 925s (COMPOSITE)/UP TO 1020s (CARBIDE FUELS)</td>
</tr>
<tr>
<td>109 MINUTES ACCUMULATED (4 TESTS) AT 44 MWt</td>
<td></td>
</tr>
</tbody>
</table>
### Relative Performance Characteristics for 75kIbf Class SC/NTR Systems

**Parameters**

<table>
<thead>
<tr>
<th></th>
<th>72 NERVA</th>
<th>NERVA DERIVATIVES</th>
<th>PBR*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Engine Cycle</strong></td>
<td>HOT BLEED</td>
<td>TOPPING (EXPANDER)</td>
<td>HOT BLEED</td>
</tr>
<tr>
<td>Fuel Form</td>
<td>GRAPHITE</td>
<td>GRAPHITE COMPOSITE</td>
<td>CARBIDE</td>
</tr>
<tr>
<td>Exhaust Temp. (K)</td>
<td>2,350-2,500</td>
<td>2,500</td>
<td>2,700</td>
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<tr>
<td>Chamber Press. (psia)</td>
<td>450</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Nozzle Exp. Ratio</td>
<td>100:1</td>
<td>500:1</td>
<td>500:1</td>
</tr>
<tr>
<td>Specific Impulse (s)</td>
<td>825-850/845-870</td>
<td>885</td>
<td>925</td>
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<tr>
<td>Engine Weight** (kg)</td>
<td>11,250</td>
<td>8,000</td>
<td>8,816</td>
</tr>
<tr>
<td>Engine Thrust/Weight (W/INT. SHIELD)</td>
<td>3.0</td>
<td>4.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Technology Readiness Level**</td>
<td>6*</td>
<td>5*</td>
<td>4-5*</td>
</tr>
</tbody>
</table>

* PERFORMANCE PARAMETERS/TECHNOLOGY MATURITY ESTIMATES PRESENTED AT THE NTP WORKSHOP HELD AT NASA/LaRC, JULY 10-12, 1990

** W/O EXTERNAL DISK SHIELD

** TRL = 6 (PRELUDE TO FLIGHT CONCEPT), TRL = 2 (CONCEPT FORMULATION)

NOTE: THRUST-TO-WEIGHT RATIOS FOR NERVA/ANDR SYSTEMS - 5-6 AT 250 kIbf LEVEL

---

### Non-Nuclear Engine Components - Performance Comparison

- SSME vs. 72 NERVA vs. "STATE-OF-THE-ART" COMPOSITE NTR:

**Hydrogen Turbopumps:** An extensive database developed since NERVA should allow significant reductions in weight, increases in reliability and reduced development time for NTR applications

- SSME: 72.6 KG/S @ 7040 PSI, 350 KG TOTAL MASS
- NERVA: ~ 40 KG/S @ 1360 PSI, 243 KG TOTAL MASS
- "SOTA* NTR: ~ 37 KG/S @ 1627 PSI, 304 KG TOTAL MASS

**Nozzle Design and Cooling:** Typical nozzle designs now capable of ~ 98% theoretical efficiency with performance significantly greater than that used on NERVA

- SSME: \( T_w = 3116\,^\circ K, P_c = 3150\,\text{PSI}, \text{HEAT FLUX CAPABILITY} \approx 16.4\,\text{KW/CM}^2 \) (HYDROGEN REGENERATIVE COOLING), NOZZLE MASS ~ 600 KG
- NERVA: \( T_w = 2350-2500\,^\circ K, P_c = 450\,\text{PSI}, \text{HEAT FLUX CAPABILITY} \approx 4.1\,\text{KW/CM}^2, \) NOZZLE MASS ~ 1050 KG (UNCOOLED GRAPHITE EXTENSION FROM ~ 25:1 TO 100:1)
- "SOTA* NTR: \( T_w = 2500-3100\,^\circ K, P_c = 1000\,\text{PSI}, \text{HEAT FLUX CAPABILITY} \approx 6.5\,\text{KW/CM}^2, \) NOZZLE MASS ~ 440 KG (UNCOOLED CARBON/CARBON EXTENSION FROM ~ 150:1 TO 500:1)

---

**NASA**

LEWIS RESEARCH CENTER

RELATIVE PERFORMANCE CHARACTERISTICS FOR 75kIbf CLASS SC/NTR SYSTEMS

NON-NUCLEAR ENGINE COMPONENTS - PERFORMANCE COMPARISON

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ELEMENT: NUCLEAR THERMAL PROPULSION

I. TECHNOLOGY NEEDS: TO DEVELOP THE TECHNOLOGIES NECESSARY FOR FLIGHT QUALIFIED NUCLEAR THERMAL PROPULSION SYSTEMS TO SUPPORT SEI MISSIONS

TARGETS: • HIGH PERFORMANCE (HIGH $T_{ex}$ AND $I_{sp}$)
  - REDUCED IMLEO (LESS PROPELLANT REQUIRED)
  - HIGHER PAYLOADS
  - REDUCED TRANSIT TIMES
  - MISSION FLEXIBILITY

