Fusion Propulsion Technology for Interstellar Missions

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Director Initiative for Interstellar Studies, Ltd

Interstellar Exploration Workshop – ESTEC
20th June 2019

MSc Avionics and Flight Control Systems
(Cranfield)

MSc Radio Astronomy
(Manchester – Jodrell Bank)

BSc Astronomy and Astrophysics
(Newcastle upon Tyne)

University studies all in the 1980s!

Royal Air Force Squadron Leader

- Engineering Officer
- Aerosystems (primarily Avionics)

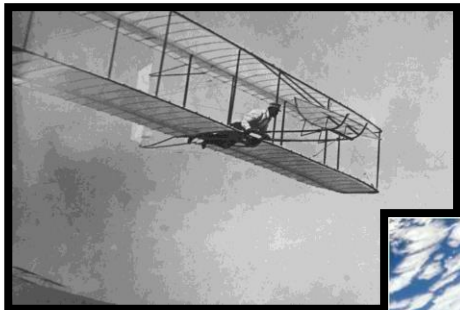
Independent Consultant – Space Industry

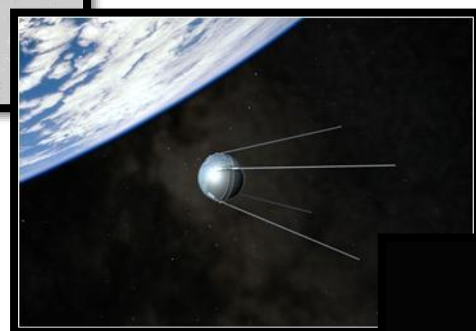
Scope

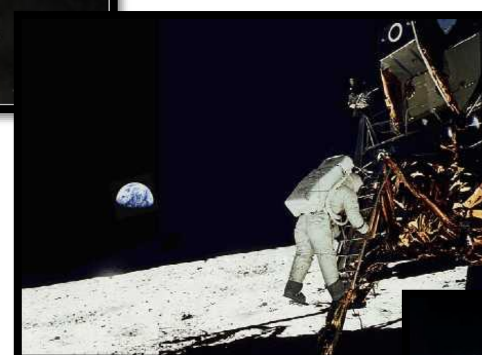
- Background
- Project Daedalus/Icarus
- Other Fusion Options
- Other Options
- Summary

