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PROJECT ICARUS: OPTIMISATION OF NUCLEAR FUSION PROPULSION FOR INTERSTELLAR MISSIONS

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The historical 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 target 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 30th 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 utilization for two different mission targets; Barnard's Star and Epsilon Eridani, 10.7 light years away. With a fixed propellant mass the number of stages (1-4) is optimized for maximum cruise velocity and minimum boost period. In the second part of this paper we re-examine the Daedalus ICF pellet design and consider alternative pellet designs for use in long duration space missions. This includes both DHe^3 and DT within a Daedalus pellet geometry and DHe^3 and DT within the geometry of typical pellets fielded at the National Ignition Facility (NIF). Some comparisons are made to the claimed performance of the historical Vista and Longshot fusion based propulsion designs. This is a submission of the Project Icarus Study Group.

I. INTRODUCTION

In the 1970s members of The British Interplanetary Society (BIS) designed a flyby interstellar probe aimed at Barnard's star as the mission target. This was a theoretical study aimed to prove that interstellar travel was possible in principle and thus addressing aspects of the Fermi paradox. This is the problem proposed by the Italian physicist Enrico Fermi in the 1950s that our theoretical expectation of encountering intelligent life in the galaxy is in contradiction to our observations. *Project Daedalus* [1] was a landmark study covering all of the major spacecraft systems, comprehensively designed by application of rigorous scientific techniques.

On the 30th 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]. This project aims to revisit the historical design and improve it with the three decades of advances in physics, engineering and our knowledge 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 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 (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.

In this study we focus on two elements (1) ICF based propellant configuration (2) Mission profile. The intention in this work is to focus on the extremes of the design envelope so as to bound the potential performance. For the ICF pellet designs we consider large configurations (as proposed for Daedalus) and small configurations (as proposed for commercial fusion reactor demonstrators). Following a similar philosophy we consider a far distant mission target (epsilon Eridani at 10.7 light years) and a close mission target (Barnard's star at 5.9 light years distance). 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 III and no down select on options will be performed until after this phase is completed.

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

$$\Delta v = v_{ex} Ln\left(M_i / M_f\right) \quad [1]$$

Figure 1 and 2 shows the basic requirements for trips to the nearest stars calculated using Eq.[1]. Figure 1 shows the cruise velocity requirements from 8 – 20% of light speed, for different distances from 3 – 20 light years, assuming different mission durations from 40 – 100 years. Figure 2 shows the mass ratio requirements for the same mission profiles. The distances for Barnard's Star and Epsilon Eridani are highlighted with horizontal dashed lines (Figure 1) and vertical dashed lines (Figure 2). The Project Daedalus engineering design is also shown with a cruise velocity of 12.2% of light speed, in a 40 year mission duration to 5.9 light years (Barnard's Star). We note that the ideal rocket equation imposes an exponentially increasing mass ratio in proportion to distance for a given mission duration.

