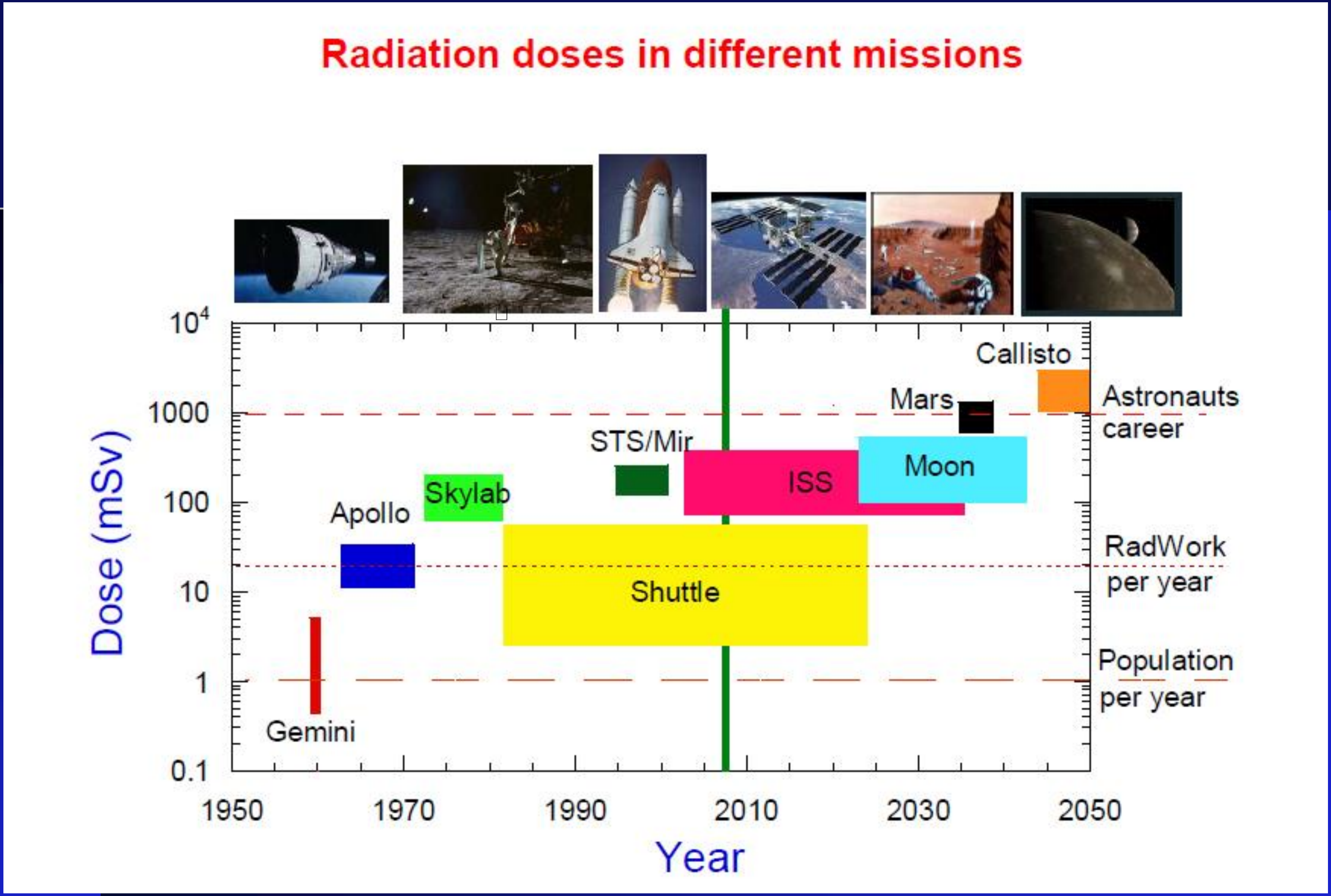
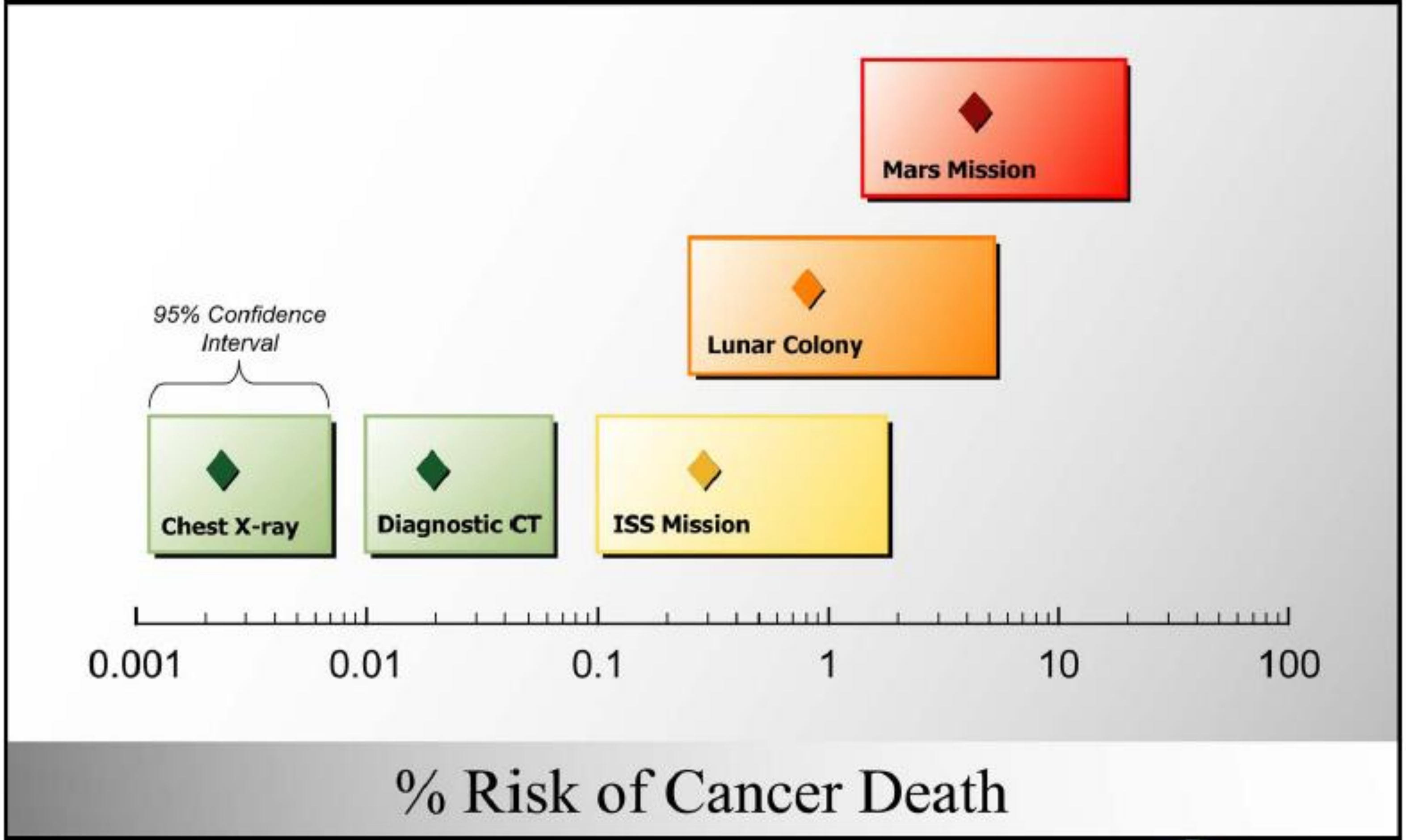
Space Radiation and Propulsion

C. Bruno, University of Rome
HESAC Meeting, November 26 2010
TechBreak Meeting, November 29-30 2010

Part 2 of talk by Durante and Bruno, HESAC #1, September 2010…



…from M. Durante's presentation at HESAC #1, September 2010…
Note bio damage scales as (dose)^2 (Bethe-Block, or Coulomb)



Durante & Cucinotta, *Nature Rev. Cancer* (2008)

SHIELDING

- In space particle flux decreases with shield matter crossed
- Particles are charged and interact with shield electrons
- → exponential attenuation with d_a = mass density/unit area [g/cm^2]

SHIELDING - GCR AND SOLAR

Most bio damage done by heavy ions (high Z), not photons

Shielding → shield thickness = d_a/density

e.g.; on ISS (Al) → d_a = 5 g/sq.cm,

but due to equipment, d_a = 5 to 40

Remember: bio damage ~ $(\text{dose})^2$

MISSIONS – Must reduce dose

- **A key concept:**

- Since dose = (flux) x time,
- and since cannot *in practice* reduce flux,

- try to reduce time of exposure = mission time!
- Conventional missions: → Hohman = boost + coast
- Faster missions: no longer Hohman

MISSIONS - Times must be reduced

Manned: constrained by physical/psychological support

air, victuals

GCR and solar radiation -> dose = flux x time

bone/muscle mass loss

enzymatic changes, …?

Unmanned: public support, apathy @ > 1-2 years: funding difficult

To reduce constraints, risks, and ensure public (financial) support

→ **faster missions !**

MISSIONS – To reduce time: use accelerated orbits

Accelerated travel makes tremendous difference in time to destination

But: mass consumption forbiddingly high with conventional propulsion

e.g.: mission to Neptune, Isp = 459 s:

Acceleration [g]	**1/100**	**1/10,000**	**Boost-coast**
Distance [mi]	**4.05E+09**	**4.05E+09**	**4.05E+09**
1/2 dist [mi]	**2.02E+09**	**2.02E+09**	**2.02E+09**
Time [yr]	**0.258**	**2.582**	**11.284**
Time [days]	**94.31**	**943.14**	**4,121**
$V_{1/2}$ [km/s]	**799.13**	**79.91**	**18.29**
$V_{1/2}$ /c [% of c]	**0.43%**	**0.043%**	**0.010%**
$WR_{1/2}$	**7.52E+77**	**1.25E+07**	**10.28**

MISSIONS - Transit time as a function of Isp

At a = 10^{-2}g, trip is fast, but: mass ratio is significant.

What compromises between mass ratio and time ?

