PROJECT ICARUS: STARSHIP RESOLUTION SUB-TEAM CONCEPT DESIGN REPORT

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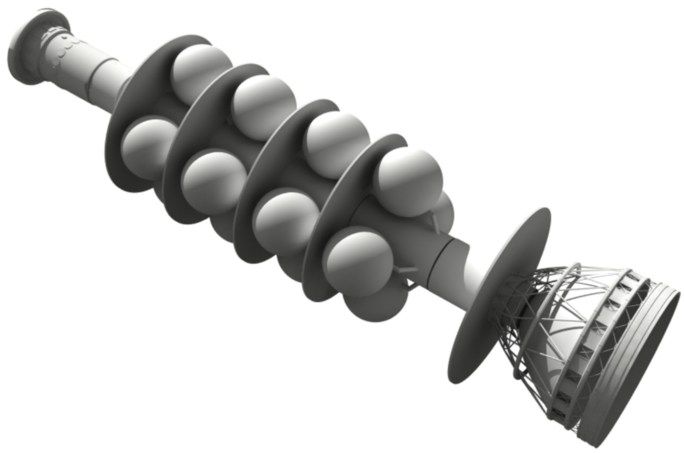
Abstract

This is a brief introduction to the Project Icarus Starship Resolution concept vehicle design, a 100% D/He^3 fuel system. This is very much an early stage of work and due to time constraints much of the work has not been completed. But this is where the design was at this point and so it is submitted anyway. In particular, the ignition model has not been completed and no assessment is done on the thermal or power systems. The philosophy adopted by this sub-team was to firstly conduct some trade studies to scope out the design space, and then to build a basic Fortran model to calculate the Daedalus performance. This was then modified for the new configuration layout and the program iterated accordingly. The program is explained, the Project Daedalus design performance is reproduced to a reasonable approximation and then the Starship Resolution model is introduced. With further work it is our belief that this could be the basis of a credible concept design. This is a submission of the Project Icarus Study Group.



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1 Introduction

In September 2009 members of the Project Icarus Study Group formed [1] to consider a redesign of the original 1970s British Interplanetary Society Starship probe, Project Daedalus [2]. This led to several years of research which has recently culminated in a re-energized design phase, and which has the aim of producing several vehicle concepts as well as providing a pathway towards down select. This work is a contribution to this process, with the intention of aiding the various sub-teams in their calculation approach to ensure the maximum number of vehicle concepts are developed over this phase. This work is also a contribution to a later Project Icarus Baseline model, a necessary step towards eventual down select and design integration.

The program has been written in the default Daedalus configuration, as a form of validated baseline. The user should only make changes to the input deck for parameter studies. However, the opportunity is there for the user to make changes to the direct source code if they so wish. The program has been deliberately written as a single input-code file to facilitate ease of use and to minimize the number of files involved in the compilation process. A brief description of the physics and engineering program is presented, followed by an overview of the Starship Resolution design.[1]

The original Project Icarus requirements were referred to as the Terms of Reference (ToR) and these were published [1]. However, under the Project Leadership of Pat Galea, the team went through an extensive requirements definition phase resulting a a revision to the ToR and the statement of Higher Level Objectives (HLOs) [3]. The revised Terms of Reference were:

- Project Icarus will build on the work of Project Daedalus, and will produce a design for an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, stellar environment, and the interstellar medium.
- The spacecraft will use current or near-future technology, and should be capable of being launched as soon as is credibly determined.

[1] the sub-team would like to acknowledge the earlier technical contributions of Stephen Baxter, and in particular for suggesting the name "Starship Resolution"

- The spacecraft shall reach its stellar destination within a century of its launch, and ideally much sooner.
- The spacecraft design shall allow missions to a variety of target stars.
- The spacecraft propulsion shall be mainly fusion based.
- The spacecraft shall decelerate for increased encounter time at the destination.

As will be shown later on in this report, we believe that the Starship Resolution concept as proposed is the basis for an engineering solution that meets these Terms of Reference constraints. The approaching of writing a Fortran program also allowed for the selection of multiple target stars, consistent with the aim of Project Icarus . The adoption of gas giant mining for fuel and the determination of launch requirements, was also based on near-term extrapolation of current technology. The proposed mission meets the 100 year requirement and the engine is mainly fusion based as required. Full deceleration to the stellar target is shown, assuming a Centauri A and B destination.

The Higher Level Objectives were defined as:

- HL-001 (Must): The spacecraft shall be decelerated sufficiently to allow it to enter orbit around a star in the Alpha Centauri A-B system.
- HL-002 (Must): The spacecraft shall arrive at the destination system no later than 100 years after the craft is launched.
- HL-003 (Must): The spacecraft shall be able to carry a payload of at least 100 tonnes, which shall be decelerated with the main spacecraft. (The payload mass does not include structural elements of the craft).
- HL-004 (Should): The spacecraft shall be able to carry a payload of at least 150 tonnes, which shall be decelerated with the main spacecraft. (The payload mass does not include structural elements of the craft).
- HL-005 (Must): The mission shall have the capability to make scientific measurements of the interstellar medium during the cruise phase to Alpha Centauri.
- HL-006 (Must): The mission shall have the capability to make scientific observations of at least one star in the Alpha Centauri system from a distance of at least one AU.
- HL-007 (Must): The mission shall have the capability to place scientific payloads into low orbit of no more than 1000 km periapsis about at least one planet in the system for the purpose of high-resolution remote-sensing observations of the atmosphere and surface.
- HL-008 (Should): The mission shall have the capability to deploy sub-probes to make in situ investigations of the atmospheres and surfaces of at least four planets in the Alpha Centauri System, including the capability of making in situ measurements at multiple locations on the same planet.
- HL-009 (Could): The mission shall have the capability to deploy sub-probes to make in situ investigations of the atmospheres and surfaces of planets orbiting different stellar components of the system.

Some of the HLO defined above are for post-concept design selection, such as the choice of specific instruments or the determination of the periapsis at the target. But as will be shown, the proposed Starship Resolution concept is the basis for a concept design solution that meets these HLO, although further analysis and further iteration of the concept is clearly required. Finally, we note that many of the systems have not been assessed for this iteration, but this was due to time constraints. Given more time, we are confident that a full and credible systems engineering assessment can be demonstrated.

2 Program Input Deck

This is the section for which the user can effect changes. The program file is titled 'picap.f95'. The program is coded up to include multi-staged engine configurations, currently up to $n = 2$. This is the default Daedalus configuration. If users feel they need an $n > 2$ program then this can be developed at short notice. In order to run the calculation as a single engine stage configuration, then $n = 1$ should be enabled. In order to run the program the user will need access to a Fortran compiler. The program has been written in F95. Free trial versions can be easily downloaded from the web. GFortran is recommended: http://gcc.gnu.org/fortran/.

The user is first asked to input the number of the star system that the vehicle is to travel to. The star numbers are defined in Table 1. The stars go out to 12.2 Light years in distance. The fuel choice must then be given. Currently this is limited to the four main TN reactions described in the next section, but others can be added if necessary.

The user is asked to input the number of engine stages, the engine mass, the number of propellant tanks per stage, the propellant mass per stage, the structure mass per stage and the payload mass which is assumed to be in the final stage. All masses are inputed in tonnes. The code is programmed for Inertial Confinement Fusion (ICF) based propulsion systems. The user is also asked to input the pulse frequency f_{hz} (Hz), the pellet mass m_{pell} (kg) and the burn fraction per stage. The exhaust velocity v_{ex} (km/s) is calculated from the input of propulsion data, such as the mass flow rate and the pulse frequency, as well as assumed divergence half angle of the nozzle exit flow.

Another option permitted for the user is to define the second stage as either an acceleration stage or a deceleration stage. This is enabled through the input parameter nr, where if $nr = 0.0$ then the second stage is used for acceleration, and if $nr = 1.0$ then the second stage is a deceleration stage. This is all factored into the mission profile and how the cruise distance and duration is calculated as well as the trajectory profile.

3 Physics & Engineering Calculations

We briefly describe here the various calculations that are performed in the program so as to be transparent on the assumptions and also to facilitate ease of modification by the users. Some constants are assumed for all calculations including the speed of light in a vacuum $c = 2.9979 \times 10^8 ms^{-1}$, 1 Astronomical Unit $au = 1.496 \times 10^{15} m$, 1 Light Year $LY = 9.4605 \times 10^{15} m$, 1 Year $Yr = 3.1536 \times 10^7 s$, acceleration due to gravity $g = 9.80665 ms^{-2}$, $\pi = 3.141592$. Many of the equations shown in this manual were developed in references [4] and [5].

Stellar Target Destination: The code allows for the input of up to 27 stars between 4.3 light years out to 12.2 light years. The specific star systems permissible are shown in Table 1. The user need only select the star number and the calculation will do the rest. The baseline destination for the Daedalus model is Barnard's star at 5.9 light years. For Project Icarus, and

Target No.	Name	Distance (LY)	Stellar Mass (Ms)
1	Proxima Centauri	4.3	0.1
2	Centauri A	4.4	1.10
3	Centauri B	4.4	0.89
4	Barnards Star	5.9	0.15
5	Wolf 359	7.6	0.2
6	Lalande 21885	8.1	0.35
7	Sirius 48915 A	8.7	2.32
8	Sirius 48915 B	8.7	0.98
9	Luyten 726-8 A	8.9	0.12
10	Luyten 726-8 B	8.9	0.1
11	Ross 154	9.5	0.31
12	Ross 248	10.3	0.25
13	Epsilon Eridani	10.7	0.85
14	Luyten 789-6	10.8	0.25
15	Ross 128	10.8	0.31
16	61 Cygni A	11.2	0.59
17	61 Cygni B	11.2	0.5
18	Epsilon Indi	11.2	0.71
19	Procyon 61421 A	11.4	1.77
20	Procyon 61421 B	11.4	0.63
21	+59DEG 1915 A	11.5	0.4
22	+59DEG 1915 B	11.5	0.4
23	Groombridge 34 A	11.6	0.38
24	Groombridge 34 B	11.6	0.16
25	Lacaille 9352	11.7	0.47
26	Tau Ceti	11.9	0.78
27	Luyten BD +5DEG 1668	12.2	0.38

Tab. 1: Stellar Target Destination Options

Starship Resolution, Alpha Centauri A & B has been selected as the stellar target, 4.4 light years away.

Fuel Options:
Currently, four fusion reaction fuel types are enabled including $D(T, He^4)n$, $D(D, He^3)n$, $D(D, He^4)p$, $D(He^3, He^4)p$. Others can be added although the energy per gram reaction release amount needs to be known. The current reactions correctly assume known values of energy deposition. The values assumed for the current reactions are $3.41 \times 10^{11} Jg^{-1}$, $0.79 \times 10^{11} Jg^{-1}$, $0.87 \times 10^{11} Jg^{-1}$ and $3.55 \times 10^{11} Jg^{-1}$ respectively. The assumed energy deposition from all reacting nuclide's, including neutrons and protons.

Rocket Equation:
The program solves the ideal rocket equation. For a single staged system the equation is given as a function of the rocket exhaust velocity, initial mass m_0 and final mass m_f as follows:

$$v_c = dv = v_{ex} Ln\Big(\frac{m_0}{m_f}\Big) \tag{1}$$

For a two-staged system it is given by:

$$dv_1 = v_{ex1} Ln\Big(\frac{m_{0,1}}{m_{f,1}}\Big) \tag{2}$$

$$dv_2 = v_{ex2} Ln\Big(\frac{m_{0,2}}{m_{f,2}}\Big) \tag{3}$$

$$v_c = dv_1 + dv_2 \tag{4}$$

The total mass ratio is then given by the multiplication of the mass ratios for each stage:

$$R_{tot} = R_1 \times R_2 \tag{5}$$

An estimate for the deceleration propellant mass requirement can also be obtained by looking at the total mass ratio. Provided the two exhaust velocities are the same this is given by:

$$R_{deburn} = sqrt(R_{tot}) \tag{6}$$

and then looking the the non-propellant mass difference. The deburn propellant mass is then given by:

$$m_{p,deburn} = (m_{pay} + m_s) \times R_{tot} - (m_{pay} + m_s) \tag{7}$$

In the program a statement is written to compare the deburn mass propellant input with that estimated from the above equation, along the lines of *"WARNING: Propellant Deburn Inconsistency with Input: 4009.69946 4000.00000"*. The calculation can then be iterated until these values are consistent.

Propulsion Performance:

The number of pellets in any stage i is given by dividing the propulsion staged mass by the mass of an ICF pellet:

$$n_{pell,i} = \frac{m_{p,i}}{m_{pell,i}} \tag{8}$$

The energy release from any pellet in a given stage i is given by multiplying the energy release (Jg^{-1}) by the mass of the pellet (kg) by the burn fraction:

$$E_{p,i} = E_{fuel} \times m_{pell,i} \times f_{b,i} \tag{9}$$

This can then be calculated on a 1 second or per stage basis.

The mass flow rate of the engine is given by multiplying the pellet mass by the pulse frequency:

$$\dot{m}_i = m_{pell,i} \times f_{hz,i} \tag{10}$$

The engine performance is represented by the Thrust, jet power and specific power which are all given by:

$$T_i = \dot{m}_i v_{ex,i} \tag{11}$$

$$P_{j,i} = \frac{1}{2}\dot{m}_i v_{ex,i}^2 \quad (12)$$

$$P_{sp,i} = \frac{P_{j,i}}{m_{e,i}} \quad (13)$$

A calculation is also performed to assess the exhaust velocity based on equations derived by Martin [6] and Bond [7].

The effective exhaust velocity is given as a function of the burn fraction f_b by:

$$\bar{v} = [1.9899(1 - f_b) + 1.8974 f_b] \times sqrt(f_b) \times 1.3248 \times 10^7 ms^{-1} \quad (14)$$

The flow in the nozzle will then not flow axially but will diverge at a half angle β, expected to be around twenty degrees. Assuming a spherical flow from the point source the effective exhaust velocity is then approximated by:

$$v_{ex} = \frac{\bar{v}}{2}(1 + cos\beta) \quad (15)$$

These equations have been coded into the PICAP program, with the half angle and the burn fraction as an input parameter and the computation performed for each stage. However, until this routine gives the accurate numbers the exhaust velocities are currently typed in explitely as an input. For Starship Resolution this is 9,210 km/s.

Mission Profile:

The distance attained under acceleration is given by the logarithmic relation:

$$S_{b,i} = v_{ex,0} t_{b,0} + v_{ex,i} t_{b,i} \times \left(1 - \frac{Log(R_i)}{R_i - 1}\right) \quad (16)$$

The total distance attained is then found by adding up the sum of the staged boosts distance and the cruise distance as follows:

$$S_{tot} = \sum_{i=1}^{n} Sb_i + S_c \quad (17)$$

The total time duration under boost is given by:

$$t_{b,i} = \sum_{i=1}^{n} \frac{m_{p,i}}{\dot{m}_{,i}} \quad (18)$$

The time duration under cruise is given as a simple linear equation:

$$t_c = \frac{S_c}{v_c} \quad (19)$$

and then the total time duration of the mission is given by:

$$t_{tot} = \sum_{i=1}^{n} t_{b,i} + t_c \quad (20)$$

Radiation Output from ICF Pellets:

Reference [7] discusses radiation output from the Daedalus pellets. The report makes the assumption that the reaction temperature is of order a few hundred eV which gives a reaction

probability for the non-neutron producing reactions of $3 \times 10^{-22} m^3 s^{-1}$ and for those producing neutrons of $6 \times 10^{-23} m^3 s^{-1}$. The reaction cross section is a measure of the probability of a fusion reaction as a function of the relative velocity of two reactant nuclei. The reaction rate is the number of fusions occurring per unit volume per unit time and is defined by $< \sigma v >$ multiplied by the reactant number densities n_1 and n_2 as follows:

$$f = n_1 n_2 < \sigma v > \tag{21}$$

For species that are reacting with itself such as in the DD reaction, then the product $n_1 n_2$ is modified so that the reaction rate becomes:

$$f = \frac{1}{2} n^2 < \sigma v > \tag{22}$$

We can then look at the reaction rate for different species which are as follows:

$$f_{DT} = n_D n_T < \sigma v >_{DT} \tag{23}$$

$$f_{DD} = \frac{1}{2} n_{DD}^2 < \sigma v >_{DD} \tag{24}$$

$$f_{DHe_3} = n_D n_{He_3} < \sigma v >_{DHe_3} \tag{25}$$

If we take the ratio of the DD versus DHe^3 reaction we get:

$$f_{DD} = \frac{1/2 n_{DD}^2 < \sigma v >_{DD}}{n_D n_{He^3} < \sigma v >_{DHe^3}} = \frac{1/2 \times 0.6}{3} = 0.1 \tag{26}$$

This equation shows that the number of neutrons produced will be 10% the number of particle pairs in the reactions. We can then use this to estimate the number of neutrons produced per pulse $n_{p,i}$ as well as the neutron production rates. These are important because the neutrons will radiate the surrounding structure and so determine the shielding requirements. We can then multiply this number by an equation which factors in the pellet mass $m_{pell,i}$, the number of grams per mole of the substance G_i, Avogadro constant $Av = 6.022 \times 10^{23} mole^{-1}$, the fraction of neutron producing reactions f_i and the burn fraction of the fuel $f_{b,i}$ as follows:

$$n_{p,i} = (m_{pell,i} \div G_i) Av \times f_i \times 1/2 \times f_{b,i} \tag{27}$$

This gives the number of neutrons per pulse. We note that the numbers calculated differ slightly from those of the Daedalus report. This is due to the burn fraction modeled. We can then find the number of neutrons per pellet by multiplying by the pulse frequency:

$$n_{pell,i} = n_{p,i} \times f_{hz,i} \tag{28}$$

Finally, it is important to note that in the Daedalus study the authors neglected radiation sources due to $x - rays$ and $\gamma - rays$ produced from the nuclear reactions due to the difficulty of such an estimation and the justification that the radiation due to these sources would likely be a small fraction of one per cent of the total nuclear energy release. Similarly, in the code we have only programmed in neutron energy deposition to determine the levels of radioactivity on any surrounds.

