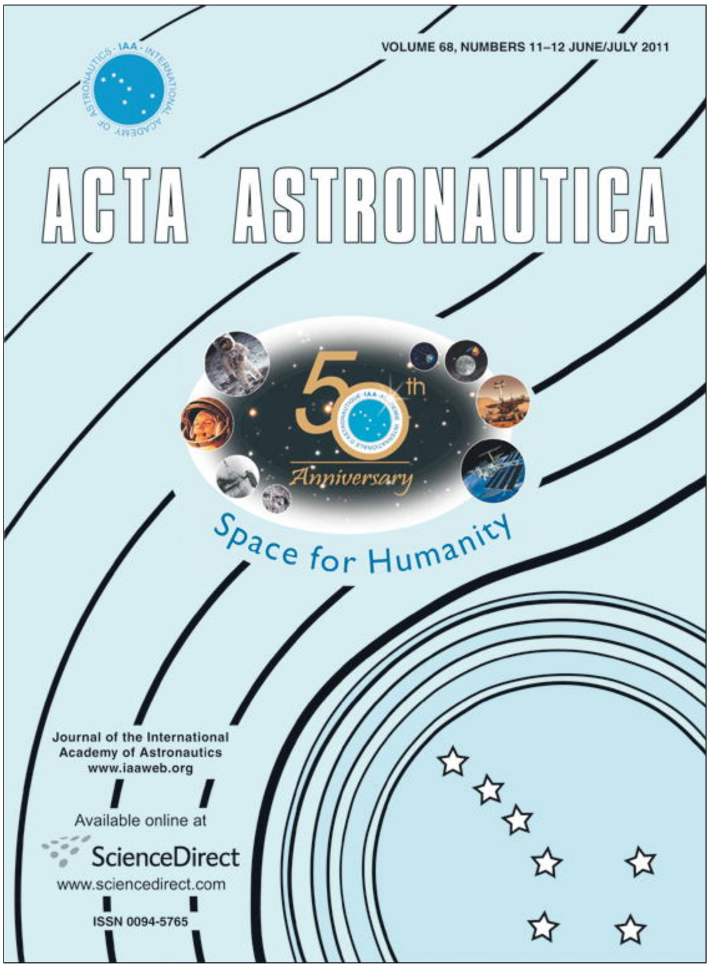
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Project Icarus: Optimisation of nuclear fusion propulsion for interstellar missions ☆

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ABSTRACT

The Daedalus spacecraft design was a two-stage configuration carrying 50,000 tonnes of DHe^3 propellant. Daedalus was powered by electron driven Inertial Confinement Fusion (ICF) to implode the pellets at a frequency of 250 Hz. The mission was to Barnard's star 5.9 light years away in a duration of around 50 years. This paper is related to the successor Project Icarus, a theoretical engineering design study that began on 30 September 2009 and is a joint initiative between the Tau Zero Foundation and The British Interplanetary Society. In the first part of this paper, we explore 'flyby' variations on the Daedalus propellant utilisation for two different mission targets: Barnard's star and Epsilon Eridani, 10.7 light years away. With a fixed propellant mass a number of staged configurations (1–4) are derived for an optimal configuration but then moving to an off-optimal configuration due to the requirement for a high final science payload mass. Some comments are then made on the ICF pellet configuration compared to the typical pellets fielded at the National Ignition Facility (NIF) and those proposed for the Vista and Longshot fusion based propulsion designs. This is a working progress report, which aims to study perturbations of the Daedalus baseline design as part of a trade study. This is a submission of the Project Icarus Study Group.

1. Introduction

In the 1970s members of The British Interplanetary Society (BIS) designed a flyby interstellar probe aimed at a Barnard's star mission. This was a theoretical study aimed at proving that interstellar travel was possible in principle. Fundamentally this addressed aspects of the Fermi paradox, which is the problem initially proposed by the Italian physicist Enrico Fermi in the 1950s. His observation was that our theoretical expectation of encountering intelligent life in the galaxy is in contradiction to our observations of there being only a single 'intelligent' life form – humans. *Project Daedalus* [1] was a landmark study covering all of the major spacecraft systems, comprehensively designed by application of rigorous scientific techniques. Arguably, *Project Daedalus* did prove that interstellar travel was possible and so highlighting further the apparent paradox first presented by Fermi.

On 30 September 2009 members of the BIS in collaboration with the Tau Zero Foundation (TZF) launched the successor *Project Icarus: son of Daedalus – flying closer to another star* [2]. *Project Icarus* aims to revisit the design and improve it with the three decades of advances in physics, engineering and our understanding of the universe. The most critical element of the vehicle design is the propulsion system, stipulated in the Project Icarus Terms of Reference (ToR) which are the engineering

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requirements, to be mainly fusion based propulsion. As the Daedalus vehicle design utilised Inertial Confinement Fusion (ICF) technology as the main scheme for producing thrust generation (i.e. nuclear pulse propulsion) [3,4] the same baseline is assumed for *Project Icarus*. This paper represents one trade study among many which is examining different ways of designing the Daedalus engine and overall vehicle configuration. Thus the calculations presented are deliberately approximate in scope and represent a working progress report into studies of the Daedalus baseline design.

The intention of this work is to focus on the extremes of the design envelope so as to bound the potential performance. We consider a comparatively distant mission target (Epsilon Eridani at 10.7 light years) and a relatively close mission target (Barnard's star at 5.9 light years distance). Following a similar philosophy a later study will aim to assess the use of ICF pellet designs such as large configurations (as proposed for Daedalus) and small configurations (as proposed for next-generation commercial fusion reactor demonstrators). It is not the intention in this brief study to produce any definitive answers but merely to aid in scoping the design space so as to better realise what likely options the Icarus design will have. Currently, *Project Icarus* is in the Concept Design Phase and no down select on options will be performed until after this phase is completed.

