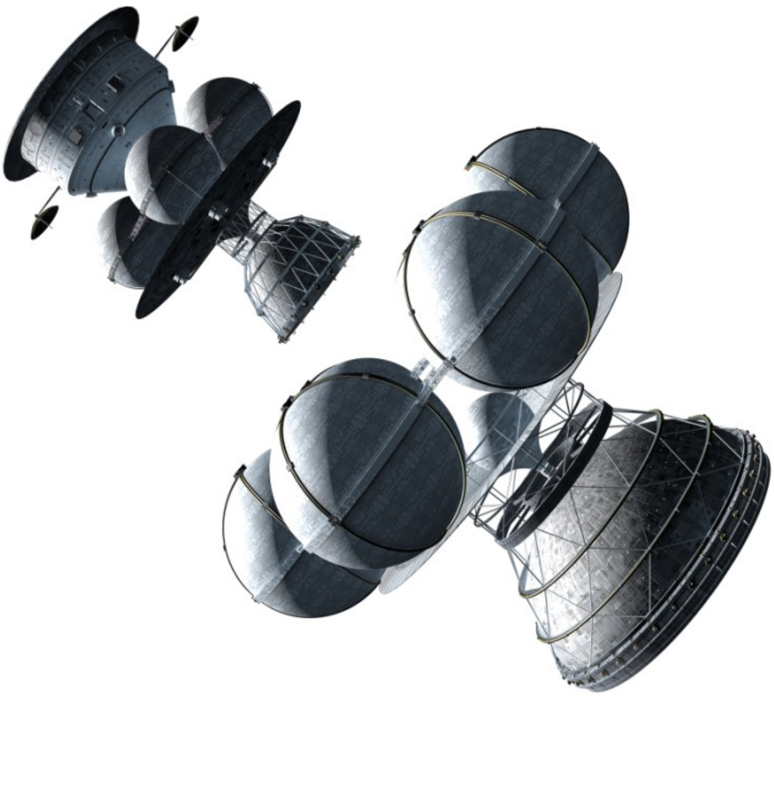
PROJECT ICARUS: PROJECT PROGRAMME DOCUMENT (PPD) - OVERVIEW PROJECT PLAN COVERING PERIOD 2009 – 2014

INCORPORATING MAJOR TASK PLAN FOR PHASE III CONCEPT DESIGN COVERING PERIOD MAY 2010 – APRIL 2011.



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12th May 2010

Summary

This report sets out the overall programme plan for Project Icarus - a theoretical engineering design study of an unmanned interstellar probe based upon the historical Project Daedalus. This is a joint volunteer initiative led by members of the Tau Zero Foundation and The British Interplanetary Society. This report covers the period 30th September 2009 to 2014 when the final executive summary reports are expected to be published. This report also describes the major task plan covering the Concept Design Phase III for the period May 2010 to April 2011. This report has been written so as to provide a single reference document from which the team can work. It is also important for any future Project Leaders to ensure that the project stays on track according to a set timeline of major milestones and key phase deliverables. These are defined. This report also covers project resourcing and risks as well as the strategy and design philosophy to be adopted by the team to evolve the final Icarus vehicle configuration, performance and mission profile.

The Daedalus front cover artwork was designed by Adrian Mann. The Project Icarus logo above was designed by the artist Alexandre Szames

PROJECT ICARUS: PROJECT PROGRAMME DOCUMENT

The text below constitutes the Project Programme Document (PPD) for Project Icarus.

Date: 12th May 2010

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Of Icarus; In ancient days two aviators procured to themselves wings. Daedalus flew safely through the middle air and was duly honoured on his landing. Icarus soared upwards to the sun till the wax melted which bound his wings and his flight ended in fiasco. The classical authorities tell us, of course, that he was only "doing a stunt"; but I prefer to think of him as the man who brought to light a serious constructional defect in the flying-machines of his day. So, too, in science. Cautious Daedalus will apply his theories where he feels confident they will safely go; but by his excess of caution their hidden weaknesses remain undiscovered. Icarus will strain his theories to the breaking-point till the weak joints gape. For the mere adventure? Perhaps partly, this is human nature. But if he is destined not yet to reach the sun and solve finally the riddle of its construction, we may at least hope to learn from his journey some hints to build a better machine.

From "Stars and Atoms," by Sir Arthur Eddington (Oxford University Press, 1927, p. 41)

1. INTRODUCTION

This report describes the programme plans for Project Icarus, a theoretical engineering design study of an unmanned interstellar probe based upon the historical British Interplanetary Society (BIS) Project Daedalus [1]. Daedalus was to be a fusion powered unmanned Starship that was designed to perform a flyby of Barnard's star, located approximately 6 light years from Earth. Research for the Daedalus project was performed in the 1970's and still today fusion power is considered a strong candidate for how we may embark on deep space missions in the future. Project Daedalus had three stated guidelines: (1) The spacecraft must use current or near future technology (2) The spacecraft must reach its destination within a human lifetime (3) The spacecraft must be designed to allow for a variety of target stars. The origin of Project Daedalus can be viewed as an attempt to address interstellar flight using more manageable nuclear pulse techniques, as opposed to the historical (and highly credible) Project Orion which many perceive to be unpopular due to the nature of its propellant [2].

A 1991 NASA study [3] investigated a strategy for developing fusion powered vehicles for a space transportation infrastructure in the future as part of a top priority policy for the US administration. The report said that critical to the implementation of this mission architecture in the 21st century was the development of a high energy mission capability with a vehicle performance from 100-20,000kms^{-1} thus enabling manned and unmanned flights to all orbiting masses within the solar system and possibly unmanned missions to the stars. The report summary said:

"*Applications for space are directly in front of us, but the development of hardware for flight will not be quick. Thus, now is the proper time for NASA to initiate a space fusion research program to develop space applicable confinement designs. An expedient and cost effective program approach is to demonstrate first principles, then to proceed directly to full scale, net power reactors. An aptly funded program, $150-200million per full scale confinement approach, may make this capability available on the order of ~30 years. That investment will pay for itself based upon one manned flight to Mars alone*" [3].

Thus, the main purpose of Project Icarus is to help to realise this goal by demonstrating first principles design. Project Daedalus demonstrated that a highly credible engineering design could be produced with modest effort and limited resources. The study is universally accepted as a paradigm changing one and since then similar projects have been undertaken such as Vista [4], AIMStar [5] and the graduate student study Longshot [6], although none to the same level of detail as Daedalus. But space agencies could not possibly have proceeded with the engineering plans for Daedalus in the late 1970's and move towards a flight ready vehicle, because most of the technology had not yet been demonstrated or, in some cases, invented. The situation has changed remarkably however in the intermediate decades with progress in fusion research, electronics, materials science and indeed astronomical detection programs. The time to revisit Project Daedalus is now. Icarus may not be the engineering blueprint for how we send the first robotic ambassadors to explore new solar systems, but it is entirely possible that Icarus will serve as an important foundation upon which to forms such blueprints for these spacecraft. It is hoped that once Project Icarus is complete international space agencies will re-examine fusion based space propulsion and begin to embark on serious studies with a view to enabling a near-future mission architecture along these lines in the decades ahead. This is ultimately the ambition of the Project Icarus Study Group. Some efforts along these lines have already occurred in the recent past [7].

Project Icarus has its origins from late 2008 when discussions between the then NASA physicist Marc Millis (but in a personal capacity) and Kelvin Long led to the proposal for a design study based upon a redesign of Daedalus. This was to include an examination of the fundamental assumptions, such as flyby only or mining He^3 from the gas giant Jupiter. One of the obvious assumptions was the choice of Barnard's star as the destination target, since shown to be erroneous [8]. Other stars may be more appropriate such as the Alpha/Proxima Centauri system which is the closest and potentially represents an interesting target in terms of the variation in stellar spectral type. Other targets such as epsilon Eridani are believed to have planets due to the observation of dust belts [9], although this target is at the outer bounds of what Icarus could realistically reach within the defined project requirements. Brown Dwarf's may also be of some interest to such a mission.

Several members of the Daedalus Study Group were then approached during Glasgow IAC 2008 and meetings between Alan Bond (facilitated by Tibor Pacher) and Bob Parkinson led to a go ahead for Project Icarus. Martyn Fogg and Richard Obousy then agreed to join the project and a core team was established to begin setting the project up. To assist in advertising the proposed project and developing the plans, a presentation was given by Long at a special session on interstellar flight at the Charterhouse Space Conference during 2009 on fusion propulsion and Project Icarus. After several months of recruitment well over a dozen volunteer designers and consultants have joined the project.

Naming the project was challenging given that numerous projects named Icarus have appeared in the past. However, in the introduction to the Daedalus study report Alan Bond states that "*it is hoped that these 'cunningly wrought' designs of Daedalus will be tested by modern day equivalents of Icarus, who will hopefully survive to suggest better methods and techniques which will work where those of Daedalus may fail, and that the results of this study will bring the day when mankind will reach out to the stars a step nearer*" [1]. So in essence, naming the successor Project Icarus was inspired by the original study group. Both Daedalus and Icarus derive their names from Greek mythology.

Project Icarus is a Tau Zero Foundation (TZF) initiative in collaboration with The British Interplanetary Society (BIS). This creates a strong support base and a process for rigorous technical review of the final design. 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.

The project was officially launched on 30th September 2009 at the HQ of The BIS in London. This event was recorded in Spaceflight magazine [10] and several of the original Project Daedalus Study Group were in attendance, including Alan Bond, Bob Parkinson, Penny Wright, Geoff Richards, Jerry Webb, Tony Wight. The founding members of Project Icarus at this event also included Andreas Tziolas and Richard Osborne who had by then joined the project. Others present who were later recruited to the team included Pat Galea, Ian Crawford, Rob Swinney and Jardine Barrington-Cook. Additional members joined at later dates. Since then the project has gone through the Phase 1 stage which involved assembling the design team and formalising the engineering requirements of the project. This was completed on 4th November 2009 and was published internally to the team in what is known as the Terms of Reference (ToR) document which stipulates the following requirements [11]:

1. **To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium.**
2. **The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.**
3. **The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner.**
4. **The spacecraft must be designed to allow for a variety of target stars.**
5. **The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).**
6. **The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.**

There is also the addition of a project scope:

'**The required milestones should be defined in order to get to a potential launch of such a mission. This should**

include a credible design, mission profile, key technological development steps and other aspects as considered appropriate.'

The ToR and project scope are then what is to be completed by the team on final report publication. The purpose of this present Project Programme Document (PPD) is to set out how the team is to accomplish this. To formalise this process it is important to ensure that the team remains on track to deliver the programme plans. It is also a useful yardstick for each designer to monitor their own research progress and to understand how their work fits into the overall programme. It is suggested that at the end of each major phase a report of this type is written by the Project Lead (PL) to ensure that the project remains on schedule and define the next phase of the work programme to be completed. Since the project started several reports have been produced. This includes an external peer reviewed publication [12] which was submitted along with other relevant papers from the BIS September 2009 symposium [13, 14, 15]. Two internally published technical reports also feed the concept design work [16, 17]. Several public blog articles have also been written by the team on aspects of Project Icarus to facilitate discussion and invite input from the general public [18-28].

As of the end of Phase II the Project Icarus design team stands as follows:

- Kelvin Long (PL)[1]
- Richard Obousy (DPL)
- Richard Osborne
- Andreas Tziolas
- Ian Crawford
- Andy Presby
- Adrian Mann
- Robert Adams
- Pat Galea
- Robert Swinney
- Adam Crowl
- James French
- Philip Reiss
- Andreas Hein
- Jardine Barrington-Cook
- Marc Millis (Consultant)
- Paul Gilster (Consultant)
- Greg Matloff (Consultant)
- Tibor Pacher (Consultant)

[1] As of Phase III Richard Obousy becomes Project Leader.

2. TASK MANAGEMENT

Project Icarus has been split into a total of 20 research modules encompassing all of the key spacecraft systems. As the design progresses sub-systems can also be defined as sub-categories of the research modules (e.g. 4.1 Laser Driver, 4.2 capsule design…). The figure below shows all of the research modules.

Because designers will want to work on many different aspects of the Icarus vehicle design, several levels of participation have been defined as follows:

- **Lead** – leading designer on research module in charge of co-ordinating research effort on respective systems or sub-systems.
- **High Active** – Performing a major contribution to the system or sub-systems relevant to the research module in co-operation with others, although not leading the overall research.
- **Low Active** – Performing a minor contribution to a system or sub-system relevant to a research module, in co-operation with others.
- **Passive** – Not directly contributing to a system or sub-system relevant to a research module although available for team discussions on subject. By default all team members have passive status on every research module.

Project Icarus System Research Modules

Most of the team were initially defined as 'Floating Designers during a probationary period. Some then became 'Core Designers' depending on their contributions, work output and proven reliability. The 'floating' role is preserved for any new members to the team and also for team members who provide one-off, or occasional contributions. .

A Design Lead has a specific and important role - to co-ordinate all research within the team relevant to the module, pertaining to old and new ideas. In this capacity the design lead needs to minimise research overlap between members but also ensure that all those High Active designers working in that area contribute towards the research programme in line with this PPD report which is to be delivered by Stage Gate 1. This should include the eventual publication of internal team only report(s) or externally peer reviewed Journal paper(s). The individual designer is free to choose which option they wish to take, but a report is deliverable evidence of research conducted and is vital to feed the design evolution. In this regard, anyone wishing to conduct research in a module should first discuss it with the design Lead and current Project Lead.

Design Leads should take 100% responsibility (known as ownership) in ensuring that the relevant Daedalus report issues are addressed and so by implication must be very familiar with the relevant Daedalus report(s). Design Leads should also co-ordinate the final Icarus publications in their area to be submitted to JBIS in 2014. The Design Leads may change throughout the project depending on availability and interest of team members.

Once the work is allocated, there is a need to monitor the progress of that work. To achieve this, a colour code has been created which is to be dynamically tracked (by either the PL or Design Leads) and continually displayed for the teams viewing. This way as the research moves forward the team can see the progress displayed on this chart. The colour code definitions are as follows:

- **Green** – Currently writing up research results in a report.
- **Violet** – Research is in the final stage of development.
- **Blue** – Research is sufficiently developed and producing calculations.
- **Yellow** – Research is in the early scoping phase of development.
- **Orange** – Research is currently in the information gathering phase.
- **Red** – Research has been assigned to a designer but no work yet started.

At the end of each major research phase every module Design Lead should also produce a (brief) review report, giving status and recommendations from research of that phase. This is to inform the current PL and the rest of the team on where to go next. The PL should then use this information to define the specific milestones for the next design phase.

Management of the different research modules is to be achieved by using a systems engineering approach and by defining timelines for project delivery. For Project Icarus, there are a total of 10 project phases and 5 key stage gates, the latter of which must be passed to proceed to the next step. An evaluation for entrance of each Stage Gate is based upon one of four criteria metrics which judge the work of the previous phase:

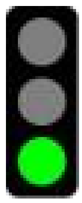
- **Go** – Proceed to next phase.
- **Kill** – Complete failure to meet Stage Gate, return to previous Stage Gate.

- **Hold** – Hold at current phase subject to further work due to current solution not acceptable but alternative may be.
- **Recycle** – Repeat last phase where the work fails to demonstrate sufficient progress and current solution is not acceptable.

An assessment at each Stage Gate is based upon the determined Deliverable (i.e. deliver report) which feeds the decision. Finally, Outputs defines the programme plan for getting to the next Stage Gate. The programme plans are described in section 8 of this report.

The research progress itself will be monitored by the use of a traffic light diagram which defines the project status relative to the programme plans. The three defined status levels will be displayed on both the private and public web site continuously and are defined as follows:

RED = Behind schedule
AMBER = Matching schedule
GREEN = Ahead of schedule



In order to undertake the design work for Project Icarus, the team must have a broad knowledge of several physics and engineering topics. Many of these topics will be familiar to designers from University study or from employment experience. However, some of these topics are also likely to be new to the designers. For this reason the 'warm-up' part of the project (Phase I & II) and the Concept Design period (Phase III) were deliberately stretched out so as to allow designers time to become familiar with many difficult technical topics. In effect all of the team members are being asked to become 'Starship designers' within a short space of time and in a part-time capacity. The programme plans have been structured to allow for this. The topics of relevance to Project Icarus include the following in no particular order:

- Space Propulsion
- Thruster Design
- Materials Technology
- Thermodynamics
- Communications Technology
- Astronomy
- Astrometry
- Orbital Dynamics
- Planetary Formation
- Reliability Analysis
- Computer Modelling
- Systems Engineering
- Nuclear Reactor Design
- Fusion Physics & Technology
- Laser Beam Physics & Technology
- Antimatter Physics & Technology
- Computing & Data Management
- Space Mission Design
- Spacecraft Navigation
- Spacecraft Guidance Control
- Fusion Fuel Mining Techniques
- Solar Sails
- Biology Identification
- Science Instruments & Probes
- Spacecraft Assembly
- Spacecraft Architecture Design

As of April 2010 among the 16 Project Icarus designers and four Consultants there are a total of 14 Bachelor of Science or Engineering degrees, 1 Bachelor of Medicine degree, 2 Bachelor Arts degrees, 10 Masters of Science or Philosophy degrees and 6 Doctor of Philosophy degrees. Several of the team are also still undergoing training, including 1 Master of Science degree and 2 PhD's. This impressive list of qualifications among the team gives confidence that the team is up to the challenge of designing the Icarus vehicle and mission architecture.

3. RESOURCE

The key resource for the project is man hours in a volunteer capacity. Throughout the approximately five years of the project the number of reliable and dedicated designers will oscillate between 15 – 20, where most of the research is conducted in the odd evening or on a weekend. Assuming a standard 8 hour session budget per week per person (32 hours per month) over 54 months of the project (1st October 2009 – 31st March 2014) this equates to between 25,950 - 34,560 total man hours. An approximate average between these two estimates puts the total man hours at 30,000 that are available for delivery of Project Icarus. If individuals put >8hours per week into the research, then the total man hours will increase. Note that as of the end of March 2010 the estimated number of man hours for the currently 16 member design team, 4 consultants and 1 artist is around 2100 man hours. For interest, the Daedalus study report states that Daedalus officially began on 10th January 1973 and the final reports were published 15th May 1978. It took 64 months or just over 5 years. The study report states that around 10,000 man hours were used by 13 core designers and several additional consultants to the project [1]. So the estimates for Project Icarus are not unreasonable.

The design team is international and reflects how many modern space missions are performed. This is also the likely way in which any future interstellar mission would be attempted. Because the project is voluntary it is essential that all team members play an important part in driving the project through to fruition. It should not be left to a select few. Both the PL and Design Leads should also keep this in mind when being overly demanding with work schedules.

Another resource for the team is financial. A donations facility has been set-up on the Icarus public blog site. This allows members of the public to make donations which can help the team to attend or present at conferences sharing results of the Icarus design study. This is also important because conference attendance allows the design team to interact on a physical level (other than just over the internet) and also allows the team to interact with experts in research fields of relevance to the project. All donations are to be made through the Tau Zero Foundation donations facility.

The progress of the team will be monitored by the Project Leader who would expect regular research updates from the team. The Project Leader will also be rotated occasionally to ensure that the project momentum is maintained and allow new energy into the project due to enthusiastic leadership. It is suggested that this rotation should occur every 10 – 18 months depending on project progress. The Project Lead should also appoint a Deputy Lead to split some of the management responsibility and reduce the burden on a single individual. The design team are expected to support the leadership in managing Project Icarus. However, in the event it is felt that the Project Leader is doing a poor job in pushing the design forward according to the programme plans outlined in this document, members of the Core Design Team only have the right to call a vote of no confidence and elect a different Project Leader. The decision of the vote will stand.

Throughout the project there are several mathematical and computational tools available to members of the design team for engineering calculations and analysis. This will be a major resource for ensuring calculation accuracy. These are listed in no particular order as potential tools at the team's disposal:

- Spreadsheets
- Fortran
- C++
- Matlab
- Particle In Cell codes
- Vlasov Solver codes
- Planetary Orbit codes
- GMAT
- Finite Element/Analysis tools
- Hydrodynamics codes
- AutoCAD drawing
- Photoshop elements
- Mathematica
- Python, SciPython, R
- CATIA

There are no major programme dependencies as such although the success of the project is affected by the following two factors (1) physics results from NIF (2) JBIS referee process and approval of final Project Icarus study papers.

4. PROGRAMME OF WORK

The table below shows a list of the final Project Daedalus Engineering Study Reports. There is no requirement that the final Project Icarus reports should mimic this structure, but all of the Project Daedalus reports should at least be encompassed within the final Project reports.

The **Final Project Icarus Study Reports** will be a matter for discussion among the team towards the end of the project. This will ideally be submitted to the Journal of the British Interplanetary Society (JBIS), in honour of Project Daedalus. However, in the event that external publication in a Journal becomes problematic, the team will make arrangements to publish the reports on the web and make them available as pdf documents for the world at large. They could be downloaded from the Icarus public web site but also loaded onto a CD for dissemination. Based upon the current research module structure and team members the breakdown listed below for the final reports is 'suggested' with working titles. Each 'bullet point' may actually represent more than one paper, such as for Primary Propulsion in which case could be defined as Part 1, 2 or 3. It is expected that the final reports will comprise a total of around 400-500 pages of text and figures. First named authors below are the expected report Lead author today, but this may change.

