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Project Icarus: Designing a Fusion Powered Interstellar Probe

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Abstract. Project Icarus is a design project to show it is possible to conceive of a credible interstellar craft to reach nearby stars such as Alpha Centauri using the power of fusion, giving reduced trip times and larger payloads. This paper describes some of the project in terms of the programme, and it outlines one of the project's key design variants ("Firefly") using it to illustrate how the designing progressed and some of its key features and design considerations. Multiple theoretical means of achieving fusion and the different potential fuels gave rise to several other designs highlighted here too, making it currently difficult to down select a 'best option'. Nevertheless, this paper will describe several potential interstellar fusion designs. Further it will show that the work has helped revitalise the subject of potential interstellar missions, not only in terms of designs, but also organisations and people. The primary source of information on this project is already published in papers submitted to the Journal of the British Interplanetary Society. However, the final report is still to be finished and only then might it be judged how well the project met the original aims, although some indication is given here.

1 Introduction

This paper will introduce some of the fusion designs (primarily the leading design Icarus Firefly) and illustrate the design process and features of a fully volunteer 'citizen' project, Project Icarus. These activities have always been at the heart of such organisations as the British Interplanetary Society, which despite its name is a worldwide membership organisation and other non-profit organisations; but now is gaining even greater potential through widespread online collaboration. We open with an overview of the project before looking at the Firefly design in some detail to show how that progressed not only in terms of the design but also to illustrate how the project itself progressed. The Firefly section is primarily broken down to the different systems that most influenced the design. Those developments of the Firefly also illustrate important steps through the overall project programme. We take a briefer look at the other designs, sometimes described as exploratory designs that did not quite reach the detail required but do show the breadth of work undertaken. An interesting snapshot is given of the specific parameters of some of these designs and how they compare to Firefly. Then we consider the programme and other issues in an attempt to complete the theoretical design cycle with the volunteer team. Finally, we discuss how the different organisations and people that are looking in to this field has significantly expanded.

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2 Project Icarus

In September 2009, some members of the British Interplanetary Society and the US based Tau Zero Foundation began a collaboration to revisit the renowned BIS Project Daedalus study [1] of the 1970s - a design of an interstellar spacecraft using fusion propulsion technology [2]. The new project was named “Project Icarus” after the son of Daedalus of ancient Greek mythology. The team used that name as suggested by the final paragraph of the original Project Daedalus report.

The Project Programme Document (PPD) [3] specified 10 phases of work:

- Phase 1 Team assembly and definition of Terms of Reference (ToRs)
- Phase 2 Construction of work programme
- Phase 3 Work programme design
- Phase 4 Work programme preliminary design
- Phase 5 Preliminary design review
- Phase 6 Work programme down select of detailed design options
- Phase 7 Work programme system integration
- Phase 8 Detailed design review
- Phase 9 Certification of theoretical design solution
- Phase 10 Publication of final design solution, submit to JBIS

Nevertheless, a large and worldwide group of volunteers undertook work which fell into three distinct stages. The first stage was primarily setting up and undertaking research into different topics that lasted three years. The second stage, also about three years, was where the major designing took place, falling into familiar categories of concepts, preliminary designs, then more detailed designs. The third and final stage was to publish any remaining papers and write up a version of a ‘full report’ combining the essence of all this work in a ‘narrative form’ more accessible to as large an audience as possible. Surprisingly, this third stage has taken as long as the other stages. Note that the project was virtually entirely theoretical – and there wasn’t any chance of ‘cutting metal’ – so the design terminology more relates to explorations of what was thought possible. All through the stages, academic papers were regularly published in peer reviewed journals – primarily the Journal of the British Interplanetary Society (JBIS). These should be sought for the detailed picture of this design exercise and its output and a number of key papers are referenced throughout this document.

The project started with a given Purpose and Terms of Reference (ToR). For clarity these were slightly amended during the programme and the current ones are listed in Appendix A along with the High-Level Objectives agreed at the time. Interestingly the original planning document, the PPD, ran through 85 pages itself and outlined a process that any engineering designer would recognise. Although the final journey was not exactly as envisaged in the PPD, significant progress toward the main objectives of the project have been achieved.

Following the issue of the ToR and start up, the PPD called for 20 research modules which certainly guided the work during the setting up and research phase.

- Astronomical target
- Mission analysis and performance
- Vehicle configuration
- Primary propulsion
- Secondary propulsion
- Fuel and fuel acquisition
- Structure and materials
- Power systems
- Communications and telemetry
- Navigation and guidance control
- Computing and Data management
- Environment control
- Ground station and Monitoring
- Science
- Instruments and payload
- Mechanisms
- Vehicle assembly
- Vehicle risk and repair
- Design realisation and technological maturity
- Design certification

The early module work resulted in research presented in many published papers in JBIS and Acta Astronautica between about 2010 and 2013. In this stage, although most modules were covered in some detail, other modules were clearly significant given the status of fusion technology. Primary propulsion, fuel and fuel acquisition were a key focus and some 20 plus potential fusion schemes were identified [4, 5, 6]. Significant progress was made investigating a suitable target, and potential science that might be achieved with particular scientific payloads [7].