As part of the overall propulsion work for *Project Icarus*, designers are reviewing the complete engine design and alternative engineering schemes. In this paper however, we start with the Daedalus vehicle and engine design as a baseline configuration and then consider perturbations thereof. We begin this paper by developing some background theory required for the later analysis. We then describe how propellant mass and mass flow rate are related to the pellet pulse frequency. We then develop some 1–4-stage Daedalus-like configurations by using optimisation equations. Further modifications lead to the configuration layout and mission profiles for each concept. Some equations are then developed to derive the minimum pulse frequency required for a given mission. Finally, some discussion is presented on different pellet designs and the maximum theoretical performance attainable. This work is under continuing development and will evolve into a later more detailed analysis of the study, all geared towards presenting design options for *Project Icarus* prior to down select.

2. Fundamental theory

We firstly examine the problem of interstellar travel generally and remind ourselves of the ideal rocket equation, fundamental to any such studies, where v_e is the propellant exhaust velocity, M_i/M_f is the initial to final mass ratio and Δv is the final velocity increment achieved:

$$v = v_e \mathrm{Ln}(M_i/M_f) \quad (1)$$

Figs. 1 and 2 show the basic requirements for trips to the nearest stars calculated using Eq. (1). Fig. 1 shows the cruise velocity requirements from 8 to 20%c (where c=3×10^8 m s^{-1}), for different mission distances from 3 to 20 light years, assuming different mission durations from 40 to 100 years. Fig. 2 shows the mass ratio requirements for the same mission profiles. Fig. 1 shows that the distance attained is correlated to the final cruise velocity and mission duration. Fig. 2 shows that the ideal rocket equation imposes an exponentially increasing mass ratio in proportion to distance for a given mission duration. The distances for Barnard's star and Epsilon Eridani are highlighted with horizontal dashed lines (Fig. 1) and vertical dashed lines (Fig. 2). These lines form the boundary of the analysis for this paper. The Project Daedalus engineering design is also shown with a cruise velocity of 12.2%c, in a 50 year mission duration to 5.9 light years (Barnard's star).

We next consider the potential mission duration to Barnard's star 5.9 light years away, given different pulse frequencies. In all calculations we assume a constant

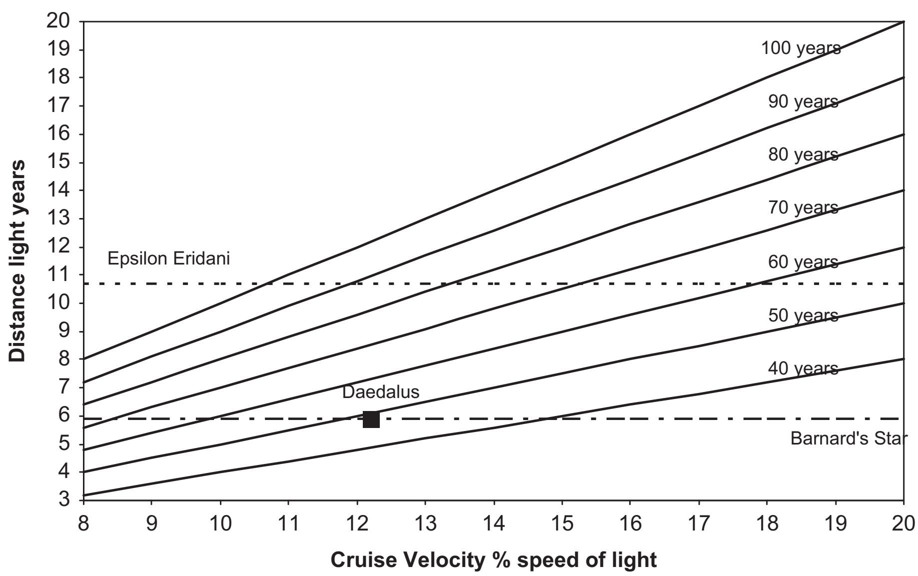

Fig. 1. Cruise velocity requirements for interstellar travel.

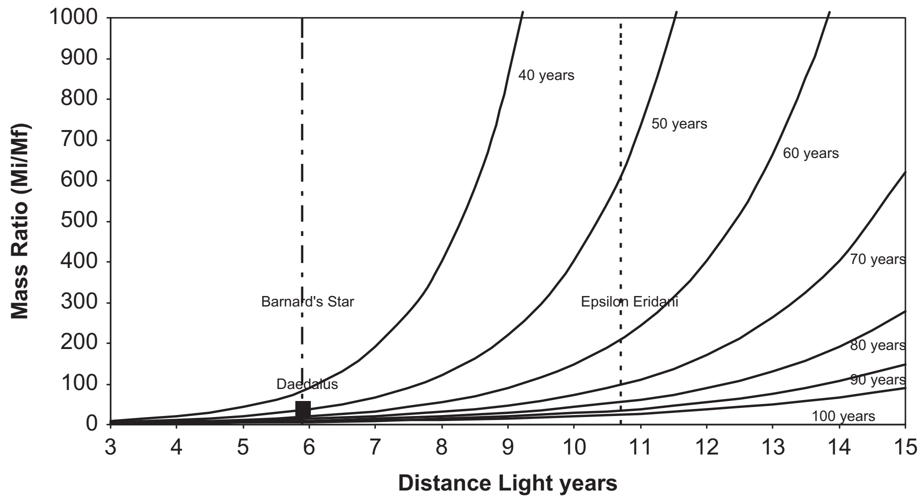

Fig. 2. Mass ratio requirements for interstellar travel.