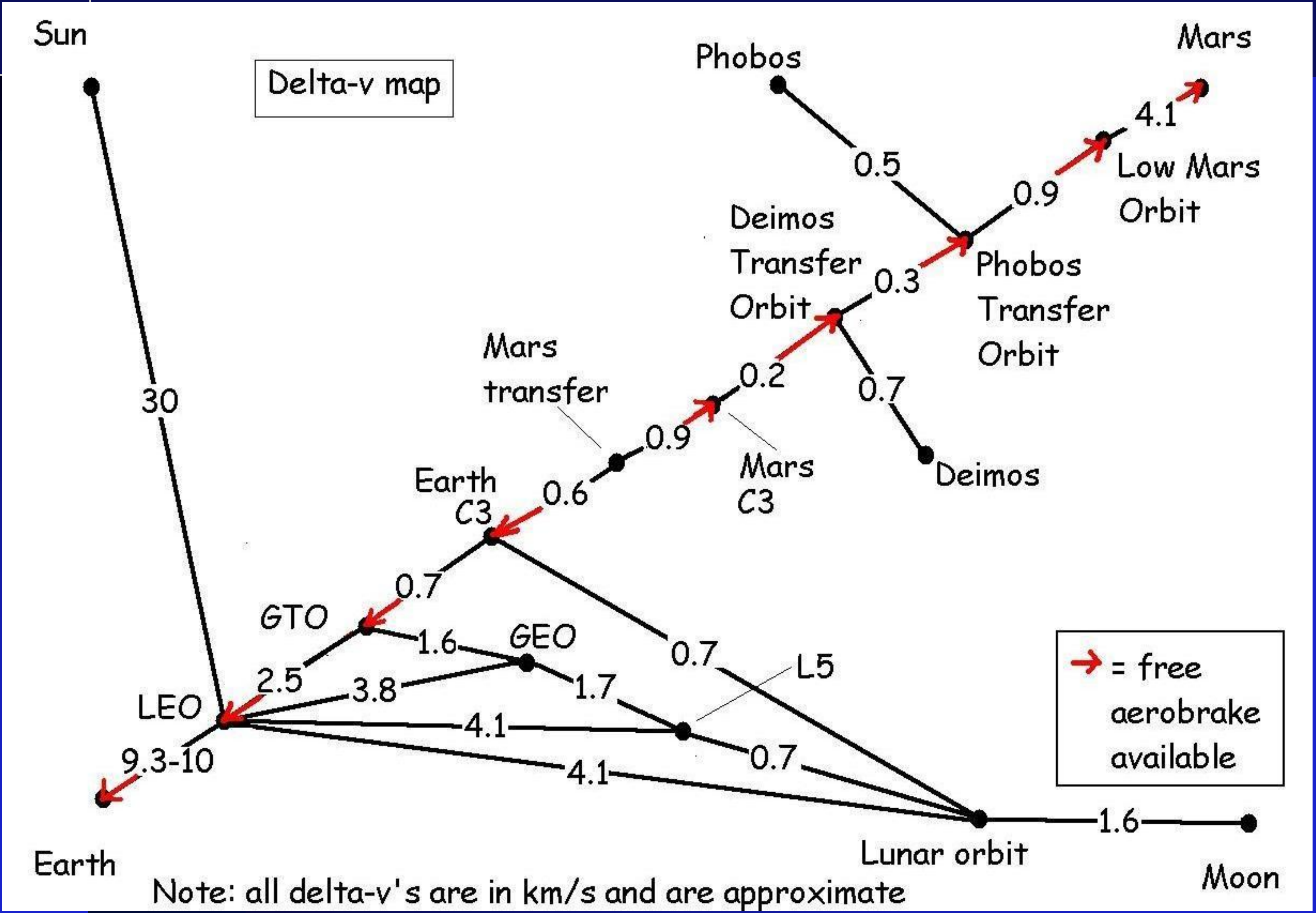
Nuclear propulsion looks feasible if Isp can be raised:

Isp (sec)	459	1,100	4,590
WR	**10.70**	**7.23**	**3.38**
Jupiter	**2.69**	**1.70**	**0.793**
Saturn	**4.92**	**3.12**	**1.45**
Uranus	**8.14**	**5.16**	**2.40**
Neptune	**11.15**	**7.07**	**3.29**
Pluto	**13.75**	**8.72**	**4.06**
Kuiper Belt	**16.29**	**10.34**	**4.81**
Heliopause	**27.86**	**17.67**	**8.22**

Increasing Isp Reduces Transit Time [**years**] and Weight Ratio

At fixed mass, higher Isp enables bigger Δ(V) and faster travel!

MISSIONS – Hohman ΔV



Note: all delta-v's are in km/s and are approximate

Some fundamentals of propulsion

- Key concepts:

- Newton's 3rd Law: eject mass m at v= Ve to create thrust T
- Newton's 2nd Law: increase T to shorten trips

- To increase T : better to increase Ve, not m!

- For no losses: Ve coincides with engineers' Isp = T/(dm/dt)

Some fundamentals of propulsion

- Thus:
- dm/dt = flowrate ~ Ve
- Thrust T ~ (dm/dt) Ve ~ $(Ve)^2$
- Power ~ T Ve ~ $(Ve)^3$
- To reduce transit time: raise T → need to raise Ve!
- But: Power will grow faster…

Some fundamentals of propulsion

How to increase Ve… or T, ~ $(Ve)^2$ ~ Kinetic Energy, KE

- To produce KE, must have Potential Energy PE: PE + KE = Constant
- Not all PE may become KE → only a fraction $\alpha < 1$:

α depends on fundamental force (gravitation, electroweak, nuclear)

$$\alpha PE = KE$$

- 1-D, classical: $\alpha PE = \frac{1}{2} m Ve^2$
- therefore $Ve = (2\,\alpha PE/m)^{1/2}$ **PE/m = J, energy density**
- ‣ thus: to increase Ve → increase J
- ‣ to increase Ve **substantially → raise J " more substantially "!**

Some fundamentals of propulsion

In summary:

- Ve rules dm/dt, thus mass to orbit and cost
- $(Ve)^2$ rules Thrust T, thus mission time
- $(Ve)^3$ rules Power P, thus size of engine
- With chemistry, P depends on the 2nd force, ~ dm(propellants)/dt
- With nuclear energy P depends on 3rd force, ~ dm(nuclear fuel)/dt

- ▸ **Ve rules everything and must be raised as much as**
- **feasible**

Propulsion - Einstein's Equation

Potential Energy $\equiv$ PE = (mass) c^2

Kinetic Energy $\equiv$ KE = Δ(PE) = α PE

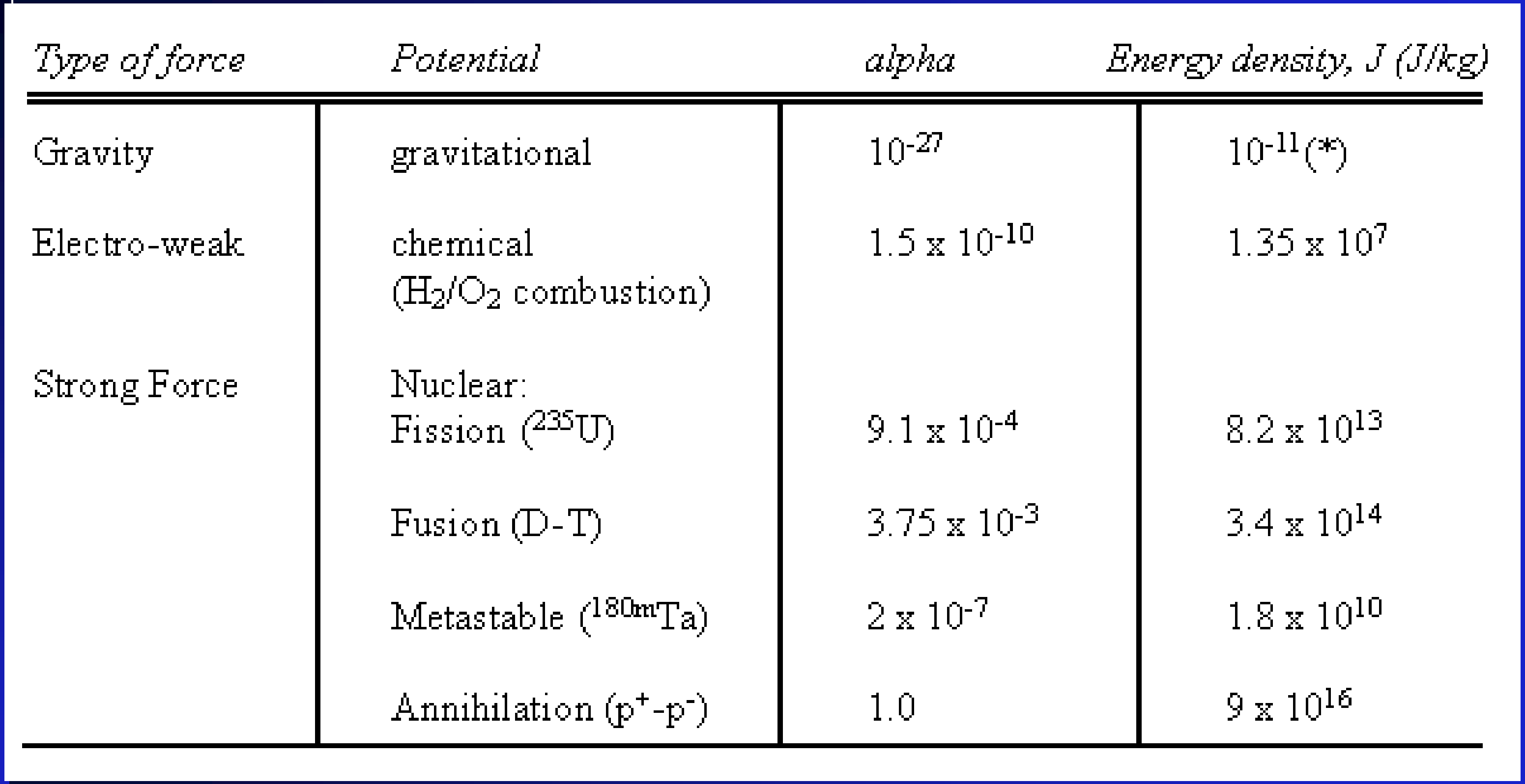
= $\Delta(mc^2)$

= $\alpha\, \Delta(mc^2)$

- α depends on the type of fundamental force!

Propulsion: Forces, Potential Energy and α

Compare α and J from fundamental physics:



Type of force	*Potential*	*alpha*	*Energy density, J (J/kg)*
Gravity	gravitational	10^{-27}	10^{-11} (*)
Electro-weak	chemical (H_2/O_2 combustion)	1.5×10^{-10}	1.35×10^{7}
Strong Force	Nuclear:		
	Fission (^{235}U)	9.1×10^{-4}	8.2×10^{13}
	Fusion (D-T)	3.75×10^{-3}	3.4×10^{14}
	Metastable (^{180m}Ta)	2×10^{-7}	1.8×10^{10}
	Annihilation (p^+-p^-)	1.0	9×10^{16}

* ***Between two 1kg-masses at 1 m distance***

- No known α between 3.75×10^{-3} and 1
- Even α = 1 produces not directly useable energy (e.g., γ rays)

MISSIONS - Energy Density J with Chemical Propellants

Are there any high-energy propellants alternatives to LOX/LH2?

The Holy Grail is…

…metallic Hydrogen → theoretical J ten times higher than LOx/H_2 …
existence, stability, control → unsolved issues...

