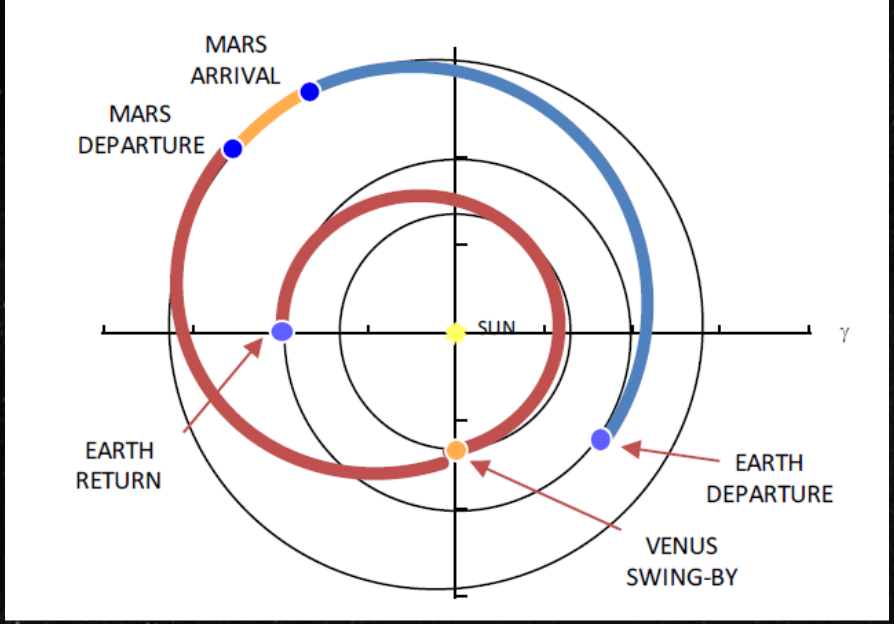
Belfort, France
8 December 2023

"I need more power, Scotty!"

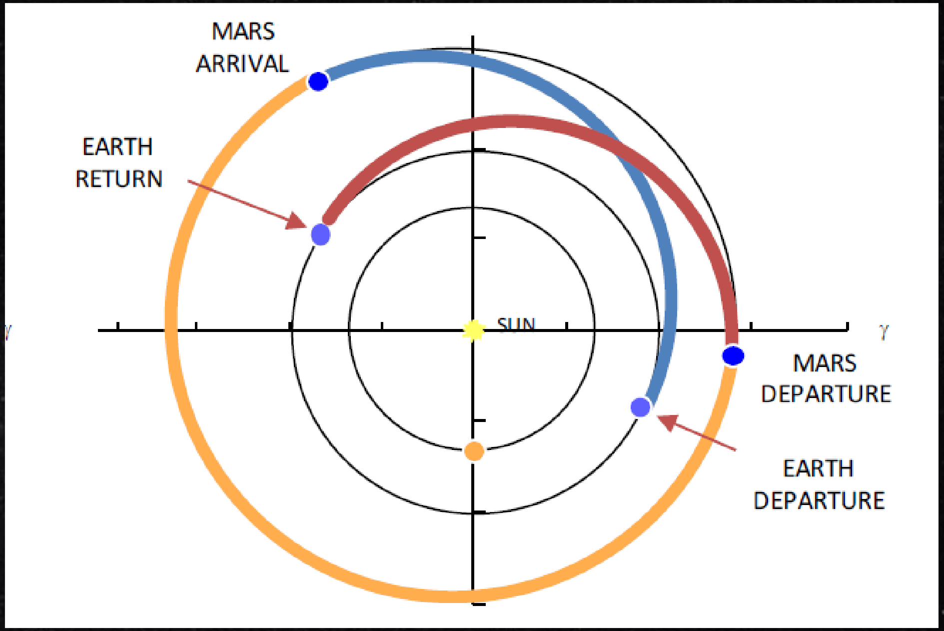
A Parametric Review of Power and Propulsion Options for Human Missions to Mars

John H Scott | Principal Technologist, Power and Energy Storage, Lyndon B. Johnson Space Center| November 6, 2023

Human Mars Mission Trajectories



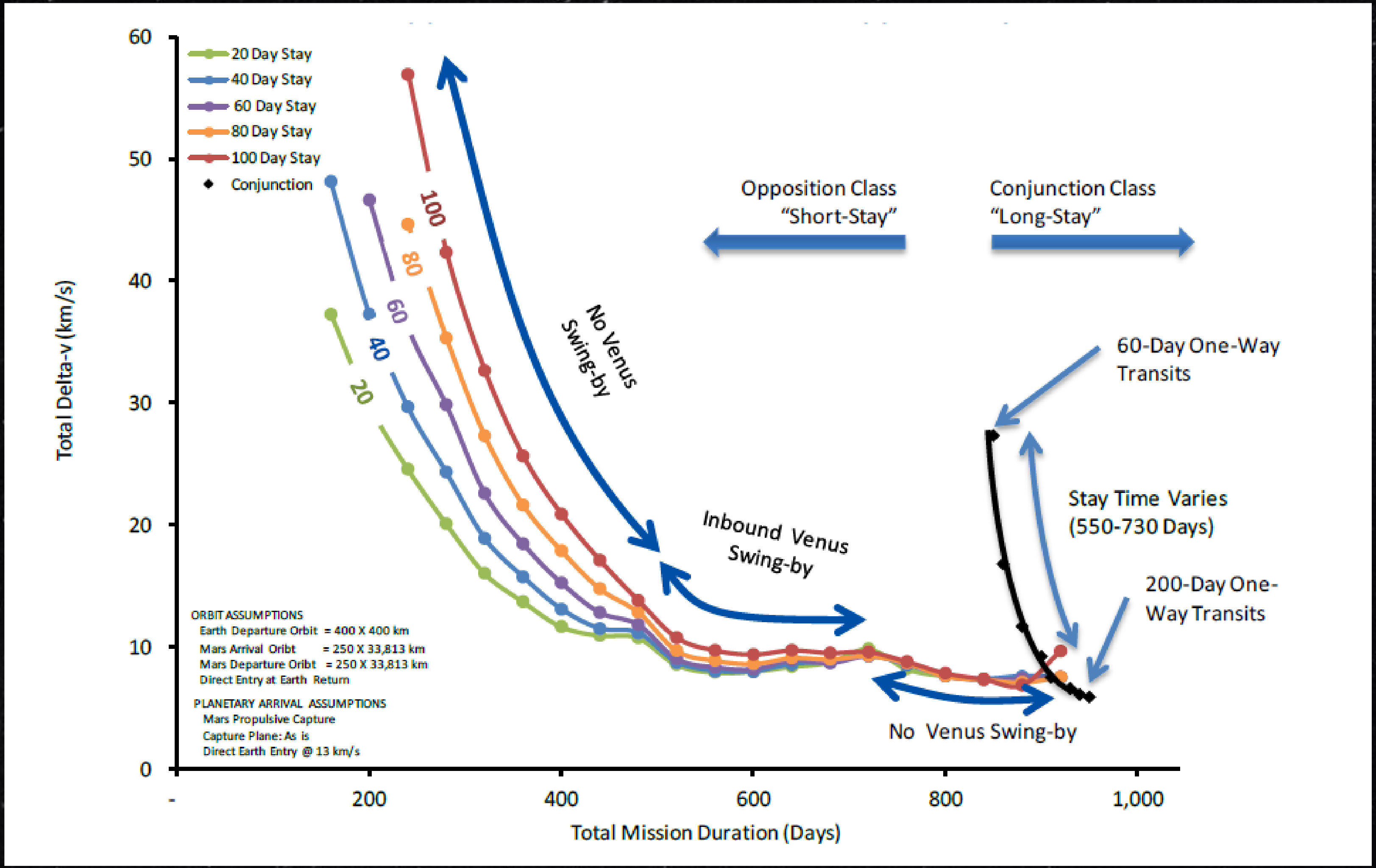
Short Stay "Opposition" Class Missions



Long Stay "Conjunction" Class Missions

NASA/SP–2009-566-ADD2

Human Mars Mission Trajectories

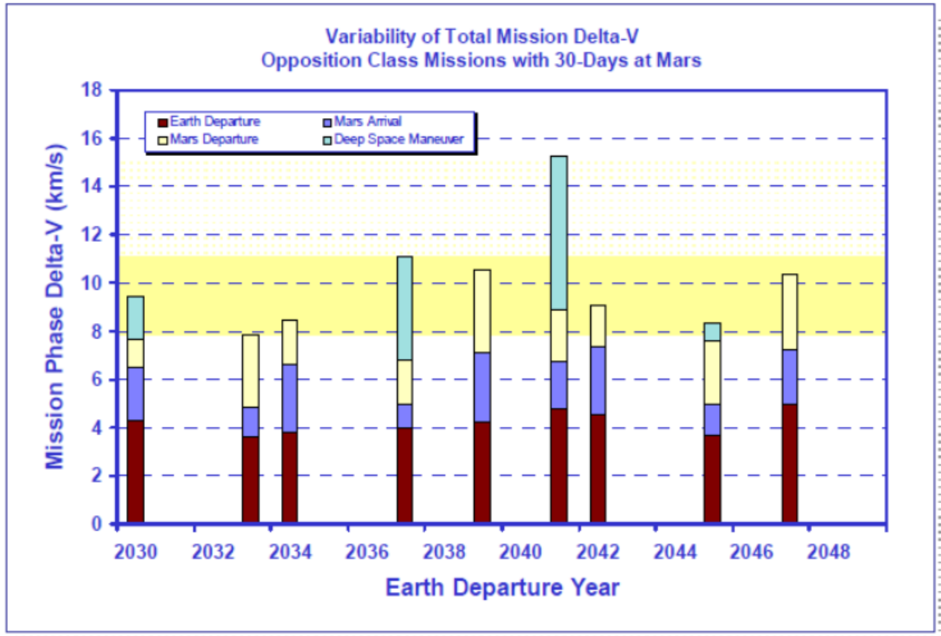


NASA/SP–2009-566-ADD2

Human Mars Mission Trajectories

Opposition Class Missions (Short-Stay)

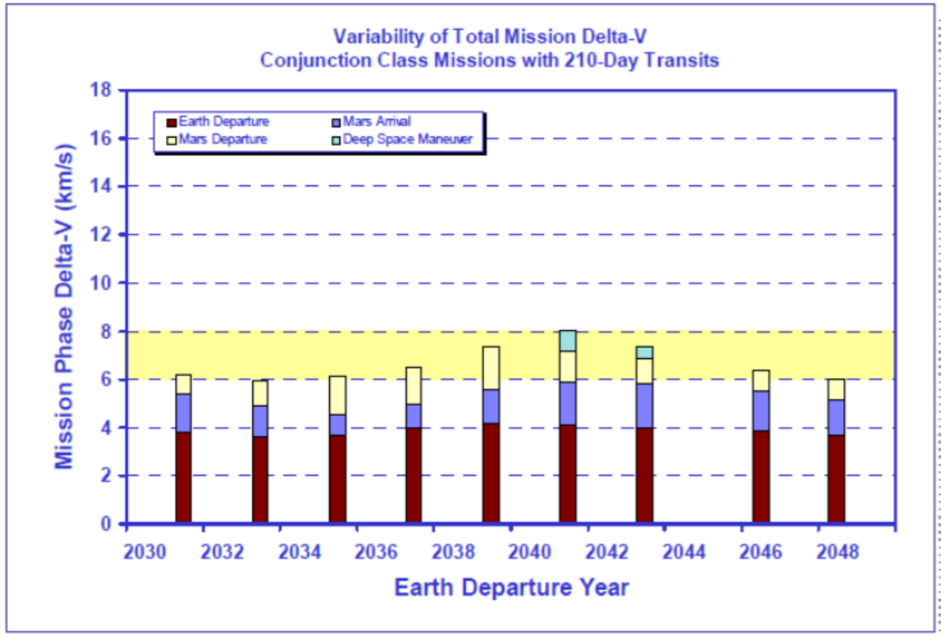
Propulsive Delta-V



Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 30 sols stat at Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

Conjunction Class Mission (Long-Stay)