• SAFE, RELIABLE OPERATIONS
  - AUTONOMOUS ROBOTIC OPERATIONS
  - MAN-RATED SYSTEMS
  - IMPROVED RETURN-TO-EARTH OPTIONS

• RADIATION-HARDENED EQUIPMENT
  - ELECTRONICS
  - TURBOPUMPS, VALVES, ...
  - NOZZLES
  - SHIELDING

• FULL SYSTEM GROUND TESTING
  - TECHNOLOGY VALIDATION - FLIGHT QUALIFICATION

SCHEMATIC OF TEST CELL SHOWING SYSTEMS FOR REMOVING SOLUBLE FISSION PRODUCTS, PARTICULATES, AND NOBLE GAS FROM THE ENGINE EXHAUST

SOURCE: INEL
ELEMENT: NUCLEAR THERMAL PROPULSION

II. TECHNOLOGY CHALLENGES/APPROACHES

<table>
<thead>
<tr>
<th>CHALLENGE</th>
<th>APPROACH</th>
</tr>
</thead>
<tbody>
<tr>
<td>• HIGH TEMPERATURE REACTOR FUELS</td>
<td>• FABRICATION/PRODUCTION DEVELOPMENT</td>
</tr>
<tr>
<td></td>
<td>• Bench Scale Testing</td>
</tr>
<tr>
<td></td>
<td>• Electric Heating Tests</td>
</tr>
<tr>
<td></td>
<td>• Nuclear Furnace Testing</td>
</tr>
<tr>
<td></td>
<td>• Reactor Design/Test</td>
</tr>
<tr>
<td></td>
<td>• Full Engine System Testing</td>
</tr>
<tr>
<td>• HIGH PERFORMANCE NOZZLES</td>
<td>• Regeneratively-Cooled Section Design/Test</td>
</tr>
<tr>
<td></td>
<td>• Uncooled Skirt (to 500:1)</td>
</tr>
<tr>
<td>• IMPROVED TURBOPUMPS</td>
<td>• High Pressure (Expander/Topping Cycle)</td>
</tr>
<tr>
<td></td>
<td>• Improved Materials</td>
</tr>
<tr>
<td></td>
<td>• Full Engine System Testing</td>
</tr>
<tr>
<td>• IMPROVED REACTOR HEAT TRANSFER</td>
<td>• Conceptual Designs/Testing</td>
</tr>
<tr>
<td></td>
<td>• Preliminary Designs/Testing</td>
</tr>
<tr>
<td></td>
<td>• Detailed Design/Element Tests</td>
</tr>
<tr>
<td></td>
<td>• Reactor Tests</td>
</tr>
<tr>
<td>• SAFE, RELIABLE AUTONOMOUS</td>
<td>• Instrumentation, Controls Development/Tests</td>
</tr>
<tr>
<td>OPERATION</td>
<td>• Full Engine System Tests</td>
</tr>
</tbody>
</table>

ELEMENT: NUCLEAR THERMAL PROPULSION

III. "STATE-OF-THE-ART" ASSESSMENT

- **REACTOR FUELS:**
  - Full system testing to 2500°K (850 sec.) for full operating life and multiple cycles was completed in Nerva/Rover program (circa 1970)
  - Composite fuel (2500-2900°K) tested in nuclear furnace to 2450°K (2750°K for 10 hrs/60 cycles in electric furnace tests - Circa 1972)
  - Binary carbide fuel (2900-3300°K) tested in nuclear furnace to 2450°K, further tests/fuel element design work required
  - Ternary carbide fuel (3300-3500°K) have been proposed but not verified

- **NOZZLES:**
  - Nozzle technology has improved significantly compared to Nerva designs. (E.g., SSME can accommodate exhaust temps >3100°K and nozzle heat fluxes 4 times greater than in Nerva)
  - Uncooled carbon composite nozzle skirts are used on smaller nozzle applications. Much engineering/validation is required for sizes proposed

- **TURBOPUMPS:**
  - 3000-7000 PSI SSME turbopump represent the SOA for turbopump technology. Composite rotor components have been proposed, but not validated
IV. TECHNOLOGY PERFORMANCE OBJECTIVES