Despite the nearly 100 internal reports and publications, the effort to design an ‘Icarus’ craft was stalling by early 2013 (see Programme and Other Issues below). Team members had been unable to agree on the

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best option for a fusion drive system, or even the best fuel. A way out of that difficulty was made by holding an internal Concept Design Competition. The large project team was divided in to sub-teams who each selected their preferred options from the fusion schemes previously identified. The five sub-teams' selections were variations of Inertial Confinement Fusion (ICF - with alternatives of fast ignition and shock ignition, and a unique version using (pre-compressed) Ultra Dense Deuterium fuel), a radically different version based on the Z-pinch effect, and a later version derived from the Plasma Jet Magneto Inertial Fusion (MIF or sometimes specifically PJMIF) principles. From the fuel options, some teams chose DHe3 (the same as Daedalus but without the Tritium trigger), while other teams chose to use DD fusion. The lack of detailed experimental evidence permitted this range of choices. More about this process is illustrated as we work through some details of Firefly below.

During the competition, other parameters that had yet been undecided had to be agreed upon. For example, the payload was set at 150 tonnes (compared to Daedalus at 450 tonnes - the fusion probes are unavoidably big which permits any large payload at a relatively marginal cost), and the efficiency of the exhaust nozzle was set at 80%. The main purpose here was to allow the vessels to be judged at the Concept Design Workshop 'desk-top fly off' on an essentially level playing field.

After the competition, it was hoped that the sub-teams would unite on the best option, perhaps taking systems or ideas from others and focus on a single Icarus design. In fact, most of the designs were progressed in some way, with each design's 'owner' becoming quite parochial about their design, but still co-operating and exchanging ideas in a friendly and co-operative way. Nevertheless, reaching a single detailed design in a similar way with a Detailed Design Workshop met with only partial success although progress was made in other modules such as Mission Analysis [8], Communications [9] and Navigation [10, 11], Power Systems and areas such as reliability. Some designs improved but only the Firefly really approached the depth that had been hoped to achieve. By considering that design in detail next, we will further illustrate the progress through the project before returning to the project programme and other issues.

3 Firefly

3.1 Introduction to Firefly

The Icarus Firefly concept was primarily designed by authors Freeland and Lamontagne and work on the design (and of course the others) began in 2013 when Freeland opted to lead a sub-team for the design competition. Some of the choices Firefly made illustrated the design trade-off process used by the teams. The primary publication of the details for Firefly were presented in JBIS in 2015 [12]. Much of the detail on Firefly here draws directly on that paper; for fuller details on the modelling and design that paper should be consulted.

Freeland had started with a model which became known as 'dirty Icarus', as in quick and dirty, which used as many of the parameters set by Daedalus as possible to consider whether it might be possible to simply add fuel and relax mission requirements to reverse the second-stage thrust and decelerate into orbit at the Alpha Centauri system [8]. Challenges with the Daedalus design (heat from Tritium decay, availability of He3 etc) [13] led him to look at alternatives based on the work of Uri Shumlak.

In the early Firefly design, Freeland comprehensively researched the use of a magnetic sail ('magsail') to aid deceleration [14] and found the magsail traded well against the main engine for deceleration - if using something with the same performance to a Daedalus second stage. But against the performance of the Z-pinch, the potential savings were largely eliminated, so a magsail was not proposed by the Firefly team in the competition workshop. Another aspect of the design that was contemplated within the design competition, was an enclosed chamber for the pinch and this was later removed when the mass savings became apparent. An open chamber allowed much of the unusable high energy neutrons and X-rays to simply escape directly in to space.

Between the design competition and the published paper in JBIS the Firefly went from the Mk 1 version to the Mk 5 as a result of the major design changes such as discarding the liquid-metal droplet fountain radiator in favour of Lamontagne's liquid metal phase-change radiator system and smaller changes as the change of coolant from Lithium to Beryllium. All the Icarus designs required a defensible radiator system and the Lamontagne solution effectively became the default and also changed the morphology of the vessel. Other work on the innovative X-ray shielding of the forward structure also influenced changes. A proper electrical power system was designed for the vessel and there may even be a few more variations in outline schematics not reflected in the Mk designation changes as structural variations were explored.

3.2 Firefly Drive System

The Icarus drive system is based on the Lorentz force. This creates the natural pinch effect whenever a large current is passed through a medium - in this case a plasma jet. An electromagnetic "pinch" is formed where the current generates a magnetic field directed in concentric lines around the current flow, and that field reacts with the current itself to create a force directed inward. This "pinches" the medium. The usefulness of a pinch was not recognised for years as there are often large instabilities which disrupt the pinch effect. This could be seen when Pollock and Barraclough studied a copper tube in 1905 that had been pinched by a bolt of lightning [15]. That copper tube is still on display at the School of Physics, University of Sydney, Australia (See Figure 1).

FIGURE 1. *Copper Pipe Crushed by the Z-Pinch from a Lightning Strike (Image credit: Univ. of Sydney)*

The study of pinches for fusion began with the publication in 1934 of Willard Harrison Bennett's analysis of the radial pressure balance in a static Z-pinch [16]. The concept was researched heavily until the mid 1950s, when Kruskal and Schwarzschild published work describing various magneto-hydrodynamic (MHD) instabilities in Z-pinch plasmas [17]. Research into Z-pinch fusion languished thereafter, until Uri Shumlak published his paper in 1998 on the use of sheared axial flow to mitigate hydrodynamic instabilities [18]. Shumlak's subsequent work - including a plethora of lab tests at the University of Washington - has been indispensable for the Firefly design [19].