Daedalus Final Study Report	Project Icarus Research Module link
Project Daedalus	20.0 Design Certification
Project Daedalus: Astronomical data on nearby stellar systems	1.0 Astronomical Target
Project Daedalus: The evidence for planetary companions of Barnard’s star	1.0 Astronomical Target
Project Daedalus: An analysis of the photometric data on Barnard’s star and its implications	1.0 Astronomical Target
Project Daedalus: The ranking of nearby stellar systems for exploration	1.0 Astronomical Target
Project Daedalus: The mission profile	2.0 Mission Analysis & Performance
Project Daedalus: The propulsion system, part I; theoretical considerations and calculations	4.0 Primary Propulsion 5.0 Secondary Propulsion
Project Daedalus: The propulsion system, part II; engineering design considerations and calculations	4.0 Primary Propulsion 5.0 Secondary Propulsion
Project Daedalus: Propellant acquisition techniques	6.0 Fuel & Fuel Acquisition
Project Daedalus: The vehicle configuration	3.0 Vehicle Configuration
Project Daedalus: Structural material selection	7.0 Structure & Materials
Project Daedalus: The structure	7.0 Structure & Materials 3.0 Vehicle Configuration
Project Daedalus: Bombardment of interstellar material and its effects on the vehicle	18.0 Vehicle Risk & Repair 12.0 Environment Control
Project Daedalus: Target system encounter protection	18.0 Vehicle Risk & Repair 12.0 Environment Control
Project Daedalus: The auxiliary power supplies	8.0 Power Systems
Project Daedalus: The computers	11.0 Computing & Data Management
Project Daedalus: The navigation problem	10.0 Navigation & Guidance
Project Daedalus: Some principles for the design of a payload for an interstellar flyby mission	14.0 Science 15.0 Instruments & Payload
Project Daedalus: The vehicle communications systems	9.0 Communications & Telemetry 13.0 Ground Station and Monitoring
Project Daedalus: The need for on-board repair	18.0 Vehicle Risk & Repair 16.0 Mechanisms
Project Daedalus: An engineering assessment	19.0 Design Realisation & Technological Maturity 20.0 Design Certification

The proposed 'working' executive summary report structure:

1. Project Icarus: **Introduction & Background to the Study**; Authors: K.Long, R.Obousy.
2. Project Icarus: **A Review of Astronomical Targets**; Authors: I.Crawford.
3. Project Icarus: **A Discussion of the Chosen Target Star Destination**; Authors: I.Crawford.
4. Project Icarus: **A Review of Mission Science for an Interstellar Probe**; Authors: I.Crawford, K.Long, R.Obousy, Tziolas.
5. Project Icarus: **Vehicle Payload & Instrument Design**; Authors: K.Long, R.Obousy, I.Crawford, A.Tziolas.
6. Project Icarus: **Mission Analysis & Performance for Preferred Target**; Authors: R.Adams, R.Obousy, K.Long, A.Tziolas, A.Crowl, A.Hein.
7. Project Icarus: **Analysis & Performance for Alternative Targets & Missions**; Authors; R.Adams, R.Obousy, K.Long, A.Tziolas.
8. Project Icarus: **A Review of the Options for Fuel & Fuel Acquisition**; Authors: A.Crowl, K.Long, A.Hein, R.Obousy.
9. Project Icarus: **A Discussion of the Chosen Fuel & Fuel Acquisition Technique**; Authors: A.Crowl, K.Long, A.Hein.
10. Project Icarus: **A Description of the Mission Architecture & Vehicle Assembly**; Authors; R.Osborne, A.Hein, K.Long, R.Adams.
11. Project Icarus: **The Justification for the Choice of Primary Propulsion**; Authors: R.Obousy, K.Long
12. Project Icarus: **Primary Propulsion Design**; Authors: R.Obousy, K.Long, A.Tziolas, R.Adams, A.Presby, A.Crowl, J.French.
13. Project Icarus: **Secondary Propulsion Design**; Authors: A.Tziolas, R.Obousy, A.Presby, R.Swinney, R.Osborne.
14. Project Icarus: **Vehicle Configuration & Layout**; Authors: K.Long, A.Mann, A.Hein, P.Reiss, J.French.
15. Project Icarus: **A Review of Materials for an Interstellar Probe**; Authors: A.Crowl, K.Long.
16. Project Icarus: **A Discussion of the Structure & Chosen Materials for the Vehicle**; Authors: A.Crowl, K.Long.
17. Project Icarus: **Vehicle Communications & Telemetry**; Authors: P.Galea, R.Swinney, J.Barrington-Cook.
18. Project Icarus: **Vehicle Navigation & Guidance Control**; Authors: R.Swinney, A.Tziolas, P.Galea, J.Barrington-Cook.
19. Project Icarus: **Mission Support & Monitoring**; Authors: P.Galea, R.Swinney, A.Tziolas, J.Barrington-Cook.
20. Project Icarus: **Computing & Data Management**; Authors: A.Tziolas, J.Barrington-Cook, P.Galea.
21. Project Icarus**: Vehicle Power Systems**; Authors: A.Presby, A.Tziolas, P.Galea.
22. Project Icarus: **A Description of Environment Control**; Authors; A.Presby, A.Tziolas.
23. Project Icarus: **A Description of the Vehicle Mechanisms**; Authors: P.Reiss, A.Crowl.
24. Project Icarus: **A Description of the Vehicle Deceleration Mechanism**; A.Tziolas/P.Reiss, I.Crawford, A.Mann.
25. Project Icarus: **A Description of the Vehicle Risk & Repair Protocols & Technology**; Authors; A.Tziolas, P.Reiss, A.Presby, K.Long.
26. Project Icarus: **Environmental Impacts & the Discovery of Life**; R.Obousy, I.Crawford, A.Presby.
27. Project Icarus: **Technological Readiness & the Interstellar Roadmap**; Authors: A.Hein, K.Long, P.Reiss.
28. Project Icarus: **Certification of Design Solution**; Authors: K.Long, R.Obousy, A.Tziolas, A.Hein.

The success of the project and the design solution are to be ‘measured’ through Module 20.0 Design Certification and Module 19.0 Design Realisation & Technological Maturity. The Lead for Module 20.0 (in collaboration with team members) should demonstrate that the chosen design solution meets the ToR (engineering requirements) and project scope and also comment on the engineering credibility of the chosen design. This should include addressing issues relating to the QUALIFICATION of the design solution, e.g. what confidence is there that the capsule design will perform as predicted? Is there any experimental basis to support the claim that the thickness of a particle shield is sufficient to withstand micrometeoroid/dust impacts throughout the mission? What flight experience is there of the chosen materials being in the vacuum of space for very long durations? The Lead for Module 19.0 (in collaboration with team members) should describe the technological maturity of fusion based propulsion systems, compare the design to Daedalus and set out the technological roadmap for how such a mission could be achieved in the future.

Ultimately, the design team should provide a confidence statement at the end of the project on the design solution. This should be undertaken by the Lead for Module 20.0 Design Certification in conjunction with the Lead for Module 18.0 Vehicle Risk & Repair, which includes reliability analysis for the mission. The confidence statement should be in two parts (1) confidence that the engineering solution is credible in future decades (2) confidence that the vehicle would reach the target star if launched in 2050 and 2100, based upon linear technology extrapolation, but with the expected caveat that predictions over such long time-scales have large associated uncertainties.

Throughout the project there should be two major design reviews, led by several members of the original Project Daedalus Study Group. These design reviews should result in actions for the design team. The requirements for these actions are defined by three levels as follows:

- <u>Level 1 Action</u>: This is a suggestion for further work but may not be pursued by the designer.
- <u>Level 2 Action</u>: This is a recommendation for further work which the reviewer feels is important to fully cover a system or topic and that the designer should aim to complete where possible.
- <u>Level 3 Action</u>: This is a mandatory action which the reviewer feels is essential in any future design work, without which a Daedalus red-design would be difficult to claim. The designer should aim to complete this although the PL has a veto on whether the design team must meet this action, within the available time constraints and resources.

The table below shows the major events to be accomplished during the project along with the deliverables and timeline.

Date of deliverable	Subject	Description	Output/Deliverable
Between September 2009 – End of December 2009	Phase 1: Team assembly & definition of terms of reference	Internal publication of the Terms of Reference for Project Icarus as well as assembly of the majority of the design team.	Internal publication of ToR document.
Between January 2009 - End of April 2010	Phase 2: Construction of work programme	Communications between team leads to nature and allocation of work programme and timescales for delivery. Work is reviews and trade studies. No design options to be selected.	Internal publication of Project Programme Document & meet Stage Gate 1
Between May 2010 – End of April 2011	Phase 3: Work programme conceptual design	A description of the different issues resulting from the various trade study reviews. This should lead to several recommendations for design options to feed the next stage	Internal/external publication of all reports with recommendations. Form concept design options & meet Stage Gate 2.
Between May 2011- End of December 2011	Phase 4: Work programme preliminary design	More focussed studies leading to fewer design options for further study.	Internal set of reports and publication of preliminary design options.
Between January 2012 – End of March 2012	Phase 5: Preliminary design review	This will be with members of Daedalus Study Group who can state actions for delivery which are to be completed as appropriate.	Pass preliminary design review & complete actions, & meet Stage Gate 3.
Between April 2010 – End of December 2012	Phase 6: Work programme, down select to detailed design options	Down select to final design option and creation of PIBM. Perform initial systems integration exercise.	Down select to Baseline Model & Internal publication of System Requirements Document.
Between January 2013 – End of June 2013.	Phase 7: Work programme, system integration	Majority of system and sub-system integration work to be performed here over several iterations.	Produce Integrated Baseline Model & internal publication of Sub-System Requirements Document.
Between July 2013 – End of September 2013.	Phase 8: Detailed design review	Final opportunity for Daedalus Study Group to scrutinise design. Actions to be completed as appropriate.	Pass detailed design review and complete actions as appropriate & meet Stage Gate 4.
Between September 2013 – End of December 2013	Phase 9: Certification of theoretical design solution	Construction of initial reports examining technological maturity (module 19) & Design Certification (module 20) based on design solution.	Internal publication of initial Certification / maturity documents & meet Stage Gate 5.
Between January 2014 – End of April 2014	Phase 10: Publication of final design solution, submit to JBIS.	Construction, submission & publication of final study reports represents the key deliverable for Project Icarus.	Publication of executive summary reports JBIS

5. GOAL DIRECTED PATHWAY

A Goal Directed Pathway (GDP) describes the vision for the programme of work, the ultimate goal being the determination of a credible design report examining all of the engineering and physics issues associated with Daedalus. More than anything Project Icarus is a design capability exercise to give a whole group of people the opportunity of undertaking such a design study. This is the reason why most of the team is purposely relatively young and inexperienced in spacecraft design, so that they can be around for several decades to inspire the next generation of designers to pick up the baton and carry on the vision of interstellar travel. More specifically the project aims to provide a technology maturity readiness measure from the 1970's and allow a more informed judgement on what missions to the stars will become plausible in future years. Such studies are required to separate rigorous assessments from speculative ones.

The GDP helps the project to achieve its end successfully and it extends from the present to the end of the project which is currently scheduled for 2014. It also has the added purpose of allowing the team to see the wider picture behind the motivation for the study. Ultimately, if a credible design solution is delivered this will be seen and commented on by professional space mission designers. It allows them an opportunity to think about longer term missions for the future and what technological steps they need to see in place before such a mission could be undertaken. The continuous striving towards 'deep space' missions also has the effect of inspiring those professional designers so that they may be emboldened to propose precursor missions to 500AU, 1000AU or even 10,000AU within the next few decades. The goal directed pathway should include the major phase milestones to be achieved throughout the project.

The following GDP has been defined for Project Icarus:

Goal Directed Pathway: ***To produce a completed set of technical reports which describe the engineering layout, functionality, physics, operation, expected performance and mission profile of an unmanned interstellar probe according to the requirements set out in the Project Icarus ToR document. The basis of this report should be a complete re-design of the historical Daedalus vehicle concept.***

6. PROGRAMME RISKS

There are several potential risks to the success of the project. One such risk is the reliability and commitment of the design team, particularly given the volunteer nature of this project. Most of the team have full-time jobs or are in full-time education and so Project Icarus is unlikely to be a daily or even weekly priority. To mitigate this, the project has been deliberately stretched out over a five-year term for a design study that could in principle be accomplished within two years with a full time team of equivalent numbers. Project Icarus is also to always remain a fun and exciting project for the designers, so that fatigue with the research does not set-in. All designers have been asked to provide a preliminary research programme for the first year and this is shown in Appendix A. All designers have also been asked to define and meet a major milestone deadline which is discussed in section 9. The risk that designers may actually leave the project is also possible and in the event that this occurs this will present a problem for the design team once the work programme has already been distributed. A way of dealing with this is discussed below. In general, designers are to be given a 'long rope' and allowed to explore independent research within the constraints of the programme plans.

Despite this, the PL should have the authority to remove people from the Project Icarus Study Group if it is felt that they are not meeting their agreed work programme of if their action leads to an undermining of the credibility of Project Icarus and our Goal Directed Pathway. Such action should only be taken with considerable thought, keeping in mind the voluntary nature of the team. If one person drops out and limited work is performed on a research module or sub-system, then it is suggested that the PL in collaboration with the team drafts a one page (only) statement summarising the status of that research module and giving a recommendation from it at the end. This is to be agreed by all the Core Design team. This will be labelled a **Research Event Action** (REA). The Project Leader at any stage may also be weak and could lead to the team failing to meet the major deliverables, resulting in the project fizzling out as people drop off. If the leadership looks weak at any time other members of the project should speak up and if necessary take action to let someone else become Lead.

It is also possible that due to some team friction a team member leaves the project in some bitterness and decides to take some action to prevent us achieving our end goals. This is unlikely given the mainly web-based interaction of the Icarus team, but is an ever present danger when dealing with large teams of unknown people. This is why each person has been carefully chosen for inclusion in Project Icarus – to minimise the possibility of such situations arising.

Another major risk to the success of the project is the inability of the design team to find a solution to a design issue. This may be due to an emerging contradiction from the ToR or just due to the difficulty of producing an engineering or physics solution. In the event that this occurs, the best approach would be to make credible assumptions about that anomalous component/function and to continue with the remaining design, leaving this problem area unresolved.

Although Project Icarus is supported by TZF and The BIS it is not dependent upon them for practical support. However, a disagreement with these parent organisations could affect the success of Project Icarus. Good relations on all sides are promoted to avoid this.

Another risk is associated with the scientific tools required to do the proper analysis. It may emerge for example that finite element structural modelling is absolutely required for the design. However, if the team could not locate someone to do such modelling then this would lower the accuracy of the engineering calculations. The relevant and required tools for each phase should be identified at an early stage where possible and suitable arrangements made for using these tools for conducting design analysis. Research could potentially be outsourced using the Project Icarus finance budget should it allow for such a facility with increased donations.

As Project Icarus gets more public exposure others may be inspired to conduct a similar undertaking. It is quite possible that in the next few years Project Icarus could find itself with a rival design study. Although the Project

Icarus Study Group would welcome such an event (being good for interstellar research) if the rival design was the ‘Ferrari’ to our ‘Lorry’ then this could harm the credibility of the Icarus design solution. A related risk is that one of the major space agencies decides to undertake such a study. With greater resources, experience, people and mathematical tools at their disposal it is possible that such a team would produce a design far superior to our own. But in this event the original motivation behind Project Icarus would have been achieved.

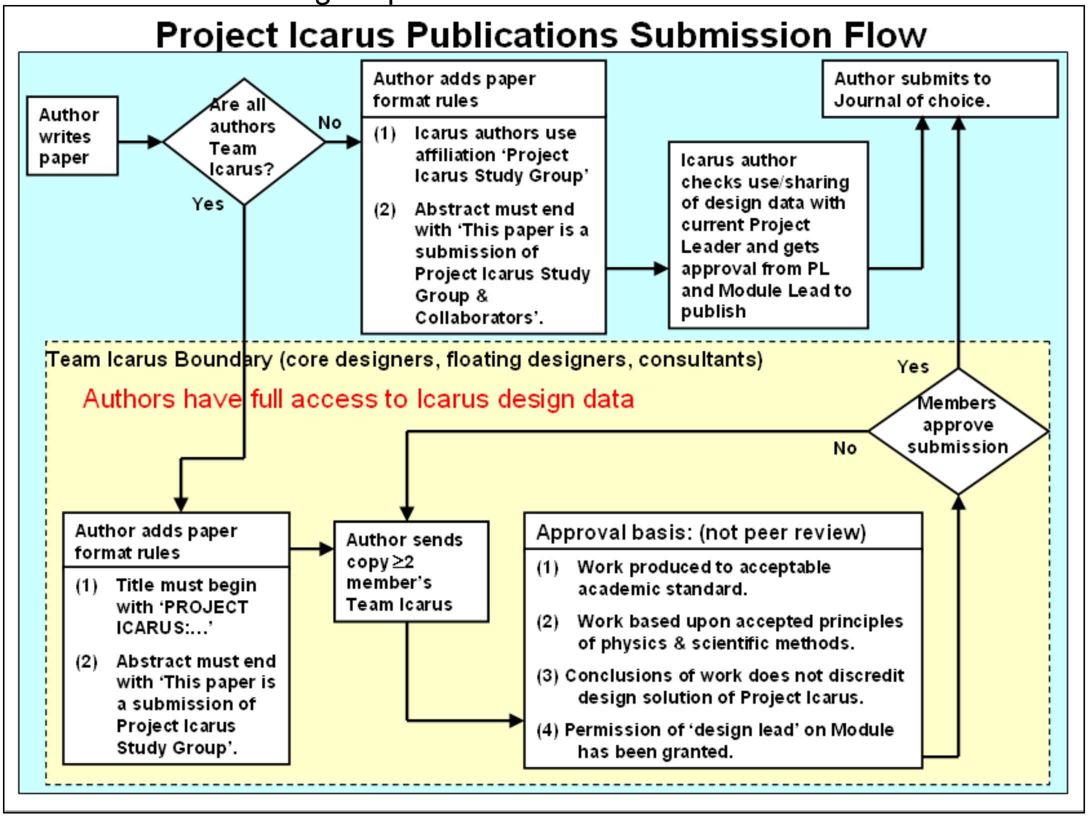
Project Icarus is linked to some major international projects, although not critically dependent upon them. This includes laser fusion research facilities such as the US National Ignition Facility (NIF) and astronomical telescopes such as used in the Kepler mission. If the programme plans of these major international projects slip then this will have an effect on the Icarus design solution, but should not prevent one from emerging. Two factors, however, might lead to a dramatic and poor outcome for Project Icarus. These are:

(1) Inability to achieve ignition at NIF
(2) Inability to find exo-solar planets within the nearby star systems.

Given progress in fusion, particularly in recent years, both of these outcomes seem unlikely. Experiments on facilities such as Nova and Omega have all indicated that NIF should achieve ignition between ~1-2MJ driver energy and recent results from early experiments indicate that NIF is already on its way to solving key laser-plasma interaction problems such as Raman and Brillouin scattering [29] although these indirect drive experiments will still need to be extrapolated to a direct drive situation, as is envisaged for space propulsion. If NIF is successful then this makes the technology transfer to space propulsion far more credible. Since astronomical observatories have identified more than 400 exosolar planets it seems at least a possibility that a star within 10-20 light years of Earth could contain planets that lie within the habitable zone of the host star. The final Project Issue design will have a chosen mission profile for a target destination. However, it would not be a huge technological leap to design a similar vehicle for any of the other target stars within say a 15 light years distance.

It is also possible (but hopefully remotely) that the quality of work produced by one member of the team is below acceptable standards. In this event the PL is to require that the person re-writes the report. The designer can also be prevented from submitting the paper externally by a PL go/no-go approval in accordance with the publication process shown below. The same standard is not applied to internal reports but they should still be of good technical and presentational quality.

Given that the main journal of choice for most Icarus papers will be the Journal of British Interplanetary Society (JBIS) the slowness of the peer review process should also be factored into any programme plans. In that if one phase requires external publication of a paper from a previous phase, the peer review process could prevent the team meeting the deliverables. To mitigate this external publication should never be placed on the critical path for the project. The publication of reports by team members should be in accordance with the agree publication flow shown below.

