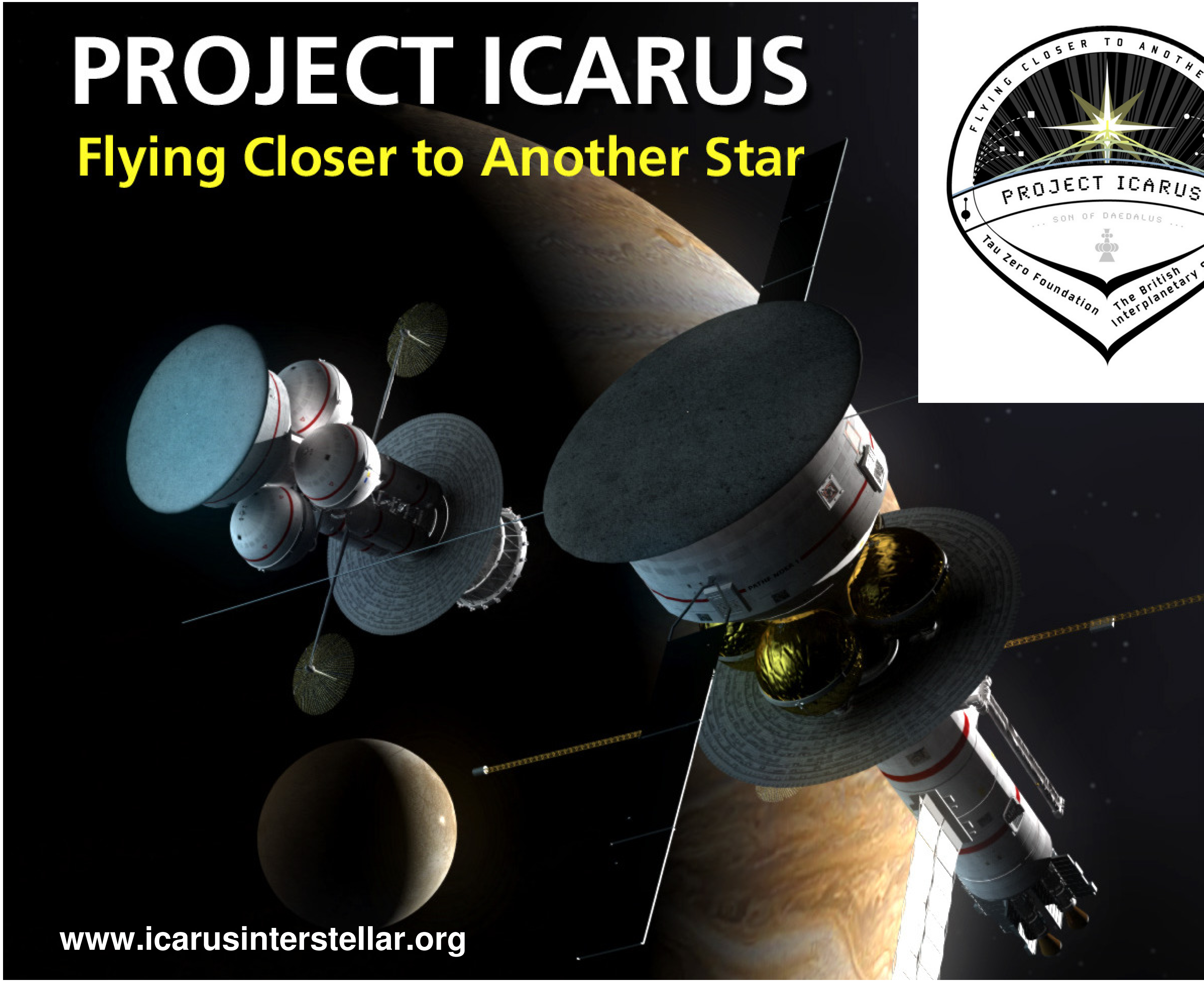
Project Icarus: Specific Power for Interstellar Missions Using Inertial Confinement Fusion Propulsion

K.F.Long, R.K.Obousy, A.Crowl

Icarus Interstellar & 100 Year Starship



FLYING CLOSER TO ANOTHER STAR
PROJECT ICARUS
... SON OF DAEDALUS ...
Tau Zero Foundation
The British Interplanetary Society

Changing the Paradigm

- Low Energy Capability:
  - Current mission planning focussed on science driven requirements, using energy capabilities from existing space transportation propulsion and power capabilities.
  - The mission is established based on science voids.
  - Current chemical energy systems yield low specific energy which lead to energy conversion systems with a low performance design, <10 km/s.
- High Energy Capability:
  - Using higher specific energy systems can deliver much higher dv, namely from nuclear processes.
  - Inherent energy releases are much greater per unit mass.
  - Can broaden current limitations and science horizons

  - We must embrace **science driven missions** which utilize **<u>higher energy capabilities</u>**. Both are important and coupled.

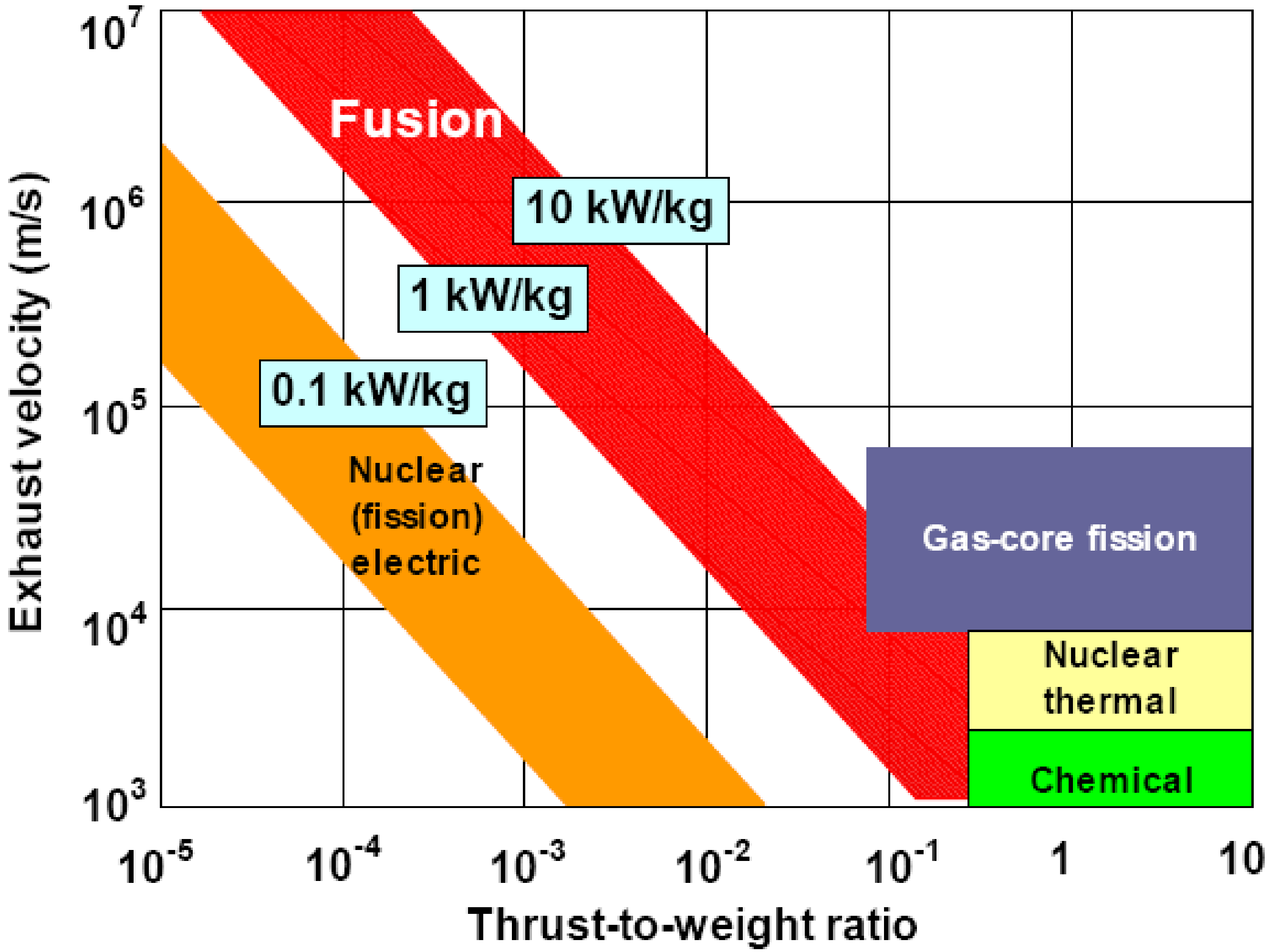
Definitions

- JET POWER is the net power of the rocket engine, after you have accounted for all the inefficiencies, the useful work performed computed from the product of THRUST and EXHAUST VELOCITY.

