512-81

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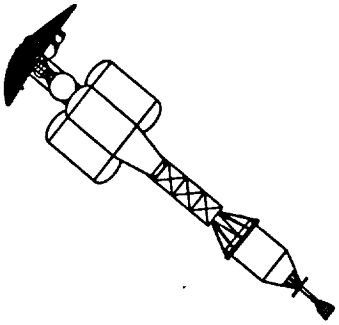
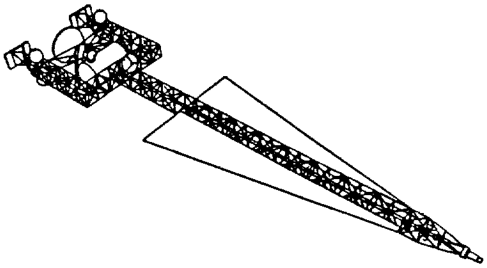
Integrated Technology Plan
for the
Civil Space Program

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)	Nuclear Thermal Propulsion (NTP)
Enables:	Robotic Science Missions	Mars Piloted
Enhances:	*Lunar & Mars Cargo, & Mars Piloted Space Exploration*	*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

PARAMETER	STATE-OF-THE ART	OBJECTIVE
THRUST (Lbf)	75K (NERVA)	75K-125K/Engine
	250K (PHOEBUS)	(May cluster multiple engines)
SPECIFIC IMPULSE (sec)	825	≥ 925
CHAMBER PRESSURE	450	500 - 1000
EXHAUST TEMP. (°K)	2300-2500	≥ 2,700 (w/ Approp. Safety & Reliability Margin)
POWER (MWt)	1100 (NERVA)	≥ 1,600
	4,200 (PHOEBUS)	1.0
LIFETIME (Hrs) Single Burn	1.0	4.5 (2X Mission req.)
Cumulative	1.5	5
REUSABILITY (No. Missions)	1	

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

Nuclear Electric Propulsion

PERFORMANCE OBJECTIVES

PARAMETER	STATE-OF-THE ART		OBJECTIVE	
POWER	SP-100			
POWER LEVEL (MWe)	0.1		≥10.0	
SPECIFIC MASS (Kg/KWe)	30		≤ 10	
PROPULSION	ION	MPD	ION	MPD
SPECIFIC IMPULSE (sec)	2000-9000	1000-5000	2000-9000	1000-7000
EFFICIENCY	0.7-0.8	0.3	0.7-0.8	>0.5
POWER LEVEL (MWe)	0.01-0.03	0.01-0.5	1 - 2	1 - 5
LIFETIME (Hrs)	10,000	?	10,000	≥ 2000
PMAD				
EFFICIENCY	0.90		0.95	
SPECIFIC MASS (Kg/KWe)	4		≤ 2.5	
REJECTION TEMP. (°K)	400		600	

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 Temperature	2700- 3100K (1995)
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*

	NASA**	DOE*
1991	$00.4M	
1992	$05.0M	$014.0M
1993	$13.0M	$055.0M
1994	$22.0M	$095.0M
1995	$39.0M	$145.0M
1996	$50.3M	$190.0M
1997	$83.0M	$210.0M

* DOE current estimate for both NTP & NEP

** NASA dollars do not include CoF

PARTICIPANTS

Lewis Research Center
Lead Center

Marshall Space Flight Center
Participating Center

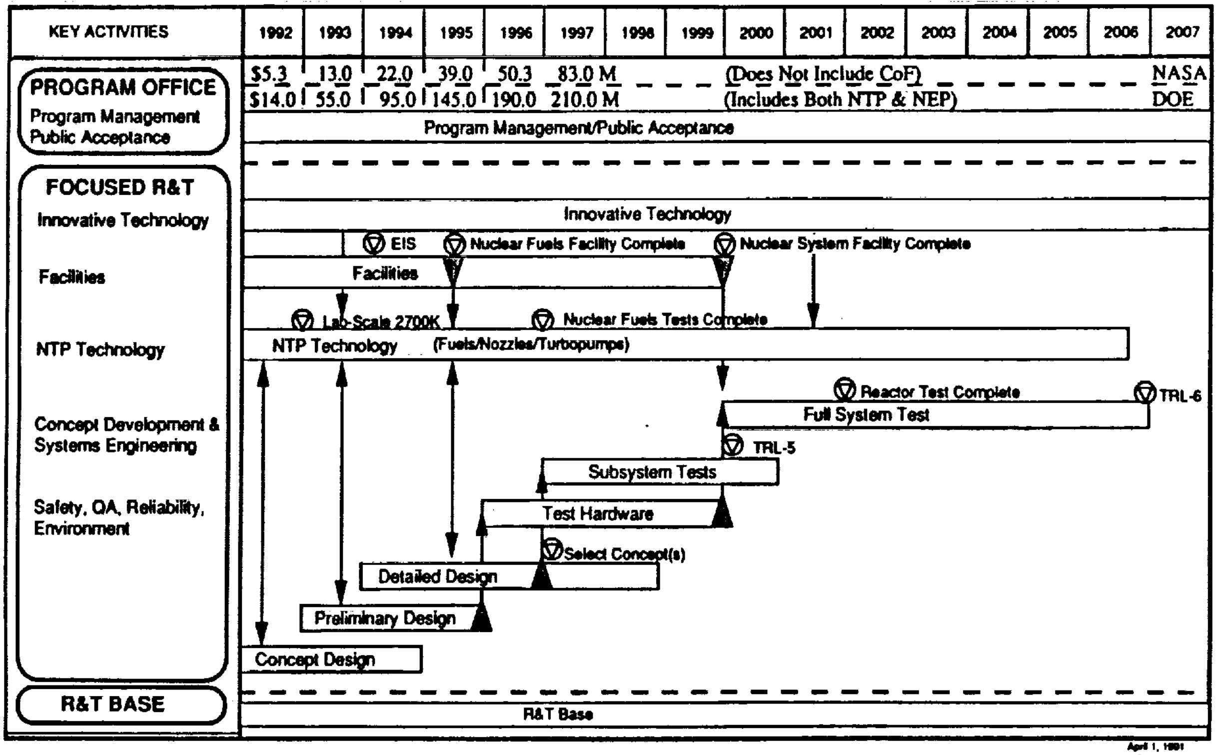
Johnson Space Center
Supporting Center

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

June 17, 1991
NP91-01

TRANSPORTATION TECHNOLOGY
SPACE TRANSPORTATION

NUCLEAR THERMAL PROPULSION ROADMAP/SCHEDULE



April 1, 1991
NP91-60

TRANSPORTATION TECHNOLOGY
SPACE TRANSPORTATION

Nuclear Electric 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

Power	> 10MWe
Specific Mass	< 10kg/kwe by 2006 < 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

	NASA**	DOE*
1991	-	
1992	$02.0M	$014.0M
1993	$06.0M	$055.0M
1994	$15.9M	$095.0M
1995	$23.0M	$145.0M
1996	$26.0M	$190.0M
1997	$45.0M	$210.0M