Propulsive Delta-V

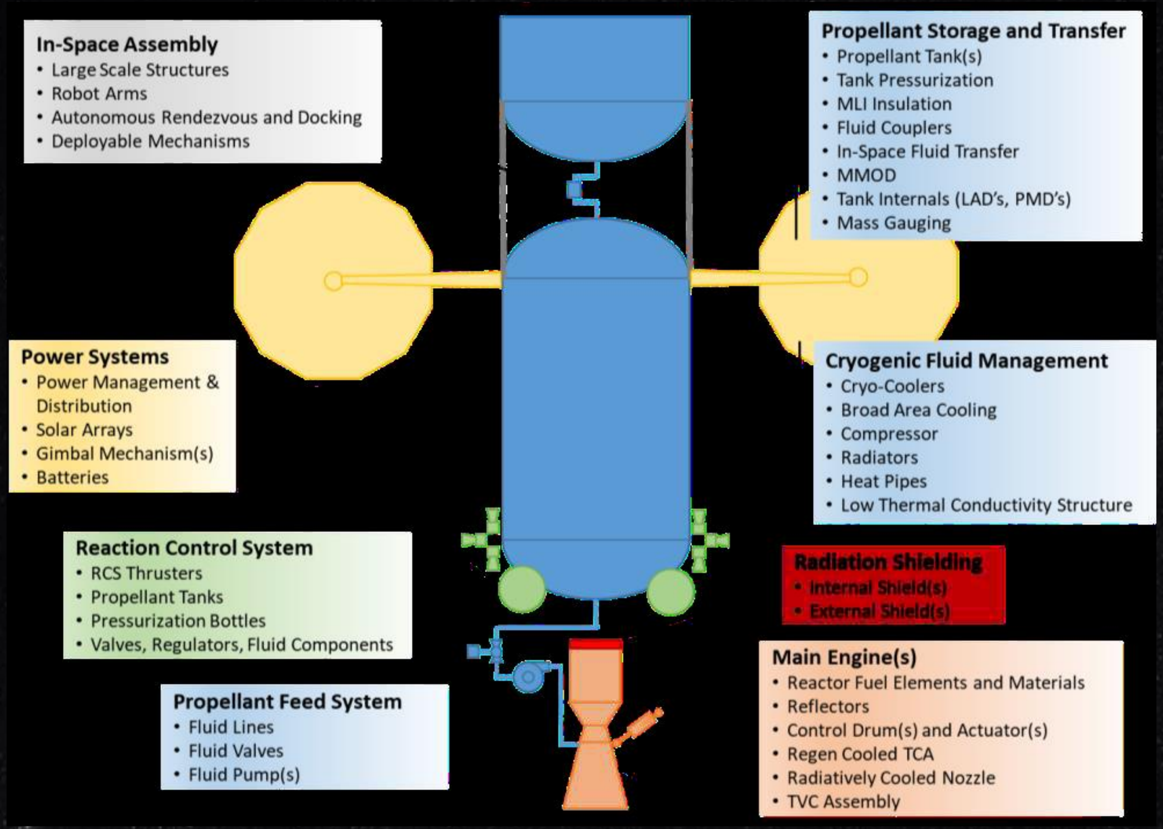


Note: Optimized trajectories assuming 407 km circular LEO departure orbit, propulsive capture at Mars into a Mars 1-Sol orbit of 250 km x 33,793 km. 210 day transits to and from Mars. Direct entry at Earth with an entry speed limit of 13 km/s.

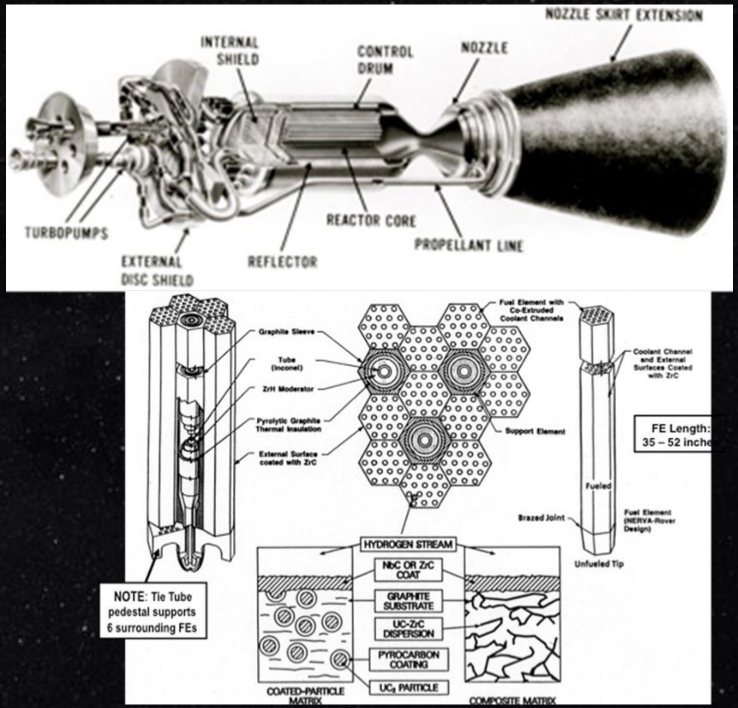
NASA/SP–2009-566

Nuclear Thermal Propulsion

Active Testing: 1958-1972
Technology Studies on-going



NASA Mars Transportation Assessment Study, 2023



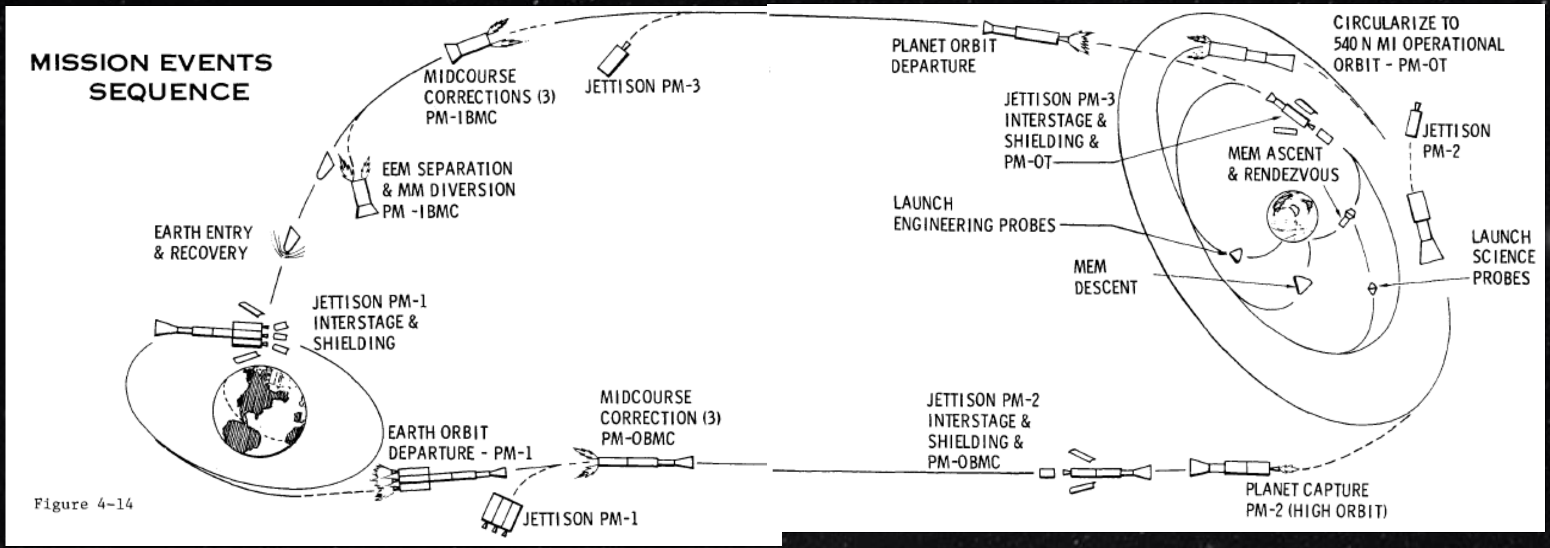
Rover/NERVA Engine

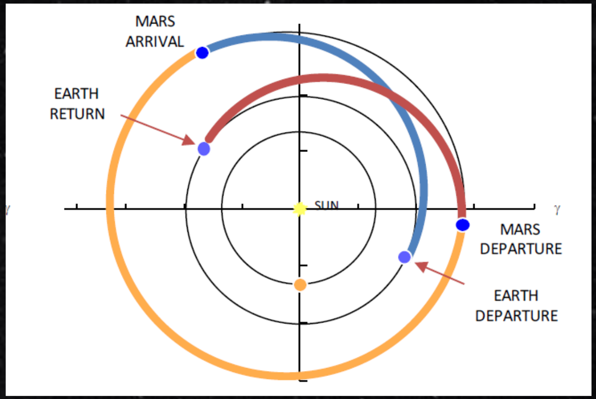
NASA/SP–2009-566-ADD2

Integrated Manned Interplanetary Spacecraft Concept Definition
(ca. 1968)

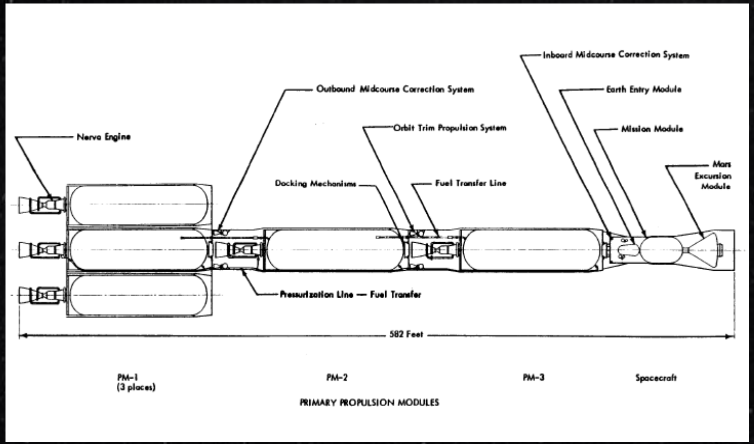
Boeing: D2-113544-3-1

Crewed Mission to Mars Surface



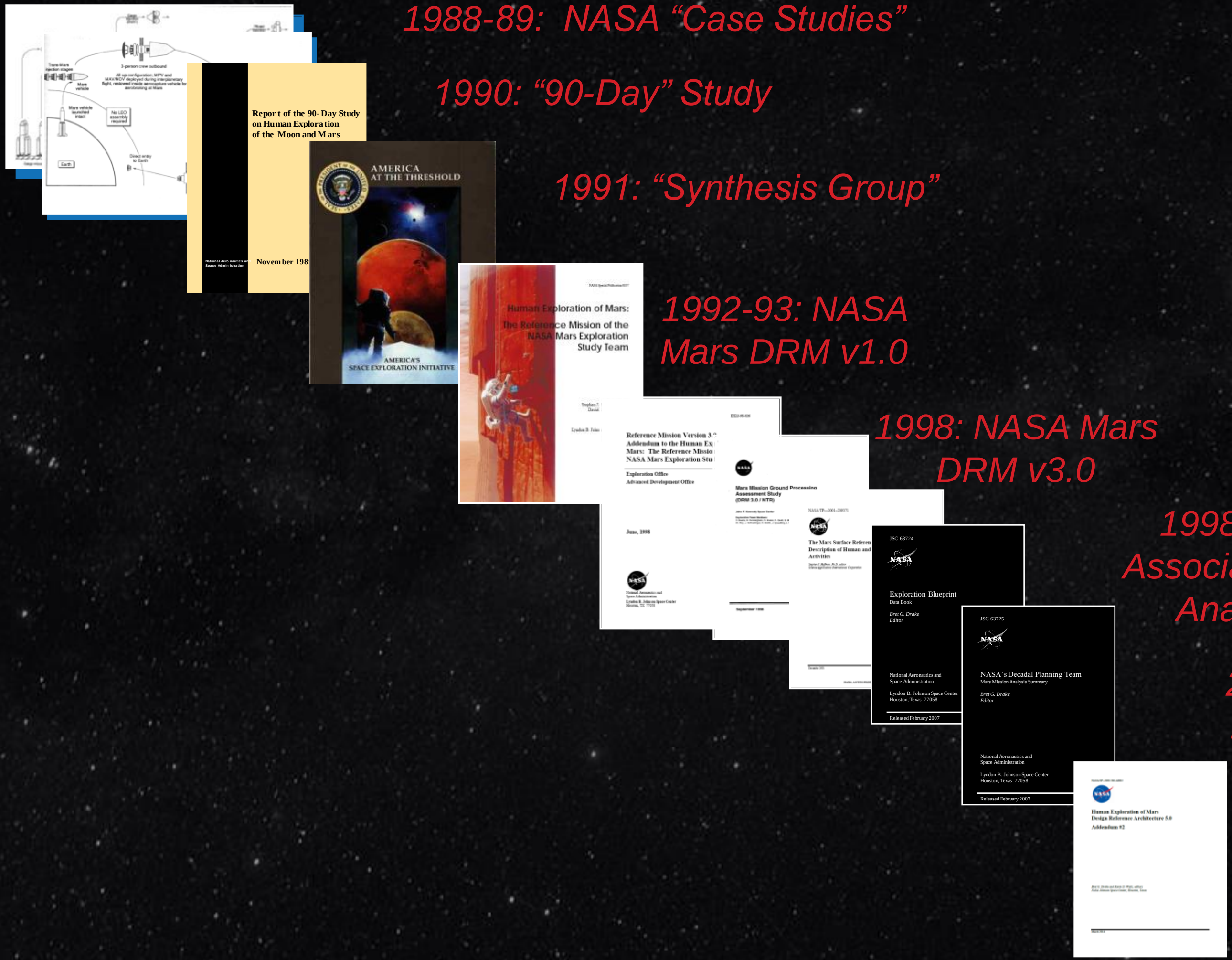


1980 Conjunction Opportunity



Transit Propulsion: Nuclear Thermal up to 3 engines
I_{sp} = ~850 s;
T = ~867 kN
Mission Duration: 1000 days
Crew on Mars Surface: 30 Days
Mass to Assembly Orbit (LEO): 290 t
Mass to Descend from Mars Orbit (30 day excursion): 43 t

Human Mars Mission Studies (1988 – 2009)



1988-89: NASA "Case Studies"

1990: "90-Day" Study

1991: "Synthesis Group"