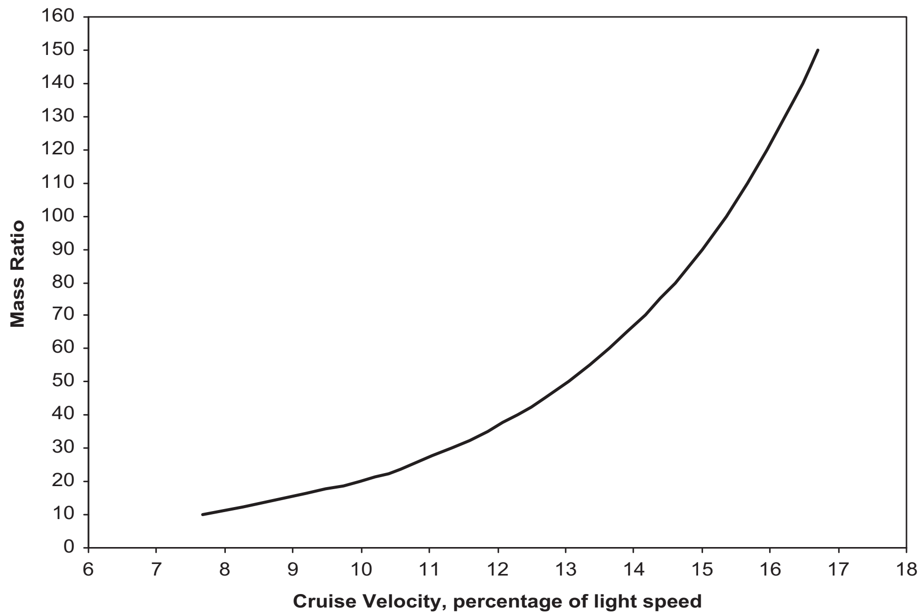

Fig. 3. The effect on final cruise velocity with mass ratio.

propellant mass of 50,000 tonnes, exhaust velocity 10^7 m s^{-1}, which for a Daedalus-like mass ratio of around 40 is consistent with a velocity increment of 12%c (3.6×10^7 m s^{-1}). The correlation between cruise velocity and the mass ratio is shown in Fig. 3. For this analysis we also note that 1 year=3.1536×10^7 s, 1l year=9.4605×10^{15} m. The total number of ICF pellets $N_{\rm pell}^{\rm tot}$ used during the boost phase can be described by relating it to the boost duration $t_{\rm b}$ and pulse frequency $f_{\rm Hz}$:

$$N_{\rm pell}^{\rm tot} = t_{\rm b} \times f_{\rm Hz} \tag{2}$$

For Daedalus, the boost phase duration was made up of two phases consisting of 2.05 years (1st stage) and 1.76 years (2nd stage) based upon optimisation of the two-stage masses for maximum velocity increment. For this analysis we approximate a total boost phase for a single stage vehicle to be 3.81 years. The Daedalus pulse frequency was 250 Hz, which gives a total of 3×10^{10} pellets. If we now assume this same number of pellets but for a different pulse frequency we arrive at a modified boost duration. For a mission with a 10 Hz frequency, this corresponds to a boost duration of around 95 years. Another way to estimate a modified boost duration is to consider the thrust difference due to a different mass flow rate $\dot{m}$. If we assume a total 50,000 tonnes (where 1 tonne=1000 kg) propellant mass and a mission duration of 3.81 years then the average mass flow rate is related by

$$\dot{m} = \frac{M_{\rm prop}}{t_b} \tag{3}$$

This computes to a mass flow rate of 0.416 kg s^{-1}. We can then relate this to the pulse frequency to estimate the average propellant mass $m_{\rm pell}$ by

$$m_{\rm pell} = \frac{\dot{m}}{f_{\rm Hz}} \tag{4}$$

which for a Daedalus pulse frequency of 250 Hz computes to an average pellet mass of 0.0017 kg. The actual Daedalus staged pellet masses are given in Table 1. If we change the pulse frequency to say 10 Hz then this results in a new mass flow rate of 0.017 kg s^{-1}, assuming the same propellant mass. Now the vehicle thrust is related to the exhaust velocity and mass flow rate by

$$T = \dot{m} \times v_e \qquad (5)$$

Table 1
Performance parameters for Project Daedalus engineering design.

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 (0.071*c*)	1.53×10^4 (0.051*c*)
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

With the average Daedalus-like pellet mass and exhaust velocity 10^7 m s^{-1} corresponding to a pulse frequency this computes to an average thrust of 4.16×10^6 N. Similarly, with the reduced pellet mass flow rate corresponding to a 10 Hz pulse frequency this computes to an average thrust of 1.7×10^5 N. So the newly derived thrust is a factor 25 less than our Daedalus-like thrust. One should therefore expect the boost duration to be increased by the same factor, so that 3.81 years × 25=95 years. This result is consistent with the estimate derived above for the boost duration. We can then estimate the distance achieved during the boost phase by use of the following logarithmic relation which neglects special relativistic effects, which we consider to be appropriate for low fractions of the speed of light [1]:

$$S_b = v_e t_b \left[1 - \frac{\mathrm{Ln}(R)}{R-1}\right] \qquad (6)$$

This results in a boost distance of 3.1 light years, which when subtracted from a total distance of 5.9 light years leaves 2.8 light years for the cruise phase. Assuming a cruise velocity of 15%c we easily determine the cruise duration by S_c/v_c, which is around 19 years. This means that for a reduced pulse frequency of 10 Hz the total mission duration will be around 114 years. Fig. 4 shows the results of conducting a similar calculation for a range of pulse frequencies and with different exhaust velocity assumptions, all for a Barnard's star mission. The profile for the Daedalus probe is also shown. Clearly, for a pulse frequency that drops below 100 Hz the total mission duration will start to increase rapidly. The *Project Icarus* ToR stipulates that the mission must be completed in less than a century. From these initial results much lower pulse frequencies would seem viable for a flyby probe. However, it is also a ToR constraint that the vehicle decelerates towards the target and so mid-range pulse