*DOE current estimate for both NTP & NEP

** NASA dollars do not include CoF

PARTICIPANTS

Lewis Research Center
Lead Center

Jet Propulsion Laboratory
Participating Center

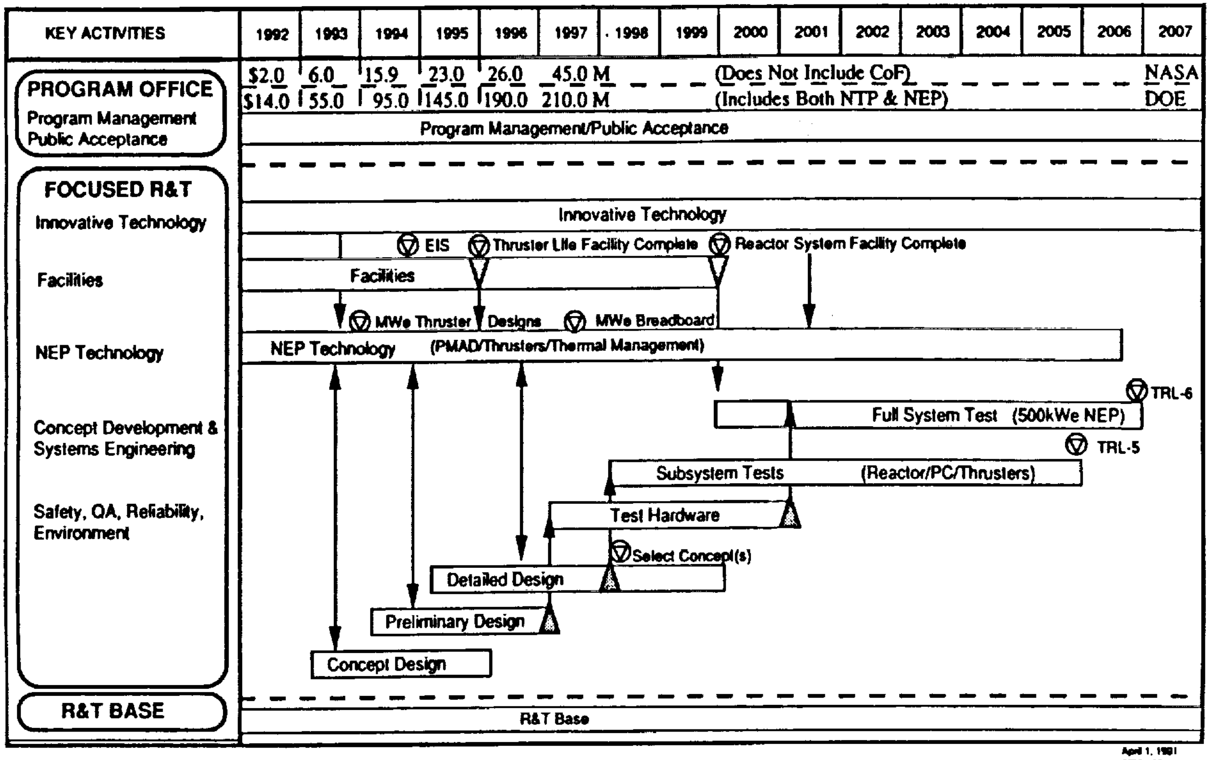
Johnson Space Center
Supporting Center

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

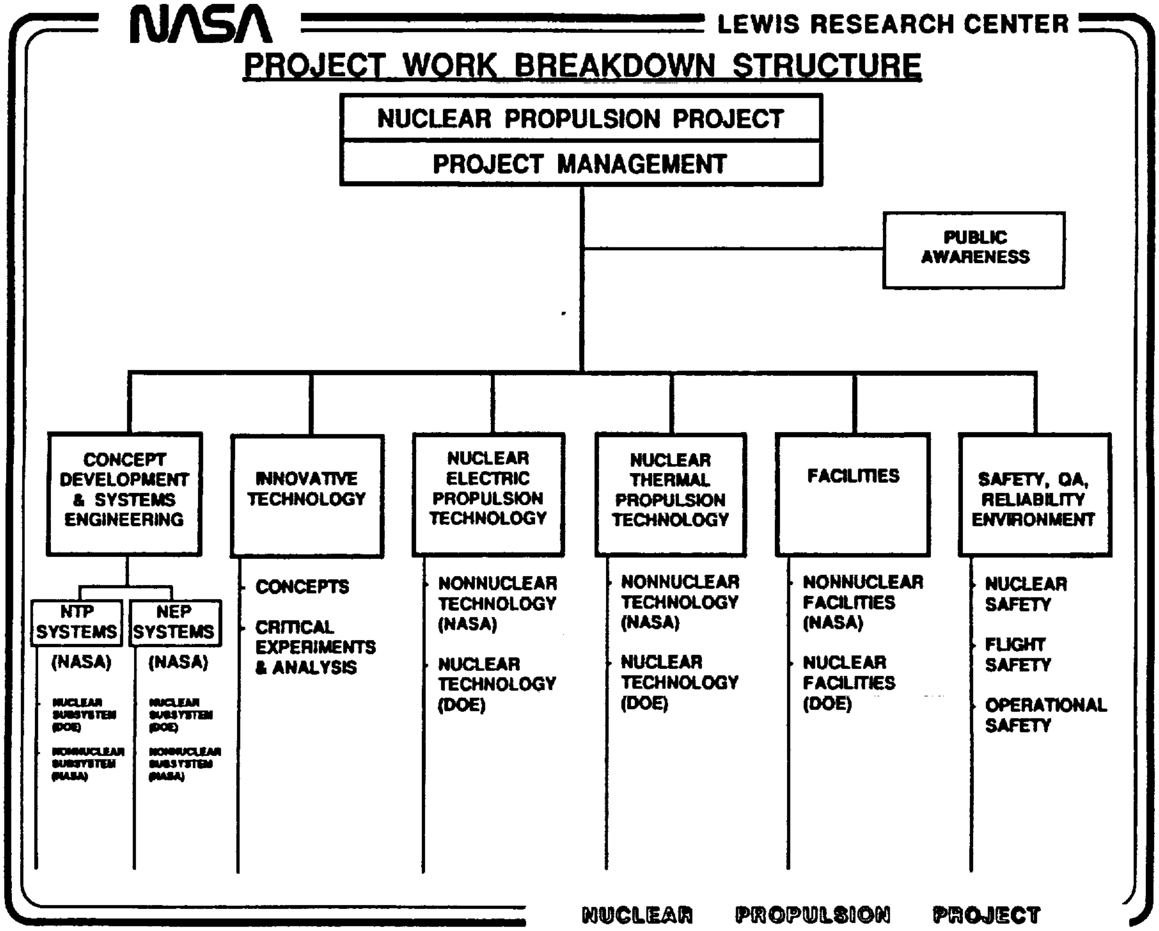
June 17, 1991
NP91-62

SPACE TRANSPORTATION

NUCLEAR ELECTRIC PROPULSION ROADMAP/SCHEDULE



April 1, 1991
NP01-03



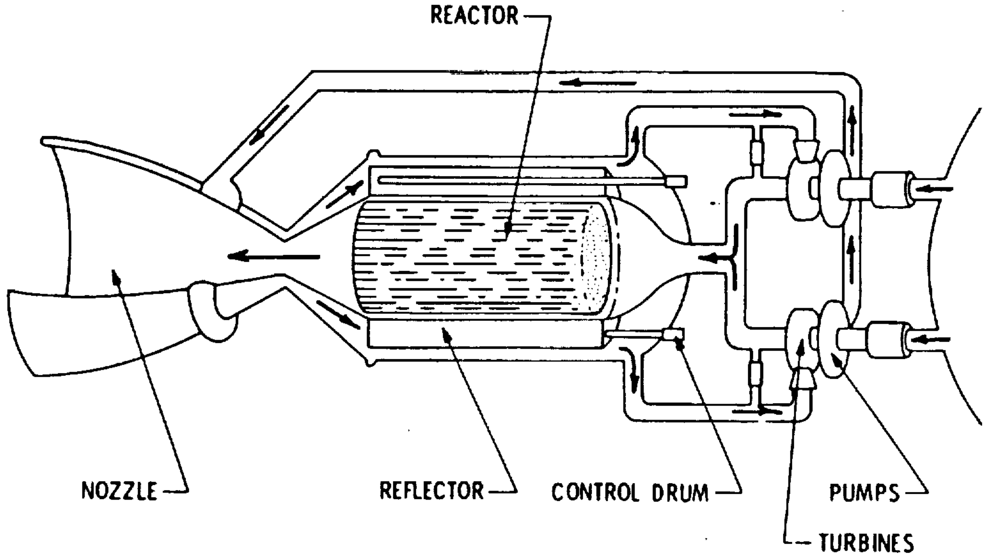
NUCLEAR THERMAL ROCKET (NTR) PROPULSION

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 DEVISE WHICH USES HEAT FROM A NUCLEAR FISSION REACTOR TO RAISE THE TEMPERATURE OF A PROPELLANT (LH_2) 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*
- *"1^{st} 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 - 100kW_e - MW_e CLASS)
  - NEP (MW_e CLASS, $\alpha \geq 15$ kg/kW_e)
  - SC/NTR (≤ 75 klbf "NERVA" CLASS)
  - "DUAL MODE" SC/NTR (≤ 75 klbf & MULTI - 10 kW_e CLASS)
- PILOTED
  - SC/NTR (≤ 75 klbf)
  - "DUAL MODE" SC/NTR (≤ 75 klbf & MULTI - 10 kW_e CLASS)

MARS TRANSFER VEHICLES

- CARGO
  - SEP/NEP (≥ 5 MW_e, $\alpha \leq 15$ kg/kW_e)
  - SC/NTR (≥ 75 klbf)
  - "DUAL MODE" SC/NTR (~ 75 klbf & 10's kW_e-MW_e)
- PILOTED
  - NEP/SEP (≥ 10 MW_e, $\alpha \leq 10$ kg/kW_e)
  - SC/NTR (≥ 75 klbf)
  - "DUAL MODE" SC/NTR (~ 75 klbf - 250 klbf & ~ 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 + MMW_e EP
  - GC/NTR
  - "SUPER" NEP (10's MW_e, $\alpha \leq 5$ kg/kW_e)

RATIONALE 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, $\epsilon = 500:1$) OPERATING AT 2360 K/850 s HAS IMLEO ~ 725 t, 102 t LIGHTER THAN REFERENCE CHEM/AB VEHICLE WITH ECCV 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

PERFORMANCE CHARACTERISTICS OF NTR SYSTEMS

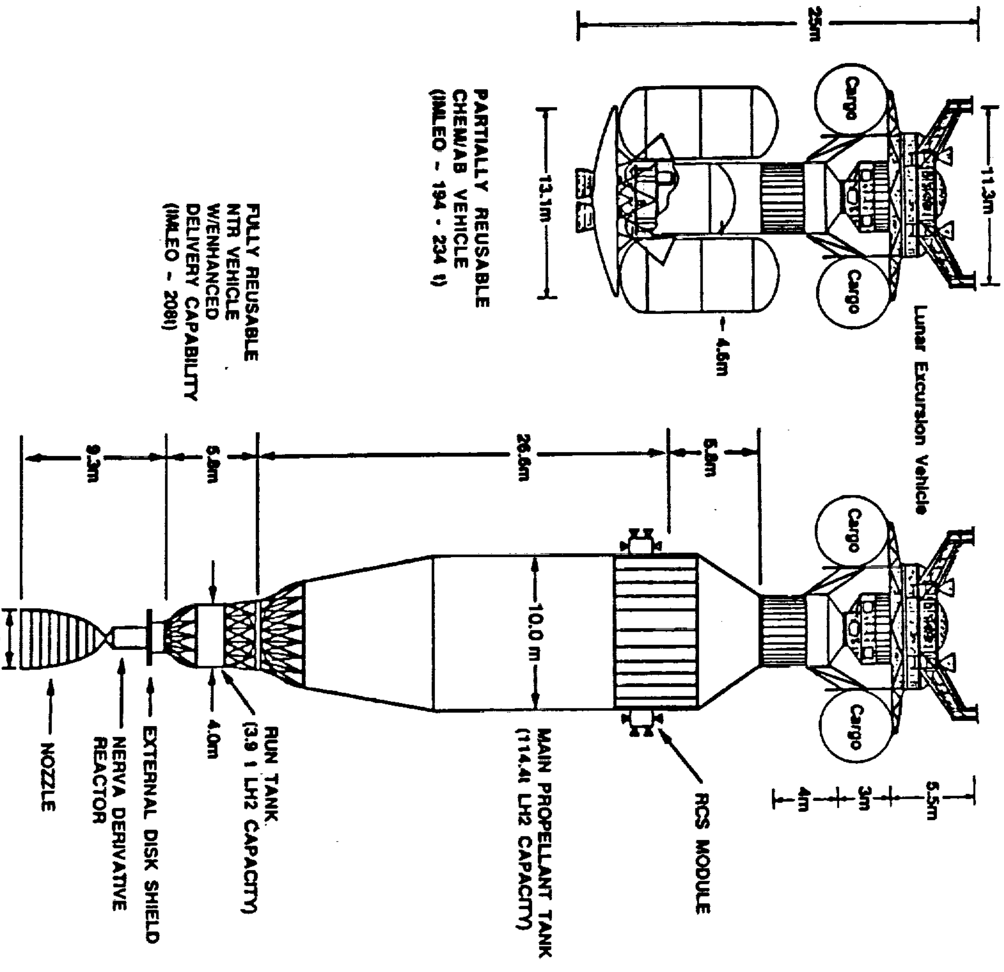
PARAMETER	GOODNESS	IMPORTANCE
SPECIFIC IMPULSE (SECONDS)	MODERATE → HIGH	IMPROVED FUEL EFFICIENCY
SPECIFIC MASS (RECIPROCAL OF SPECIFIC POWER, kg/kWj)	LOW	ENGINE HAS GOOD POWER PRODUCING CAPABILITY
ENGINE THRUST/WEIGHT	MODERATE → HIGH	OPERATIONAL FLEXIBILITY

LUNAR NTR APPLICATIONS

WHY NTR FOR LUNAR MISSIONS?