- SPECIFIC POWER is for the propulsion system, engine + power source + thermal management system.

$$P_j = \frac{1}{2}\dot{m}V_{ex}^2 = \frac{1}{2}V_{ex}T$$

Propulsion Capability



Flyby Mission: 1-4-Stage

TABLE 2-5a. Alpha Centauri fly-by mission performance capabilities and requirements for variations in specific power for: single-stage vehicle, 10 MT payload, 4,000 MT propellant mass.

α_p, kW/kg	1.0	10.0	100.0
t, years	460	213	99
Δv, km/s	4,184	9,015	19,422
M_o, MT	4,205	4,205	4,205
P_j, MW	195	1,950	19,500
F, N	1,800	8,440	39,200
<Isp>, seconds	141,180	304,167	655,307

TABLE 2-5b. Alpha Centauri fly-by mission performance capabilities and requirements for variations in specific power for: 2-stage vehicle, 10 MT payload, 4,000 MT propellant mass.

α_p, kW/kg	1.0	10.0	100.0
t, years	414	192	98
Δv, km/s	4,646	10,011	21,569
M_o, MT	4,873	4,873	4,873
P_j, MW, Stage 1	816	8,162	81,620
P_j, MW Stage 2	37	370	3,500
T, N	2,600	12,100	56,000
<Isp>, seconds	153,110	329,870	710,675

- **Fusion Energy for Space Missions in the 21st Century, NASA TM4298, Normal R.Schulze, 1991.**

Flyby Mission: 1-4-Stage

TABLE 2-5c. Alpha Centauri fly-by mission performance capabilities and requirements for variations in specific power for: 3-stage vehicle, 10 MT payload, 65,400 MT propellant mass.

α_p, kW/kg	1.0	10.0	100.0
t, years	365	170	79
Δv, km/s	5,270	11,360	24,460
M_o, MT	80,000	80,000	80,000
P_j, MW, Stage 1	13,900	139,000	1,390,000
P_j, MW Stage 2	694	6,940	69,400
P_j, MW Stage 3	35	350	3,500
F, N	54,900	255,000	1,180,000
<Isp>, seconds	120,000	258,000	555,102

TABLE 2-5d. Alpha Centauri fly-by mission performance capabilities and requirements for variations in specific power for: 4-stage vehicle, 10 MT payload, 1,308,000 MT propellant mass.

α_p, kW/kg	1.0	10.0	100.0
t, years	332	154	71
Δv, km/s	5,800	12,500	26,900
M_o, MT	1,600,000	1,600,000	1,600,000
P_j, MW, Stage 1	277,700	2,770,000	27,770,000
P_j, MW Stage 2	13,900	139,000	1,390,000
P_j, MW Stage 3	694	6,940	69,400
P_j, MW Stage 4	35	350	3,500
F, N	1,330,000	6,170,000	28,700,000
<Isp>, seconds	98,700	212,700	458,200

- **Fusion Energy for Space Missions in the 21st Century, NASA TM4298, Normal R.Schulze, 1991.**

Flyby Mission: 1-4-Stage

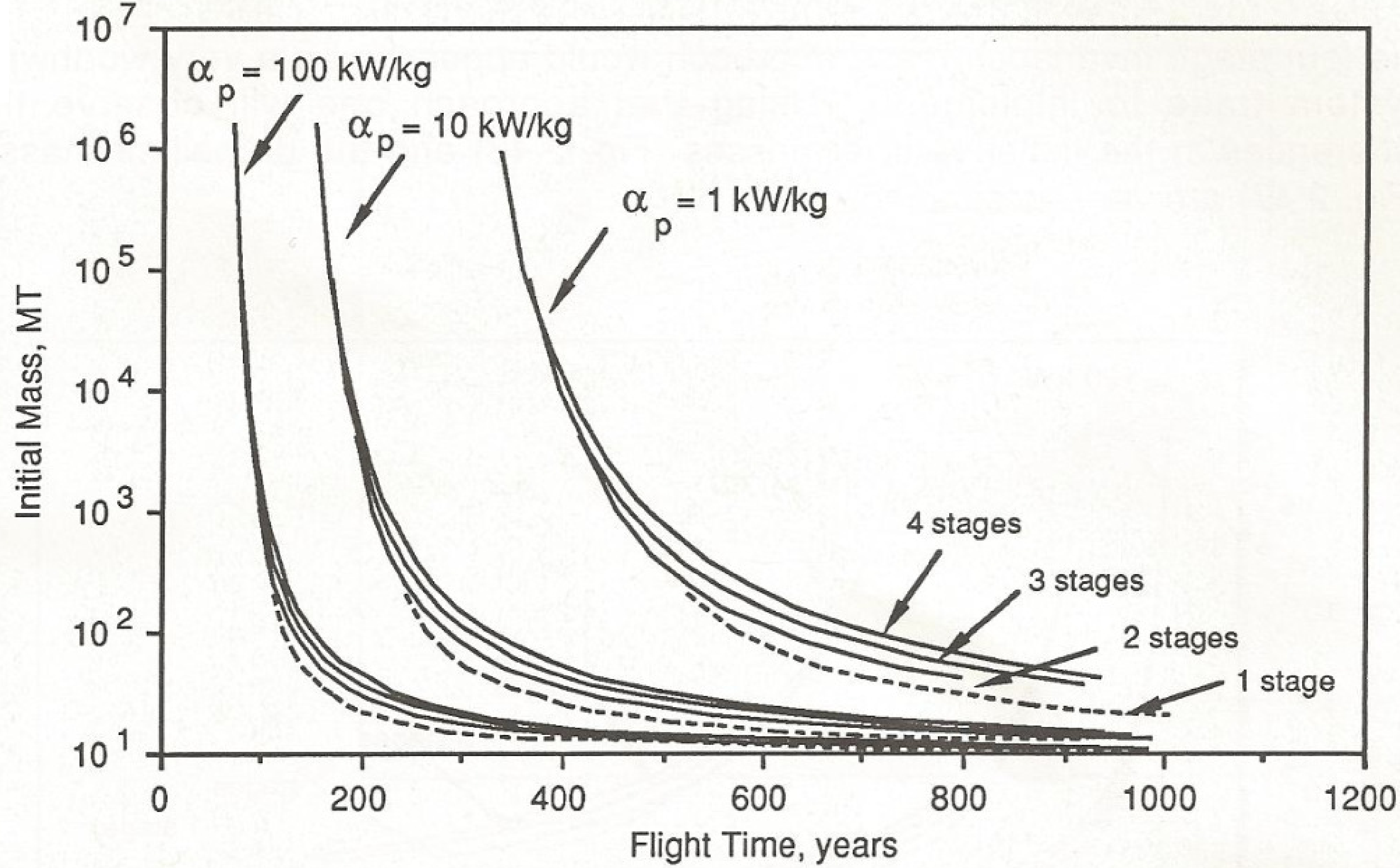


Fig. 2.46. Alpha Centuri fly-by mission, initial mass variations with flight duration for 1 to 4 stages.