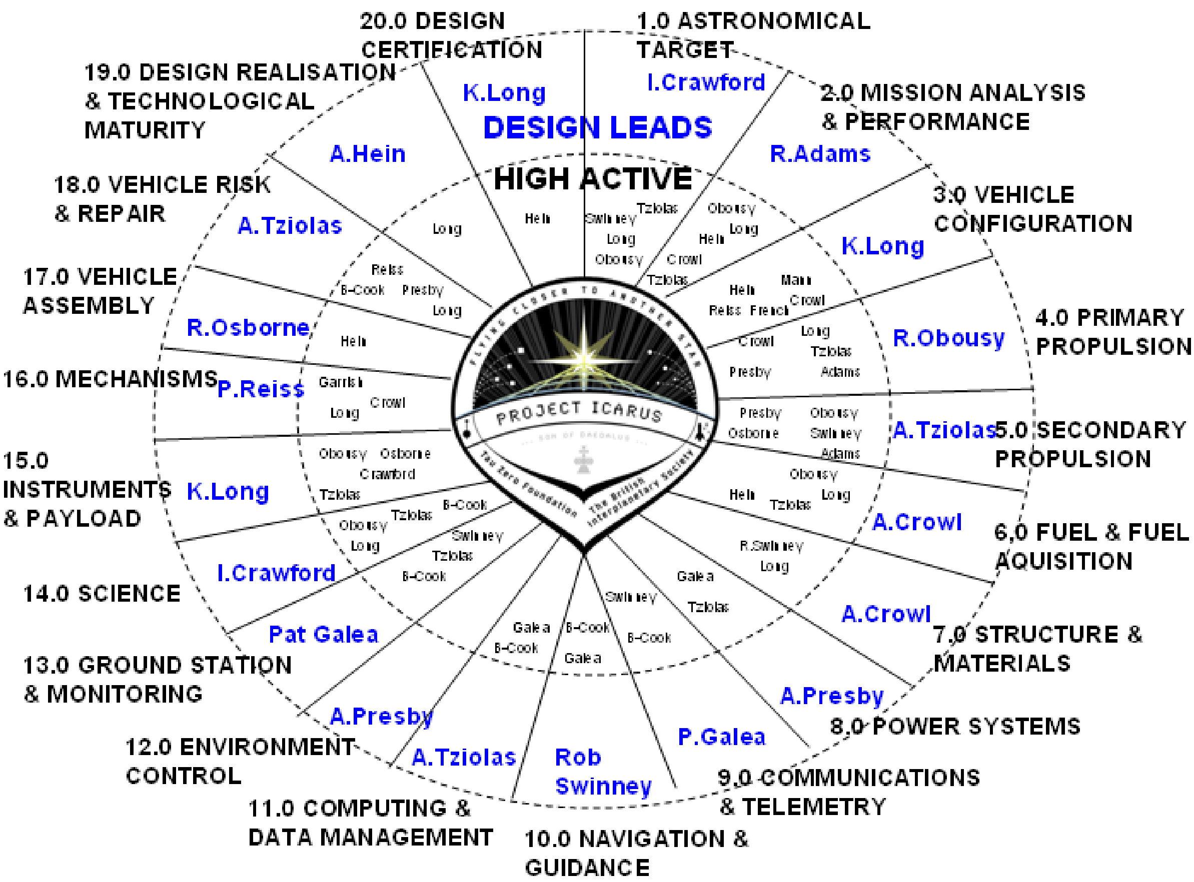


Three levels of risk (low/medium/high) have been defined for the different events/activities that could prevent Project Icarus being successful. The risks are compared against the question: "*What is the risk that if this event or activity occurs it will reduce the probability of the team producing a complete, credible and relevant final study report?*" The assessed results are shown in the table below.

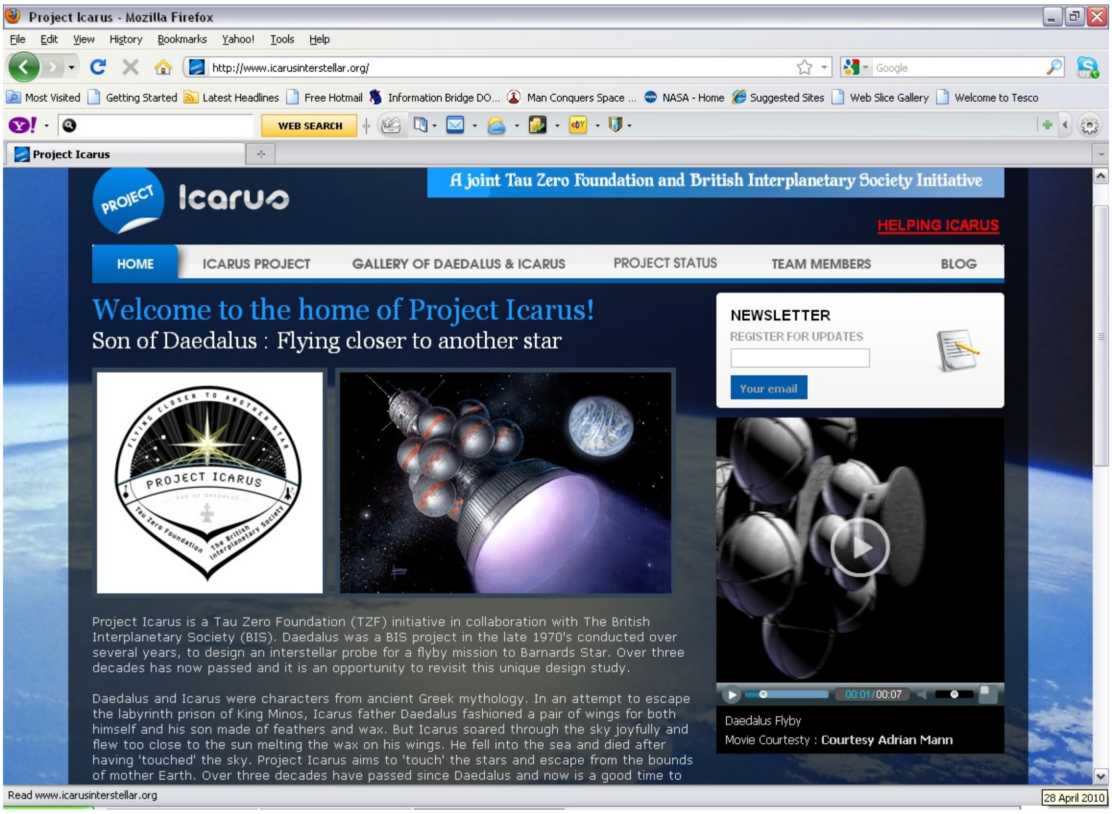
Event/Activity	Risk
Some individual designers leave team	Low
Weak Project Leadership	Low
Team friction issues/disagreements	Low
Lack of TZF/BIS support	Low
Competitive design team produces similar design study report	Low
Long delays with Journal publications	Low
Failure to identify earth-sized worlds in the habitable zone within tens of light years distance.	Low
Many individual designers leave team	Medium
Low quality reports published externally by design team	Medium
Strong evidence that no Earth-sized worlds exist in the habitable zone within tens of light years distance.	Medium
Lack of science tools to conduct reasonable analysis of important engineering problems	Medium
Inability of design team to find engineering solution that meets ToR	High
Failure of NIF to achieve ignition	High

7. DESIGN INTERACTIONS

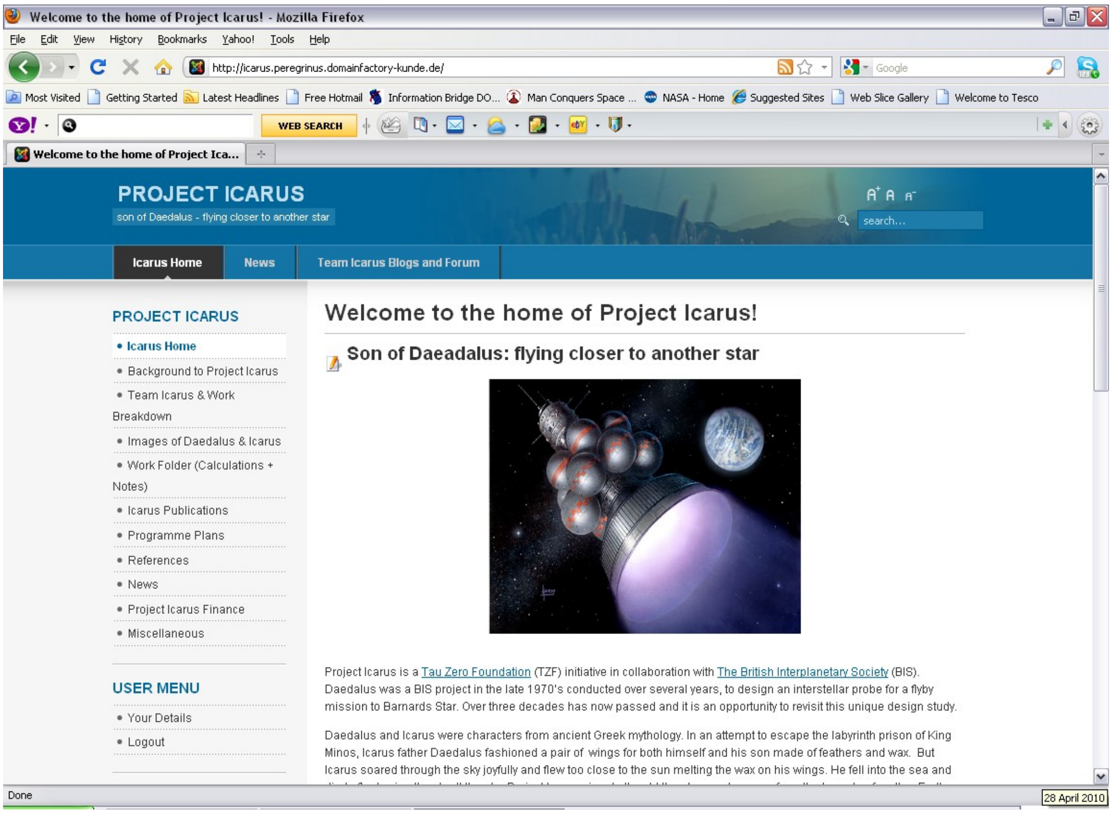
The Project Icarus Study Group consists of voluntary designers. This limits the interactions as all the volunteers have other more important commitments. The team is also international, based in the United Kingdom, United States, Germany, Hungary and Australia. Because of this most of the design work will be performed over the World Wide Web using a special team only Joomla-based web site that has been set up for this purpose. This supplements the public Project Icarus web site. The landing page for both is shown below. Other interaction outlets include post, email, Skype and teleconference. On rare occasions some of the team members may meet at an international conference. On this occasion a workshop session get-together will be organised for the team to discuss design related issues. The structure of the team leading up to the end of Phase 2 is shown in the chart below. As well as the designer-designer interactions, there are also interactions with people external to the team. This includes members of the original Project Daedalus Study Group and other people such as Friedwardt Winterberg who had a seminal affect on the Daedalus design solution.



Project Icarus Study Group active participation roles.



Project Icarus public web site.



Project Icarus private team only web site

The determination of research modules also leads naturally to the definition of design teams within Project Icarus. In this regard, designers wear many 'hats' and the teams so far are as follows:

ASTRONOMICAL TARGET TEAM
Ian Crawford (Lead)
Kelvin Long
Richard Obousy
Rob Swinney
Andreas Tziolas

MISSION ANALYSIS TEAM
Rob Adams (Lead)
Andreas Hein
Richard Obousy
Andreas Tziolas
Adam Crowl
Kelvin Long

VEHICLE CONFIGURATION TEAM
Kelvin Long (Lead)
Andreas Hein
Phillip Reiss
Adrian Mann
James French
Adam Crowl

PRIMARY PROPULSION TEAM
Richard Obousy (Lead)
Kelvin Long
Andreas Tziolas
Rob Adams
Adam Crowl
Andy Presby

SECONDARY PROPULSION TEAM
Andreas Tziolas (Lead)
Richard Obousy
Andy Presby
Richard Osborne
Rob Swinney
Rob Adams

STRUCTURE & MATERIALS TEAM
Adam Crowl (Lead)
Kelvin Long
Rob Swinney

FUEL & FUEL ACQUISITION TEAM
Adam Crowl (Lead)
Kelvin Long
Andreas Hein
Richard Obousy

POWER SYSTEMS TEAM
Andy Presby (Lead)
Pat Galea
Andreas Tziolas

COMMUNICATIONS & TELEMETRY TEAM
Pat Galea (Lead)
Jardine Barrington-Cook
Rob Swinney

NAVIGATION & GUIDANCE TEAM
Rob Swinney (Lead)
Pat Galea
Jardine Barrington-Cook

COMPUTING & DATA MANAGMENT TEAM
Andreas Tziolas (Lead)
Pat Galea
Jardine Barrington-Cook

ENVIRONMENT CONTROL TEAM
Andy Presby (Lead)

GROUND STATION & MONITORING TEAM
Pat Galea (Lead)
Andreas Tziolas
Rob Swinney
Jardine Barrington-Cook

SCIENCE TEAM
Ian Crawford (Lead)
Kelvin Long
Richard Obousy
Andreas Tziolas
Jardine Barrington-Cook

INSTRUMENTS & PAYLOAD TEAM
Kelvin Long (Lead)
Richard Obousy
Ian Crawford
Andreas Tziolas
Richard Osborne

MECHANISMS TEAM
Phillip Reiss (Lead)
Kelvin Long
Adam Crowl

VEHICLE ASSEMBLY TEAM
Richard Osborne (Lead)
Andreas Hein

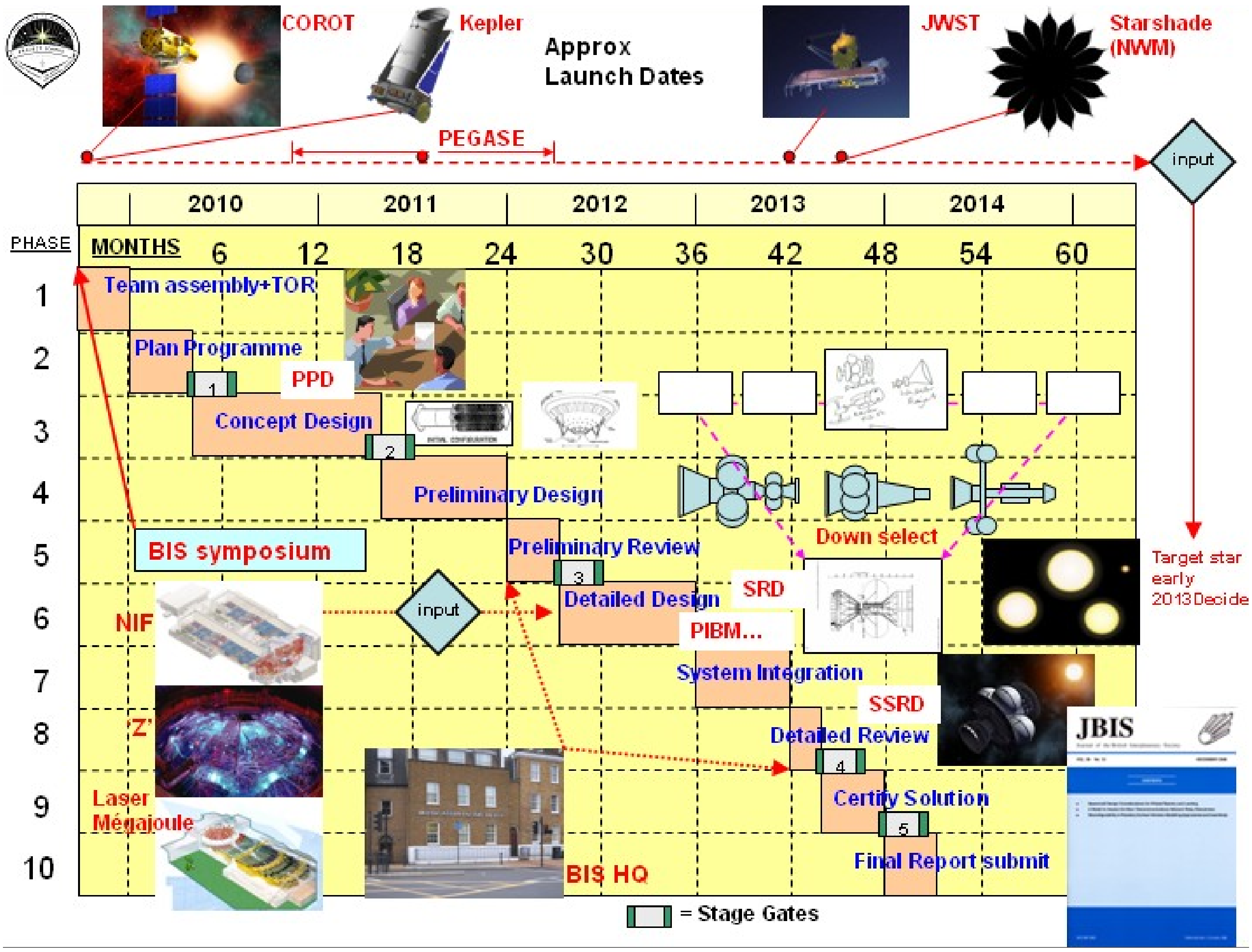
VEHICLE RISK & REPAIR TEAM
Andreas Tziolas (Lead)
Kelvin Long
Andy Presby
Phillip Reiss
Jardine Barrington-Cook

TECHNOLOGICAL MATURITY TEAM
Andreas Hein (Lead)
Kelvin Long

DESIGN CERTIFICATION TEAM
Kelvin Long (Lead)
Andreas Hein

8. DETAILED PLANS

In this section we describe the detailed plans for each phase with chart figures and timelines and major milestones. The programme plans for Project Icarus are shown in the figure below. This includes the ten key phases split over 54 months of the project and leads through three major design iterations: Concept Design, Preliminary Design and Detailed Design. Down selection then leads to final design solution and publication of the final Project Icarus study papers. Each phase is explained in detail below.



PHASE 1 TEAM ASSEMBLY & DEFINITION OF TERMS OF REFERENCE (up to end of 2009).

This is the phase that has been completed and continued until the end of 2009. TOR was frozen after the September symposium. Essentially, the TOR forms the project requirements and for Project Icarus these are currently qualitative in origin. By the end of this phase all members of the Project Icarus Study Group would have completed a preliminary reading of the Daedalus Study Group Report.

Key Phase Deliverable: Internal publication of ToR & team assembly. End of December 2009.

Note by authors: The team has successfully completed Phase I described above.

PHASE 2 CONSTRUCTION OF WORK PROGRAMME (up to spring 2010).
Once the team is fully assembled, agreement was to be reached on who is researching what areas of Icarus. This includes a discussion of the TOR and what constraints these place on our design space (e.g. what stars can be reached at what speed? what possible laser driver options exist? …). One of the team's initial tasks will be to translate the TOR into quantitative system requirements where possible (e.g. mass, size, speeds…) and at the system level (e.g. propulsion) with upper and lower design bounds. This covers both mission and lifetime requirements. This also involves the identification of critical design features (e.g. laser driver) and external design drivers (e.g. astronomical discoveries, fusion breakthroughs..) that may occur during the Project Icarus design. Design/mission constraints are also to be identified where possible. The system requirements and programme plans once agreed are recorded in this PPD. All agreed work will be non-specific (i.e. studying potential for use of antimatter catalysed fusion). Additional studies not identified in the initial programme plans will also be permitted, although the primary objective of team members is to fulfil their research obligations as agreed. The completion of this phase will mark the entrance through the 1st Stage Gate provided all criteria are met.
Key Phase Deliverable: Internal publication of PPD. End of April 2010.

Stage Gate 1 Criteria: Team has been assembled; TOR has been adequately translated into PPD; description of PPD. Outputs: Determination of conceptual design programme among Team Icarus to meet next Stage Gate delivery.

Note by authors: The publication of this PPD report marks the successful completion of Phase II described above.

PHASE 3 WORK PROGRAMME CONCEPTUAL DESIGN (spring 2010 to spring 2011).
This will consist of many trade studies and reviews exploring the different technologies available, all designed to meet the requirements. These are described in section 9. The analysis should largely be performed at an approximate level. This will be a largely unfocussed phase and team members can publish reports at their leisure on the work they are doing, within their allocated research areas. Additional studies outside of allocated research areas may also be completed as desired, but should not overtake the priority of core research. However, all studies should have the aim of cycling their design analysis until a solution is derived that appears to meet the requirements. This will minimise the work later on. As each piece of work is completed, the conclusions of this study should feed the configuration and layout for the Icarus design or mission profile. This means that each study should be accompanied by either an externally or internally published report with clear conclusions/recommendations from the work and appropriate references. This phase should also include an examination of other space architectures such as for Vista and Longshot. Ideally, the Journal of the British Interplanetary Society (JBIS) will be the submission choice for the majority of the externally published papers, although other Journals will also be

acceptable if an author wishes to do so. During this phase effort should also be made to employ the use of a requirements management tool such as DOORs or RAPSODY which can then be used in all future design work. The completion of this phase will mark the entrance through the 2nd Stage Gate provided all criteria are met.
Key Phase Deliverable: Published set of papers exploring concept design options. End of April 2011.

Stage Gate 2 Criteria: Large body of research published internally/externally which demonstrates that the majority of the Daedalus/Icarus systems have been scoped. Adequate team appraisal of Daedalus design and alternatives.
Outputs: Determination of preliminary design work among Team Icarus to reach the next Stage Gate delivery. The PL should construct a programme plan for the next phase of work in collaboration with the incumbent PL, if it is to change.

PHASE 4 WORK PROGRAMME PRELIMINARY DESIGN (spring 2011 up to end of 2011).

These will be more focused studies looking at different aspects of the design options for possible inclusion. Again, members can publish at their leisure but mainly within agreed research areas. By the end of this phase several options for the Icarus design will begin to emerge, although no final down select will yet be performed. The various options will be described and debated for consideration. Discriminators and morphology tables may be used to define the advantages and disadvantages of the different options. Initial drawing layouts in the form of sketches will be produced to illustrate the various options. It is suggested that around 5 design configuration options would be appropriate, perhaps with sub-options (e.g. different fuels). These should be called Option A, B, C….with sub-options A1, A2….continuing. All design option layouts should be controlled and co-ordinated by the person responsible for Module 3.0 Vehicle Configuration in collaboration with the current Project Lead. Basic technical drawing layouts for each option should be created along with a basic description of the systems and components.