- Potential Performance Benefits
  - High Isp and T/W_e 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: ΔV, flight time/thrust time
  - Operations in "nearby" space environment
  - "Free Return" trajectory available without penalty

LUNAR TRANSPORTATION VEHICLE SIZE COMPARISON



MARS NTR APPLICATIONS

Nuclear Thermal Propulsion Vehicle Opposition/Swingby Mission Mass Statement

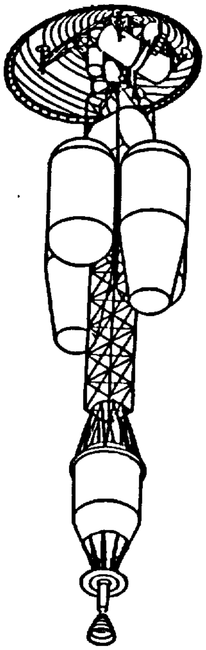
(SOURCE: MSFC)

NERVA: $I_{SP} = 925$ s
$T/W_{eng} = 4.0$

ADV. NTR: $I_{SP} = 1050$ s
$T/W_{eng} = 20.0$

2016 opposition with Venus swingby 434 day mission time

Element	*NERVA*[*]	*Advanced NTR*
MEV desc aerobrake	7000	7000
MEV ascent stage	22464	22464
MEV descent stage	18659	18659
MEV surface cargo	25000	25000
MEV total	73118	73118
MTV crew hab module 'dry'	28531	28531
MTV consumables & resupply	5408	5408
MTV science	1000	1000
MTV crew habitat system tot	34939	34939
MTV frame, struts & RCS inert wt	4808	4808
Reactor/engine weight	9684	1701
Radiation shadow shield weight	4500	4500
EOC propellant (dV= 1799 m/s)	17598	13075
TEI propellant (dV= 4230 m/s)	61951	44301
EOC/TEI common tank wt (1)	13358	10501
MOC propellant (dV= 2830 m/s)	101810	75163
MOC tanks (2)	19128	15696
TMI propellant (dV=4105 m/s)	237850	165190
TMI tanks (2)	36636	27503
ECCV	7000	7000
Cargo to Mars orbit only	0	0
IMLEO	622380	477495



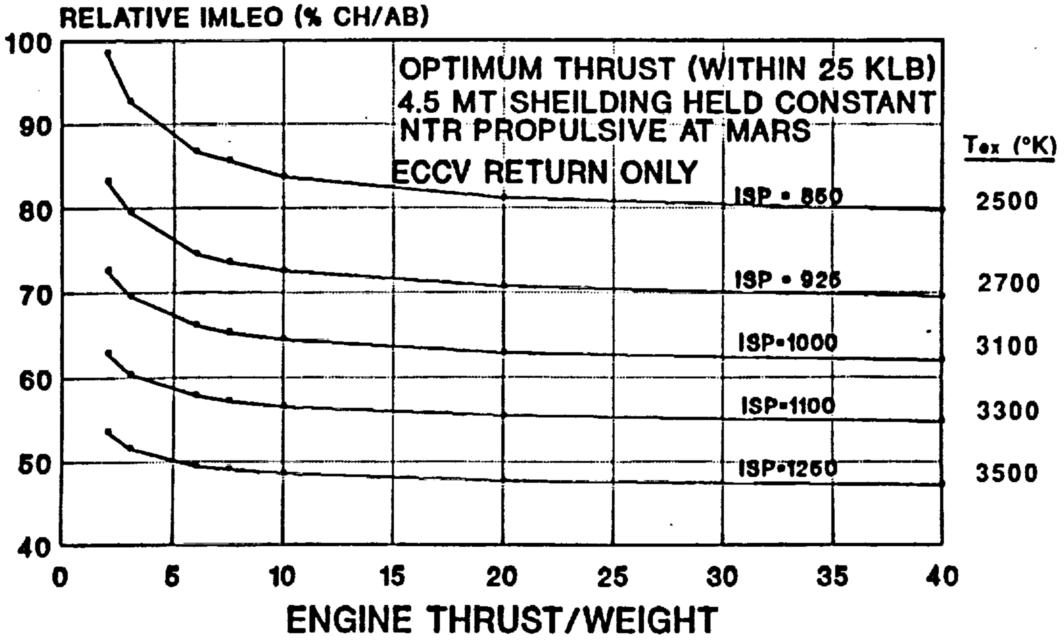
Crew of 4, 30-day stay;
Inbound Venus swingby;
Elliptic parking orbit
at Mars, 250 km x 24 hrs;
Apsidal rotation
penalty optimized;
25 t. surface cargo;
925 Isp;
Reusable return

[*] PARAMETERS ARE ACTUALLY FOR COMPOSITE FUEL NERVA DERIVATIVE ENGINE SYSTEM

NASA LEWIS RESEARCH CENTER

NTR MARS PERFORMANCE THRUST/WEIGHT AND ISP VARIATIONS

MULTI PERIGEE EARTH ESCAPE BURN



NUCLEAR PROPULSION PROJECT

NTR TECHNOLOGY

- PAST ACCOMPLISHMENTS
- "STATE-OF-THE-ART" PROJECTIONS
- TECHNOLOGY CHALLENGES AND NEEDS

NUCLEAR PROPULSION PROJECT

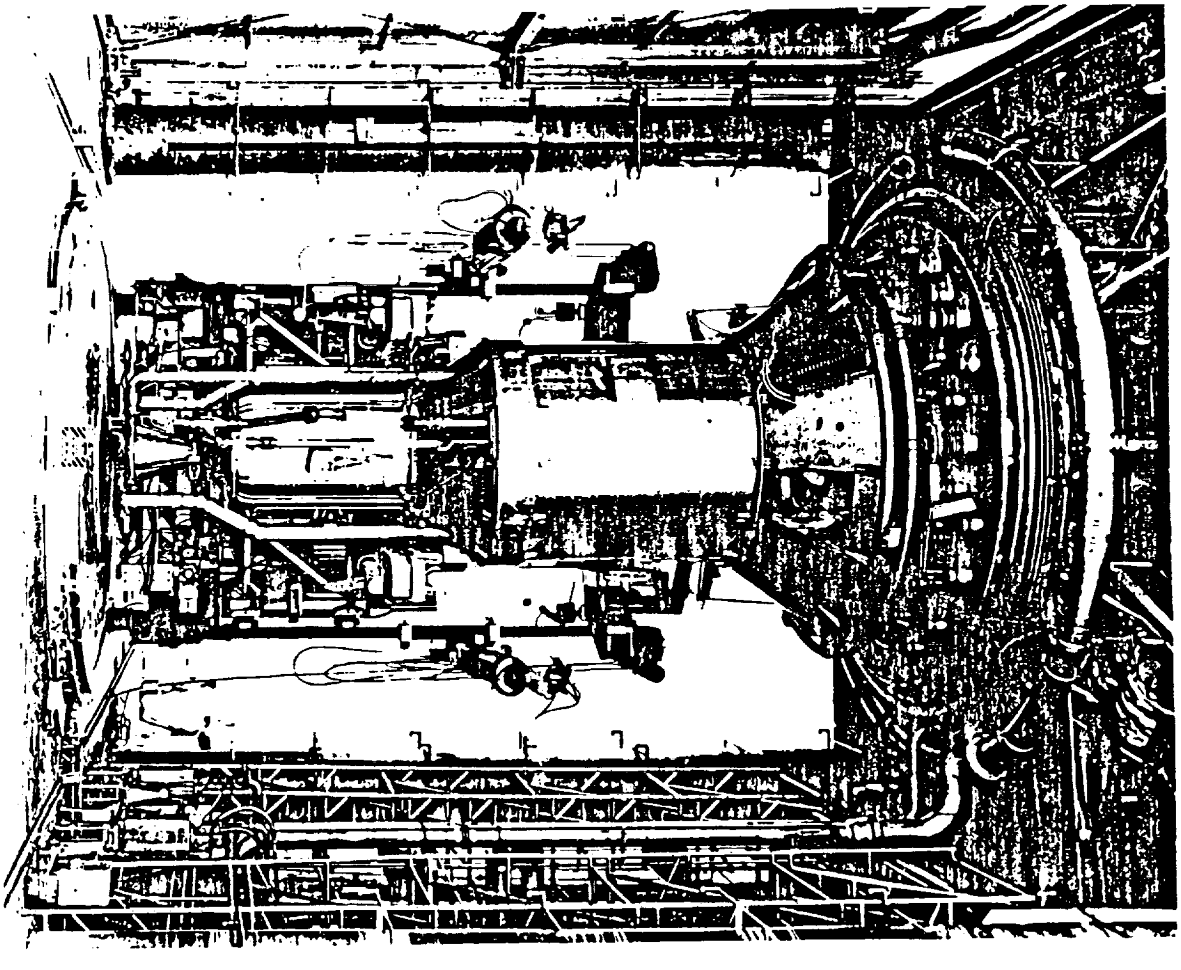
ROVER/NERVA PROGRAM SUMMARY

- 20 REACTORS DESIGNED, BUILT, AND TESTED BETWEEN 1955 AND 1973 AT A COST OF APPROXIMATELY $1.4 BILLION. (FIRST REACTOR TEST: KIWI-A, JULY 1959)
- DEMONSTRATED PERFORMANCE

POWER (MWt)	~1100 (NRX SERIES) - 4100 (PHOEBUS -2A)
THRUST (klbf)	~55 (NRX SERIES) - 210 (PHOEBUS -2A)
PEAK/EXIT FUEL TEMPS. (K)	~2750/2550 (PEWEE)
EQUIV. SPECIFIC IMPULSE(S)	~850 (PEWEE)
BURN ENDURANCE	1-2 HOURS
- NRX-A6	62 MINUTES AT 1125 MWt (SINGLE BURN)
- NUCLEAR FURNACE	109 MINUTES ACCUMULATED (4 TESTS) AT 44 MWt
START/STOP	28 AUTO START-UPS/SHUTDOWNS WITH XE

- BROAD AND DEEP DATABASE ACHIEVED/USED IN PRELIMINARY NERVA "FLIGHT ENGINE" DESIGN (1972)
- ANTICIPATED PERFORMANCE

BURN ENDURANCE	~10 HOURS (DEMONSTRATED IN ELECTRIC FURNACE TESTS AT WESTINGHOUSE)
SPECIFIC IMPULSE	UP TO 925s (COMPOSITE)/UP TO 1020s (CARBIDE FUELS)



PROTOTYPE NERVA ENGINE - THE NRX/XE -

RELATIVE PERFORMANCE CHARACTERISTICS FOR 75klbf CLASS SC/NTR SYSTEMS

PARAMETERS	'72 NERVA	NERVA DERIVATIVES			PBR*
ENGINE CYCLE	HOT BLEED/ TOPPING	TOPPING (EXPANDER)			HOT BLEED
FUEL FORM	GRAPHITE	GRAPHITE	COMPOSITE	CARBIDE	UC$_2$/ZrC KERNEL
EXHAUST TEMP. (K)	2,350-2,500	2,500	2,700	3,100	3,200
CHAMBER PRESS. (psia)	450	1,000	1,000	1,000	1,000
NOZZLE EXP. RATIO	100:1	500:1	500:1	500:1	100:1
SPECIFIC IMPULSE (s)	825-850/ 845-870	885	925	1,020	971
ENGINE WEIGHT++(kg)	11,250	8,000	8,816	9,313	1702
ENGINE THRUST/ WEIGHT (W/INT. SHIELD)	3.0	4.3	3.9	3.7	20
TECHNOLOGY READINESS LEVEL**	6*	5*	4-5*	3-4*	2*

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* PERFORMANCE PARAMETERS/TECHNOLOGY MATURITY ESTIMATES PRESENTED AT THE NTP WORKSHOP HELD AT NASA/LeRC, 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/NDR SYSTEMS ~ 5-6 AT 250 klbf 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_{ex} ~ 3116°K, Pc ~ 3150 PSI, HEAT FLUX CAPABILITY ~ 16.4 KW/CM^2 (HYDROGEN REGENERATIVE COOLING), NOZZLE MASS ~ 600 KG
- NERVA:	T_{ex} ~ 2350-2500°K, Pc ~450 PSI, HEAT FLUX CAPABILITY ~ 4.1 KW/CM^2, NOZZLE MASS ~ 1050 KG (UNCOOLED GRAPHITE EXTENSION FROM ~ 25:1 TO 100:1)
- "SOTA" NTR:	T_{ex} ~ 2500-3100°K, Pc ~ 1000 PSI, HEAT FLUX CAPABILITY ~ 6.5 KW/CM^2, NOZZLE MASS ~ 440 KG (UNCOOLED CARBON/CARBON EXTENSION FROM ~ 150:1 TO 500:1)