In addition to Shumlak's work, Sandia National Labs is studying Z-pinches with their high-powered "Z Machine", and NASA has recently started research into Z-pinch propulsion at their Charger One facility at the Marshall Space Flight Center [20].

Firefly built on the work of Shumlak who had found that a sheared axial flow helped smooth the instabilities and maintained a pinch of nearly a metre. Using that model the team were able to show that to provide the thrust required for the target cruise speed of 4.7%c they required a 5 million Amp current through the plasma jet and a pinch of over 40 metres. This potential use of such a pinch has not been tested with a fusable plasma which remains to be experimentally proven. Furthermore, despite the relative ease of physically modelling it, the continuous operation and extension from one metre to an over 40 metre stabilized plasma pinch are considered significant uncertainties of the Firefly drive system. If it proves impossible to move from Shumlak's 15 microsecond operation to fully continuous the design could fall back on pulsed operation, albeit at a reduced performance.

3.3 Fuel

In deciding the fuel for their design, it was noted that the reaction cross-sections become orders of magnitude smaller as one progresses down the list of potential fusion reactions [21]. In fact, the main reactions commonly considered for both terrestrial fusion power and fusion propulsion are Deuterium Tritium (DT), Deuterium Helium 3 (DHe3) and Deuterium Deuterium (DD). (Notwithstanding more recent research such as into the even more difficult proton-Boron (pB) fusion.)

DT fusion is the easiest to ignite, though it ejects a high-energy (14.1 MeV) neutron that poses significant problems for any engine design. Furthermore, Tritium has a very short half-life of just over 12 years, so it can't be stored for use during the deceleration phase.

DHe3 fusion is often favoured as an alternative because it is intrinsically aneutronic, but any DHe3 plasma produces unavoidable DD reactions as well, and at a higher rate in most temperature ranges. The DD side-reactions produce their own neutrons plus Tritium, which reacts immediately with available deuterium in the plasma to produce the DT high energy 14.1 MeV neutrons. This all significantly limits the nominal aneutronic benefit. A critical thought in the design of an Icarus vehicle that may be built 'in the coming decades' was that He3 is almost completely non-existent on Earth, and it is incredibly scarce even in remote places like the Moon. The source identified by Daedalus was the gas giants [22], but some later forecasting put that

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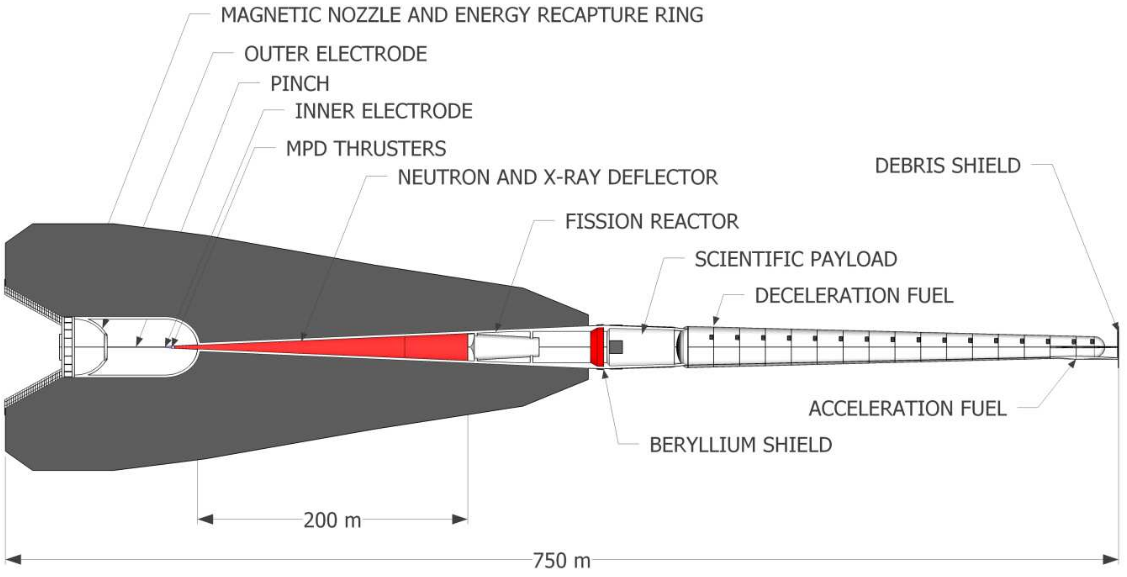

FIGURE 2. *Outline schematic of Firefly (Image credit: Michel Lamontagne)*

likelihood at nearly 100 years away [23].

For these reasons, the Firefly sub-team chose to focus on pure DD fusion. Deuterium is readily available via seawater distillation here on Earth, and it can survive storage indefinitely, given an appropriate refrigeration system. Deuterium is a chemical explosive if reacted with oxygen, but it isn't radioactive. The major downside is waste energy.