…and Ve (Isp) goes up only by $(2J)^{1/2}$ → Isp ~ 1700s

→ Must increase J by orders of magnitude → Nuclear energy

Propulsion: nuclear energy

- The highest α: → nuclear force:
- J of order of 10^{13} [j/kg]
- J of LOx/LH_2 : 10^7 [j/kg] !

Nothing can beat the J (and Ve) of nuclear energy

Nuclear Propulsion: Ve from Special Relativity

Calculate Isp:

- Assume ideal expansion (to pe=0): Isp = V_e ≡ V (for short)
- Obtaining Ve is a 3-stage process:

Possible addition of inert mass, Mp

Pot. Energy → Microenergy of matter → Thermalization → Orderly bulk motion

(e.g., Vibr., Transl., Ionization, n, e^-, α^+)

(equilibrium)

at V = Ve

- V from relativistic energy balance: $m_o c^2 = (1-\alpha) m_o c^2 + \frac{1}{2}\frac{m_o(1-\alpha)V^2}{\sqrt{1-\frac{V^2}{c^2}}} + \frac{1}{2}\frac{Mp_o V^2}{\sqrt{1-\frac{V^2}{c^2}}}$

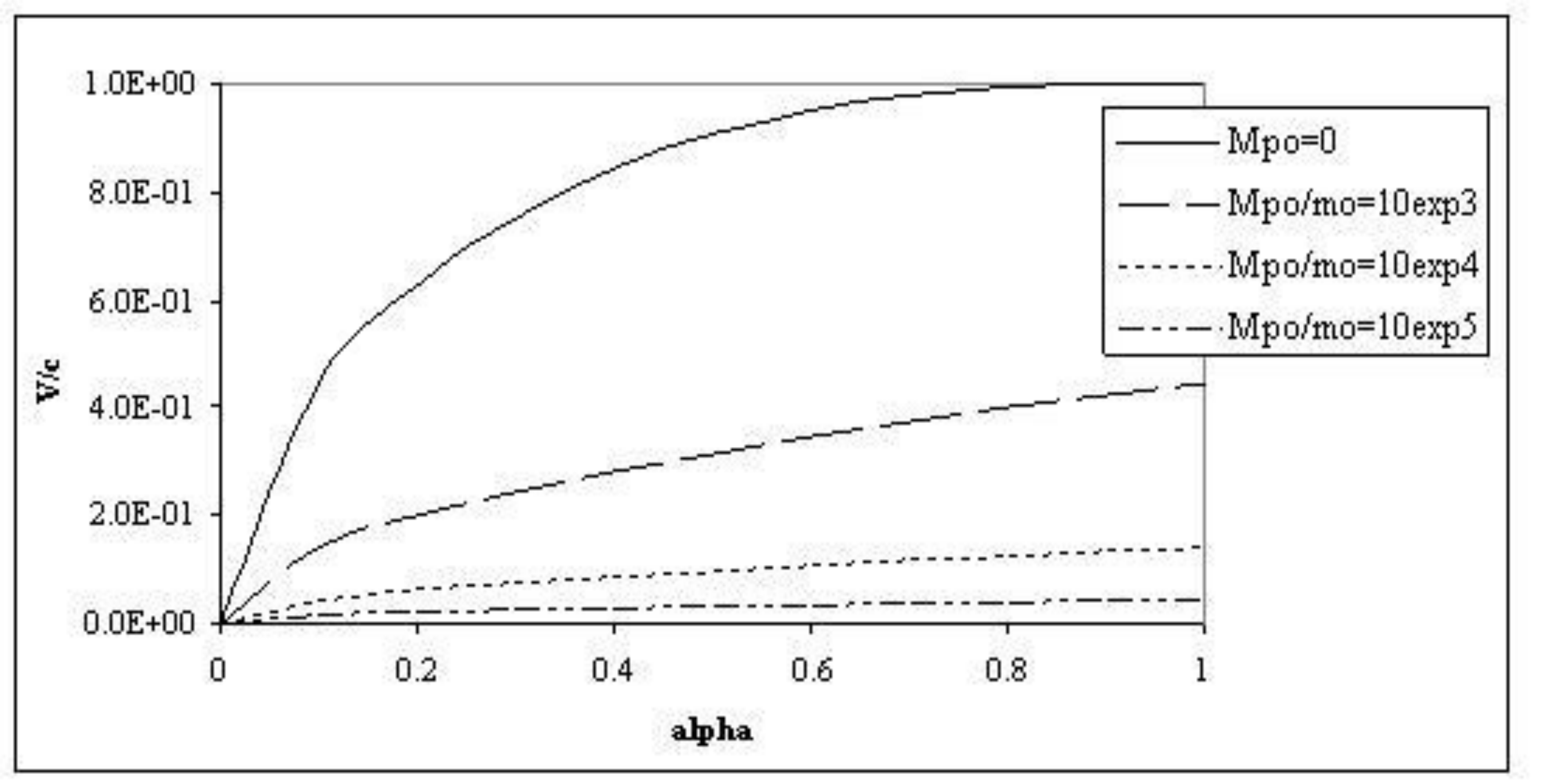
Plot normalized specific impulse, Isp/c = V/c = Ve/c:

NOTE:

m_0 = fission fuel mass at rest

M = added inert propellant, e.g., H2

Nuclear Propulsion - Isp as a function of α and added inert



Isp/c is a function of α:
limit Isp = speed of light !

Nuclear Propulsion - Thrust F

- Satisfies both
  - ✓ $F \cdot Isp = P$, thrust power = $\eta_{tot} \times P_{reactor}$
  - ✓ $F = Isp \cdot \dot{m}$ (m = total mass rate ejected)
- $F = (P \cdot \dot{m})^{1/2}$ grows slowly with P_R,

~ reactor cost

- Thus, in terms of inert mass addition, or μ

$$F = \sqrt{\alpha} \cdot \dot{m}_0 \cdot c \cdot \sqrt{\eta_{tot}} \cdot \left[z \cdot (1-\alpha) \Big/ \sqrt{1-(V/c)^2} + \mu \Big/ \sqrt{1-(V/c)^2} \right]^{1/2}$$

Where z: = 1 : unreacted fuel also ejected
= 0 : unreacted fuel stays inside reactor

- generally F □ $\sqrt{\mu}$; if only fission/fusion fragments are ejected, $\mu = 0$
- Thrust may be written $F = \sqrt{\alpha} \cdot \dot{m}_0 \cdot c \cdot \sqrt{\eta_{tot}} \cdot \Phi\left(z, \alpha, \mu, \frac{V}{c} \right)$

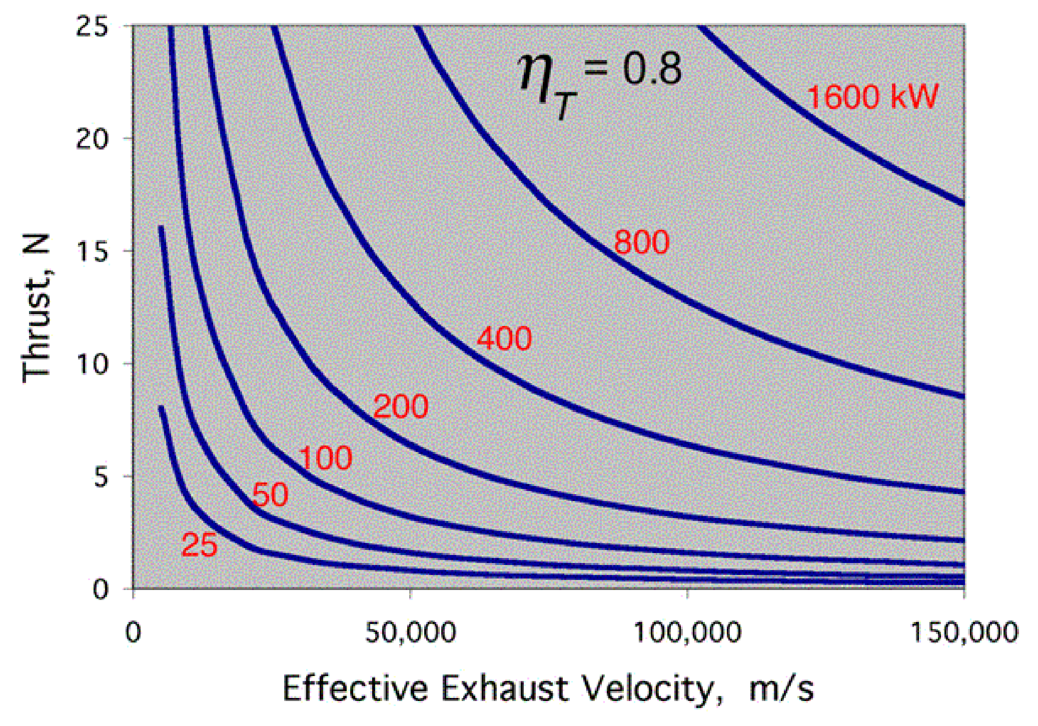
Limit thrust

Amplification factor

Nuclear Propulsion Thrust Power P

Look at the
power needed by F:

$$P = (\rho_e A_e)\cdot c^3 \left[f^3 \big/ \sqrt{1\text{-}f^2} \right]$$



- ➢ **Note Trade off between F and Isp**

- ➢ P scales as F · Isp = F · V = V^3 [ideally, Ve = Isp]

- ➢ P scales with Isp^3: ‘high’ thrust (‘fast’) missions need ‘much larger’ P, → nuclear power

Nuclear Propulsion - How to exploit Nuclear Power

Most of what said applies to thermal exploitation. But power may be used differently…

Two strategies:

NTR (Nuclear Thermal Rockets): expand hot fluid, as in chemical rockets.

E.g., with H_2 and max T = 3000K → Isp ~ 1000 s, thermal efficiency ≈ 1 (all heat absorbed by H_2).

Bulk power density ~ 10^{-3} to 10^{-1} kg/kW. NTR may be very compact, e.g., with ^{242}Am fuel, 40 MW from a 300-kg reactor are feasible.

NER/NEP (Nuclear Electric Rocket/Propulsion): run hot fluid in a cycle to generate electric power and feed it to an electric thruster (ET), f.i., ion, arcjet, MPD,…

Isp is that of ET: may be ~ 10^5 – 10^6 s and higher.

Thermal efficiency: 30-50%; ET efficiency: 70-80%; needs space radiator(s).