LEWIS RESEARCH CENTER

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

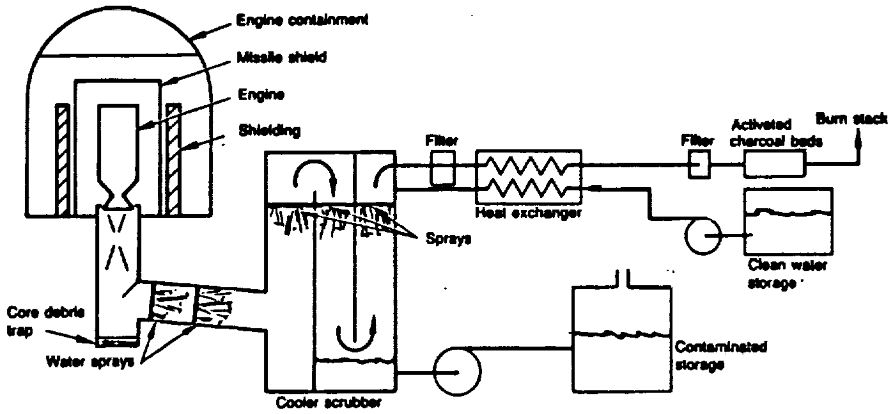
  } for given propellent loading

- **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

NUCLEAR PROPULSION PROJECT

Lewis Research Center

EFFLUENT TREATMENT SYSTEMS



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

CHALLENGE	APPROACH
• HIGH TEMPERATURE REACTOR FUELS	• FABRICATION/PRODUCTION DEVELOPMENT BENCH SCALE TESTING ELECTRIC HEATING TESTS NUCLEAR FURNACE TESTING REACTOR DESIGN/TEST FULL ENGINE SYSTEM TESTING
• HIGH PERFORMANCE NOZZLES	• REGENERATIVELY-COOLED SECTION DESIGN/TEST UNCOOLED SKIRT (TO 500:1)
• IMPROVED TURBOPUMPS	• HIGH PRESSURE (EXPANDER/TOPPING CYCLE) IMPROVED MATERIALS FULL ENGINE SYSTEM TESTING
• IMPROVED REACTOR HEAT TRANSFER	• CONCEPTUAL DESIGNS/TESTING PRELIMINARY DESIGNS/TESTING DETAILED DESIGN/ELEMENT TESTS REACTOR TESTS FULL ENGINE SYSTEM TESTS
• SAFE, RELIABLE AUTONOMOUS OPERATION	• INSTRUMENTATION, CONTROLS DEVELOPMENT/TESTS FULL ENGINE SYSTEM TESTS

ELEMENT: NUCLEAR THERMAL PROPULSION

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

- REACTOR FUELS:
  - FULL SYSTEM TESTING TO 2500°K (850 SEC I_{sp}) 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

ELEMENT: NUCLEAR THERMAL PROPULSION

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: LH_2 STORAGE AND TRANSFER
- **THERMAL PROTECTION**
  EX: LIGHTWEIGHT SUPER-MLI ("SUPERFLOC") } TO REDUCE/ELIMINATE LH2 BOILOFF
  REFRIGERATION
- **"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**

a-3

FOCUSED TECHNOLOGY: NUCLEAR PROPULSION
SUMMARY

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

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

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SUPPLEMENTAL INFORMATION

NUCLEAR PROPULSION PROJECT

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)

SOLID CORE **SYSTEMS**

- NERVA
- NERVA-DERIVATIVE
- PARTICLE BED
- PELLET BED
- CERMET REACTOR
- WIRE CORE REACTOR
- ADVANCED DUMBO
- TUNGSTEN/H_2O REACTOR
- LOW PRESSURE CORE
- FOIL REACTOR

LIQUID CORE **SYSTEMS**

- LIQUID ANNULAR CORE REACTOR
- DROPLET CORE REACTOR

GAS CORE **SYSTEMS**

- VAPOR CORE REACTOR
- CLOSED CYCLE "NUCLEAR LIGHT BULB"
- OPEN-CYCLE "POROUS WALL" REACTOR

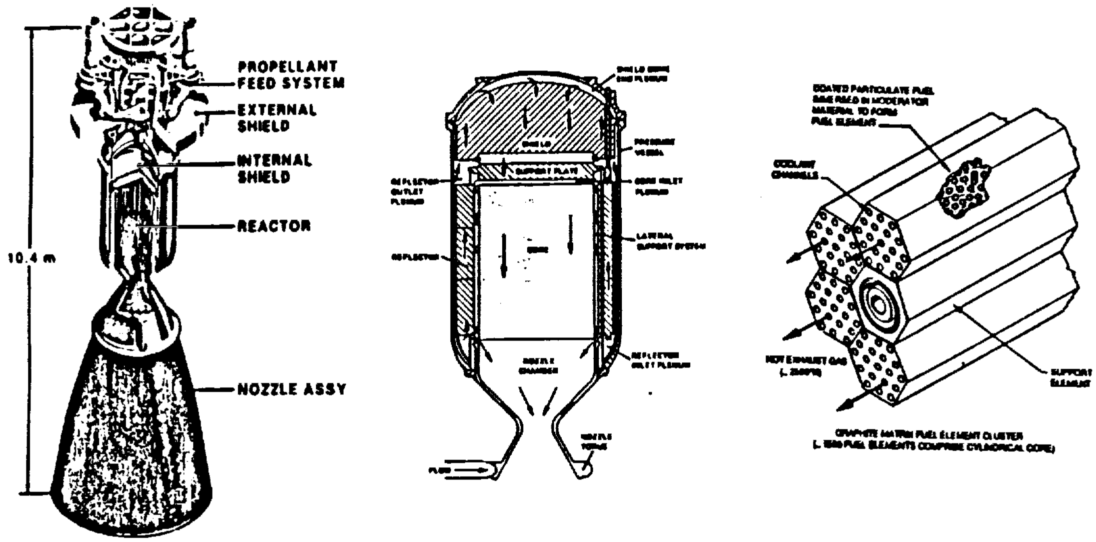
HYBRIDS/IN-SITU **PROPELLANT CONCEPTS**

- DUAL MODE NTR
- NIMF

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/GRAPHITE REACTION
  - FUEL ELEMENTS CLUSTERED TOGETHER TO FORM A GRAPHITE CORE WITH EACH ELEMENT PRODUCING ~ 1 TO 1.25 MWt. 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

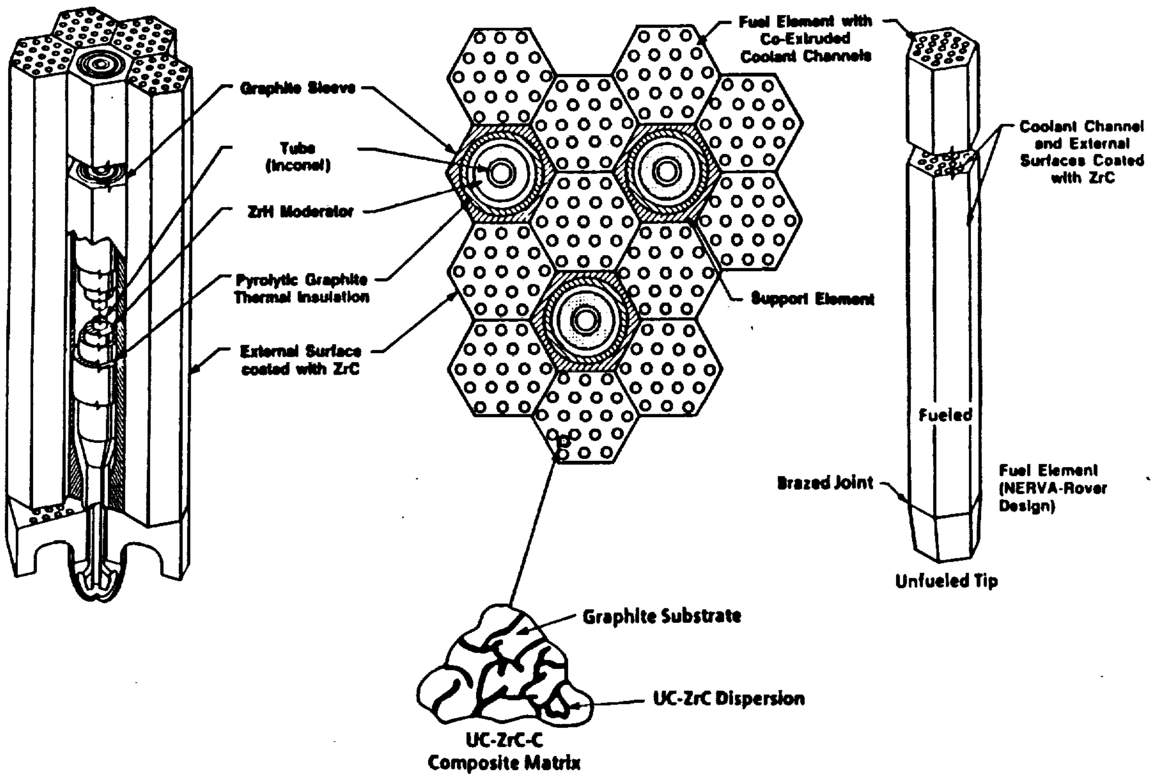
CUT-AWAY AND SCHEMATIC FLOW DESCRIPTION OF THE NERVA BASELINE ENGINE



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 (ZrH_x) 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**

NDR - BASED ON PROVEN NERVA/ROVER REACTORS

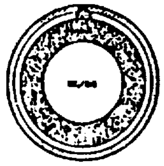


SOLID CORE NTR CONCEPTS

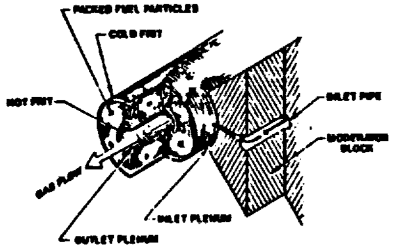
- *PARTICLE BED REACTOR (PBR)*
  - COMPACT HIGH POWER DENSITY CONCEPT PROPOSED BY BROOKHAVEN NATIONAL LABORATORY (BNL)
  - UTILIZES DIRECT COOLING OF SMALL (500-700 μm DIAMETER) COATED PARTICULATE FUEL (CPF) BY THE HYDROGEN PROPELLANT
  - THE CPF IS PACKED BETWEEN TWO CONCENTRIC POROUS CYLINDERS, CALLED "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

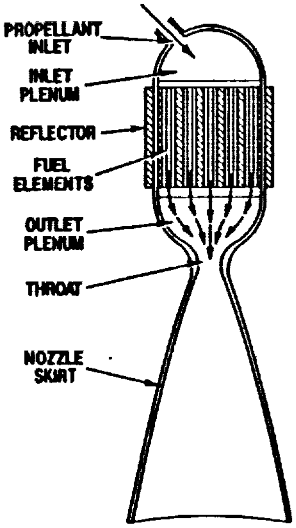
FUEL PARTICLE



BASELINE FUEL ELEMENT & MODERATOR BLOCK



ROCKET



SOLID CORE NTR CONCEPTS

- CERMET REACTOR
  - TECHNOLOGY INVESTIGATED/DEVELOPED BY GE/ANL DURING 1960'S FOR THE ROVER PROJECT AND THE AIRCRAFT NUCLEAR PROPULSION ROGRAM
  - FUEL IS 60% U02/40% 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