- **Fusion Energy for Space Missions in the 21st Century, NASA TM4298, Normal R.Schulze, 1991.**

Flyby Mission: 1-4-Stage

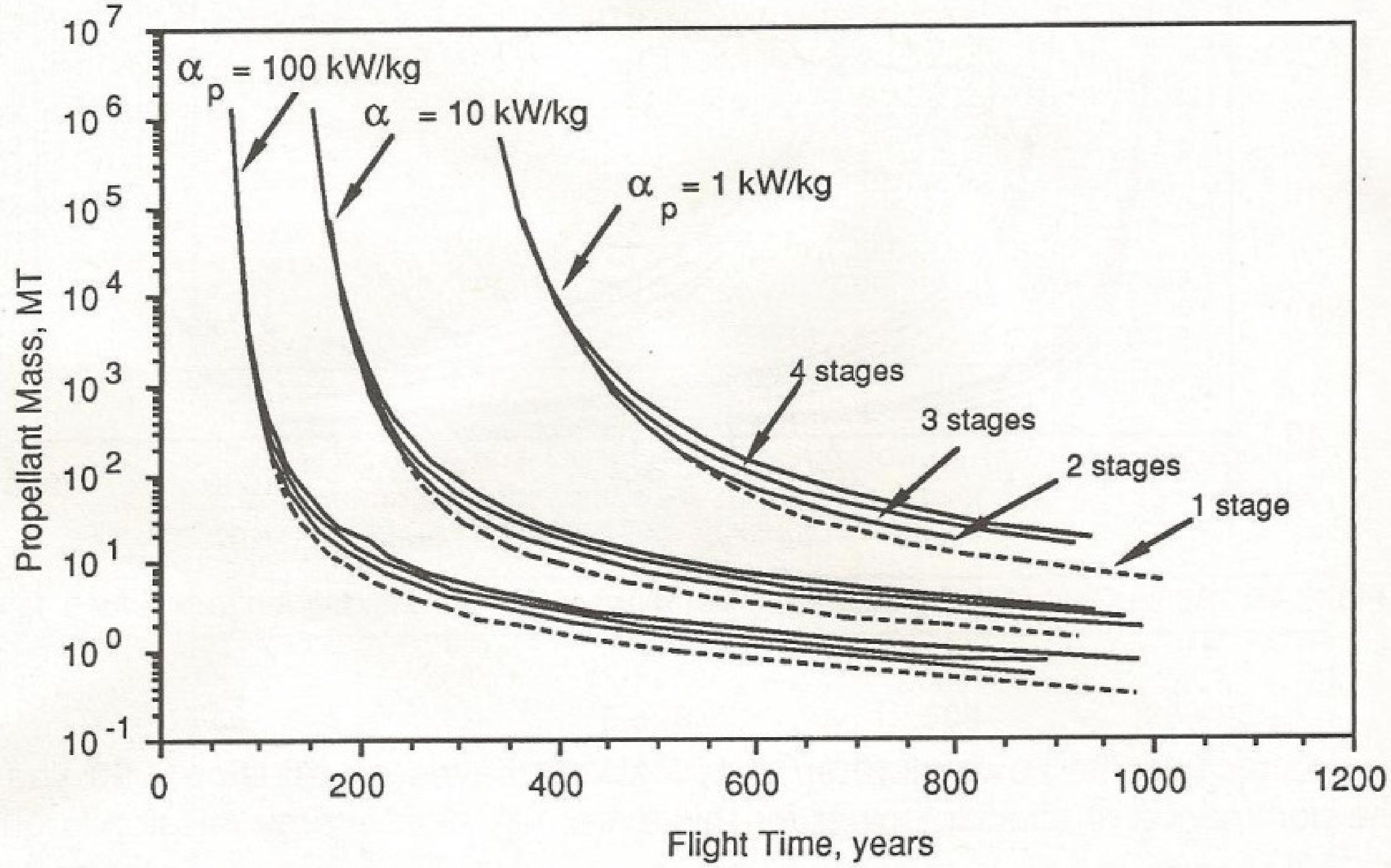
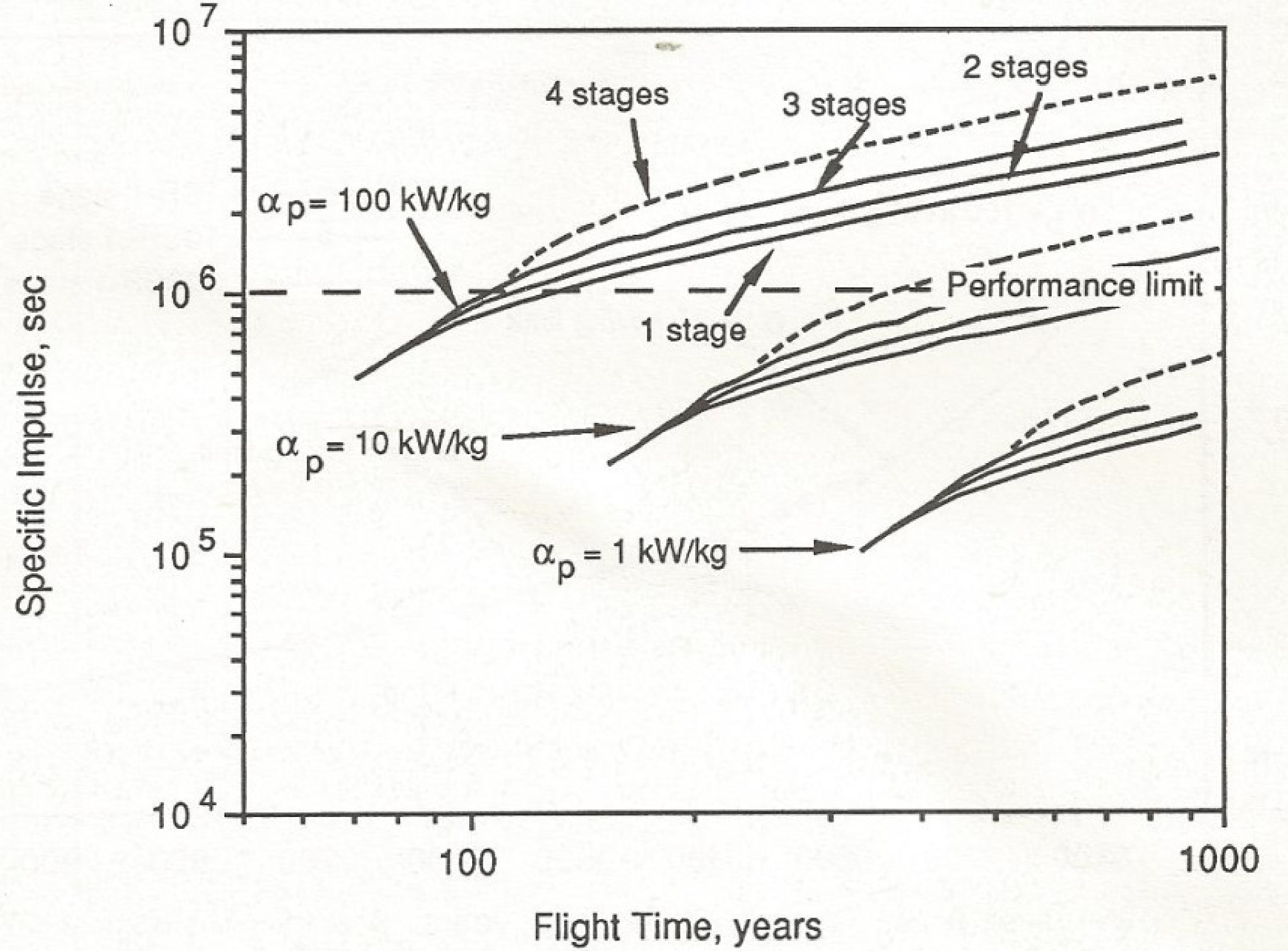


Fig. 2.47. Alpha Centuri flyby mission, propellant mass variations with mission duration for 1 to 4 stages.