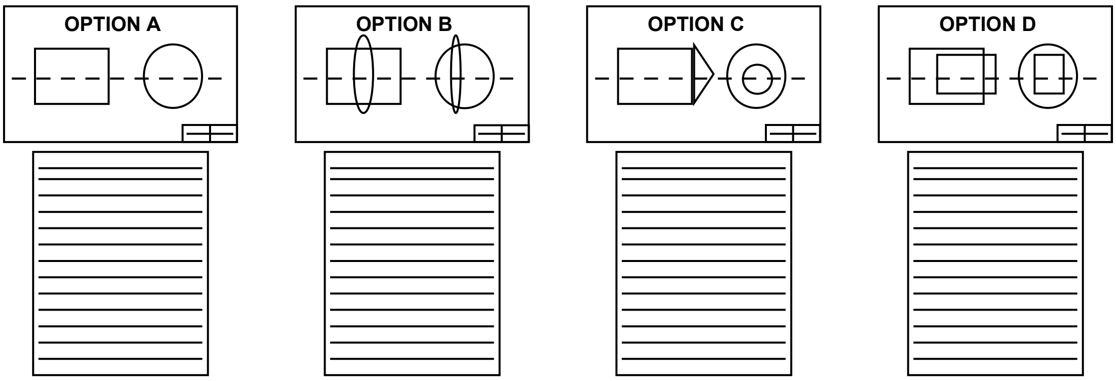


Illustration of several down selected option layouts & specifications.

Each of the options (and sub-options) should be formed by going through each of the research modules and spacecraft systems and listing them, i.e. for solar system escape one may list the following options:

1. 1st Stage main engine burn
2. 2-burn escape manoeuvre
3. Solar sail assist.
4. Laser beam assist
5. Chemical + nuclear electric
6. External nuclear pulse (Orion).

Key Phase Deliverable: Published set of papers exploring preliminary design options. End of December 2011.

PHASE 5 PRELIMINARY DESIGN REVIEW (early 2012).

This will be the first opportunity for the Design Review Panel (Daedalus study group) to scrutinise our work and this would be done at a pre-arranged meeting at BIS HQ, with several short presentations being given over one day. This will ideally take place between January-March 2012 subject to the availability of panel members. The review panel would then be required to give constructive feedback on our progress, and summarise how they think we are doing towards meeting the requirements. Their recommendations will be considered in accordance with the definitions described in section 4 (Level 1-3 action). This could be an open session or a closed session (to be debated). For those members who cannot make the review, slide contributions can be submitted and presented on their behalf by other team members. The completion of this phase will mark the entrance through the 3rd Stage Gate provided all criteria are met. The defined actions and responses should be written up in meeting minutes by the PL or designated secretary. This will be published internally.
Key Phase Deliverable: Pass preliminary design review and complete actions as appropriate. January - March 2012.

Stage Gate 3 Criteria: Completion of preliminary design work and the identification of several credible options for the Icarus design. Appropriate presentation of research and design options at Preliminary Design Review. Completion of additional actions as determined by Design Review Panel. Outputs: Determination of final detailed design and system integration work programme among Team to meet next Stage Gate delivery. The work programme for the next phase should be written up by the current PL, in collaboration with the next PL if it is to change.

PHASE 6 WORK PROGRAMME DOWN SELECT TO DETAILED DESIGN OPTIONS (early 2012 - end of 2012).

Using input from design review panel and carrying out further research and calculations where required, the team will then move towards the down select of a final design solution for Icarus. This represents the product design realisation. The down selection process may be performed in stages. Technical drawing layouts will be constructed according to British Standards 308 to show the design configuration. At some point, most aspects of the design will become frozen and the team will conduct more detailed studies. The progress and defined technologies to date will be recorded in a System Requirements Document (SRD).

The down select will depend upon data from historical (i.e. JET), existing and shortly starting fusion research facilities. This includes the US National Ignition Facility, US Z-Machine and the French Laser MegaJoule. This way, our decision process will be based upon the most up to date technological advances in fusion.

Similarly, data from existing and upcoming ground based and space based telescopes will also be used to feed the decision into the target star system. This may include the Kepler telescope (launched 2009), CoRoT (launched 2006), James Webb Space Telescope (planned launch 2014), PEGASE (planned launch 2010-2012) and the New Worlds Mission Starshade (currently in the planning stages). Although some of these could be too late to feed Project Icarus decisions, as with several others that are planned such as the Terrestrial Planet Finder (no launch date specified). Conventional fusion research and modern astronomical observations will therefore form an input into the design of the Icarus configuration and mission profile. A decision on the choice of target star and other candidates should be made in early 2013.

It is expected that the down selected design configuration will evolve through several versions as calculations are refined and more work is performed. To record this progress and maintain consistency with evolving calculations, different versions will be generated within a system model spreadsheet program (controlled by Module 3.0 Vehicle Configuration by a designated systems engineer) that is available to all members of the team to provide data on the current design layout and allow all calculations to be linked. This will have the title 'Project Icarus Baseline Model' (PIBM), with the different versions recorded consecutively as follows: PIBMv1.0, PIBMv2.0, PIBMv3.0…… On occasions, where minor updates to calculations are made, sub-versions may also be defined (i.e. PIBMV3.2). This way, the evolving layout will be clearly recorded for designers use. Each version release will be agreed upon by the 'Core Design Team', and that will then become the updated design configuration, upon which further calculations should ideally be based. The PIBM will be defined in the International System of Units otherwise known as *Systéme International* (kg, m, s, K) and constants will also be listed for all subsequent calculations[2]. Configuration management will be required to ensure that any releases are communicated to the team and maintain consistency with the requirements. Towards the end of Phase 6 the first attempts should be made to perform some basic level of system integration (system integration iteration 1). The aim of this phase is to achieve an advanced Bronze design configuration.

Key Phase Deliverable: Down select to PIBM and internal publication of SRD. Perform an initial attempt at system level integration. End of December 2012.

[2] Prior to this, designers are free to use their units of choice and constants to chosen accuracy.

PHASE 7 WORK PROGRAMME SYSTEM INTEGRATION (end of 2012 - summer 2013).

This will be more detailed design calculations converging towards an optimised design. Discussions will be required in advance to determine which performance parameters the design is to be optimized towards although some of these will be pre-determined by the requirements (e.g. minimal fight time). Emphasis will be placed upon the sub-system design, as determined by sub-system requirements (translated from system requirements). This will also include further consideration for system (system integration iteration 2) and sub-system integration throughout this phase with appropriate system interface description. The system integration should be performed early in this phase followed by several iterations of the sub-system integration (sub-systems integration iteration 1-3). Several are required to identify inconsistencies in the design from each research module. All of this will be recorded in a Sub-System Requirements Document (SSRD) published internally to the team. Detailed technical drawings will be required for presentation in the subsequent phase. The aim of this phase is to move the design through a silver design configuration and eventually into a gold configuration layout.

Key Phase Deliverable: Integrated PIBM and internal publication of SSRD. System and sub-system integration performed. End of June 2013.

PHASE 8 DETAILED DESIGN REVIEW (Summer 2013).

This will be a final opportunity for the review panel (Daedalus team) to assess our work constructively. Their comments will be used to tidy up any loose ends should they be required (e.g. additional calculations). All defined actions and the response should be recorded in minutes of the meeting by the current PL or designated secretary. The completion of this phase will mark the entrance through the 4th Stage Gate provided all criteria are met.

Key Phase Deliverable: Pass detailed design review and complete actions as appropriate. June – August 2013.

Stage Gate 4 Criteria: Down select to final design. Adequate system Integration. Generation of SRD/SSRD. Matured definition of PIBM. Appropriate presentation of research and design at Detailed Design Review. Completion of additional actions as determined by Design Review Panel. Outputs: Assignment of certification scope and final report assignments to team Members for completion and delivery, as determined by the PL.

PHASE 9 CERTIFICATION OF THEORETICAL DESIGN SOLUTION (summer 2013 - end of 2013).

This will involve a team assessment that we have met the original terms of reference and also consideration of the development programme and technological milestones required to make Icarus happen. This assessment will be performed by the Project Icarus Study Group and not the Daedalus Design Review Panel. It is our own assessment of our work. We will also be required to assess the technology proposed for the Icarus design, against the requirements (i.e. have we met our project requirement)? We will also be required to assess the maturity of the proposed technology and how it compares to the Daedalus design. This will be achieved by applying

Technology Readiness Levels[3] [30] and Icarus will be measured between TRL1-9. Finally, we will be required to describe the following: system performance specification and functionality, reliability and risks in the design (i.e. failure modes and associated probability of failure) and our mitigation, life-time performance (launch to end), design margins, redundancy and the identification of outstanding issues for further research. We should also describe the technological roadmap for increasing an Icarus-like design to full flight maturity. Hopefully, we have allowed for these factors in the design. Some post-design analysis should be conducted to ensure that all systems and sub-systems are verified (i.e. meet the requirements). All of the certification work will be recorded in an internally published document the Icarus Certification Document (ICD). The completion of this phase will mark the entrance through the 5th Stage Gate provided all criteria are met.
Key Phase Deliverable: Internal publication of ICD and Icarus design certification. End of December 2013.

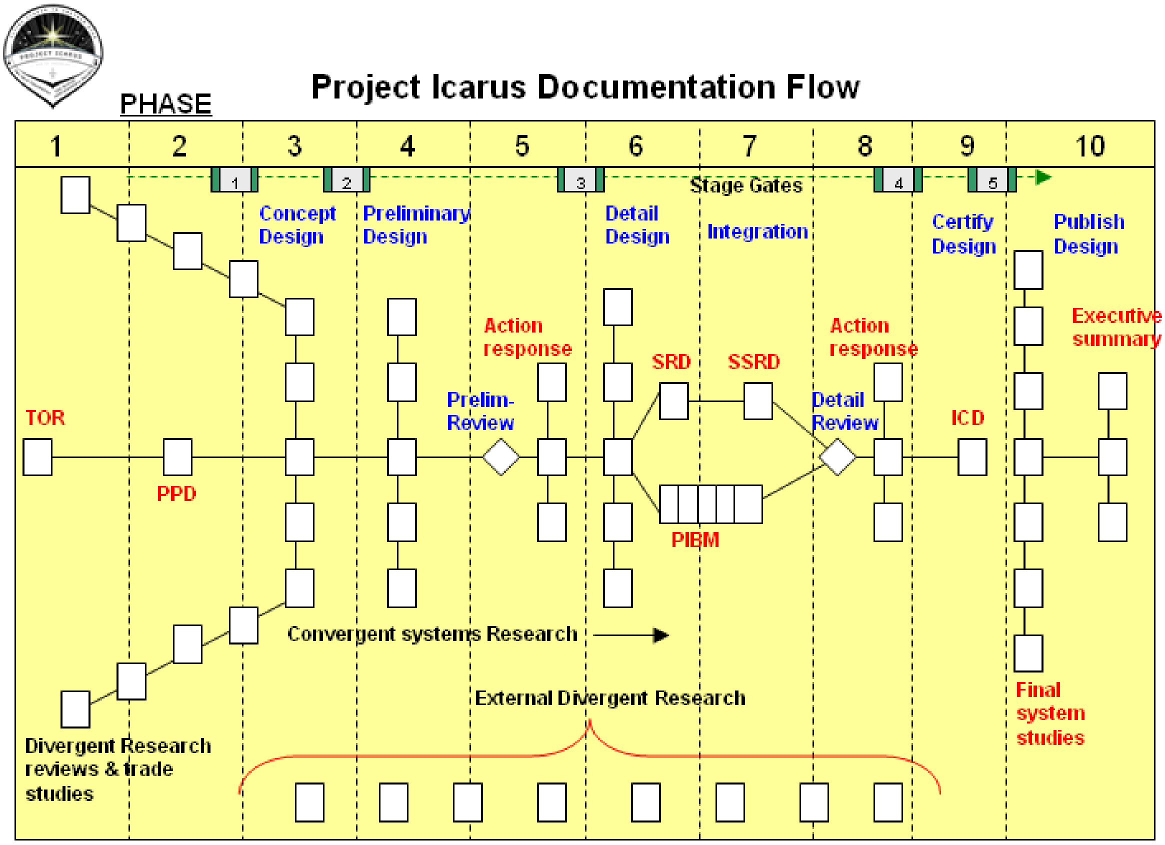
Stage Gate 5 Criteria: Completion of Certification scope, technology maturity measurement and technological roadmap. Outputs: Determination of final publication programme and eventual demonstration of Project Icarus design.

PHASE 10 PUBLICATION OF FINAL DESIGN SOLUTION (submit early 2014).

This delivery of the final Icarus reports in JBIS will be the end of this project for the team and an opportunity for the wider world to scrutinise our work. All final reports will need to be co-ordinated and could be short, referring- to earlier published work (possibly several dozen reports over the few years, see below). But the ambition is to produce perhaps two dozen or so reports detailing the final design of Icarus (named authors only) along with several final executive summary reports in JBIS detailing the whole of the design and mission profile (co-authored and approved by all of the Project Icarus Study Group). In essence, the publication of the executive summary reports represents the key Deliverable for Project Icarus and all other work published will be referenced within. In one of the reports, detailed drawings of the design layout should be included, as well as 3D models. The publication of the final Project Icarus papers should coincide with delivery of a technical presentation by representative team members. Subsequent presentations may also be required at future conferences, Universities or Industry, where team members should participate whenever possible. Ideally, an actual demonstration model will also be built for these presentations[4].
Key Phase Deliverable: Submission and acceptance of Project Icarus final design reports. End of March 2014.

[3] TRL1=Basic principles observed and reported; TRL2=Technology concept and/or application formulated; TRL3=Analytical and experimental critical function and/or characteristic proof-of-concept; TRL4=Component and/or breadboard validation in laboratory environment; TRL5=Component and/or breadboard validation in relevant environment; TRL6=System/subsystem model or prototype demonstration in a relevant environment (ground or space); TRL7=System prototype demonstration in a space environment; TRL8=Actual system completed and 'flight qualified' through test and demonstration (ground or space); TRL9=Actual system 'flight proven' through successful mission operations.

[4] This could later be donated to either The British Interplanetary Society or The London Science Museum.



9. CONCEPT DESIGN PHASE 3 MAJOR TASKS

Starting at the beginning of May 2010 Project Icarus begins the Concept Design Phase 3. This will consist of several research reviews and trade studies all focussed on identifying design options for the future and the technological and scientific state of art. The following paragraphs describes the agreed milestone deliverables for each of the research module Leads that are to be achieved by the end of Phase 3.

Title: **Research Module 1.0 Astronomical Target**
Lead: Ian Crawford

Definition: The target system: including the primary and any secondary stars and any possible planets and belts of smaller bodies. The primary driver for the choice of target destination will be high science return: especially planetological and astrobiological data from the close up study of terrestrial planets or satellites.

Scope: Information concerning the known star systems within 15 light years will be gathered, assessed, and processed with a view to recommending several targets for the Icarus probe that appears reasonable within the context of present knowledge. The report produced for this module will be based on a table containing recent observational data for the stellar neighbourhood, plus derived parameters to fill in gaps or unknowns where needed. Each star in the table will be linked to a text section where the nature of the star and its astrophysical points of interest are described. Astrophysical and astrobiological arguments concerning each system will also be deployed to speculatively assess its potential for hosting a life-bearing planet. The output of this module will serve as a tool to assist team members in their decision to select a nominal target for Project Icarus, with the caveat that its recommendations can only be regarded as speculative. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (4) The spacecraft must be designed to allow for a variety of target stars.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to astronomical target. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 2.0 Mission Analysis & Performance**
Lead: Rob Adams

Definition: This includes a description of the mission profile and trajectory, along with vehicle boost periods, flight time, energy release, mass ratio, specific impulse and required vehicle performance (i.e. thrust) to achieve escape and eventual cruise velocity to the target.

Scope: This work should review several different options for the Icarus mission covering both the boost, cruise and deceleration phases. In particular, the options for gravity assist and the two-burn maneuver should be explored. Comparisons should be made to the Daedalus mission profile and various alternative mission profiles identified. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner (4) The spacecraft must be designed to allow for a variety of target stars (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to mission analysis and performance. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st March 2011

Title: **Research Module 3.0 Vehicle Configuration**
Lead: Kelvin Long

Definition: This includes a complete description of the vehicle layout with all dimensions and components defined. Orthographic projections will be required as well as 3D models.

Scope: The total component and mass breakdown of the Daedalus vehicle should be compiled. Several engineering sketch options for alternative vehicle layouts within the existing Daedalus configuration should be explored. This is then to be extended to include potential modifications that could be made upon down select to the Icarus configuration, based upon some of the ideas already emerging. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus) (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to vehicle configuration. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 4.0 Primary Propulsion**
Lead: Richard Obousy

The primary propulsion module will cover all aspects of the Icarus vehicle acceleration. Major areas of study will include confirmation that ICF pulse fusion is the most effective fusion propulsion mechanism with comparison studies against magnetic, IEC and the Marx generator systems. In addition, a determination of the optimum driver will be performed with a focus on lasers, ion and electron drivers. A study of exotic drivers will also be performed, for example di-positronium lasers and wakefield accelerators. Another important research feature for primary propulsion will be the possible capsule designs for any ICF system with relevant simulations. A detailed study of antimatter catalysed fusion will be performed, and its utility, integration and possible optimising effects on fusion propulsion. Studies will also be performed on the recent suggestion that an ultra-dense form of Deuterium exists, and the validity of this claim will be determined. If this should be true then this will have significant repercussions on the Icarus design. A study of the efficacy of the Oberth 2 burn manoeuvre will be performed, including a parametric study on the specific impulse, specific power and mission time vs. interstellar escape velocity. A study of engine components will also be performed including a study of the chambers, valves, tanks and nozzles. Finally, a study of the field coils will be undertaken as well as research into possible methods designed to bootstrap the electromagnetic current generated by nuclear pulse to run subsequent ignition cycles.

Scope: A major exploration of fusion based propulsion will be explored beginning with a study of the original Daedalus design and a determination of areas where technology has advanced such that the original design can be improved and/or optimized. Areas of focus include ignition systems, field coil arrangements and nuclear pulse current bootstrapping, the utility of antimatter catalysed fusion and an analysis of exotic drivers, for example x-ray lasers and Wakefield accelerators. For each component, the expected performance will be analysed and options for performance gain will be identified. An exhaustive study of current fusion systems will be performed along with possible alternatives to the pulsed fusion concept (the Polywell for example). In addition, the Oberth 2 burn manoeuvre will also be studies in an effort to optimize Δv. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner(5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus) (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to primary propulsion. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 5.0 Secondary Propulsion**
Lead: Andreas Tziolas

Definition: Secondary propulsion systems are all supplementary propulsion methods appropriate to interstellar missions. This includes any backup propulsion systems which have the main function of accelerating the vehicle to a higher velocity. This may also include redundant attitude and control methods and in general any auxiliary propulsion systems which have the main function of orbital thrusting and control.

Scope: A review will be conducted into various options for supplementary boost mechanisms and orbital/trajectory correction systems. Contemporary as well as near-future and innovative thrusters used in modern spacecraft are eligible. Inclusive in this study are the particular features of the fuel method used by the propulsion device and its usefulness within the scope of interstellar mission timelines. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to secondary propulsion. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 6.0 Fuel & Fuel Acquisition**
Lead: Adam Crowl

Definition: This includes what fuels are used for the primary and secondary propulsion as well as the availability and acquisition of those fuels (i.e. from Jupiter atmosphere) and an assessment of the technology and infrastructure required to obtain them. Fuel storage issues, during boost-phase, cruise and braking phases should also be considered.

Scope: During this work many options for fusion based fuels should be identified. Acquisition and mining techniques should also be discussed. These should include novel fuels such as ultradense Deuterium or antiprotons and their storage. Recommendations for several preferred fuel and mining options should be made. Possibility for refuelling in the target system and the minimum requirements for useful ISRU should be examined. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner(5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to fuel and fuel acquisition. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 7.0 Structures & Materials**
Lead: Adam Crowl

Definition: This includes a description of all of the materials used in the vehicle, their mechanical properties and response to the exposed internal and external environment (i.e. pressure). Some consideration should be given to the manufacture of novel materials and the in-situ acquisition and manufacture of replacement materials by the probe.

Scope: A thorough review of historical, modern and future materials technologies should be conducted. The requirements for deep space missions of decades long duration should be identified. Several candidate materials for the different structures used in the Daedalus configuration should be given. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined(5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to structures and materials. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 8.0 Power Systems**
Lead: Andy Presby

Definition: This includes the design of any electrical systems on board including power generation, storage, management, distribution and control. This module could also include a discussion of electromagnetic compatibility engineering.

Scope: A review is to be conducted into the various types of power systems there are that could be used in an Icarus type mission. This review is to include space nuclear reactor technology. A review should also be conducted into what historical and modern spacecraft use for power supply. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to power systems. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 9.0 Communications & Telemetry**
Lead: Pat Galea

Definition: This includes transponders, antennas and equipment for signal production, amplification and transmission. Consideration should be given to transmitter bandwidth, range and power output requirements. Some work should also be done to address the issue of radio signal attenuation at long distances from ground control, and transmitter alignment with the receiving station.