Bulk power density: low, ~ 1/100 of that of NTR

Nuclear Propulsion - Application Strategies

Schematics of NTR – Nuclear Thermal Rocket

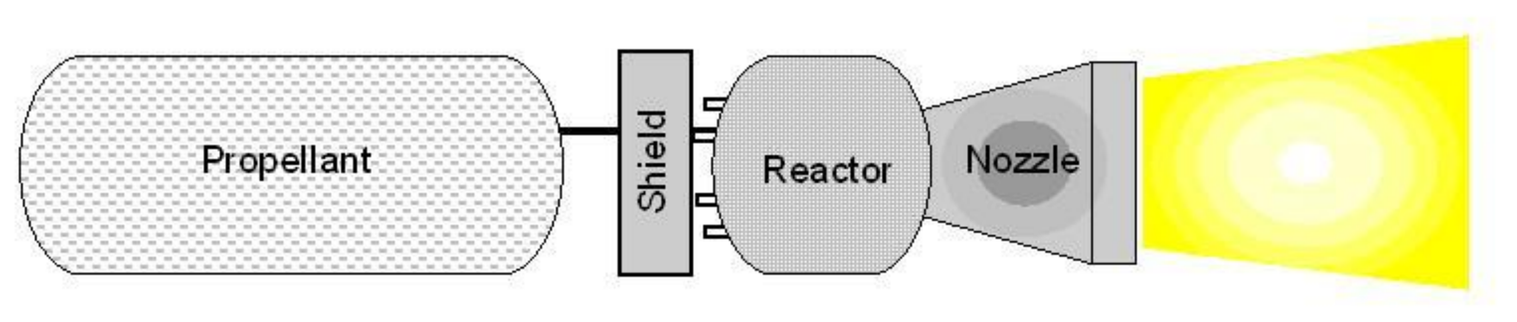


Figure 7-6: *Conceptual scheme of a Nuclear Thermal Rocket (Bond, 2002)*

Nuclear Propulsion - Application Strategies

Schematics of NER – Nuclear Electric Rocket

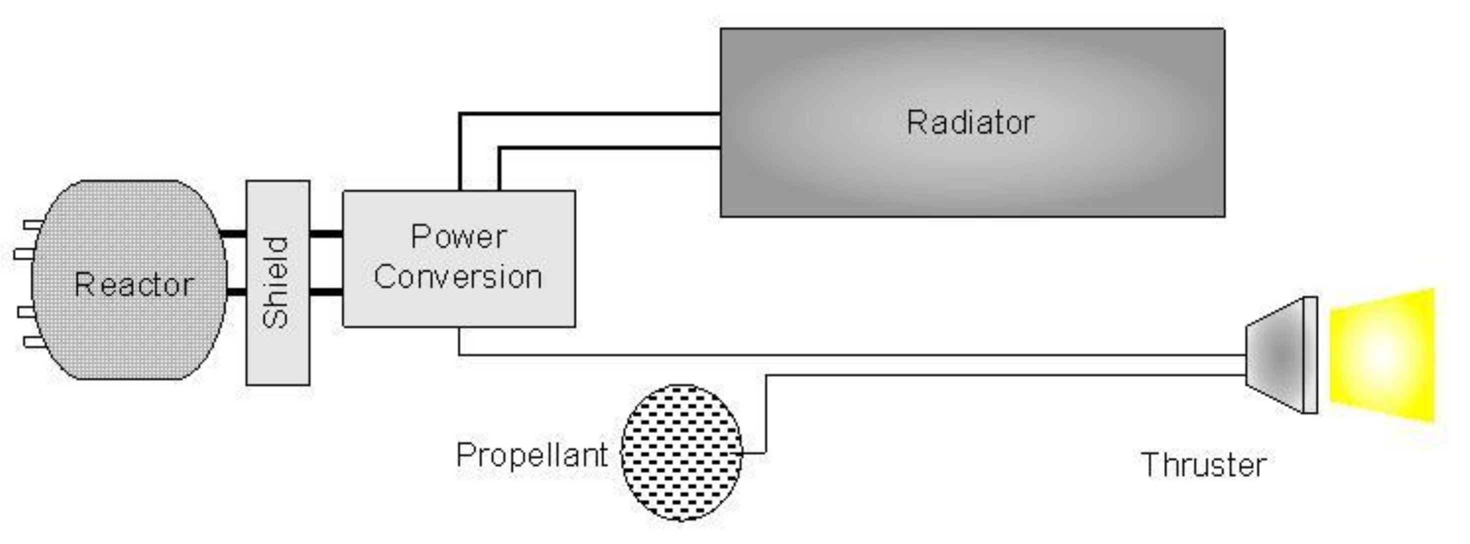
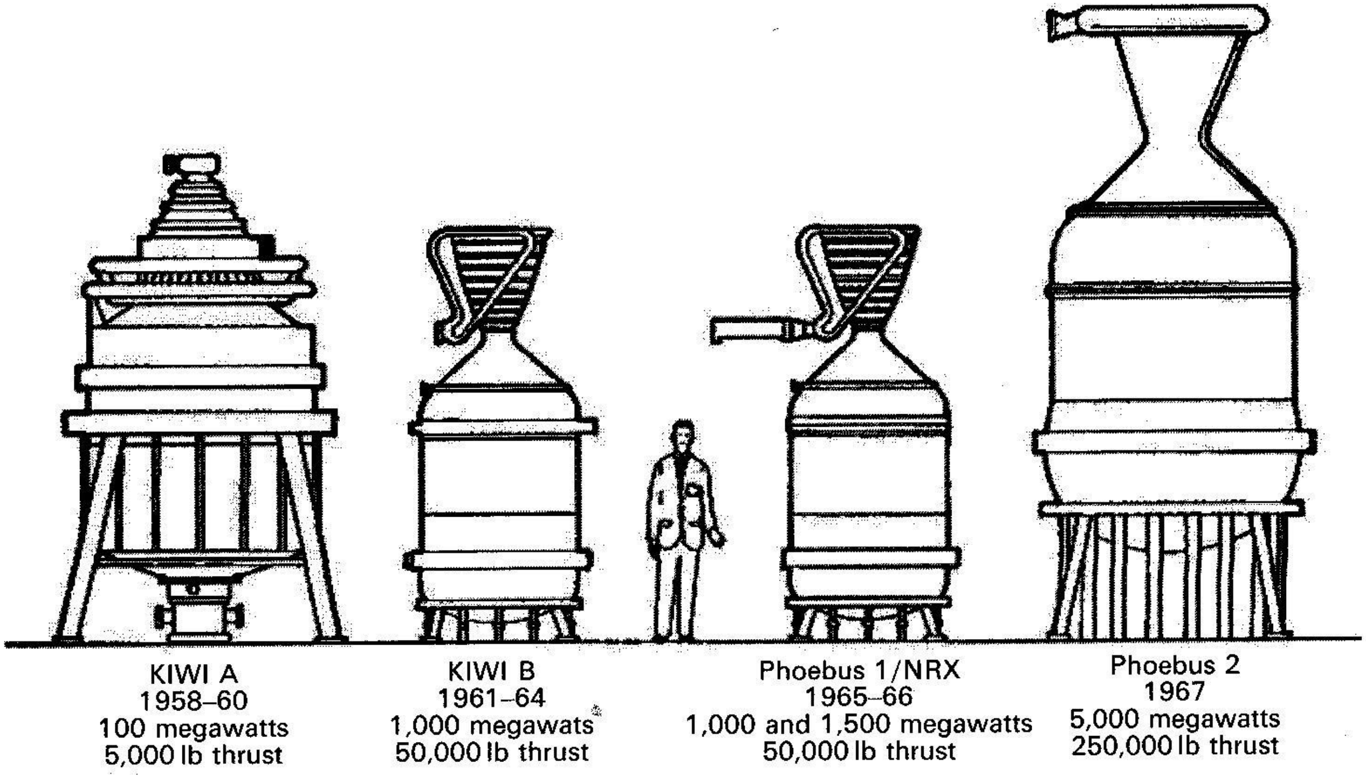


Figure 7-7: *Conceptual scheme of a Nuclear-Electric Rocket. Note the mandatory radiator (Bond, 2002)*

Nuclear Propulsion - NTR Applications

NTR – US Developments (1954-1972)



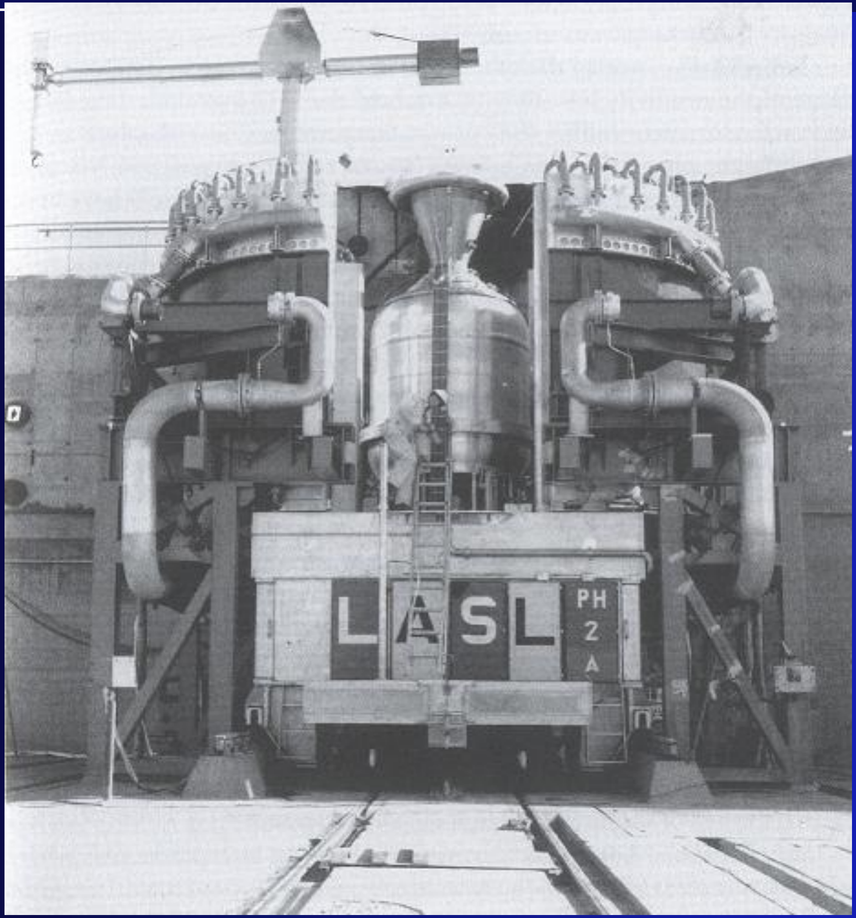
The NERVA family of engines.

Courtesy NASA.

[M.Turner, "Rocket and Spacecraft Propulsion", 2005]

Nuclear Propulsion - NTR Applications

NTR – US Developments (1954-1972)



The Phoebus IIA solid-core nuclear reactor on its Los Alamos test stand (Dewar, 2004). Reactor was tested at 4.2 GW for 12 min.