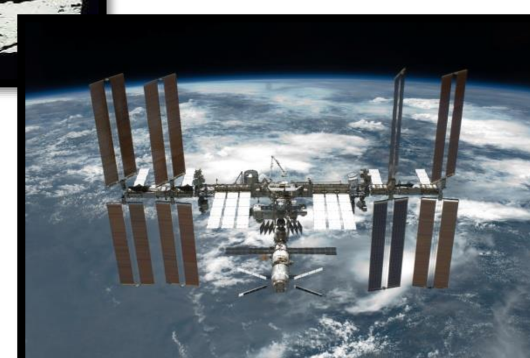
British Interplanetary Society

Long term thinking









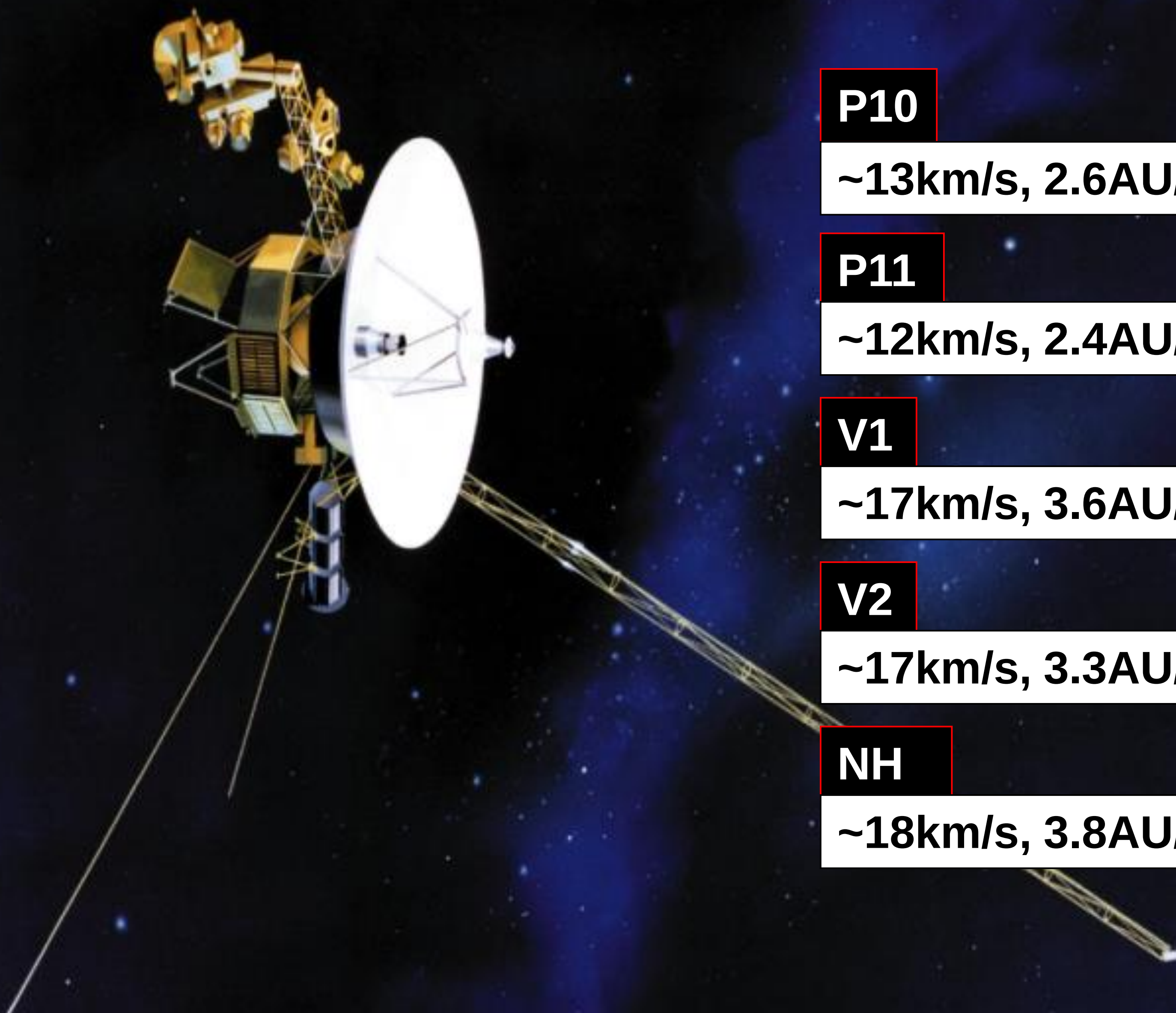
- We tend to underestimate what we can accomplish on long timescales.