1992-93: NASA Mars DRM v1.0

1998: NASA Mars DRM v3.0

1998-2001: Associated v3.0 Analyses

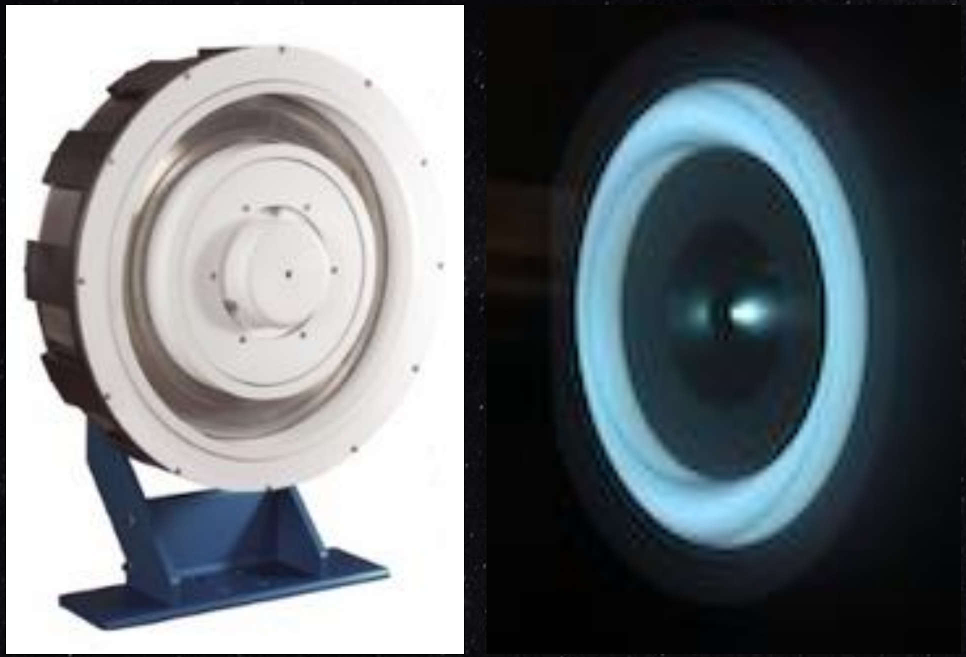
2002-2004: DPT/NExT

2007-9 Mars Design Reference Architecture 5.0

Electric Propulsion

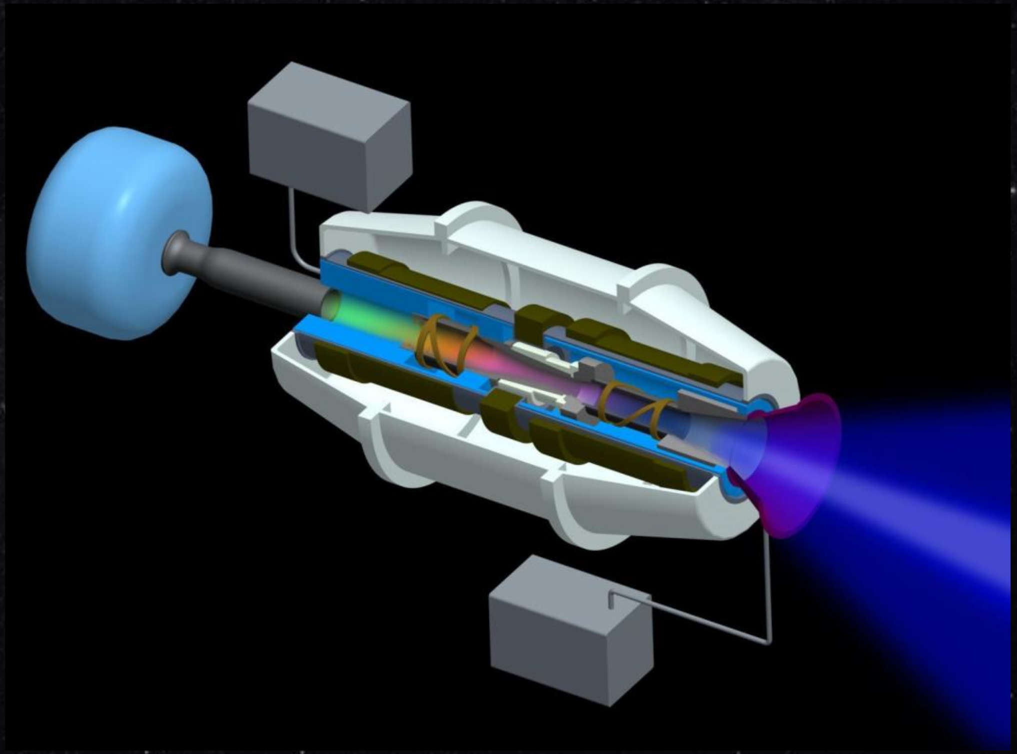
1980's forward

Hall Effect



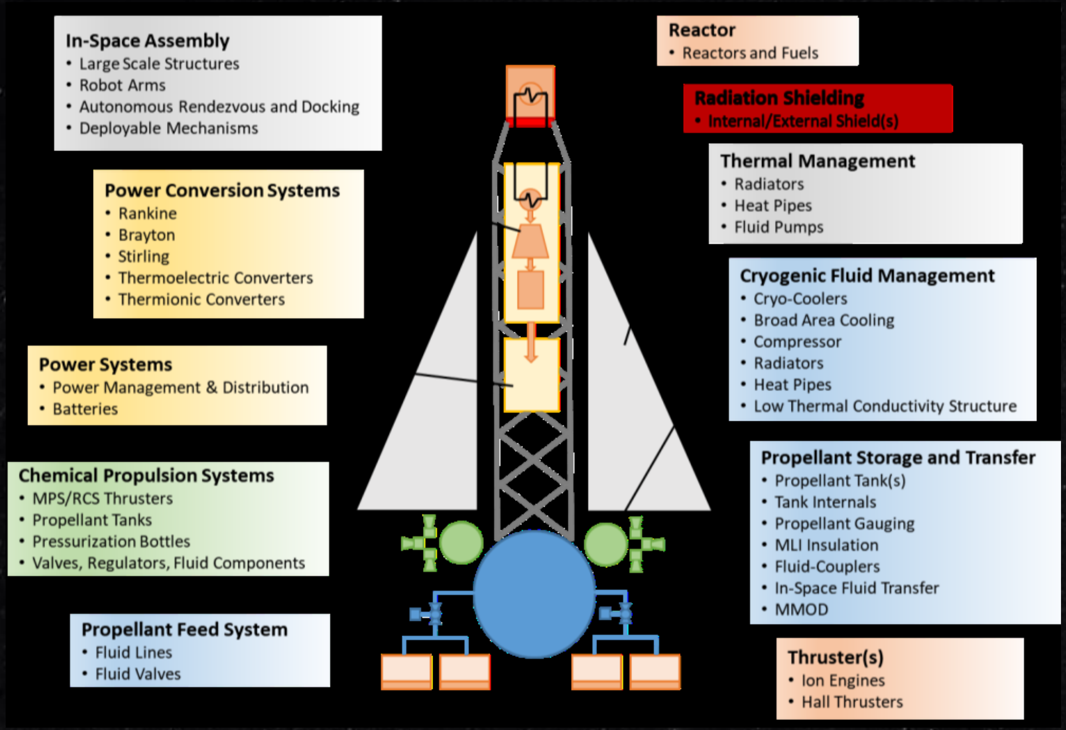
NASA Mars Transportation Assessment Study, 2023