Nuclear Propulsion - Application Strategies

Nuclear propulsion strategies:

Nuclear Electric Propulsion

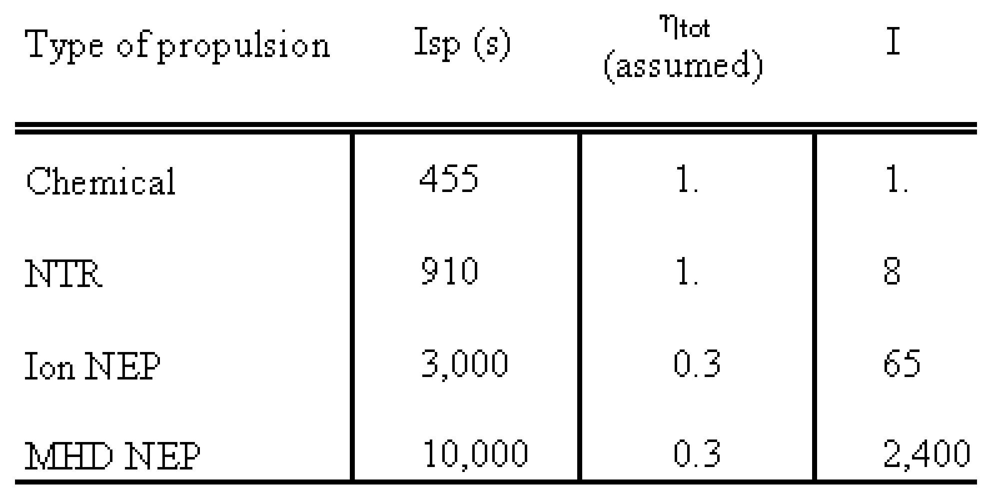
Two main NEP classes: charged species accelerated by:

- ☐ Coulomb Force (only electric field imposed)
- ☐ Lorentz' forces (electric and magnetic field)

Nuclear Propulsion - Comparisons

- Must set ground rules (otherwise, ‘apples & pears’)
- Here: based on $I_{tot,s} = (I_{sp}\ t_{operation})/(M_P + m) \sim Isp^3\ \eta_{tot}/P_{Reactor}$

  $I_{tot,s}$ is a distance traveled/unit ‘fuel’ mass, as in cars
- Normalize $I_{tot,s}$ using $I_{tot,s}$ of LOX/LH_2 : this ratio is the ‘performance Index, I’ :

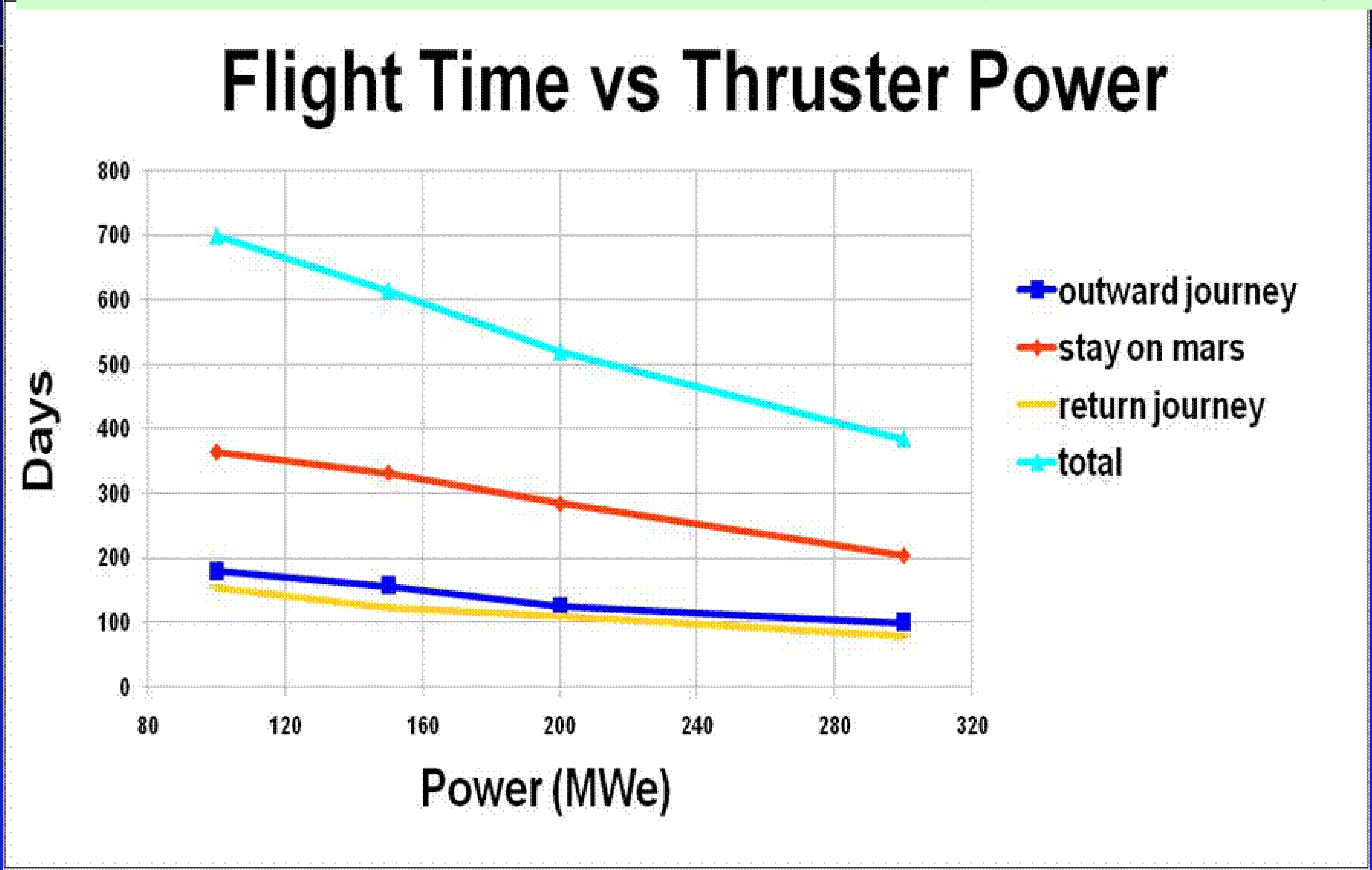


Type of propulsion	Isp (s)	η_{tot} (assumed)	I
Chemical	455	1.	1.
NTR	910	1.	8
Ion NEP	3,000	0.3	65
MHD NEP	10,000	0.3	2,400

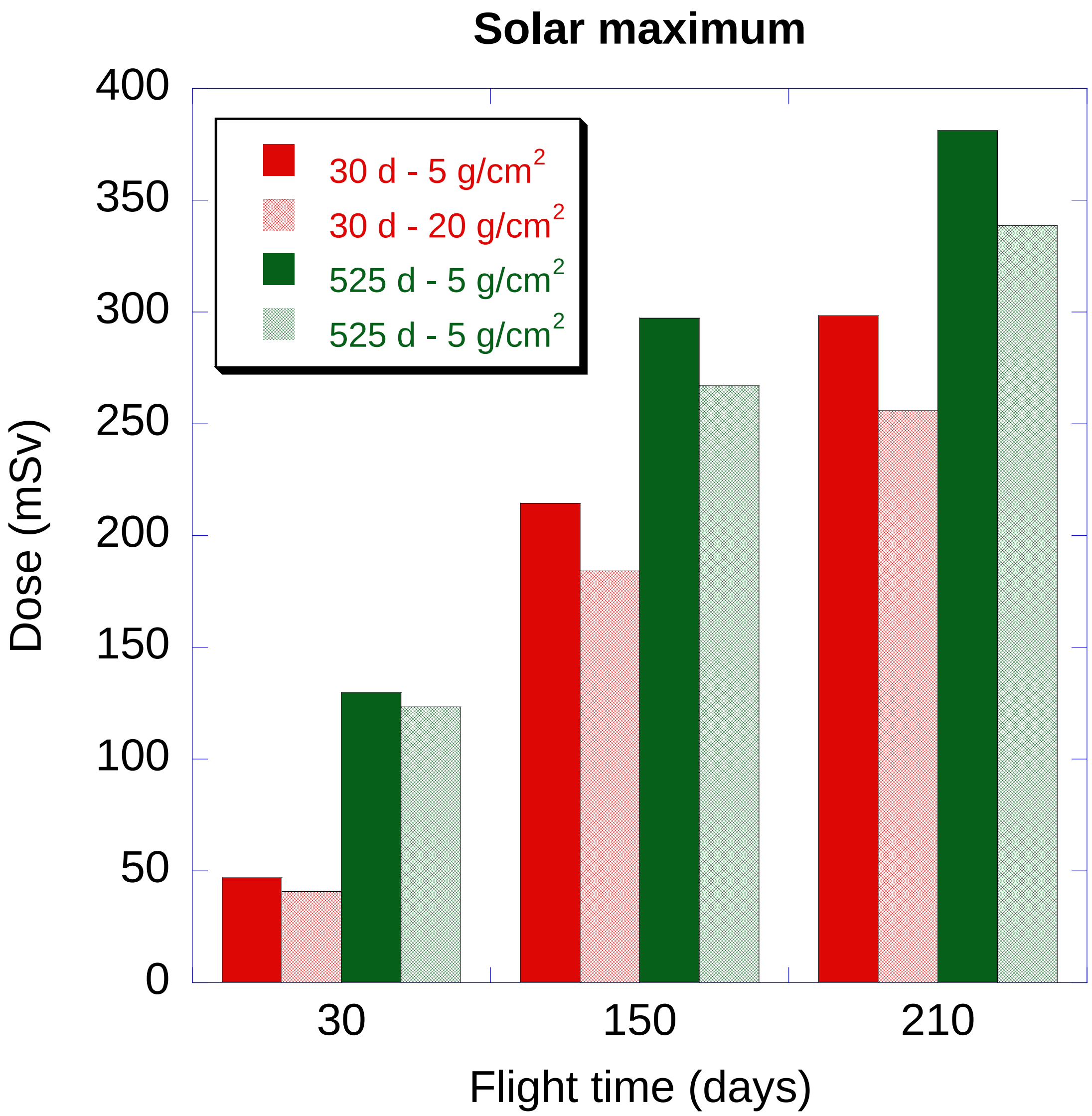
NEP: Apply to Manned Mars Mission (M3):