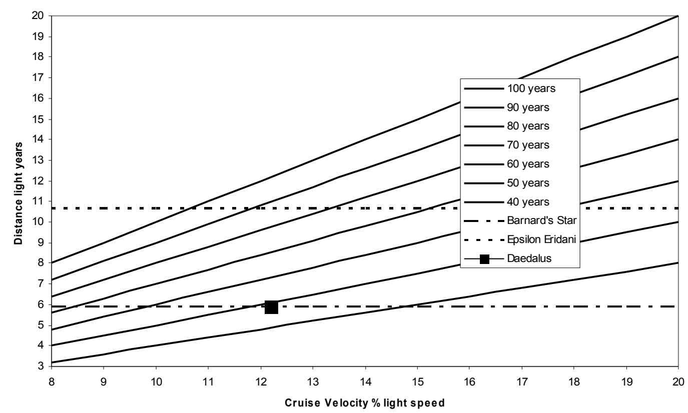

Fig. 1: Cruise velocity requirements for interstellar travel

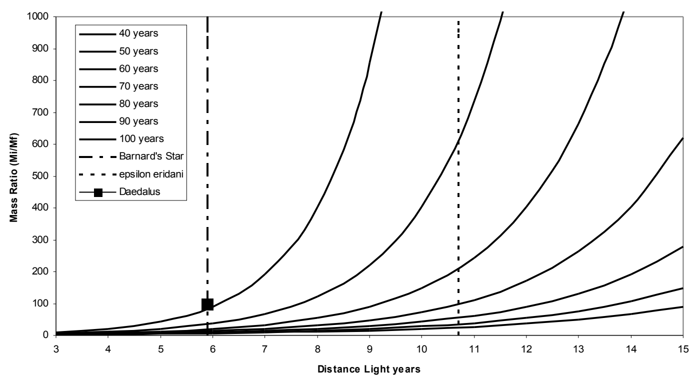

Fig. 2: Mass ratio requirements for interstellar travel

We next consider the potential mission duration to a target like Barnard's star 5.9 light years away, given different pulse frequencies. In all calculations we assume a constant propellant mass of 50,000 tonnes, exhaust velocity 10^7 ms^{-1}, mass ratio = 90, consistent with a velocity increment of 15 % light speed (4.5×10^7ms^{-1}). The correlation between cruise velocity and the mass ratio is shown in Figure 3. For this analysis we also note that 1 year = 3.1536×10^7s, 1ly = 9.4605×10^{15}m. The total number of ICF pellets N_{pell}^{tot} used during the boost phase can be described by relating it to the boost duration and pulse frequency

$$N_{pell}^{tot} = t_b \times f_{Hz} \quad [2]$$

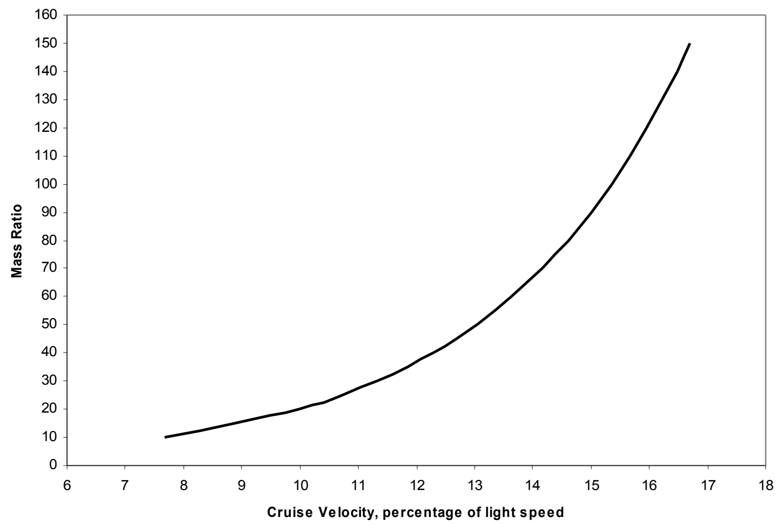

Fig. 3: The effect on final cruise velocity with mass ratio

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). 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 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. We assume a total 50,000 tonnes (where 1tonne = 1000 kg) propellant mass and a mission duration of 3.81 years then the average mass flow rate is related by

$$M_{prop} = \dot{m} \times t_b \qquad [3]$$

This computes to a mass flow rate of 0.416 kgs^{-1}. We can then relate this to the pulse frequency to estimate the average propellant mass by

$$\dot{m} = m_{pell} \times f_{Hz} \qquad [4]$$

Which for a Daedalus pulse frequency of 250 Hz computes to an average pellet mass of 0.0017 kg (for interest the actual Daedalus pellet masses are given in Table 1). If we then change the pulse frequency to say 10 Hz then this results in a new mass flow rate of 0.017 kgs^{-1}. Now the vehicle Thrust is related to the exhaust velocity and mass flow rate by

$$T = \dot{m} \times v_e \qquad [5]$$

With the average Daedalus-like pellet mass and pulse frequency this computes to an average thrust of 4.16×10^6 N. Similarly, with the reduced pellet mass corresponding to a 10 Hz pulse frequency this computes to an average thrust of 1.66×10^5 N. So the newly derive 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 relation [1]

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

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 % of light speed we easily determine the cruise duration by S_c/v_c which is around 19 years. This means that for the reduced pulse frequency of 10 Hz the total mission duration will be around 114 years. Figure 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 target. 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 frequencies of around 100 – 150 Hz would seem more appropriate for a Barnard's star mission. Also shown below in Figure 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. To keep the mission within the ToR century constraint would require a pulse frequency of at least 30 Hz. With a pulse frequency of less than 10 Hz and a slight reduced exhaust velocity from the $10^7 ms^{-1}$ nominal, total mission durations easily approach a millennium.