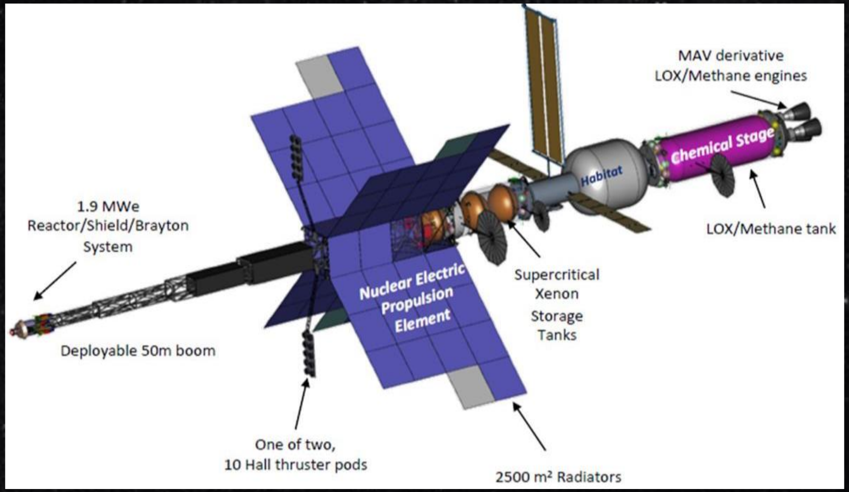
Plasma



Longmier et al, AIAA-2012-3930

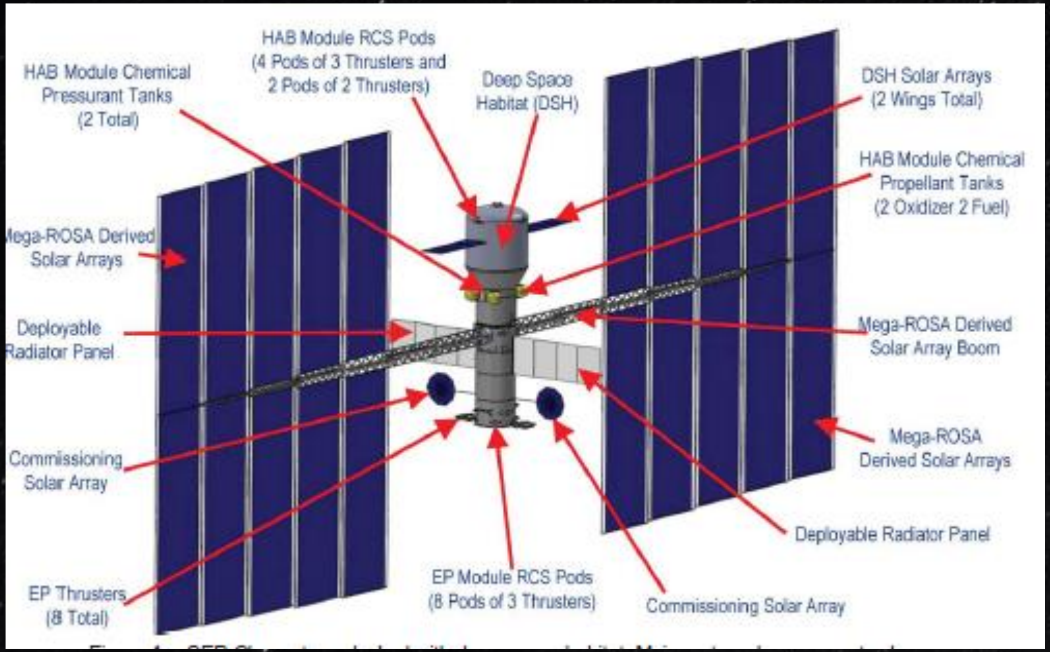
Nuclear Electric Propulsion

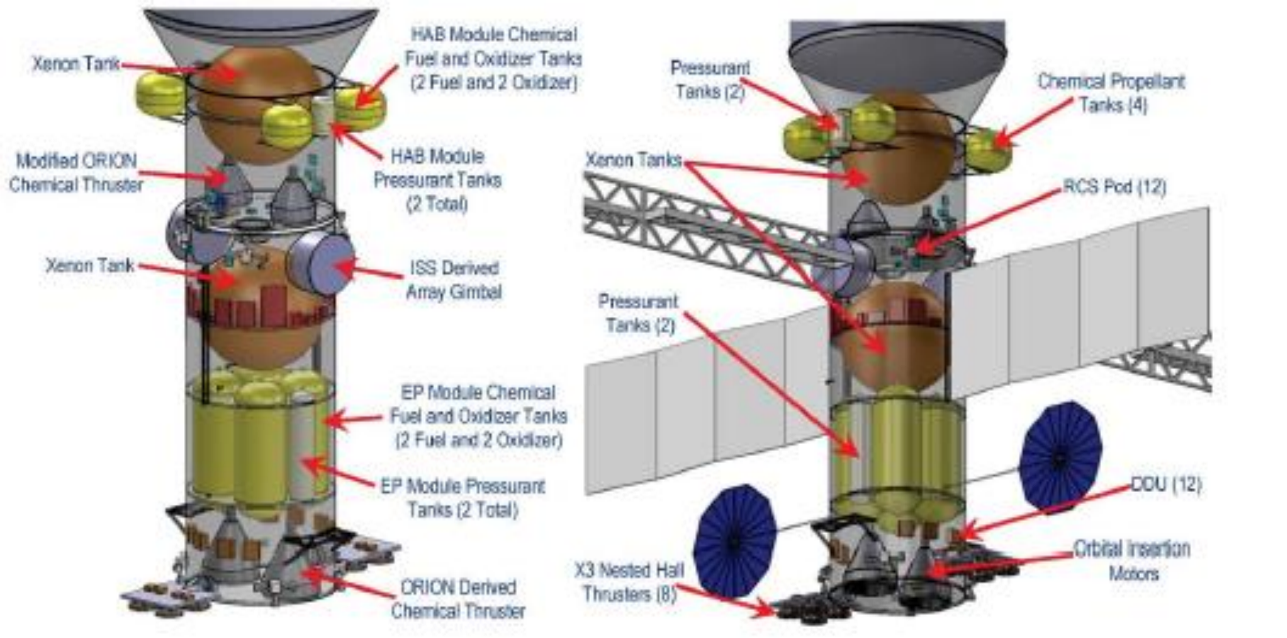




NASA Mars Transportation Assessment Study, 2023

Solar Electric Propulsion



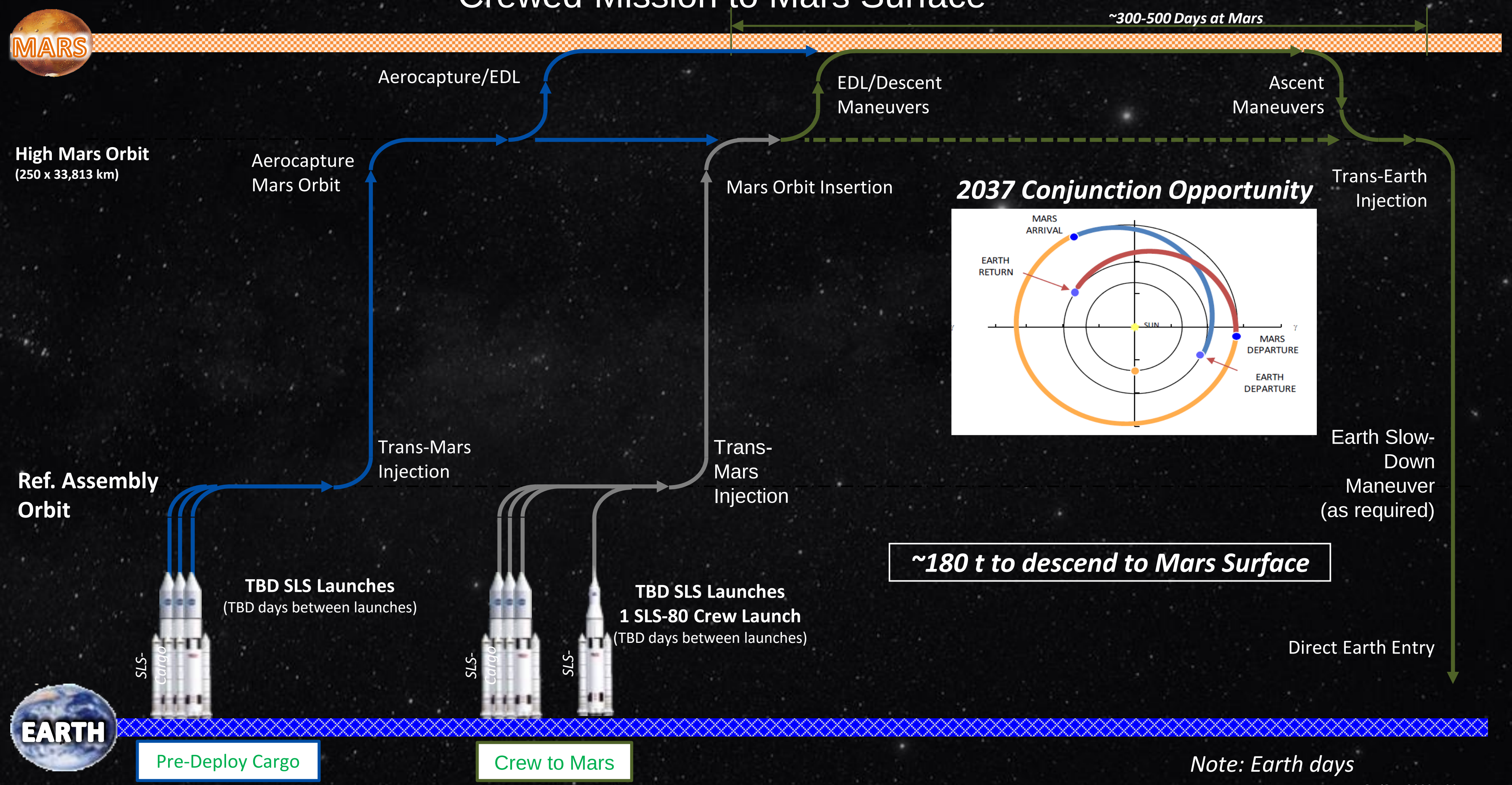


Mercer & Oleson, NASA/TM-2014-5492

Study: Design Reference Architecture 5.0

(ca. 2009)

Crewed Mission to Mars Surface

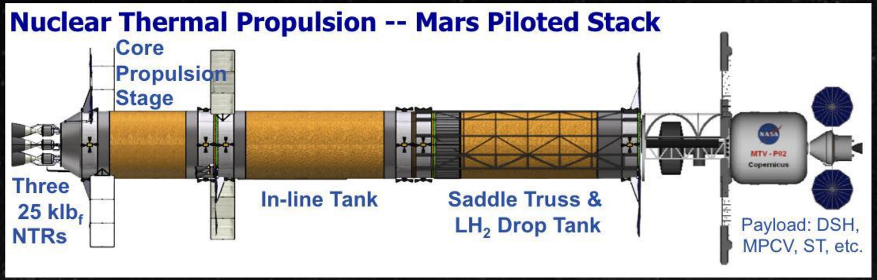


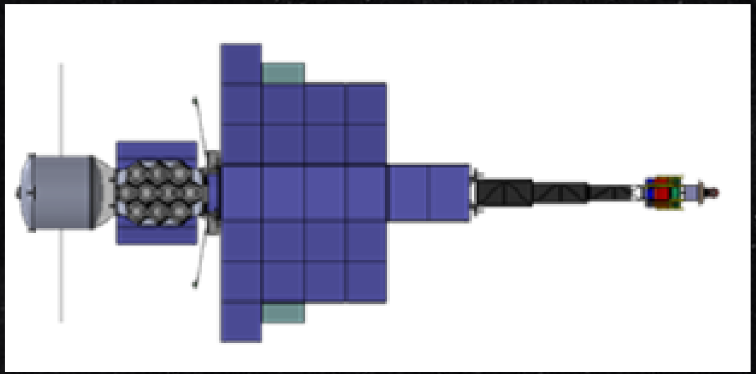
NASA/SP–2009-566

Study: Design Reference Architecture 5.0
(ca. 2009)

Transit Propulsion Options and Results

NASA/SP–2009-566-ADD2





Transit Propulsion: Nuclear Thermal up to 3 engines firing
Propellant: Cryogenic H_2
I_{sp} = ~900 s;
T = ~111 kN

Mission Duration: 914 days
Crew on Mars Surface: 539 Days
Mass to Assembly Orbit (LEO): 890 t

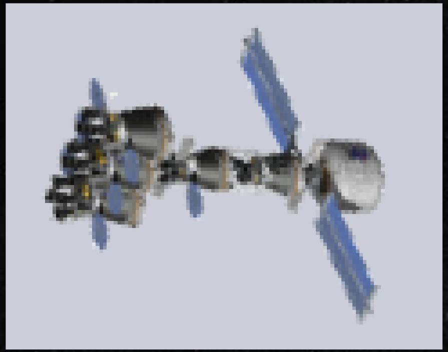
Transit Propulsion: Nuclear Electric (Hall) propulsion with 8 engines firing
Propellant: Xe
I_{sp} = ~5000 s;
P = 300 kW_e (15 N) each
Assumed MMH/N_2O_4 chemical stage for exiting Earth gravity well

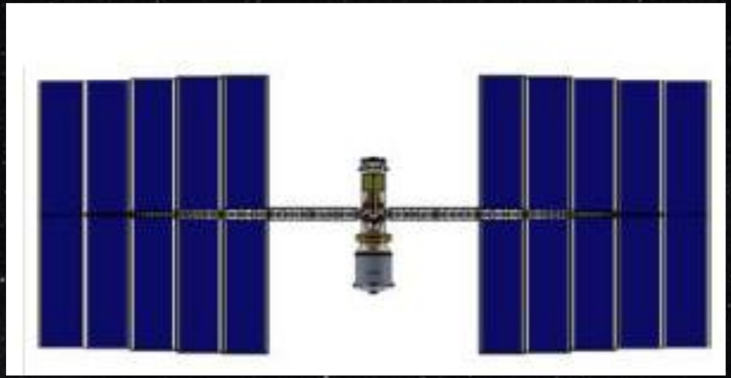
Mission Duration: 980 days
Crew on Mars Surface: 400 Days
Mass to Assembly Orbit (LEO): 770 t

Study: Design Reference Architecture 5.0
(ca. 2009)

NASA/SP–2009-566-ADD2

Transit Propulsion Options and Results





Transit Propulsion: Chemical (Aerojet RL-10) with 5 engines
Propellant: LO_2/LH_2
I_{sp} = 462 s;
T = 110 kN each

Mission Duration: 880 days
Crew on Mars Surface: 500 Days
Mass to Assembly Orbit (LEO): 1250 t

Transit Propulsion: Solar Electric (Hall) propulsion with 10 engines continuous firing
Propellant: Xe
I_{sp} = ~2400 s;
P = 125 kW_e/each (6 N)
Assumed MMH/N_2O_4 chemical stage for exiting Earth gravity well

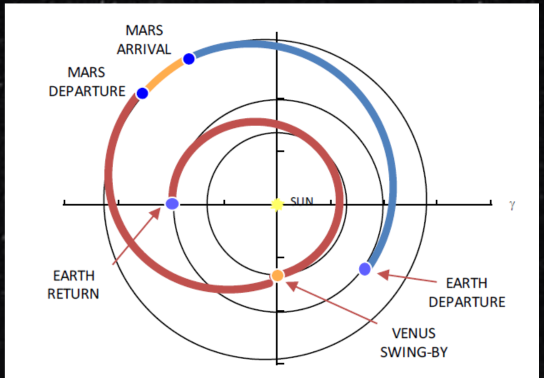
Mission Duration: 1065 days
Crew on Mars Surface: 300 Days
Mass to Assembly Orbit (LEO): 780 t

Study: Mars Transportation Assessment

(2019-2022)

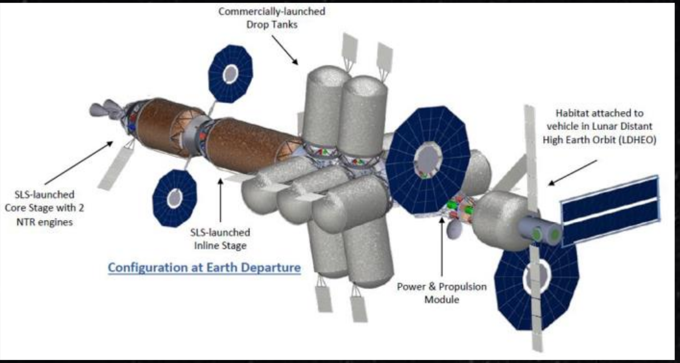
NASA Mars Transportation Assessment Study, 2023

Opposition Class
2039 Opportunity

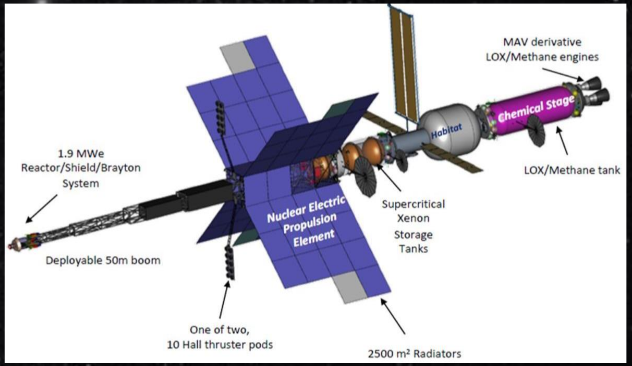


Campaign Mass to Mars Orbit: 195 t

Reactor Topping Temperature: 1200 K
System α: 15 kg/kW$_e$



Crewed Vehicle: Nuclear Thermal Propulsion



Crewed Vehicle: Nuclear Electric Propulsion

Transit Propulsion: Nuclear Thermal
Propellant: Cryogenic H_2
I_{sp} = 900 s;
T = 111 kN each engine (4 on piloted vehicle)
Operating Life: 4 hours