Travel Time vs. Power

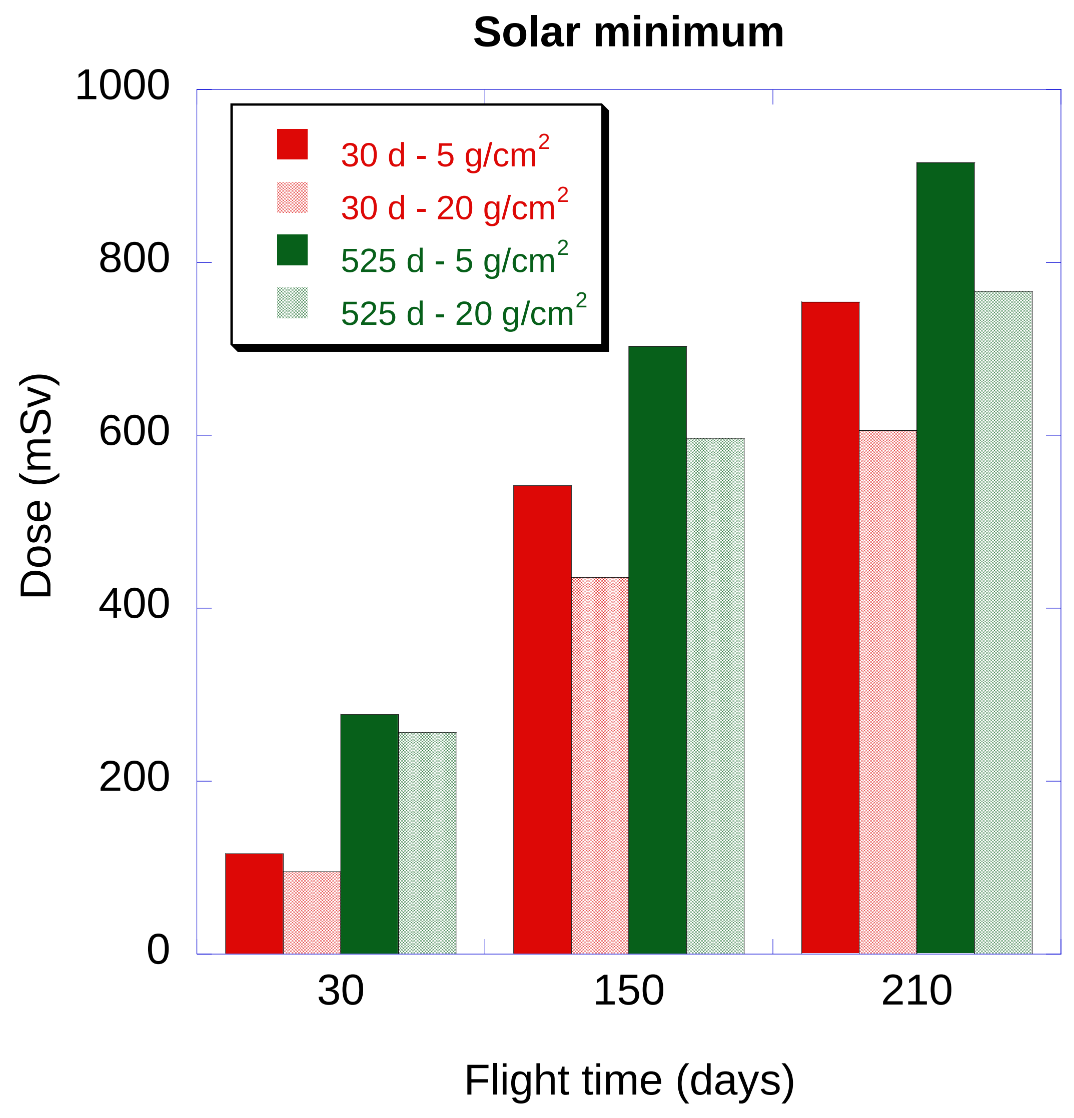
(Bruno et al, IAC 2009)



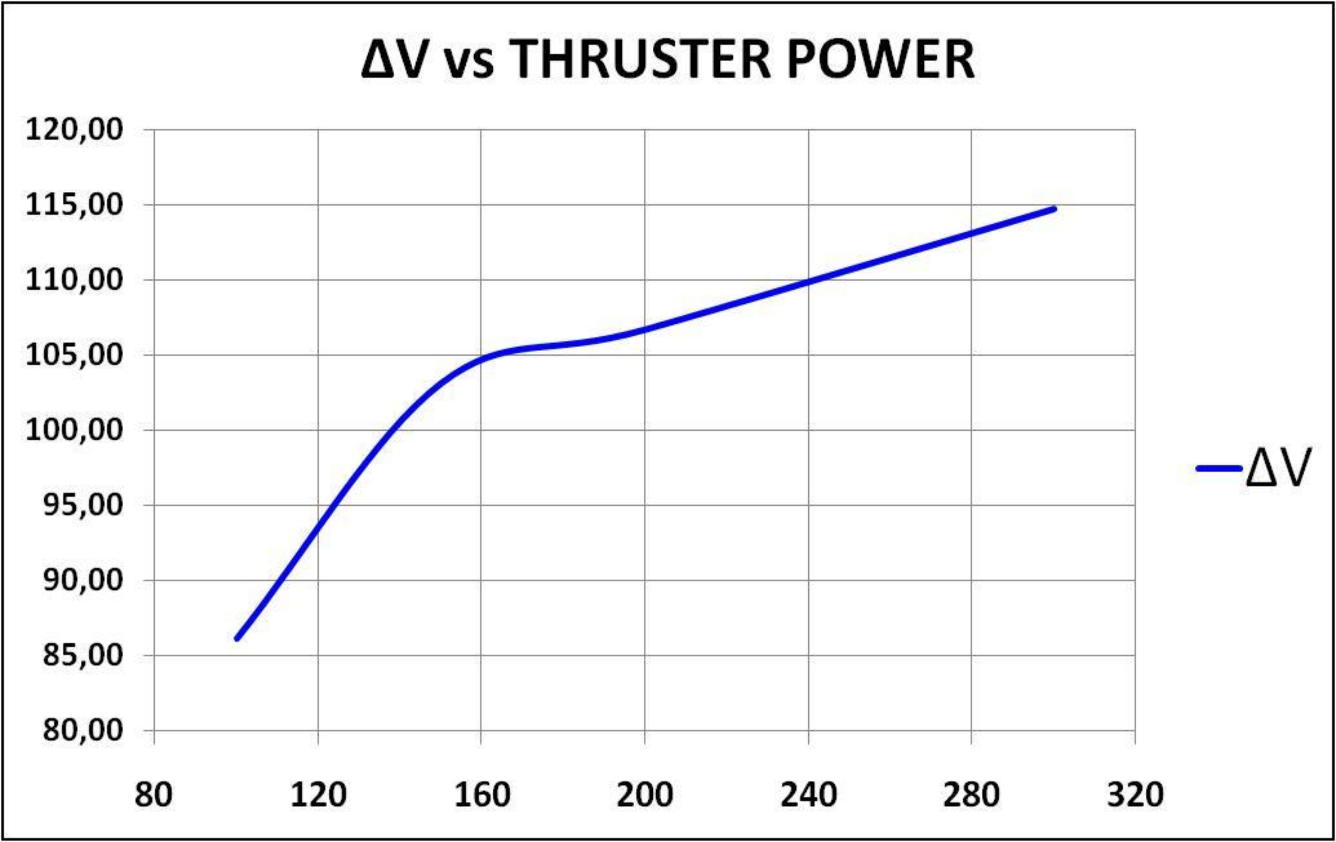
(M3) – Dose vs. Time and Shield *[Durante & Bruno 2010]*



(M3) - Dose vs. Time and Shield



NEP: Apply to Manned Mars Mission (M3):
Delta V versus Power



NEP

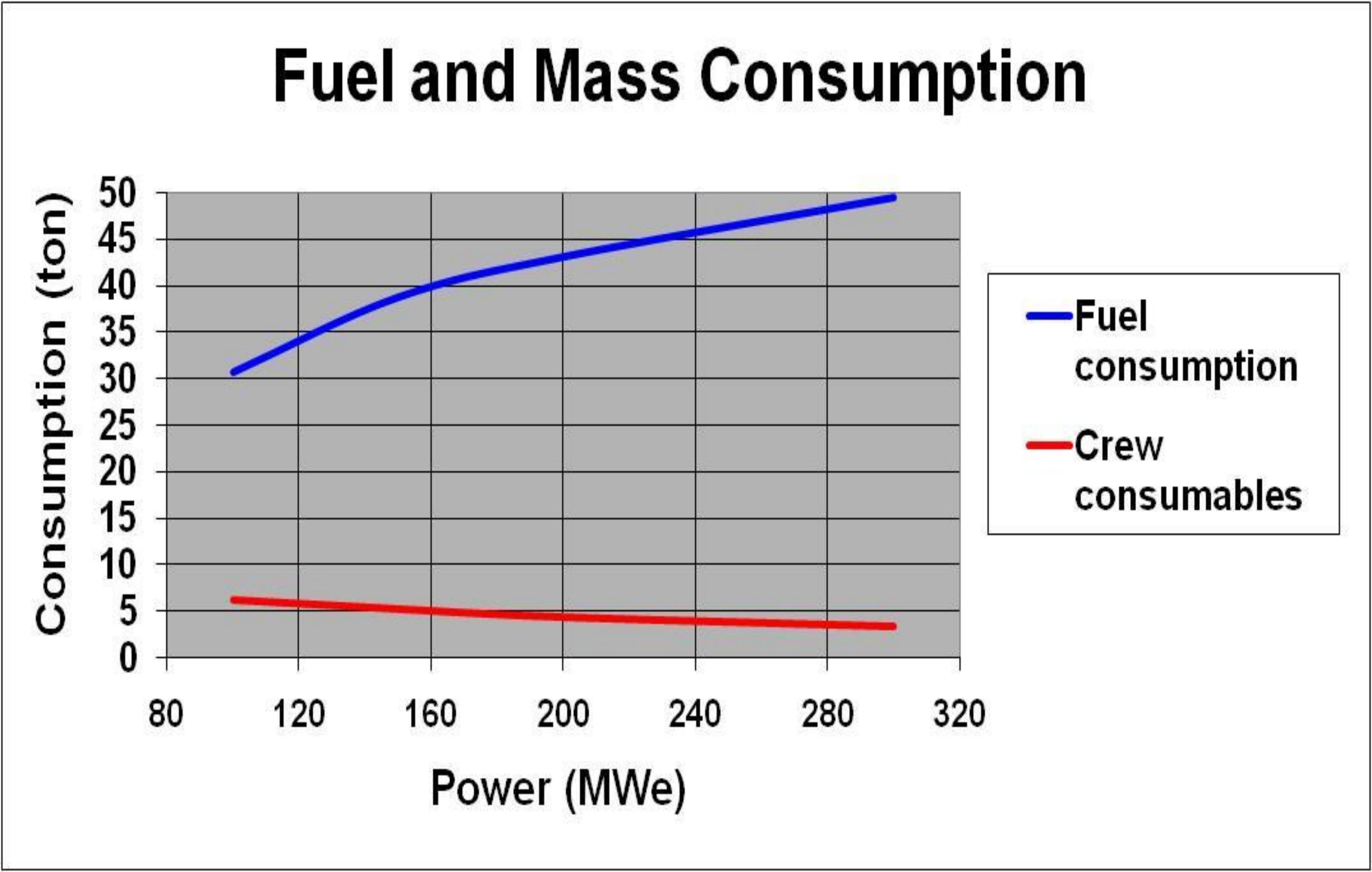
Power (MWe)	Total ΔV (km/s)
100	86.2
150	103.2
200	106.7
300	114.8

(MASS: 120 to160 ton)

Compared with CP total ΔV is 406.76% to 574.9% higher!