Particle Bombardment Shield:

Material	Atomic Number	Density (kgm^{-3})	Heat of Sublimation H_s ($Jkgm^{-1}$)
Lithium	3	0.356	0.513
Beryllium	4	0.410	0.401
Boron	5	0.410	0.401
Graphite	6	0.410	0.401
Aluminium	13	0.410	0.401

Tab. 2: Particle Bombardment Shield Material Options

The particle bombardment shield mass ablation rate dm/dt is considered based on work reported in Martin [8]. For a first approximation model we assume the Benedikt relation reported as equation (5) in the referenced Daedalus work. This is given by:

$$\frac{dm}{dt} = \frac{\eta A_o}{H_s} \frac{\rho \beta c^3}{(1-\beta^2)^{0.5}} \Big(\frac{1}{(1-\beta^2)^{0.5}} \Big) \tag{29}$$

In this equation η is a thermal heating impact parameter which we assume the default to be 0.25, A_o is the shield surface area, ρ is the mass density of the shield material, H_s is the heat of sublimation ($Jkgm^{-1}$) for the different materials. The data for the various material options is shown in table 2. The calculation estimates the mass ablation rate, shield thickness requirement (for a given $29m^3$ volume) and shield mass requirement, assuming a cylindrical payload configuration. Finally, a value for the matter density of combined Hydrogen gas and dust grain density is assumed of $\rho \sim 10^{-23} kgm^{-3}$ as an approximation. Reference [8] discusses interstellar gas densities for Hydrogen of $1.67 \times 10^{-21} kgm^{-3}$ and grain densities of $1.4 \times 10^{-23} kgm^{-3}$. For consistency with producing a 1978 Daedalus baseline these values can be used and the default is as described above. However, in light of the decades since of observational and theoretical developments, users are advised to consult modern text for best estimates on interstellar properties [9]. It may also be possible to program in a density gradient depending on the target star and the direction of travel in the local stellar neighborhood, but this is left for future work. Note also, that currently the particle shield calculations do not take account of mass loss due to heating by energetic electrons, protons or other ions which interact with the structural material. In the current model the mass ablation rate is not calculating correctly, so although we have an estimate shield mass of around 54 tonnes, similar to Daedalus, it is expected that this number will be reduced due to the small radii. But for now this is adopted as a conservative figure.

Stellar Target Encounter Time: Some calculations are performed to estimate the amount of time spent at the stellar target. This is mainly useful for a flyby probe or when there is some excess velocity remaining. Firstly, encounter times are given for crossings of 10 AU, 100 AU and 1,000 AU. Next, we adopt the model discussed in reference [10] which assumes that the debris cloud surrounding a stellar system is proportional to the stellar mass of that system. For our own solar system, the debris cloud is said to be out to around 0.1 light years, to the region of the Oort Cloud. The authors use this to develop the following relation:

$$R_c = 0.1 \Big(\frac{m}{m_s} \Big)^{1/3} \tag{30}$$

So that for Barnard's star with a value of $m/m_s = 0.15$ the debris radius is calculated to be 0.053 light years with an encounter time at 12.2%c within the stellar debris diameter to be around 317 days. The authors note the caveat that this model makes assumptions about stellar

formation processes and that different types of stars may not form in the same way. However, for the purposes of establishing a Daedalus baseline this model is adopted in the program. However, it is worth noting that 0.1 light years corresponds to around 6,324 AU, when in fact we now know today that the Oort cloud goes out as far as around 50,000 AU which is around 0.8 light years. For this reason, any user wanting to adopt a modern stellar system debris model is advised to replace the 0.1 in the equation of the program to 0.8, which at 12.2% cruise speed would have a crossing diameter of around 2,546 days. This is provided as a variable option in the source code labeled θ.

Waste Heat

The radiator efficiency is provided as an input for both engine stages. A value of around P_{sp} 300 kW/kg is the Project Icarus (agreed) recommended value from studies of other fusion systems and in the interest of being credible. A conversion efficiency of 0.25 is assumed. Both of these can be altered in the input deck. The mass of the radiators is then found by first dividing the engine stage jet power by the conversion efficiency to get the generated output power:

$$P_{gen} = \frac{P_j}{\eta} \tag{31}$$

The total amount of waste heat is then found by:

$$P_{heat} = (1 - \eta) \times P_{gen} \tag{32}$$

and the radiator mass by diving by the radiator efficiency as follows:

$$m_{rad} = \frac{P_{heat}}{P_{sp}} \tag{33}$$

Due to time constraints there was not time to complete the waste heat analysis and to do an assessment for the Starship Resolution vehicle. This will be completed in the future.

Power Supply

The power supply is provided as an input for both engine stages. It is given as the specific electrical power supply energy and the Project Icarus (agreed) recommended value is around 200 kWe/kg (with 50% efficiency) although this can be altered in the input deck. The mass of the power supply is then estimated by diving the engine stage jet power by the specific electrical power supply energy as follows:

$$m_{power} = \frac{P_j}{P_e} \tag{34}$$

Due to time constraints there was no time to complete the power supply analysis and to do an assessment for the Starship Resolution vehicle. This will be completed in the future.

Communications

There wasn't time to do an assessment of the communications system for the vehicle or to fold the relevant equations into the program. However, this sub-team expects to utilize both radio and laser communications and it is planned to incorporate the appropriate physics into a future version of the program. Galea has already done extensive analysis of the communications problem [25].

Nozzle Design

For the Daedalus study a nozzle efficiency of 95% was assumed, which means that this amount of charged particles is released from the fusion reactions into direct thrust. However, discussions within the Project Icarus team suggest that this is too optimistic and a value of 75% is recommended. Both are provided as an option in the input deck.

Due to time constraints there was no time to complete the nozzle design analysis and to do an assessment for the Starship Resolution vehicle. This will be completed in the future.

Ignition System

The ignition of an Inertial Confinement Fusion (ICF) capsule can be examined from the perspective of the hydrodynamic implosion and compression phase, followed by the ignition and burn phase. In this section we examine the fundamental physics issues relating to the hot spot ignition of a conventional direct drive based capsule design. For the purposes of this study, we assume a conventional ICF target design with an outer radius of 1.11 mm, ablator thickness of 0.16 mm. The design assumes a fuel surrounded by a solid fuel layer and then an ablator material. The code allows the user to input information about the hot spot conditions and then it calculates whether energy loss or energy gain is achieved. The output file echo's the input and also calculates various performance properties. It is possible to run the code assuming energy deposition from all product ions or to neglect the energy from any neutrons or protons.

Due to time constraints there was no time to complete an assessment of the ignition system for the Starship Resolution vehicle. This will be completed in the future. However, we present some of the initial work which is a stepping stone to a full hydrodynamic implosion, ignition and burn description based on both conventional ICF and shock ignition ICF.

The Physics Model

In this work we ignore the implosion and compression phase and only concentrate on the ignition element. At this point, it is assumed that the target has been compressed up to a smaller volume with a high number density and temperature, particularly within a central hot spot region. The hydrodynamic compression will lead to the generation of mechanical work through a PdV process adding energy to the hot spot. In addition, once the central hot spot region has ignited, it will begin to generate He^4 alpha particles and then deposit them into the surrounding fuel. This will also heat up the material and add energy. Whilst these energy addition processes are occurring, several energy loss mechanisms will be in effect. This includes the loss of energy due to electron thermal conduction away from the central hot spot, as well as radiation loss through the process of Bremsstrahlung emission. The race for the capsule, is to inertially confine the central hot spot sufficiently long enough for the energy deposition (and subsequent Thermonuclear burn wave) to propagate and fully ignite all of the fuel, before the energy loss mechanisms and capsule disassembly can detract energy from it. The four competing effects here are modeled.

In the model below we assume that the hot spot has a radius r (cm) and is imploded with a velocity v (cms^{-1}), ρ is the hot-spot density (g/cm^3), T is the hot-spot temperature (keV). Electrons and ions are assumed to be in equilibrium. The total number of particles in the hot-spot is defined by n_0 (cm^{-3}). The Maxwell average cross section is defined by $\langle\sigma v\rangle$ which for a DT fuel is around $\sim 10^{-27}$ $(cm^3 s^{-1})$ at $1keV$

We approach the problem from the principle of total energy conservation in that the sum of the energy gains minus the sum of the energy losses should be greater than zero in order to get ignition and eventually gain. The energy gains are represented by the PdV mechanical work per unit volume P_w and the alpha particle deposition thermonuclear heating rate per unit volume P_α. The energy losses are represented by the radiation losses (due to Bremsstrahlung emission) per unit volume P_r and the electron conduction losses (approximated with a Spitzer

conductivity) per unit volume P_e.

$$P_w + P_\alpha - P_r - P_e > 0 \tag{35}$$

Another energy gain term should technically be added to account for the neutron energy deposition, but reference [11] makes the point that this is small and so can be neglected. The model being represented is illustrated in Figure 1. We now derive each of the individual terms required to generate the ignition model.

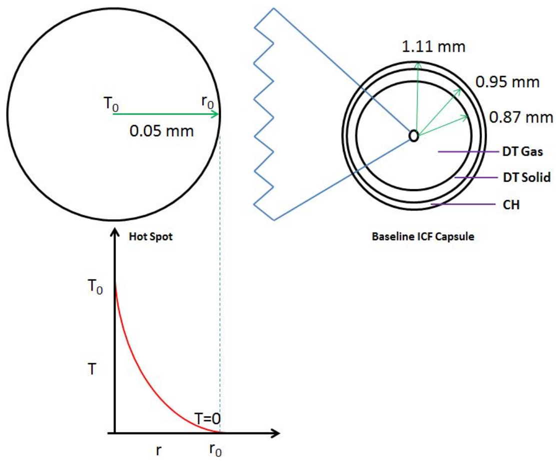

Fig. 1: Physical ICF Model Under Development

PdV Work

To estimate the rate of mechanical work per unit volume P_w performed on the hot-spot region of the fuel we adopt the model of a piston compressing a gas with a uniform pressure distribution. The work rate per unit volume is then given by

$$P_w = \frac{P(\frac{dV}{dt})}{V} = \frac{PAv}{V} = \frac{3 \times Pv}{r} \tag{36}$$

We can then use the fact that $P = nk_BT$ for an isothermal ideal gas equation of state and that $\rho = n_i m_i + n_e m_e$, which refers to the number density and mass of the ions and electrons. Reference [12] provides the solution to this equation as follows: [1]

$$P_w(Wcm^{-3}) = \frac{2.3 \times 10^{15} \times \rho T}{r} \left(\frac{v}{10^7}\right) \tag{37}$$

Alpha-Particle Deposition

The thermonuclear heating rate per unit volume P_α is found by multiplying the burn rate $\dot{\phi}$ and the fractional alpha particle deposition F_α as follows

$$P_\alpha = \rho\dot{\phi}\epsilon_\alpha F_\alpha \tag{38}$$

[1] This author has not yet been able to successfully derive the coefficient shown in reference [12]

Reaction	Products	Atomic Mass (amu)	Energy (J/g)(total)	Energy (J/g)fraction
$D+T$	He^4(3.52 MeV) + n(14.06 MeV)	5	3.41×10^{11}	0.68×10^{11}
$D+D$	He^3(0.82 MeV) + n(2.45 MeV)	4	0.79×10^{11}	0.20×10^{11}
$D+D$	He^4(3.67 MeV) + p(14.67 MeV)	4	0.87×10^{11}	0.24×10^{11}
$D+He^3$	He^4(3.67 MeV) + p(14.67 MeV)	5	3.55×10^{11}	0.71×10^{11}

Tab. 3: Energy Release (J/g) for Various Fusion Reactions. The Total Includes all Particle Energies but Fraction Refers to the Energy Release from All Products Minus the protons and neutrons for the Heavy Ion Energy Deposition Rate

Where the burn rate is given by the following approximation

$$\dot{\phi} = \frac{1}{2}(1-\phi)n_0\langle\sigma v\rangle \approx 1.2 \times 10^{23}\rho\langle\sigma v\rangle \tag{39}$$

The burn fraction is given by [12]

$$\phi = \frac{\rho r}{\rho r + 6(gcm^{-2})} \tag{40}$$

We can estimate the energy release per reaction ϵ_α by counting up the atomic mass of the reacting species. We then multiple the energy release in units of MeV by $1.609 \times 10^{-13} MeV$ and then multiplying this by the Avogadro number $6.022 \times 10^{23} atoms^{-1}$, as the number of constituent particles (atoms or molecules) in one mole of a given substance. We then divide the total by the atomic mass N (grams/mole) to arrive at the total energy release per gram. This is shown in the equation below. Table 1 shows the energy release data for various fusion reactions. Also shown is the energy release but not including the excess protons and neutrons, labeled fraction. It is seen in Table 1 that for a DT plasma we assume an alpha-particle energy per gram of 0.68×10^{11} Jg^{-1}.

$$\epsilon_i(Jg^{-1}) = \frac{E(MeV) \times 1.609 \times 10^{-13} J \times 6.022 \times 10^{23} mol^{-1}}{N gmol^{-1}} \tag{41}$$

We can then substitute these terms into the equation for P_α and then divide by 10^{-17} which is a normalization of the Maxwell averaged cross section. The heating rate per unit volume is then given by [12]:

$$P_\alpha(Wcm^{-3}) = 8 \times 10^{16}\rho^2\langle\frac{\sigma v}{10^{-17}}\rangle F_\alpha \tag{42}$$

The reaction cross section $\langle\sigma v\rangle$ is averaged over a Maxwellian distribution of particles and for an equimolar mixture of DT or otherwise. The approximate cross section in $cm^2 s^{-1}$ for the different reactions is given approximately in Table 2.