Scope: A thorough review should be conducted into the technology to be used for interstellar space communications. This is to include the physical properties of radio propagation, associated technology and other potential transmission mechanisms such as lasers. The review should also consider bandwidth, data management requirements and accurate aiming of the transmitter as well as novel methods of assisting long distance communications such as by using relay stations or exploiting the gravitational lens of the Sun and/or the target star. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to communications and telemetry. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 10.0 Navigation & Guidance Control**
Lead: Rob Swinney

Definition: This includes vehicle attitude control and response and a considering of some of the technology that could be used for this purpose, linked with the secondary propulsion module.

Scope: A review should be conducted into the vehicle requirements for attitude control systems. This should include a review of Daedalus and potential changes identified based upon current or near future technology. The technology to be used for vehicle autonomous navigation should also be explored. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (4) The spacecraft must be designed to allow for a variety of target stars

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to navigation and guidance control. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 11.0 Computing & Data Management**
Lead: Andreas Tziolas

Definition: The computing needs appropriate to an interstellar mission are explored. Processing methods, processor architectures, information nodes, data storage, backup and analysis modules are reviewed. An essential aspect of this design, given the accelerated rate at which processing capabilities are escalating, is the error catching and command redundancy which must be applied. In addition, hardware/software issues are addressed, with a flexible code design which will allow for in-transit updates to be performed.

Scope: A review should be conducted into the current state of art in computing technology useful for space missions. This review should be extended to include linear extrapolation of near-future technology and artificial intelligence systems that could be employed. A distributive computing architecture relating to both the hardware and the software of this machine is envisioned, with supporting studies on this subject planned. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to computing and data management. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 12.0 Environment Control**
Lead: Andy Presby

Definition: This includes protection and environmental control of all systems from mission thermal, particle, and electromagnetic environment and likely exposures internally to thermal gradients and self generated electromagnetic fields.

Scope: A review should be conducted into the internal environment control requirements and associated technology. A review should also be conducted into the externally applied environmental factors. Requirements for environment control and mitigation should be identified. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (4) The spacecraft must be designed to allow for a variety of target stars (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus)

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to environment control. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 13.0 Ground Station & Monitoring**
Lead: Pat Galea

Definition: This includes consideration for long term monitoring of vehicle systems and observations, mission performance, as well as a capability to upload instructions for changes in mission parameters. The monitoring station could be earth based, space based or other.

Scope: A review should be conducted of ground based operations for use in monitoring and controlling historical deep space probes. The core facilities and requirements should then be scaled for an interstellar mission, or appropriate novel alternatives examined. Options for long distance control and monitoring should be explored. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to ground station and monitoring. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 14.0 Science**
Lead: Ian Crawford

Definition: This includes all of the necessary solar and planetary science that would be undertaken by the Icarus design. Consideration should be given to the potential for in flight science capture such as at Jupiter flyby or the Kuiper belt, measurements at the solar terminal shock layer, addressing the Pioneer anomaly or optical measurements at the Focal Point. The determination of science data is a key driver for Project Icarus.

Scope: A review is to be conducted into the likely science drivers to motivate such a mission as Icarus. This should include reference to historical interplanetary probes. The core scientific returns of an interstellar mission should be identified and prioritised to inform the instrument technology that may be required. Consideration should also be given as the the type and number of different probes to be included assuming arrival at the target star and associated planets. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (4) The spacecraft must be designed to allow for a variety of target stars.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to mission science. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 15.0 Instruments & Payload**
Lead: Kelvin Long

Definition: This includes the design of any instruments required, including imaging technology. For minimisation of payload mass, the number of instruments may need to be minimised, but designed with high reliability. This module will also cover payload issues, where instruments are assigned payload status.

Scope: This should include a review of the types of instruments that could be used on an Icarus mission and linked with the key science drivers identified from the science module. Consideration should be given to the effect of different payload masses on the overall vehicle performance, assuming a Daedalus configuration. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (4) The spacecraft must be designed to allow for a variety of target stars (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to instruments and payload. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 16.0 Mechanisms**
Lead: Phillip Reiss

Definition: This includes mechanisms such as gyroscopes for guidance and control, robotic arms for external repair, any kind of deployable device such as aids for braking or solar energy conversion and thrust vectoring mechanisms. Consideration should be given to the components, their integration into the spacecraft and their mechanical properties.

Scope: A review is to be conducted into the types of mechanisms used on Daedalus and others that could be used on Icarus. This review should include references to historical spacecraft and consideration of novel technologies such as for robotic arm repairs or MagSail braking. The purpose, functionality and ideas for vehicle location for these different mechanisms should be identified. A stress on the long-term properties under the extreme conditions of an interstellar mission shall be made. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to vehicle mechanisms. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 17.0 Vehicle Assembly**
Lead: Richard Osborne

Definition: This includes a description of the likely assembly procedure for the Icarus vehicle, be it in orbit or on ground. If the vehicle is to be assembled in orbit, consideration should be given to what launch vehicles would be appropriate and how many are required.

Scope: Several options for the mission architecture should be defined, from vehicle manufacturing to assembly. This should include options based upon current state of the art technology as well as future technology based upon linear extrapolation only. Novel architecture options should also be discussed such as the use of a space elevator. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus) (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to astronomical target vehicle assembly. Any work should show a clear linkage to the original Daedalus design and the current ToR.

This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 18.0 Vehicle Risk & Repair**
Lead: Andreas Tziolas

Definition: This includes internal and external, such as from micrometeoroid or dust impact hazards, radiation shielding from high energy particles generated in nuclear fuel reactions, space environment. Protocols will be designed which describe deliverables from other modules/subsystems to be folded into a full scope risk and repair simulation. Methods for on board automated repair systems are included in these studies (e.g. wardens, robotic arms, etc).

Scope: A review should be conducted into the potential failure modes of the Icarus mission. A preliminary reliability analysis for a Daedalus-like mission should be performed. This requires the identification and review of both internal and external risks to the mission. The technology that could be used to mitigate these risks should be discussed. A failure-rate-analysis simulation will be designed, with early code written, which can be used to validate changes to other modules as they emerge. The range of robotic hardware which can be used for on-board repair will also be reviewed. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (4) The spacecraft must be designed to allow for a variety of target stars (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to vehicle risk and repair. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Title: **Research Module 19.0 Design Realisation & Technological Maturity**
Lead: Andreas Hein

Definition: This describes the key steps to achieving the assembly and launch of the Icarus vehicle and may or may not have associated timescales. The technological maturity of the Icarus design should be 'measured'.

Scope: This review should link into the mission architecture assessments and discuss the technologies and associated fruition timescale to enable such as architectures. Considerations for different technological roadmaps to attain these different architectures should also be discussed. From this study several potential dates for the mission assembly and launch should be identified. Consideration should also be given to how the technological readiness of Daedalus-Icarus type propulsion systems can be measured near the end of the project. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to design realisation and technological maturity. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

Title: **Research Module 20.0 Design Certification**
Lead: Kelvin Long

Definition: This includes the qualification that the theoretical design is based upon sounds principles of science and will work in principle. Relevant failure modes are to be considered such as margin, redundancy, reliability of technology. Because Icarus would be a deep space long duration mission, it is likely that larger performance margins will be required to minimise system failures.

Scope: This initial work should consider the different ways that the final design solution can be certified as having met the initial engineering requirements (ToR) and that a credible engineering solution has been produced. Specific research topics for the concept design phase are described in the Appendix.

ToR Relevance: (1) To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium (2) The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined (3) The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner (4) The spacecraft must be designed to allow for a variety of target stars (5) The spacecraft propulsion must be mainly fusion based (i.e. Daedalus) (6) The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination.

Deliverable: Internal &/or externally published report(s) covering the agreed scope relevant to design certification. Any work should show a clear linkage to the original Daedalus design and the current ToR. This should specify clear conclusions & recommendations on options for the future with appropriate evidence and references. Consistency with the Project Icarus design philosophy should be observed.

Due Date: 31st April 2011

10. STRATEGY & DESIGN PHILOSOPHY

In this section we briefly describe the philosophy to be adopted in creating the Icarus design. The most important tool at the designer's disposal is analytical physics. This allows one to estimate performance effects from simple 'number crunching'. Given the limitations of the team's capacity and resources, heavy reliance on analytical tools will be employed. However, all designers should make the major assumptions used in their analyses clear. For the nominal configuration and performance, this represents the best estimate calculation that can be performed within the constraints detailed. Due to the assumptions made an uncertainty will be associated with all answers, which is difficult to estimate, e.g. $\Delta V=10{,}000 kms^{-1} \pm 10\%$, or the number density of Hydrogen in interstellar space is n=20 atoms.cm^{-3} to within an uncertainty of $\pm 2\sigma$ (standard deviation). Where designers feel that it is appropriate to state such uncertainties then they should do so, but would have to consider the addition effect of multiple uncertainties in a problem and indeed distinguish between systematic and random uncertainties, particularly in relation to observations. However, this could be a laborious process.

Instead, it is suggested that designers rely upon a second calculation set, which we shall call a 'worst case' calculation. Such an approach was adopted to underwrite the landing gears of the Apollo Lunar Lander [31], where details of the surface properties and landing speed, angle were unknown. Such an approach, if sufficiently conservative should allow for a pessimistic calculation in the design parameter being studied. Consideration should also be given to the effect of accumulated uncertainties and so the effect of multiple worst case scenarios could be examined. We shall call this an 'accumulated worst case' calculation. It is expected that the level of scientific assessment for the design will be to a similar level of detail as that of the Daedalus design.

In accordance with the need to develop a 'worst case' analysis of the vehicle performance, it is also constructive to develop a performance margin which can be defined as follows: "**The difference between the worst case engineering performance that meets the mission requirements and the lower bound uncertainty on the nominal engineering performance throughout the mission**". This will be adopted for all engineering systems. The nominal performance will always be greater than the worst case performance and the worst case performance should not result in the mission failure to high probability. We are led to the first philosophy to be adopted by the design team:

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.

There are also several key watchwords for Project Icarus to ensure that all design solutions are appropriate. The final design must be a CREDIBLE proposal and not based upon speculative physics. It must be a PRACTICAL design. It must be derived using accepted natural laws and using SCIENTIFIC methods which are supported by experiments. It must be based upon only NEAR-FUTURE technology as determined by simple linear extrapolation of current technologies. The team must produce an ENGINEERED design as though the vehicle were close to flight readiness, to ensure that approximations and margins are appropriate. There is also the addition of a RELIABILITY watchword, to ensure that both en-route and upon arrival all of the scientific instruments and spacecraft systems will function, and it is to be assumed that this implies redundancy. The watchwords are captured within the next design philosophy:

Design Philosophy 2: The designer shall solve problems and produce work output in the spirit of the project watchwords.

Project Icarus has two big observational dependencies over the duration of the project. This includes observations of exo-solar planets as provided by telescopes such as Kepler and CoRoT. Any new information on the discovery of planets within 15 light years will have a radical effect on the design solution. E.g. if an earth like world is located within this distance then it is likely that such a destination would become the mission target for the Icarus probe. Similarly, there are a number of experiments going on in the fusion physics field at this time. Particularly in the fields of inertial confinement fusion (NIF), Magnetic confinement fusion (JET) and Z-Pinch inertial confinement (Z-facility). These facilities are all operational and any physics discoveries or technological inventions associated with these will have an effect on the Icarus design. Any data is to be exploited where possible and this is reflected in an explicit design philosophy:

Design Philosophy 3: The designer shall remain well informed with current scientific and technological developments which may impact the Icarus design and mission.

The use of modern technology will form a key part of the Icarus design solution. However, if the technology is limited to ‘current’ then the design will rapidly becoming outdated. Given that an Icarus like probe would not be launched for at least many decades, it is appropriate to speculate about future technologies. However, if the design is limited to only ‘near-future’ technology then the configuration will be highly speculative. It is necessary to ground the design in what we know today for the sake of technological accuracy. As a result of this speculation the final design could end up being a mix of modern technology and near future technology. Project Daedalus allowed for such extrapolations into the future as a major design philosophy but it is worth noting that this did lead to some contradictions in the design. The final

Daedalus study reports discuss a time frame of 30-40 years as being appropriate for any extrapolations of current technology. After this time the uncertainty in any extrapolations will become large. With this in mind, Project Icarus will look at far future technology such as in the year 2100, but in general the final design solution and mission profile should be based upon linear and not exponential (e.g. technological singularities) extrapolations of current technology, where nearness to current technology is preferred. This is indicated by the design philosophy:

Design Philosophy 4: Extrapolations of current technology is to be of a linear type only and limited to a few decades hence.

The final Icarus design could be very similar to Daedalus (shown below) or very different. There are two main approaches to proceed with the design evolution. Firstly, the team could start from a new baseline and upon completion of the fundamental trade studies and literature reviews, put together a completely new vehicle configuration and mission profile. This would be a difficult approach to proceed from, given the volunteer nature of the team and the limited resources. Alternatively, the team could start from the Daedalus configuration (illustrated below) and then consider perturbations of the engineering layout and mission profile then from this re-derive a new design. This would be the easiest approach and is the one suggested to be adopted by the team. In this way our baseline is already established to allow calculations to begin immediately. This approach is indicated by the next design philosophy:

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 optimised configuration.

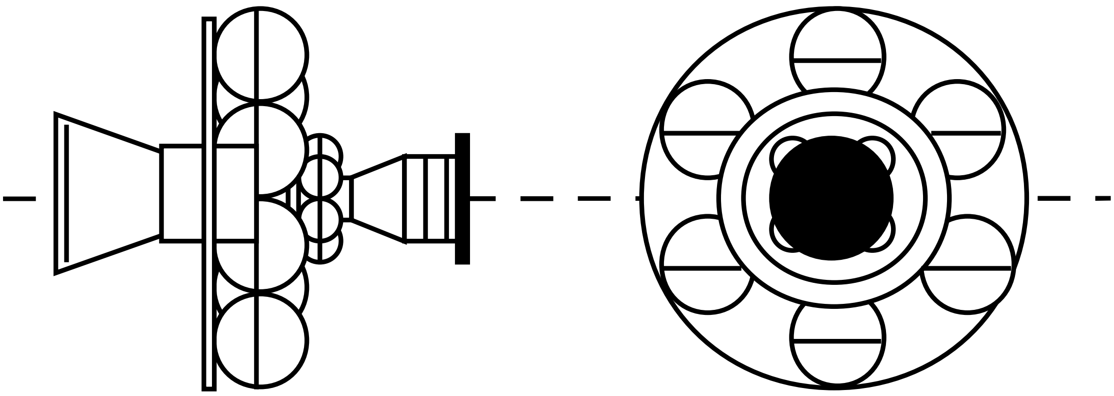


Illustration of Daedalus configuration layout.

Designers will also be tempted to make the Icarus design ‘appear pretty’ and invoke non-useful design features which only add mass to the vehicle configuration. This behaviour is to be avoided where possible and designers should derive the vehicle configuration solely from the engineering and physics calculations. If there is no clear performance or mission benefit to the addition of the design feature, then it should not be included. A design philosophy acts as a constant reminder to attempt to derive solutions from the engineering principles alone:

<u>Design Philosophy 6</u>: The vehicle configuration is to be derived solely from engineering and physics calculations where possible.

With the excitement of exo-solar planet discoveries the team will be tempted to choose a mission target early. There will also be pressure from science planners on the team to choose a target. The selection of a target certainly makes the engineering calculations easier. However, with the pace of astronomical discoveries this decision would be premature. It is advised that designers wait until late in the project to select the target star destination, so as to get maximum benefit from any discoveries being made. Project Daedalus suffered from this because the belief of planets in orbit around Barnard's star was later shown to be erroneous [8]. A design philosophy acts as a reminder to resist the temptation to select a target early in the project:

<u>Design Philosophy 7</u>: The team is to maintain an open-door mission policy for as long as is appropriate during the study.

Since the publication of works by authors like Eric Drexler, the subject of nano-technology has become increasingly important as it is realised that this technology has potential applications in all walks of life. With this in mind, it would be reasonable to expect that some aspects of an interstellar probe design may be constructed using nano-technology. This will be considered in some respects within the materials research module; however, it is accepted that this is such a big subject matter that all designers should be considering the applications to their research areas. For this reason nano-technology is incorporated as a design philosophy:

<u>Design Philosophy 8</u>: All designers will keep a weather eye on the potential application of nano-technology for use in their respective systems or sub-systems.

11. EVOLUTION OF DESIGN SOLUTION

It is useful to consider the philosophical approach to deriving the final Icarus design solution. It is proposed that for Icarus a design approach is put into place to evolve the design solution. There are two ways to approach this.

1. To realise several key features of the new design (e.g. MagSail, booms, reactors) and then throw them together in a systematic way until something emerges that looks like a credible engineering design. Then perform optimisation studies.
2. To start with the Daedalus design as a template and then any new features/modification can be added onto the Daedalus design. Similarly, any unnecessary features can be removed from the Daedalus design. Then perform optimisation studies.

The disadvantage with both approaches is that we are starting with a design that may not be an optimal solution for the particular mission derived. So optimisation will be from first principles analysis. For Project Icarus, it is proposed that approach 2 is adopted throughout the concept design phase and possibly for much of the preliminary design phase. However, by the latter half of the preliminary design phase it will be necessary to re-optimise the design until a credible engineering solution emerges forming the Project Icarus Baseline Model (PIBM). In order to begin the design process an assumption of Daedalus design to start may also require an assumption of identical mission (e.g. Barnard's star) in order to progress the design.

Starting the design process from the Daedalus design would also make for an easier job for the team in that there are two potential outcome extremes to the Project Icarus design process (a) minimal re-design is completed, resulting from either a lack of team effort or a conclusion that the Daedalus design is broadly accurate and highly optimised for the stated mission, or a combination thereof. This would represent an Option 1.0 design path. (b) Maximum re-design is completed, resulting from either an enormous amount of effort by the team or a conclusion that the Daedalus design is broadly inaccurate and not well optimised for the stated mission, or a combination thereof. The ambition of Project Icarus is to have maximum effort with a complete assessment of the engineering solutions and optimality. In the event that situation (a) occurs this will at least rescue the efforts of those in Team Icarus as having performed some useful work in having conducted a technical review of the Daedalus design. Hence starting from the Daedalus design and considering perturbations of the solution thereafter would appear to be a rational approach to evolving the design.

Assuming that the design configuration is to be derived from perturbations of the Daedalus baseline, it is then necessary to consider how the full design solution is to be evolved. As mentioned previously this is a gradual evolutionary process with the effect of each change considered but also should allow for revolutionary design ideas to be included. E.g. the discovery of ultra-dense Deuterium would be an important event worthy of a radical redesign.

As a detailed design configuration for the Icarus vehicle becomes apparent, it will be necessary to generate a Project Icarus Baseline Model (PIBM) which should be looked after by the Lead designer responsible for the vehicle configuration (currently by K.Long). Eventually, the PIBM will evolve through different versions (e.g. V1.0, V1.2, V1.3, V2.0…..) and should be accompanied by CAD models and spreadsheet models. The spreadsheet should include the component breakdown and linkage. All design calculations conducted by the team would then be clear with regards to what version of the baseline model had been used. For Project Icarus, designers will also need to define emergent performance properties upon which to optimise the design solution. Any optimisation process will involve a process of de-optimisation as a compromise is reached between various performance parameters. Options include; spacecraft speed; spacecraft specific impulse; spacecraft Thrust/Weight; spacecraft mass ratio. Such decisions will come under Research Module 20.0 Mission Analysis & Performance in collaboration with the Core Design Team.

Once the chosen design configuration is evolved sufficiently it will go through three main design quality levels. These are as follows:

Bronze design; Basic Concept definition: A single design configuration has been down selected based upon the scoping of various options covering all twenty research modules and all the Daedalus engineering systems. This configuration may not be fully optimal.

Silver design; Preliminary definition: an optimal configuration has been chosen with the majority of systems and sub-systems integrated. The expected performance of the design is initially defined.

Gold design; Detailed definition: A final configuration has been chosen with all systems and sub-systems integrated. The full performance of the design is defined. The Figure below illustrates the design evolution to be followed.