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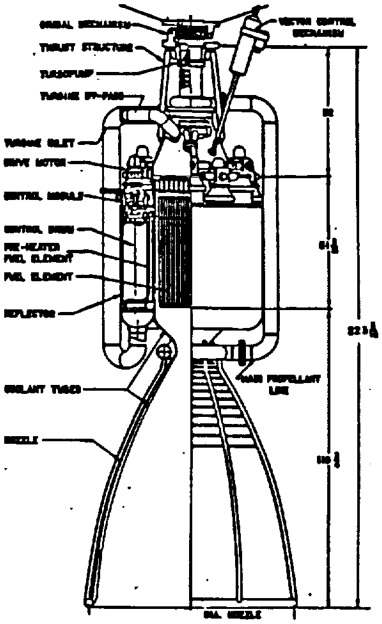
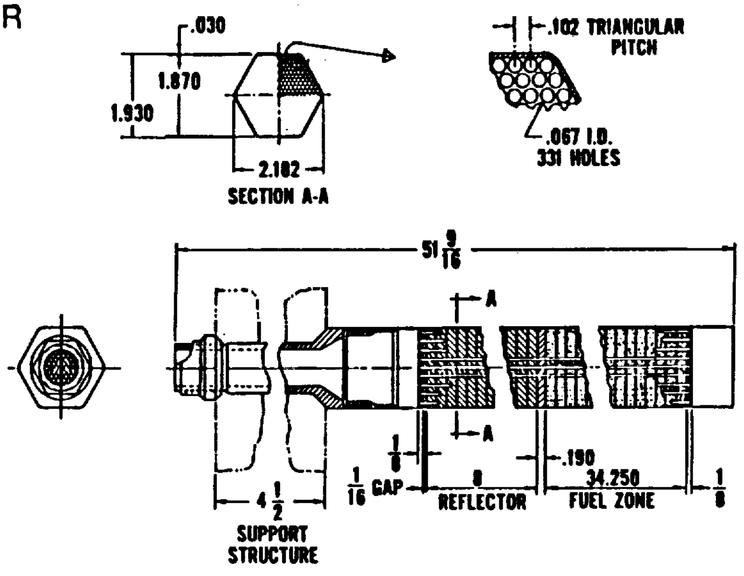
CERMET FUEL REACTOR



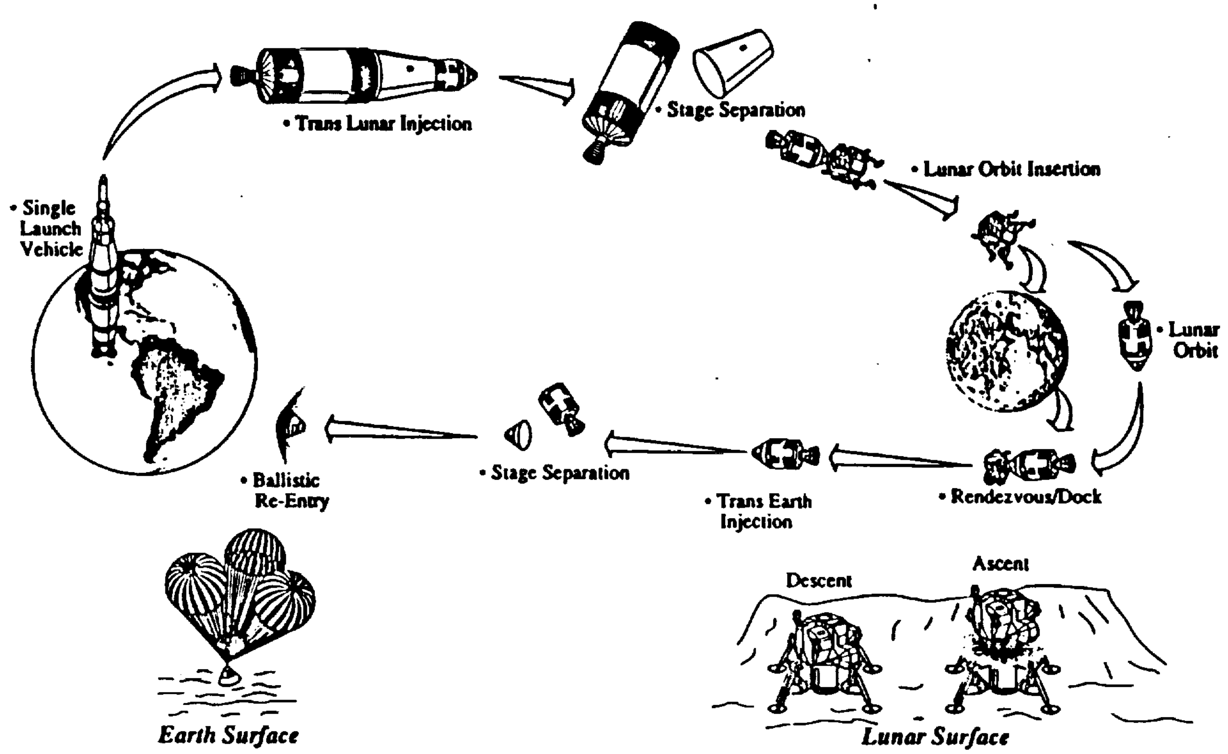
NUCLEAR THERMAL PROPULSION ENGINE
CERMET CORE 2000 Mwt



FUEL ELEMENT

NUCLEAR PROPULSION PROJECT

Lunar In-Space Transportation
(Apollo Mission Profile - Expendable)



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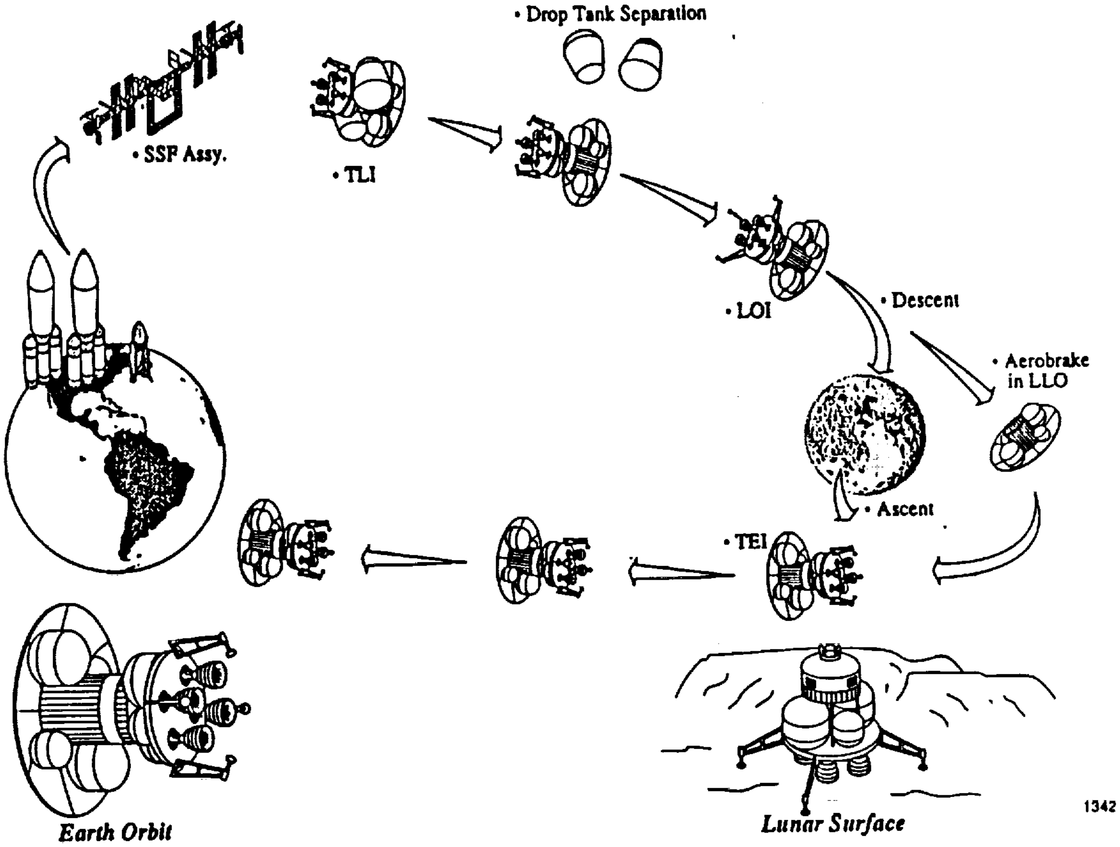
Lunar In-Space Transportation
(FY 90 Lunar Mission Scenario - Partially Reusable)



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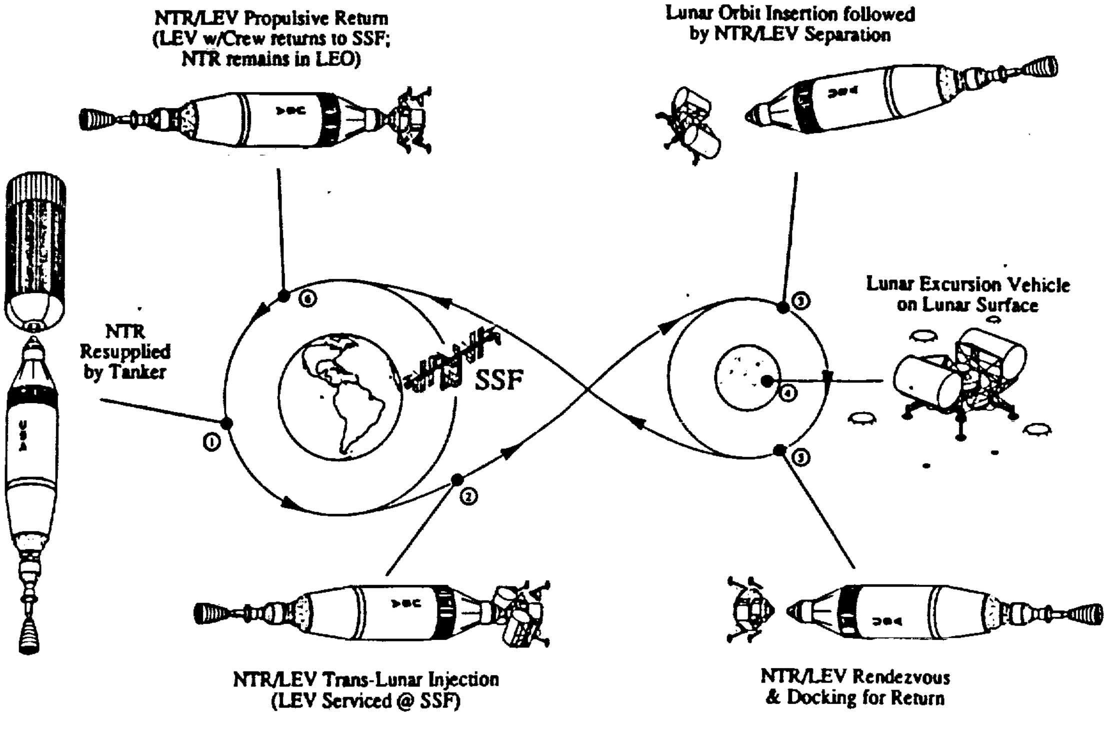
Lunar In-Space Transportation
(Fully Reusable NTR Scenario)