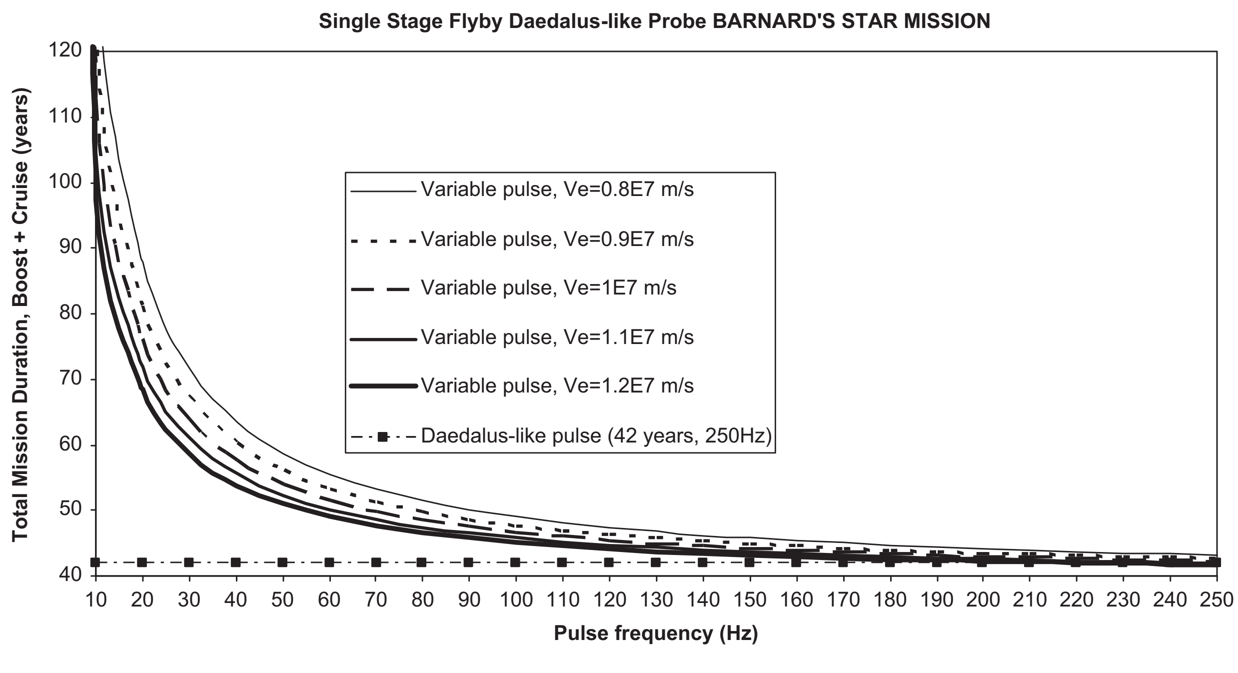

Fig. 4. Total mission duration to Barnard's star as a function of pulse frequency.

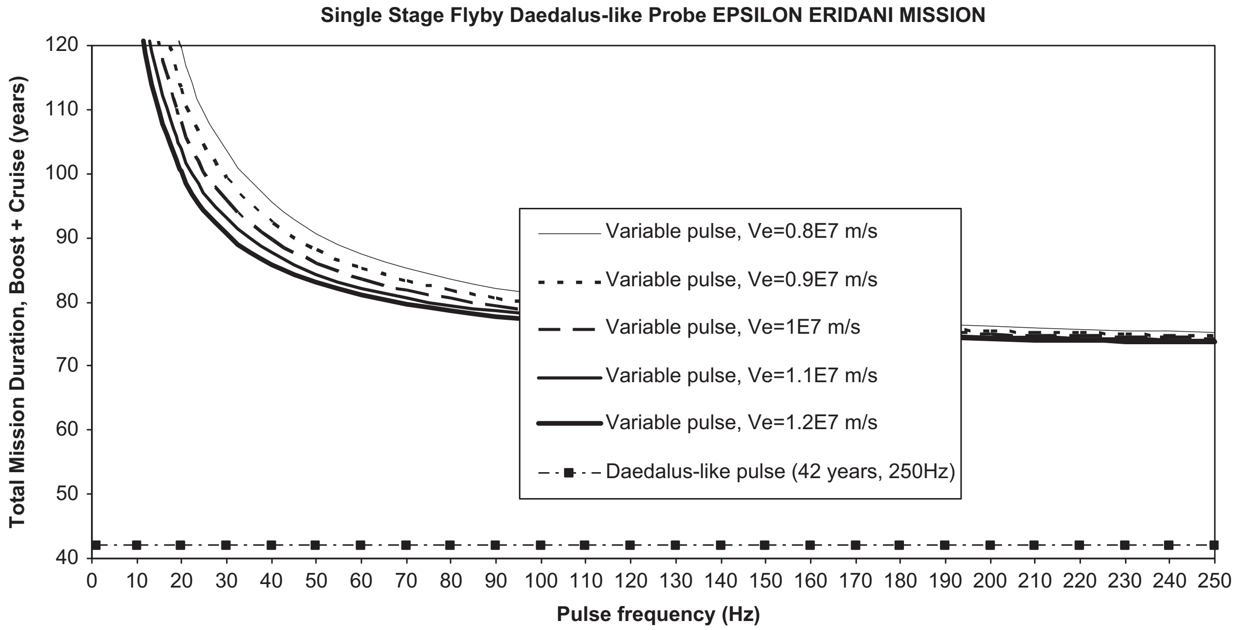

Fig. 5. Total mission duration to epsilon Eridani as a function of pulse frequency.

frequencies of around 100–150 Hz would seem more appropriate for a Barnard's star mission. Also shown below in Fig. 5 is a similar analysis for a mission to Epsilon Eridani 10.7 light years away. Using a Daedalus pulse frequency of 250 Hz the total mission duration will include a 3.7 year boost phase and a 70 year cruise phase with a total mission duration of 74 years. A pulse frequency of 10 Hz will require a boost phase of 93 years and a cruise phase of 51 years with a total mission duration of 144 years. With a pulse frequency of less than 10 Hz and a slightly reduced exhaust velocity from the $10^7\,\mathrm{m\,s^{-1}}$ nominal, total mission durations easily approach a millennium.