Ideal Rocket Equation

$$\Delta v = v_{ex} Ln(\frac{m_o}{m_f})$$

Konstantin Tsiolkovsky
Formulated the "*aviation formula*" in 1887

Interstellar Precursor Probes



P10

~13km/s, 2.6AU/year, Mar 72

P11

~12km/s, 2.4AU/year, Apr 73

V1

~17km/s, 3.6AU/year, Aug 77

V2

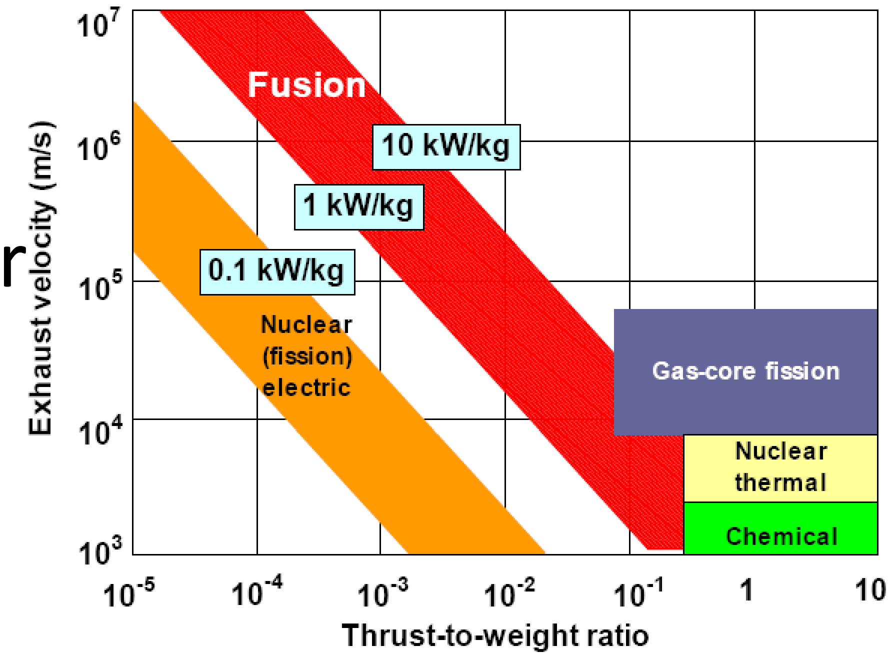