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

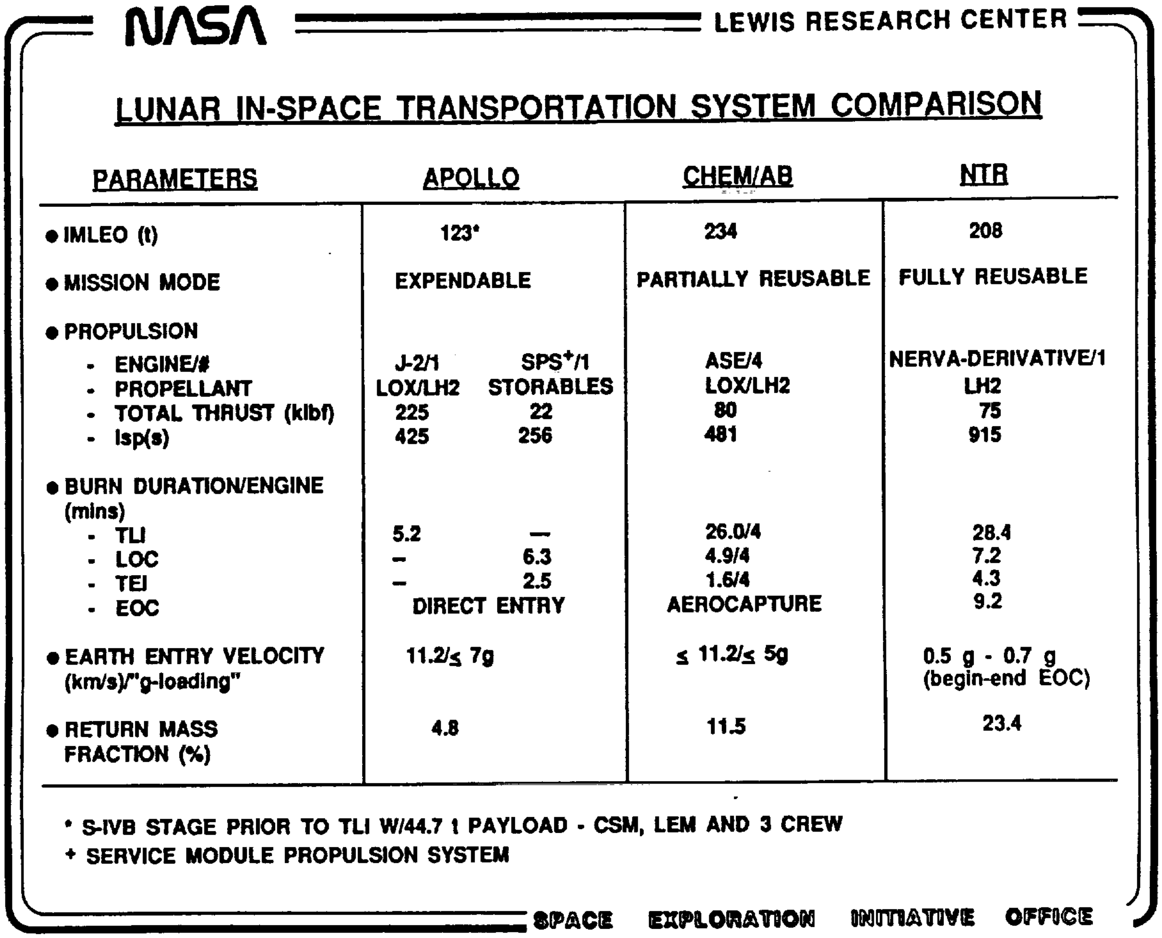
Lunar Orbit Insertion followed
by NTR/LEV Separation

NTR
Resupplied
by Tanker

Lunar Excursion Vehicle
on Lunar Surface

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

NTR/LEV Rendezvous
& Docking for Return



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LUNAR IN-SPACE TRANSPORTATION SYSTEM COMPARISON

PARAMETERS	APOLLO		CHEM/AB	NTR
• IMLEO (t)	123*		234	208
• MISSION MODE	EXPENDABLE		PARTIALLY REUSABLE	FULLY REUSABLE
• PROPULSION				
- ENGINE/#	J-2/1	SPS^{+}/1	ASE/4	NERVA-DERIVATIVE/1
- PROPELLANT	LOX/LH2	STORABLES	LOX/LH2	LH2
- TOTAL THRUST (klbf)	225	22	80	75
- Isp(s)	425	256	481	915
• BURN DURATION/ENGINE (mins)				
- TLI	5.2	—	26.0/4	28.4
- LOC	–	6.3	4.9/4	7.2
- TEI	–	2.5	1.6/4	4.3
- EOC	DIRECT ENTRY		AEROCAPTURE	9.2
• EARTH ENTRY VELOCITY (km/s)/"g-loading"	11.2/≤ 7g		≤ 11.2/≤ 5g	0.5 g - 0.7 g (begin-end EOC)
• RETURN MASS FRACTION (%)	4.8		11.5	23.4

* S-IVB STAGE PRIOR TO TLI W/44.7 t PAYLOAD - CSM, LEM AND 3 CREW

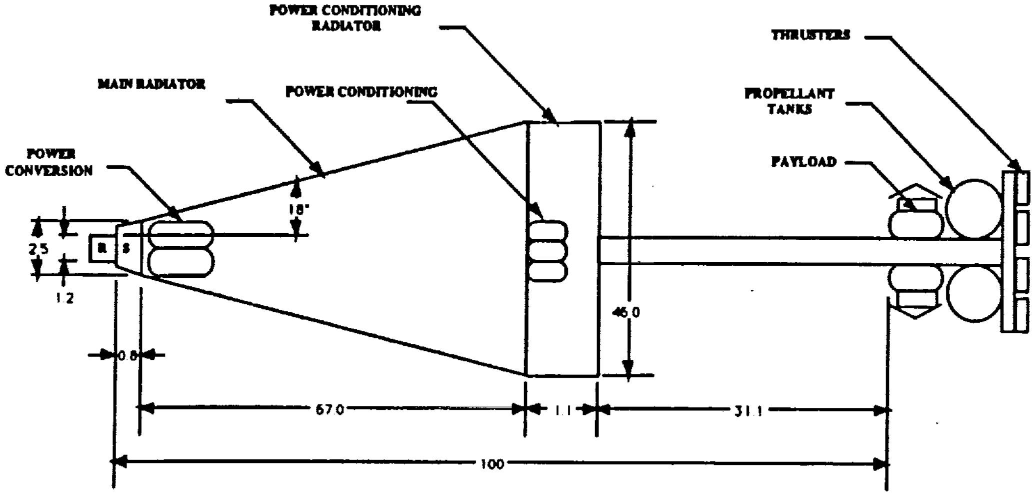
+ SERVICE MODULE PROPULSION SYSTEM

SPACE EXPLORATION INITIATIVE OFFICE

NUCLEAR ELECTRIC PROPULSION

James H. Gilland
NASA Lewis Research Center

NEP VEHICLE SCHEMATIC



DIMENSIONS IN METERS
NOT DRAWN TO SCALE

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

NUCLEAR PROPULSION PROJECT

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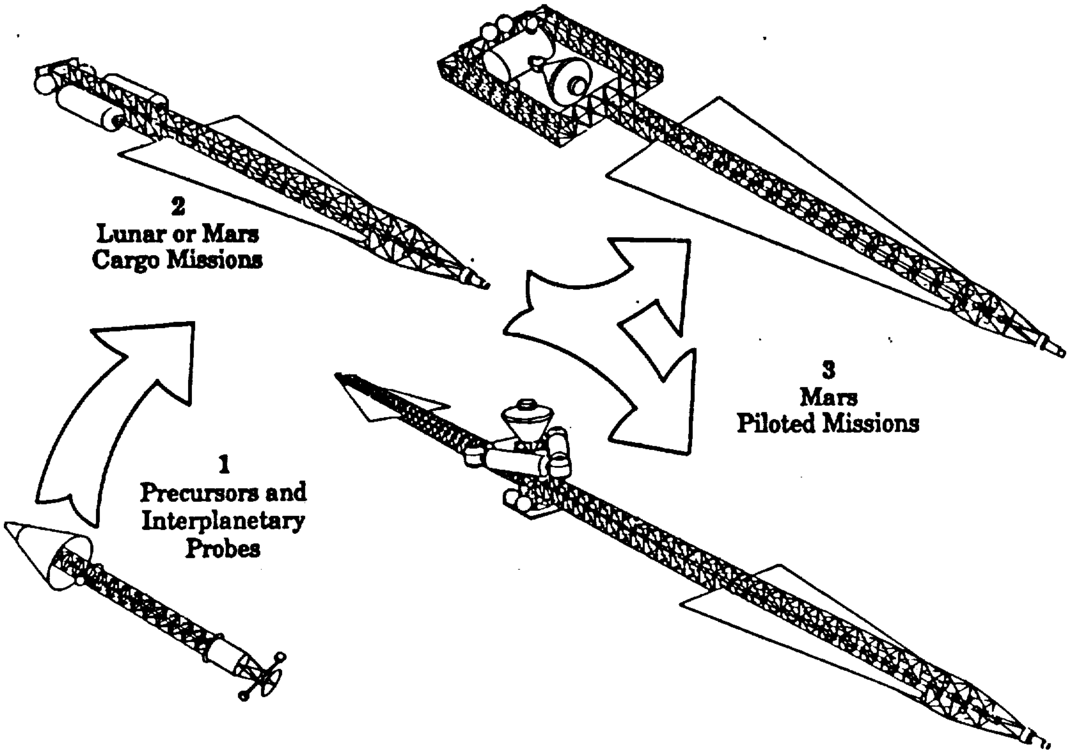
Mission Evolution



ADVANCED SPACE ANALYSIS OFFICE

NEP SYSTEM/MISSION CHARACTERISTICS

NEP Performance Parameters

Specific Impulse (Isp): Determines Propellant Mass

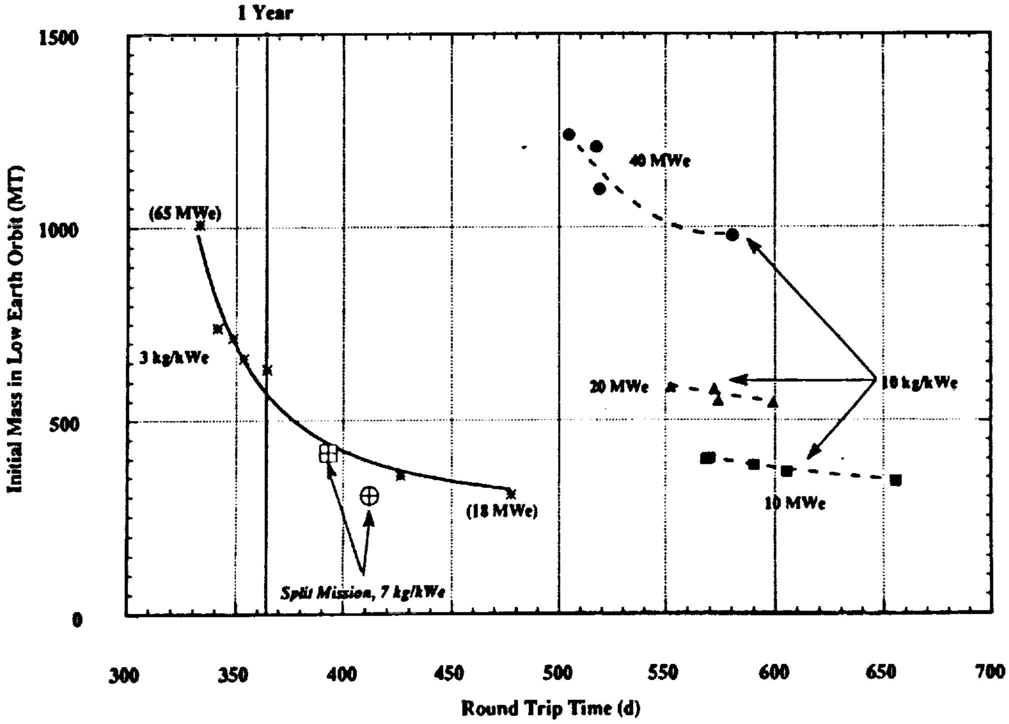
Power Level (P_e): Affects Trip Time

System Specific Mass (α): Determines Trip Time Limits

Thruster Efficiency (η): Affects Trip Time, Vehicle Mass

MISSION BENEFIT	ENABLING PARAMETER	NEP CAPABILITIES
Reduced Propellant Mass	Isp	2000 - 10000 seconds
	α	<10 kg/kWe
	η	>50%
Reduced Trip Time	α	<10 kg/kWe
	Pe	>=10 MWe
	η	>50%
Mission Tolerance	Isp	2000 - 10000 seconds