3. Configuration layouts

Table 1 shows the vehicle specification and performance for the 1st and 2nd stage Daedalus engine design. This is the starting point in any further analysis for different options, although we assume a constant exhaust velocity of $10^7\,\mathrm{m\,s^{-1}}$ in this paper so we refer to our baseline as Daedalus-like. We now consider different Daedalus variants, which have between 1 and 4 stages but with a constant total propellant mass of 50,000 tonnes and constant total structure mass of 2670 tonnes identical to our two-stage baseline. From this analysis we derive four different concepts as described below.

The derivation of these concepts involved several iterations. First an approach was adopted as described by Turner [6] to derive the optimum mass fractions for each stage. This is defined to be some fraction of unity from the total wet mass and includes the stage propellant, structure and payload. This involves computing the mass ratio R for a single stage Daedalus configuration (=19.73) as a fair test of the optimisation, the mass fractions A, B, C and D for each stage is then defined by

$$\text{Two-stage}: \quad A = R - 1/R; \quad B = 1/R;$$
$$\text{Three-stage}: \quad A = R - 1/R; \quad B = R - 1/R^2; \quad C = 1/R^2;$$
$$\text{Four-stage}: \quad A = R - 1/R; \quad B = R - 1/R^2; \quad C = R - 1/R^3; \quad D = 1/R^3$$

For the analysis the engine mass between the nominal Daedalus 1st and 2nd stage was found to be approximately in the ratio of 3.1. This same ratio was then adopted in deriving smaller engine masses for the lower stages. The engines masses were computed to be 988, 318, 103 and 33 tonnes for the 1st, 2nd, 3rd and 4th stage, respectively, of each configuration, although no assessment was performed on the actual specifics of engine design and whether these small engines sizes are even possible. There would obviously be a physical limit to how small the engine could be made, one of the reasons why it is no use to advance beyond 4 stages, apart from the diminishing gain in velocity increment. It is recognised that the assumption may not be valid, but for the purposes of this crude trade study the assumption is made until further work on potential engine designs is performed.

For the configurations derived, the aim of this analysis was to optimise for near equal payload fraction which was assumed to represent a configuration with optimum velocity increments. The payload fraction is the ratio of payload mass to sum of propellant and structure mass. Because the total mass has been fixed, this means that for increased number of stages the final science payload mass will decrease. For the 3 and 4-stage configurations this came out as 170 and 50 tonnes, respectively, which compares with the 450 tonnes for the nominal 2-stage design. In order to get some final payload mass back a minor amount of the structure and propellant masses were then swopped between the stages which moved the configuration further away from optimum, which leads to the payload fractions described above. For the first stage of each configuration the actual mass fractions are within around 10% of the theoretical optimum but for the higher stages the optimality gets progressively worse. Thus the final configurations are not fully optimised and this is due to a decision to maintain a reasonably high final science payload mass. If this decision had not been made then the final stage masses (structure+payload+propellant) for the 3 and 4-stage configurations would have been 0.0025 and 0.0001 M_{tot}, respectively (where M_{tot}=52,670 tonnes is the total vehicle wet mass), which computes to 132 and 5 tonnes, respectively, leaving little margin for a science payload. This suggests a trade-off is required and a reason for maintaining a low number of stages.

4. Configuration performance

We already know the 2-stage mission profile as this is the Daedalus baseline, although we need to extend this to an Epsilon Eridani mission as well as Barnard's star. For each configuration we need to describe the acceleration profile along with the staged and final velocity increment achieved for the cruise phase. Each boost phase duration will also be described including the final mission duration.

Because the propellant mass was held constant at 50,000 tonnes it had to be distributed over the different stages. This was done starting with the first stage and assuming the large pellet mass size and this overlapped into the second stage. Once the 46,000 tonnes was reached (the total propellant mass for Daedalus containing the large pellet masses) then any remaining mass in the second stage was assigned a small pellet mass and so on for any subsequent stages. In other words for all the concepts 46,000 tonnes was made up of large ~3 g pellet masses and 4000 tonnes was made up of small ~0.3 g pellet masses, consistent with the baseline design as shown in Table 1. It is recognised that in reality the engine performance will be sensitive to the pellet mass and for different stages in the vehicle the pellets may be design optimised for each stage. However, this assumption will have to remain a caveat for this initial study.

The total number of large and small pellets was then calculated for each stage and each was then separately divided by the nominal 250 Hz pulse frequency to get an estimate for the burn duration, i.e.

$$t_b = \frac{N_{pell}^{per\_stage}}{f_{Hz}} \tag{7}$$

Once the burn time per stage was obtained the distance travelled per stage burn could be calculated using Eq. (6) with a modified additional term added to the equation to take into account the initial velocity at the start of each stage burn:

$$S_b = v_o t_b + v_e t_b \left[1 - \frac{\text{Ln}(R)}{R-1}\right] \tag{8}$$

The initial velocity v_o was obtained by using Eq. [1].

The configurations and performance for the 3 and 4-stage concepts are shown in Table 3. We note that final cruise velocities are obtained of 13.8%c and 15.3%c for the 3 and 4-stage concept, respectively. Assuming the same boost profile, one can then work out the total mission duration to the two astronomical targets. For Barnard's star 5.9 light years away, the total boost duration will last for 3.1 years for the 3-stage and 3.6 years for the 4-stage concept, leading to a total mission duration of 40.5 and 35.4 years, respectively. For epsilon Eridani 10.7 light years away, the total boost duration will be the same and the total mission duration for the 3 and 4-stage concepts will be 78.4 and 70.5 years, respectively. To put these numbers into context, for the 2-stage Daedalus-like concept employed in this work as a baseline, the final cruise velocity was 12.3%c with a total boost duration of 3.81 years. The total mission duration to Barnard's star was 49.9 years and for epsilon Eridani was 88.9 years. This is shown in Table 2. The mission profiles and concept configurations are illustrated in Figs. 6 and 7 (Table 3).

Now that we have a working mission profile and performance for each of the configurations, it will be possible to consider further optimisation of the trajectory based upon the pulse frequency. We can choose to optimise this parameter for the maximum cruise velocity (to minimise total mission duration) whilst aiming for a minimum boost period (to maximise propellant utilisation early on). Although the latter requirement is done in conjunction with the desire to aim for a reasonable detonation repetition rate so as to not over stress the engines, vehicle structure and laser driver requirements.