• INNOVATIVE CONCEPTS
  - CLOSED CYCLE GAS CORE: -10,000K 1500-3000
  - OPEN CYCLE GAS CORE: 20,000K 3000-5000

• TURBOPUMPS: HIGH PRESSURES (-500-1000 ATMS) REQUIRED FOR CRITICALITY WILL REQUIRE TECHNOLOGY ADVANCES BEYOND SSME

• MATERIALS: LIGHTWEIGHT, HIGH STRENGTH PRESSURE VESSEL MATERIALS TO IMPROVE ENGINE THRUST-TO-WEIGHT PERFORMANCE

• NOZZLES: TRANSPIRATION-COOLED NOZZLE DESIGNS TO ENABLE HIGH-ISP OPERATION

• LIGHTWEIGHT, HIGH TEMPERATURE RADIATORS TO ALLOW HIGH ISP OPERATION AND IMPROVE ENGINE THRUST-TO-WEIGHT

SYNERGY WITH OTHER TECHNOLOGY AREAS

• CHEMICAL ROCKET SYSTEMS
  - EX: HYDROGEN TURBOPUMPS REGENERATIVELY-COOLED NOZZLES

• LIGHTWEIGHT, HIGH STRENGTH CRYOGENIC TANKS
  - EX: AL/LI, COMPOSITE MATERIALS

• CRYO FLUID SYSTEMS
  - EX: LH₂ STORAGE AND TRANSFER

• THERMAL PROTECTION
  - EX: LIGHTWEIGHT SUPER-MLI ("SUPERFLOC") TO REDUCE/ELIMINATE LH₂ BOILOFF

• "SLUSH HYDROGEN" TECHNOLOGY BEING PURSUED IN NASP PROGRAM CAN IMPROVE PERFORMANCE BY REDUCING TANK VOLUME AND MASS

• "DUAL MODE" NTR OPERATION - LOW LEVEL POWER PRODUCTION (~ 50 kWe) FOR REFRIGERATION MAY LEAD TO MORE "ROBUST" NTR VEHICLE
FOCUSED TECHNOLOGY: NUCLEAR PROPULSION
SUMMARY

- IMPACT:
  - Nuclear Propulsion Enables and/or Enhances Space Exploration Missions

<table>
<thead>
<tr>
<th>Nuclear Electric Propulsion (NEP)</th>
<th>Nuclear Thermal Propulsion (NTP)</th>
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<tbody>
<tr>
<td>Enables: Robotic Science Missions</td>
<td>Mars Piloted</td>
</tr>
<tr>
<td>Enhances: Lunar &amp; Mars Cargo, &amp; Mars Piloted Space Exploration</td>
<td>Lunar &amp; Mars Cargo, Lunar Piloted &amp; Robotic Science Space Exploration</td>
</tr>
</tbody>
</table>

- USER COORDINATION:
  - Exploration Studies Identify Nuclear Propulsion as a Key Technology
  - OAET/RZ - Provide Performance Predictions for NASA Studies
  - OSSA Study on NEP for Robotic Science Missions
  - DOE, DoD & NASA Included on Steering Committee (also Astronaut Office)

- TECHNICAL REVIEWS:
  - Interagency Design Review Teams will Periodically Review Technical Progress

- OVERALL TECHNICAL AND PROGRAMMATIC STATUS:
  - High Priority Technology Areas Identified (some efforts initiated)
  - Budget Deliberations Continue
  - Single Multi Agency Plan Defined for FY92 Implementation

- MAJOR TECHNICAL/PROGRAMMATIC ISSUES:
  - Agency/Department Roles
  - Funding to Initiate Technical Efforts
  - Projected Budget Does Not Support Schedules

SUPPLEMENTAL INFORMATION
NUCLEAR THERMAL PROPULSION WORKSHOP RESULTS

- 17 NTR CONCEPTS WERE PRESENTED FOR EVALUATION AT THE NTP WORKSHOP SPONSORED BY LeRC/NASA HEADQUARTERS (JULY 10-12, 1990)

<table>
<thead>
<tr>
<th>SOLID CORE SYSTEMS</th>
<th>LIQUID CORE SYSTEMS</th>
<th>GAS CORE SYSTEMS</th>
<th>HYBRIDS/IN-SITU PROPELLANT CONCEPTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NERVA</td>
<td>- LIQUID ANNULAR CORE REACTOR</td>
<td>- VAPOR CORE REACTOR</td>
<td>- DUAL MODE NTR</td>
</tr>
<tr>
<td>NERVA-DERIVATIVE</td>
<td>- DROPLET CORE REACTOR</td>
<td>- CLOSED CYCLE &quot;NUCLEAR LIGHT BULB&quot;</td>
<td>- NIMF</td>
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<tr>
<td>PARTICLE BED</td>
<td></td>
<td></td>
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<tr>
<td>PELLET BED</td>
<td></td>
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<tr>
<td>WIRE CORE REACTOR</td>
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<tr>
<td>CERMET REACTOR</td>
<td></td>
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<tr>
<td>ADVANCED DUMBO</td>
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<tr>
<td>TUNGSTEN$_2$O$_2$ REACTOR</td>
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<tr>
<td>LOW PRESSURE CORE</td>
<td></td>
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<tr>
<td>FOIL REACTOR</td>
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</tr>
</tbody>
</table>