Bremsstrahlung Emission

The radiation loss rate per unit volume P_r is assumed to be all via Bremsstrahlung emission which is escaping the hot-spot region of the fuel. Classically, in the theory of electrodynamics this is photons emitted when electrons accelerate around positive ions during Coulomb collisions. Quantum mechanically, it is due to electrons undergoing transitions between two states

Reaction	1 keV	2 keV	5 keV	10 keV	20 keV	Peak keV
$D+T$	8×10^{-27}	5×10^{-25}	2×10^{-23}	1×10^{-22}	8×10^{-21}	1×10^{-21}
$D+D$	4×10^{-28}	8×10^{-27}	2×10^{-25}	1×10^{-24}	8×10^{-24}	4×10^{-22}
$D+He^3$	≈ 0	1×10^{-29}	9×10^{-25}	5×10^{-25}	1×10^{-23}	5×10^{-22}

Tab. 4: Approximate Maxwell Averaged Cross Section Values (cm^2s^{-1}) As Function Temperature (keV)

of the continuum in the field of an atom. It is a temperature dependent and density dependent phenomena. It is given by the following analytical relation [12]:

$$P_r(Wcm^{-3}) = 3.0\times10^{16}\rho^2T^{0.5} \tag{43}$$

Electron Conduction

The conduction losses are approximated by a Spitzer conductivity [13] assuming a steady-state temperature profile. We start with the heating rate:

$$Q = -\kappa\nabla T \tag{44}$$

Where the Spitzer Conductivity is given by

$$\kappa = \frac{9.4\times10^{12}S(z)T^{5/2}}{ZLn\Lambda} \tag{45}$$

So that

$$Q = -\frac{9.4\times10^{12}S(z)}{ZLn\Lambda}T^{5/2}\nabla T \tag{46}$$

According to reference [12] the temperature can be represented by a function so that $T\rightarrow 0$ at $r=r_0$ for simplicity, as follows

$$T = T_0\Big(1-\Big(\frac{r}{r_0}\Big)^2\Big)^{2/7} \tag{47}$$

We can differentiate this equation. We start by letting

$$u = 1-\Big(\frac{r}{r_0}\Big)^2 \tag{48}$$

We can then apply the differential chain rule

$$\frac{dT}{dr} = \frac{dT}{du}\times\frac{du}{dr} \tag{49}$$

Then

$$\frac{du}{dr} = -\frac{2r}{r_0^2} \tag{50}$$

and

$$\frac{dT}{du} = -\frac{2}{7}\Big(1-\Big(\frac{r}{r_0}\Big)^2\Big)^{-5/7} \tag{51}$$

Z	1	2	3	4	∞
δ	0.225	0.356	0.513	0.791	1
ϵ	0.419	0.410	0.401	0.396	0.4

Tab. 5: Spitzer Conduction Values

therefore

$$\frac{dT}{dr} = -\frac{4rT_0}{7r_0^2} \times \left(1 - \left(\frac{r}{r_0}\right)^2\right)^{-5/7} \tag{52}$$

and

$$T^{5/2}\nabla T = -\frac{4T^{7/2}}{7r} \times \left(1 - \left(\frac{r}{r_0}\right)^2\right)^{-5/7} \tag{53}$$

if we then evaluate this at T_0 where $r = r_0$ then $(1 - (r(=0)/r_0))^{-}5/7 \rightarrow 1$ and we are left with

$$T^{5/2}\nabla T = -\frac{4}{7}\frac{T^{7/2}}{r} \tag{54}$$

So that the heating rate becomes the following and with the dropping of the subscripts

$$Q = -\frac{9.4 \times 10^{12} S(z)}{ZLn\Lambda}\frac{4}{7}\frac{T^{7/2}}{r} \tag{55}$$

In the Spitzer conduction Z is the electric charge. The term $S(Z)$ is defined by a δ and an ϵ term to calculate the correct conduction, which correspond to the different Z numbers as follows:

$$S(z) = \frac{\delta(z)\epsilon(z)}{\delta(z=1)\epsilon(z=1)} \tag{56}$$

The term Λ is the Coulomb Logarithm, which defines the logarithm of the ratio of the upper and lower cut-offs in Coulomb collisions, with values typically between $5 \leq \Lambda \leq 15$. The maximum impact parameter between two Coulomb collisions is given by the Debye shielding distance λ_D which suppresses the Coulomb field at larger distances. It is given by

$$\lambda_D = \left(\frac{\epsilon_0 \kappa_B T}{n_0 e^2}\right)^{1/2} \tag{57}$$

If we then assume that $Ln\Lambda = 2$ (assumed to be a constant) and $Z = 1$, then we get

$$Q = -\frac{2.686 \times 10^{12} T^{7/2}}{r} \tag{58}$$

The electron conduction loss rate per unit volume is given by equating it to the volume heating as follows:

$$P_e = \frac{AQ}{V} = \frac{4\pi r^2 Q}{4\pi r^3/3} = \frac{3Q}{r} \tag{59}$$

$$P_e = \frac{3 \times 9.4 \times 10^{12} S(z)}{ZLn\Lambda}\frac{4}{7}\frac{T^{7/2}}{r^2} \tag{60}$$

So that finally we get the equation described in [12] as follows:

$$P_e(Wcm^{-3}) = \frac{8 \times 10^{12} T^{7/2}}{r^2} \tag{61}$$

Currently, the PICAP program will simply estimate the energy gains and the energy losses in the capsule hot spot and then estimate the total energy and state if the system has achieved ignition or not. In the future we plan to evolve a more in depth physics model, to include hydrodynamic implosion (so that the implosion velocity is calculated explicitly rather than as an input parameter) as well as the ignition and burn. This may involved building a finite different sub-routine to calculate the thermonuclear propagating wave burn accurately as well as the correct energy deposition from the hot spot reactions and He^4 alpha particles specifically.

Payload/Propellant Ratio

In the Daedalus Mission profile report [2] the authors discuss the high mass ratios required for interstellar flight and they show how they choose to optimize the payload/propellant ratio. They assumed for a particular value of specific mass there is a value the mass ratio which makes the payload/propellant mass ratio a maximum. For a 40 year mission to be possible the Daedalus designers concluded that a specific engine mass lower than $2.5 \times 10^{-8} kgW^{-1}$ would be required. The optimum for a mass ratio of 150 was payload/propellant mass = 0.0036. Although the final Daedalus design had a first stage engine mass of 1,290 tons producing 44 TW of power, equating to a specific mass of $2.5 \times 10^{-8} kgW^{-1}$. These calculations are reproduced in the code for the problem being modeled as a check. The parameters are computed per stage as well as a total for a more than one engine stage system.

The specific engine mass is given by:

$$\lambda = \frac{m_{e,i}^2 t_{b,i}}{m_{p,i} v_{ex}^2} \tag{62}$$

The payload/propellant mass ratio is then given as follows where we remove the i notation for simplicity:

$$\frac{m_{pay}}{m_p} = \frac{1}{R-1} - \frac{1}{2} \times \frac{\lambda v_{ex}^3 \left(\frac{R}{R-1} Ln(R-1)\right)}{v_{ex} t_b Ln(R) - S_b} \tag{63}$$

Medusa Sail Deceleration

The program allows for the application of a Medusa Sail deceleration mechanism, using the theory as developed by Solem [14, 15, 16]. This involves a large sail canopy, connected by various spinnaker and servo-winches, to the main vehicle. Pellets or units are detonated inside the sail area, imparting a pressure force and thereby thrust in the opposite direction of motion. A correction to the cruise velocity, mission distance and overall mission profile is made when the Medusa Sail is applied. The Medusa Sail option is enabled by making $med = 1.0$ on the input deck. If $med = 0.0$ then the Medusa sail option is disabled. The working assumption in the current model is to use a high-strength polymer (e.g. polyethylene) which has a material density of around $990 kgm^{-3}$. The user also specifies the sail material Young's modulus of elasticity, tensile strength of the spinnaker material, which for the high-strength polymer are given values of $220 GNm^2$ and $5 GNm^2$ respectively. The distance to the detonation point from the spacecraft is also specified, as well as the time between detonations.

The Specific impulse of the Medusa Sail is given by:

$$I_{sp} = \frac{25}{24g}\frac{A_p}{\pi r^2}\sqrt{\frac{2E}{5m_b}} \tag{64}$$

Where g is the acceleration due to gravity, A_p is the projected area of the canopy, r is the detonation distance from the spacecraft, E is the energy release per detonation, m_b is the mass of an individual unit. This can then be multiplied by acceleration due to gravity to get the exhaust velocity v_{ex}:

$$v_{ex} = \frac{25}{24}\frac{A_p}{\pi r^2}\sqrt{\frac{2E}{5m_b}} \tag{65}$$

The impulsive pressure delivered by each detonation is given by:

$$P = \frac{1}{8\pi}\sqrt{\frac{2m_b^5}{5E^3}}\frac{r^2}{t^5}\Big(1 - \frac{m_b r^2}{10Et^2}\Big) \tag{66}$$

Where t is the approximate debris expansion time per detonation.

The average thrust is given by:

$$T = \frac{25}{25\delta t}\frac{A_p}{\pi r^2}\sqrt{\frac{2m_b E}{5}} \tag{67}$$

Where δt is the time between detonations.

The approximate radius of the canopy debris cloud per detonation is given by:

$$r = t\sqrt{\frac{10E_{particle}}{m_{unit}}} \tag{68}$$

Where $E_{particle}$ is the approximate energy of the explosion per detonation, leading to the emitted particles.

The mass of the sail canopy is given by:

$$m_c = \frac{25}{12\sigma_{max}}\sqrt{\frac{\rho_s Y m_b E}{5}} \tag{69}$$

Where σ_{max} is the tensile strength, Y is the Young's Modulus of elasticity, ρ_s is the

Note that although the Medusa Sail calculations have been coded into the program, the adoption of a Medusa sail does not currently form a part of the Starship Resolution baseline model. It is our belief that deceleration can be accomplished through reverse engine thrust alone. However, it would be worth having a brief discussion phase where the Medusa Sail (and MagSails) were considered as a trade off with propellant mass.

Construction Program

The program contains some basic estimates of the number of Single Stage To Orbit launch vehicles required to construct the dry vehicle mass (structure + payload) in Low Earth Orbit. It is assumed that the vehicle carries 10 tonnes to LEO at a cost of £650/kg. The program then calculates the number of vehicles required, the total assembly launch cost and the assembly cost per mission launch.

The program also calculates the same output for an assumed type of launch vehicles. This includes Medium Lift vehicles (10 tonnes to LEO), Medium Heavy Lift vehicles (20 tonnes to LEO), Heavy lift vehicles (50 tonnes to LEO), Super Heavy lift vehicles (100 tonnes to LEO). These are computed for different specific costs, including: £10,000/kg, £5,000/kg, £1,000/kg, £500/kg, £100/kg.

4 Program Output File

The output from the calculation is printed to separate dump file titled "picap.dat". The date and time is printed at the top of the calculation output as a record for the specific calculation performed. When you run the program this will be produced in the same directory folder. The output starts by echoing some of the input parameters including the destination star chosen, its distance and stellar mass. It will also echo the fuel choice chosen and the payload mass. The relativistic beta is displayed.

The output will then include various parameters, depending on the number of engine stages included into the design, which is currently $1 < n < 2$. Specific information about the design and mission are printed. The total output dump includes the following: structure mass (tonnes), propellant mass (tonnes), ICF pellet mass (kg), assumed burn up fractions, number of propellant tanks, number ICF pellets in total, pulse frequency (Hz), mass flow rate (kg/s), effective exhaust velocity (km/s), exhaust velocity (km/s), average acceleration rate (m/s^2), mass ratio, velocity increments (km/s, %c), engine mass (tonnes), engine specific mass, payload/propellant ratio, engine thrust (MN), jet power (TW), power supply mass (tonnes), assumed radiator efficiency, radiator mass (tonnes), energy release (J/pellet, J/sec/J/stage), Q value for pellet ignition, specific power (MW/kg), neutrons/pulse, neutrons/sec, boost time (years), boost distance (m, AU, LY). The program will also give a summary table of the total mission performance.All parameters are displayed in SI notation.

All key configuration and performance parameters are then printed in sections per engine stage. The assumption is made that the target system is around 10, 100 and 1000 AU across and this is assumed to be the domain of encounter corresponding to the encounter time of crossing, although a stellar debris model is also adopted. This is mainly of use to flyby studies but is included anyway. A trajectory profile table is shown displaying the time (Years) and distance (LY). This is displayed so that the user can copy the rows and columns describing the mission profile into a spread sheet tool for mission profile visualization. Finally, some information is printed to assess the mission architecture requirements in terms of number of launches to LEO and cost. It is the opinion of the Starship Resolution sub-team that performing a full cost analysis at this time is not a useful activity, due to the large uncertainties associated with any extrapolations.

The full PICAP Fortran code is displayed in Appendix A for scrutiny and adoption by others.

5 Project Daedalus Validation

The code was run for the nominal Project Daedalus design. Appendix B and C shows the output for calculations running with either a two-stage or a single stage design configuration, both in flyby only mode. Where there are differences in the Appendix B output compared to Project Daedalus, this is largely due to the fact that propellant mass drops have not currently been coded into the program, which will effect the mass ratio at each stage burn. Table 6 below shows a brief comparison between the 1978 Project Daedalus study and the values produced by this code. The output is in reasonably good approximation to the Project Daedalus study and we can consider this a validation of the PICAP program.

Performance Parameter	Daedalus Group (1978)	PICAP (2013)	% difference
Boost Phase 1 (Years)	2.05	2.054	0.19
Boost Phase 2 (Years)	1.76	1.762	0.11
Cruise Phase (Years)	45	46.132	2.45
Total Mission Duration (Years)	48.81	49.948	2.28
Exhaust Velocity First Stage (km/s)	10,600	10,608	0.08
Exhaust Velocity Second Stage (km/s)	9,210	9,266	0.60
Total Cruise Velocity (km/s)	36,600	36,986	1.04
Thrust First Stage (MN)	7.54	7.53	0.13
Thrust Second Stage (MN)	0.663	0.667	0.60
Distance First Stage Burn (LY)	0.0503	0.0509	1.18
Distance Second Stage Burn (LY)	0.210	0.1615	23.09
Bombardment Shield Mass (tonnes)	50	53.65	6.80

Tab. 6: Comparison of 1978 Daedalus vehicle design calculations with 2013 Picap code calculations for validation

6 Starship Resolution Associated Studies

6.1 Design Philosophy

The approach taken by this sub-team was to firstly examine the propellant, exhaust velocity, pulse frequency, cruise velocity and total mission duration trade space. Studies were then performed on a perturbed Daedalus design. These studies then informed the decision about where the Starship Resolution concept vehicle design should be. Work was then started on the development of a comprehensive physics and engineering program written in Fortran, to reproduce as much of the Project Daedalus design as time would allow. This was then altered for a Starship Resolution concept and iterations led to the chosen design solution.

The main driving requirement of this sub-team was to reduce the mass from the Project Daedalus study. This was accomplished for both the total propellant mass and the total structure mass. The payload mass was chosen to be around 150 tonnes on the basis of several previous studies performed by the Project Icarus Study Group, namely Long [17] and Crawford [18], where both studies seem to converge on a payload mass range of between 100-200 tonnes for Project Icarus, hence 150 tonnes seemed to be a good average to base calculations on, but with the expectation that the payload mass may gradually increase throughout the integration and higher level design phases, up to 200 tonnes. So for Starship Resolution we are assuming a 50 tonnes mass margin on the payload.

We also need to keep in mind the defined engineering philosophies for Project Icarus as originally described in the Project Program Document (PPD) [19]. These were

- Design Philosophy 1: The designer is to rely upon worst case calculations as a means of capturing problem uncertainties and allowing a pessimistic assessment of the problem.

- Design Philosophy 2: The designer shall solve problems and produce work output in the spirit of the project watchwords, namely: credible, practical, scientific, near-future, engineered, reliability.
- Design Philosophy 3: The designer shall remain well informed with current scientific and technological developments which may impact the Icarus design and mission.
- Design Philosophy 4: Extrapolations of current technology is to be of a linear type only and limited to a few decades hence.
- Design Philosophy 5: The Icarus vehicle design and mission profile is to be derived by considering perturbations of the Daedalus baseline design. The design is then to be evolved to a newly optimized configuration.
- Design Philosophy 6: The vehicle configuration is to be derived solely from engineering and physics calculations where possible.
- Design Philosophy 7: The team is to maintain an open-door mission policy for as long as is appropriate during the study.
- Design Philosophy 8: All designers will keep a weather eye on the potential application of nano-technology for use in their respective systems or sub-systems.

It is the opinion of the Starship Resolution sub-team that the concept design proposed below is consistent with the above design philosophies, although specific details on nano-technology are yet to be incorporated, but they will be at the sub-systems integration level.

6.2 Study 1: Propellant Utilization Study

Extensive studies were conducted [20] to explore the trade space for Project Icarus vehicle, assuming a perturbed Daedalus 2nd engine stage, but carrying a 150 tons science payload to full orbital deceleration about the target star system of Centauri A and B, 4.4 light years away, and completing the mission in 100 years or less. Various calculations were performed using Back of Envelope methods as well as the construction of a detailed Spread sheet model under the assumption of given mass distributions and stage drop-offs. The work investigated a large range of exhaust velocities (7,210 km/s, 8,210 km/s, 9,210 km/s) and made the assumption that there were representative of D/D and D/He^3 fuels. Three total propellant mass were studied including 16,000 tons, 20,000 tons and 24,000 tons. The pulse frequency was varied to include 75 Hz, 100 Hz, 150 Hz, 200 Hz, 250 Hz. From the calculations performed it was concluded that exhaust velocities exceeding 8,210 km/s and pulse frequencies greater than 150 Hz will likely be required in order to meet the engineering requirements and stated constraints. A preliminary concept definition was derived, and this assumed a total propellant mass requirement of 24,000 tons, allowing a cruise velocity of 5.17-5.66%c to be reached, taking between 86-100 years to complete the mission. Engine performance requirements were in the likely range 0.04-0.07 kg/s (mass flow rate), 8,210-9,210 km/s (exhaust velocity), 0.35-0.66 MN (thrust), 1.5-3 TW (jet power) and 4.58-9.6 MW/kg (specific power). This report resulted in the data shown below in Figure 2, as a possible design reference range for Starship Resolution.