NEP PERFORMANCE FOR PILOTED MARS MISSION 2016 OPPOSITION



NEP TECHNOLOGY DEVELOPMENT APPROACH

Evolutionary Approach

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

Ultimate Goal: Mars Piloted Mission in 2016 - 2019 Time Frame

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

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PATHWAYS TO EVOLUTION

MISSION	EVOLVING SP-100 TECHNOLOGY	EVOLVING HIGHER RISK TECHNOLOGIES
INTERPLANETARY PROBES/PRECURSORS	SP-100 THERMOELECTRIC 100 kWe	SP-100 THERMOELECTRIC 100 kWe
LUNAR/MARS CARGO	GROWTH SP-100 K-RANKINE 1-5 MWe	ADVANCED REACTOR ADVANCED POWER CONVERSION 1-5 MWe
MANNED MARS	GROWTH SP-100 K-RANKINE	ADVANCED REACTOR ADVANCED POWER CONVERSION
"ALL UP"	10-20 MWe	10-20 MWe
"QUICK TRIP"	——	40-60 MWe

EVOLUTION OF NEP TECHNOLOGIES

	PRESENT	GOAL
Power		
Nuclear SP-100	100 kWe	>=10 MWe
	~45 kg/kWe	<= 10 kg/kWe
	GES 2001	TRL 6 by 2006
	UN Fuel Pin	
	TE Conversion	
	1350 K	
	K Heat Pipe	

Propulsion

Thrusters	Ion	MPD	Ion	MPD
Isp (s)	2000 - 9000	1000 - 5000	2000 - 9000	1000 - 7000
η	.7 - .8	.3	.7 - .8	>.5
Pe (MWe)	.01 - .03	.01 - .5	1 - 2	1 - 5
Lifetime(h)	10000	?	10000	>= 2000

Power Management and Distribution (PMAD)

PRESENT	GOAL
$\eta \sim 0.90$	$\eta \sim 0.95$
4 kg/kWe	<= 2.5 kg/kWe
400 K Rejection Temp.	700 K Rejection Temp.

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

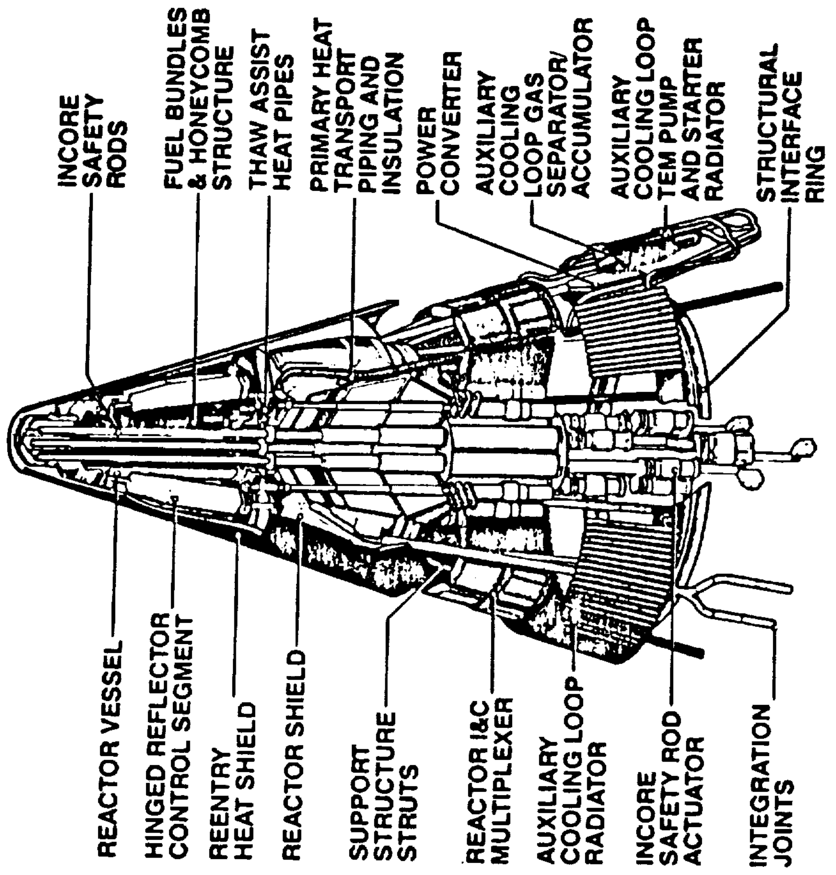
POWER (10 MWe):

- 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/m^2)
- 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

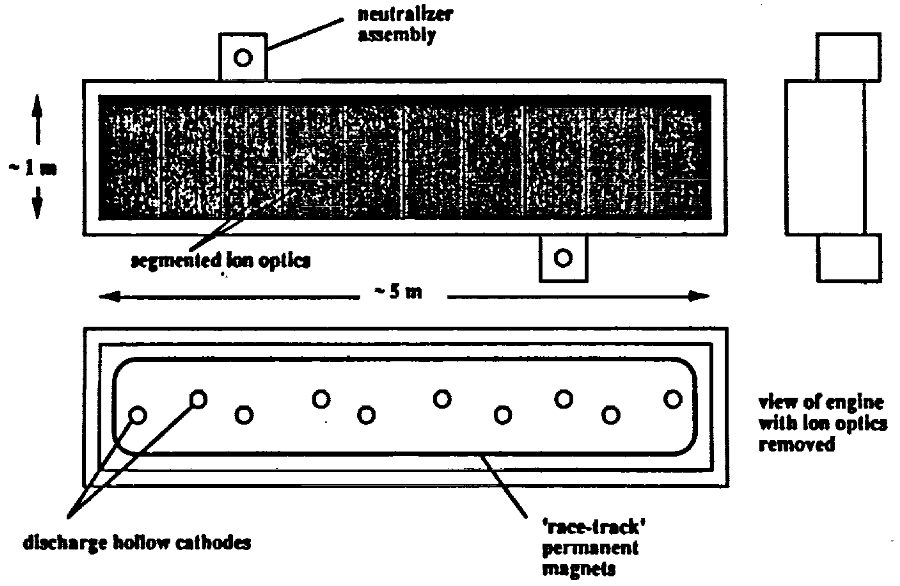
PROPULSION:

- Argon Ion Thrusters
  - 1.25 MWe thrusters
  - 5000 - 9000 s Isp
  - 1 m X 5 m Grids
  - 10,000 hours Lifetime

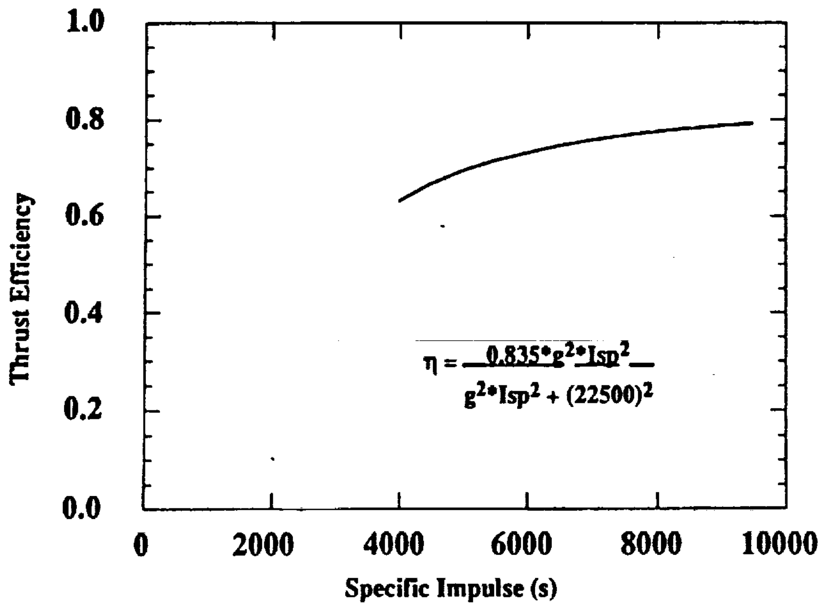
REACTOR POWER ASSEMBLY



EXAMPLE 1.25 MWe ARGON ION ENGINE DESIGN

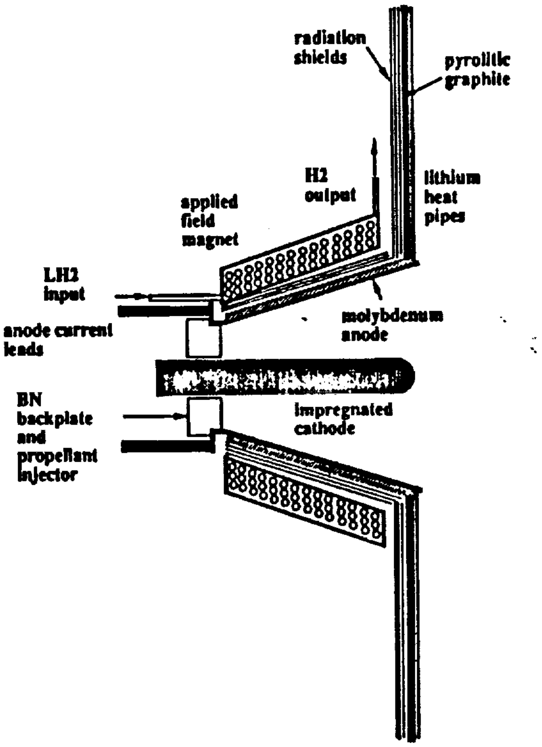


PROJECTED ARGON ION THRUSTER PERFORMANCE



$$\eta = \frac{0.835 * g^2 * Isp^2}{g^2 * Isp^2 + (22500)^2}$$

EXAMPLE 2.5 MWe HYDROGEN MPD THRUSTER DESIGN



NEP SUBSYSTEM TRADE SPACE

Reactor	Power Conversion	Radiator	PMAD	Thruster
Fuel Pin (SP-100)	Themoelectric	Pumped Loop	Si	Ion
Advanced Fuel Pin	Brayton		GaAs	MPD
NERVA- Derived	Rankine	Refractory Metal HP	SiC	Pulsed Inductive (PIT)
Cermet	Adv. Brayton	Carbon Composite HP	AC	
Thermionic	Thermionic		DC	Electron Cyclotron Resonance (ECR)
Particle Bed	MHD/Rankine	Ceramic Fabric HP		Ion Cyclotron Resonance (ICR)
Pellet Bed		Bubble Membrane		Pulsed Electrothermal (PET)
In-Core Boiling K				
		Liquid Droplet		Deflagration
				VariableIsp
				Pulsed Plasmoid