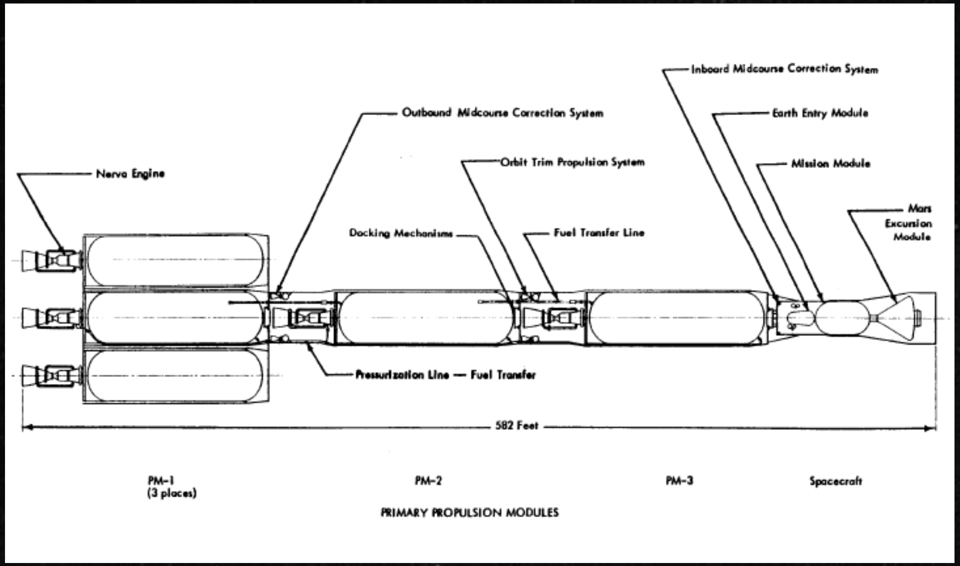
Piloted Mission Duration: 690 days
Crew on Mars Surface: 30 Days
Campaign Mass to Aggregation Orbit: 934 t

Transit Propulsion: Nuclear Electric (Hall)
Propellant: Xe
I_{sp} = 2600 s;
P = 100 kW$_e$ (5 N) each engine (20 on piloted vehicle)
Operating Life: 2 years
Assumed LO_2/LCH_4 chemical stage for exiting Earth gravity well

Piloted Mission Duration: 760 days
Crew on Mars Surface: 30 Days
Campaign Mass to Assembly Orbit: 678 t

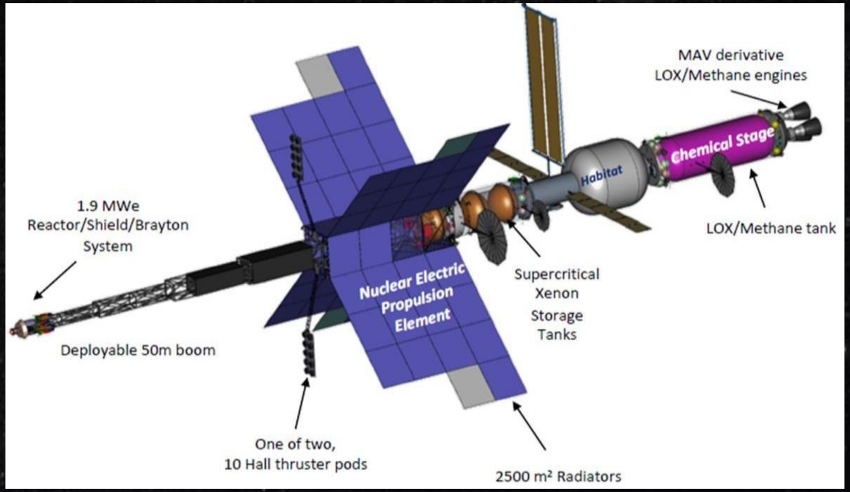
Crewed Mars Mission Performance Growth

1968



Mission Class: Conjunction “Long Stay”
Transit Propulsion: Nuclear Thermal
Piloted Mission Duration: 1000 days
Crew on Mars Surface: 30 Days
Campaign Mass to Aggregation Orbit: 290 t

2023



Mission Class: Opposition “Short Stay”
Transit Propulsion: Nuclear Electric / Chemical
Piloted Mission Duration: 760 days
Crew on Mars Surface: 30 Days
Campaign Mass to Aggregation Orbit: 678 t

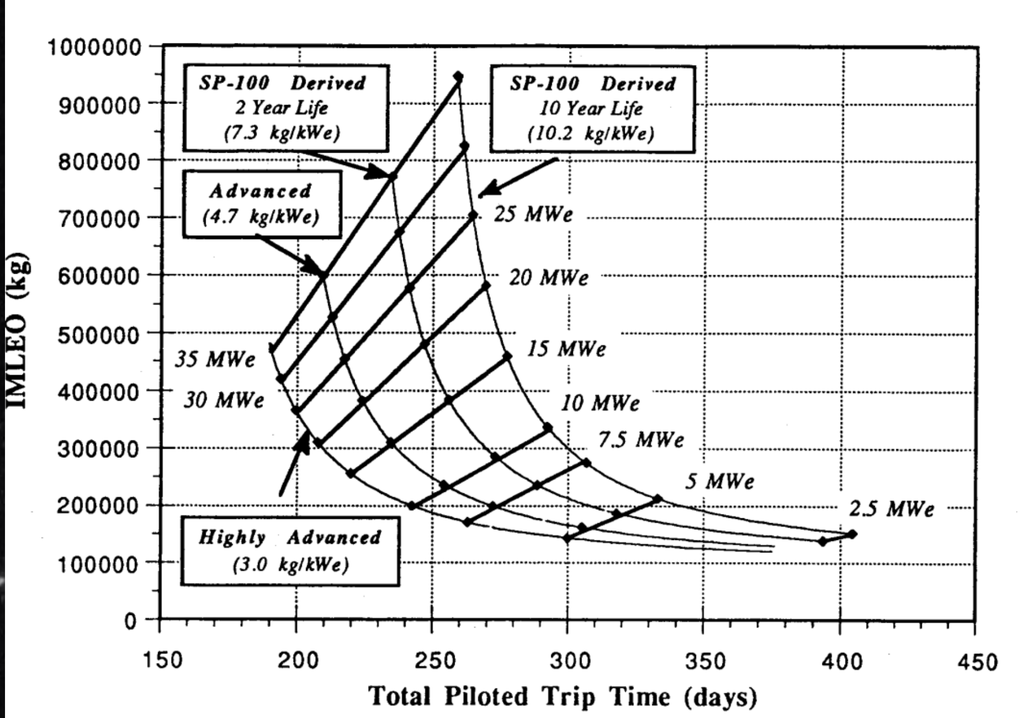
Study: Parametric Mars Transit Calculations
(ca. 1993)

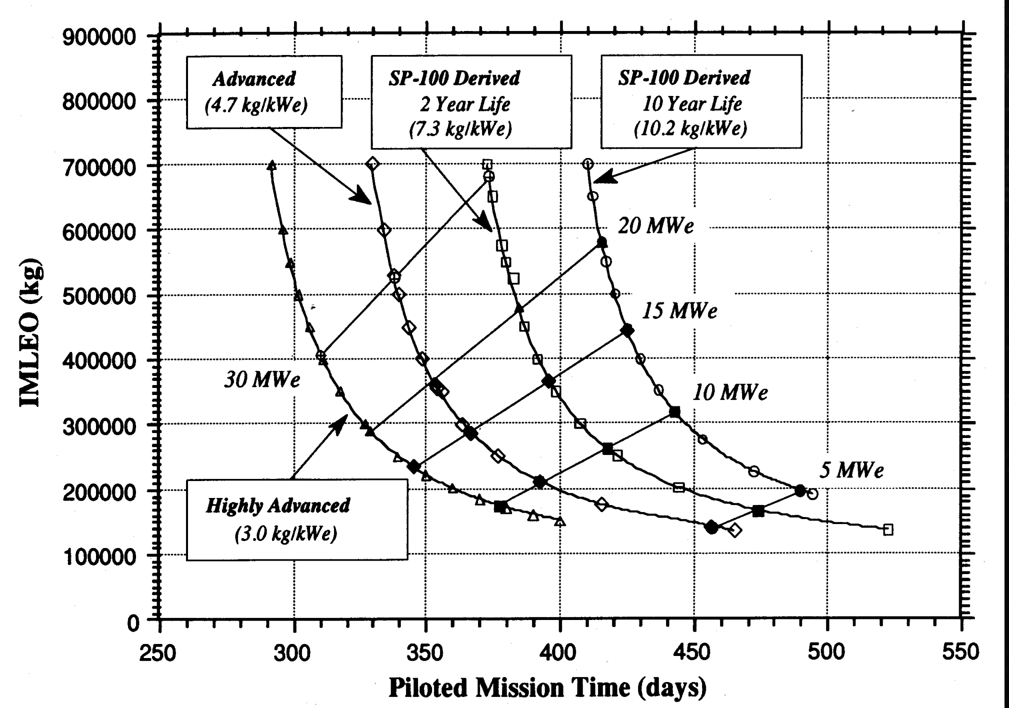
Crewed Missions to Mars Surface

George, Dudzinski, et al, "Piloted Mars Mission Planning: NEP Technology and Power Levels," Space Technology Applications International Forum (STAIF), Albuquerque, NM, 1993.

Conjunction "Long Stay" Class
Synthesis Group "America at the Threshold" 1991

Opposition "Short Stay" Class (*25 Days on Surface*)
"90-Day Study on the Human Exploration of the Moon and Mars" 1989

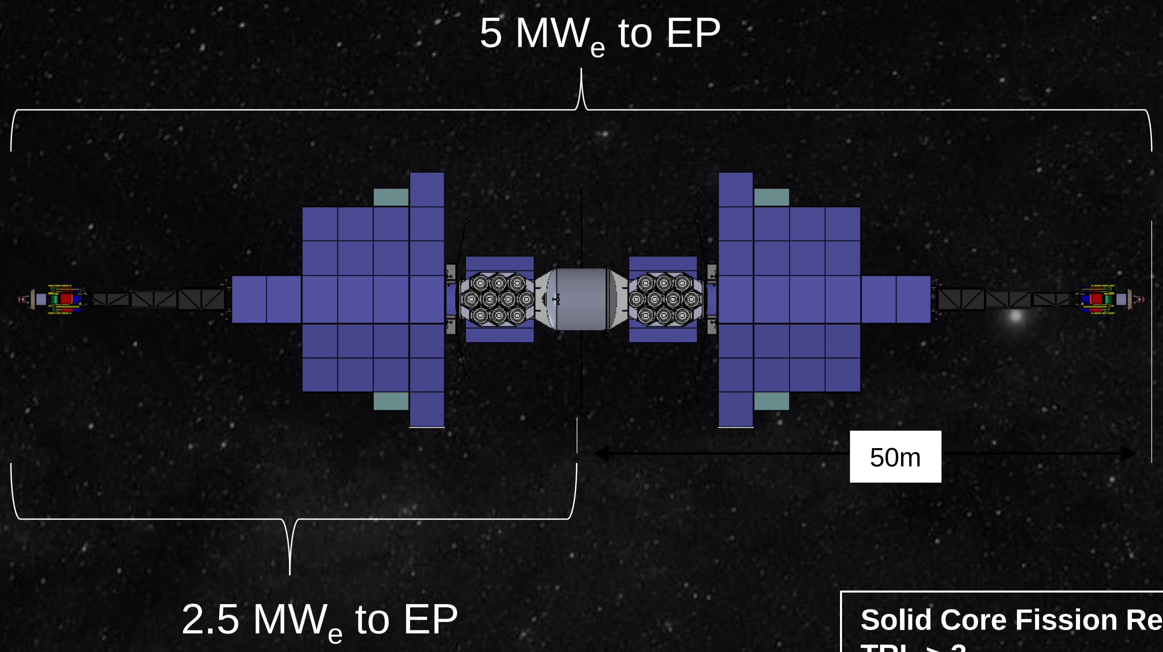


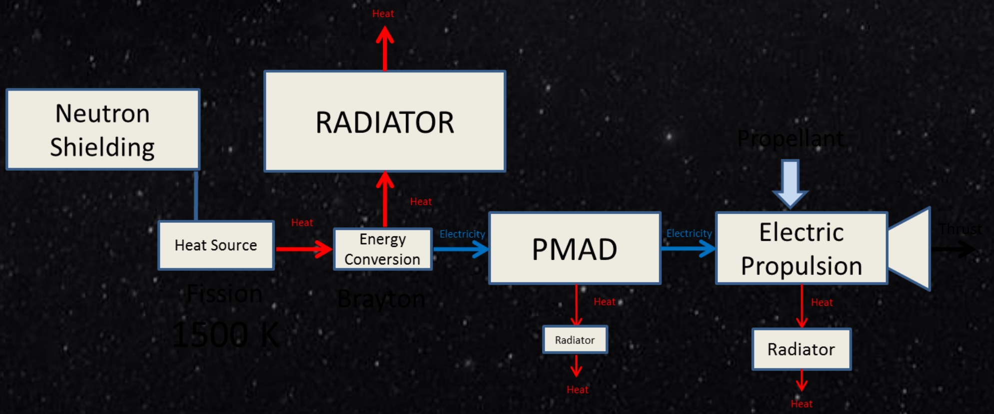


<u>Not</u> including surface stay time
Total crewed duration: 900-1000 days

Including 25 day surface stay time

Reference Nuclear Electric Propulsion (NEP) Concept





Solid Core Fission Reactor
TRL > 3

Brayton conversion
T_{top} = 1500 K
T_{rad} = 500 K avg.