3.4 The Firefly Fusion Drive

To create the necessary pinch the Firefly interstellar drive requires a huge current of 5 MA and a total input power of 1170 GW - a significant fraction of the average power consumption for the entire United States [24]. Consequently, the only practical source of power for the drive is the fusion reactor itself. The aim would be to recover one quarter of the output power to use to keep the drive running although this would reduce the exhaust velocity. The actual means for doing this energy recapture was one of the key outstanding design issues for Firefly. The drive would require a separate source of power for start-up although in this case the requirement is brief – the energy required is only of the order of an artificial lightning bolt. Using data directly from the original Daedalus Project it was estimated that the Firefly start-up is achievable using a bank of ultra-capacitors charged from the secondary power system - a pair of 1 MWe fission reactors would be enough to charge the capacitor bank in just 75 seconds. A more precise calculation of the start-up power requirement remains to be completed. Despite the size of the capacitor bank originally proposed in Daedalus, an implosion code may suggest an increased resistance due to changing inductance during the implosion will quench the driving current. This is a known problem in the Z-pinch community leaving some to be sceptical of this design; the implosion dynamics simply may not work, because the pinch is too long leading to a very high inductance. These issues will require further experimental evidence.

3.5 Shielding

Deuterium fusion releases almost half of its energy in the form of high-energy neutrons, and the high densities and temperatures in the pinch region yield significant Bremsstrahlung (X-ray) radiation. Because the core is essentially a line, all this radiation is emitted cylindrically.

A designer's initial reaction to a system emitting high radiation doses might be to provide shielding, but in this case the resulting mass would be prohibitive [25]. A better solution was to do the exact opposite, ie, devise the geometry of the vessel such that the drive is remote from the rest of the ship, and then construct the Z-pinch drive to allow the X-rays and neutrons to escape directly into space before interacting with anything else on the vessel.

Shielding is then only needed for the small angle where the engine is structurally attached to the vessel, and for the rails that carry the return current and coolants.

To protect the forward structure, Firefly uses a long conical shield with walls coated in iridium and inclined at three degrees. The incline allows the shallow angle deflection of Bremsstrahlung X-rays into space, mimicking the design of an X-ray telescope such as Chandra [26]. The interior of the cone contains pressurised deuterium gas as an ideal substance to scatter forward-bound neutrons; any remaining neutrons that penetrate the entire length of the conical shield are blocked by a final shield of solid beryllium. Neutrons that do get absorbed by any structure or shielding contribute to the heating and are handled by the cooling system.

3.6 The Cooling System

Even though waste X-rays and neutrons are channeled directly into space, the heating of the electrodes, magnetic nozzle, and drive support structure is still significant. Radiators will be needed to dispose of the waste heat, and for a starship, they must be extraordinarily efficient. A conventional radiator is too limited, so Firefly uses an extreme phase-change radiator with liquid beryllium as the working fluid (since it has the highest heat of vaporization per gram of any element at 33 kJ/g). A working temperature of 2500 K and an operating pressure of 0.5 atmospheres were required. Firefly's design uses zirconium carbide on structural elements exposed to the drive's neutron and X-ray fluxes. The radiators themselves are constructed of carbon-carbon (for mass savings and emissivity), with an interior coating of zirconium carbide for corrosion resistance.

The Z-pinch drive requires a large conductor to serve as a return path for the high current in the pinch. This conductor requires cooling, and thus would necessarily lie behind the cooling channels that comprise the inner edges of the radiators. It was recognized during the design phase that with a metallic coolant, the coolant itself could serve as the conductor, thereby eliminating another large mass.

If the coolant system for some reason fails, the liquid beryllium in the cooling channels will vaporize, driving the path's electrical resistance up tremendously. (Liquid metals are good conductors, but gases are not.) This will impede the flow of current through the pinch, shutting it off. This arrangement thus provides an automatic shutoff in the event of overheating.

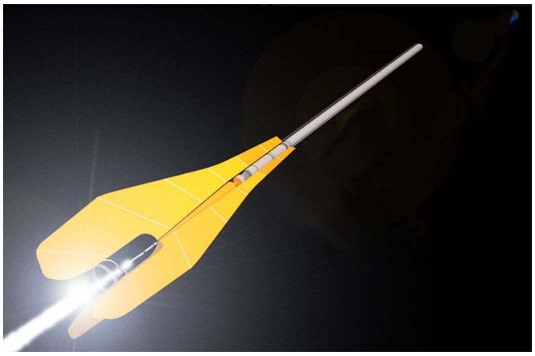

FIGURE 3. *Firefly in flight (Image credit: Michel Lamontagne)*

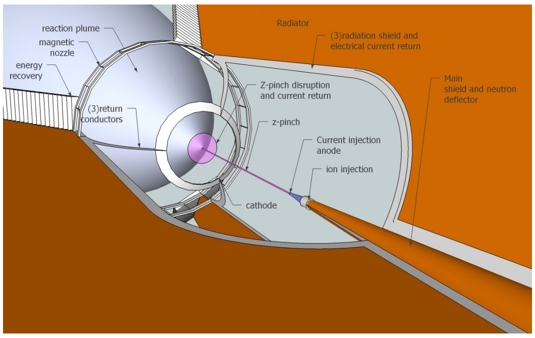

FIGURE 4. *Firefly fusion chamber (Image credit: Michel Lamontagne)*

When the drive is off, the beryllium coolant will solidify in the radiator system, mostly in the cooling pipes. Starting the drive, then, is simply a matter of pushing a current through the solid beryllium to melt it. The circuit can be completed via plasma injected into the pinch - just at currents too low to initiate fusion. Once the beryllium melts, the current can be pushed higher to initiate the fusion. This provides a rather elegant way to start and stop the engine.

In addition to the main radiator system, there are additional cryogenic systems to cool the fuel tanks and the superconducting wire in the magnetic nozzle ring. These elements are all hidden behind radiation shields cooled by the radiator system, so the cryogenic systems are generally just more fault-tolerant implementations of existing technology.