After this study was completed it was realised that the adoption of 8,210 km/s to represent the exhaust velocity of D/D reactions was in error. According to a paper by Bob Parkinson [26] the exhaust velocity for D/D reactions is around 4,746 km/s, so the lower exhaust velocities adopted above are more representative of a poor performing D/He^3 fuel reaction.

Parameter	Value
Initial Propellant Mass (tons)	24,000
Engine Mass (tons	318
Payload Mass (tons)	150
Shield Mass (tons)	50
Additional Structure Mass (tons)	600
Propellant Tank Mass (tons)	120
Total Dry Mass (tons)	1,238
Total Wet Mass (tons)	25,238
Payload Mass Fraction	0.12
Propellant Fraction	0.95
Burn 1 Description	8,000 tons propellant burn, 40 tons tank mass drop at burn end, 250 tons structural mass drop at burn end, end structure mass 350 tons, end propellant mass 16,000 tons, mass ratio 1.464.
Burn 2 Description	6,500 tons propellant burn, 32.5 tons tank mass drop at burn end, zero structural mass drop at burn end, end structure mass 350 tons, end propellant mass 9,500 tons, mass ratio 1.622.
Burn 3 Description	6,500 tons propellant burn, 32.5 tons tank mass drop at burn end, 250 tons structural mass drop at burn end, end structure mass 100 tons, end propellant mass 3,000 tons, mass ratio 2.66.
Burn 4 Description	3,000 tons propellant deburn, 15 tons tank mass drop at burn end, zero tons structural mass drop at burn end, end structure mass 100 tons, end propellant mass 0 tons, mass ratio 5.739.
Additional Propulsion for Stellar system transit	4-gridded Nuclear Electric ion engine, reference Fearn [6]
Additional Deceleration	None but two-burn Oberth manoeuvre as a possible swing by from Centauri A to Centauri B if the cruise velocity has been shed sufficiently to ~few% of cruise speed.
Main Engine Ignition Method	Shock Assisted ICF, 10 MJ beam input per detonation
Fuel	DHe^3 and/or DD (TBD)
Exhaust Velocity (km/s)	8,210 – 9,210
Thrust (MN)	0.35 – 0.66
Mass Flow Rate (kg/s)	0.0432 – 0.072
Pulse Frequency (Hz)	150 - 250
Jet Power (TW)	1.46 – 3.05
Specific Power (MW/kg)	4.58 – 9.6
Total Boost Time (Years)	9.25 – 15.41
Total Cruise Time (Years)	75.98 – 83.15
Total Deburn Time (Years)	1.32 – 2.2
Total Mission time (Years)	86.55 – 100.76
Final Cruise Velocity (km/s)	15,510 – 16,980 [5.17 – 5.66%c]

Fig. 2: Results of Propellant Utilization Trade Studies, showing possible design space for starship Resolution reference mission [20]

6.3 Study 2: Daedalus Scaling Studies

A further study was performed [21] to examine Daedalus 2nd stage scaling calculations. It was concluded that the likely design point for the Starship Resolution configuration and performance is with a total propellant mass of around 22,000 – 24,000 tons, achieving a peak cruise speed of 4.61 – 4.74

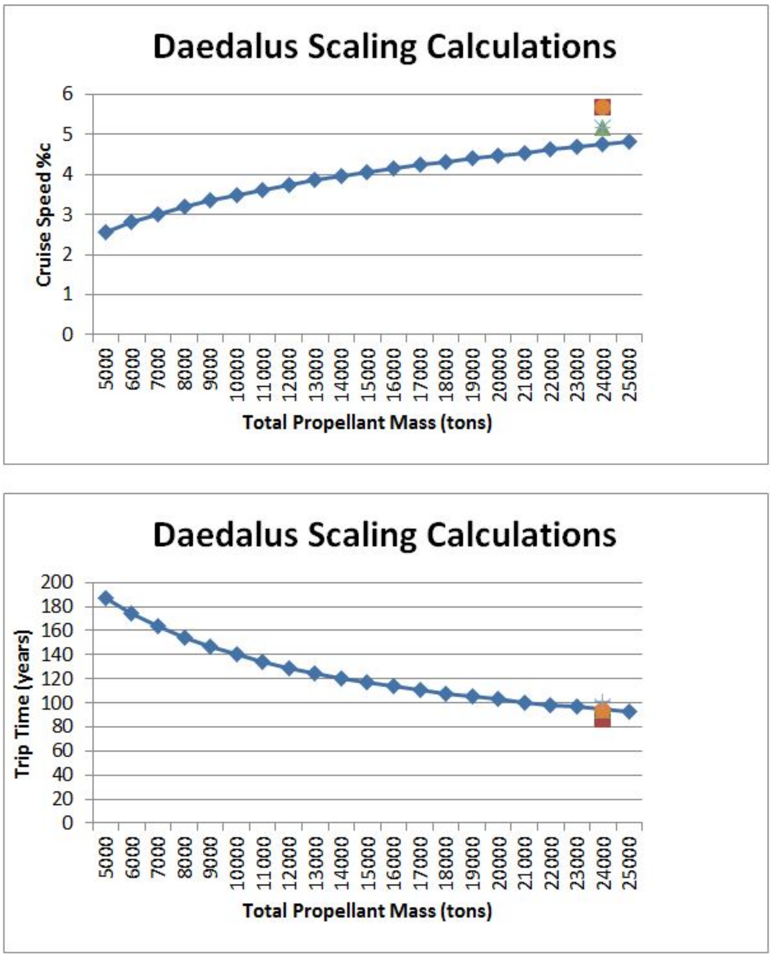

Fig. 3: Results of Daedalus scaling calculations [21]

6.4 Study 3: Gas Giant Mining Balloon Analysis

Some analysis was performed on the possibility of mining He^3 from the gas giants, particularly Uranus and Jupiter. This was on the basis that this was the default mission architecture for the Project Daedalus study. For some time many in the Project Icarus Study Group had spoken out against gas giant mining, but it is the view of the Starship Resolution sub-team that reasonable extrapolations of existing technology demonstrate that gas giant mining is entirely feasible within the next century and indeed is commensurate with expected developments in space technology and space infrastructure as part of the establishment of a solar system wide economy. This, and the fact that He^3 gives a much large energy release (more bang for the buck) than any of the other fusion based reactions, as well as its highly aneutronic nature, influenced this design team to incorporate He^3 as a proportion of the propulsion fuel, along with Deuterium.

A study has been completed [22] to show what is required in terms of the number of missions and under the assumption of different propellant masses. The results of this study are reproduced below in Figure 4 for scrutiny and were used in making the decision on what He^3/D ratio should be used in the Starship Resolution concept vehicle design, but traded off with performance requirements.

Helium-3 Requirement (Tons)	Number of balloons at 100MW power output each		Number of balloons at 10MW power output each		Number of balloons at 1MW power output each	
	1 Earth year for full acquisition	10 Earth years for full acquisition	1 Earth year for full acquisition	10 Earth years for full acquisition	1 Earth year for full acquisition	10 Earth years for full acquisition
4000	11	1	110	11	1103	110
4500	12	1	124	12	1241	124
5000	14	1	138	14	1379	138
5500	15	2	152	15	1517	152
6000	17	2	165	17	1654	165
7000	19	2	193	19	1930	193
8000	22	2	221	22	2206	221

Fig. 4: Balloon requirements per power output level, operating duration and volume of He^3 required

In the end, for Starship Resolution we decided to go with 100% D/He^3 fuel and the total propellant mass was 24,600 tonnes. Assuming two thirds of this was He^3 this would mean a minining requirement of around 16,400 tonnes. The table shows the mining requirements for 8,000 tonnes of He^3 so we can double this to get an estimate. Starship Resolution would required 44 balloons at 100 MW power output each over 1 full Earths year of acquisition, or 4 balloons over 10 Earth years for full acquisition. Assuming a 10 MW power output each Starship Resolution would required 442 balloons at 1 Earth year for full acquisition or 44 balloons for 10 Earths year for full acquisition. This seems entirely reasonable from the standpoint of todays technology.

6.5 Study 4: Shock Ignition ICF

The key part of the internal Project Icarus design competition was to facilitate design space scoping so as to inform our down-select process. The key distinguishing parameter for this is the propulsion and ignition system, with no two designs having the same ignition system. For this study, shock assisted Inertial Confinement Fusion (ICF) was assumed. This is a form of direct drive implosion and ignition but it involves the use of a thick ablator shell so as to facilitate absorption of the electron energy deposition, which augments the implosion. In addition, shock ignition does not ignite the central hot spot region to thermonuclear conditions on the first

	Indirect Drive (hohlraum)	Direct Drive	Shock Ignition	Fast ignition
Electron preheat into fuel	high	high	low	high
Compression	high density	high density	low density	high density
Implosion velocity (m/s)	fast (~4×10⁷)	fast (~4×10⁷)	Slow (~3×10⁷)	slow
Adiabat	high	high	low	high
Central hot spot	yes	yes	yes	no
Hot spot temperature	> $T_{i,theshold}$	> $T_{i,theshold}$	< $T_{i,theshold}$	< $T_{i,theshold}$
RT instabilities	low	high	low	high
Gain	~10-20	~10-20	100-250	~10-100
Driver energy (minimum)	> 1 MJ	> 1 MJ	< 1 MJ	1 MJ+100 kJ
Min Number driver pulses	1	1	1	2
Long Pulse/Short Pulse	LP	LP	LP	LP+SP
Compression/Ignition	coupled	coupled	de-coupled	de-coupled
Target design	complex	simple	simple	complex
Shell thickness	thin	thin	thick	thin

Fig. 5: Balloon requirements per power output level, operating duration and volume of He^3 required

implosion shock, but only after a rebounded collision shock. A description of shock assisted ignition was given in an earlier report [23]. A comparison of the shock ignition scheme to other methods is shown in Figure 5. In the earlier report [23], it was discussed how the scaling of the National Ignition Facility (NIF) energy gain with laser energy is given by

$$E_{gain} = 126 \times E(MJ)^{1/2} \tag{70}$$

So that energy gains of 5-10 times higher than conventional ICF schemes can be accomplished using a shock ignition based approach. For a NIF point design, assuming 1.8 MJ, this would correspond to an energy gain of 169 MJ or a Q factor of around 94. For a 10 MJ laser system, as proposed for the Starship Resolution vehicle (on the basis of credible next generation technology), this would give an energy gain of 398 MJ and a Q factor of around 40. But these are for NIF like capsule masses, which are typically around milli-grams in mass.

However, conversations between K.Long and and laser-fusion physicists at LLNL have elucidated further information about this scaling law. It was reported that the scaling law was a fit to the capsule designs so only went up to capsules scaled for maximum energy/power attainable on NIF, i.e. 1.8 MJ/500 TW which could be increased to 3 MJ/800 TW for a NIF like design, but with increased laser plasma instabilities as the energy goes up. In general, most ICF gain curves for a given target type will scale as driver energy to sub-linear power, i.e. 0.5-0.7. For the purposes of this report, we assume the original energy scaling law as shown above, but this caveat will need to be considered in any future work or adoption of this specific ignition scheme.

6.6 Study 5: Medusa Sail for Deceleration

Some brief trade studies were conducted to scope out the feasibility of using a Medusa sail as the deceleration stage. For this study all 'units' were assumed to be 25 kg in mass, with a starting

Vehicle	Reference Design	Single Stage	Single Stage with Medusa
Propellant mass (tonnes)	22,000	18,000	18,000
DD	18,000	18,000	18,000
DHe^3	4,000	–	–
δ v1 (%c)	4.84	9.95	9.95
tb1 (Years)	13.2	12.3	13.2
δ v2 (%c)	4.63	–	–
tb2 (Years)	2.93	–	–
t_{cruise} (Years)	81.7	40.35	40.35
$t_{mission}$ (Years)	97.9	53.6	53.6
δ v remaining (%c)	0.2	9.95	9.95

Tab. 7: Basic comparison of reference design to addition of Medusa sail

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	0.01	0.12	1.25	11.96
Final δv (km/s)	29,833	29,799	29,465	26,268

Tab. 8: Medusa Sail Studies 30 units total

detonation point from the rear of the vehicle of 1,000 m over a 5,000 m radius canopy area. Each unit to start with was assumed to release 100 GJ of energy. Several of these variables were then assessed as variables. The sail material was assumed to be a high-strength polymer such as polyethylene and appropriate values for the material properties were assumed.

Table 4 below shows the calculation of the nominal reference design (see the next chapter) but for a single stage design configuration only. This is then compared to adding a Medusa sail deceleration stage with the above assumptions. It can be seen from Table 7 and 8 that adding the Medusa sail in its current configuration has no effect on the final velocity increment. It is necessary then to conduct some studies into varying the energy release per unit, the number of units and the detonation distance and sail area.

Tables 8, 9 and 10 shows the results of deploying the Medusa sail for varying parameters. In particular assuming 30 units, 300 units or 3,000 units which would equate to a total unit mass of 0.75 tonnes, 22.5 tonnes and 75 tonnes respectively. With these configurations the reduction in velocity is not sufficient to effect full orbital insertion.

It is necessary to consider a direct comparison with the reference point mission then, which involves around 4,000 tonnes of He^3 for the decelerated deburn. Assuming each unit has a mass of 25 kg, this equates to 160,000 units. Tables 11-13 shows the results assuming a 5,000 m sail radius and over a 1,000 m detonation point. The results are shown again for different energy

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	0.03	0.19	1.43	12.52
Final δv (km/s)	29,827	29,781	29,409	26,102

Tab. 9: Medusa Sail Studies 300 units total

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	0.022	0.73	3.26	17.91
Final δv	29,771	29,604	28,868	24,493

Tab. 10: Medusa Sail Studies 3000 units total

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	5.11	16.19	51.39	100+
Final δv	28,311	25,006	14,501	0

Tab. 11: Medusa Sail Studies 160,000 units total assuming 5,000 m sail radius and 1,000 m detonation distance

released per unit.

It is clear, examining the results of these brief studies, that in order to use a Medusa Sail (instead of reverse engine thrust) for deceleration into the target, a quantities of units would be required well in excess of 100,000 and each would need to give at least 100 GJ energy release, and ideally a greater number. This doesn't seem unreasonable and although direct deceleration via reverse engine burn remains the preferred route to effecting orbital velocity, it would seem prudent to conduct further studies to trade fuel propellant for 'unit' propellant via the Medusa scheme. It is recommended that Medusa sail should be considered as an option in down select. However, there are two additional factors to consider in this issue (1) whether the radioactive material needed for the units can be sourced and (2) the implications of detonating large yields whilst approaching a stellar system, and how this could be perceived by a would be intelligent species. The decision process should be guided by a performance gain versus mass trade-off with reverse engine thrust propellant.

7 Starship Resolution Concept Design

In this section we briefly show the chosen layout for the Starship Resolution concept vehicle design. The full description of the vehicle is given in Appendix D but will be described briefly here. It is not expected that this configuration is the final word, but merely the beginning of an iterative process, which includes factoring in margins and uncertainties to evolve an improved design.