SOLID CORE NTR CONCEPTS

- ROVER/NERVA
  - PARTICLES OF COATED URANIUM CARBIDE (UC$_2$) ARE DISPERSED IN A GRAPHITE MATRIX WITH HEXAGONALLY SHAPED FUEL ELEMENTS PRODUCED USING AN EXTRUSION PROCESS. GRAPHITE FUNCTIONS AS BOTH HEAT EXCHANGER AND MODERATOR.
  - ELEMENTS HAVE 19 AXIAL COOLANT CHANNELS COATED WITH CARBIDES OF NIOBIUM (NbC) OR ZIRCONIUM (ZrC) TO PREVENT HYDROGEN/GRAFITE REACTION.
  - FUEL ELEMENTS CLUSTERED TOGETHER TO FORM A GRAPHITE CORE WITH EACH ELEMENT PRODUCING 1 TO 1.25 MW. SIX ELEMENT CLUSTERS WERE SUPPORTED BY AN UNFUELED TIE ROD/TUBE TUBE ELEMENT.
  - HIGHER TEMPERATURE "COMPOSITE" AND "CARBIDE" FUEL ELEMENT DESIGNS TESTED IN THE NUCLEAR FURNACE TEST BED REACTOR NEAR THE PROGRAM END.
SOLID CORE NTR CONCEPTS (CONTINUED)

- **NERVA DERIVATIVE REACTOR (NDR)**
  - Mixture of UC-ZrC is blended in graphite substrate to form a composite matrix with potential for improved temperature operation (~ 2700K)
  - Incorporation of additional zirconium hydride (ZrH2) moderator in "2 pass" regeneratively cooled tie tubes reduces critical mass requirement
  - Energy extracted from tie tubes can be used to heat turbine drive gases in an expander cycle, reduce cooldown propellant requirements, and generate electrical power in a "dual mode" system
SOLID CORE NTR CONCEPTS

- **PARTICLE BED REACTOR (PBR)**
  - COMPACT HIGH POWER DENSITY CONCEPT PROPOSED BY BROOKHAVEN NATIONAL LABORATORY (BNL)
  - UTILIZES DIRECT COOLING OF SMALL (500-700 \( \mu m \) DIAMETER) COATED PARTICULATE FUEL (CPF) BY THE HYDROGEN PROPELLANT
  - THE CPF IS PACKED BETWEEN TWO CONCENTRIC POROUS CYLINDERS, CALLED "FRITS" WHICH CONFINE THE PARTICLES, BUT ALLOW COOLANT PENETRATION.
  - ANNULAR FUEL ELEMENTS ARE ARRAYED IN CYLINDRICAL MODERATOR BLOCK TO FORM PBR CORE
  - COOLANT FLOW IS RADially INWARD, THROUGH THE PACKED BED AND AXIALLY OUT THE INNER ANNULAR CHANNEL
  - HIGH HEAT TRANSFER SURFACE AREA AND BED POWER DENSITIES OFFER POTENTIAL FOR SMALL, LOW MASS NTR SYSTEMS WITH HIGH THRUST-TO-WEIGHT CAPABILITY
SCHEMATIC REPRESENTATION OF
A PARTICLE BED REACTOR BASED ROCKET CONCEPT

FUEL PARTICLE

BASELINE FUEL ELEMENT & MODERATOR BLOCK

ROCKET

PROPELLANT INLET
INLET PLENUM
REFLECTOR
FUEL ELEMENTS
OUTLET PLENUM
THROAT
NOZZLE SKIRT

SOLID CORE NTR CONCEPTS

• CERMET REACTOR
  - TECHNOLOGY INVESTIGATED/DEVELOPED BY GE/ANL DURING 1960'S FOR THE ROVER PROJECT AND THE AIRCRAFT NUCLEAR PROPULSION PROGRAM
  - FUEL IS 60% UO2/40% TUNGSTEN, HIGHLY ENRICHED IN A FAST REACTOR CONFIGURATION/-163 HEX-SHAPED FUEL ELEMENTS
  - FUEL ELEMENT IS CLAD WITH TUNGSTEN-RHENIUM PROVIDING RETENTION OF FISSION PRODUCT GASES
  - FUEL SPECIMEN TESTS CONDUCTED UP TO ~2800 K
  - SPECIFIC IMPULSE: 832 s WITH CAPABILITY IN THE 800-900 s RANGE
  - ENGINE THRUST-TO-WEIGHT RATIO: ≤5
Lunar In-Space Transportation
(Apollo Mission Profile - Expendable)

- Single Launch Vehicle
- Trans Lunar Injection
- Stage Separation
- Lunar Orbit Insertion
- Lunar Orbit
- Ballistic Re-Entry
- Stage Separation
- Trans Earth Injection
- Rendezvous/Dock
- Descent
- Ascent
Lunar In-Space Transportation
(FY 90 Lunar Mission Scenario - Partially Reusable)

- Drop Tank Separation
- TLI
- LOI
- Descent
- Ascent
- Aero brake in LLO

Earth Orbit

Lunar Surface

NASA
LEWIS RESEARCH CENTER

Lunar In-Space Transportation
(Fully Reusable NTR Scenario)