- **Fusion Energy for Space Missions in the 21st Century, NASA TM4298, Normal R.Schulze, 1991.**

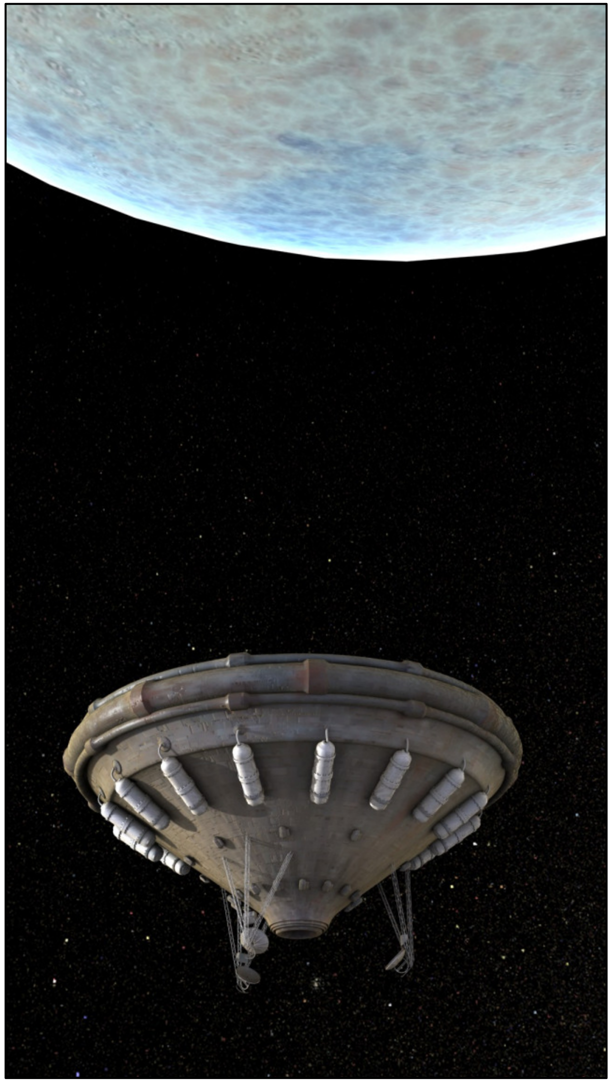
Flyby Mission: 1-4-Stage

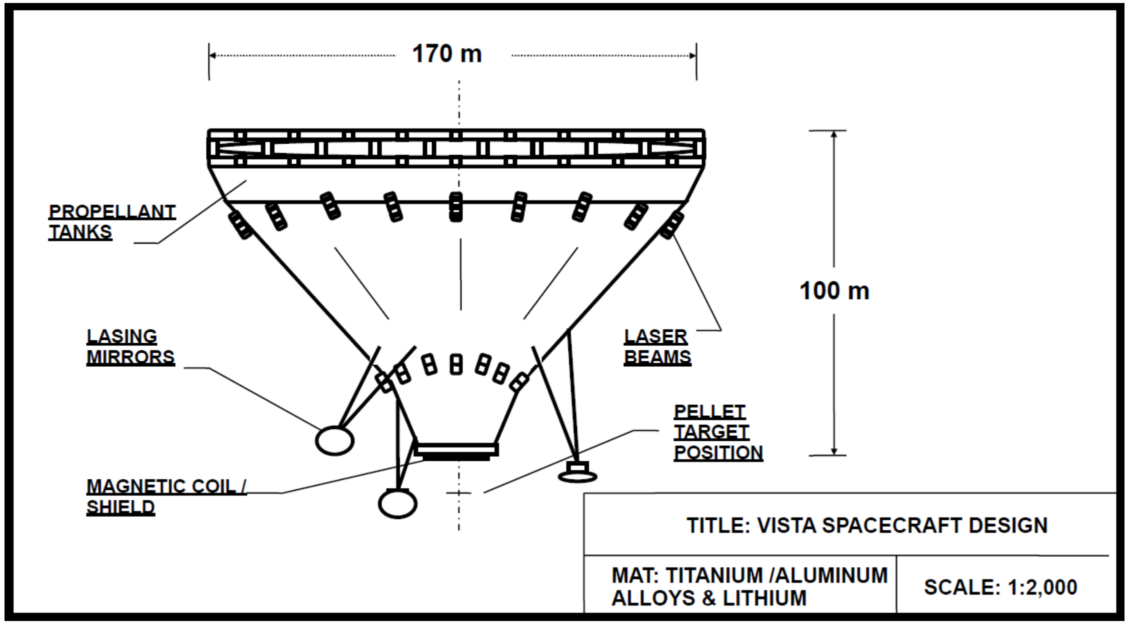


. 2.48. Alpha Centuri flyby mission, specific impulse variations for 1 to 4 stage

- **Fusion Energy for Space Missions in the 21st Century, NASA TM4298, Normal R.Schulze, 1991.**