Figure 7 shows the trajectory of the flight on its journey to the agreed destination target of Centauri B 4.4 light years away. The vehicle carries a payload of 150 tonnes and is fronted by a Beryllium particle shield of approximately 54 tonnes in mass (which is expected to be much lower in the preliminary design definition). There are a total of 16 propellant tanks, 12 of which

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	20.45	64.76	100+	100+
Final δv	23,734	10.515	0	0

Tab. 12: Medusa Sail Studies 160,000 units total assuming 10,000 m sail radius and 1,000 m detonation distance

Energy Release Per Unit (GJ)	100	1,000	10,000	100,000
δv reduction (%c)	0.65	100+	100+	100+
Final δv	29,644	0	0	0

Tab. 13: Medusa Sail Studies 160,000 units total assuming 10,000 m sail radius and 500 m detonation distance

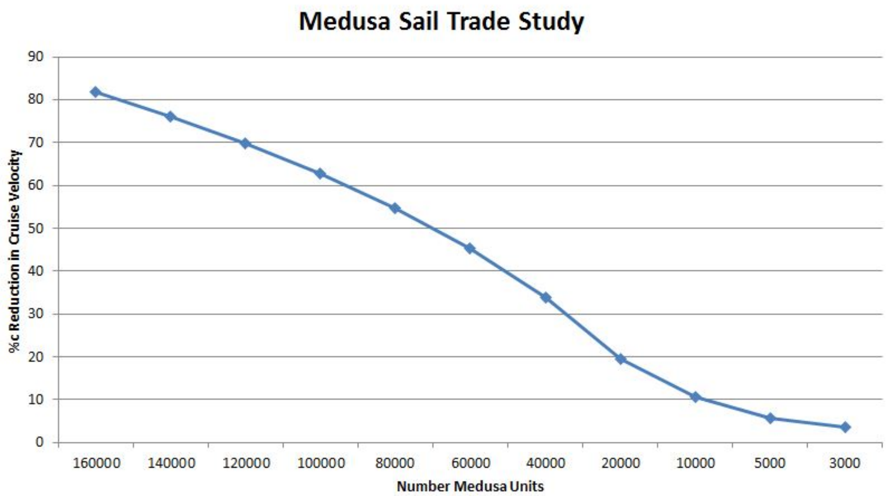

Fig. 6: Effect of Medusa Sail on Reference design assuming 100 GJ/unit, 25kg units, 500 m detonation distance and 10,000 m sail radius

are used for the acceleration run, and 4 for the deceleration burn. The boost phase involves 20,700 tonnes D/He^3. The deburn phase involves 3,900 tonnes D/He^3 only.

It is expected that after the acceleration phase is completed that the spent propellant tanks will be discarded along with parts of the structure mass. It is expected that this total discarded mass could be as high as 200 tonnes and this mass is factored into the second stage structure as a mass reduction, but it is left for future analysis to iterate the calculations with these assumptions further. Note that we have not included propellant mass drops in the calculations, which would effect the mass ratio and so give a slightly improved performance on the velocity burns, although this could be subsumed by this 200 tonnes reduction in the structure drop.

For this configuration the pulse frequency is assumed to be 150 Hz for both engine burn stages. The vehicles uses ICF capsule masses equivalent to the Project Daedalus second stage, namely 0.000288 kg each in mass with a 9.97 mm capsule geometry size. The capsules are ignited via a shock assisted ignition scheme, utilizing laser drivers (not electron beams), although this team has not yet had time to build the required ignition and burn model.

The vehicle starts off with a total structure mass of 1,000 tonnes as well as an addition 318 tonnes mass for the engine. In addition to this is the 150 tonnes payload mass and the approximately 54 tonnes particle shield mass. The first stage boost period lasts for a total duration of 15.18 years (admittedly too long and to be revised later). At the end of this burn period the vehicle has reached a distance of 17,350 AU or 0.274 LY. The engine thrust during this burn is 0.397 MN and the total jet power is 1.832 TW.

The vehicle then coasts in cruise mode at a cruise velocity of 14,481 km/s or 4.83% of the speed of light. The cruise period lasts for 81.475 years until the vehicle reaches a distance of 248,891 AU or 3.936 LY. At this point, the vehicle engages the reverse engine thrust (after firing radial thrusters and turning the entire vehicle around by 180 degrees) which has a thrust of 0.397 MN and a jet power of 1.832 TW and achieves a velocity of 4.83%c. The total deburn period lasts for a duration of 2.86 years. At the end of the deburn period the vehicle will reach the target star system 4.4 light years distance. In the particular model shown here, there is still an excess velocity of around 1 km/s but this is assumed to be in the noise of the future iterations and only a minor tweaking of the model is required. In particular, the model currently does not include propellant mass drops or structure mass drops, and these will effect the mass ratio and so the performance. A slightly higher reverse engine thrust is expected when these mass ratio changes are made. The Table 14 below gives a summary of the Starship Resolution concept vehicle design configuration.

As the vehicle moves through its various burn stages it will shed structural mass, although the boom structure linking the engine to the payload will remain in tact. Eventually, once the stellar system is reached the entire engine bell and boom will be jetisonned, along with the particle shield, and the payload will then move independently throughout the target system. As well as deploying orbital probes, atmospheric penetrators, and even small landers, the science probe will also deploy a set of STARWISP probes [27]. The laser system on board the main engine section will then be used to propel these STARWISP probes around the stellar system. These will range in mass from grams to kilograms in size, each picking up information about the target system and relaying it back to the main vehicle.

A full description of the output from the PICAP code is shown in Appendix D, for the Starship Resolution vehicle. The Figures 8 and 9 and 10 (Appendix E) also show the configuration layout. The output in Appendix D also shows some of the estimated costs for the construction and assembly of such a vehicle, given some basic assumptions about launch vehicles costs using conventional rockets or Single Stage to Orbit Space planes.

Performance Parameter	Starship Resolution
Vehicle Length (m)	2000
Vehicle Widgth (m)	50
Propellant Mass First Stage (tonnes)	20,700
Propellant Mass Deburn (tonnes)	3,900
Engine Mass (tonnes)	318
Structure Mass (tonnes)	1,000
Number Propellant Tanks First Stage	12
Number Propellant Tanks Deburn Stage	4
Boost Phase 1 (Years)	15.184
Cruise Phase (Years)	81.475
Deburn Phase (Years)	2.861
Total Mision Duration (Years)	99.519
Excess Velocity at Target (km/s)	1.28
Exhaust Velocity First Stage (km/s)	9,210
Mass Flow Rate First Stage (kg/s)	0.0432
Exhaust Velocity Second Stage (km/s)	9,210
Mass Flow Rate Deburn Stage (kg/s)	0.0432
ICF Capsule Mass (kg)	0.000288
Total Cruise Velocity (km/s)	14,481.476 (4.830%c)
Thrust First Stage (MN)	0.398
Jet Power First Stage (TW)	1.832
Thrust Deburn Stage (MN)	0.398
Jet Power Deburn Stage (TW)	1.832
Distance First Stage Burn (LY)	0.274
Distance Second Stage Burn (LY)	0.189
Bombardment Shield Mass (tonnes)	53.65
Bombardment Shield Thickness (mm)	9.01
Payload Mass (tonnes)	150

Tab. 14: Starship Resolution Configuration Layout and Performance Overview

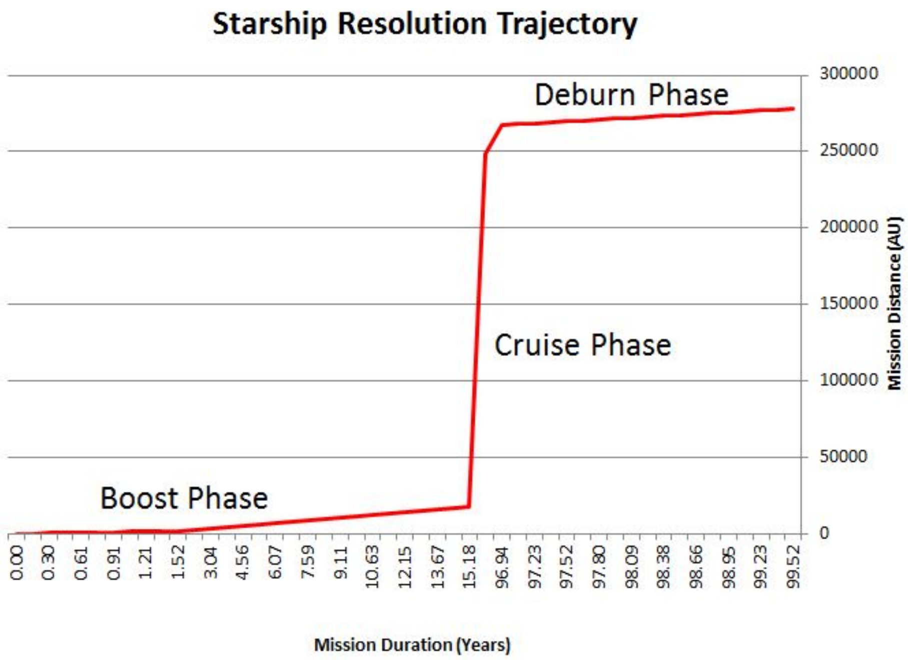

Fig. 7: Starship Resolution Mission Trajectory for Decelerated Burn

8 Conclusions

In this report we have introduced the Starship Resolution concept vehicle design and the method for obtaining the design reference mission. We have also discussed the utilization of a comprehensive physics code, the PICAP program, which is coded up in Fortran and validated (within a reasonable approximation) to the historical Project Daedalus design. The biggest differences between the code and the 1970s design are due to the lack of modeling propellant tank drops. The program can be developed further, to include optimization algorithms et cetera, but we do not attempt this at this point. Members of the Project Icarus Study Group are encouraged to use this program so as to facilitate their own design evolution as well as improve their personal designer capability aims. More physics and engineering is still to be developed in order to attain a full code design model.

A credible design solution to the Project Icarus requirements definition is presented in the Starship Resolution layout. This is a pre-down select configuration and due to time constraints there is a lack of fidelity in certain areas. Essentially, Starship Resolution is a single stage system (unlike the two-stage Daedalus design) which utilizes reverse engine thrust to effect full deceleration into the stellar system, identified to be Centauri B. The design uses a mixture of D/D and D/He^3 fuel. An option to employ a Medusa sail for deceleration is proposed for further study and it should not be ruled out at this time until further analysis has been completed.

As far as this sub-team is concerned, on paper the Starship Resolution concept would appear to meet the engineering requirements, but with the following caveats (1) the boost time of 13.2

years is far too long and efforts should be made to bring this right down to just a few years trip time (2) a full implosion, ignition and burn model has not been completed and this will need to be done to construct a credible physics model (3) little attention has been paid to the areas of power supply, thermals, radiation shielding and communications, which will need further attention on second iteration. The quoted masses for the power supply and radiators shown in Appendix D should be ignored at this time, because the algorithms currently loaded into the program are not credible given the enormous masses they seem to predict.

It is proposed that the Fortran code and the reference design, Starship Resolution, should both be seen as the basis of a starting point upon which to evolve a design solution that fully meets the Project Icarus requirements.

9 Acknowledgments

The Starship Resolution sub-team would like to acknowledge the technical input of Stephen Baxter which has proven to be a very useful peer review process on the calculations. Adrian Mann is thanked for doing the graphics.

References

[1] Long, K.F, R.K.Obousy, M.Fogg et al., Project Icarus: Son of Daedalus - Flying Closer to Another Star, JBIS, 2010.

[2] Bond, A &A.Martin, Project Daedalus: The Mission Profile, JBIS, 1978.

[3] Galea, P, Project Icarus Primary Propulsion Selection Phase Plan, December 2012.

[4] Long, K.F, Deep Space Propulsion: A Roadmap to Interstellar Flight, Springer, 2011.

[5] Long, K.F, R.K.Obousy, A.Hein, Project Icarus: Optimisation of Nuclear Fusion Propulsion for Interstellar Missions, Acta Astronautica, 68, pp.1820-1829, 2011.

[6] Martin, A.R and A.Bond, Project Daedalus: The Propulsion System, Part I: Theoretical Considerations and Calculations, S44-S62, JBIS, 1978.

[7] Bond, A &A.Martin, Project Daedalus: The Propulsion System, Part II: Engineering Design Considerations and Calculations, S63-S82, JBIS, 1978.

[8] Martin, A, Project Daedalus: Bombardment by Interstellar Material and its Effects on the Vehicle, JBIS, 1978.

[9] Crawford, I, Project Icarus: A Review of Local Interstellar Medium Properties of Relevance for Space Missions to the Nearest Stars, Acta Astronautica, 2010.

[10] Bond, A, Project Daedalus: Target System Encounter Protection, JBIS, S123-S125, 1978.

[11] Pfalzner, S, An Introduction to Inertial Confinement Fusion, Taylor & Francis, 2006.

[12] Lindl, J.D, Inertial confinement Fusion, The Quest for ignition and Energy Gain Using Indirect drive, Springer, 1998.

[13] Spitzer, L, Jr, Physics of Fully Ionized Gases, Dover Publication, 2006 (originally published 1914)

[14] Solem, J.C, The Moon and the Medusa: Use of Lunar Assets in Nuclear-Pulse-Propelled Space Travel, JBIS, 53, pp.362-370, 2000.

[15] Solem, J.C, Nuclear Explosive Propulsion for Interplanetary Travel: Extension of the Medusa Concept for Higher Specific Impulse, JBIS, 47, pp.229-238, 1994.

[16] Solem, J.C, Medusa: Nuclear Explosive Propulsion for Interplanetary Travel, JBIS, 46, pp.21-26, 1993.

[17] Long, K.F, I.Crawford, R.Osborne, R.Obousy, A.Tziolas, Project Icarus: Some Initial Considerations for Payload Options for the Icarus Mission, Internal Team Report, 7th May 2011.

[18] Crawford, I.A, Project Icarus: Some Preliminary Thoughts on the Selection of Probes and Instruments for the Icarus Interstellar Mission, Internal Team Report, 8th April 2012.

[19] Long, K.F & R.K.Obousy, Project Icarus Project Program Document (PPD) - Overview Project Plan Covering Period 2009 - 2014, 12th May 2010.

[20] Long, K.F, Project Icarus: Starship Resolution Trade Study Into Propellant Utilization and Propulsive Performance, Internal Team report, 18th March 2013.

[21] Long, K.F, Project Icarus: Daedalus Scaling Studies for Starship Resolution, Internal Team Report, 20th March 2013.

[22] Osborne, R, Starship Resolution Study - Gas Giant Mining Balloon Analysis, Project Icarus Technical Memorandum, 30th September 2013.

[23] Long, K.F, Project Icarus: A Brief Consideration of Shock Ignition for the Main Engine Energy Generation Mechanism, 7th May 2011.

[24] Long, K.F, Project Icarus: Use of Medusa Sail for the Icarus Mission, 7th May 2011.

[25] Galea, P, Project Icarus: Communications and Telemetry, Radio Frequency Systems for Interstellar Communications

[26] Parkinson, R, Using Daedalus for Local Transport, JBIS, 62, pp.422-426, 2009.

[27] Forward, R.L, Starwisp: An Ultra-Light Interstellar Probe, 22, 3, May-June, 1985.

Appendix A: Fortran PICAP Program

```
Program removed for public release version
```