3.7 Morphology and Model Results

The resultant vessel is 750 m long, with the appearance of a lawn dart (with the three radiator fins), the exhaust velocity would be 12,000 km/s giving an Isp of around 1.2 million seconds. The thrust would be 600 kN. The dry mass is 2200 tonnes (with the bulk dedicated to the radiator system) and the wet mass including payload is 23,550 tonnes (compared to Daedalus at 54,000 tonnes). Fuller details are available [25].

3.8 Firefly Mission Summary

The Firefly team envisaged fabrication on Earth before launch and assembly in orbit akin to the International Space Station. Multiple launches would be required, a significant portion of which would be the mass of fuel. Here distilled Deuterium might be delivered using a more cost-effective delivery system like a future Skylon [27] or Hydrogen gas gun [28]. At launch, the Firefly vessel would accelerate to maximum velocity of 4.7%c in 10 years, cruise for 85 years, and then decelerate into orbit in 5 years. On arrival, the main probe would eject a probe cluster to Alpha Centauri B and enter orbit around Alpha Centauri A itself. Sub-probes would be deployed to investigate both systems thoroughly.

3.9 Further Work for Icarus Firefly

Z-pinches have already reached TRL 4, with experiments at the University of Washington, Sandia National Labs and NASA's Charger One facility in Huntsville [20]. Shumlak's sheared flow approach has not been tested with a fusable plasma and further work is required on establishing continuous operation and extending the pinch as envisaged here. A precise calculation of the start-up power requirement is outstanding and a scheme for a suitable energy extraction system to power the continuous fusion drive is required.

4 Other Icarus Designs

The other sub-team designs did not meet the detail of Firefly but made positive contributions throughout the process. We briefly discuss these other designs here.

4.1 Ghost

The Ghost team was primarily made up of students and post-grads at the Technical University of Munich (TUM). Although it was considered that they delivered the best report at the design competition [29] their neutron pumped laser used to initiate the ICF fast ignition with DD fuel later suffered greatly as the performance requirements to meet the mission increased. Ultimately the design faltered as the mass of the system would have been shown to increase unacceptably to meet the mission targets (even compared to usual giant fusion rockets).

4.2 Endeavour (Originally Resolution)

Starting as the Resolution design for the design competition this vehicle was the closest to the original Daedalus using laser initiated ICF shock ignition and DHe3 fuel (but with no Tritium trigger). As with most of the other designs, a long and slender spacecraft design was used to place the reaction chamber/nozzle away from the rest of the craft and reducing the bulk shielding requirements. Resolution evolved around a single stage and would simply discard empty tanks during the initial phases. To take advantage of redundancy and assuming much of the high energy neutrons etc would be still retained in the pellet (as with Daedalus) the design moved on to a multiple parallel stage version and be retitled Endeavour. A full description of Endeavour is still to be finalised.

4.3 Ultra Dense Deuterium (UDD)

Project Icarus Designer Milos Stanic became aware of the research undertaken by the Swedish group under Holmlid [30, 31] where there were results suggesting the identification of 'Ultra Dense Deuterium'. This was a form of Deuterium that would be in a similar state to 'Metallic hydrogen', a form of highly compressed Hydrogen that might be found under circumstances such as near the centre of large gas planets like Jupiter. If UDD really exists and can be produced, the pellets would no longer require any further compression for fusion and a peta Watt laser would suffice to ignite the fusion. A 2-stage, multiple engined vehicle was designed for the design competition [32] but no further work was carried out pending independent validation of Holmlid's group's results. The claimed superior UDD performance at the competition workshop was found to be a small calculation error and given that the fuel was essentially DD the corrected performance fell in line with other DD vehicles.

4.4 Zeus (Plasma Jet Magneto Inertial Fusion, with DD Fuel)

The Zeus design came after the design competition due to the availability of the student chapter at Drexel University in Philadelphia taking an interest. The design team, supported by other longer-term members of the project, came up with a design for the PJMIF variant at the detailed design workshop in Atlanta in 2014. The work was based on the research of Thio [33], unfortunately the Zeus modelling by the team was never quite completed satisfactorily and the performance claimed at the Atlanta workshop was likely incorrect. Despite some innovative thinking this variant needs further work [34].

Those designs and earlier concepts such as Leviathan (multimode and multi-fuel) [35] and precursor outline concepts such as Pathfinder (advanced plasma, to 1,000 AU in 20 years) and Starfinder (reduced scale Daedalus, 2 variants, one to go 10,000 AU and the larger to go 50,000 AU) [36] will be found in some detail in the Project Icarus Final Report (to be published). The comparison of some variants and key parameters is in the team's online table accessed March 2019. Note as some work is *still* ongoing the figures are 'live'; and not necessarily validated.

5 Programme and Other Issues

While the project and programme were new and there were exciting early activities ongoing (ending in the creation of Icarus Interstellar Inc, in the US, and the DARPA/NASA 100 Year Starship Programme), the first phases of the PPD went ahead relatively smoothly. But when those developments took away many of the key designers involved with Project Icarus, the actual spacecraft design effort stalled (if any designing had got started beyond the research and trade studies). The Project Icarus team was a big part of the combined team that won the DARPA $500K 100YSS bid, but subsequent integration efforts proved difficult and precipitated a large changeover of active personnel in the project team, causing one of the biggest disruptions to the project.