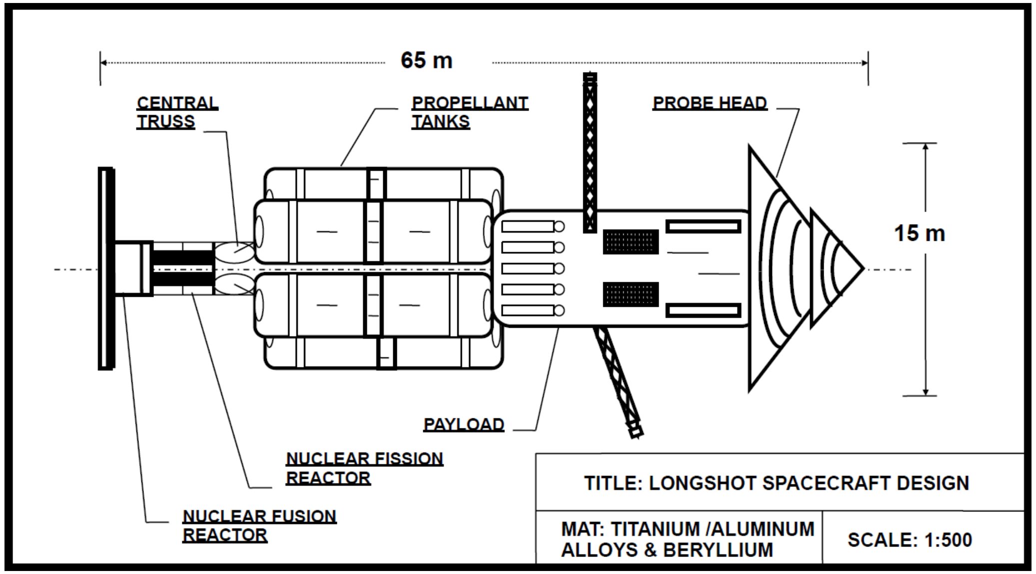
Vista, 1987-2000

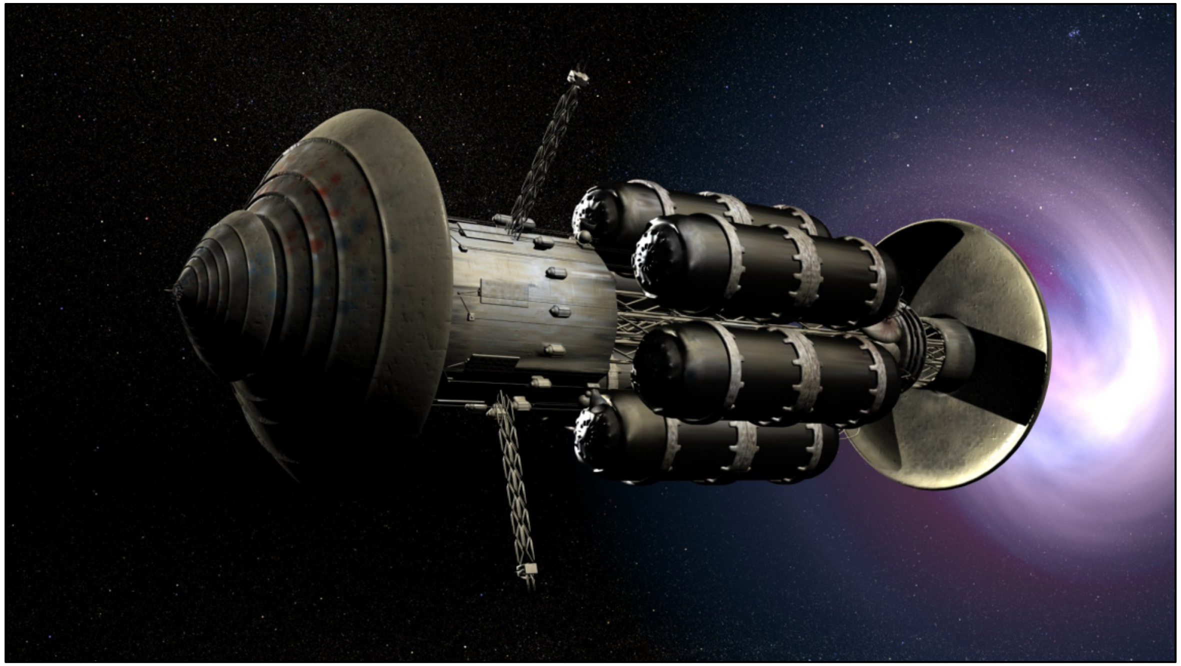




- 6,000 tons, 4,165 tons propellant, 1,835 tons dry mass.
- $T=2.4\times10^5$N (Mars mission)
- Vex=170 km/s
- P_j = 20.4 GW
- **P_{sp} = 11.1 kW/kg**

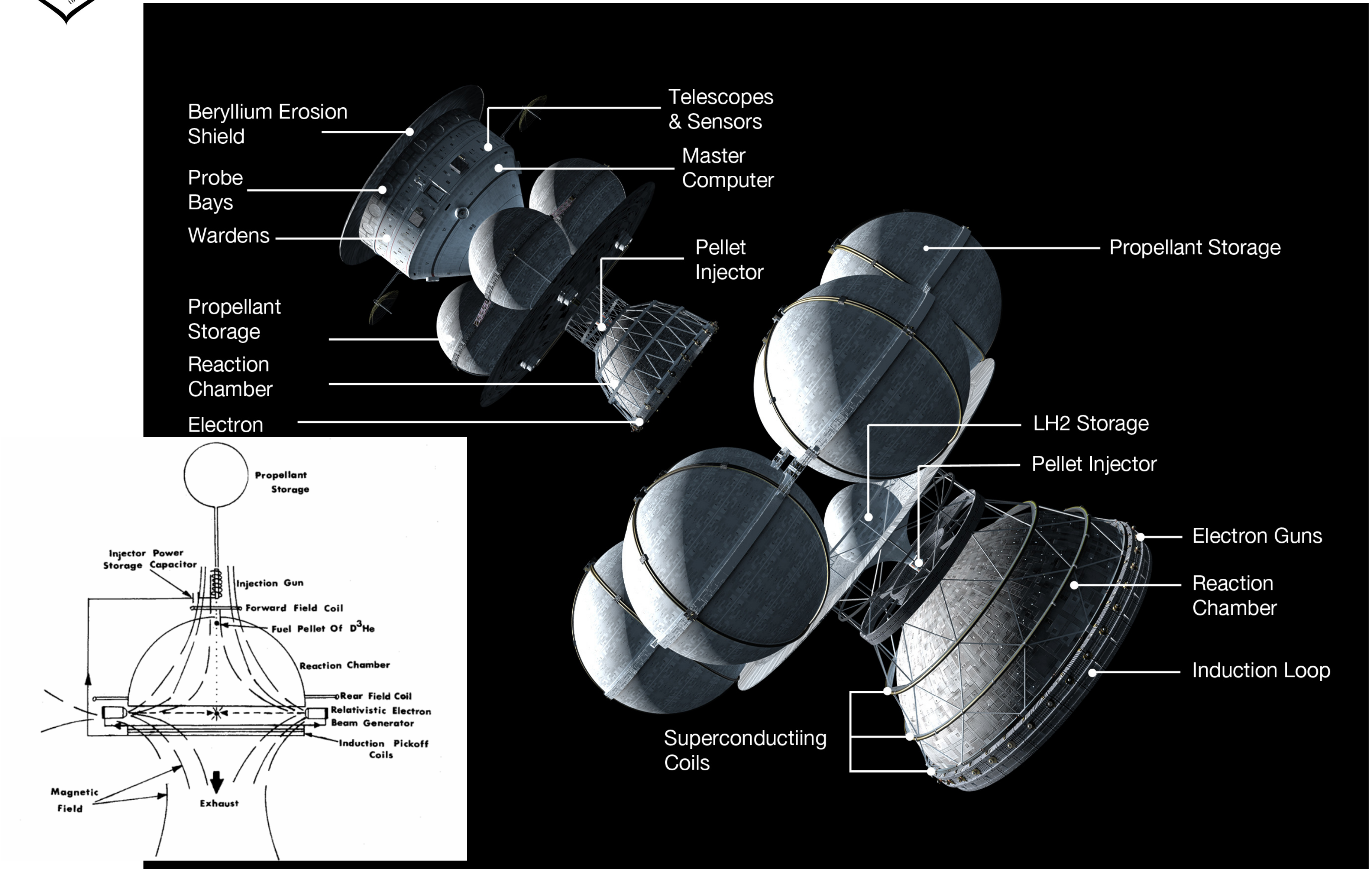
Project Longshot, 1988



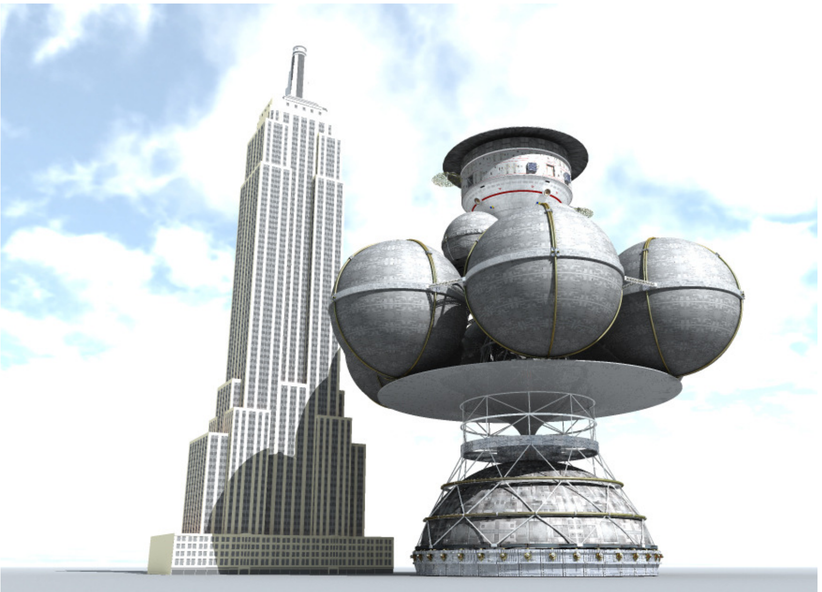


- Vex=9,810km/s
- P_j=730 kW/kg
- Need **P_{sp}=285 kW/kg** to achieve mission.