Appendix B: Program Output File Two Stage Project Daedalus Set-Up

```
Year, Month, Date=20130721
 Hours, Minutes, Seconds=231133.889
 #############################################################
  PPPPPPPP   IIIIIIII    CCCCCCCC    AAAAAAAA      PPPPPPPP
  PP    PP      II       CC          AA    AA      PP    PP
  PP    PP      II       CC          AA    AA      PP    PP
  PPPPPPPP      II       CC          AAAAAAAA      PPPPPPPP
  PP            II       CC          AA    AA      PP
  PP            II       CC          AA    AA      PP
  PP         IIIIIIII    CCCCCCCC    AA    AA      PP
 #############################################################
  PROJECT ICARUS CONFIGURATION AND PERFORMANCE PROGRAM
 #############################################################

 Project Icarus Configuration And Performance (PICAP) Program
 Version 2.0
 ============================================================
 Electron beam energy per pulse (kJ):   1.00000000
 Electron beam power per pulse (W):   1.00000000E+14
 Stellar Destination Target=
  Barnards Star
 Stellar Mass=
  0.15Ms
 The stage 1 fuel reaction modelled is D(He3,He4)p
 The stage 2 fuel reaction modelled is D(He3,He4)p
 Effective exhaust velocity (km/s):   10938.3857
 Effective exhaust velocity (km/s):   9554.63379
 Exhaust velocity (km/s):   10608.5527
 Exhaust velocity (km/s):   9266.52637
 Particle Bombardment Shield material is Beryllium
 Relatavistic beta (v/c):  0.123371214
 Target distance (LY):   5.90000010
 Payload mass (tonnes):   450.000000


  FIRST ENGINE STAGE:-
 =============================================
 Mass (Structure(tonnes), Propellant(tonnes):   1690.00000       46000.0000
 ICF pellet mass (kg):   2.83999997E-03
 Assumed pellet burn up fraction:  0.174999997
 Number propellant tanks:   6.00000000
 Number ICF pellets (total, per tank):   1.61971835E+10   2.69953050E+09
 Mass flow rate (kg/s):  0.709999979
 Exhaust velocity (km/s):   10608.5527
 Average acceleration rate (m/s2):  0.338358045
```

```
Mass ratio:   7.89655161
Velocity increment (km/s, %c):   21921.7910      7.31232262
Engine mass (tonnes):   988.000000
Engine Specific mass:   2.47295571E-08
Payload/Propellant Ratio:  0.212805554
Engine Thrust (MN):   7.53207207
Jet Power (TW):   39.9521942
Energy Release (J/pellet, J/sec, J/stage):   1.76434987E+11   4.41087479E+13   7.14437498E+23
Q value for Pellet Ignition:   65.3462906
Specific Power (MW/kg):   40.4374428
Neutrons/pulse:   2.99293412E+21
Neutrons/s:   7.48233518E+23
Boost time (Years):   2.05443740
Boost distance (m, AU, LY):   4.81373391E+14   3217.73682      5.08824475E-02

 SECOND ENGINE STAGE:-
=============================================
Mass (Structure(tonnes), Propellant(tonnes):   530.000000      4000.00000
ICF pellet mass (kg):   2.88000010E-04
Assumed pellet burn up fraction:  0.133000001
Number propellant tanks:   4.00000000
Number ICF pellets (total, per tank):   1.38888888E+10   3.47222221E+09
Mass flow rate (kg/s):   7.20000044E-02
Exhaust velocity (km/s):   9266.52637
Average acceleration rate (m/s2):  0.271151423
Mass ratio:   5.08163261
Velocity increment (km/s, %c):   15063.9668      5.02479839
Engine mass (tonnes):   318.000000
Engine Specific mass:   1.02870452E-07
Payload/Propellant Ratio:  0.291913390
Payload/Propellant Ratio:   5.40321209E-02
Total Engine Specific mass:   3.10016546E-08
Engine Thrust (MN):  0.667189956
Jet Power (TW):   3.09126663
Energy Release (J/pellet, J/sec, J/stage):   1.35979203E+10   3.39947998E+12   4.72149999E+22
Q value for Pellet Ignition:   33.9948006
Specific Power (MW/kg):   9.72096443
Neutrons/pulse:   2.30666703E+20
Neutrons/s:   5.76666747E+22
Boost time (Years):   1.76165497
Boost distance (m, AU, LY):   1.52764685E+15   10211.5439     0.161476344

 OVERALL PERFORMANCE:-
=============================================
Total Mass Ratio:   40.1273727
Final cruise velocity (km/s, %c):   36985.7578      12.3371210
Total cruise distance (m, AU, LY):   5.38079301E+16   359678.688      5.68764162
Total cruise duration (Years):   46.1323051
Total mission duration (Years)):   49.9483986
```

```
Total Mission Distance (m, AU, LY):   5.58169483E+16   373107.969       5.90000010

 STELLAR ENCOUNTER:-
=============================================
Total 10 AU encounter time (Days):  0.468148172
Total 100 AU encounter time (Days):   4.68148136
Total 1000 AU encounter time (Days):   46.8148117
Stellar Debris radius (LY):   5.31665385E-02
Stellar Debris radius (AU):   3362.17944
Stellar Debris Diameter encounter time (Days):   314.591827

 PARTICLE SHIELD:-
=============================================
Particle Bombardment Shield Area (m^2):   3216.99023
Particle shield mass ablation rate (kg/s):   5.25331689E-06
Particle shield minimum thickness required for mission (mm):   9.01463699
Particle shield minimum mass required for mission (tonnes):   53.6500015

   MEDUSA SAIL DECELERATION:-
=============================================
Medusa Exhaust Velocity (km/s):   1041.66663
Medusa Specific Impulse (s):   106220.438
Total Medusa Unit Mass (tonnes):   750.000000
Radius of Gas Debris expansion from single unit (km):   20.0000000
Maximum Conservative Spinnaker Mass (tonnes):           4
Impulsive Pressure (N/m2):   2.48057942E-04
Average Thrust (kN):   26041.6660
Single Unit Mass (kg):   25.0000000
Number Units:   30.0000000
Wet (incl.Medusa) Mass (tonnes):   1038.40002
dry (incl.Medusa) Mass (tonnes):   1033.65002
Medusa delta V (km/s):   4.77590847
Pre-Medusa delta V (km/s):   36985.7578       12.3371210
Final effected velocity (km/s):   36980.9805
Percentage Medusa dv Reduction:   1.29167121E-02

 TRAJECTORY DATA BELOW:-
=============================================
    Time(Years)    Distance(AU)
    49.9483986       373107.969
    3.81609249       13429.2812
    3.72800970       12918.7031
    3.63992691       12408.1260
    3.55184412       11897.5498
    3.46376133       11386.9717
    3.37567854       10876.3945
    3.28759575       10365.8174
    3.19951320       9855.24023
    3.11143041       9344.66309
```

```
     3.02334762       8834.08594
     2.93526483       8323.50879
     2.84718204       7812.93164
     2.75909948       7302.35449
     2.67101669       6791.77734
     2.58293390       6281.20020
     2.49485111       5770.62305
     2.40676832       5260.04541
     2.31868577       4749.46826
     2.23060298       4238.89111
     2.05443740       3217.73682
     1.95171547       3056.84985
     1.84899366       2895.96313
     1.74627185       2735.07642
     1.64354992       2574.18945
     1.54082799       2413.30273
     1.43810618       2252.41577
     1.33538425       2091.52881
     1.23266244       1930.64221
     1.12994063       1769.75525
     1.02721870       1608.86841
    0.924496830       1447.98157
    0.821774960       1287.09473
    0.719053090       1126.20789
    0.616331220       965.321106
    0.513609350       804.434204
    0.410887480       643.547363
    0.308165610       482.660553
    0.205443740       321.773682
    0.184899375       289.596313
    0.164354995       257.418945
    0.143810615       225.241577
    0.123266242       193.064209
    0.102721870       160.886841
     8.21774974E-02   128.709473
     6.16331212E-02   96.5321045
     4.10887487E-02   64.3547363
     2.05443744E-02   32.1773682
     0.00000000       0.00000000

MISSION ARCHITECTURE REQUIREMENTS:-
=============================================

SKYLON LAUNCH VEHICLE
Total Dry Mass (tonnes) to LEO:        2670
Number SKYLON launch Vehicles:         296
Specific Cost (£/kg):         650
Total Assembly Launch Cost (£billions):   1.73549998
Assembly Cost Per Launch (£millions):   5.86317539
```

```
MEDIUM LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   10.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number MEDIUM LIFT launch Vehicles:   267.000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   5.00000000
Assembly Cost (£100/kg) Per Launch (£millions):  0.999999940

MEDIUM HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   20.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number MEDIUM HEAVY LIFT launch Vehicles:   133.500000
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   200.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   20.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   1.99999988

HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   50.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number HEAVY LIFT launch Vehicles:   53.4000015
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   250.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   25.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   4.99999952

SUPER HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   100.000000
Total Dry Mass (tonnes) to LEO:   2670.00000
```

```
Number HEAVY LIFT launch Vehicles:   26.7000008
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   1000.00000
Assembly Cost (£5,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£500/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   9.99999905

============================================================
END OF CALCULATION SUMMARY
```

Appendix C: Program Output File Single Stage Project Daedalus Set-Up

```
Year, Month, Date=20130721
 Hours, Minutes, Seconds=232219.284
 ##############################################################
  PPPPPPPP   IIIIIII    CCCCCCCC    AAAAAAAA      PPPPPPPP
  PP    PP      II      CC          AA    AA      PP    PP
  PP    PP      II      CC          AA    AA      PP    PP
  PPPPPPPP      II      CC          AAAAAAAA      PPPPPPPP
  PP            II      CC          AA    AA      PP
  PP            II      CC          AA    AA      PP
  PP         IIIIIII    CCCCCCCC    AA    AA      PP
 ##############################################################
  PROJECT ICARUS CONFIGURATION AND PERFORMANCE PROGRAM
 ##############################################################

 Project Icarus Configuration And Performance (PICAP) Program
 Version 2.0
 ============================================================
 Electron beam energy per pulse (kJ):   1.00000000
 Electron beam power per pulse (W):   1.00000000E+14
 Stellar Destination Target=
  Barnards Star
 Stellar Mass=
  0.15Ms
 The fuel reaction modelled is D(He3,He4)p
 The stage 1 fuel reaction modelled is D(He3,He4)p
 The stage 2 fuel reaction modelled is D(He3,He4)p
 Effective exhaust velocity (km/s):   10938.3857
 Effective exhaust velocity (km/s):   9554.63379
 Exhaust velocity (km/s):   10608.5527
```

```
Exhaust velocity (km/s):   9266.52637
Particle Bombardment Shield material is Beryllium
Relatavistic beta (v/c):  0.110168509
Target distance (LY):   5.90000010
Payload mass (tonnes):   450.000000

 ENGINE STAGE:-
=============================================
Mass (Structure(tonnes), Propellant(tonnes):   1690.00000       46000.0000
ICF pellet mass (kg):   2.83999997E-03
Assumed pellet burn up fraction:  0.174999997
Number propellant tanks:   6.00000000
Number ICF pellets (total, per tank):   1.61971835E+10   2.69953050E+09
Mass flow rate (kg/s):  0.709999979
Exhaust velocity (km/s):   10608.5527
Average acceleration rate (m/s2):  0.509775162
Mass ratio:   22.4953270
Final cruise velocity (km/s, %c):   33027.6875       11.0168514
Engine mass (tonnes):   988.000000
Engine Specific mass:   2.47295571E-08
Payload/Propellant Ratio:  0.127157986
Engine Thrust (MN):   7.53207207
Jet Power (MN):   39.9521942
Power Supply mass (tonnes):   199760976.
Assumed Radiator Efficiency (kW/kg):   300.000000
Radiator Mass (tonnes):      399521
Energy Release (J/pellet, J/sec, J/stage):   1.76434987E+11   4.41087479E+13   7.14437498E+23
Q value for Pellet Ignition:   65.3462906
Specific Power (MW/kg):   40.4374428
Neutrons/pulse:   2.99293412E+21
Neutrons/s:   7.48233518E+23
Boost time (Years):   2.05443740
Boost distance (m, AU, LY):   5.87766476E+14   3928.92041       6.21284805E-02

 OVERALL PERFORMANCE:-
=============================================
Total Mass Ratio:   22.4953270
Final cruise velocity (km/s, %c):   33027.6875       11.0168514
Total cruise distance (m, AU, LY):   5.52291820E+16   369179.031       5.83787155
Total cruise duration (Years):   53.0253868
Total mission duration (Years)):   55.0798225
Total Mission Distance (m, AU, LY):   5.58169483E+16   373107.969       5.90000010

 STELLAR ENCOUNTER:-
=============================================
Total 10 AU encounter time (Days):  0.524251521
Total 100 AU encounter time (Days):   5.24251461
Total 1000 AU encounter time (Days):   52.4251442
Stellar Debris radius (LY):   5.31665385E-02
```

```
Stellar Debris radius (AU):   3362.17944
Stellar Debris Diameter encounter time (Days):   352.292786

 PARTICLE SHIELD:-
=============================================
Particle Bombardment Shield Area (m^2):   3216.99023
Particle shield mass ablation rate (kg/s):   3.72621412E-06
Particle shield minimum thickness required for mission (mm):   9.01463699
Particle shield minimum mass required for mission (tonnes):   53.6500015

   MEDUSA SAIL DECELERATION:-
=============================================
Medusa Exhaust Velocity (km/s):   1041.66663
Medusa Specific Impulse (s):   106220.438
Total Medusa Unit Mass (tonnes):   750.000000
Radius of Gas Debris expansion from single unit (km):   20.0000000
Maximum Conservative Spinnaker Mass (tonnes):           4
Impulsive Pressure (N/m2):   2.48057942E-04
Average Thrust (kN):   26041.6660
Single Unit Mass (kg):   25.0000000
Number Units:   30.0000000
Wet (incl.Medusa) Mass (tonnes):   2198.39990
dry (incl.Medusa) Mass (tonnes):   2193.64990
Medusa delta V (km/s):   2.25310063
Pre-Medusa delta V (km/s):   33027.6875       11.0168514
Final effected velocity (km/s):   33025.4336
Percentage Medusa dv Reduction:   6.82429317E-03

 TRAJECTORY DATA BELOW:-
=============================================
    Time(Years)    Distance(AU)
    55.0798225      373107.969
    2.05443740      3928.92041
    1.84899366      3732.47437
    1.84899366      3536.02832
    1.64354992      3339.58252
    1.64354992      3143.13647
    1.43810618      2946.69043
    1.43810618      2750.24414
    1.23266244      2553.79810
    1.23266244      2357.35229
    1.02721870      2160.90625
    1.02721870      1964.46021
   0.821774960      1768.01416
   0.821774960      1571.56824
   0.616331220      1375.12207
   0.616331220      1178.67615
   0.410887480      982.230103
   0.410887480      785.784119
```

```
    0.205443740       589.338074
    0.205443740       392.892059
     1.95171547       3732.47437
     1.84899366       3536.02832
     1.74627185       3339.58252
     1.64354992       3143.13647
     1.54082799       2946.69043
     1.43810618       2750.24414
     1.33538425       2553.79810
     1.23266244       2357.35229
     1.12994063       2160.90625
     1.02721870       1964.46021
    0.924496830       1768.01416
    0.821774960       1571.56824
    0.719053090       1375.12207
    0.616331220       1178.67615
    0.513609350       982.230103
    0.410887480       785.784119
    0.308165610       589.338074
    0.205443740       392.892059
    0.184899375       353.602844
    0.164354995       314.313629
    0.143810615       275.024445
    0.123266242       235.735214
    0.102721870       196.446030
     8.21774974E-02   157.156815
     6.16331212E-02   117.867607
     4.10887487E-02   78.5784073
     2.05443744E-02   39.2892036
     0.00000000       0.00000000

MISSION ARCHITECTURE REQUIREMENTS:-
=============================================

SKYLON LAUNCH VEHICLE
Total Dry Mass (tonnes) to LEO:        2670
Number SKYLON launch Vehicles:         296
Specific Cost (£/kg):         650
Total Assembly Launch Cost (£billions):   1.73549998
Assembly Cost Per Launch (£millions):   5.86317539

MEDIUM LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   10.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number MEDIUM LIFT launch Vehicles:   267.000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
```

```
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   5.00000000
Assembly Cost (£100/kg) Per Launch (£millions):  0.999999940

MEDIUM HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   20.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number MEDIUM HEAVY LIFT launch Vehicles:   133.500000
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   200.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   20.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   1.99999988

HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   50.0000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number HEAVY LIFT launch Vehicles:   53.4000015
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   250.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   25.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   4.99999952

SUPER HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   100.000000
Total Dry Mass (tonnes) to LEO:   2670.00000
Number HEAVY LIFT launch Vehicles:   26.7000008
Total Assembly (£10,000/kg) Launch Cost (£billions):   26.7000008
Total Assembly (£5,000/kg) Launch Cost (£billions):   13.3500004
Total Assembly (£1,000/kg) Launch Cost (£billions):   2.67000008
Total Assembly (£500/kg) Launch Cost (£billions):   1.33500004
Total Assembly (£100/kg) Launch Cost (£billions):  0.266999990
Assembly Cost (£10,000/kg) Per Launch (£millions):   1000.00000
Assembly Cost (£5,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   100.000000
```

```
Assembly Cost (£500/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   9.99999905

=============================================================
END OF CALCULATION SUMMARY
```