NTR/LEV Propulsive Return
(LEV w/Crew returns to SSF; NTR remains in LEO)

NTR/LEV Trans-Lunar Injection
(LEV Serviced @ SSF)

Lunar Orbit Insertion followed by NTR/LEV Separation

Lunar Excursion Vehicle on Lunar Surface

NTR/LEV Rendezvous & Docking for Return

PR12-24
## LUNAR IN-SPACE TRANSPORTATION SYSTEM COMPARISON

<table>
<thead>
<tr>
<th>PARAMETERS</th>
<th>APOLLO</th>
<th>CHEM/AB</th>
<th>NTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMLEO (t)</td>
<td>123°</td>
<td>234</td>
<td>208</td>
</tr>
<tr>
<td>Mission Mode</td>
<td>EXPENDABLE</td>
<td>PARTIALLY REUSABLE</td>
<td>FULLY REUSABLE</td>
</tr>
<tr>
<td>Propulsion</td>
<td>J-2/1 SPS+/I</td>
<td>ASE/4 LOX/LH2</td>
<td>NERVA-DERIVATIVE/1 LH2</td>
</tr>
<tr>
<td>Engine/#</td>
<td>LOX/LH2 STORABLES</td>
<td>LOX/LH2</td>
<td>LOX/LH2</td>
</tr>
<tr>
<td>Propellant</td>
<td>225 22</td>
<td>80 481</td>
<td>75 915</td>
</tr>
<tr>
<td>Total Thrust (kbf)</td>
<td>425 256</td>
<td>5.2 6.3</td>
<td>26.0/4 4.9/4 1.6/4</td>
</tr>
<tr>
<td>Burn Duration/Engine (mins)</td>
<td>DIRECT ENTRY</td>
<td>AEROCAPTURE</td>
<td>28.4 7.2 4.3</td>
</tr>
<tr>
<td>TLI</td>
<td>5.2</td>
<td>26.0/4 4.9/4 1.6/4</td>
<td></td>
</tr>
<tr>
<td>LOC</td>
<td>6.3</td>
<td>28.4 7.2 4.3</td>
<td></td>
</tr>
<tr>
<td>TEI</td>
<td>2.5</td>
<td>28.4 7.2 4.3</td>
<td></td>
</tr>
<tr>
<td>EOC</td>
<td></td>
<td>28.4 7.2 4.3</td>
<td></td>
</tr>
<tr>
<td>Earth Entry Velocity (km/s)/&quot;g-loading&quot;</td>
<td>11.2/≤ 7g ≤ 11.2/≤ 5g 0.5 g - 0.7 g (begin-end EOC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return Mass Fraction (%)</td>
<td>4.8 11.5</td>
<td>23.4</td>
<td></td>
</tr>
</tbody>
</table>

* S-IVB STAGE PRIOR TO TLI w/44.7 t PAYLOAD - CSM, LEM AND 3 CREW
+ SERVICE MODULE PROPULSION SYSTEM

---

**NUCLEAR ELECTRIC PROPULSION**

James H. Gilland
NASA Lewis Research Center
NEP VEHICLE SCHEMATIC

NEP TECHNOLOGIES FOR SEI

- Power Systems
  - Reactors
  - Power Conversion - Static, Dynamic
  - Heat Rejection - Heat Pipes
  - Power Management and Distribution

- Propulsion Systems
  - kWe - MWe Thrusters - Ion, MPD, Other
  - Power Processors
NUCLEAR ELECTRIC PROPULSION MISSION ADVANTAGES

- Progressive Technology Development Paths
  - Evolutionary Development to Meet a Wide Range of Missions
  - Commonality with Surface Power Technology

- Low Propellant Requirements
  - Low Vehicle Mass
  - Small Resupply Mass

- Reduced Interplanetary Trip Times

- Tolerant of Mission Variations
  - Changes in Payload
  - Broad Launch Windows
  - Reduced Dependence on Mission Opportunity
**NEP SYSTEM/MISSION CHARACTERISTICS**

**NEP Performance Parameters**

Specific Impulse ($Isp$): Determines Propellant Mass

Power Level ($P_e$): Affects Trip Time

System Specific Mass ($\alpha$): Determines Trip Time Limits

Thruster Efficiency ($\eta$): Affects Trip Time, Vehicle Mass

**MISSION BENEFIT**

- Reduced Propellant Mass
- Reduced Trip Time
- Mission Tolerance

**ENABLING PARAMETER**

- $Isp$
- $\alpha$
- $\eta$

**NEP CAPABILITIES**

- $2000 \text{-} 10000 \text{ seconds}$
- $<10 \text{ kg/kWe}$
- $>50\%$

---

**NEP PERFORMANCE FOR PILOTTED MARS MISSION 2016 OPPOSITION**

Diagram illustrating the relationship between initial mass in low Earth orbit (MT) and round trip time (d) for various power levels and specific impulses.
NEP TECHNOLOGY DEVELOPMENT APPROACH