Project Daedalus, 1978

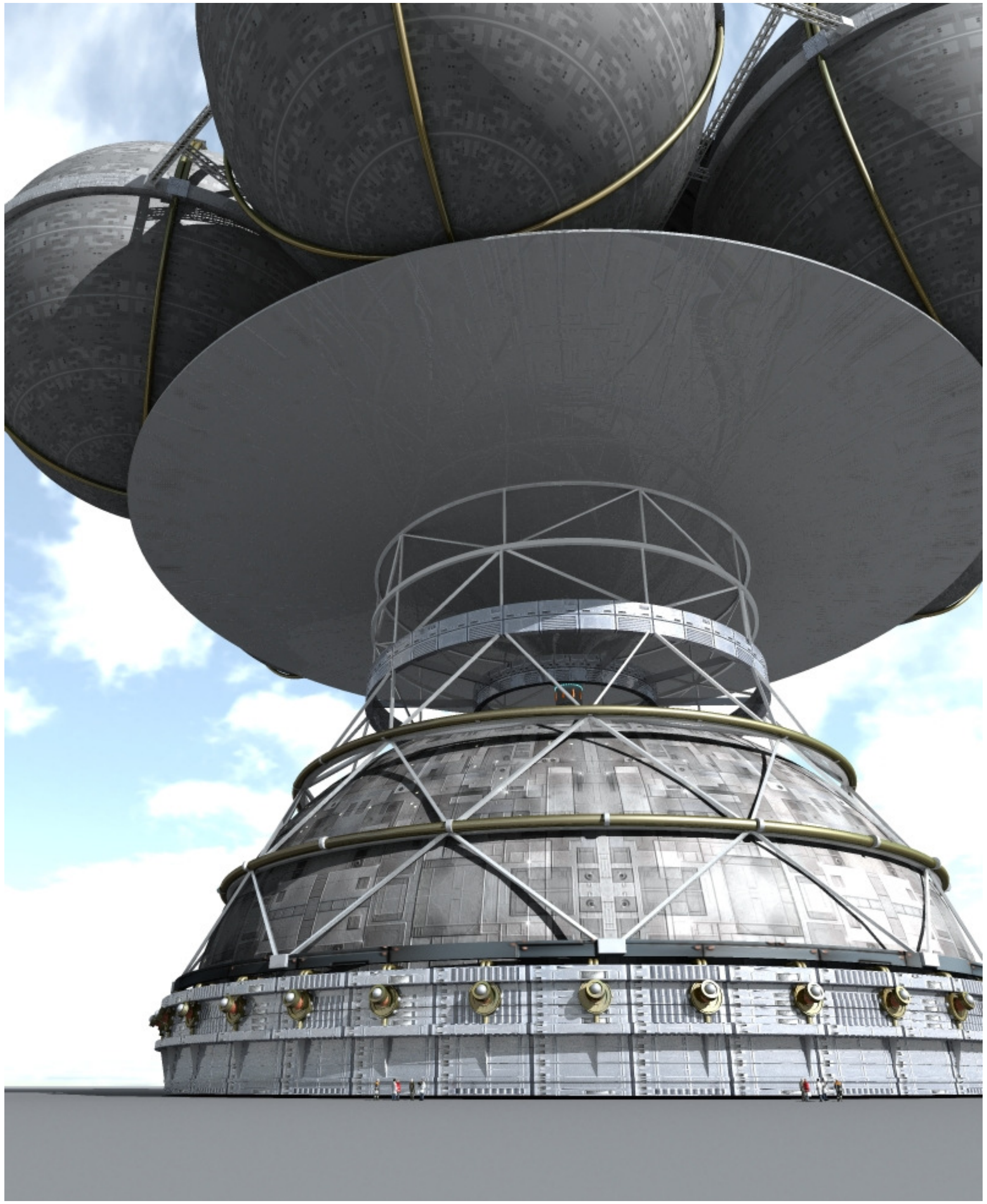


Project Daedalus, 1978



Parameter	1st stage value	2nd stage value
Propellant mass (tonnes)	46,000	4000
Staging mass (tonnes)	1690	980
Boost duration (years)	2.05	1.76
Number tanks	6	4
Propellant mass per tank (tonnes)	7666.6	1000
Exhaust velocity (km/s)	1.06×10^4	0.921×10^4
Specific impulse (million s)	1.08	0.94
Stage velocity increment (km/s)	2.13×10^4 ($0.071c$)	1.53×10^4 ($0.051c$)
Thrust (N)	7.54×10^6	6.63×10^5
Pellet pulse frequency (Hz)	250	250
Pellet mass (kg)	0.00284	0.000288
Number pellets	1.6197×10^{10}	1.3888×10^{10}
Number pellets per tank	2.6995×10^9	7.5213×10^9
Pellet outer radius (cm)	1.97	0.916
Blow-off fraction	0.237	0.261
Burn-up fraction	0.175	0.133
Pellet mean density (kg/m^3)	89.1	89.1
Pellet mass flow rate (kg/s)	0.711	0.072
Driver energy (GJ)	2.7	40
Average debris velocity (km/s)	1.1×10^4	0.96×10^4
Neutron production rate (n/pulse)	6×10^{21}	4.5×10^{20}
Neutron production rate (n/s)	1.5×10^{24}	1.1×10^{23}
Energy release (GJ)	171.82	13.271
Q-value	66.6	33.2

Project Daedalus, 1978



Project Daedalus, 1978

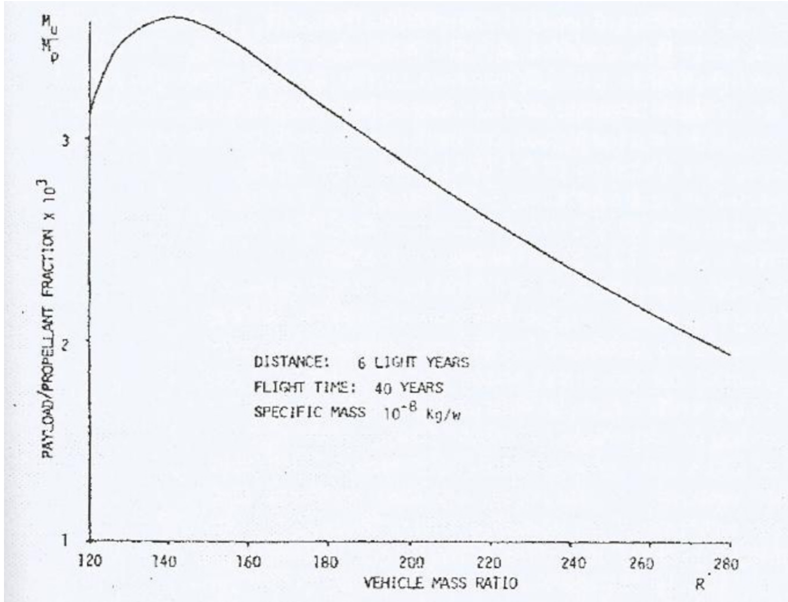
- High mass ratios required for interstellar.
- Low abundance of He-3 would dominate the mission costs.
- Chose to optimize payload/propellant ratio.
- Assumed for a particular value of specific mass there is a value of R which makes mu/mp a maximum.