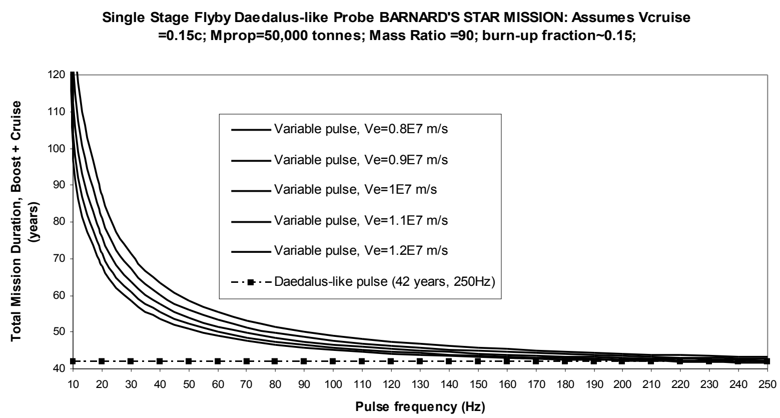

Fig. 4: Total mission duration to Barnard's Star as a function of pulse frequency

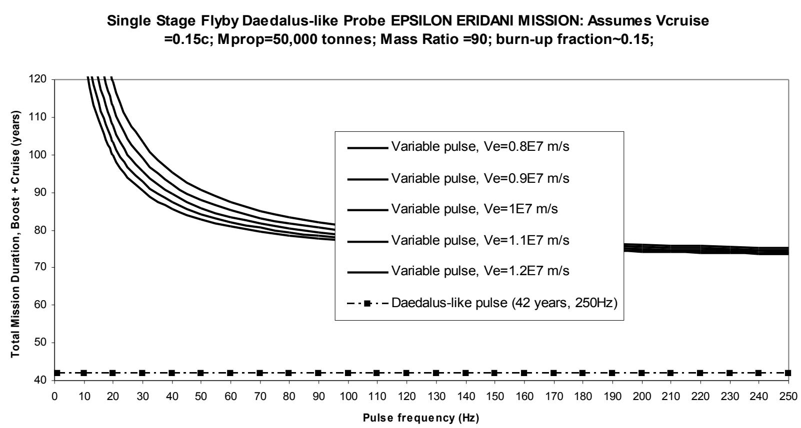

Fig. 5: Total mission duration to epsilon Eridani as a function of pulse frequency

II. CONFIGURATION LAYOUTS

Table 1 shows the vehicle specification and performance for the 1st and 2nd stage Daedalus engine design. This is the starting baseline in any further analysis for different options, although we assume a constant exhaust velocity of 107m/s so we refer to our baseline as Daedalus-like instead of Daedalus. Later assumptions in the pellet masses also make the use of this terminology appropriate. We now consider different Daedalus variants which have between 1 – 4 stages but with a constant propellant mass of 50,000 tonnes and constant total structure mass of 2670 tonnes. From this analysis we have four different concepts as illustrated in Figure 6.

Parameter	1st Stage value	2nd Stage value
Propellant mass (tonnes)	46,000	4,000
Structure mass (tonnes)	1,690	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 (0.71c)	3.66×10^4 (0.12c)
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 (J)	2.7×10^9	4×10^8
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

Table 1: Performance parameters for Project Daedalus engineering design

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 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, D for each stage is then defined by

Two-Stage: $A = R\text{-}1 / R$; $B = 1 / R$;

Three-Stage: $A = R\text{-}1 / R$; $B = R\text{-}1 / R^2$; $C = 1 / R^2$;

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

For the analysis the engine mass between the nominal Daedalus 1st and 2nd stage was found to be approximately in the ratio of π. This same ratio was then adopted in deriving smaller engine mass for the lower stages. The engines masses were computed to be 988 tonnes, 318 tonnes, 103 tonnes and 33 tonnes for the 1st, 2nd, 3rd, 4th stage respectively of each configuration. There would obviously be a physical limit to how small the engine could be made, just one of the reasons why it is no use to advance beyond 4-stages, apart from the decreasing gain in velocity increment.