The internal Concept Design Competition in 2013 was conceived as a way to break the impasse with respect to the team's path forward, and to re-focus on the design process. This also meant that certain design criteria could be agreed between the sub-teams and would ensure any comparisons of different variants were sensible (described above).

Throughout there were many challenges with managing Project Icarus, some immediately recognisable for normal business or academia, for example simply coordinating call times for an international team. For four years the project team held weekly team online conference calls (Jan-Mar, May-Jul and Sep-Nov); different days and times were tried but even the most favoured one of Thursday's 2200 hrs London time, meant an hour later in Central Europe, 1700 hrs on the East coast of America but middle of the night for Indian team members and sunrise in Australia. Ad hoc meetings were equally difficult.

Then there was the challenge of efficiently sharing documents and tasking mechanisms. Preferred means went from emails, through Dropbox to Google Docs, and exploring tools such as team Forums, Wiki, Slack etc. A 100% satisfactory solution was never found here, and this is probably due to the volunteer nature of the project; only subsets of the team would ever use particular tools. Although inevitably most kept returning to simply exchanging emails which often hindered the design process.

Maintaining motivation of volunteers was a huge challenge over extended periods of time. Members would fall out or just move on. Contributions waxed and waned with life situations, jobs, family and home moves. We gained from help from various groups of university students (both undergrad and grads), primarily the Technical University of Munich and Drexel University in Philadelphia, but those would naturally dissemble after a year or two. Student contribution rarely survived longer than about a year.

Some of these problems were helped by regular attendance at conferences and giving presentations - but in the majority of cases attendance at these events were self-funded - which was obviously quite challenging for volunteers. Breaking the team down in sub-teams did help the smaller groups to make much quicker advances by reducing the need to co-ordinate large team activities. It certainly allowed an element of friendly competition to encourage progress.

Some insurmountable roadblocks were encountered due to missing skill sets (eg MHD modelling and fund

Icarus Variants					**Ship**		
Parameter	**Units**		**Daedalus**	**Firefly Mk V**	**Ghost**	**Zeus**	**Endeavour**
Boost time	days		2000	3800	6404	1500	3376.25
	years		5.5	10.4	17.5	4.1	9.3
Delta V required	km/s	V	50000	14100	15523.5	14500	24752
% speed of light			16.67%	4.70%	5.17%	4.83%	8.25%
ISP		s	1,019,368	1,220,000	594,690	5,000,000	836,901
Ejection velocity (effective)	m/s	Ve	10,000,000	11,968,200	5,833,909	49,050,000	8,210,000
			3.33%	3.99%	1.94%	16.35%	2.74%
Mass ratio		Mo/Mf	148.41	3.25	14.31	1.34	20.39
Ship weight at start	tonnes	Mo	150,000	24,000	187,587	1,000	25,238
Fuel	tonnes		148,989	16,611	166,000	256	24,000
Ship weight at finish	tonnes	Mf	1,011	7,389	21,587	744	1,238
Time under power	days		2000	3800	6404	1500	3376.25
Fuel consumption	kg/s	m=(Mo-Mf)/t	0.8622	0.0506	0.3000	0.0020	0.0823
Force	N	F=m x Ve	8,622,066	605,535	1,750,260	96,861	675,470
Nozzle efficiency		N	0.98	0.8	0.85	0.8	0.8
Thrust power	GW	Pe=F*Ve/2	43,110	3,624	5,105	2,376	2,773
Power required to exhaust	GW	Pe=F*Ve/2n	43,990	4,529	6,006	2,969	3,466
Drive efficiency			99.90%	35.00%	35.00%	95.00%	35.00%
Total power	GW		44,034	12,941	17,161	3,126	9,903
Radiation	GW		44	8,412	11,155	156	6,437
Burn up fraction			0.12	0.8	0.738	0.8	0.8
Overall efficiency			11.99%	28.00%	25.83%	76.00%	28.00%
Stop time	days			1200	160	1100	
Delta V required	km/s	V		14100	3291	14500	
% speed of light				4.70%	1.10%	4.83%	
ISP		s		1,220,000	594,690	5,000,000	
Ejection velocity	m/s	Ve		11,968,200	5,833,909	49,050,000	
Mass ratio		Mo/Mf		3.25	1.76	1.34	
Ship weight at start	tonnes	Mo		7,389	10,010	744	
Fuel	tonnes			5,114	4,200	190	
Ship weight at finish	tonnes	Mf		2,275	5,810	554	
Time under power	days			1200	160	1100	
Fuel consumption	kg/s	m=(Mo-Mf)/t		0.0493	0.3038	0.0020	
Force	N	F=m x Ve		590,323	1,772,455	98,280	
Nozzle efficiency		N		0.8	0.85	0.8	
Thrust power	GW	Pe=F*Ve/2		3,533	5,170	2,410	
Power required to exhaust	GW	Pe=F*Ve/2n		4,416	6,083	3,013	
Drive efficiency				35%	35.00%	95.00%	
Total power	GW			12,616	17,379	3,171	
Radiation	GW			8,201	11,296	159	
Burn up fraction				0.8	0.738	0.8	
Overall efficiency				28.00%	25.83%	76.00%	

TABLE 1. *Comparison of Variants and Key Parameters as of March 2019*

raising etc) and this remained an issue throughout the project.