$$\alpha_{Total} = \sim 13 \text{ kg/kW}_e$$

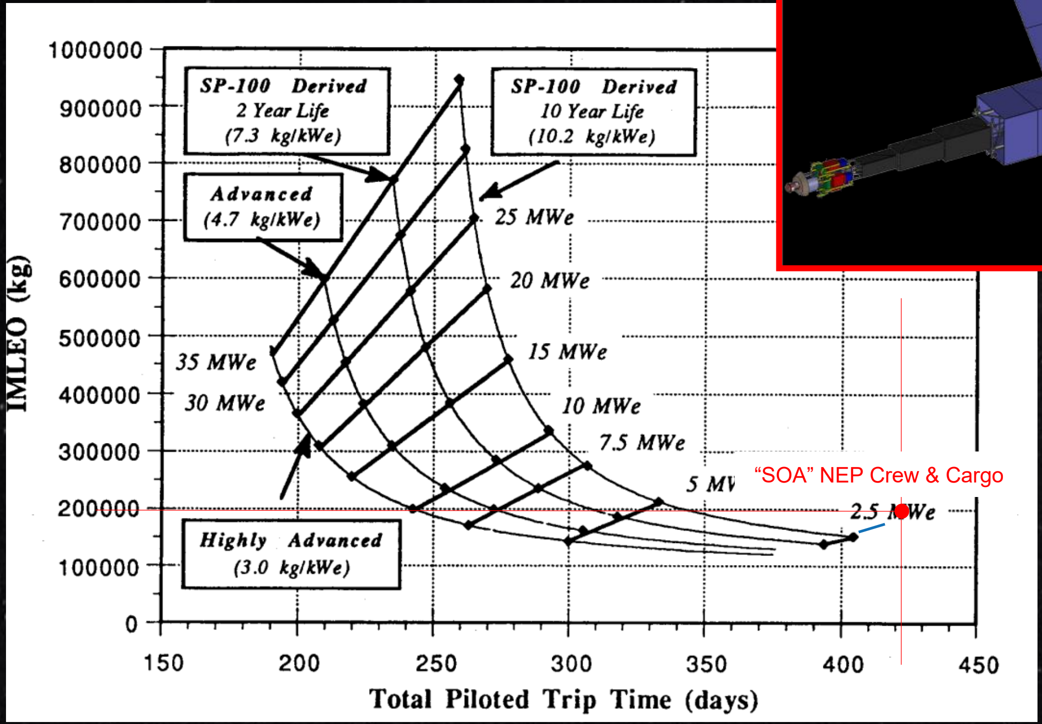
Study: Parametric Mars Transit Calculations
(ca. 1993)

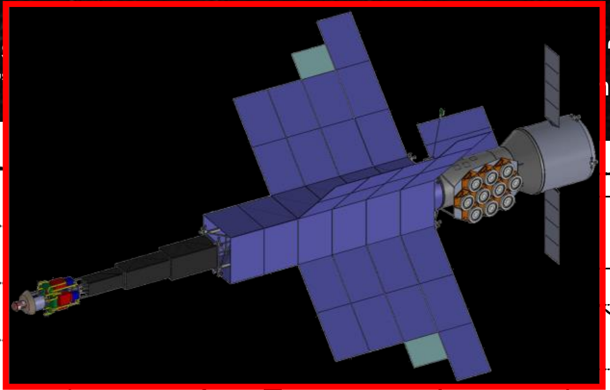
Crewed Missions to Mars Surface with “SOA” 2.5 MW_e Fission NEP (α_T = ~13 kg/kW_e)

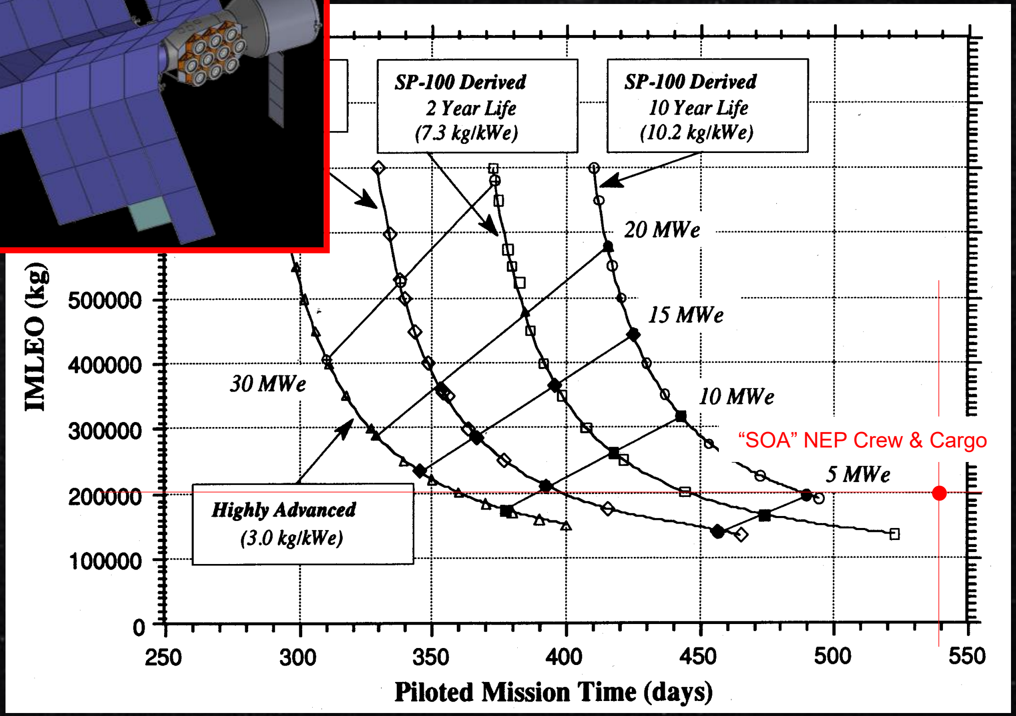
George, Dudzinski, et al, “Piloted Mars Mission Planning: NEP Technology and Power Levels,” Space Technology Applications International Forum (STAIF), Albuquerque, NM, 1993.

Conjunction “Long Stay” Clas
Synthesis Group “America at the Threshold”

“Short Stay” Class (*25 Days on Surface*)
the Human Exploration of the Moon and Mars” 1989







Not including surface stay time
Total crewed duration: ~900 days

“Long Stay”
- Launch Mass = ~400 t
- Piloted transit time = 420 days

Including 25 day surface stay time

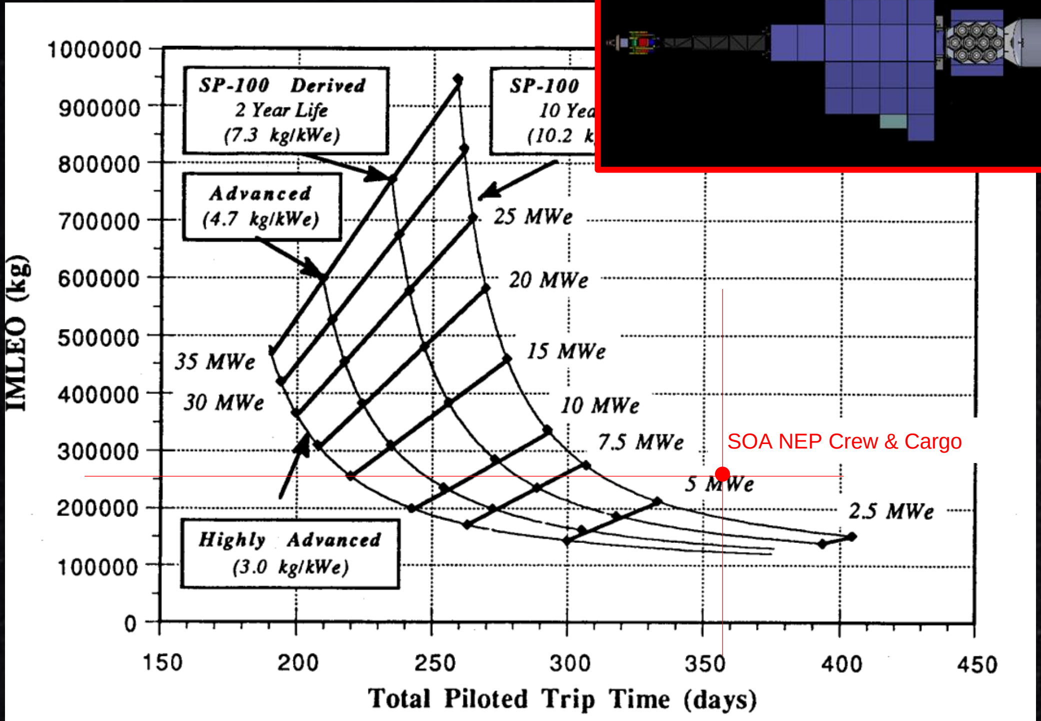
“Short Stay”
- Launch Mass = ~400 t
- Total piloted time = 540 days

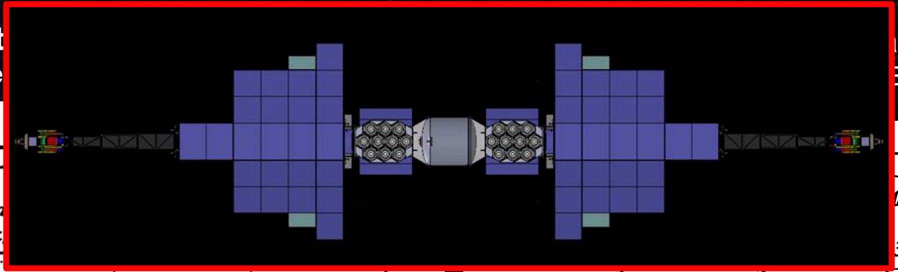
Study: Parametric Mars Transit Calculations
(ca. 1993)

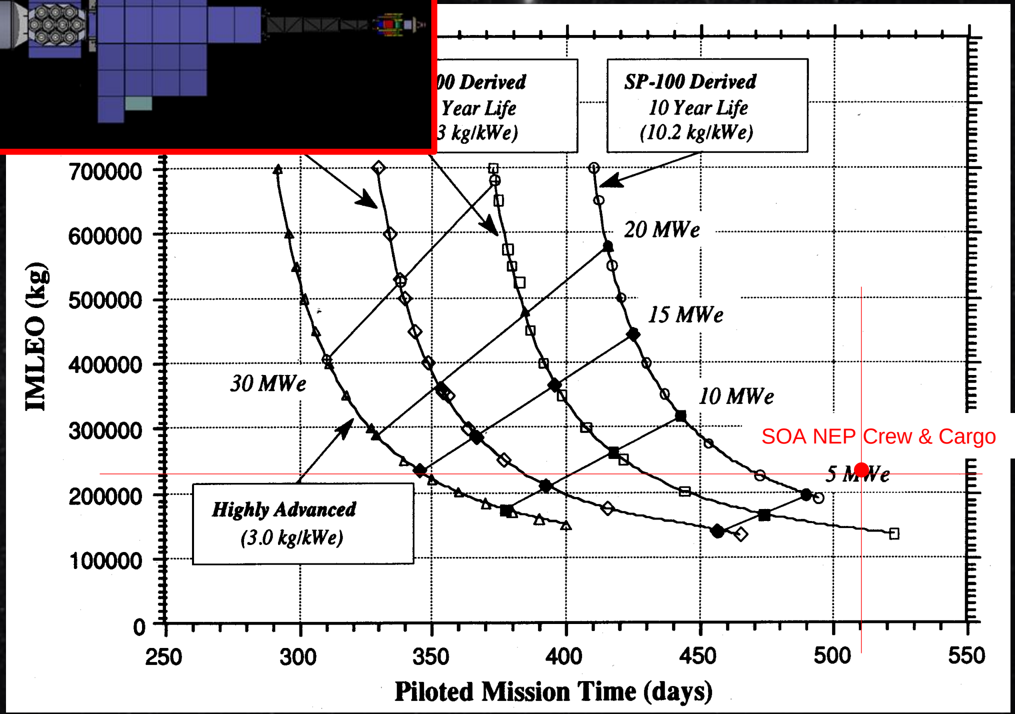
Crewed Missions to Mars Surface with "SOA" 5 MW_e Fission NEP (α_T = ~13 kg/kW_e)

Conjunction "Long St
Synthesis Group "America at the

y" Class (*25 Days on Surface*)
Exploration of the Moon and Mars" 1989







Not including surface stay time
Total crewed duration: ~900 days

"Long Stay"
- Launch Mass = ~500 t
- Piloted transit time = 360 days

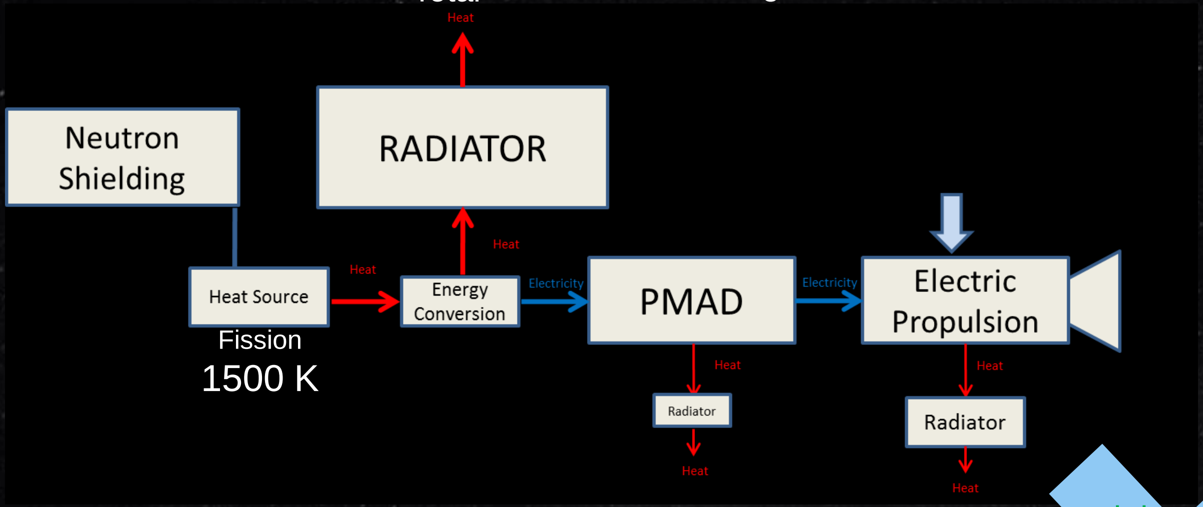
Including 25 day surface stay time

"Short Stay"
- Launch Mass = ~480 t
- Total piloted time = 510 days

“Advanced” Nuclear Electric Propulsion (NEP)