~17km/s, 3.3AU/year, Sep 77

NH

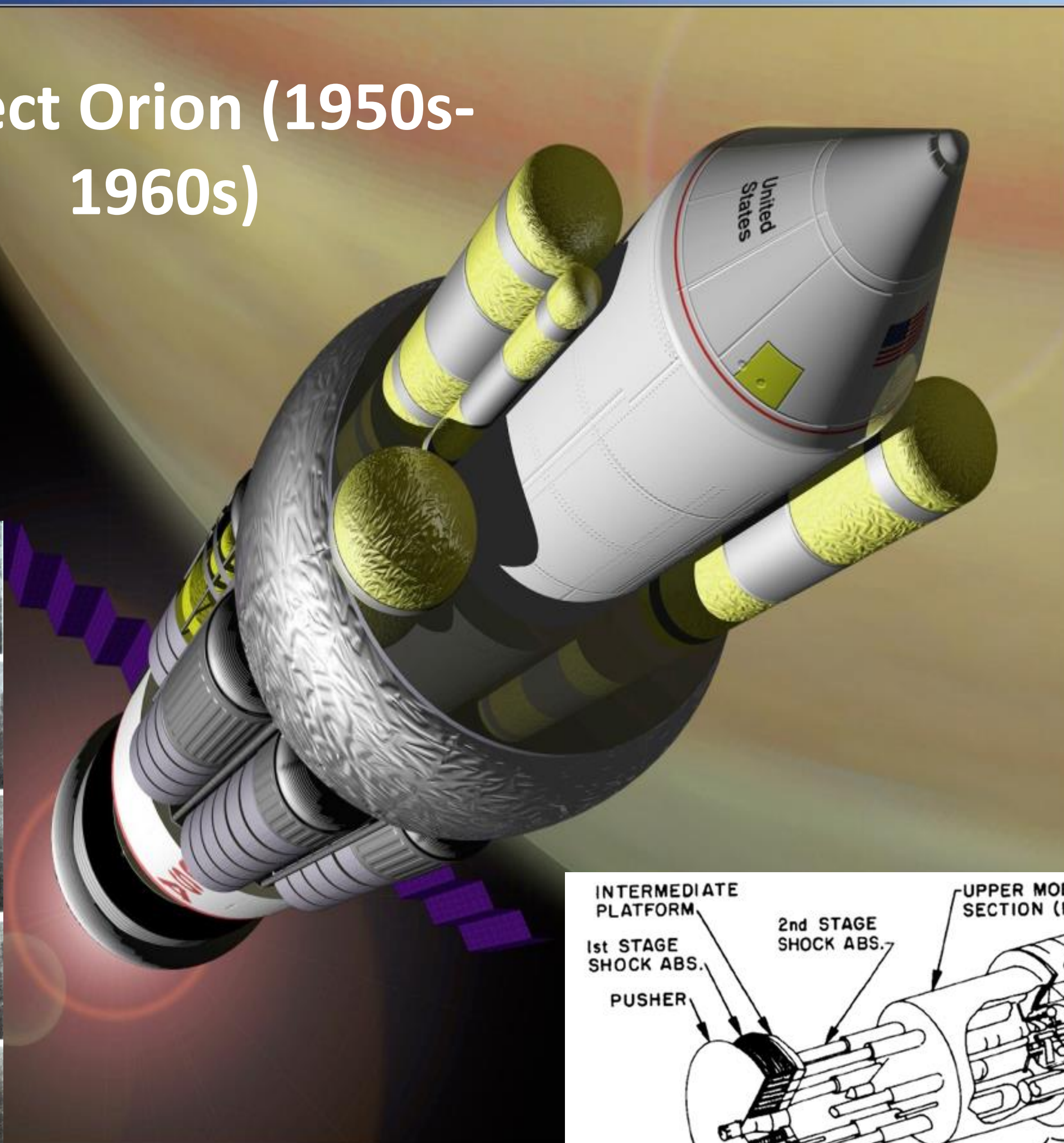
~18km/s, 3.8AU/year, Jan 06

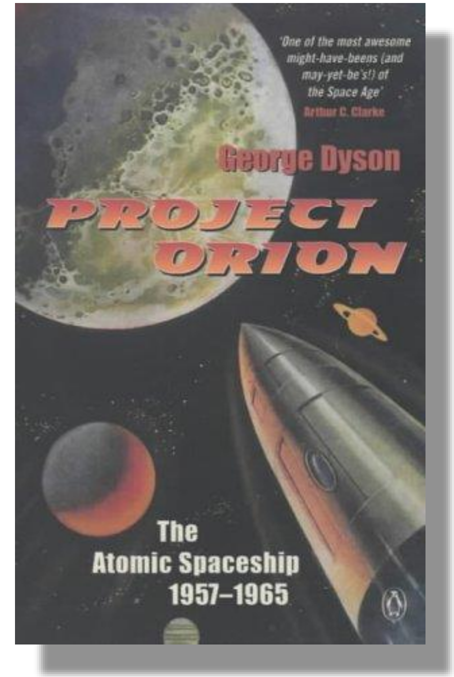
Why Fusion?

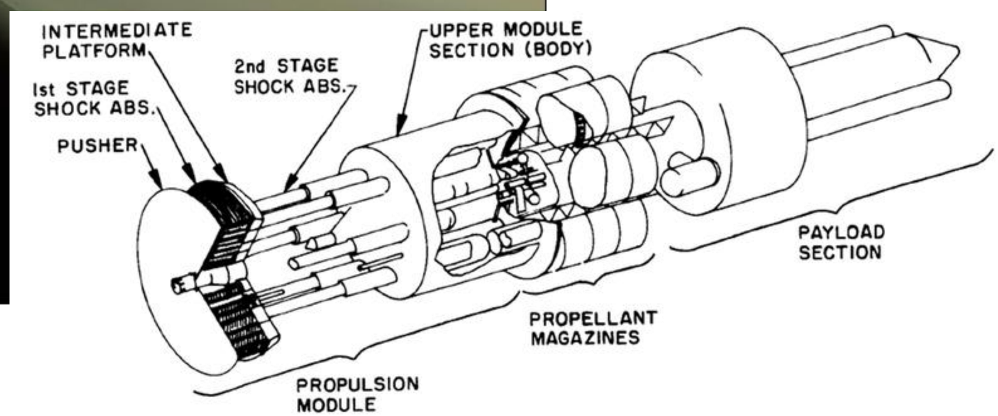
- Believed to give:
  - High Isp/Vex
  - Proven science & near term technology
- But Low T/W



Project Orion (1950s-1960s)