The overall project programme timescale has been much extended from the original scheme for various reasons alluded to above, but it is now nearing completion with the progress being made to publish the Project Icarus Final Report. Nevertheless, reading the various published JBIS papers will give a detailed understanding of the project, particularly all the research done and the various design work.

6 Organisations and People

Prior to the start of Project Icarus, the field of interstellar studies had mostly fallen in to the backwaters of research. The BIS continued and continues to promote all things astronautical and was steadfast in its support of long term thinking in space. TAU Zero Foundation continued to look at low level TRL physics and promote future thinking. But during Project Icarus we have seen the formation of Icarus Interstellar a non-profit in the US around 2011, along with the Tennessee Valley Interstellar Workshop (TVIW) in its early years. Members of Project Icarus, through the new Icarus Interstellar, became key partners in the winning of the DARPA 100 Year Starship award and that organisation rolls on. Subsequently the Initiative for Interstellar Studies formed in the UK in 2012 and was incorporated as a not-for-profit in the UK in 2014 and then incorporated later in the US a sister organisation, a non-profit called the *Institute* for Interstellar Studies. Furthermore, Interstellar Studies is now back on the curriculum at various universities and with PhDs and masters projects focussed on the ultra-deep space missions and options.

The field was primarily supported by volunteers and some professionals working in their spare time but in 2016 an announcement changed the financial landscape. Breakthrough Initiatives, a foundation set up by philanthropic billionaires launched the 'Starshot' programme and were planning to spend up to $100 million over 10 years developing the technology to achieve the first interstellar mission (although in this case it was for miniature beamed sail spacecraft on a chip rather than fusion). The project team included a paper on the alternatives: 'Sailships Vs Fusion Rockets' by Benford J. [37] These developments might in some small way be the result of the activities of the members of Project Icarus and hence one of the aims has evidently come to fruition.

7 Summary and Conclusions

The all-volunteer Project Icarus team was able to help revitalise the subject of interstellar missions. Scores of supporters around the world contributed in various ways, some making great contributions, some small, and in the end several designs for how an interstellar probe driven by fusion power could explore the nearby star system have been outlined.

In some ways Icarus Firefly was the only Icarus variant that matched the depth of design of the original BIS Daedalus study, but the combination of all the ideas has broadened the field more than before. The interstellar probe Firefly, a Z-pinch fusion drive with DD fuel, would reach and explore the stars of the Alpha Centauri system in about 100 years mission time, cruising at just under 5%c through the interstellar medium using some 16,000 tonnes of fuel - a saving on the original 50,000 tonnes of DHe3 of Daedalus. Further work is required to solve some of the remaining issues for Firefly, particularly energy extraction to power the continuous Z-pinch fusion drive. Nevertheless, Project Icarus has shown that notwithstanding difficult engineering challenges there appears to be a credible future for fusion powered spacecraft, certainly for ultra-deep space.

The volunteers have shown that the potential for contributing to an advanced field, using the connectivity of, and knowledge available through the internet is possible and should be a resource for future activities. It is recognised that there are challenges for managing a volunteer organisation and project, but nevertheless they might be a resource that could be better exploited, in a good way, by others.

8 Acknowledgements

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9 Appendix

9.1 Project Icarus Terms of Reference and Higher-Level Objectives

Purpose

The purpose of Project Icarus has been defined as follows:

- To design a credible interstellar probe that is a concept design for a potential mission in the coming centuries.
- To allow a direct technology comparison with Daedalus and provide an assessment of the maturity of fusion based space propulsion for future precursor missions.
- To generate greater interest in the real term prospects for interstellar precursor missions that are based on credible science.
- To motivate a new generation of scientists to be interested in designing space missions that go beyond our solar system.

Revised ToRs

1. 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.
2. The spacecraft will use current or near-future technology, and should be capable of being launched as soon as is credibly determined.
3. The spacecraft shall reach its stellar destination within a century of its launch, and ideally much sooner.
4. The spacecraft design shall allow missions to a variety of target stars.
5. The spacecraft propulsion shall be mainly fusion based.
6. The spacecraft shall decelerate for increased encounter time at the destination.

Higher Level Objectives

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 subprobes 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 subprobes to make in situ investigations of the atmospheres and surfaces of planets orbiting different stellar components of the system.

References

[1] Bond, A. and Martin, A. (1978). *Project Daedalus*. JBIS.

[2] Long, K.F., Obousy, R.K., Tziolas, A.C. *et al.* (Nov/Dec 2009). *Project Icarus: Son of Daedalus - Flying Closer to Another Star*. JBIS, **62(11/12)**:403–416.

[3] Long, K.F. and K., O.R. (12 May 2010). *Project Icarus: Project Programme Document (PPD)*. Issued.

[4] Stanic, M. (2012). *Project Icarus: Nuclear Fusion Propulsion Concept Comparison*. JBIS, **68**:232–243.

[5] Freeland, R.M. (2013). *Project Icarus: Fission Fusion Hybrid Fuel for Interstellar Propulsion*. JBIS, **66**:290–296.

[6] Long, K.F. (Aug 2016). *Project Icarus: Development of Fusion Based Space Propulsion for Interstellar Missions*. JBIS, **69(8)**:289–295.

[7] Crawford, I.A. (Jan 2016). *Project Icarus: Preliminary Thoughts on the Selection of Probes and Instruments for an Icarus-Style Interstellar Mission*. JBIS, **69(1)**:4–10.