Evolutionary Approach

Earth Orbit => Interplanetary Robotic => Lunar Cargo => Mars Cargo, Piloted


Address both Integrated System Design and Subsystem Technologies

Ground Testing of Subsystems, some Integrated Assemblies

Flight Testing of Progressively More Advanced NEP Systems to Obtain Flight Experience

PATHWAYS TO EVOLUTION

<table>
<thead>
<tr>
<th>MISSION</th>
<th>EVOLVING SP-100 TECHNOLOGY</th>
<th>EVOLVING HIGHER RISK TECHNOLOGIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTERPLANETARY PROBES/PRECURSORS</td>
<td>SP-100 THERMOELECTRIC 100 kWe</td>
<td>SP-100 THERMOELECTRIC 100 kWe</td>
</tr>
<tr>
<td>LUNAR/MARS CARGO</td>
<td>GROWTH SP-100 K-RANKINE 1-5 MWe</td>
<td>ADVANCED REACTOR ADVANCED POWER CONVERSION 1-5 MWe</td>
</tr>
<tr>
<td>MANNED MARS</td>
<td>GROWTH SP-100 K-RANKINE 10-20 MWe</td>
<td>ADVANCED REACTOR ADVANCED POWER CONVERSION 10-20 MWe</td>
</tr>
</tbody>
</table>

"ALL UP" "QUICK TRIP"
### EVOLUTION OF NEP TECHNOLOGIES

#### Power
<table>
<thead>
<tr>
<th>Nuclear SP-100</th>
<th>Present</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kWe</td>
<td>&gt;=10 MWe</td>
<td></td>
</tr>
<tr>
<td>~45 kg/kWe</td>
<td>&lt;= 10 kg/kWe</td>
<td></td>
</tr>
<tr>
<td>GES 2001</td>
<td>TRL 6 by 2006</td>
<td></td>
</tr>
<tr>
<td>UN Fuel Pin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TE Conversion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1350 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K Heat Pipe</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Propulsion

<table>
<thead>
<tr>
<th>Thrusters</th>
<th>Ion</th>
<th>MPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isp (s)</td>
<td>2000 - 9000</td>
<td>1000 - 5000</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.7 - 0.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Pe (MWe)</td>
<td>0.01 - 0.03</td>
<td>0.01 - 0.5</td>
</tr>
<tr>
<td>Lifetime(h)</td>
<td>10000</td>
<td>?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thrusters</th>
<th>Ion</th>
<th>MPD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isp (s)</td>
<td>2000 - 9000</td>
<td>1000 - 7000</td>
</tr>
<tr>
<td>( \eta )</td>
<td>0.7 - 0.8</td>
<td>&gt;0.5</td>
</tr>
<tr>
<td>Pe (MWe)</td>
<td>1 - 2</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Lifetime(h)</td>
<td>10000</td>
<td>&gt;= 2000</td>
</tr>
</tbody>
</table>

#### Power Management and Distribution (PMAD)

<table>
<thead>
<tr>
<th>PMAD</th>
<th>Present</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>~ 0.90</td>
<td>~ 0.95</td>
</tr>
<tr>
<td>4 kg/kWe</td>
<td></td>
<td>&lt;= 2.5 kg/kWe</td>
</tr>
<tr>
<td>400 K Rejection Temp.</td>
<td></td>
<td>700 K Rejection Temp.</td>
</tr>
</tbody>
</table>

### ASSOCIATED NEP TECHNOLOGY EFFORTS

#### Space Nuclear Power
- DOE MMWe Program - 10's - 100's MWe in Earth Orbit
- DoD/DOE/NASA SP-100 Program - 100 kWe, TRL 6 in 1999 - 2001

#### Electric Propulsion
- NASA OAET Base R&T in Electric Propulsion - Resistojet, Arcjet, Ion, MPD Thrusters
- Air Force Electric Propulsion Program - Arcjet, MPD Thrusters, SEP Flight Tests
- International - USSR (MPD, Closed Drift Hall Thrusters)
- Japan (Ion, MPD Thrusters)
- ESA (Arcjet, Ion, MPD Thrusters)
REPRESENTATIVE MARS NEP SYSTEM

POWER (10 MWe):
- UN Fuel Pin, Li Cooled Reactor (SP-100 Technology)
- 1350 K Reactor Outlet Temperature
- K-Rankine Power Conversion System
- K Heat Pipe Radiator (5.5 kg/m²)
- Man-Rated Shadow Shield - 5 Rem/year 100 m from Shield, 40 m Diameter Dose Plane
- 10 Year Lifetime
- 5000 V DC Shielded Coaxial Transmission Line
- 600 K Power Conditioning

PROPULSION:
- Argon Ion Thrusters
  - 1.25 MWe thrusters
  - 5000 - 9000 s Isp
  - 1 m X 5 m Grids
  - 10,000 hours Lifetime
EXAMPLE 1.25 MWe ARGON ION ENGINE DESIGN