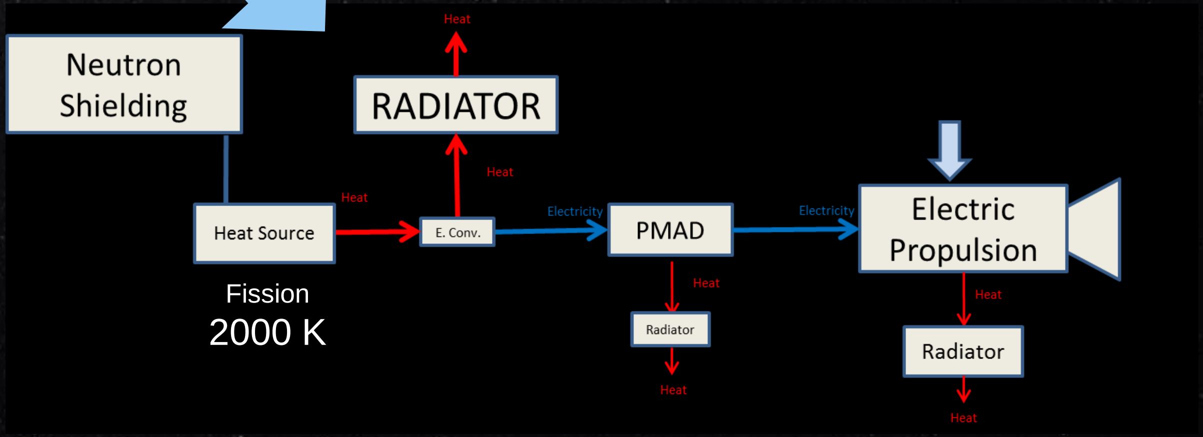
Scott, J., George, J., and Tarditi, A., “Direct Energy Conversion for Low Specific Mass In-Space Power and Propulsion” in Proceedings of Nuclear and Emerging Technologies for Space (NETS 2013), Albuquerque, NM, February 2013

α_{Total} = ~13 kg/kW$_e$



+$$

α_{Total} = **5** kg/kW$_e$



Notional Advanced Solid Core Fission Reactor
TRL < 3

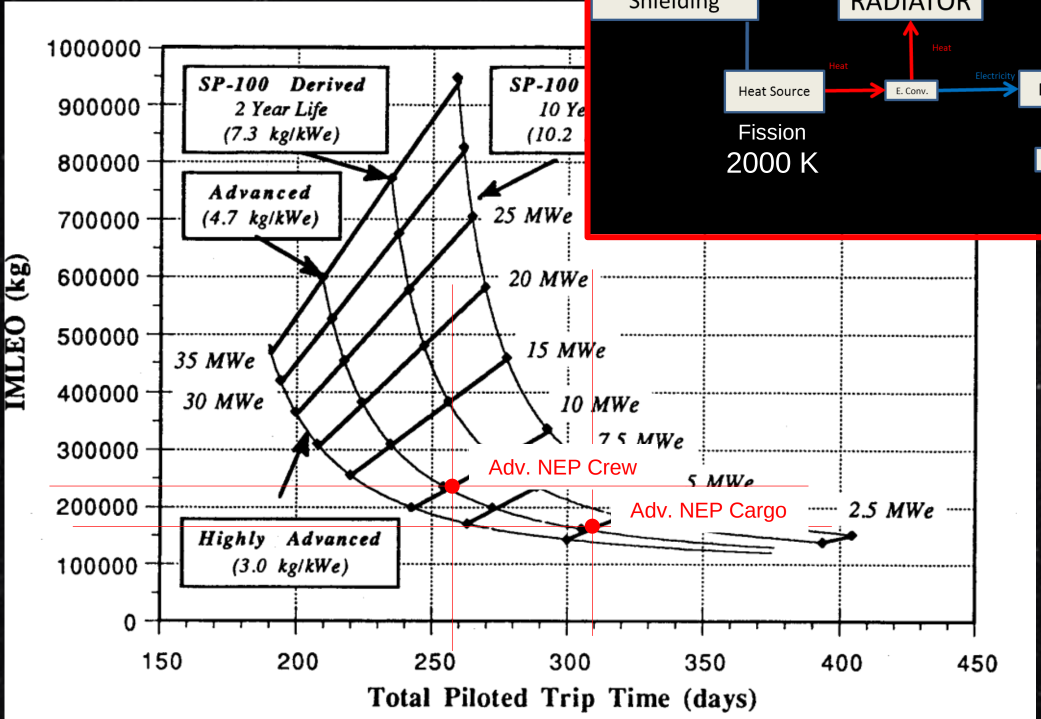
Thermionic or Rankine conversion
Advanced PMAD
T_{top} = 2000 K
T_{rad} = 1500 K

Study: Parametric Mars Transit Calculations
(ca. 1993)

Crewed Missions to Mars Surface with "Advanced" Fission NEP (α_T = ~5 kg/kW$_e$)

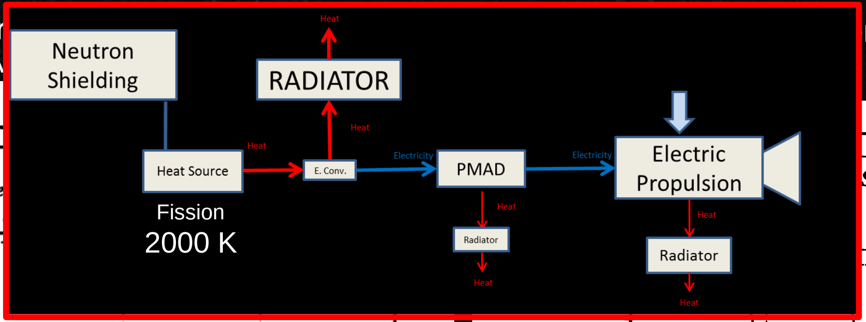
George, Dudzinski, et al, "Piloted Mars Mission Planning: NEP Technology and Power Levels," Space Technology Applications International Forum (STAIF), Albuquerque, NM, 1993.

Conjunction … Synthesis Group "A…

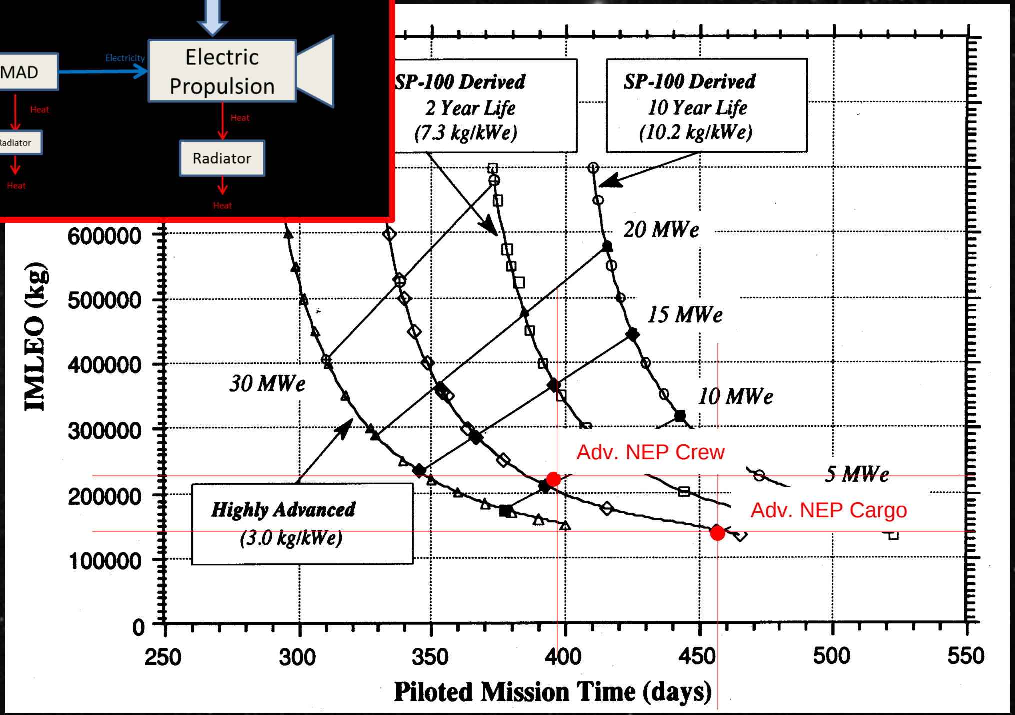


Not including surface stay time
Total crewed duration: ~900 days

"Long Stay"
- Launch Mass = ~400 t
- Piloted transit time = 260 days



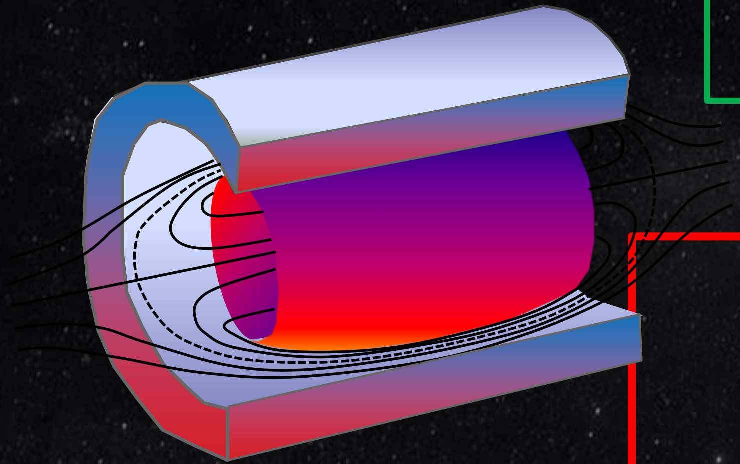
…n **"Short Stay" Class (*25 Days on Surface*)**
…on the Human Exploration of the Moon and Mars" 1989



Including 25 day surface stay time

"Short Stay"
- Launch Mass = ~360 t
- Total piloted time = 400 days

Beyond Fission?



Goals:

Low-α

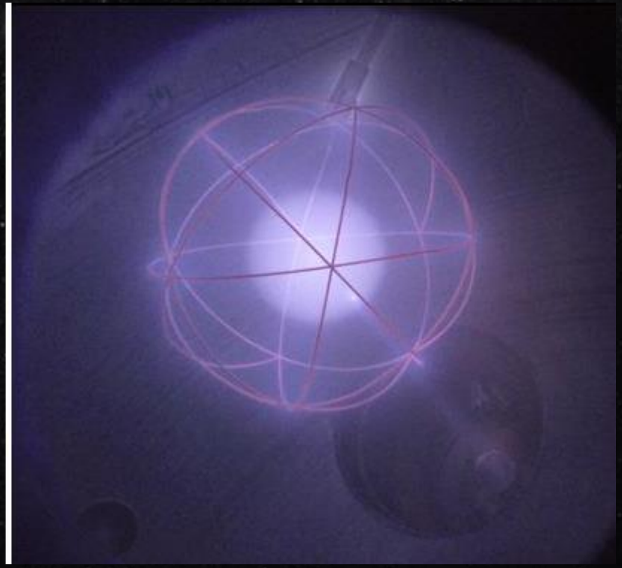
DDT&E cost ~ SEP

Issues:

TRL << 3

Nuclear Physics

Risk of Development Failure



Low-TRL Energy Sources

Example: Aneutronic Fusion Energy Source

Scott, J., George, J., and Tarditi, A., "Direct Energy Conversion for Low Specific Mass In-Space Power and Propulsion" in Proceedings of Nuclear and Emerging Technologies for Space (NETS 2013), Albuquerque, NM, February 2013

Fusion Fuel Pairs (Product Energy)

$D + T = n^0$ (14.07 MeV) + ^4He (3.52 MeV)

$D + D = n^0$ (2.45 MeV) + ^3He (0.82 MeV) (50%)
$D + D = p$ (3.02 MeV) + T (1.01 MeV) (50%)

$D + {^3He} = p$ (14.68 MeV) + ^4He (3.67 MeV)

$p + {^{11}B} = 3\ {^4He}$ (8.7 MeV)