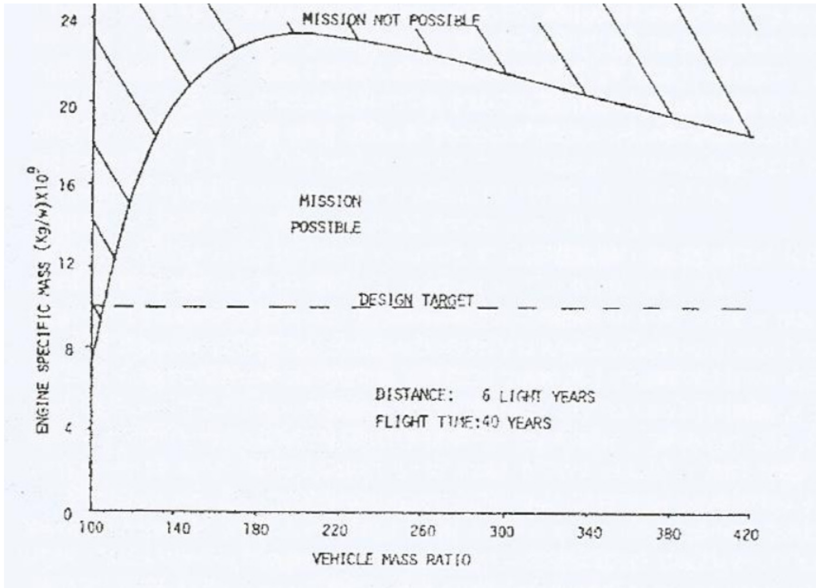
$$m_e = \frac{\lambda v_{ex}^2 m_p}{2t_a}$$

$$\frac{m_u}{m_p} = \frac{1}{R-1} - \frac{1}{2}\frac{\lambda v_{ex}^3\left(\frac{R}{R-1}Ln(R-1)\right)}{v_{ex}tLn(R) - S}$$

Project Daedalus, 1978

- For 40 year mission to be possible, require specific engine mass lower than 2.5×10^{-8} kg/W.
- Chose 1×10^{-8} kg/W but difficult to achieve.
- Optimum R at 150 with mu/mp=0.0036.
- But final design had 1st stage engine mass of 1,290 tons producing 44 TW power, equating to specific mass 2.5×10^{-8} kg/W.





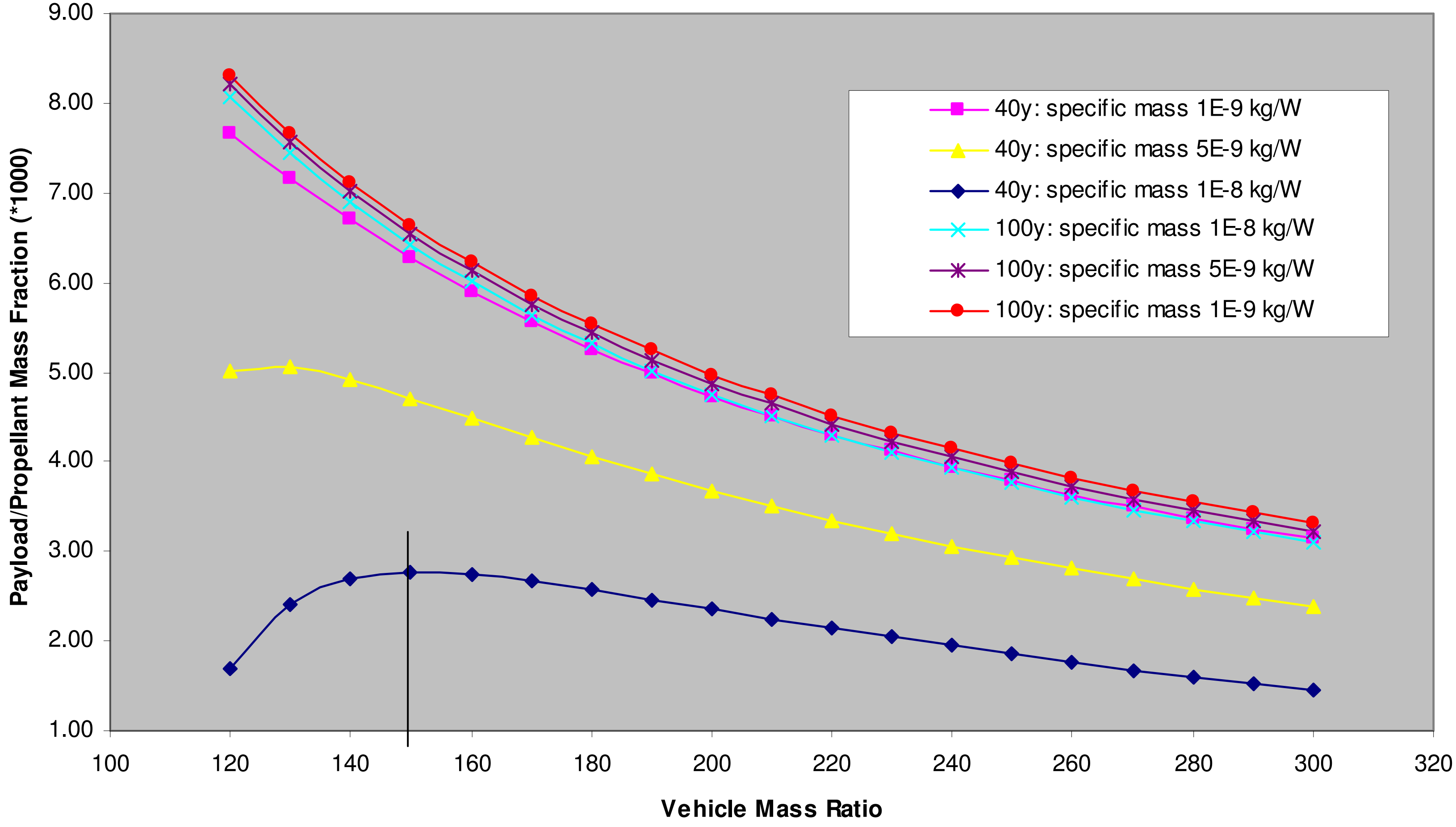
Project Daedalus, 1978

$$P_j = \frac{1}{2}\dot{m}V_{ex}^2 = \frac{1}{2}V_{ex}T$$

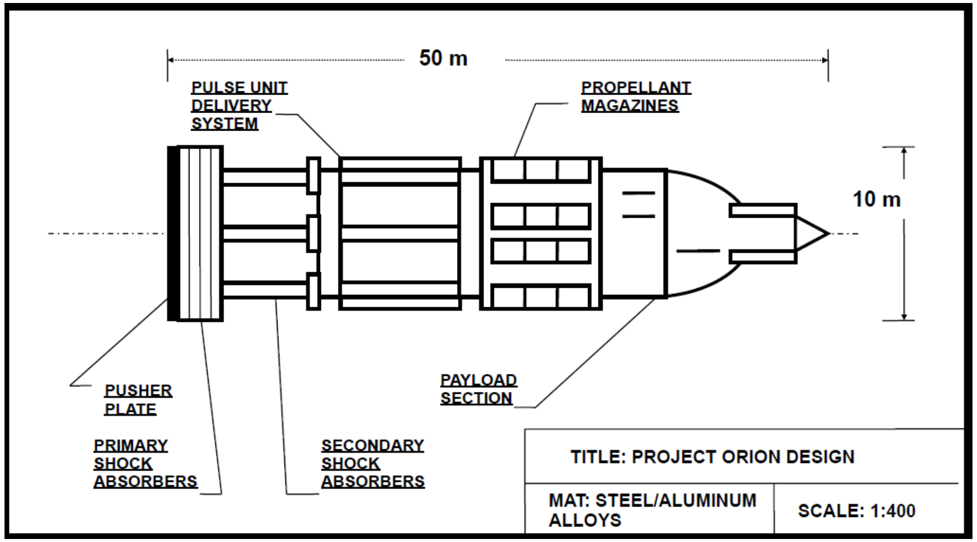
- $P_j = 0.5 \times 10^6 \times 10^7 ms^{-1} \times 7.54 \times 10^6 N \sim 40TW$
- P_{sp}=40TW / 944,000 kg ~**42.4 MW/kg**