PROJECTED ARGON ION THRUSTER PERFORMANCE

\[ \eta = \frac{0.835 \times 10^2 I_s p^2}{g^2 I_s p^2 + (22500)^2} \]

Thrust Efficiency

Specific Impulse (s)
EXAMPLE 2.5 MW e HYDROGEN MPD THRUSTER DESIGN

NEP SUBSYSTEM TRADE SPACE

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Conversion</th>
<th>Radiator</th>
<th>PMAD</th>
<th>Thruster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Pin (SP-100)</td>
<td>Themoelectric</td>
<td>Pumped Loop</td>
<td>Si</td>
<td>Ion</td>
</tr>
<tr>
<td>Advanced Fuel Pin</td>
<td>Brayton</td>
<td>Refractory Metal HP</td>
<td>GaAs</td>
<td>MPD</td>
</tr>
<tr>
<td>NERVA- Derived</td>
<td>Rankine</td>
<td>Carbon Composite HP</td>
<td>SiC</td>
<td>Pulsed Inductive (PIT)</td>
</tr>
<tr>
<td>Cermet</td>
<td>Adv. Brayton</td>
<td>Ceramic Fabric HP</td>
<td>AC</td>
<td>Electron Cyclotron Resonance (ECR)</td>
</tr>
<tr>
<td>Thermionic</td>
<td>Thermionic</td>
<td></td>
<td>DC</td>
<td>Ion Cyclotron Resonance (ICR)</td>
</tr>
<tr>
<td>Particle Bed</td>
<td>MHD/Rankine</td>
<td>Bubble Membrane</td>
<td></td>
<td>Pulsed Electrothermal (PET)</td>
</tr>
<tr>
<td>Pellet Bed</td>
<td></td>
<td></td>
<td></td>
<td>Deflagration</td>
</tr>
<tr>
<td>In-Core Boiling K</td>
<td></td>
<td></td>
<td></td>
<td>Variable Isp</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulsed Plasmoid</td>
</tr>
</tbody>
</table>
### NEP TECHNOLOGY EMPHASIS

#### TECHNOLOGY

<table>
<thead>
<tr>
<th>System Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $\alpha$ - reduced radiator mass</td>
</tr>
<tr>
<td>Low $\alpha$ - compact reactor design</td>
</tr>
</tbody>
</table>

#### Reactor
- High Temperature Fuels, Materials
- High Fuel Burnup

#### Power Conversion
- High Temperature Materials
- Low $\alpha$ - reduced radiator mass

#### Power Management and Distribution (PMAD)
- High Power Electronics
  - Enabling - Reliability
  - Low $\alpha$ - reduced PMAD radiator mass
- Radiation Resistant Electronics
  - Enabling - Reliability
- High Temperature Electronics
- Efficient Electronics
  - Low $\alpha$, $\beta_e$ - reduced PMAD radiator mass; lower power source requirements

---

### NEP TECHNOLOGY EMPHASIS

#### TECHNOLOGY

<table>
<thead>
<tr>
<th>System Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $\alpha$ - Dominant mass in MWe space power systems</td>
</tr>
</tbody>
</table>

#### Heat Rejection (Radiator)
- High Temperature, Low Mass Materials

#### Thrusters
- High Power
  - Enabling - System reliability, simplicity
- Efficient
  - Improved vehicle mass, trip time; lower power source requirements
- Long Lifetime
  - Maximize reliability; Minimize complexity; Reduce mass

---

PR12-34
ADDITIONAL INFORMATION

NEP Mission Charts

- Mission - System Requirement Guidelines
- Robotic Probe Missions
- NEP Lunar Cargo Assessment
  - 10 kg/kWe System compared to Chem Aerobrake over 5 year cargo mission cycle
- Sensitivity of Mars Mission to $\alpha$
  - $\alpha$ values range from 7 to 15 kg/kWe
  - Power, Isp optimized
  - Lines are optimum performance for each $\alpha$
- Sensitivity of Mars Mission to Power, Isp
  - Constant $\alpha$ of ~10 kg/kWe
  - Performance insensitive to Isp above 5000 seconds
  - Dashed line is optimum performance "envelope"
### NEP Mission Guidelines