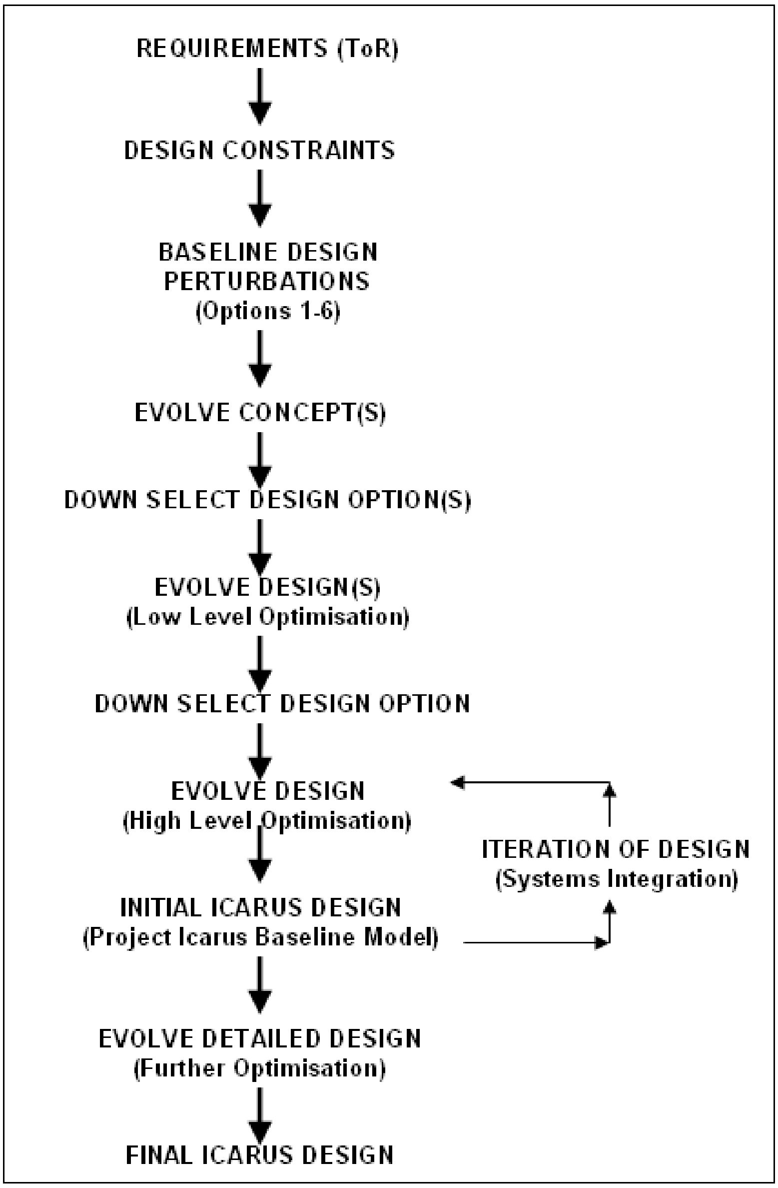
The final design solution may be very similar to Daedalus or could even be radically different. In between there are various system and sub-system attributes which can also be compared to the Daedalus design. These are defined in the range of Options 1 – 6 as shown in the table below. The characteristics will differ depending upon the system under study but the culmination of these different design solutions will lead to the pathways which allow the down selection to the final design.

In the event of a disagreement among the team on a design decision, the team will follow a defined resolution:

1. Formalise issue in the form of a question for debate.
2. Design team debates question with no agreed consensus or decision.
3. Design team asks opinion of Consultants.
4. Consultants respond.
5. Design team has a second debate with no agreed consensus or decision.
6. Team members vote on decision. This vote is limited to the Core Design Team only.
7. Majority vote carries and determines the design decision.

Option	Characteristics
1.0	Daedalus with improved calculations
2.0	Daedalus with minor subsystem changes
3.0	Daedalus with major system changes
4.0	New design with major system attributes to Daedalus
5.0	New design with minor subsystem attributes to Daedalus
6.0	New and radically different design

To date the discussions among the Project Icarus Study Group have already generated several possible design modifications to be explored. These need to be properly evaluated in an appropriate trade study with the aim of design improvement/efficiency or performance enhancement. The table below shows an example of the different sorts of configuration design options that may be derived labelled Options B – F. The boxes marked in grey background represent a credible design option forward as an example.



PROJECT ICARUS RESEARCH MODULES		OPTION A / DAEDALUS	OPTION B	OPTION C	OPTION D	OPTION E	OPTION F
1	Astronomical target	Barnard's star 5.9ly	Alpha Cent, 4.3ly	Tau Ceti	Epsilon Eridani, 10.7ly	Wolf 349, 7.6ly	Ross 154, 9.5ly
2	Mission analysis & performance	flyby, 50y	probe, 100 y	probe, 60y, magsail	probe, 100y	probe, 50y, rev-engine	flyby, 50y, Starwisps
3	Vehicle configuration	2-stage, 6+4 tanks, 54ktons	2-stage, 20ktons	3-stage, 54ktons	3-stage, 20ktons	4-stage, 54ktons	4-stage, 20ktons
4	Primary propulsion	ICF, e- laser, injectors, 250Hz	ICF-laser	MCF	ECF	antimatter ICF-laser	gamma-ray laser-ICF
5	Secondary propulsion	Nuclear ion	plasma drive	solar sail	laser beam	Hall thruster	chemical
6	Fuel & fuel acquisition	DHe3, Jupiter mining	DHe3, moon	B-p earth	DD, earth	DD, Oort cloud	DHe3, Uranus/Neptune
7	Structure & materials	Mol/Be, tri-spine, struts/ties	tub-spine, Mol/Be	geo-spine, Mol/Be	tri-spine, Ti	tri-spine, Fe	no spine
8	Power systems	reactor+induc loop capacitors	nuclear reactors	tethers	batteries	solar cells	charged capacitors
9	Communications & telemetry	radio/laser, 2nd stage antenna	grav lens antenna	5 relay stations	30 relay stations	follow-up probes	engine fairing antennas
10	Navigation & guidance control	5m scope, distant stars, coms	laser guided	advanced beacons	autonomus control	pulsars	multiple targets
11	Computing & data management	autonomous, adaptive	supercomputing	distributive platform	relay links	artificial intelligence	solar system-web
12	Environment control	shield cloud	micro-waves	fusion exhaust	HE charges	gamma-rays	x-rays
13	Ground station & monitoring	Project Cyclops antenna	lunar monitoring station	lunar orbit station	earth orbit station	Pluto station	grav lens point
14	Science	3 star + 15 planetary probes	1star + 17 planet	5star + 20 planet	10 star + 10 planet	2 star + 100 planet	50 star + 50 planet
15	Instruments & payload	probes, 5m scopes, inst, 450tons	30tons, probes, inst	50tons, probes, inst	100tons, probes, inst	10tonnes, probes, inst	300tons, probes, inst
16	Mechanisms	remote wardens	attached wardens	robotic arms	extendable booms	magsails	magnetic launch ramp
17	Vehicle assembly	rocket launch to LEO, build Callisto	SSTO to LEO, build	build lunar orbit	build on moon	build Lagrange point	Jupiter orbit
18	Vehicle risk & repair	wardens, Be shield, shield cloud	wardens, Pb shield	Be shield, shield cloud	Pb shield, laser beam	Be shield, laser beam	B field coil, laser beam
19	Design realisation & tech maturity	massive space infratructure	ISSv2-type infra	Mars colony	all inner s/system infra	lunar colony	all outer s/system infra
20	Design certification	reliability analysis only	ground experiments	cube-sat tests	exoplanet results	ignition at NIF	orbital flight trials

Meanwhile, some of the ideas discussed are listed below in no particular order. This demonstrates the variety of ideas that have been generated pre-concept design phase:

- Use of Di-Positronium laser for achieving ICF ignition.
- Use of Ultradense Deuterium.
- Adoption of distributed computing platform.
- Application of fault correction systems as used in Airbus A380.
- Use of artificial intelligence in autonomous vehicle control and decision making.
- Use of two-burn trajectory manoeuvre for solar system escape.
- Reverse engine burn for vehicle deceleration to target.
- Potential use of solar sail technology to (1) enhance part of the boost phase (2) enable vehicle deceleration via MagSail (3) use in sub-probes at destination.

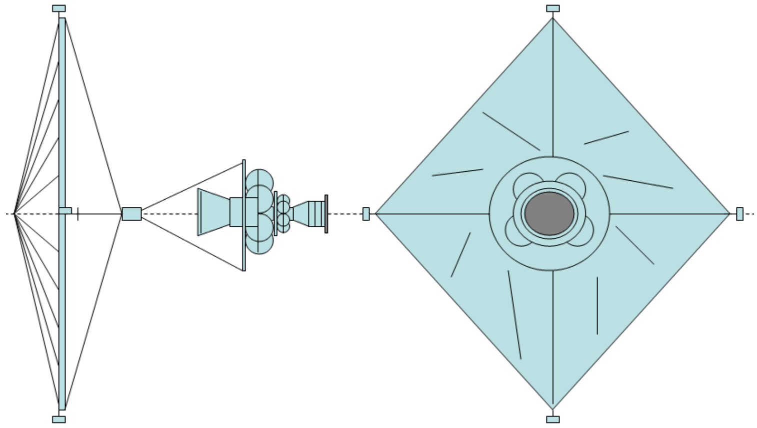


Illustration of solar sail propelled Daedalus for initial boost phase

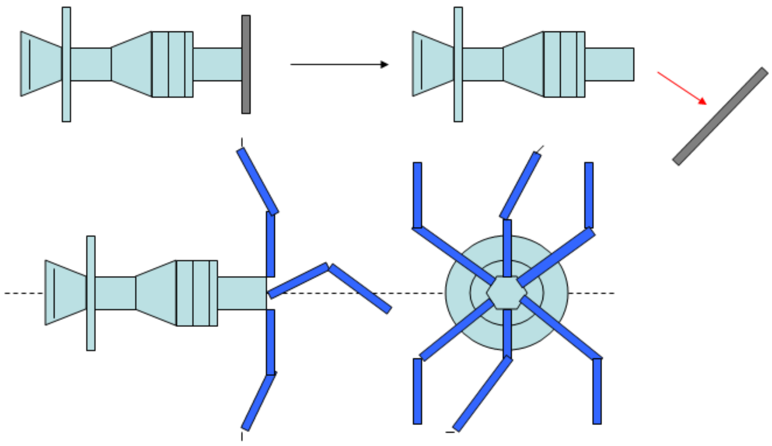


Illustration of MagSail deployment from Daedalus 2nd stage.

- Use of plasma-drive (VASIMR) engines to augment early boost phase.
- Application of fast ignition technique to achieve high energy gain for reduced driver requirements.
- Employment of different fusion ignition mechanisms such as magnetic fusion or electrostatic fusion.
- Use of dropped stages to act as antenna relay stations along route.

- Sending fuel supplies ahead of main vehicle for en-route re-fuelling. This could include fuel pellets accelerated along the trajectory which are then retrieved with a magnetic scoop.

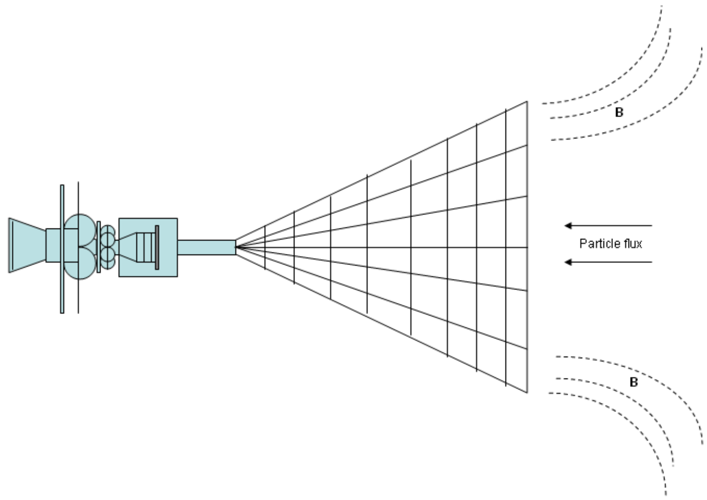


Illustration of magnetic Ramscoop attached to Daedalus 1st stage.

- Fuelling en-route (i.e. Deuterium in Oort cloud comets) or en-route at the target destination.
- Launch of decelerated sub-probes in target system whilst main vehicle remains in flyby mode.
- Use of directed long range energy beam to augment initial part of vehicle boost phase.
- Massive reduction in payload mass from 450tonnes, particularly due to electronic and computing advances.
- Use of anti-protons to catalyze fusion reactions.
- Use of Orion type external nuclear pulse propulsion to augment initial part of boost phase.
- Start of boost phase at edge of solar system, i.e. Pluto.
- Fuel mining of alternative gas giants of other sources such as particle generated reactions, lunar He3, solar wind, asteroids, comets or objects in the Oort cloud.
- Consideration given to alternative propellant combinations such as D/D, D/T and B/p of use in parts of the mission.
- Use of ISS/STS-type robotic arms for warden repair operations.

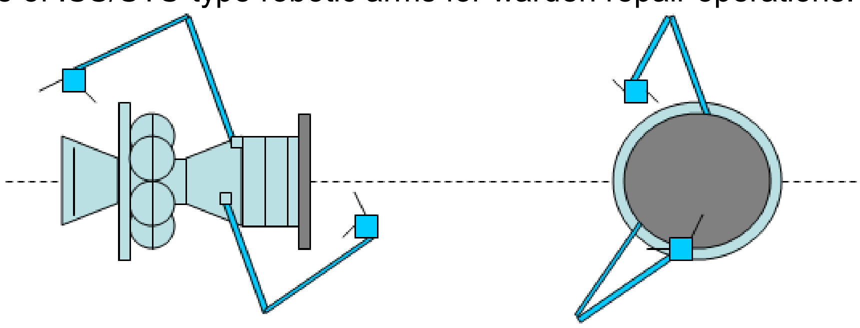


Illustration of robotic repair arms attached to Daedalus 2nd stage.

- Use of space tethers for power generation.
- Use of counter rotating flywheel pair for energy storage.
- Use of Radioactive Thermoelectric Generators (RTGs).
- Use of nuclear-electric engine to begin early orbital change manoeuvres.
- Use of laser as energy driver.
- Use of gamma-ray laser as energy driver.
- Use of precursor mission probes ahead of main vehicle to detect interstellar medium particle/dust density.
- Use of dropped satellites to act as communication relay stations and boost main vehicle signal.
- Use of gravitational lensing point to boost radio communications from main vehicle.
- Use of Single Stage to Orbit (SSTO) for delivery of mission architecture.
- Use of reverse engine thrust for main vehicle deceleration.
- Use of nano-materials in parts of main vehicle.
- Deployment of microwave decelerated Starwisp probes at target destination.
- Application of main vehicle to conduct exotic en-route science such as Pioneer anomaly, arm of gravitational wave detector, Unruh effect, dark matter.
- Assembly of the Icarus probe on Earth (or orbit), the moon (or orbit), asteroid, Lagrange point, around gas giants.
- Application of long wavelength planetary observations during cruise phase of mission.
- Use of planetary Orbiters or soft Landers at target destination.
- Use of electric sail as a possible deceleration method?
- Use of instrument unit around engine stage fairings as on Saturn V.
- Use of fuel pellet launcher for early boost phase and reduced propellant mass.
- Use of drop propellant tanks instead of engine stages.
- Use of >2 engine stages on mission.

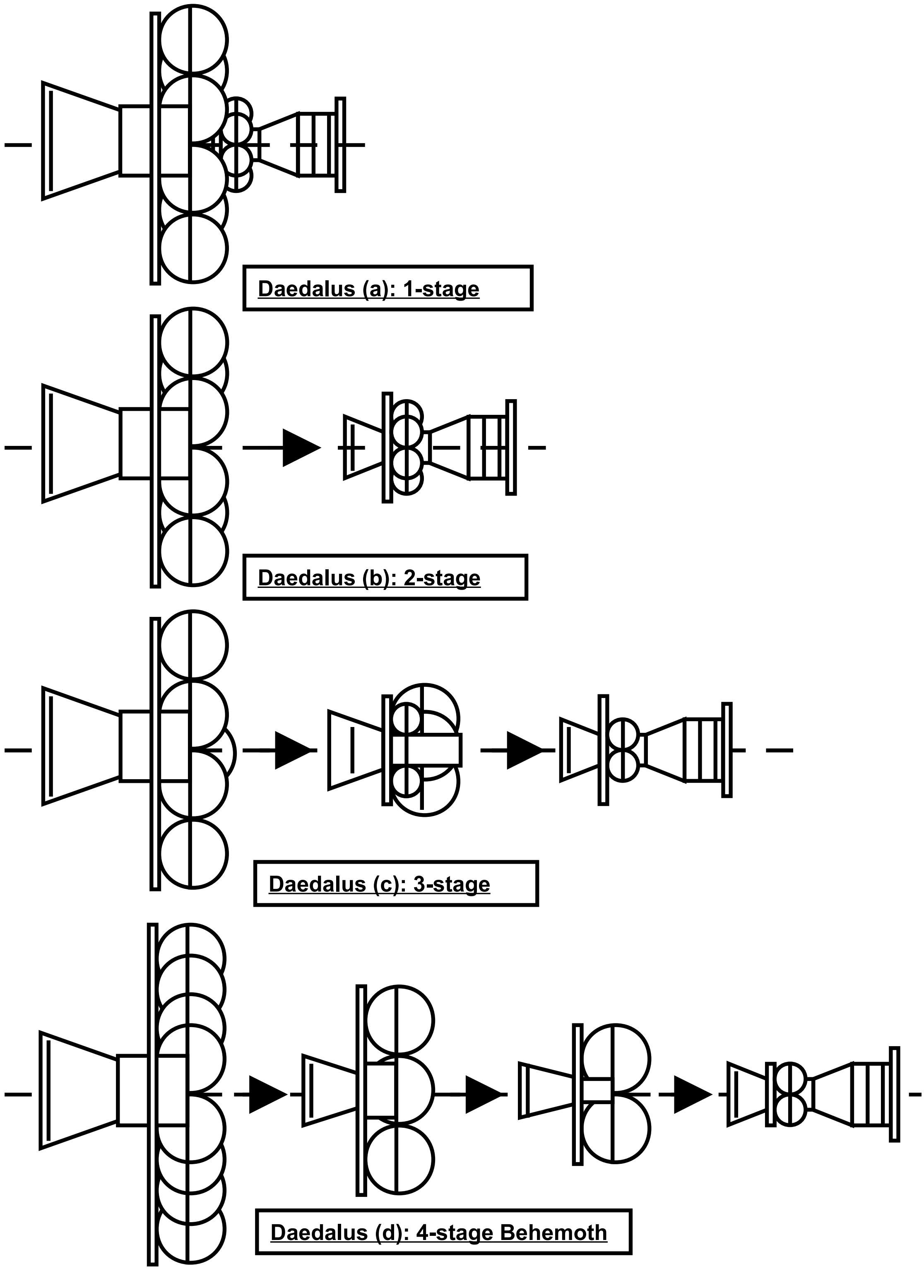


Illustration of Daedalus-Like concepts with multiple stages.

12. DESIGN CONSTRAINTS

A previous document (ToR) set out the initial objectives for Project Icarus which was QUALITATIVE REQUIREMENTS. These are discussed below along with some attempt to translate these into engineering QUANTITATIVE REQUIREMENTS with minimum and maximum bounds. The original ToR was kept to a minimum, six, in order to prevent a situation where inconsistencies in the requirements occur. Ideally, the ToR should be general so as not to prejudge the design solution. However, for Project Icarus some solutions were forced upon the design. These act to constrain the design space and are known as 'forced parameters'. These include:

- Current or near future technology.
- Mainly fusion based propulsion.
- Fast transit time to destination in under a century.

How do we interpret the project scope and ToR and what should we do to answer it? This section begins this process by interpreting each one of the engineering requirements so as to feed later design discussions on what options will be appropriate.

Term of Reference 1:

"*To design an unmanned probe that is capable of delivering useful scientific data about the target star, associated planetary bodies, solar environment and the interstellar medium.*"

Definitions:

Unmanned refers to a spacecraft not designed to carry a human payload. This greatly simplifies the safety aspects of the mission, not being concerned with harming human life. This also means that the spacecraft can be as small as required, as determined by the system constraints. In principle the maximum mass is not limited although a limit would be implied by the acceleration requirements for a 100 year mission and engine performance.

Probe refers to a robotic satellite or spacecraft that is initially remotely controlled but with some degree of autonomy in decision making. The probe is capable of measuring something and translating the results for useful interpretation about the target solar environment (defined below) across space.

Useful scientific data refers to information about the target system and surrounding environments that must be communicated back to the ground station on earth, adding to our knowledge of the universe. The minimum that this can represent is scientific data of the target system that cannot be obtained from long range observations. No maximum data is apparent, except as governed by the total payload mass limitations which also limits the number and size of instruments. This suggests that radio transmitting technologies or some alternative is required on the spacecraft.

Planetary bodies Includes planets, Dwarf Planets, Moons, Asteroids.

Solar environment includes particles, fields and their associated physical properties.

Interstellar medium defined as the exo-solar space external to our own solar system and the target solar system, comprised largely of dilute mixture of ions, atoms, molecules, larger dust grains, cosmic rays and the galactic magnetic field. It may also contain free floating objects (i.e. non-gravitationally bounded planets).

Imposed Constraints:

- No manned payload.
- Scientific instruments required, number and type to be determined.
- Autonomous computer required that can run for 100 years or less. Implies same for any on board electronics.
- Communication antenna(s) and receiver required that can function for 100 years or less.
- Advanced notice of the contents of the target star system required through deep space astronomical observations.
- Advanced knowledge required of space through which trajectory will be defined, i.e. content, number density of ISM. Suggests advanced scout missions required ahead of probe.
- Passing through potentially high density regions of the ISM suggests that a protective shield may be required to mitigate particle bombardment or alternative solution. This will require research into the density of the local ISM to determine shield thickness.

Term of Reference 2:

"*The spacecraft must use current or near future technology and be designed to be launched as soon as is credibly determined.*"

Definitions:

Current technology refers to technology that is being applied today in some capacity or exists as ready for some as yet undefined application.