Table 2
Daedalus variants.

	1-Stage concept	2-Stage concept
1st stage	50,000 tonnes propellant 2670 tonnes structure ΔV 29,819 km/s (0.099c) Burn time 3.81 years Stage distance 0.107 light years	46,000 tonnes propellant 1690 tonnes structure ΔV 20,664 km/s (0.069c) Burn time 2.05 years Stage distance 0.048 light years
2nd stage	–	4000 tonnes propellant 980 tonnes structure ΔV 16,256 km/s (0.054c) Burn time 1.76 years Stage distance 0.224 light years
Final payload[a]	450 tonnes	450 tonnes
Cruise velocity	29,819 km/s (0.099c)	36,921 km/s (0.123c)
Total burn time	3.81 years	3.81 years
Boost distance	0.107 light years	0.224 light years
Cruise time BS[b]	58.29 years	46.12 years
Total mission BS	62.1 years	49.93 years
Cruise time EE[c]	106.58 years	85.12 years
Total mission EE	110.39 years	88.93 years

[a] Refers to science payload.
[b] BS=Barnard's star.
[c] EE=Epsilon Eridani.

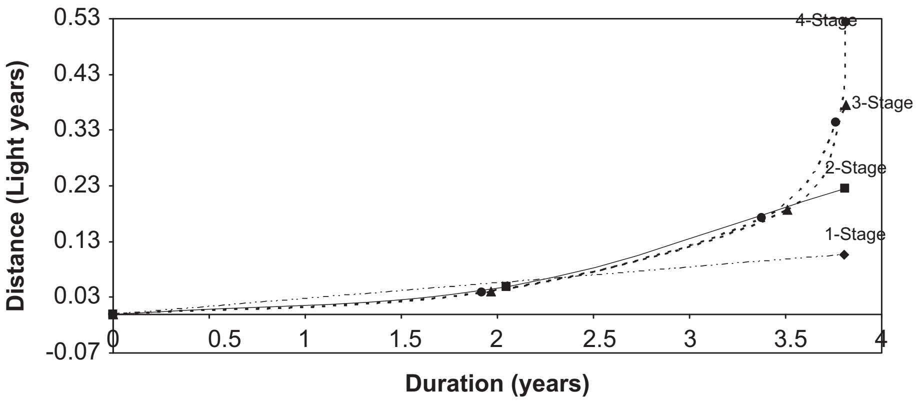

Fig. 6. Mission profiles for different Daedalus-like staged configurations during boost phase.

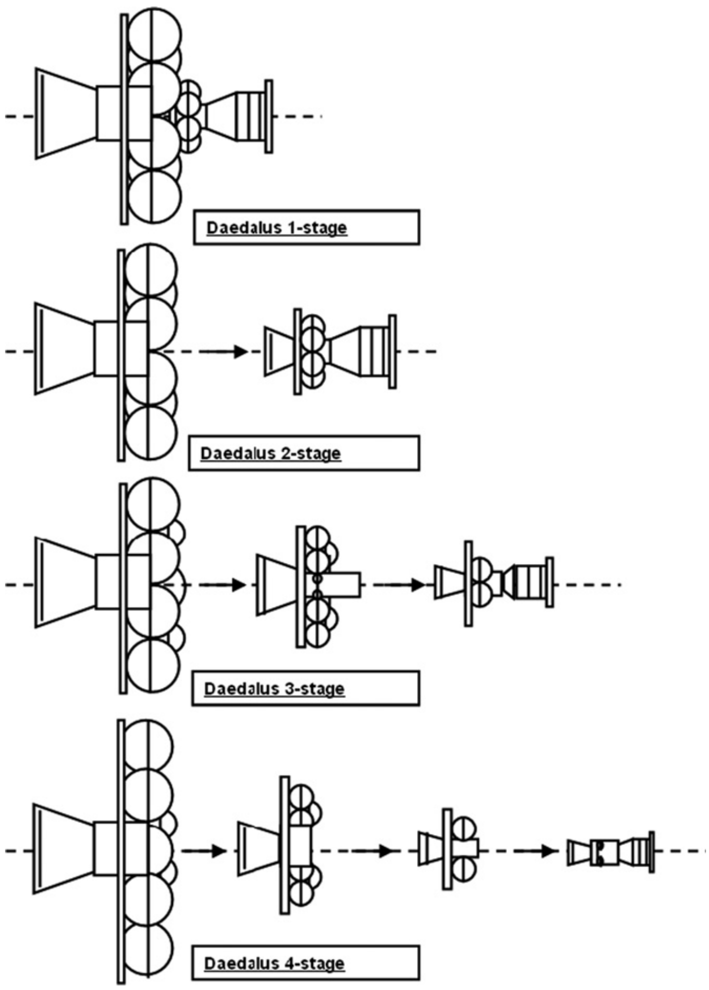

Fig. 7. Daedalus-like concept variants with 1–4 stages.

This will then lead us to a revised mission profile. From an examination of Figs. 4 and 5 we observe that this requirement appears to be met for a pulse frequency of around 100–150 Hz, which corresponds to a boost duration of around 6–9 years, as is easily demonstrated by using Eq. (2). Minimising the pulse frequency further leads to an exponentially increased mission duration. The optimum pulse frequency for a given mission and vehicle parameters can best be observed by combining Eqs. (2) and (8) to give an expression for the total mission duration:

$$t_{tot} = \frac{S_{tot}}{V_c} + \frac{N_{pell}^{tot}}{f_{Hz}}\left[1 - \frac{V_o}{V_c} - \frac{V_e}{V_c}\left(1 - \frac{\mathrm{Ln}(R)}{R-1}\right)\right] \quad (9)$$

In this equation V_o is the initial velocity at final stage burn and V_c is the total cruise velocity after final stage

Table 3
Daedalus variants.