For the configurations derived the target was to optimise for near equal payload fraction which was assumed to represent a configuration with optimum velocity increments. For the 3-stage concept these were obtained to be 0.161, 0.172 and 0.159 for the 1st, 2nd and 3rd stage respectively. For the 4-stage concept these were obtained to be 0.193, 0.209, 0.191 and 0.214 for the 1st, 2nd, 3rd and 4th stage respectively. This compares with 0.104 and 0.09 for the 2-stage Daedalus-like concept used in this analysis. For this near-optimum configuration the mass ratios in the 3-stage concept were found to be 6.13, 3.52 and 2.89 for the 1st, 2nd and 3rd stage respectively. For the 4-stage concept the mass ratios were found to be 5.45, 3.38, 2.47 and 2.15 for the 1st, 2nd, 3rd and 4th stage respectively. This compares with mass ratios of 7.89 and 5.08 for the 1st and 2nd stage 2-stage Daedalus-like concept used in this analysis.

Because the total mass has been fixed, this means that for increased number of stages the final science payload ratio will decrease. For the 3 and 4-stage configurations this came out as 170 tonnes 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 moves the configuration slightly away from optimum, which leads to the payload fractions described above.

We already know the two-stage mission profile as this is the Daedalus baseline, although we need to extend this to an epsilon Eridani mission target 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 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 until the 46,000 tonnes was reached into the higher stages. All tanks which constituted part of this mass were then assigned large pellets with mass 3g. All other masses were assigned pellet masses of 0.3g. 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.

$$t_b = N_{pell,per\_stage} \times f_{Hz}^{-1} \qquad [7]$$

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

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

The initial velocity was obtained by using Eq.[1]. The configurations and performance for the 3 and 4-stage concepts is shown in Table 2. We note that final cruise velocities are obtained of 13.8% and 15.3% light speed for the 3 and 4-stage concept respectively. Assuming the same boost profile, one can the work out the total mission duration to our 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 years 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% of light speed 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. The mission profiles for the various concepts are illustrated in Figure 6.

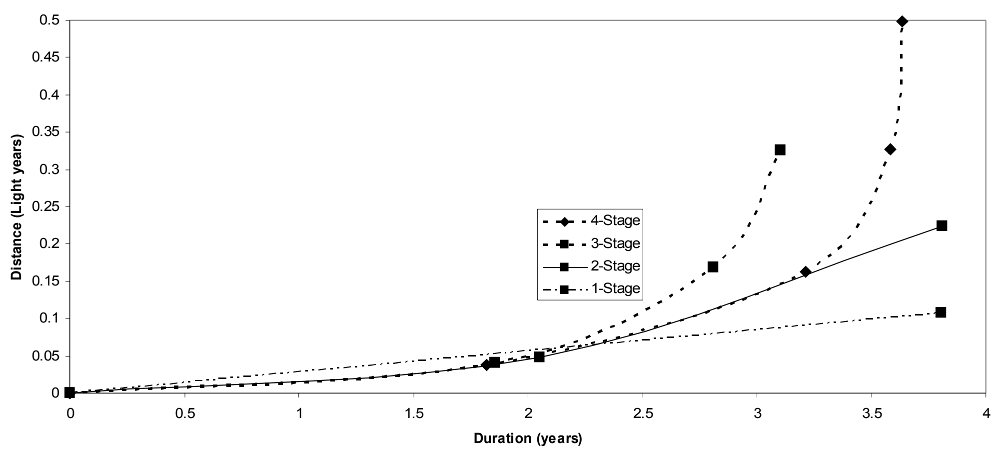

Fig. 6: Mission profiles for different staged configurations during boost phase

	1-Stage Concept	2-Stage Concept
1st stage	50,000 tonnes propellant	46,000 tonnes propellant
	2670 tonnes structure	1690 tonnes structure
	dV 29,819 km/s (0.099c)	dV 20,664 km/s (0.069c)
	Burn time 3.81 years	Burn time 2.05 years
	Stage distance 0.107 light years	Stage distance 0.048 light years
2nd stage		4000 tonnes propellant
		980 tonnes structure
	--	dV 16,256 km/s (0.054c)
		Burn time 1.76 years
		Stage distance 0.224 light years
Final payload	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	58.29 years	46.12 years
Total Mission BS	62.1 years	49.93 years
Cruise time EE	106.58 years	85.12 years
Total Mission EE	110.39 years	88.93 years

Table 2: Daedalus variants with constant total propellant mass 50,000 tonnes, total structure mass 2670 tonnes and constant exhaust velocity 10^7 m/s.