Near future technology refers to technology that we can linearly extrapolate with a high degree of confidence will exist in the coming decades and not coming centuries. This therefore rules out any technology not based upon proven laws of physics or associated with any hypothesised technological singularities.

As soon refers to a point in time in the future as determined by a proposed roadmap to technological fruition.

Credibly refers to the use of established scientific and engineering practices to derive all design solutions, subject to academic rigour.

Imposed Constraints:

- Implies can only use current or near future technology, probably 50 years is an appropriate extrapolated time frame, but due to the nature of this project extrapolations up to around a century will also be considered.

Term of Reference 3:

"*The spacecraft must reach its stellar destination within as fast a time as possible, not exceeding a century and ideally much sooner.*"

Definitions:

Stellar destination is defined as the region of space encompassed by a solar derived gravity field and the associated solar atmospheric influence.

Fast a time refers to speeds which are likely within the range 10-20% of light speed as measured from a distant observed based on the Earth. Relativistic effects will be ignored in this context.

Century as measured on the Earth-solar orbit basis and this is the limiting time of the mission profile from launch at the assembly point (here assumed to be within 1AU of the Earth) to arrival at the stellar destination (defined above).

Imposed Constraints

- Suggests that high cruise velocity increment is required which dictates highly efficient/optimised engine design and capsule design. High exhaust velocity should therefore be a design aim.
- Require materials that can survive in the vacuum of space for 100 years or less with limited aging or fatigue.

Term of Reference 4:

"*The spacecraft must be designed to allow for a variety of target stars.*"

Definitions:

Variety refers to the definition of several potential destinations (defined below) based upon a compromise between scientific interest and engineering constraints.

Target stars are defined to be interstellar destinations (defined above) within 10-15 light years of The Sun.

Imposed Constraints

- Suggests that a detailed survey of nearest star systems is required.

Term of Reference 5:

"*The spacecraft propulsion must be mainly fusion based (i.e. Daedalus).*"

Definitions:

Propulsion in this context (primary mode) is defined to be the primary mechanism by which the vehicle obtains greater than 90% of the thrust generation during the boost phase of the mission. This does not refer to any secondary propulsion drives.

Mainly fusion based refers to where the main 'combustion' cycle relies upon some mechanism which releases energy through the combined reaction of fusion based isotopes, usually elements much lighter than iron.

Imposed Constraints

- Require reaction chamber for fusion ignition for use in the primary propulsion.
- Required propellant tanks to store fuel and possibly cryogenic systems.
- If engine has pulsed detonation (as Daedalus) then require analysis of structural load distribution due to continued stress and gradually increased fatigue.
- Energetic fusion reactions carry a radiation risk to vehicle payload. Suggests that radiation shield is required.

Term of Reference 6:

"*The spacecraft mission must be designed so as to allow some deceleration for increased encounter time at the destination*."

Definitions:

Mission is defined as the start of the boost phase to complete power failure and end of data transmission of the main vehicle.

Deceleration is defined as a negative rate of change in the main vehicle velocity so that the cruise velocity is brought to a slow limit.

Encounter time is defined from the arrival of the main vehicle in the stellar destination (defined above) to either an exit from the interstellar destination or power shut down, resulting in a communications transmission loss.

Destination refers to the interstellar destination (defined above) where the main vehicle trajectory is aimed.

Imposed Constraints

- Require communications and regular health check of trajectory profile and vehicle status throughout mission.
- Require some means of decelerating the vehicle, the amount and duration of which is to be determined.

Project Scope:

"*The required milestones should be defined in order to get to a potential launch of such a mission. This should include a credible design, mission profile, key technological development steps and other aspects as considered appropriate*."

Definitions:

Potential launch is defined as a state of social, political, economic and technological society readiness where such a vehicle could be designed, built, assembled and launched within 20 years of the decision to do so.

Credible design is defined as when an external academic peer review of the final concept design would conclude that the vehicle had been designed to acceptable engineering and science standards and if built could in theory achieve its mission aims.

Mission profile is defined as the power, thrust and velocity requirements for a given trajectory as described by the mission (defined above).

Key technological development steps is defined as the main technological inventions and 'daughter' inventions as well as the industrial background upon which such inventions would occur, necessary to make such a mission (defined above) practically possible. This would also set the time-scale upon which these steps could plausibly occur.

Imposed Constraints

- Constrained to non-speculative methods in order to maintain credibility. Approximations in numbers or assumptions are not to be considered the same as speculation.
- Detailed definition of engine performance required throughout the mission.

From above, some preliminary quantitative requirements emerge for the Icarus vehicle. These are described in the Table below and form the starting point of any design calculations. The data gives the 'likely' lower and upper bound parameter space for any future Icarus design but these are not fixed bounds and instead are giving merely to promote discussion. The final solution would probably be between these two extremes. It should be noted however that **all the estimates below are for flyby probe only** and future work should aim to fold the ToR requirement for deceleration constraints into our design space, as the project evolves. Without knowing the mechanism(s) by which this would occur, at this stage it is difficult to account for deceleration. However, it is worth noting that if reverse engine thrust is used, then essentially this will double the mission duration. The calculations below also ignore the possibility of Brown Dwarf targets in between our location and Alpha Centauri, not to suggest that these may not be of interest. Each of the rows is unrelated unless specified in the comments section.

Parameter	Minimum	Daedalus	Maximum	Comment
Target destination	Alpha Centauri 4.3ly	Barnard's star 5.9ly	Lalande 25372 15ly	Lalande is example of max but actually several stars around this distance.
Mission duration total	22 years	48 years	100 years	Min based on assumption of 0.2c upper velocity bound to α-Cent assuming t(boost)<<t(cruise).
Mission duration cruise phase	22 years	~44years	<100y	Min assuming boost phase negligible. Max imposed by ToR requirement assuming negligible boost phase.
Total ΔV	0.04c	0.12c	0.2-0.3c	Min based on min cruise speed given elsewhere in table. Max chosen as higher not considered feasible.
Cruise velocity	13,000km/s (0.04c)	36,000km/s (0.12c)	60,000km/s (0.2c)	Min based on 100y mission to αCent assuming boost phase negligible. Max based on 0.2c expected limit.
Size	10×5m	190×50m	400×100m	Dimensions all assumed as approximate length & width. Min given by slightly larger than Cassini Huygens but probably unrealistic. Max given by double Daedalus size, undesirable.
Total spacecraft Mass	40,000tonnes	54,000tonnes	500,000tonnes	Max estimated as being a margin above separate calculations (April 2010) performed by Long (350ktonnes) and Crowl (450ktonnes) assuming thrust, acceleration arguments over 100 years. Min based on mi/mb=exp(ΔV/Ve) assuming minVe, minΔV defined elsewhere in this table so that mi~14×mb, with mb~2670tonnes (Daedalus). Min assumed D/He3 propellant.
Propellant mass	37,000tonnes	50,000tonnes	460,000tonnes	Max assuming Daedalus scaling that Mprop = 0.92×Mtot & extrapolated from total mass estimate. Min assuming propellant mass scales with same Daedalus gradient for distance, i.e. 5.9ly=a(50,000tonnes), a=0.00012, then apply to Alpha Centauri 4.3ly, to get propellant mass.
Total payload mass	2tonnes (Cassini)	450tonnes	450tonnes	Max based on design decision that should be much less than Daedalus.
Min KE to cruise speed	1.7×10^{18}J	3.5×10^{22}J	9×10^{23}J (0.2c)	Estimated from 0.5mV^2 neglecting stage drops. Min assumed min total mass and cruise velocity defined elsewhere in table. Max assumed max total mass and cruise velocity defined elsewhere in table.
Min power to cruise speed	0.3TW	291TW	285TW (0.2c)	For Daedalus assumed min KE over boost period 3.81y. Min defined at min boost duration defined elsewhere in table. Max defined at max boost duration defined elsewhere in table.
No.sub-probes	1	18	thousands	Min based on requirement to deliver useful science data about target destination. Max based on Starwisp or nano-probe concepts.
Technology	2010 (present)	1970s-2020	2100	For max linear extrapolation of technology past this time is considered too speculative.
Boost phase duration	0.2y	2.05y + 1.76y	100y	Min assuming accelerates up to 0.2c cruise velocity. Max assuming min slow acceleration 0.01g all the way to target but neglects deceleration requirement.
Boost phase		0.014g ($0.14m/s^2$)		Min based on duration of acceleration up to 0.2c where lower acceleration breaks ToR 100year

acceleration	>0.01g	0.013g (0.13m/s^2) 0.067g (0.676m/s^2)	1g	requirement. Max based on likely practical limit with technology. Quoted Daedalus numbers represent 1st stage ignition, 2nd stage ignition, 2nd stage burnout.
No. stages	1	2	5	Min based on required from ToR to deliver probe to target. For max more than 5 not expected to contribute significant ΔV to be worth inclusion.
No. propellant tanks	1	6L+4s	38L+26s	Max assuming Daedalus scaling with N(L) = 92% Mprop on max total propellant mass given elsewhere in table. Where 1L=7666tonnes & 1s=1000tonnes.
Engine burn time	~months	2.05y+1.76y ~ 4y	~decades	Without knowing more about the engine performance for Icarus this is difficult to assess.
Thrust	3.6×10^4N	6.63×10^5N(2nd) -7.54×10^6N (1st)	1.88×10^7N	Thrust =Ve*mdot, with Ve stated in table & thrusts equates to Daedalus mdot =0.71kg/s (1st) & 0.0072kg/s (2nd). Thrust then calculated for min and max with these two mdot values, but using min & max Ve given in table below. So assumes Daedalus mass flow rates.
Pellet pulse frequency	10Hz	250Hz	1000Hz	Min based on requirement to have a propulsive effect & typical rate for near-future demonstrator reactors, but no account given of energy release/pellet to reach target. Max based on what is practically credible, this is double the max 500Hz considered by Daedalus.
ICF capsule Q	~10	63 (1st) 35 (2nd)	~few thousand	Min based on requirement to have a gain of >1 to derive propulsive effect and consistent with typical Q quoted for next generation demonstrator reactors. Max based on what is credible from historical research & is at least double historical Project Vista. Daedalus Q calculated by A.Crowl.
Exhaust velocity	~5000km/s	92,10km/s (2nd) -10,600km/s (1st)	26,500km/s	Min based on 100 year requirement with multiple staged design which leads to >20,000km/s ΔV. Max based on theoretical enthalpy release for fusion reactions of 348MJ/kg.
Specific impulse	0.5million s	0.921-1.06mil s	2.65million s	Both min & max from estimate of Ve.
Data transmission rate	20kbps	864kbits/s	1Mbps	For Daedalus transmitted with input power 1MW at 432kHz bandwidth. Min & max opposite based on BOE calculation from Pat Galea.
Encounter time at target	~days	~days	~years	Min based on ToR requirement to decelerate at target for increased encounter time. Max based on bring probe to complete halt in system prior to power loss.

13. CONCLUSIONS

This report has described the overall programme plans and Phase III major task deliverables for Project Icarus. The delivery of this report by the end of April 2010 marks the passing of Stage Gate 1. The challenge for any Project Leader is to keep the programme plans on track as best we are able within the constraints of our volunteer design capacity. The most important task for any future Project Lead will be (1) adherence to programme plans/deliverables (2) defining the next phase of work (3) recording any key events/decisions in a newsletter (4) maintaining the team momentum. All designers are encouraged to assist the team Leadership in meeting these tasks throughout the project. Indeed, if Project Icarus is to be a success then it will be because members of the design 'team' have contributed as agreed. This is then the major hurdle that a fragmented, volunteer, international team needs to address. The future will show if the Project Icarus Study Group fulfils its promise and does the original Project Daedalus Study Group proud. To the stars incrementally we must progress.

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APPENDIX: PHASE III TRADE STUDY/REVIEW TOPICS FOR PROJECT ICARUS: APRIL 2010 – APRIL 2011

Designer Name:	**Kelvin Long**
Study 1	**PROJECT ICARUS: Concept design considerations for fuel and fuel acquisition – Part 1.** This work will examine fuel and fuel acquisition techniques for: Lunar/moon(s), asteroids with emphasis on He3. This study will also examine the potential for fuel mining from the solar wind and the interstellar medium en route. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: An Initial Review of Inertial Confinement Fusion for Space Propulsion.** The attainment of fusion ignition on earth is an ongoing research programme which promises to revolutionise our industrial energy supplies. Another application of this technology, should it prove viable, is to spacecraft propulsion. Several historical studies have explored this theme over the years including Projects Daedalus, Longshot and Vista. The current design study, Icarus, will be designed to rely upon ICF technology for the main propulsive drive. This paper briefly reviews the subject of ICF technology as applied to historical projects and discusses some of the important physics issues. Finally, Some recommendations are made for likely capsule designs appropriate for an Icarus-like spacecraft with an interstellar mission. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: A First Look at Spacecraft Reliability Analysis Using An Approximate Physics Model.** This brief study will be an attempt to look at reliability analysis from the perspective of a fluid based model or aerodynamic analogue. Assumptions will be made about different particle/dust density within the solar system(s) and ISM and then a calculation performed for the range or 'stopping distance' of a representative probe passing through these mediums at different velocities. If time allows a Fortran programme will be constructed to explore this idea. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: A Review of Historical Solar System Explorers & Scientific Drivers.** For several decades now robotic exploration of our solar system has been underway. A series of spacecraft have been sent to most of the planets and to the edge of our solar system. This paper reviews the science basis for these missions and other proposals which have been made, which go beyond the vicinity of our immediate solar system. This information is then used to develop science based drivers for an unmanned interstellar mission. The results of this study are then used to suggest different payload

	configuration layouts. This research is relevant to the 'science' module and 'instruments & payload' module. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: A Review Fusion Research Facilities & the Scalability for Space Applications.** The report is a discussion of historical, current and projected laser facilities on earth for use as inertial confinement fusion drivers. This will also examine some lasers outside of the fusion research community that may have potential for Icarus. As well as the performance, this report will also examine the technology, operation and size of these facilities and consider potential scaling issues for space propulsion applications. Some consideration is given to the effect of vehicle shock pulse on the laser optics. This is a submission of the Project Icarus Study Group.
Study 6	**PROJECT ICARUS: A Concept Design Review of Daedalus-like Vehicles for A Variety of Target Missions.** The report will build on some of the work already completed in constructing concept sketches of Daedalus-like vehicles based upon a flyby only design. In this extension, optimum mass ratio configurations will be developed. The report will also contain a discussion of the likely performance and engineering issues related to each configuration. Finally, some consideration will be given to deceleration of each vehicle concept assuming reverse engine burn as the mechanism. This is a submission of the Project Icarus Study Group.
Study 7	**PROJECT ICARUS: Preliminary Design of a Charged Particle Detector & Plasma Analyzer.** This instrument would be designed to take measurements of the solar, exo-solar and inter-planetary winds. Charged particle properties such as energies, populations, spectral distributions and angular distributions would be measured. Such an instrument was included on the Pioneer 10 and 11 spacecraft. The instrument would be mounted on the main bus but could be adapted for inclusion in the planetary probes or to take measurements of planetary radiation belts. This is a submission of the Project Icarus Study Group.
Study 8	**PROJECT ICARUS: Inventory of Daedalus vehicle systems and mass breakdown.** This paper will examine the complete Daedalus design and identify all of the components. This will result in a complete inventory and mass breakdown of each system. This will assist in the formation of a later Project Icarus Baseline Model. This is a submission of the Project Icarus Study Group.

Study 9	**PROJECT ICARUS: Initial considerations for qualifying the Icarus design solution.** This paper will briefly examine some of the factors to be identified in the certification of the Icarus vehicle later on in the study. This involves looking at ways of qualifying the key technologies so as to give some confidence in their flight potential for a long duration mission. The full study for this work will be completed during the latter part of the project. This is a submission of the Project Icarus Study Group.
Study 10	**PROJECT ICARUS: Use of external nuclear pulse technology for initial boost phase of mission.** This brief review will discuss the potential for using external nuclear pulse propulsion to augment part of the early part of the boost phase of the mission. All assumptions will be based upon those published in the Project Orion literature and similar published studies only. This is a submission of the Project Icarus Study Group.

Designer Name:	**Andreas Tziolas**
Study 1	**PROJECT ICARUS: Secondary propulsion methods and technologies for interstellar assists.** In this paper a review of propulsion technologies is performed. An outline of the format of the paper follows, where contemporary and near future propulsion methods are examined. A title and description of the overall principle of operation of this technology is given. The fuel source of this technology is reviewed and evaluated for long term performance. The specific impulse of this technology is compared against its potential delta-v contribution to an interstellar Icarus-type mission. A figure of merit could be constructed here, based on the total velocity gain per kg of propellant. Could this be used on the Icarus as a secondary propulsion method, propellant acquisition module, science probe propulsion module or for attitude control? Idea: Secondary propulsion systems used in the initial stages of the mission (in solar-system) could also be used as late mission (in target solar-system) science probe main propulsion systems. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Operational disciplines for effective vehicle risk & repair.** This report is an early operational outline for determining the potential vehicle risk from individual subsystems, that will ultimately provide us with the overall mission success rate. The codes will be kept out of the publication at this stage. The repair rate is also factored in at this stage, where the check, test, evaluate and repair approach to spacecraft subsystems will be

	outlined. Suggestions for repair warden implementation will be proposed at this stage. This will be the first appearance of the Test and Repair Rail system that has been discussed within previous vIcarus notes. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Distributive computing software for system reliability.** Instead of opting for a review of computational methods here, a different vision for the computing system on board the Icarus probe will be explored. A distributive computation platform that is used to actively delegate and compare necessary tasks on the fly, with built in error checking. For this idea, a block diagram outlining decision making and error checking process will be provided. This will become the backbone of Icarus' mainframe, to which computational tasks will be added as needed. Only software will be addressed here. Hardware specifications are arguably outside possible speculation for a mission launch in 20 years. This is a submission of the Project Icarus Study Group.

Designer Name:	**Pat Galea**
Study 1	**PROJECT ICARUS: The Use of Relay Stations for Interstellar Communications.** The distances involved in interstellar travel make the transmission of data from the craft back to Sol a significant challenge. By dropping one or more relay stations en route, it may be possible to (a) reduce the Icarus transmitter power requirement; (b) reduce the Icarus transmitter aiming tolerance; (c) improve the data bandwidth. This paper provides a quantitative analysis of the benefits to be obtained by adding relay stations. The paper also considers the potential for re-using expended stages as relays. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Using the Gravitational Lens to Improve the Transmission of Interstellar Probe Data.** Every star acts as a gravitational lens, focusing electromagnetic radiation. It is theoretically possible to use this effect to improve significantly communications between a probe at a distant star and Sol. This paper examines whether Icarus can take advantage of this system for improving communications, and/or provide a test bed for performing experiments using this technique to assist future missions. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Optical Lasers for Interstellar Communications.** Optical laser communication systems hold great potential for

	communicating over the long distances involved in interstellar missions. Lasers produce tight beams that do not spread as much as radio beams, due to the much higher frequency of light. This allows much greater power to remain present at the receiving end, thus requiring less power at the transmitter and/or providing greater bandwidth. This paper examines the use of optical lasers for Icarus communications, and considers which laser technologies (e.g. CO_2, Neodymium doped glass/crystal) could provide an appropriate solution. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Radio Frequency Systems for Interstellar Communications.** Radio frequency systems have been used since the dawn of the space age for communicating with distant craft. This paper examines the current and extrapolated state of radio antenna physics and technology used in spacecraft, and presents analysis of whether and to what extent radio systems can be used for communications with Icarus. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: Preliminary assessment of the use of solar sail technology in different parts of the mission profile.** While the terms of reference for the project specify that the spacecraft propulsion system will be mainly fusion-based, aspects of the mission and overall architecture could be implemented or assisted by the use of solar sails. This study examines the potential application of solar sails in several areas of the mission. This includes: assisted boosting of the Icarus probe out of our solar system; deploying sub-probes in the target solar system for exploring local planets and other objects of interest; deploying a relay station at the Sun's gravitational focus to receive transmissions from the distant Icarus craft. This paper discusses some of the engineering requirements for these potential roles as well as any potential performance enhancements to the mission. This is a submission of the Project Icarus Study Group.
Study 6	**PROJECT ICARUS: A review of current 'ground' support infrastructure for deep space missions.** This report will review the 'ground' support structure for historical missions such as New Horizons, Voyager, Pioneer, Galileo and Cassini. The results will then be extrapolated to an interstellar mission over several decades duration. This is a submission of the Project Icarus Study Group.
Study 7	**Project Icarus: A brief review of electronics technology used in spacecraft and with comparison to Daedalus.** This short study will examine the key electronics technology used in spacecraft today such as microelectronics and

	semiconductor components. The electronics intended for Daedalus is listed, discussed and then suggestions made for potential improvements, with emphasis on mass reduction and power improvement. An obvious example would be a move from transistor to integrated circuit technology. This is a submission of the Project Icarus Study Group.