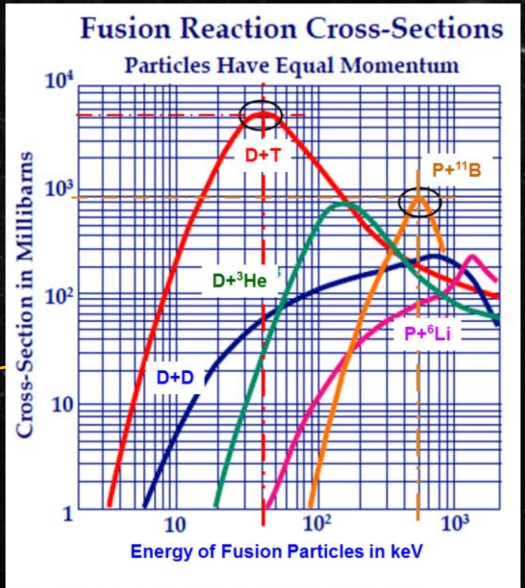
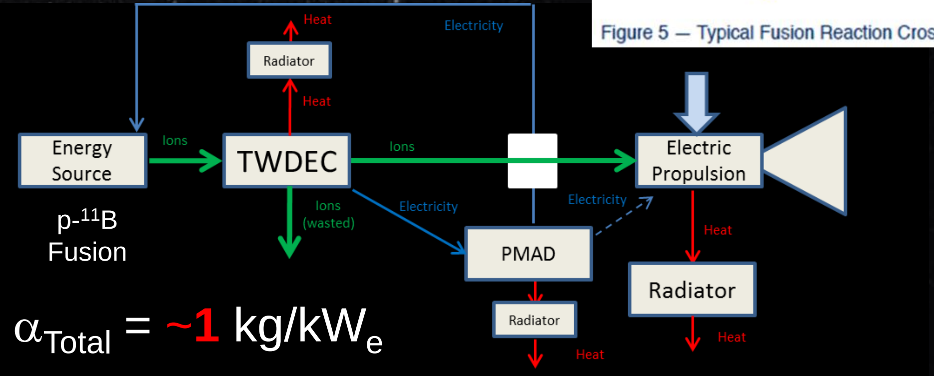


Figure 5 — Typical Fusion Reaction Cross Sections

p-^{11}B Fusion Reactor
TRL << 3

Direct conversion to power
Direct conversion to thrust



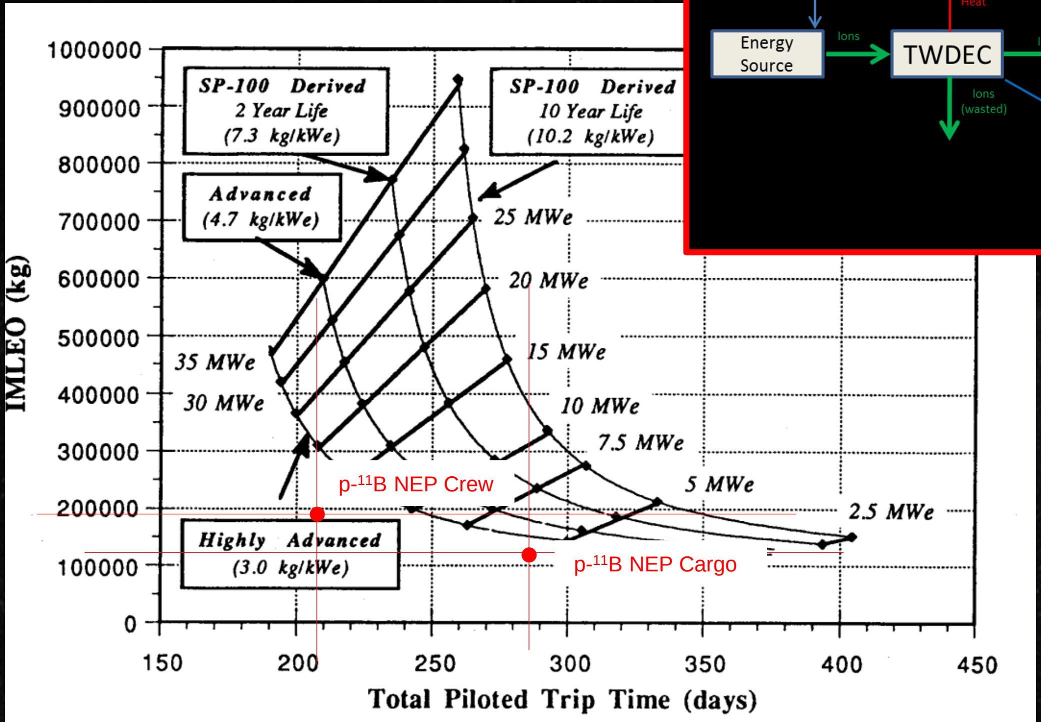
α_{Total} = ~1 kg/kW$_e$

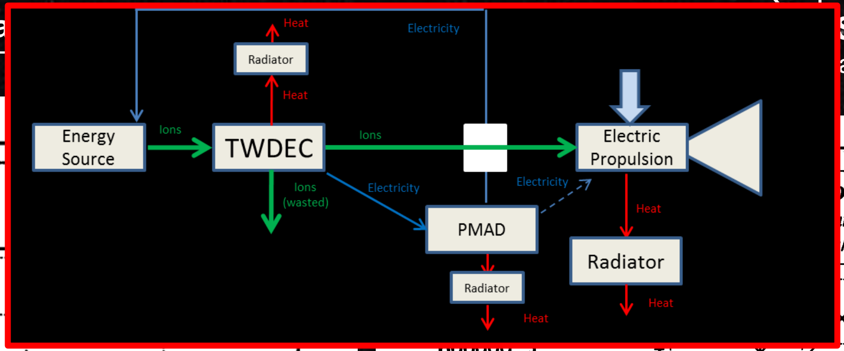
Study: Parametric Mars Transit Calculations
(ca. 1993)

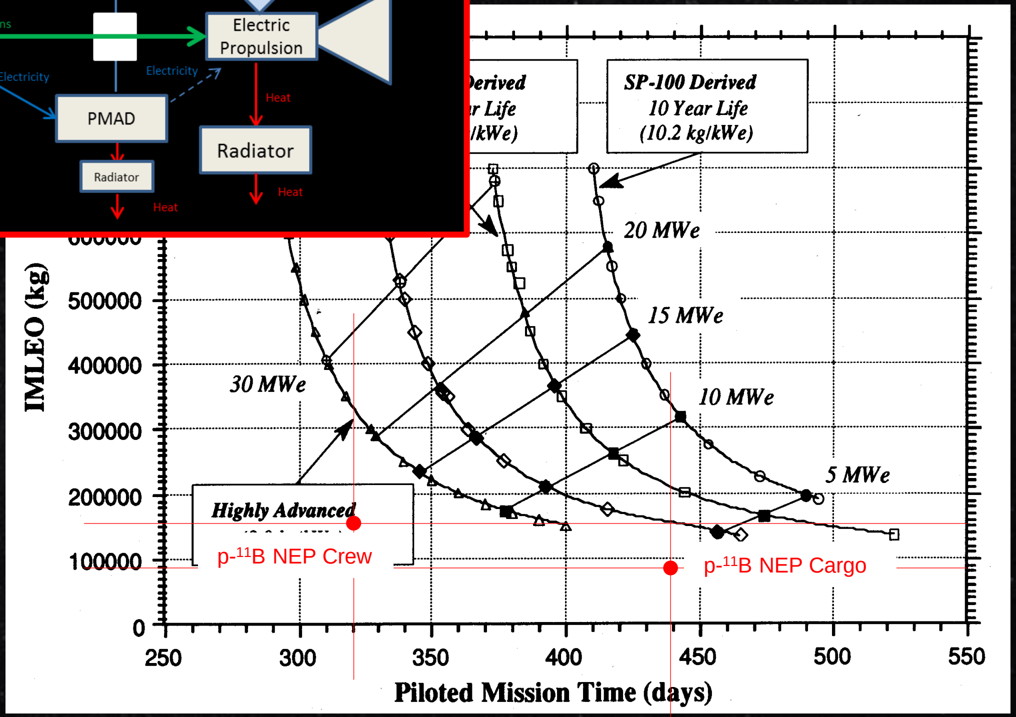
Crewed Missions to Mars Surface with Aneutronic Fusion (α_T = ~1 kg/kW$_e$)

Conjunction "Long Sta
Synthesis Group "America at the

Stay" Class (*25 Days on Surface*)
an Exploration of the Moon and Mars" 1989







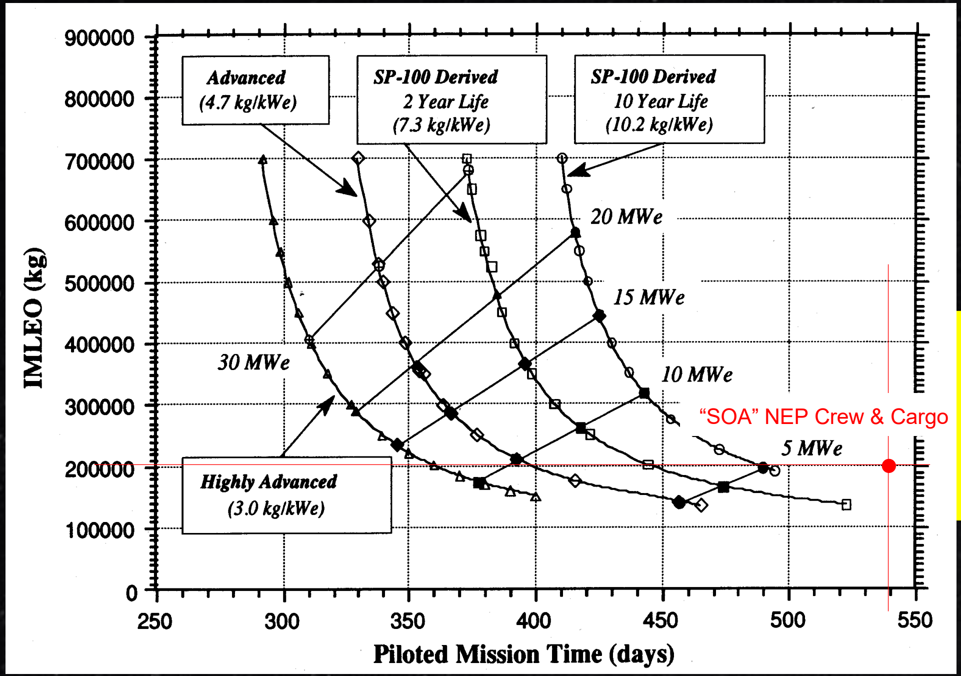
Not including surface stay time
Total crewed duration: ~900 days

Including 25 day surface stay time

"Long Stay"
- Launch Mass = ~330 t
- Piloted transit time = 210 days

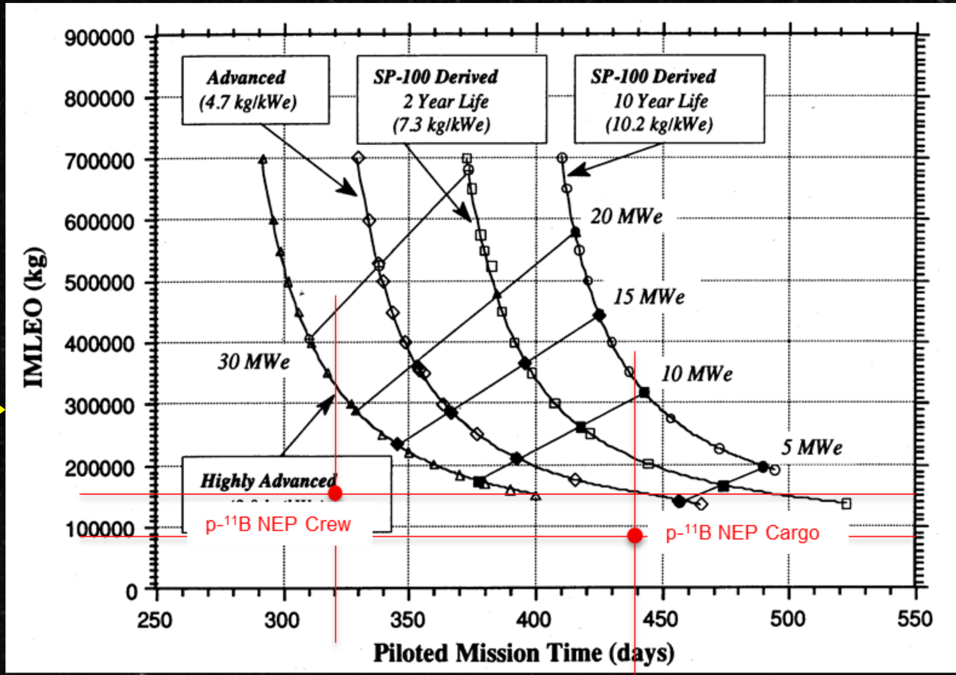
"Short Stay"
- Launch Mass = ~260 t
- Total piloted time = 320 days

More Power for Mars?
Green Power for Earth?



2.5 MW_e power.

- 400 t launched to assembly orbit
- 84 t to descend from Mars orbit
- ~25 day surface stay
- ~550 day mission duration
- *Evolutionary Fission technology*
- *Moderate Technology Risk*
- *Incremental spinoff*



15 MW_e power.

- 260 t launched to assembly orbit
- 84 t to descend from Mars orbit
- ~25 day surface stay
- ~300 day mission duration
- *Advanced fusion technology*
- *High Technology Risk*
- *Disruptive spinoff*