<table>
<thead>
<tr>
<th>Mission</th>
<th>Total Power (MWe)</th>
<th>Thruster Power (MWe)</th>
<th>Operating Time (y)</th>
<th>Thruster Time (s)</th>
<th>Isp</th>
<th>ƞ</th>
<th>α</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital Transfer/Precursor</td>
<td>0.1 - 1</td>
<td>0.01 - 0.05</td>
<td>3 - 10</td>
<td>1 - 2</td>
<td>2000</td>
<td>&gt;50</td>
<td>10 - 30</td>
<td>1990-8000</td>
</tr>
<tr>
<td>Interplanetary Probe</td>
<td>0.1 - 1</td>
<td>0.01 - 0.05</td>
<td>10 - 12</td>
<td>6 - 10</td>
<td>5000</td>
<td>&gt;50</td>
<td>30 - 50</td>
<td>1990-10000</td>
</tr>
<tr>
<td>Lunar Cargo</td>
<td>0.5 - 5</td>
<td>0.1 - 1</td>
<td>3 - 10</td>
<td>1 - 2</td>
<td>3000</td>
<td>&gt;50</td>
<td>10 - 20</td>
<td>2005-10000</td>
</tr>
<tr>
<td>Mars Cargo</td>
<td>2 - 10</td>
<td>0.5 - 2</td>
<td>5 - 10</td>
<td>2 - 3</td>
<td>5000</td>
<td>&gt;50</td>
<td>10 - 20</td>
<td>2010-10000</td>
</tr>
<tr>
<td>Mars Piloted</td>
<td>5 - 20*</td>
<td>1 - 5</td>
<td>5 - 10</td>
<td>1 - 2</td>
<td>5000</td>
<td>&gt;50</td>
<td>10 - 20</td>
<td>2014-10000</td>
</tr>
<tr>
<td>Mars Fast</td>
<td>10 - 60*</td>
<td>5 - 10</td>
<td>3 - 10</td>
<td>1 - 2</td>
<td>6000</td>
<td>&gt;50</td>
<td>1 - 5</td>
<td>2016-10000</td>
</tr>
</tbody>
</table>

*Total Power Includes Option for Multiple Propulsion Modules

### JPL Robotic Science Missions

**Future Candidate Deep Space Missions Utilizing Nuclear Electric Propulsions**

- Neptune Orbiter/Probe
- Pluto/Charon Orbiter/Probe
- Uranus Orbiter/Probe
- Comet Nucleus Sample Return (a.k.a. Rosetta)
- Jupiter Grand Tour
- Multiple Main-Belt Asteroid Rendezvous
- Interstellar Probe

PR12-36
NEP Lunar Cargo Mission

- Cargo missions: minimize propellant mass by allowing trip time to vary

- Groundrules
  - Total mass required for 5 year mission
  - 58 MT (LEV and cargo) to LLO per year
  - Compare to 90-day study Chem/AB vehicle

- NEP vehicle
  - One mission to Moon and back per year
  - Return to LEO empty for refurbishment and resupply
  - 10 kg/kWe assumed as specific mass

<table>
<thead>
<tr>
<th>Optimized Case</th>
<th>Modular Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal Power</td>
<td>Common 5 MWe</td>
</tr>
<tr>
<td>Optimal Isp</td>
<td>Vary Isp to obtain trip time</td>
</tr>
</tbody>
</table>

NEP Lunar Cargo Vehicle Mission Performance

"Optimized" Case: Specific Impulse and Power optimized for minimum mass

"Modular" Case: Fixed 5 MWe power, varying specific impulse

[Graphs showing performance data]
NEP PERFORMANCE FOR 2016 OPPOSITION-CLASS MISSION

COMPARISON OF POWER SYSTEMS WITH ION THRUSTERS

60 days BETWEEN MARS ARRIVAL/DEPARTURE (STAY TIME > 30 days)

ADVANCED SPACE ANALYSIS OFFICE
NEP Technology Charts

- Scaling of Growth SP-100 System over range of powers
  - Scaling up to 10 - 20 MWe studied by GE for LeRC
  - Little economy of scale beyond 10 MWe; radiator mass dominates

- Range of Power Systems Presented at NEP Workshop
- Range of Thruster Systems Presented at NEP Workshop

Growth SP-100 Manned NEP Power Systems
(1300 K Turbine Inlet, 10 yr life, Man-Rated, 2+2 PCU Redundancy)
(100 m separation distance for Rankine, exceeded by Brayton)
POWER/REACTOR CONCEPTS

Concepts May Be Grouped According to Reactor Type:

Liquid Metal Cooled
- SP-100
- Cermet K/Rankine
- 10 MWe K/Rankine
- RMBLR (In-Core Boiling K)

Gas Cooled
- ENABLER
- Particle Bed
- Pellet Bed
- NEPTUNE

Static Conversion
- In-Core Thermionic
- TORCHLITE
- SP-100 w/HYTEC

Vapor Core
- UF₄/MHD

PROPULSION CONCEPTS

Concepts May Be Grouped According to Acceleration Mechanism:

Electrostatic
- Ion Engine

Steady Electromagnetic
- MPD Thruster
- Electron Cyclotron Resonance Engine
- Ion Cyclotron Resonance Engine
- NEPTUNE (High Power MPD Thruster)
- Variable Isp Plasma Rocket

Pulsed Electromagnetic
- Pulsed Inductive Thruster
- Pulsed Electrothermal Thruster
- Deflagration Thruster
- Pulsed Plasmoid Thruster