PROPELLANTS CONSUMPTION?

NEP: Apply to Manned Mars Mission (M3):
Consumables versus Power



M3 with NEP - Conclusions

- **The combination of Isp and power of Gridded Ion Systems for a M3 predicts times and masses significantly better than with CP and, very likely , NTP**

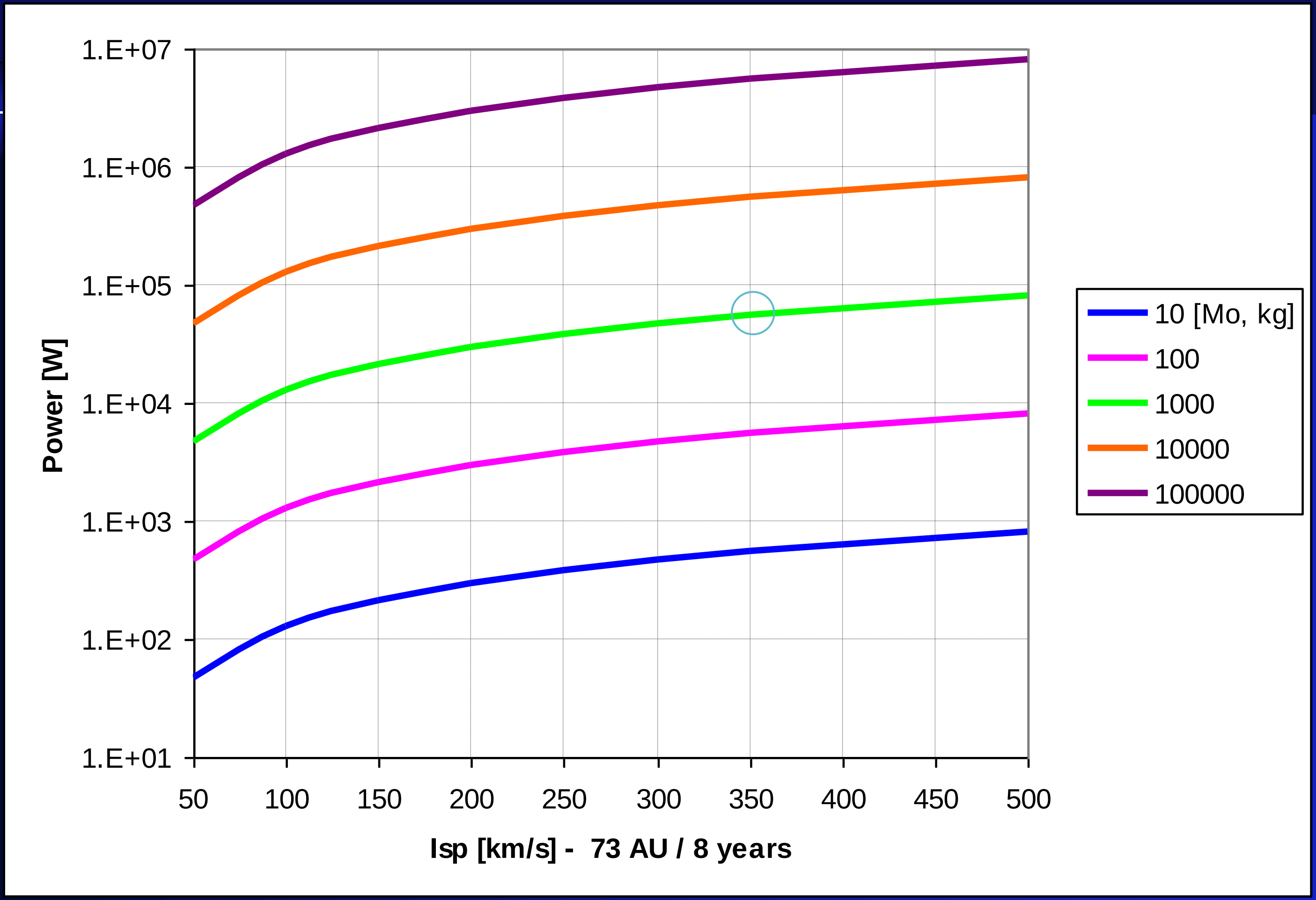
The dose to crew may be drastically reduced with NP

NEP: Apply to Interstellar Precursor Mission

- Unmanned probe, powered by NEP, may reach heliopause, Sedna (an OCO) perihelion (73 AU) and other interesting orbits in reasonable times and P/L ratios
- Time, P/L depend on alpha=NEP Power/NEP mass

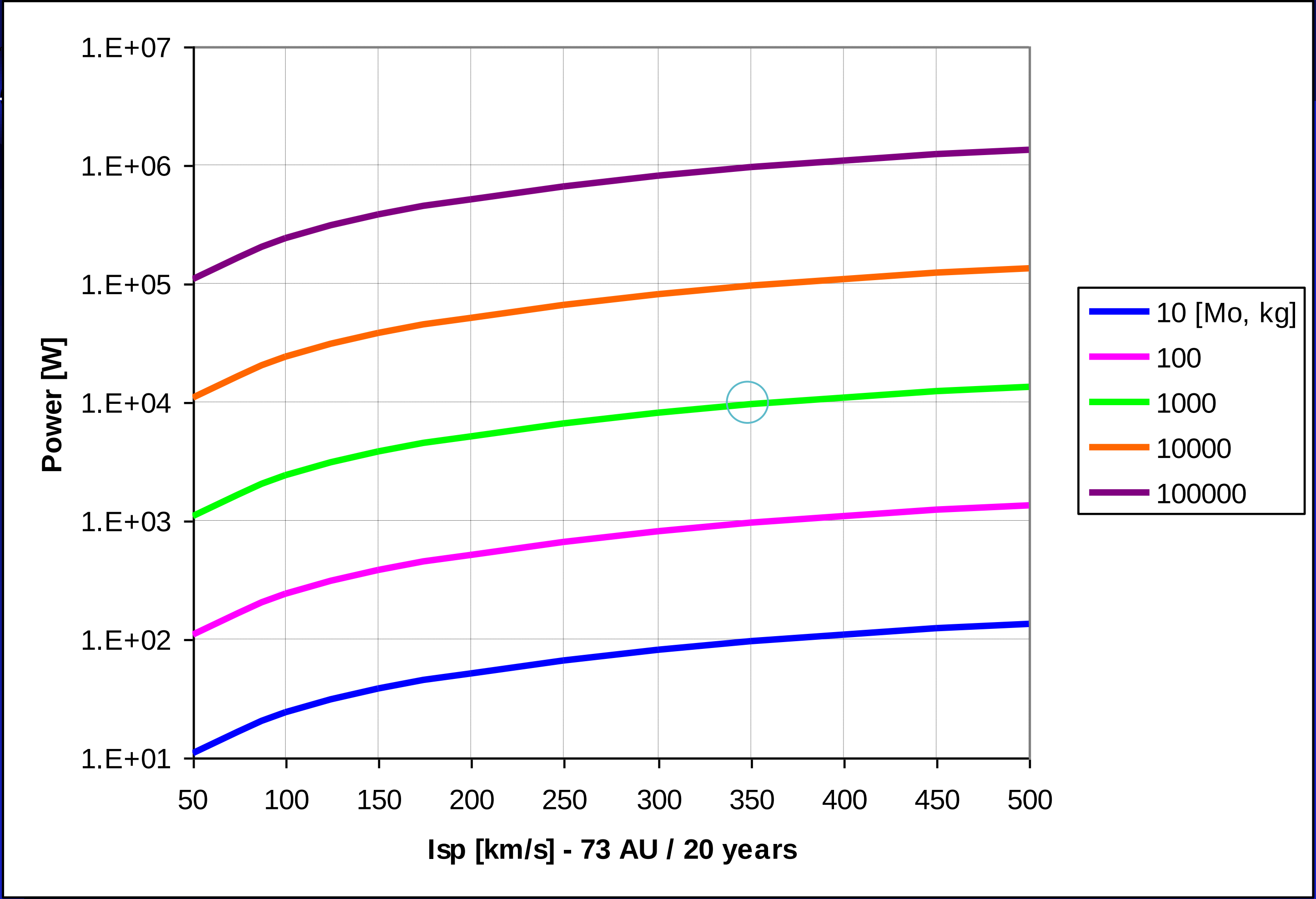
SAPIENZA
UNIVERSITY OF ROME

73 AU Distance



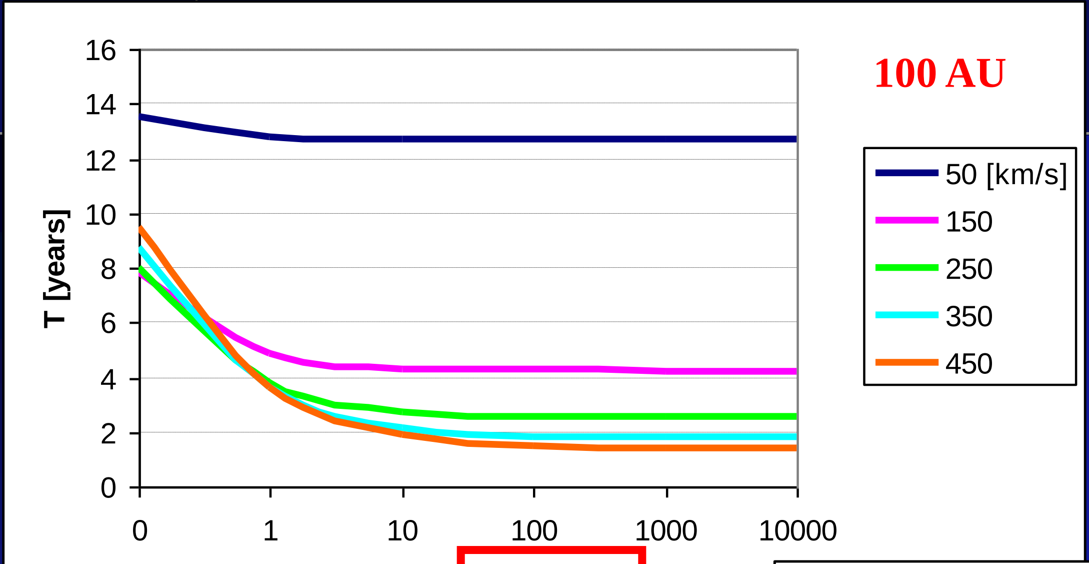
Power as function of Isp; 8-year mission. Initial mass M_0 as parameter. Needs an order of magnitude more power than a 20-year mission