Appendix D: Program Output File Starship Resolution Concept Vehicle Design

```
Year, Month, Date=20131020
 Hours, Minutes, Seconds=084342.022
 ##############################################################
  PPPPPPPP   IIIIIIII    CCCCCCCC    AAAAAAAA      PPPPPPPP
  PP    PP      II       CC          AA    AA      PP    PP
  PP    PP      II       CC          AA    AA      PP    PP
  PPPPPPPP      II       CC          AAAAAAAA      PPPPPPPP
  PP            II       CC          AA    AA      PP
  PP            II       CC          AA    AA      PP
  PP         IIIIIIII    CCCCCCCC    AA    AA      PP
 ##############################################################
  PROJECT ICARUS CONFIGURATION AND PERFORMANCE PROGRAM
 ##############################################################

 Project Icarus Configuration And Performance (PICAP) Program
 Version 2.0
 =============================================================

 The fuel reaction modelled is D(He3,He4)p
 =======================================================

 PROBLEM OUTPUT:-

 Laser beam energy per pulse (kJ):   10.0000000
 Laser beam power per pulse (W):   8.30000005E+11
 Stellar Destination Target=
  Alpha Centauri B
 Stellar Mass=
  0.89Ms
 Particle Bombardment Shield material is Beryllium
 Estimated Deburn Propellant mass requirement (tonnes):   4782.95166
 WARNING: Propellant Deburn Inconsistency with Input:   4782.95166       3900.00000
 The stage 1 fuel reaction modelled is D(He3,He4)p
 The stage 2 fuel reaction modelled is D(He3,He4)p

 Target distance (LY):   4.40000010
 Payload mass (tonnes):   150.000000
```

```
 FIRST ENGINE STAGE:-
=============================================
Mass (Structure(tonnes), Propellant(tonnes):   1000.00000       20700.0000
ICF pellet mass (kg):   2.88000010E-04
Assumed pellet burn up fraction:  0.133000001
Number propellant tanks:   12.0000000
Number ICF pellets (total, per tank):   7.18749942E+10   5.98958285E+09
Pulse Frequency (Hz):   150.000000
Mass flow rate (kg/s):   4.32000011E-02
Exhaust velocity (km/s):   9210.00000
Average acceleration rate (m/s2):   3.02222110E-02
Mass ratio:   4.81802607
Velocity increment (km/s, %c):   14481.4756       4.83050060
Engine mass (tonnes):   318.000000
Engine Specific mass:   1.73561787E-07
Payload/Propellant Ratio:  0.306072503
Engine Thrust (MN):  0.397872001
Jet Power (TW):   1.83220065
Assumed Radiator Efficiency (kW/kg):   300.000000
Energy Release (J/pellet, J/sec, J/stage):   1.35979203E+10   2.03968807E+12   1.46602571E+23
Q value for Pellet Ignition:   5.03626680
Specific Power (MW/kg):   5.76163721
Neutrons/pulse:   2.30666703E+20
Neutrons/s:   3.46000053E+22
Boost time (Years):   15.1838751
Boost distance (m, AU, LY):   2.59568308E+15   17350.8242      0.274370611

 SECOND ENGINE STAGE:-
=============================================
Mass (Structure(tonnes), Propellant(tonnes):   500.000000       3900.00000
ICF pellet mass (kg):   2.88000010E-04
Assumed pellet burn up fraction:  0.133000001
Number propellant tanks:   4.00000000
Number ICF pellets (total, per tank):   1.35416658E+10   3.38541645E+09
Pulse Frequency (Hz):   150.000000
Mass flow rate (kg/s):   4.32000011E-02
Exhaust velocity (km/s):   9210.00000
Average acceleration rate (m/s2):  0.160395965
Mass ratio:   4.81735420
Velocity increment (km/s, %c):   14480.1914       4.83007193
Engine mass (tonnes):   318.000000
Engine Specific mass:   1.73561787E-07
Payload/Propellant Ratio:  0.325760782
Payload/Propellant Ratio:  0.145054594
Total Engine Specific mass:   3.47123574E-07
Engine Thrust (MN):  0.397872001
Jet Power (TW):   1.83220065
```

```
Assumed Radiator Efficiency (kW/kg):   300.000000
Energy Release (J/pellet, J/sec, J/stage):   1.35979203E+10   2.03968807E+12   2.76207747E+22
Q value for Pellet Ignition:   33.9948006
Specific Power (MW/kg):   5.76163721
Neutrons/pulse:   2.30666703E+20
Neutrons/s:   3.46000053E+22
Boost time (Years):   2.86073017
Boost distance (m, AU, LY):   1.79636725E+15   12007.8027      0.189880803

 OVERALL PERFORMANCE:-
=============================================
Total Mass Ratio:   23.2101383
Final cruise velocity (km/s, %c):   1.28417969       4.28676605E-04
Total cruise distance (m, AU, LY):   3.72341495E+16   248891.391       3.93574858
Total cruise duration (Years):   81.4750519
Total mission duration (Years)):   99.5196533
Total Mission Distance (m, AU, LY):   4.16262003E+16   278250.000       4.40000010

 STELLAR ENCOUNTER:-
=============================================
Total 10 AU encounter time (Days):   13483.1709
Total 100 AU encounter time (Days):   134831.703
Total 1000 AU encounter time (Days):   1348317.00
Stellar Debris radius (LY):   9.61937532E-02
Stellar Debris radius (AU):   6083.16211
Stellar Debris Diameter encounter time (Days):   16392202.0

 PARTICLE SHIELD:-
=============================================
Particle Bombardment Shield Area (m^2):   706.858215
Particle shield mass ablation rate (kg/s):             NaN
Particle shield minimum thickness required for mission (mm):   41.0266151
Particle shield minimum mass required for mission (tonnes):   53.6500015

   MEDUSA SAIL DECELERATION:-
=============================================
No Medusa Sail Selected

   IGNITION PHYSICS:-
=============================================

Outer Radius(mm):   9.15999985
Ablator Thickness (mm):   1.00000000
Hot Spot Radius(mm):  0.200000003
Hot Spot Density (g/cm^3):   1200.00000
Hot Spot Areal Density (g/cm^2):   240.000000
Hot Spot Temperature (keV):   2.00000000
Implosion Velocity (cm/s):   70000000.0
Hot Spot Temperature (keV):   2.00000000
```

```
initial In Flight Aspect Ratio IFAR:   9.15999985
Convergence Ratio:   45.7999992
Symmetry Ratio:   40.7999992
Particle Deposition Fraction:   1.00000000
Burn Up Fraction:  0.975609779
Mechanical Work, Pw (W/cm^3) is:   2.31840008E+27
Particle Deposition, Pa (W/cm^3) is:   6.13439970E+30
Radiation Emission, Pr (W/cm^3) is:   2.11635916E+26
Electron Conduction, Pe (W/cm^3) is:   3.86013552E+36
Total System Energy (W/cm^3) is:  -3.86012950E+36
The capsule has achieved overall ENERGY LOSS

 TRAJECTORY DATA BELOW:-
=============================================
    Time(Years)    Distance(AU)
    99.5196533       278250.031
    99.3766174       277649.625