	3-Stage concept	4-Stage concept
1st stage	44,081 tonnes propellant 1300 tonnes structure ΔV 18,137 km/s (0.06c) Burn time 1.97 years Stage distance 0.04 light years	44,149 tonnes propellant 1150 tonnes structure ΔV 16,949 km/s (0.056c) Burn time 1.92 years Stage distance 0.039 light years
2nd stage	6218 tonnes propellant 1000 tonnes structure ΔV 12,587 km/s (0.042c) Burn time 1.54 years Stage distance 0.187 light years	7050 tonnes propellant 1050 tonnes structure ΔV 12,179 km/s (0.041c) Burn time 1.45 years Stage distance 0.172 light years
3rd stage	1070 tonnes propellant 370 tonnes structure ΔV 10,619 km/s (0.035c) Burn time 0.3 years Stage distance 0.375 light years	1235 tonnes propellant 360 tonnes structure ΔV 9035 km/s (0.03c) 0.38 years Stage distance 0.344 light years
4th stage	–	236 tonnes propellant 110 tonnes structure ΔV 7634 km/s (0.025c) Burn time 0.05 years Stage distance 0.524 light years
Final payload[a]	170 tonnes	51 tonnes
Cruise velocity	41,343 km/s (0.138c)	45,796 km/s (0.153c)
Total burn time	3.81 years	3.81 years
Boost distance	0.375 light years	0.524 light years
Cruise time BS[b]	40.09 years	35.22 years
Total mission BS	43.91 years	39.03 years
Cruise time EE[c]	74.92 years	66.66 years
Total mission EE	78.74 years	70.48 years

[a] Refers to science payload.
[b] BS=Barnard's star.
[c] EE=Epsilon Eridani.

Table 4
Minimum pulse frequency requirements and maximum allowable boost period duration.

Configuration	Barnard's star (Hz)	Epsilon Eridani (Hz)
2-Stage	5	20
3-Stage	3	6
4-Stage	2	3

burn. R is the mass ratio of the final stage. Any numbers put into this equation must be self consistent with a designed mission profile and vehicle configuration. This can then be re-arranged to find the minimum pulse frequency required to achieve the stated mission duration of 100 years:

$$f_{Hz} = N_{pell}^{tot}\left[1-\frac{V_o}{V_c}-\frac{V_e}{V_c}\left(1-\frac{\mathrm{Ln}(R)}{R-1}\right)\right]\left(t_{tot}-\frac{S_{tot}}{V_c}\right)^{-1} \tag{10}$$

If we assume an exhaust velocity of 10^7 m s^{-1}, total propellant number 3×10^{10}, and the final cruise velocities achieved for each configuration derived and their respective final staged mass ratios, this leads to the results shown in Table 4 for the minimum pulse frequency required for a 100 year mission, but for flyby (no deceleration) only.

5. ICF pellets

The discussion above assumed the nominal Daedalus DHe^3 pellet design. However, we ideally also need to consider the use of a DT propellant combination as well as a different type of pellet design. For this we can turn to a design that is much smaller, something typical of a National Ignition Facility (NIF) baseline target [5]. The obvious fact to point out is that the much smaller pellets will have much less mass to potentially ignite and so produce a much smaller amount of energy. The difference is an energy release of tens to hundreds of GJ for the Daedalus-like pellets compared to only 10–20 MJ for the NIF-like pellets. This will inevitably affect the acceleration profile and thereby elongate the boost duration. The two different pellet geometries can be chosen to represent extremes of design mass and radii. It is assumed that any ICF pellet design chosen for the Icarus vehicle will likely be smaller than those used for Daedalus (to minimise propellant mass) but much bigger than those being used for NIF (in order to get the required energy out). Fig. 8 shows the Daedalus and NIF pellets compared. Future research will consider these two extremes in pellet design as applied to the vehicle configuration layouts and mission profiles derived in this paper.

It is worth comparing the pellet sizes discussed above to those for other theoretical design studies that utilised ICF based propulsion schemes. The first was Project Longshot [7], a US Naval Academy study conducted in the 1980s for a mission to Alpha Centauri in around 100 years. It proposed the use of DHe^3 fuel with pellet masses between 0.005 and 0.085 g detonated at a pulse frequency between 14 and 250 Hz. Another (more credible) study was Project VISTA [8] led by a designer from Lawrence Livermore National Laboratory in the late 1980s and was designed for interplanetary missions. This was again an ICF based engine design but would use a DT propellant combination and the ignition by a 5 MJ laser driver would be enhanced by the use of a Fast Ignition technique to produce 7500 MJ per pellet, which would allow high energy gain up to 1500. The pellets would be detonated at a rate of between 0 and 30 Hz and each had a mass of 0.066 g. Comparing the pellet configurations proposed for these vehicles to the designs proposed for Daedalus we observe that these are a lot lower than the 1st stage pellet mass, although this could be a result of lack of a proper design evaluation for LONGSHOT and a less ambitious mission requirement for VISTA. However, it does make one question the large 1st stage pellet masses proposed

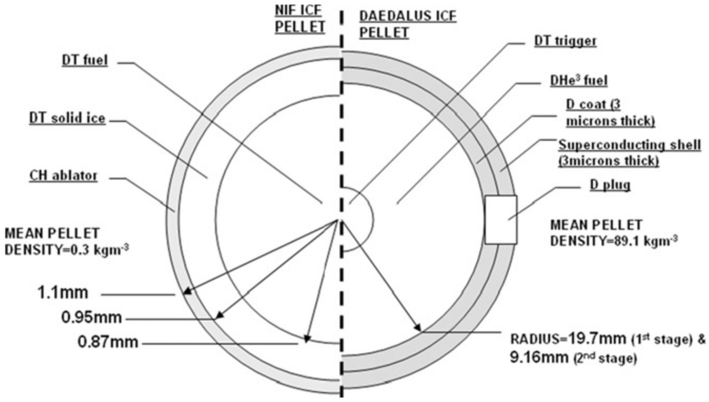

Fig. 8. NIF/Daedalus ICF pellet design comparison.