	3-Stage Concept	4-Stage Concept
1st stage	44,081 tonnes propellant	44,149 tonnes propellant
	1,300 tonnes structure	1,150 tonnes structure
	dV 18,137 km/s (0.06c)	dV 16,949 km/s (0.056c)
	Burn time 1.86 years	Burn time 1.818 years
	Stage distance 0.04 light years	Stage distance 0.038 light years
2nd stage	6,218 tonnes propellant	7,050 tonnes propellant
	1,000 tonnes structure	1,050 tonnes structure
	dV 12,587 km/s (0.042c)	dV 12,179 km/s (0.041c)
	Burn time 0.95 years	Burn time 1.295 years
	Stage distance 0.168 light years	Stage distance 0.163 light years
3rd stage	1,070 tonnes propellant	1,235 tonnes propellant
	370 tonnes propellant	360 tonnes structure
	dV 10,619 km/s (0.035c)	dV 9,035 km/s (0.03c)
	Burn time 0.296 years	0.367 years
	Stage distance 0.325 light years	Stage distance 0.327 light years
4th stage		236 tonnes propellant
	---	110 tonnes propellant
		dV 7,634 km/s (0.025c)
		Burn time 0.053 years
		Stage distance 0.498 light years
Final payload	170 tonnes	51 tonnes
Cruise velocity	41,343 km/s (0.138c)	45,796 km/s (0.153c)
Total burn time	3.106 years	3.636 years
Boost distance	0.325 light years	0.498 light years
Cruise time BS	40.45 years	35.39 years
Total Mission BS	43.56 years	39.02 years
Cruise time EE	75.29 years	66.83 years
Total Mission EE	78.39 years	70.47 years

Table 3: Daedalus variants with constant total propellant mass 50,000 tonnes, total structure mass 2670 tonnes and constant exhaust velocity 10^7 m/s.

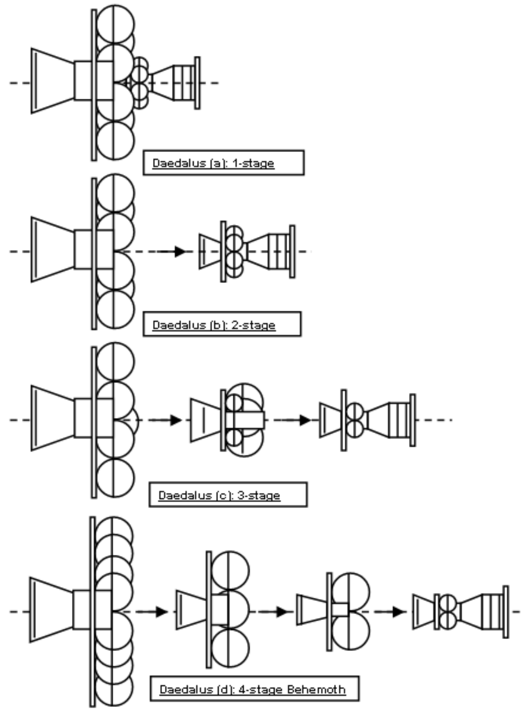

Fig. 6: Daedalus concept variants with 1 - 4 stages

III. FURTHER OPTIMISATION OF PERFORMANCE

Now that we have a working mission profile and performance for each of the configurations, we next consider further optimisation of the trajectory based upon the pulse frequency. We choose to optimise this parameter for maximum cruise velocity (to minimise total mission duration) and 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. This will then lead us to a revised mission profile. We first need to analyse the configuration but with a different pulse frequency spanning from 10 - 250 Hz.

TO BE DONE

IV. ICF PELLET CONSIDERATIONS FOR ICARUS

The discussion above assumed the nominal Daedalus DHe^3 pellet design. However, we also need to consider the use of a DT propellant combination as well as a different type of pellet. For this we turn to a design that is much smaller, something typical of a National Ignition Facility (NIF) baseline target [5]. For this scoping analysis we approximate this design by use of a 20mm and 10mm radii geometry for the 1st stage and 2nd stage pellets respectively. To represent a NIF type pellet we use a much smaller 2mm and 1mm pellet design respectively. These are illustrated in Figure 8. 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 10-20MJ for the NIF-like pellets. This will inevitably affect the acceleration profile and thereby elongate the boost duration. The two different pellet geometries are 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 but much bigger than those being used for NIF.