[8] Baxter, S. (Jan 2016). *Project Icarus: Exploring Alpha Centauri: Trajectories and Strategies for Sub Probe Deployment*. JBIS, **69(1)**:11–19.

[9] Milne, P. *et al.* (Aug 2016). *Project Icarus: Communications Data Link Designs Between Icarus and Earth and between Icarus Spacecraft*. JBIS, **69(8)**:278–289.

[10] Smith, R.A., Sheikh, S., and Swinney, R.W. (Nov 2016). *Navigation to Alpha Centauri Star System*. JBIS, **69(11)**:379–390.

[11] Smith, R.A. and Swinney, R.W. (Nov 2016). *Granularity and Ambiguity in Navigating the Void*. JBIS, **69(11)**:390–401.

[12] Freeland, R.M. and Lamontagne, M. (2015). *Firefly Icarus: An Unmanned Interstellar Probe using Z-Pinch Fusion Propulsion*. JBIS, **68**:68–80.

[13] French, J.R. (Jul/Aug 2013). *A Review of the Daedalus Main Propulsion System*. JBIS, **66(7/8)**:248–249.

[14] Freeland, R.M. (Sep/Oct 2015). *Mathematics of Magsails*. JBIS, **68(9/10)**:306–323.

[15] Pollock, J.A. and Barraclough, S. (1905). *Proc. R. Soc. New South Wales*. Proc. R. Soc.

[16] Bennett, W.H. (1934). *Magnetically Self-Focussing Streams*. Phys. Rev., **45**.

[17] Kruskal, M. and Schwarzchild, M. (London, 1954). *Some Instabilities of a Completely Ionized Plasma*. Proc. Royal Society.

[18] Shumlak, U. and Roderick, N.F. (1998). *Mitigation of the Rayleigh-Taylor Instability by Sheared Axial Flows*. Physics of Plasmas, **5**.

[19] ZAP, U. (11 Jan 2013). *Flow Z-Pinch Experiment*. Publications. URL `http://www.aa.washington.edu/research/zap/publications.html`.

[20] Advanced Concepts Office (ED04), M.S.F.C. (8 Oct 2010). *Z-Pinch Pulsed Plasma Propulsion Technology Development*. Final Report.

[21] Kaye, G.W.C. and Laby, T.H. (Longmans Green and Co, 1995). *4.7.4 Nuclear Fusion*. Tables of Physical and Chemical Constants.

[22] Parkinson, R. (1978). *Project Daedalus: Propellant Acquisition Techniques*. JBIS, **Daedalus Final Report**:S83–89.

[23] Osbourne, R. (2012). *Project Icarus: Fuel Acquisition*. Internal Paper.

DOI: 10.5281/zenodo.3747274

[24] of Energy, U.D. (1949-2005). *U.S. Energy Consumption by Source*. Energy Information Administration. URL `http://www.eia.doe.gov/aer/txt/ptb0103.html`.

[25] Freeland, R.M. (21/22 Oct 2013). *Project Icarus Module 4 Primary Propulsion Report*. Project Icarus Concept Design Workshop.

[26] NASA (8 Apr 2019). *Chandra X-ray telescope*. NASA. URL `https://www.nasa.gov/mission_pages/chandra/spacecraft/index.html`.

[27] Hempsell, M. and Bond, A. (Nov/Dec 2014). *Skylon: An Example of Commercial Launch System Development*. JBIS, **67(11/12)**:434–439.

[28] Week, A. and Technology, S. (9 Sep 1996). *SHARP Gun Accelerates Scramjets to Mach 9*. Aviation Week and Space Technology, page 63.

[29] Team, T.G. (20 Oct 2013). *Project Icarus TUM Ghost Team Design submission for the Concept Design Competition*. Concept Design Competition, **11**.

[30] Badiei, S., Andersson, P.U., and Holmlid, L. (2010). *Production of ultradense deuterium: A compact future fusion fuel.* Applied Physics Letters, **96(12)**:124,103–3.

[31] Andersson, P., Lonn, B., and Holmlid, L. (2011). *Efficient source for the production of ultradense deuterium D(1) for laser-induced fusion (ICF).* Review of Scientific Instruments, **82(1)**:013,503–8.

[32] Milos, S. (11 Dec 13). *Project Icarus: Ultra Dense Deuterium based vehicle concept.* Project Icarus internal report.

[33] Thio, Y.C.F., Freze, B., Kirkpatrick, R.C. *et al.* (1999). *High Energy Space Propulsion Based on Magnetized Target Fusion.* NASA Marshall Space Flight Center, **AIAA(992703)**.

[34] Tunchi, D., Evinsteyn, D. *et al.* (18 Nov 2015). *Project Icarus: Zeus An Unmanned Interstellar Voyage Preliminary Spacecraft Design*. Internal Drexel University Project Icarus Chapter Report, **10**.

[35] Long, K.F. *et al.* (2012). *Project Icarus: Nuclear Fusion Space Propulsion and The Icarus Leviathan Concept,* Space Chronicle:. JBIS, **65(1)**.

[36] Swinney, R.W. *et al.* (2012). *Project Icarus: Exploring the Interstellar Roadmap using the Icarus Pathfinder and Starfinder Probe Concepts*. JBIS, **65**:244–254.

[37] Benford, J. (May/Jun 2017). *Sailships Vs Fusion Rockets: A Contrarian View*. JBIS, **70(5/6)**.

DOI: 10.5281/zenodo.3747274