Designer Name:	**Richard Obousy**
Study 1	**PROJECT ICARUS: Analysis for the two-burn manoeuvre for increased ΔV.** The Oberth two-burn manoeuvre offers considerable improvements on fuel efficiency when compared to the direct burn and can produce an increased specific mechanical energy for a given delta-V budget. The potential utility of this manoeuvre will be explored in the context of an interstellar mission. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Could antimatter be generated and stored in sufficient quantity to assist with space exploration missions?** Antimatter may prove to be an invaluable fuel for interstellar missions if it could be produced and stored in high enough quantities. In this study we explore some of the current options for antimatter production, and also examine some of the proposed storage methods. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Evaluation of Antimatter Catalysed Fusion for Interstellar Propulsion.** Antiproton annihilation offers a unique mechanism to initiate nuclear fusion and could provide a considerable reduction in propellant system mass. In this paper we study the physics behind the concept and evaluate it in the context of spacecraft propulsion. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Analysis of the Possible use of Ultradense Deuterium as Starship Fuel.** Recent research suggests that Deuterium in an ultradense form has been created in the lab. Such a material would make fusion reactions much easier to initiate and would be invaluable for spacecraft propulsion. In this paper we analyse this claim and discuss the possible implications for interstellar spacecraft. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: Analysis and Comparison of the Possible Fusion Ignition Systems for Spacecraft Propulsion.**

	A number of methods exist for the ignition of nuclear fuel that could be utilised for spacecraft propulsion. These include the Tokomak design, electrostatic fusion and the super-Marx generator. In this paper we analyse some of the pros and cons of each proposal and determine which ignition technique would be optimum for a space propulsion system. We will pay particular attention to the mass of each system and its level of technological maturity. Finally we discuss why ICF is generally favored as a propulsion system by comparing key metrics. This is a submission of the Project Icarus Study Group.

Designer Name:	**Ian Crawford**
Study 1	**PROJECT ICARUS: An initial consideration of science objectives, and associated payload elements, for representative mission profiles.** The science objectives of the Icarus mission will be considered from the perspectives of interstellar medium studies, stellar astrophysics, planetary science and astrobiology. As the final mission architecture will not have been defined at this stage, and in order to inform the down-selection of different mission profiles, the study will consider science objectives for several different profiles, including: (i) full payload deceleration in the target system; (ii) deceleration of low-mass sub-probes; and (iii) an undecelerated flyby of the target system. These different mission profiles will be used to estimate realistic payload mass constraints, and representative payload elements capable of meeting both the science objectives and the mass constraints will be identified. This work will use two different target stars having different distances as examples of what may be achieved within the overall flight time (<100 years) specified by the Icarus Terms of reference -- i.e. a nearby star (e.g. the alpha Centauri system) as an example incorporating full deceleration at the target, and a more distant star (e.g. epsilon Eridani) as an example of a fast flyby. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Rough Guide to the Solar Neighbourhood.** Available information concerning the known star systems within 15 ly will be gathered, assessed, and processed with a view to recommending a target for the Icarus probe that appears reasonable within the context of present knowledge. This will be associated with the clear caveat that by the time it becomes possible to launch an interstellar mission, the quantity and quality of observational data of the contents of nearby star systems will have advanced enormously. Hence recommendations generated by this module can only be regarded as speculative. The report produced for this module will be based

	on a table containing recent observational data for the solar neighbourhood, plus derived parameters to fill in gaps or unknowns where needed. Methods of calculation of such parameters will be detailed. Each star in the table will be linked to a text section where the nature of the star and its astrophysical points of interest are described. Astrophysical and astrobiological arguments concerning each system will also be deployed to speculatively assess its potential for hosting a life-bearing planet. It is intended that this module will function as a tool that will assist team members in their decision to select a nominal target for Project Icarus. This is a submission of the Project Icarus Study Group.

Designer Name:	**Adam Crowl**
Study 1	**PROJECT ICARUS: Hybrid Mag-Beam/fusion plasma deceleration for system probe.** Analysis of the potential for decelerating an orbital stellar system probe via magnetic deflection of main engine plasma and/or accelerated plasma stream. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Assessing Mag-Sail & Plasma magnet for Braking.** Analysis of braking from cruising speed to system encounter speed via magnetic-sail and/or plasma-magnet. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Bae Photon Thrusters for Sub-probes.** Analysis of the potential for propelling and placing sub-probes via multiple-photon reflection system developed by Young K. Bae. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Capacitors for "Icarus".** Examination of mass-savings via replacing original "Daedalus" capacitors with ultra-capacitors, including EEStor and 'digital quantum battery. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: In-situ Parts Manufacturing via Rapid Prototyping.** Examination of potential for on-board parts repair and manufacture via rapid prototyping technology. This is a submission of the Project Icarus Study Group.
Study 6	**PROJECT ICARUS: Concept design considerations for fuel and fuel acquisition – Part 3.** This work will examine fuel and fuel acquisition techniques for:

	Kuiper belt objects, Oort cloud objects terrestrial sources i.e. D, T, Li/B, B/p, particle collider generated sources. This work will also examine the potential of ultradense Deuterium. This is a submission of the Project Icarus Study Group.
Study 7	**PROJECT ICARUS: A Preliminary Review of Potential Aerospace Materials for Applications in an Interstellar Mission.** This report examines candidate materials for the applications of spacecraft structures for a long duration mission. This review includes an examination of metal alloys and composite materials. Candidate materials are identified for spacecraft main structure, fuel tanks and payload sections. A discussion of the Daedalus material choices is also examined in the context of modern materials data. This is a submission of the Project Icarus Study Group.
Study 8	**PROJECT ICARUS: A Review of Materials Used in Historical Spacecraft Missions**. This report examines some historical spacecraft such as Voyager, Pioneer, Galileo and Cassini-Huygens. The materials used in these missions are examined and material requirements are extrapolated for longer duration missions. Some conclusions are given on the choice of selecting some of these materials for an Icarus like mission. This is a submission of the Project Icarus Study Group.
Study 9	**Analysis of Interstellar Propulsion application of IEC.** Extends the studies by R. Bussard of the high exhaust velocity modes of Polywell and wire-gridded Electrostatic confinement fusion power systems. Studies system parameters required to efficiently fuse high-energy fusion reactions i.e. D-D, D-3He. Examines mass-growth of parasitic sub-systems. This is a submission of the Project Icarus Study Group.
Study 10	**Analysis of Interstellar Propulsion application of MCF.** Examines the power/mass ratio of Magnetic Confinement Fusion in high exhaust velocity applications, as well as expected fusion-to-jet-power efficiency, mass growth trends of parasitic sub-systems such as radiators, shielding & confinement magnets. This is a submission of the Project Icarus Study Group.
Study 11	**PROJECT ICARUS: assessment of Daedalus vehicle inventory and mass breakdown.** This brief study assembles the Daedalus component inventory and mass breakdown in the form of a spreadsheet. The results are compared to the Robert Freitas REPRO paper for corrections. The output will be in the form of a spreadsheet. This is for the use of Module 3.0 Vehicle Configuration. This is a submission of the Project Icarus Study Group.

Designer Name:	**Andrew Presby**
Study 1	**PROJECT ICARUS: Environmental Hazards to Interstellar Spacecraft.** A great deal has been learned about the space environment since Team-Daedalus completed their historic study. A survey of new data and discoveries in these areas must be completed before any environmental control design can be contemplated. This study will use the time while environmental control design drivers (notably propulsion, payload, and comms) go through their initial definition. Its output should ideally result in a mathematical model for use in estimating the thermal, particle/radiation bombardment, magnetic field, and chemical environment that Icarus will experience over the mission. Publish results in: JBIS? This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Space Power Technologies for Interstellar Flight.** The last thirty years have produced advances in many relevant energy and power technologies including some that were unavailable to the Daedalus study team. This study will use the time while environmental control design drivers (notably propulsion, payload, and comms) go through their initial definition to complete Andreas Tziolas' survey of candidate power system technologies for the Icarus mission presented for the 2009 BIS Symposium. The study's output should ideally provide a summary of each technology (power sources, power conversion, energy storage, heat rejection equipment at a minimum and power management and distribution equipment if possible) and considerations on its use. For power sources, this should include a plot of approximate power output vs mission duration. For conversion devices, plot of overall device efficiency (<u>not</u> as fractions of Carnot) vs source and sink temperature conditions. For heat rejection equipment, the relationship between waste heat power output, radiator area, mass, and temperature should be presented. The reliability and longevity of the technologies should be catalogued or estimated from available data if possible. Radiation shielding from nuclear power sources is explicitly included in this study. Publish results in**:** primarily internal power technology "catalogue", a JBIS article, blog posts, and possibly a Journal of Propulsion and Power article if the survey can be sufficiently condensed. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Considerations for power system design in interstellar spacecraft.** If Study 1 and 2 indicate that there <u>are</u> some special

	considerations then(TENTATIVE): This study explores aspects of spacecraft power management and distribution system unique to interstellar spacecraft. Possible topics include benefits and opportunities due to extreme cold, danger of s/c charging due to cosmic ray bombardment, or special shielding needs. Publish results in: internal design documents and blog status updates. Any unique considerations should be published in a JBIS article as a minimum to reach those parties interested in interstellar flight. Truly unique things should go to Journal of Propulsion and Power or other relevant peer reviewed publications to reach a broader segment of the space community. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Environmental Hazard Mitigation Options for Interstellar Spacecraft.** Surveys options to mitigate the hazards discussed in 'PROJECT ICARUS: Environmental Hazards to Interstellar Spacecraft.' This discussion will include an introduction to spacecraft electromagnetic compatibility, thermal control, and radiation and particle shielding. Each section will include a review of DAEDALUS' solutions to these problems (if applicable). This is a submission of the Project Icarus Study Group.

Designer Name:	**Andreas M. Hein**
Study 1	**PROJECT ICARUS: Stakeholder analysis and prediction of technological maturity of key technologies for the development of the Icarus interstellar probe.** Project Icarus reassesses the original Daedalus concept of a fusion-propelled interstellar probe. Daedalus was conducted by the British Interplanetary Society during the 1970's. Large scale space exploration projects like interstellar probes require a high level of continuous investments over long periods. Due to the project duration of several decades, a high level of sustainability is needed, which highly depends on the long-term commitment of important stakeholders. An additional challenge is the proposed use of technology, which is not yet existent or has to be extrapolated into the future. In order to respect these factors, scenarios for the societal, technological, scientific and political context for different time frames are constructed, in which the development of Icarus might become probable. On the basis of the scenarios, stakeholders are identified, which might be interested in a long-term commitment into such a project. To address the maturity of key technologies, estimates for different time-frames are made within the scenarios. Finally, implications of the results for the development of Icarus are derived. This is a submission of the Project Icarus Study Group.

Study 2	**PROJECT ICARUS: Multidisciplinary Design Optimisation of the Icarus spacecraft.** The Icarus spacecraft design depends on many parameters like target star distance, propulsion performance, payload mass etc.. For a preliminary design study, appropriate optimization methods are selected and applied to the design problem at hand. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Evaluation of technological/social and political Projections for the next 100 Years and Implications for an Interstellar Mission.** Module: 19.0 (Relates to A.Hein study 1) Several projections of the global political, social and technological development in the next decades have been conducted in recent years. The implications of these projections on the hypothetical development of an interstellar probe are assessed. Several scenarios will be developed and their results used as inputs for the development of potential mission architectures. Crucial parameters are energy production and consumption, the evolution and role of space technology and the allocation of resources for large-scale scientific endeavours. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Architecture development for atmospheric Helium-3 mining of the outer solar system gas planets for space exploration and power generation.** Project Icarus reassesses the original Daedalus concept of a fusion-propelled interstellar probe. Daedalus was conducted by the British Interplanetary Society during the 1970's. The fusion propulsion of the Daedalus probe required large amounts of Helium 3, which is highly abundant within the atmospheres of the outer solar system gas planets. Therefore, the Daedalus study proposed a large-scale mining of Jupiter. Helium 3 mining of the gas planets was also proposed to provide fuel supply for power generation on Earth. In this paper, an architecture is developed, which is intended to primarily satisfy the needs of the stakeholders related to Earth-based power generation. This primal goal is intended to increase the sustainability of space exploration projects like Icarus, by a common use of infrastructure. First, different scenarios for the societal, technological, scientific and political context are developed, in which He3 mining might become attractive for Earth-based energy generation. Second, the architecture elements are identified and the environmental conditions of the different gas planets assessed with respect to atmospheric mining and transportation. Third, different architectures are compared and the most attractive one selected. Fourth, the selected architecture is developed in more detail. Finally, the implications of this

	architecture for space exploration and power generation are analysed. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: Assessment of the Viability of a Space Elevator for Space Transportation during the next 100 Years** Module: 2.0, 19.0 (Relates to A.Hein study 1,3 and 4) The concept of a "Space Elevator" was recently re-evaluated due to the potential usage of Carbon Nanotubes as a material for the Earth-to-Space tether. Recent results showed that the initially projected theoretical high strength of the Carbon Nanotube fibers can't be reached in practice. A lower material strength is not prohibitive for the development of an elevator, but increases the tether thickness ratio and therefore the mass of the system. Another critical point is the climber power transmission system, which affects the payload ratio of the system. On the basis of recent publications, a technological roadmap is developed with projections for the availability of key technologies necessary for the space elevator. With respect to crucial parameters like resource allocation and technology commonality, a possible date for the realisation of this transportation system is suggested. This is a submission of the Project Icarus Study Group.
Study 6	**PROJECT ICARUS: Initial considerations for design realisation & technological maturity.** This study will be a preliminary look at how the TRL of the final Icarus design is to be measured and also compared to the Daedalus design. Key comparators will be identified. Some initial considerations will also be given for the definition of a technological roadmap for making such a mission happen. Essentially, this work sets out a programme for interstellar exploration. The full study for this work will be completed during the latter part of the project. This is a submission of the Project Icarus Study Group.

Designer Name:	**Rob Swinney**
Study 1	**PROJECT ICARUS: A modern review of navigation & guidance requirements for an interstellar mission.** This study will review the navigation and guidance requirements starting from the original Daedalus report in particular its specifications and assumptions and bearing in mind that the mission profile for Icarus may be different and is yet to be down-selected. Some potential outlines may be included based on a review of current systems given their relevance to an Icarus-style mission. Consideration will be given to the equipment longevity. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: A review of astrometric measurements**

	relevant to an interstellar mission. This study will review the current accuracies of stellar distances including an investigation in to the technologies required to make these measurements whilst travelling at high speed. Included will be a consideration of the contribution to the science and technology of astrometric observations from an Icarus-style mission. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: An investigation into attitude control systems and the links to thruster technology and computer systems.** This study will consider any developments in the secondary propulsion system and the computer systems with particular reference to the integration of the attitude control systems (of main vehicle, probes and sub-probes...?). This is a submission of the Project Icarus Study Group.

Designer Name:	**Philipp Reiss**
Study 1	**PROJECT ICARUS: Repair Warden Technology.** An interstellar mission with an uncommon duration of about 60 years requires the possibility of onboard repair since during its extraordinary lifetime the vehicle and its subsystems are exposed to environment where no material and mechanism has ever been used before. To enable flexible repair for a huge variety of subsystems, the use of mobile robotic repair devices such as repair wardens shall be investigated within this report and the design of such systems and their interfaces shall be discussed. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Review of Historical Planetary Probes.** From the beginning of history, humankind has explored the universe by observing planets and stars visually from the Earth's surface. Since the 1960's we are able to get this information first hand by sending out probes and landers to other planets. Besides exploring our moon and various planets, probes already flew to comets and asteroids and some even leave our solar system. Planetary probes changed our understanding of the universe as they revealed the secrets of the rings of Saturn or discovered water on Mars. The report gives an overview about the evolution of planetary probes (and an outlook for the possible applications for an interstellar mission). This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: Small Satellite Technology.** (This study would be well supported by study 2 as the dimensioning of small satellites can be orientated on former

	planetary probes) Microsats, Cubesats and Nanosats are currently mainly built by universities and space related institutes to perform experiments and technology verification in space. Furthermore these systems are used for Earth observation and atmospheric measurements. But the applications for small satellites can be far more than that as they include some major advantages compared to larger satellite systems. They are small which means that they can easily be implemented inside larger spacecraft. They have limited number of subsystems which makes them more fail safe. As a matter of consequence, small satellites are more cost effective and simple to be manufactured. Assuming a large interstellar spacecraft which passes various planets and stars during its mission, auxiliary small satellites could be used to explore these objects while they are passed by. Due to their size and simplicity they could be stowed as a part of the payload and directly be launched from onboard their mother ship when their target object is reached. This is a submission of the Project Icarus Study Group.

Designer Name:	**Richard Osborne**
Study 1	**PROJECT ICARUS: Systems Architectures for interstellar starship construction infrastructure.** An analysis of systems architectures for the support of interstellar starship construction is undertaken. The technological, politico-economic and cultural impacts on development are examined for each system architecture. The feasibility of interstellar starship construction within each architecture can then be evaluated. Architectures based on modest extrapolation of current technological trends, through to architectures based on the impact of a technological singularity are examined - all in the context of potential interstellar starship infrastructure. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: An overview of the impact of a technological singularity on inner solar system infrastructure development and interstellar starship construction.** The impact of a full technological singularity and mundane technological singularities are analysed in the context of inner solar system infrastructure development, and interstellar starship construction opportunities arising from such infrastructure. A range of accelerators for interstellar starship construction can then be identified, enabling the technology readiness levels requirements to commence starship construction to be evaluated. This is a submission of the Project Icarus Study Group.

Study 3	**PROJECT ICARUS: The impact of SSTO introduction on interstellar starship construction.** The impact of SSTO introduction on the systems architectures required for interstellar starship construction is examined. The effect of first generation or follow on generation SSTOs on development rates is evaluated. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Project Icarus: Systems Architecture analysis for post launch support of interstellar starships.** This will follow on as a progression of the other work, coupled with interaction with other team members. This is a submission of the Project Icarus Study Group.

Designer Name:	**Jardine Barrington-Cook**
Study 1	**PROJECT ICARUS: On board software design philosophy and testing approach.** In this paper a review of current on board software, and likely near term available technologies will be presented. Basic requirements for the Icarus on board software will be gathered. This will include main mission management software, maintenance and repair software, on board data handling, and sub-probe software. Some consideration of instrument software, and observational optimisation will be included. Redundancy and resilience in software design, and software failure modes will be considered. A trade off of available technologies, approaches to on-board software design, implementation methods and testing will be carried out. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: A generic system science mission.** This paper will attempt to define a terminal scientific delivery package for the investigation of a generic solar system. Such a system would be expected to include remote sensing, planetary orbiters, out-of-ecliptic missions, and minor bodies rendezvous. Basic science goals will be defined to enable broad priorities to be set. The utility and feasibility of hard/soft lander, rover, and in-atmosphere probes will be examined, and an approach to target selection and deployment examined. Opportunities for intelligent tailoring and mission configuration will be outlined. An approach to unexpected targets of opportunity will be considered. This is a submission of the Project Icarus Study Group.
Study 3	**PROJECT ICARUS: In system sub-probe targeting and navigation issues.** This companion paper will look at the problems of planning sub

	probe trajectories and manoeuvres to maximise science return from the payload sub probes which are available, and the locally sensed scientific targets. It will define the required sensing, trajectory planning, optimisation and programming to allow the definition of an in system mission, and the launch of sub probes to explore the target system. This is a submission of the Project Icarus Study Group.
Study 4	**PROJECT ICARUS: Strategies for secure data return.** This paper will examine the issues associated with interstellar data return to the science community on Earth. In particular the broadcast approach, structure and content of the telemetry stream, data repetition strategies and a trade off of one-way versus two-way communication will be considered. Overall data set size, and metrics for mission success will be considered. This is a submission of the Project Icarus Study Group.
Study 5	**PROJECT ICARUS: The Daedalus wardens revisited.** This paper will look at the design configuration and programming of autonomous, free flying repair robots for Icarus, including the technical feasibility, and a trade off against alternative repair mechanisms, as well as an examination of warden failure modes, and likely mission impact. This is a submission of the Project Icarus Study Group.

Designer Name:	**James French**
Study 1	**PROJECT ICARUS: A Preliminary review of the Daedalus primary engine components and consideration given to alternatives.** This review will examine the two Daedalus propulsion reports and look at the various engineering components in the primary engine design. This includes transmission lines, induction loop, pellet injectors, injector and power capacitors, field coils, actuators and any other components associated with the engine ignition system. These components will be listed as well as their primary engineering function. Consideration will then be given to alternative technologies from modern state of the art or near-term projected that could be used in a Daedalus re-design. A report will be produced which summarises the components and any recommended alternatives. This is a submission of the Project Icarus Study Group.
Study 2	**PROJECT ICARUS: Evaluation of application of the gas core nuclear reactor to the Icarus mission.** The gas core fission reactor is a concept for achieving improved performance relative to solid core reactors by operating at a temperature at which the nuclear fuel is a gas. The nuclear material is contained in the chamber by means of a stable vortex

	induced by tangential injection of the reaction mass fluid (usually hydrogen). The extreme temperature of the core allows heating of the reaction mass to much higher temperature than conventional reactors of the Nerva variety thus leading to higher exhaust velocity and specific impulse. While the stable vortex has been demonstrated in cold flow, no such critical assembly has ever been operated. A number of practical considerations stand in the way of actual use including, but not limited to, heat transfer to the reaction mass fluid, limitations on cooling of the structure of the engine and details such as how to start and stop the reactor. Even if the gas core reactor propulsion system lived up to its potential performance, said performance is entirely inadequate for an interstellar spacecraft. That said however, such a system might well be useful as secondary propulsion. This is a submission of the Project Icarus Study Group.