    99.2335815       277049.250
    99.0905457       276448.844
    98.9475098       275848.469
    98.8044739       275248.062
    98.6614380       274647.688
    98.5184021       274047.281
    98.3753662       273446.906
    98.2323303       272846.500
    98.0892944       272246.125
    97.9462585       271645.719
    97.8032227       271045.344
    97.6601791       270444.938
    97.5171432       269844.562
    97.3741074       269244.156
    97.2310715       268643.781
    97.0880356       268043.375
    96.9449997       267443.000
    81.4750519       248891.391
    15.1838751       17350.8242
    14.4246807       16483.2832
    13.6654873       15615.7412
    12.9062939       14748.2012
    12.1471004       13880.6592
    11.3879061       13013.1182
    10.6287127       12145.5771
    9.86951828       11278.0352
    9.11032581       10410.4951
    8.35113144       9542.95312
    7.59193754       8675.41211
    6.83274364       7807.87061
    6.07355022       6940.32959
    5.31435633       6072.78857
```

```
    4.55516291       5205.24756
    3.79596877       4337.70605
    3.03677511       3470.16479
    2.27758145       2602.62378
    1.51838756       1735.08240
    1.36654878       1561.57422
    1.21471000       1388.06592
    1.06287122       1214.55774
   0.911032498       1041.04944
   0.759193778       867.541199
   0.607354999       694.032959
   0.455516249       520.524719
   0.303677499       347.016479
   0.151838750       173.508240
    0.00000000       0.00000000

MISSION ARCHITECTURE REQUIREMENTS:-
=============================================

SKYLON LAUNCH VEHICLE
Total Dry Mass (tonnes) to LEO:        1650
Number SKYLON launch Vehicles:         183
Specific Cost (£/kg):         650
Total Assembly Launch Cost (£billions):   1.07249999
Assembly Cost Per Launch (£millions):   5.86065578

MEDIUM LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   10.0000000
Total Dry Mass (tonnes) to LEO:   1650.00000
Number MEDIUM LIFT launch Vehicles:   165.000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   16.5000000
Total Assembly (£5,000/kg) Launch Cost (£billions):   8.25000000
Total Assembly (£1,000/kg) Launch Cost (£billions):   1.64999998
Total Assembly (£500/kg) Launch Cost (£billions):  0.824999988
Total Assembly (£100/kg) Launch Cost (£billions):  0.165000007
Assembly Cost (£10,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   5.00000000
Assembly Cost (£100/kg) Per Launch (£millions):   1.00000000

MEDIUM HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   20.0000000
Total Dry Mass (tonnes) to LEO:   1650.00000
Number MEDIUM HEAVY LIFT launch Vehicles:   82.5000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   16.5000000
Total Assembly (£5,000/kg) Launch Cost (£billions):   8.25000000
Total Assembly (£1,000/kg) Launch Cost (£billions):   1.64999998
Total Assembly (£500/kg) Launch Cost (£billions):  0.824999988
```

```
Total Assembly (£100/kg) Launch Cost (£billions):  0.165000007
Assembly Cost (£10,000/kg) Per Launch (£millions):   200.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   20.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   10.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   2.00000000

HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   50.0000000
Total Dry Mass (tonnes) to LEO:   1650.00000
Number HEAVY LIFT launch Vehicles:   33.0000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   16.5000000
Total Assembly (£5,000/kg) Launch Cost (£billions):   8.25000000
Total Assembly (£1,000/kg) Launch Cost (£billions):   1.64999998
Total Assembly (£500/kg) Launch Cost (£billions):  0.824999988
Total Assembly (£100/kg) Launch Cost (£billions):  0.165000007
Assembly Cost (£10,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£5,000/kg) Per Launch (£millions):   250.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£500/kg) Per Launch (£millions):   25.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   5.00000000

SUPER HEAVY LIFT SCENARIO:-
Total Payload Mass to LEO (tonnes):   100.000000
Total Dry Mass (tonnes) to LEO:   1650.00000
Number HEAVY LIFT launch Vehicles:   16.5000000
Total Assembly (£10,000/kg) Launch Cost (£billions):   16.5000000
Total Assembly (£5,000/kg) Launch Cost (£billions):   8.25000000
Total Assembly (£1,000/kg) Launch Cost (£billions):   1.64999998
Total Assembly (£500/kg) Launch Cost (£billions):  0.824999988
Total Assembly (£100/kg) Launch Cost (£billions):  0.165000007
Assembly Cost (£10,000/kg) Per Launch (£millions):   1000.00000
Assembly Cost (£5,000/kg) Per Launch (£millions):   500.000000
Assembly Cost (£1,000/kg) Per Launch (£millions):   100.000000
Assembly Cost (£500/kg) Per Launch (£millions):   50.0000000
Assembly Cost (£100/kg) Per Launch (£millions):   10.0000000

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END OF CALCULATION SUMMARY
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Appendix E: Starship Resolution Concept Vehicle Design

The following three figures shows an approximate description of what Starship Resolution may look like. It is not claimed this is a comprehensive concept design, but merely a pre-concept design with much further analysis required. But it is believed that the fidelity of analysis to date in determining this layout and performance is sufficient to inform down-select.

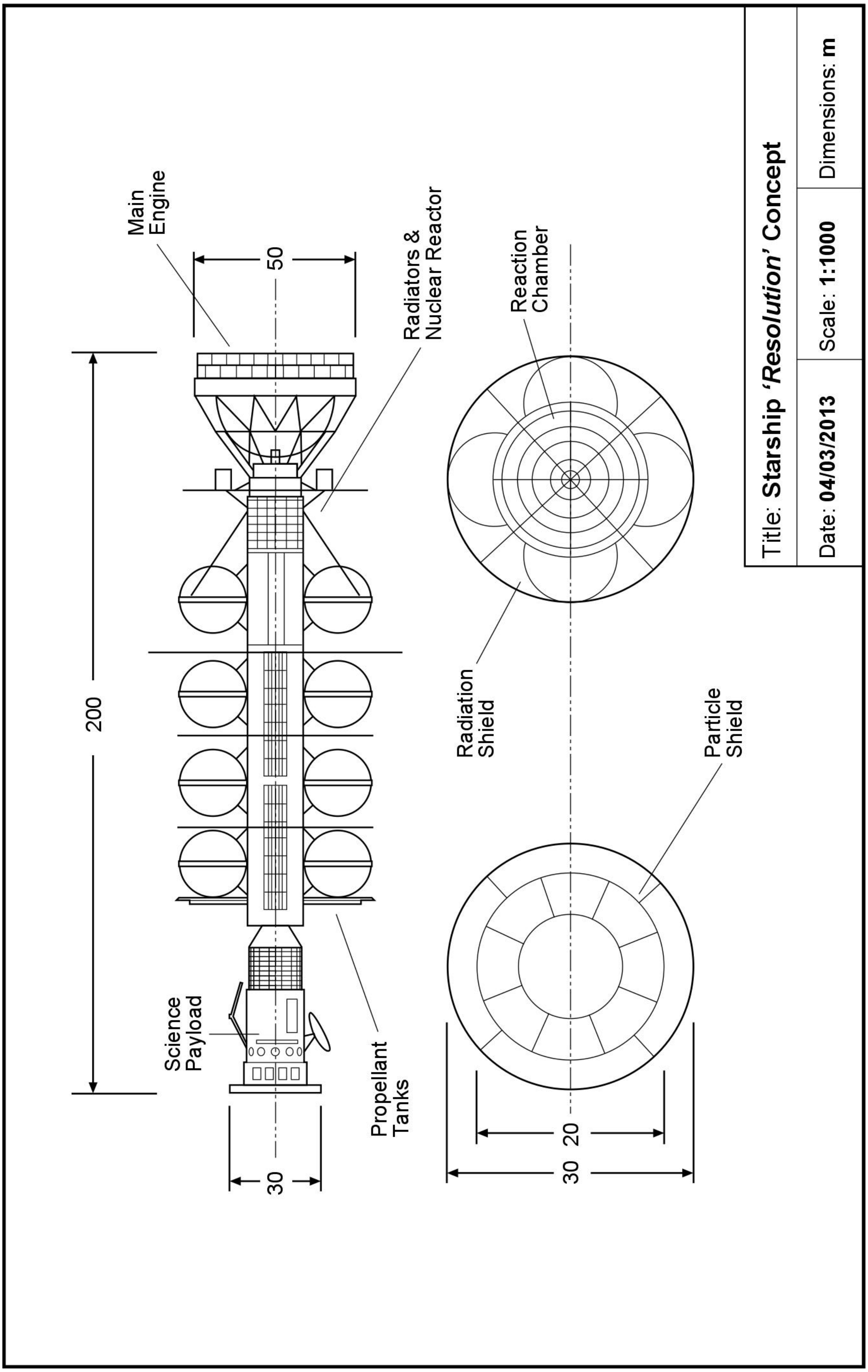

Fig. 8: Engineering Layout of Starship Resolution Concept Vehicle Design (Kelvin Long & Adrian Mann

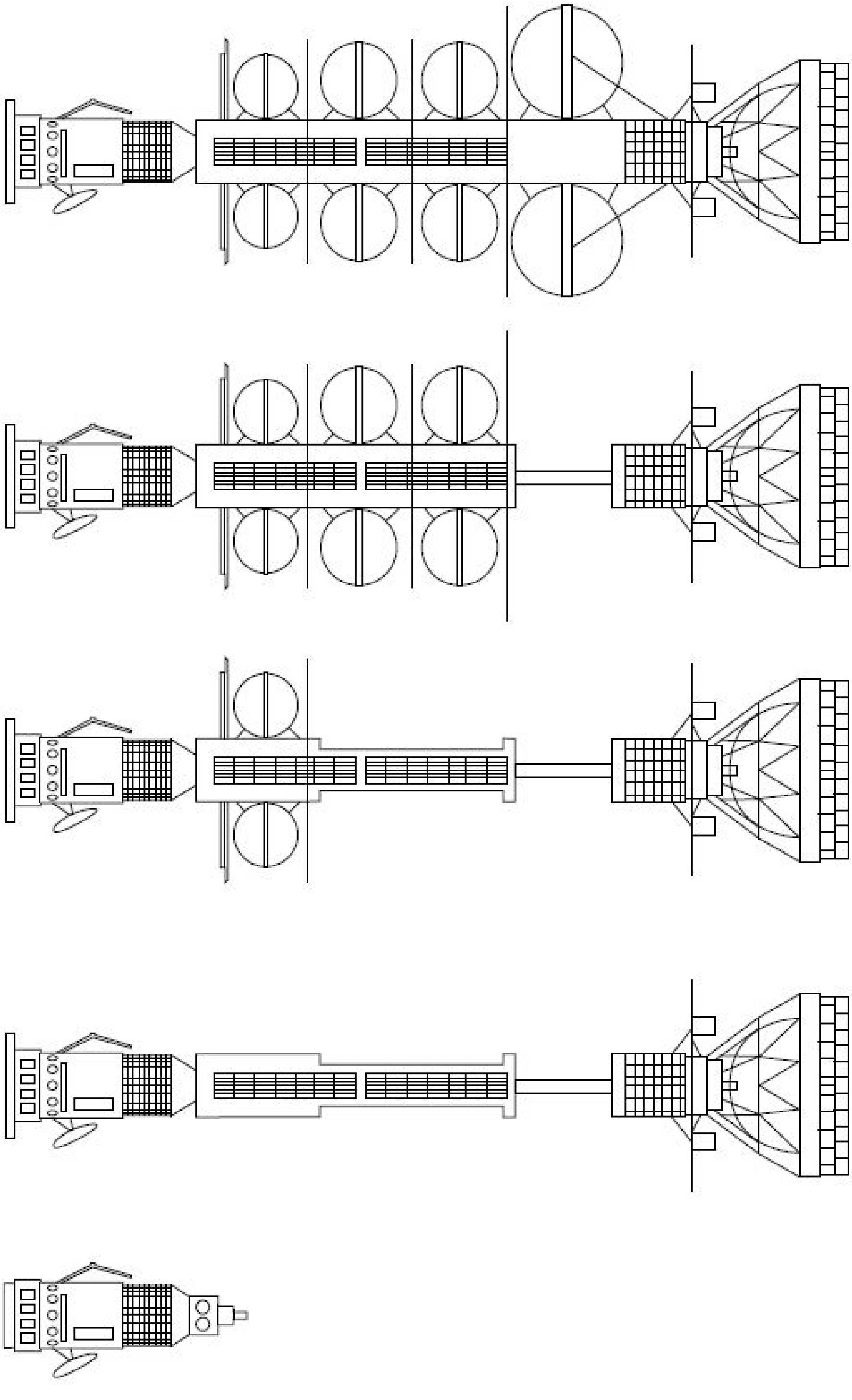

Fig. 9: Starship Resolution Concept Vehicle Design Mission Description, including both structure and propellant mass drops, but demonstrated on an earlier model of Starship Resolution (Kelvin Long & Adrian Mann)

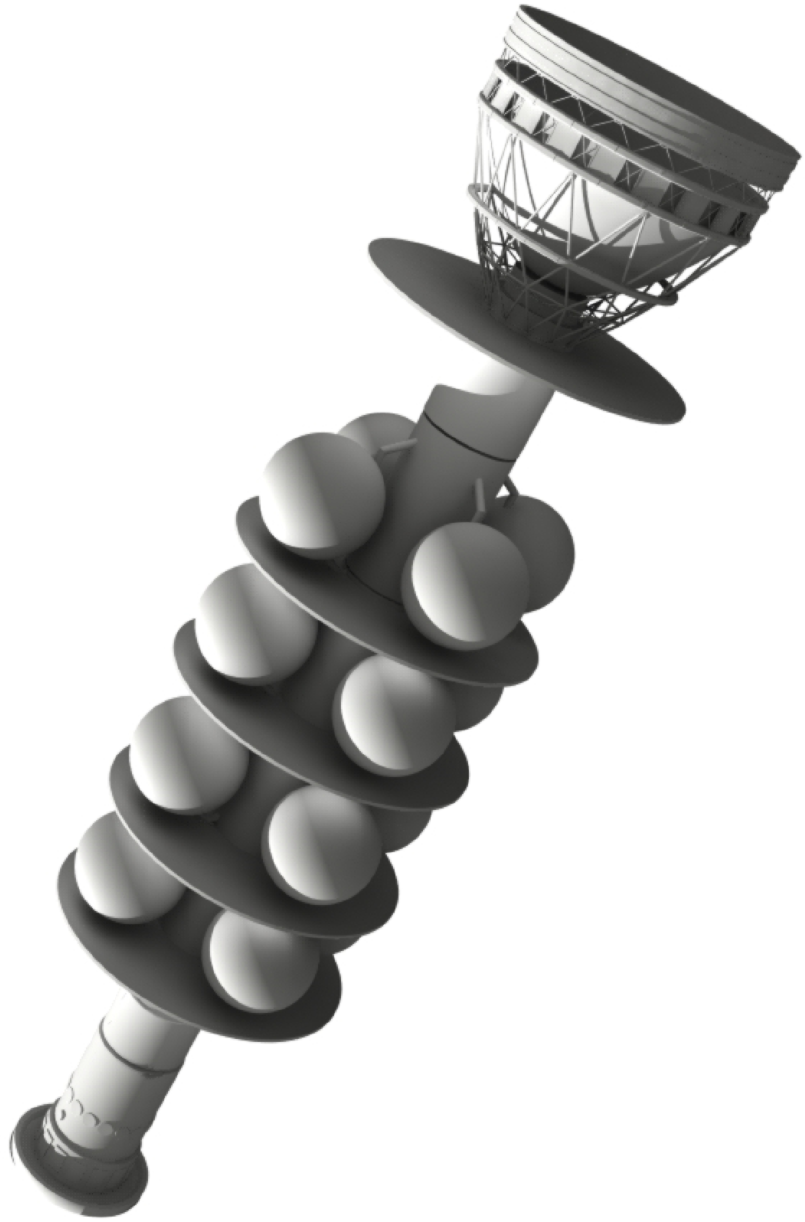

Fig. 10: Engineering Graphic of Starship Resolution Concept Vehicle Design (Adrian Mann)

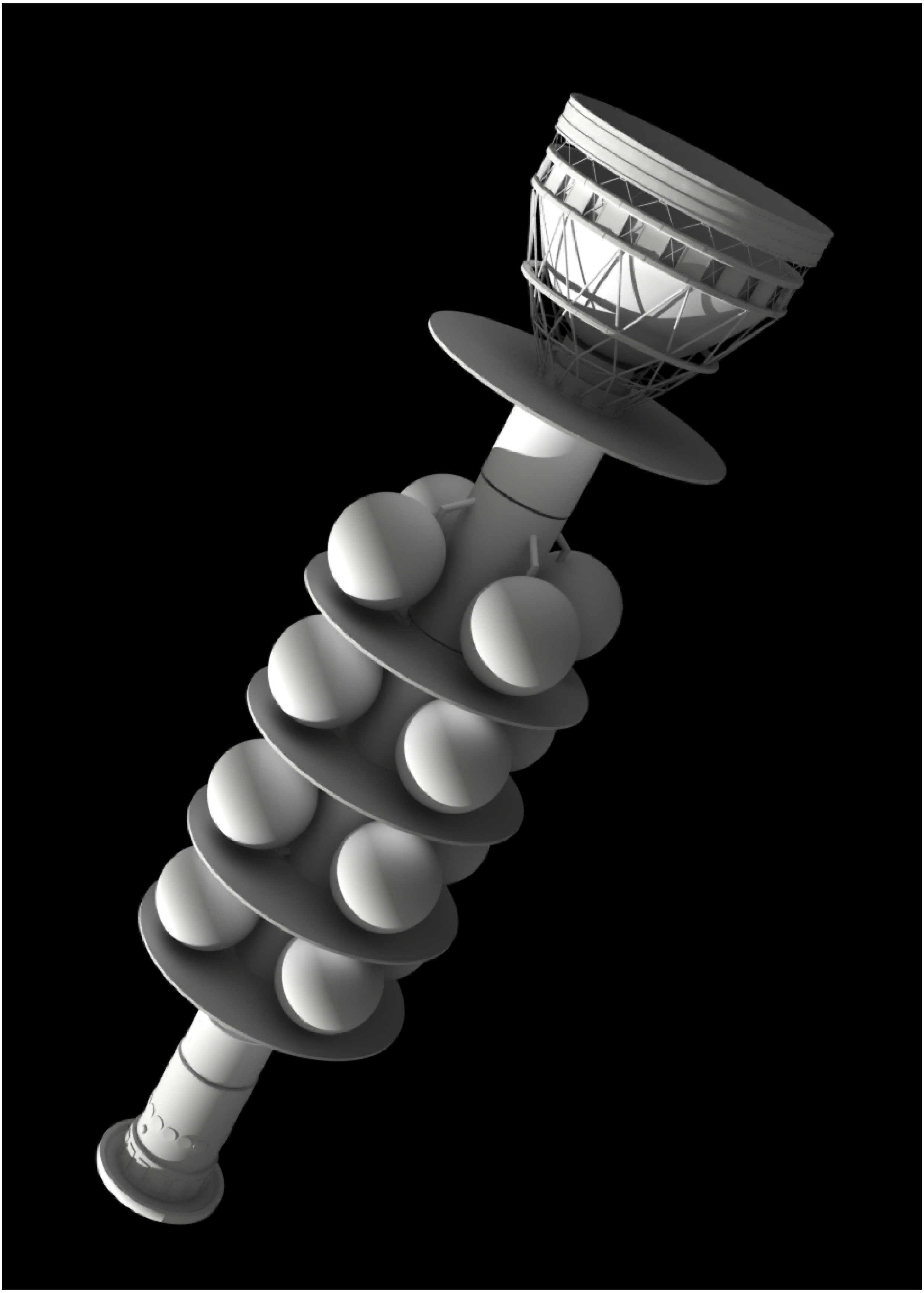

Fig. 11: Engineering Graphic of Starship Resolution Concept Vehicle Design (Adrian Mann)

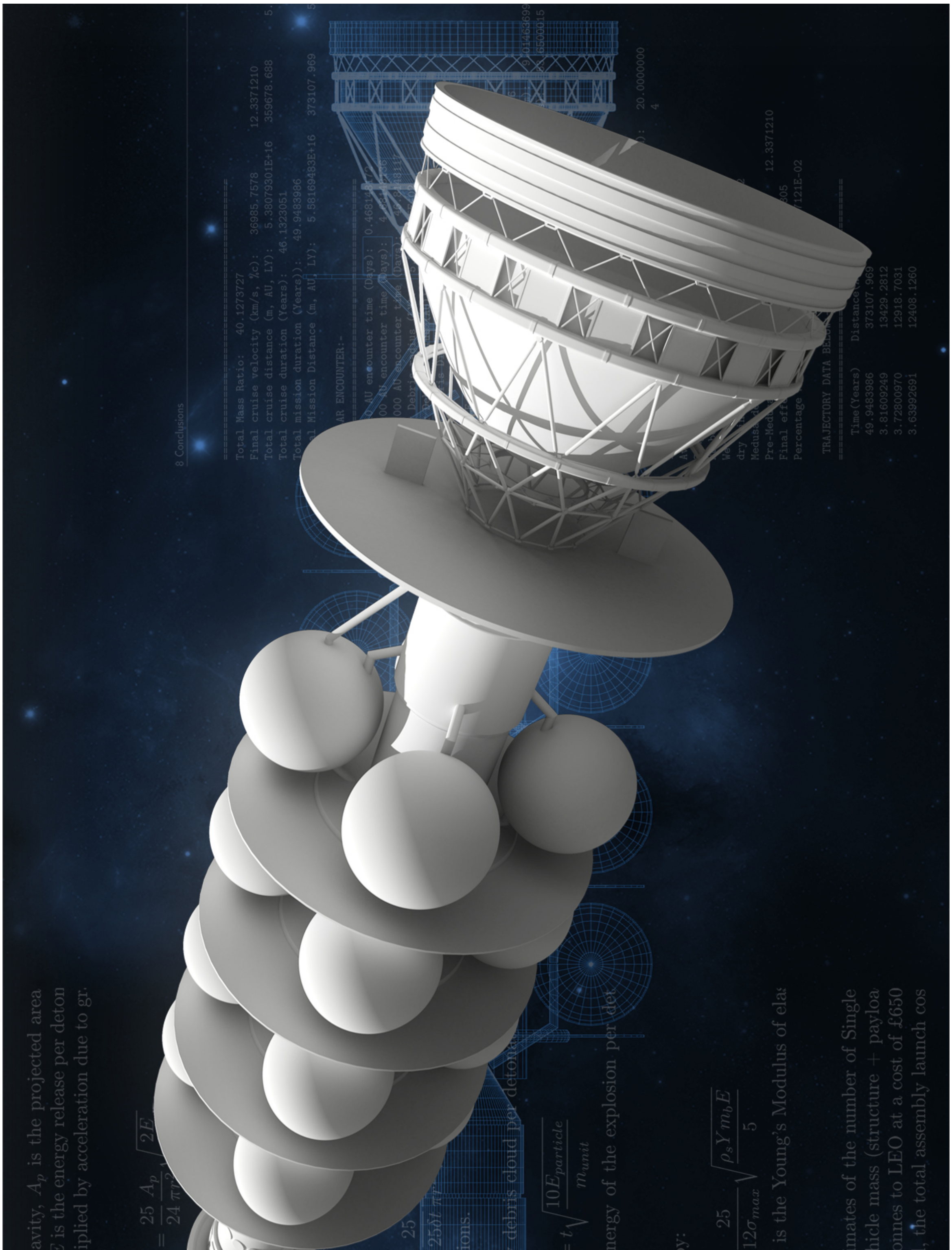

Fig. 12: Engineering Graphic of Starship Resolution Concept Vehicle Design (Adrian Mann)

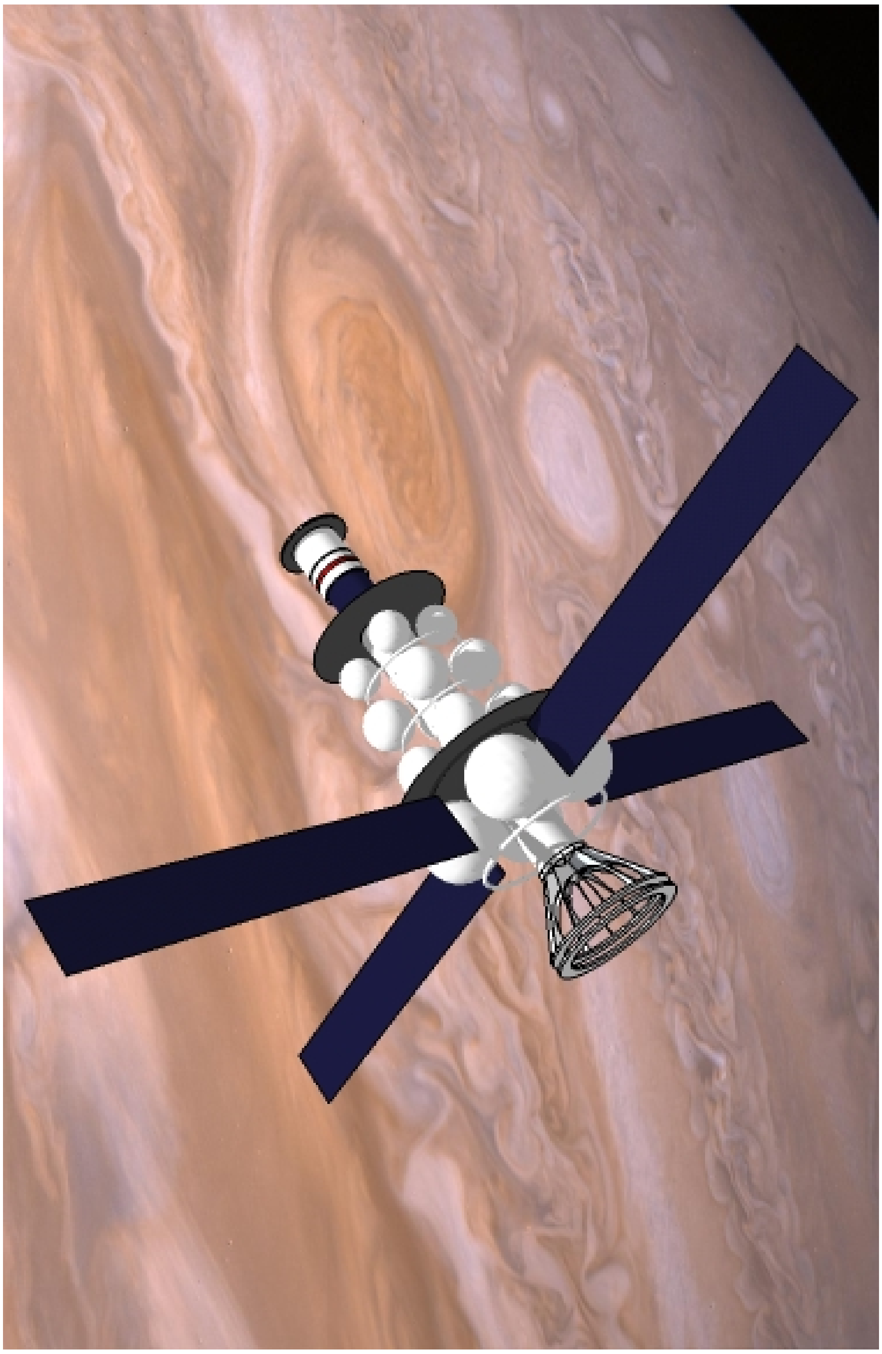

Fig. 13: Illustration of Starship Resolution Concept Vehicle Design (Micahel Lamontagne)