In this paper there are two principal reaction combinations we shall consider along with their respective energy release, those due to DT and DHe^3. DHe^3 reactions have the advantage that they produce fewer neutrons than DT. T will also decay to He^3 with a half life of around 12.5 years. we assume a pellet design containing a mixture of DT propellant at 3 grams mass which is what would typically be loaded into a civilian based ICF reactor. We calculate the molar mass of the combination to be $H_1^2 + H_1^3 \approx 5g/mole$. The amount of propellant in moles is given by

$$N(moles) = \frac{mass(g)}{molar\_mass(g/mole)} \approx \frac{3g}{5g/mole} = 1.66moles \qquad [9]$$

We then calculate the number of DT nuclei in the pellet which is the molar amount multiplied by a constant known as the Avogadro's number N_A. The number of nuclei is then found to be 1.003×10^{23} atoms. We then assume an energy release per reaction for the He^4 product to be 3.52 MeV which we multiply by the number of atoms in the pellet to give us an estimate for the total energy release in the form of He^4 products which is 3.53×10^{24} MeV or the equivalent of 135 tons TNT. We can do a similar calculation for DHe^3 and we find that the total energy release in the form of He^4 products with energy of 3.67 MeV per reaction is 3.68×10^{24} MeV or the equivalent of 140 tons TNT.

So what is the maximum performance that you can get from a fusion based rocket engine? 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 produces 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 $\rightarrow$ 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 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.

$$V_e = \left(\frac{2E_{kin}}{m}\right)^{1/2} \qquad [10]$$

Then using $E = mc^2$, the mass cancels and we are left with an equation for the exhaust velocity as a function of the fractional energy release to be $V_e = (2\varepsilon)^{1/2} \approx 0.088c$. This is nearly 9% of light speed and corresponds to a velocity of 26,500 km/s. The performance for the two propellant combinations is shown in Table 4. This is then the maximum performance of a fusion based engine. Although not discussed in this paper it is worth nothing that DD propellant combinations will yield an exhaust velocity of 4-5% of light speed.

Propellant/Products	Total energy release Tons TNT	Exhaust velocity (km/s)
DT/ He^4 + n	135	26,400 (8.67%c)
DHe^3/ He^4 + p	140	26,500 (8.85%c)

Table 4. Fusion reaction energy release

Now that we have calculated the maximum theoretical exhaust velocity for our different propellant combinations of DT and DHe3 we can apply this new exhaust velocity to our different staged configurations to derive a minimum performance boundary. Because any exhaust velocity will likely be much less than these values this gives us an extreme design point from which to base assessments.