NEP TECHNOLOGY EMPHASIS

TECHNOLOGY	SYSTEM IMPACT
Reactor	
High Temperature Fuels, Materials	Low α - reduced radiator mass
High Fuel Burnup	Low α - compact reactor design
Power Conversion	
High Temperature Materials	Low α - reduced radiator mass
Power Management and Distribution (PMAD)	
High Power Electronics	Enabling - Reliability
Radiation Resistant Electronics	Enabling - Reliability
High Temperature Electronics	Low α - reduced PMAD radiator mass
Efficient Electronics	Low α, Pe - reduced PMAD radiator mass ; lower power source requirements

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NEP TECHNOLOGY EMPHASIS

TECHNOLOGY	SYSTEM IMPACT
Heat Rejection (Radiator)	
High Temperature, Low Mass Materials	Low α - Dominant mass in MWe space power systems
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

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 α**
  - α values range from 7 to 15 kg/kWe
  - Power, Isp optimized
  - Lines are optimum performance for each α
- **Sensitivity of Mars Mission to Power, Isp**
  - Constant α of ~10 kg/kWe
  - Performance insensitive to Isp above 5000 seconds
  - Dashed line is optimum performance "envelope"

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NEP MISSION GUIDELINES

Mission	Total Power (MWe)	Thruster Power (MWe)	Operating Time (y)	Thruster Time (y)	Isp (s)	η (%)	α (kg/kWe)	Need Date
Orbital Transfer/ Precursor	0.1 - 1	0.01 - 0.05	3 - 10	1 - 2	2000 -8000	>50	10 - 30	1990- 2005
Interplanetary Probe	0.1 - 1	0.01 - 0.05	10-12	6 - 10	5000 -10000	>50	30 - 50	1990- 2005
Lunar Cargo	0.5 - 5	0.1 - 1	3 -1 0	1 - 2	3000 -10000	>50	10 - 20	2005-
Mars Cargo	2 - 10	0.5 - 2	5 - 10	2 - 3	5000 -10000	>50	10 - 20	2010-
Mars Piloted	5 - 20*	1 - 5	5 - 10	1 - 2	5000 -10000	>50	10 - 20	2014-
Mars Fast	10 - 60*	5 - 10	3 - 10	1 - 2	6000 -10000	>50	1 - 5	2016-

*Total Power Includes Option for Multiple Propulsion Modules

NUCLEAR PROPULSION PROJECT

ROBOTIC SCIENCE MISSIONS

JPL

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

RJB
4-30-91

√

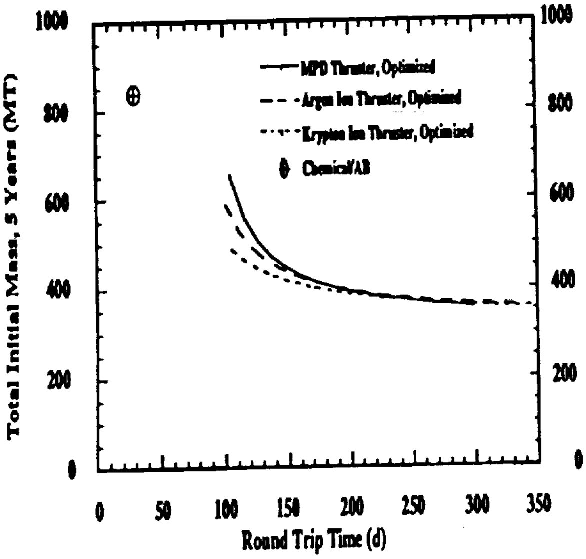
NEP Lunar Cargo Mission

- 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

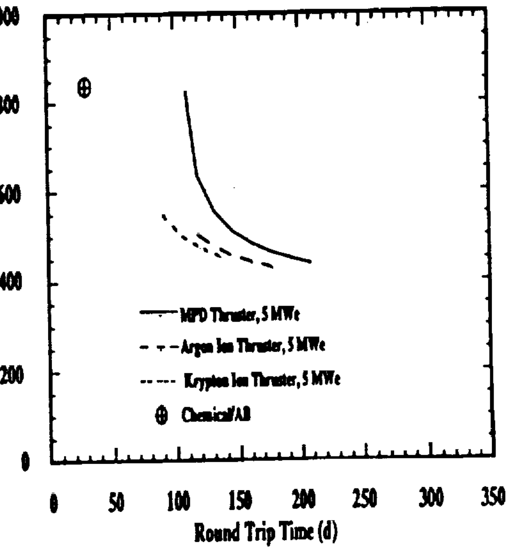
Optimized Case	Modular Case
Optimal Power	Common 5 MWe
Optimal Isp	Vary Isp to obtain trip time

NEP Lunar Cargo Vehicle Mission Performance

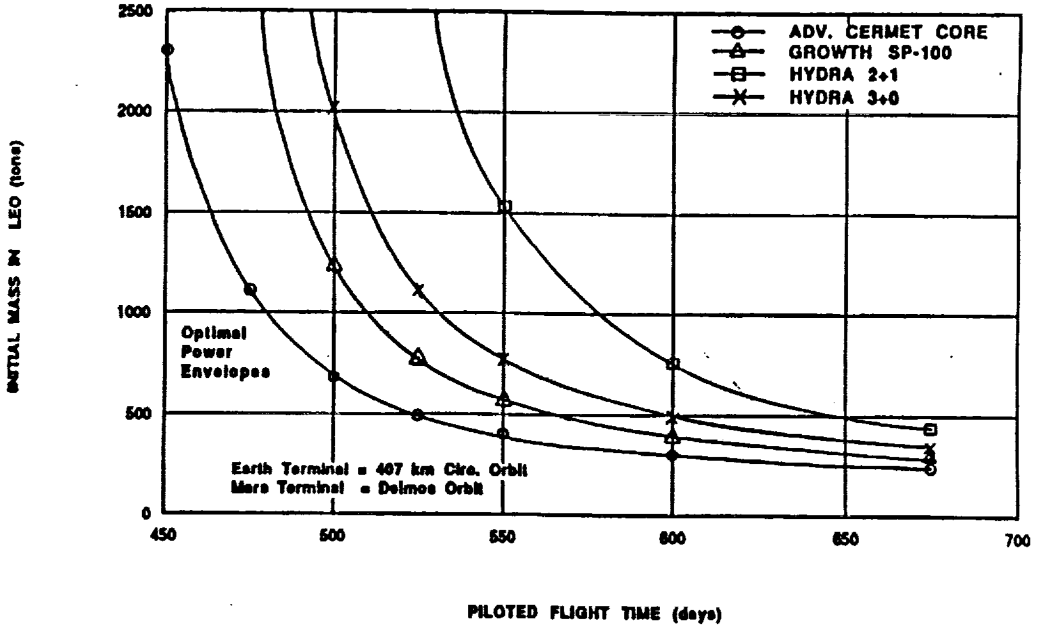
"Optimized" Case: Specific Impulse and Power optimized for minimum mass



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



TANKS JETTISONED

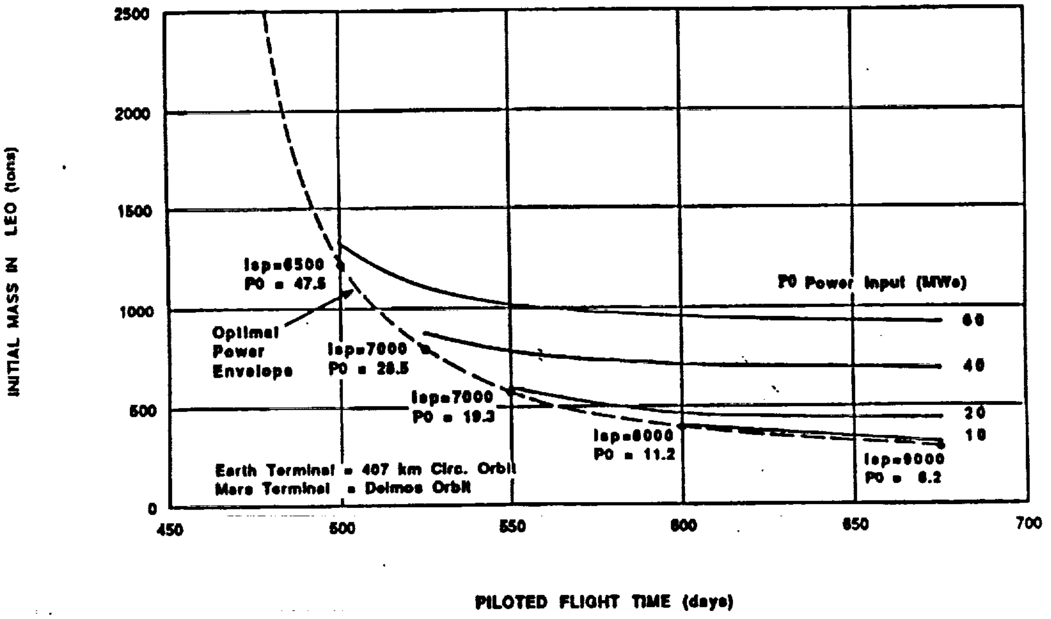


NEP PERFORMANCE FOR 2016 OPPOSITION-CLASS MISSION

COMPARISON OF POWER SYSTEMS WITH ION THRUSTERS

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

TANKS JETTISONED



NEP PERFORMANCE FOR 2016 OPPOSITION-CLASS MISSION

GROWTH SP-100 REACTOR WITH ION THRUSTERS

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

LEWIS RESEARCH CENTER

NEP Technology Charts

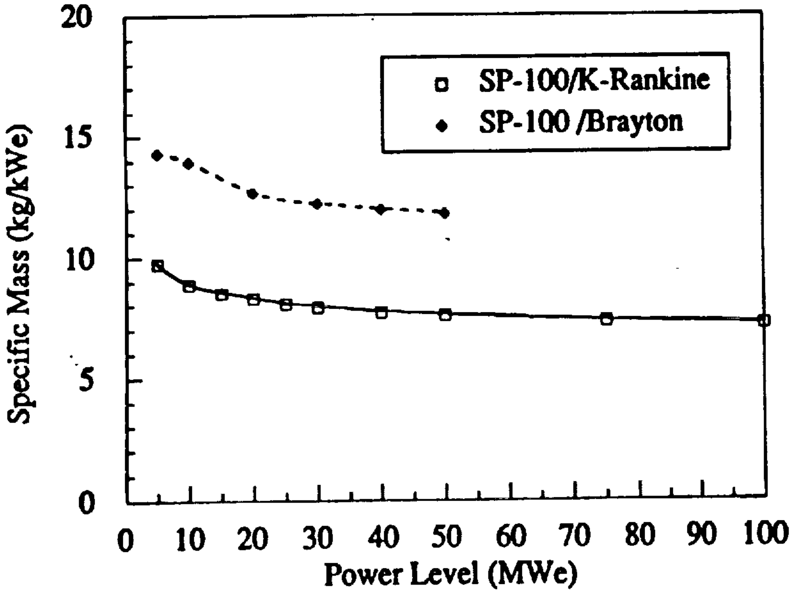
- **Scaling of Growth SP-100 System over range of powers**
  - Scaling up to 10 - 20 MWe studied by GE for LeRC
  - Little economy of scale beyond 10 MWe; radiator mass dominates
- **Range of Power Systems Presented at NEP Workshop**
- **Range of Thruster Systems Presented at NEP Workshop**

NUCLEAR PROPULSION PROJECT

LEWIS RESEARCH CENTER

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)



ADVANCED SPACE ANALYSIS OFFICE

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

- **UF_4/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**