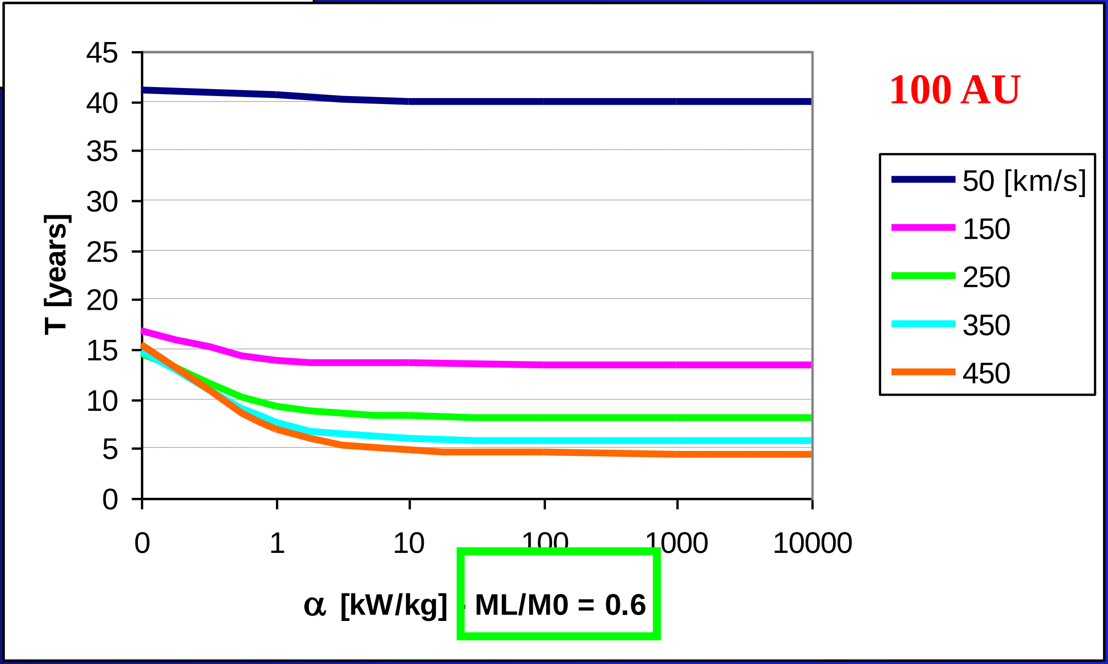
73 AU Distance



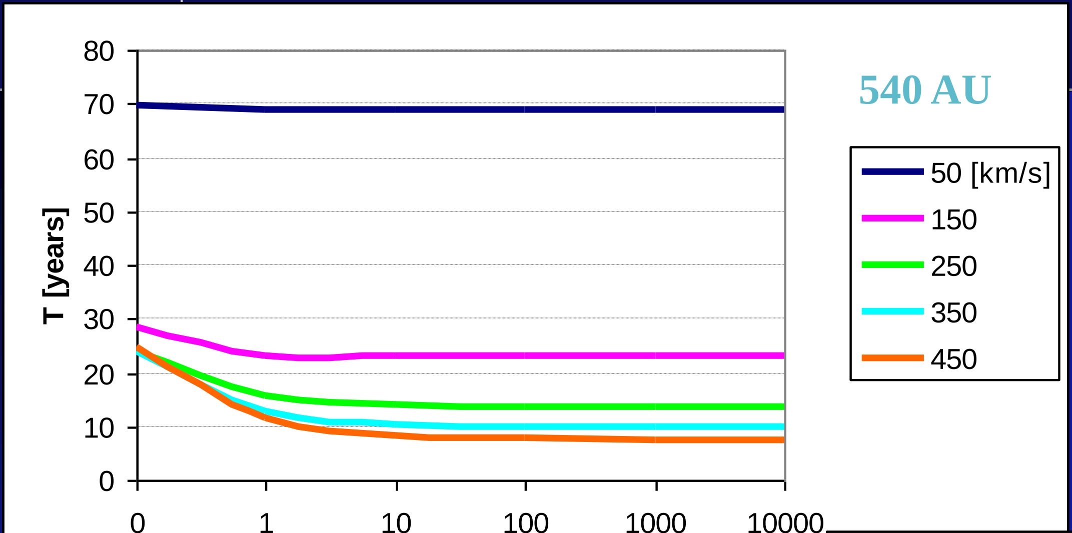
Power as function of Isp; 20-year mission and initial mass M_0 as parameter

A 100 AU Mission for Two Mass Ratios

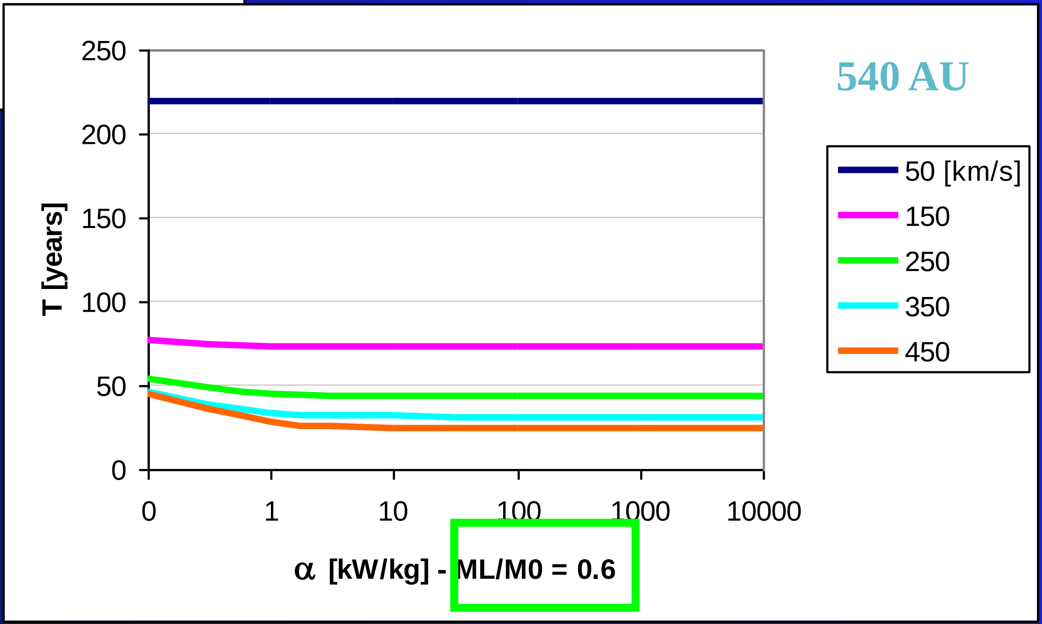




540 AU ('FOCAL') Mission for Two Mass Ratios



α [kW/kg] - ML/M0 = 0.1



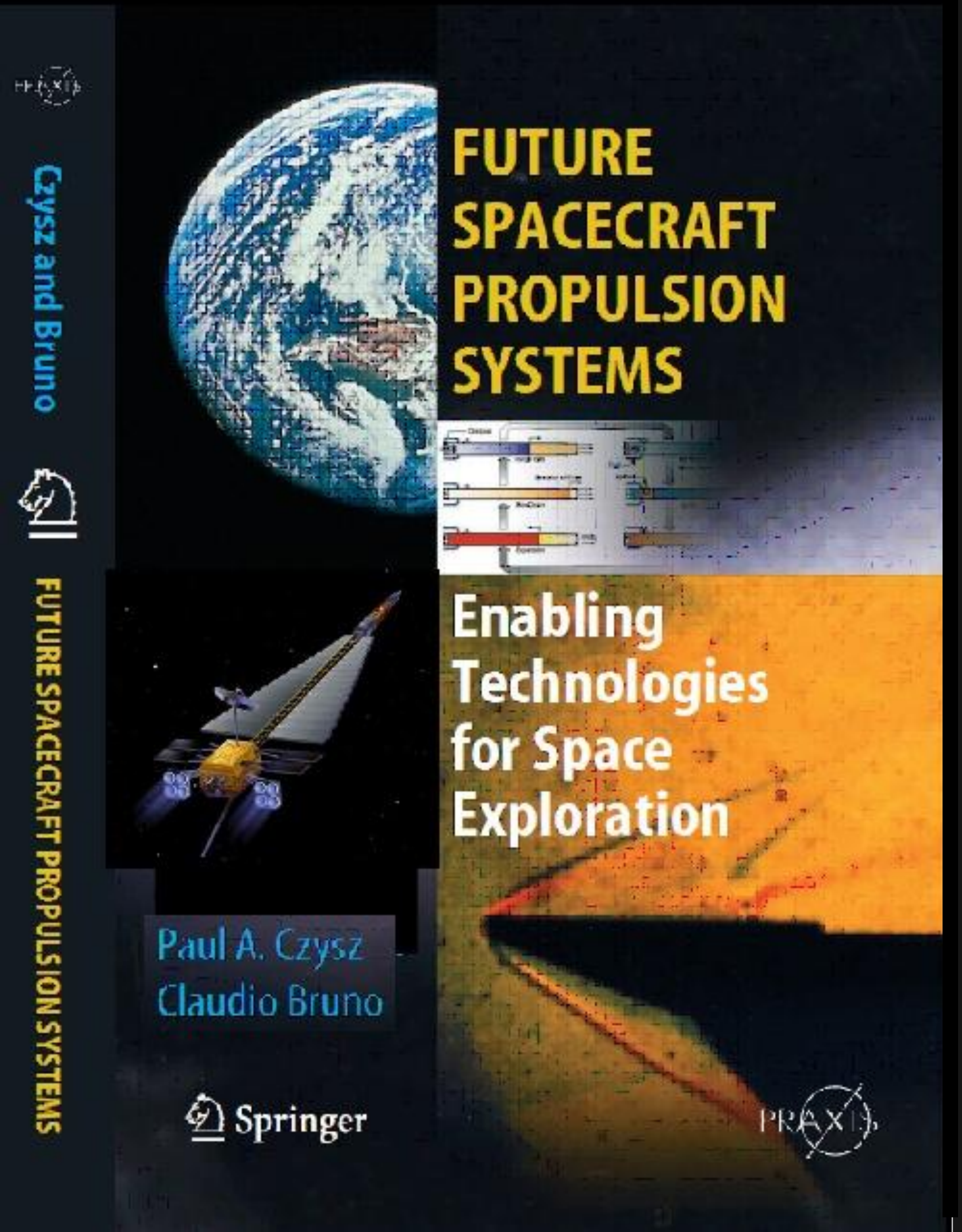
α [kW/kg] - ML/M0 = 0.6

NP – MAJOR ISSUES

- Reactor Lifetime, Integrity
- Reactor In-Flight Refueling
- NEP: Electric Thruster Lifetime
- NTR: materials, fuel
- Public (and specialists…) acceptance
- …

Missions with NP - Some Conclusions

- No other propulsion system has the performance potential of NP.
- NP can drastically reduce a M3 transit time and crew radiation dose.
- Correlating dose and health risks (cancer,..) indispensable: risk estimates for a M3 vary too much (e.g., 1% to 30%).
  → R&D in this area needed!
- NTP probably suited to intercept asteroids
- Investing in NP is key to affordable, safe Human Exploration



For excruciating details:
see the book by

Prof. Claudio Bruno
University of Rome
and
Prof. Paul Czysz
St. Louis University