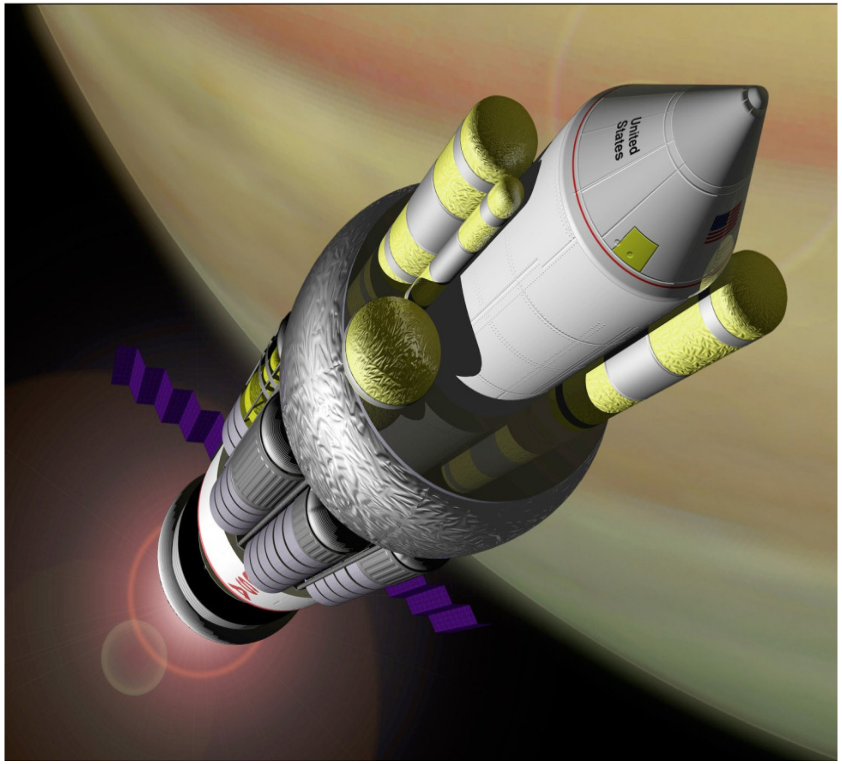
Project Daedalus, 1978

- The lower the specific engine mass the higher the payload/propellant mass fraction.



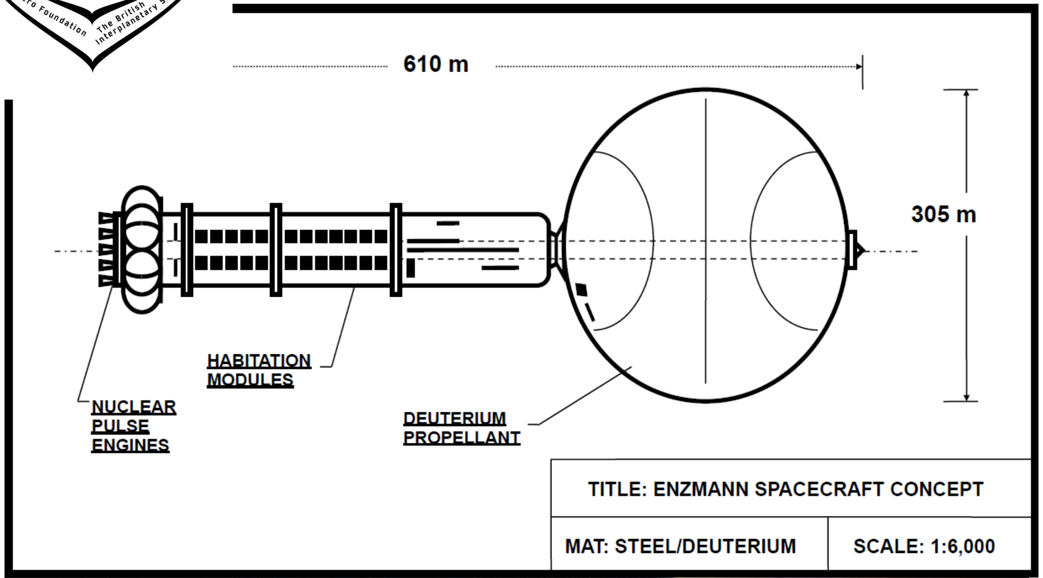
Interstellar (Dyson) Orion, 1960s

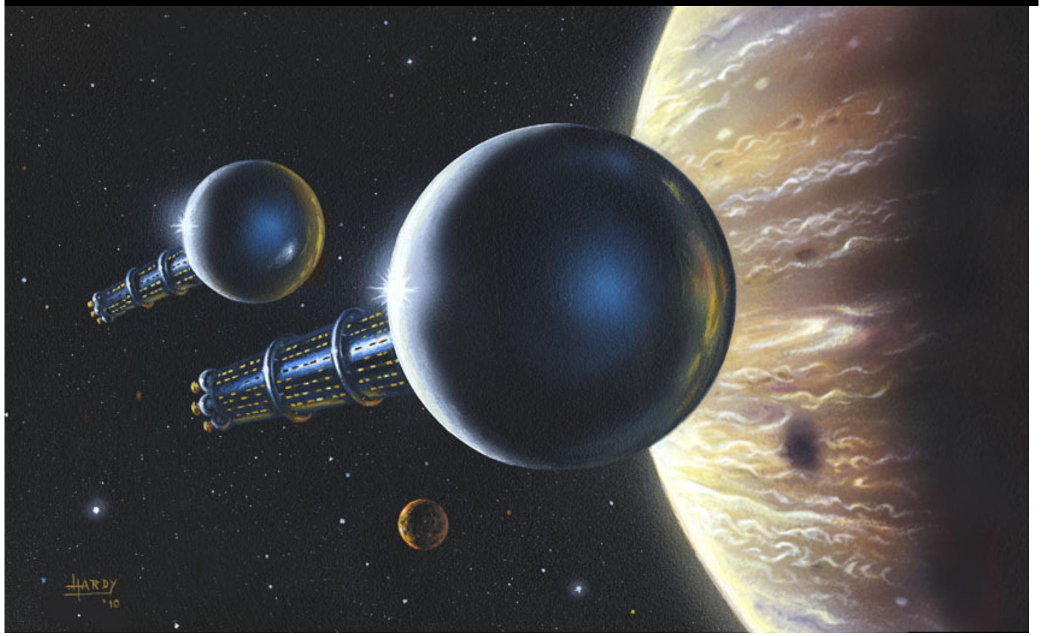




- Vex=15,000 km/s
- $T=1\times10^{9}$ N
- $P_j=7.5\times10^{15}$W
- P_{sp}=75 MW/kg

Enzmann (slow boat) Starship, 1960s





Parameter	Value
Dry spacecraft mass (tons)	30,000
Propellant mass (tons)	3×10^6
Start population	200
End population	2,000
Total Mass Ratio	101
Mass Ratio	10.05
Exhaust Velocity (km/s)	11,700
Total Delta.V (km/s)	54,000 (0.18c)
Cruise Velocity (km/s)	27,000 (0.09c)
Total acceleration time (years)	18.95
Mass Flow Rate (kg/s)	5.02
Start Acceleration (m/s^2)	0.019 (0.002g)
Total Cruise time (years)	41.05
Total Mission time (years)	60

- Vex=11,700 km/s
- M_{dot}=5.02 kg/s
- Pj=344 TW
- M_{dry}=30,000 tons
- P_{sp}=11.5 MW/kg

Conclusions

- Examined specific power requirements for an interstellar mission.
- Strong correlation with mission time.
- For interstellar probe (robotic or crewed) the specific power likely in the 10s MW/kg range.