<u>TO BE DONE</u>

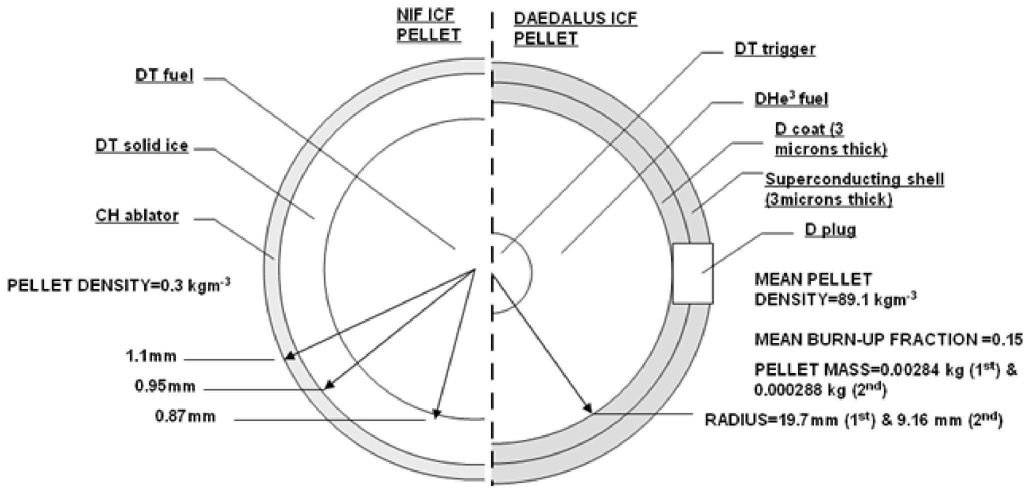

Fig. 7: NIF/Daedalus ICF pellet design comparison

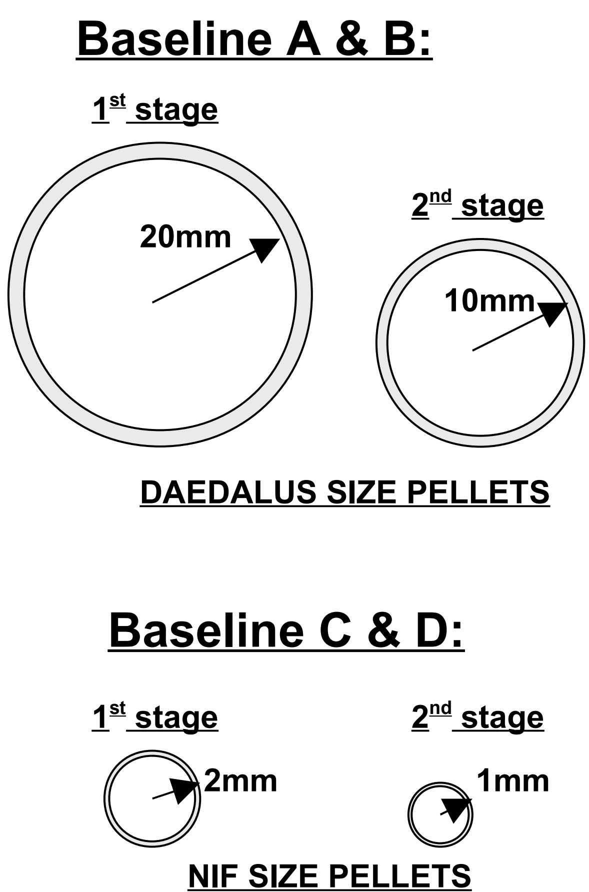

Fig. 8: Illustration of pellet configurations considered for the analysis

	A-1st stage (Daedalus size)	A-2nd stage (Daedalus size)	C-1st stage (NIF size)	C-2nd stage (NIF size)
Fuel	DHe^3	DT	DT	DHe^3
Pellet mass (g)	3	0.3	0.0003	0.0002
Radius (mm)	20	10	2	1
Average pellet density (kg/m^3)	89.5	71.8	9.1	47.7
Stage mass (t)	46,000	4,000	46,000	4,000
Number pellets	1.533×10^{10}	1.333×10^{10}	1.533×10^{14}	2×10^{13}
Number tanks	6	4	6	4
Pellets per tank	2.555×10^{9}	3.333×10^{9}	2.555×10^{13}	5×10^{12}
Energy per pellet (MJ)	171,820	13,271	20	10
Energy per pellet (tons TNT)	40.9	3.16	0.005	0.002
Energy per tank (MJ)	4.39×10^{14}	4.423×10^{13}	5.11×10^{14}	5×10^{13}
Energy per stage (MJ)	2.634×10^{15}	1.769×10^{14}	3.066×10^{15}	2×10^{14}
Energy per tank (Gtons TNT)	104	10.5	121.7	11.9
Energy per stage (Gtons TNT)	627	42	730	47.6
Energy of stage over 3.81 year boost period (ktons/s)	5.2	0.35	6.08	0.39
Energy over 250Hz (MJ/s)	4.29×10^{7}	3.32×10^{6}	5×10^{3}	2.5×10^{3}
Energy over 250Hz (ktons/s)	10.2	0.79	0.0012	0.00059
Stage burn duration (years)	2.05	1.76	2.05	1.76
Mass flow rate of stage (kg/s)	0.711	0.072	0.711	0.727
Exhaust velocity (km/s)	10^{4}	10^{4}	10^{4}	10^{4}
Thrust (N)	7.11×10^{6}	7.2×10^{5}	7.11×10^{6}	7.2×10^{5}

Table 5: Various Pellet configurations considered for the analysis

V. CONCLUSIONS

In this paper we have discussed two mission profile targets and 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.

It is worth considering the implications of this work to other theoretical design studies that utilised ICF based propulsion schemes. The first was Project Longshot [7], a US Naval Academy study conducted in the 1980's for a mission to Alpha Centauri in around 100 years. It proposed the use of DHe^3 fuel with pellet masses between 0.005 – 0.085 g detonated at a pulse frequency between 14 – 250 Hz. Another (more credible) study was Project VISTA [8] led by a designer from Lawrence Livermore National Laboratory in the late 1980's 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 5MJ laser driver would be enhanced by the use of a Fast Ignition technique to produce 7,500MJ per pellet which would allow high energy gain up to 1500. The pellets would be detonated at a rate of between 0 – 30 Hz and each had a mass of 0.066 g. Comparing the pellet configurations proposed for these vehicles to the concepts studied in this work we conclude that………

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