Table 5
Fusion reaction energy release from single reaction assessment.

Propellant/products	Exhaust velocity (km/s)
DT/He^4+n	26,400 (8.67%c)
DHe^3/He^4+p	26,500 (8.85%c)
DD/He3+n	12,500 (4.17%c)
DD/T+p	13,900 (4.64%c)

for Daedalus and to aim for something smaller in the design. This will be the subject of future research.

It is also constructive to consider what is the maximum performance that you can get from a fusion based rocket engine? This is also important in determining the type of fuel to use in an ICF pellet. We can approach this question in terms of exhaust velocity. We shall calculate the maximum performance based upon two methods. Firstly, we shall simply look at the difference in mass between the two reacting particle species and then consider the kinetic energy of the excess mass.

Next we shall examine the question from the stand point of enthalpy. We begin by examining the DHe^3 reaction, which gives the products of He^4 and a proton. Looking at the atomic mass unit balance between the reaction products and the released products we have: 2.013553+3.014932→4.001506+1.007276. The difference in mass between the two sides of the reaction is 0.019703. We next consider what kinetic energy is associated with this mass difference. The fractional energy release ε for the DHe^3 combination is simply the mass difference divided by the total mass of the reacting products 0.019703/(2.013553+3.014932)=0.00392. A similar calculation for the DT propellant combinations will yield a fractional energy release of 0.00375. We then work out the thermal exhaust velocity V_e by inverting the equation for kinetic energy:

$$V_e = \left(\frac{2E_{kin}}{m}\right)^{1/2} \tag{11}$$

Then using $E=\varepsilon mc^2$, the mass cancels and we are left with an equation for the exhaust velocity as a function of the fractional energy release to be $V_e = (2\varepsilon)^{1/2}\ c \approx 0.088c$. This is nearly 9%$c$ and corresponds to a velocity of 26,500 km/s. The performance for the two propellant combinations is shown in Table 5. This is the maximum theoretical performance of a fusion based engine although subsequent energy from reacting products will also increase this maximum. In reality, efficiency issues will come in such as burn fraction and this will reduce the potential exhaust velocity. Neutron energy losses will also reduce the DT exhaust velocity, not an issue for DHe^3 which produces protons in the reaction (also useful for magnetic thrust directivity due to the charge). For comparison a Daedalus-like engine has an exhaust velocity of around 10,000 km s^{-1}, much less than the theoretical values shown in Table 5.

6. Conclusions

In this paper we have assessed two mission profiles and discussed two types of ICF pellet configurations for a nuclear pulse propulsion based engine. These results form the lower and upper bound extremes of the design envelope to aid further design discussions. The concepts presented are not claimed to be 'designs' or even properly optimised but merely configuration concepts to assist in scoping the design envelope. In fact the need to maintain a high final science payload mass took the configurations off-optimal. The 3 and 4-stage configurations presented above were not optimum designs and future work will aim to continue to evolve these concepts towards a fully optimum layout. These results suggests a trade-off where you can have either a low final science payload mass (and maintain an optimal configuration) or much higher final science payload mass (but for a non-optimal configuration). The problem is more pronounced the higher the number of stages, hence a move to a 4-stage configuration should be avoided and even a move to a 3-stage configuration would require some thought for a fixed total vehicle wet mass.

The results show that within a constrained total propellant and total structure mass increased staging leads to a decreased final payload mass. Hence to maintain a constant payload one must either increase the total mass or be satisfied with a lower staging layout. In order to reach a destination further in distance one must either increase the cruise speed attained or elongate the total mission duration. Within the constraints of a total vehicle mass the advantages of moving to a 4-stage design do not allow for significant performance enhancement whilst also reducing the final science payload mass. A 4-stage design is therefore not recommended within the constraints of this study unless a final science payload mass of 50 tonnes is considered acceptable. It is suggested that the Daedalus pulse frequency of 250 Hz was ambitious and in order to reduce the impact on the engine and structure a more moderate pulse frequency of less than 150 Hz would be more appropriate, consistent with the frequencies discussed for next-generation nuclear fusion reactors. Dropping the pulse frequency much below 50 would lead to an elongated mission duration. Clearly, pellet masses of the size fielded at NIF are completely inadequate for the required mission performance, whether filled with DT or DHe^3, suggesting a minimum pellet mass of order on hundredth of a gram but something less than the large pellet masses proposed for the Daedalus 1st stage in order to decrease the overall propellant mass, a philosophical aim of the *Project Icarus Study Group*.

Initial calculation suggests that the 100 year limit imposed by the project ToR could allow a target at 20 light years distance to be reached but assuming a cruise speed of 0.2*c* is attained, an ambitious project. Cruise speeds of 0.1–0.15*c* are more likely suggesting an upper distance boundary of around 15 light years. Such a mission would necessitate a mass ratio of around 100 and that depends inversely on the mission duration, i.e. the quicker the mission is achieved the larger the mass ratio required.

From the results of this initial scoping study to date and some other considerations (i.e. reliability) some performance ranges are recommended as likely parameters for the Icarus mission:

Mission duration: 40–70 years
Cruise speed: 0.1–0.15*c*
Boost phase: 2–5 years
Exhaust velocity: $0.8\text{–}1.2 \times 10^7$ m s^{-1}
Mass ratio: 10–150
Pellet size: 0.01–1 g
Pulse frequency: 10–150 Hz
Science payload: 50–200 tonnes
Number stages: 2–3

All above assumes flyby only and consideration is required as to the effects of deceleration, which may alter the conclusions. It should be the aim of the continuing design work to reduce the overall mass of the propellant and vehicle structure whilst aiming for a more efficient engine design for high performance such as by investigating fast ignition and antimatter catalysed fusion techniques. Future work will evolve the Daedalus-like configurations further and then apply different propellant combinations (DHe^3, DT) to each one so as to better understand the performance limitations of varying pellet designs for a given mission profile.

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