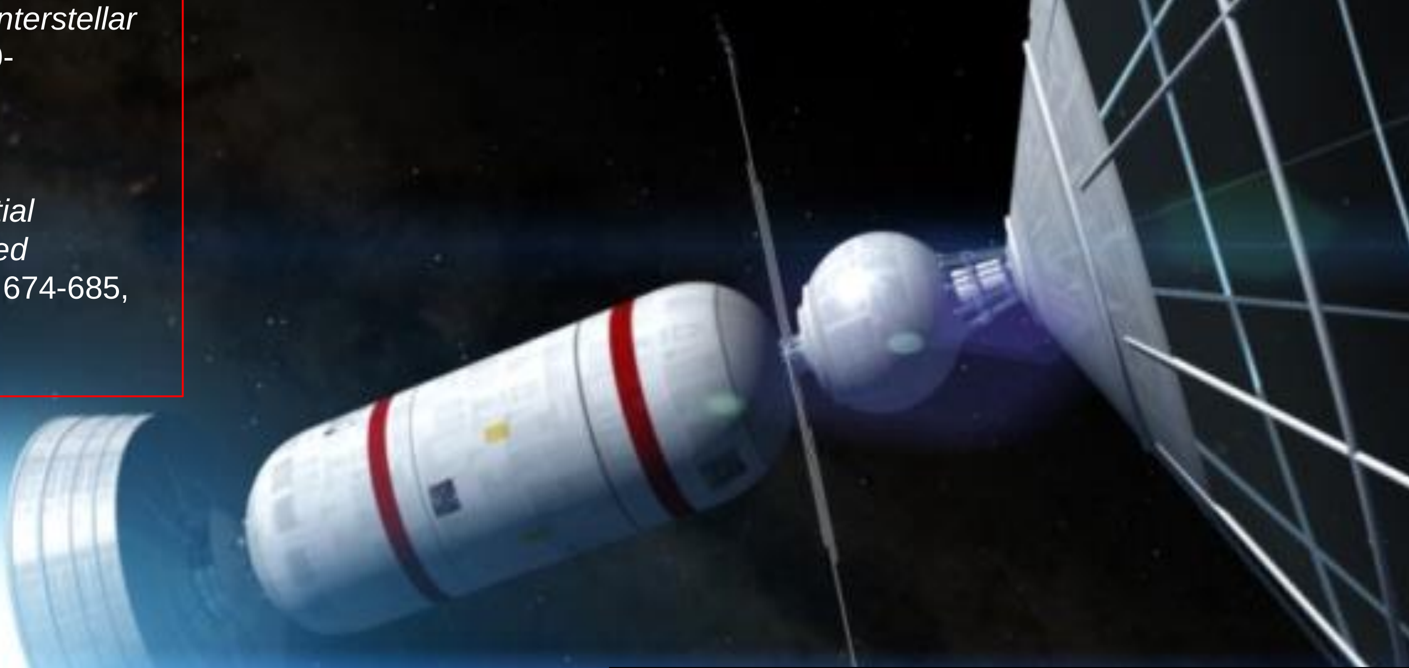


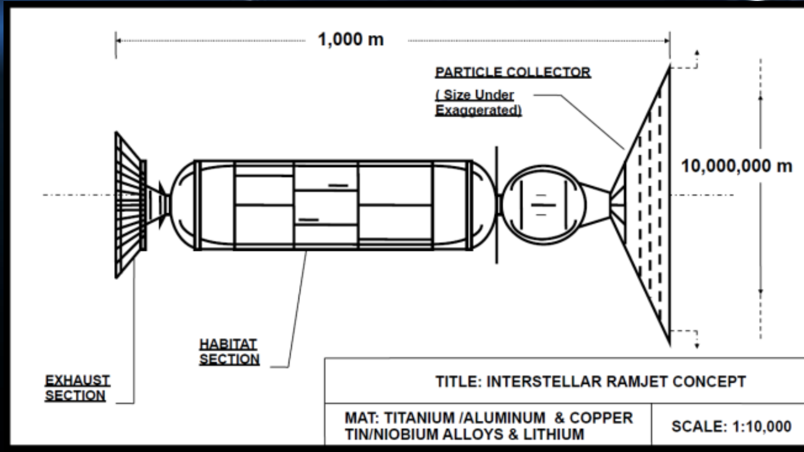


Interstellar Ramjet (1960)

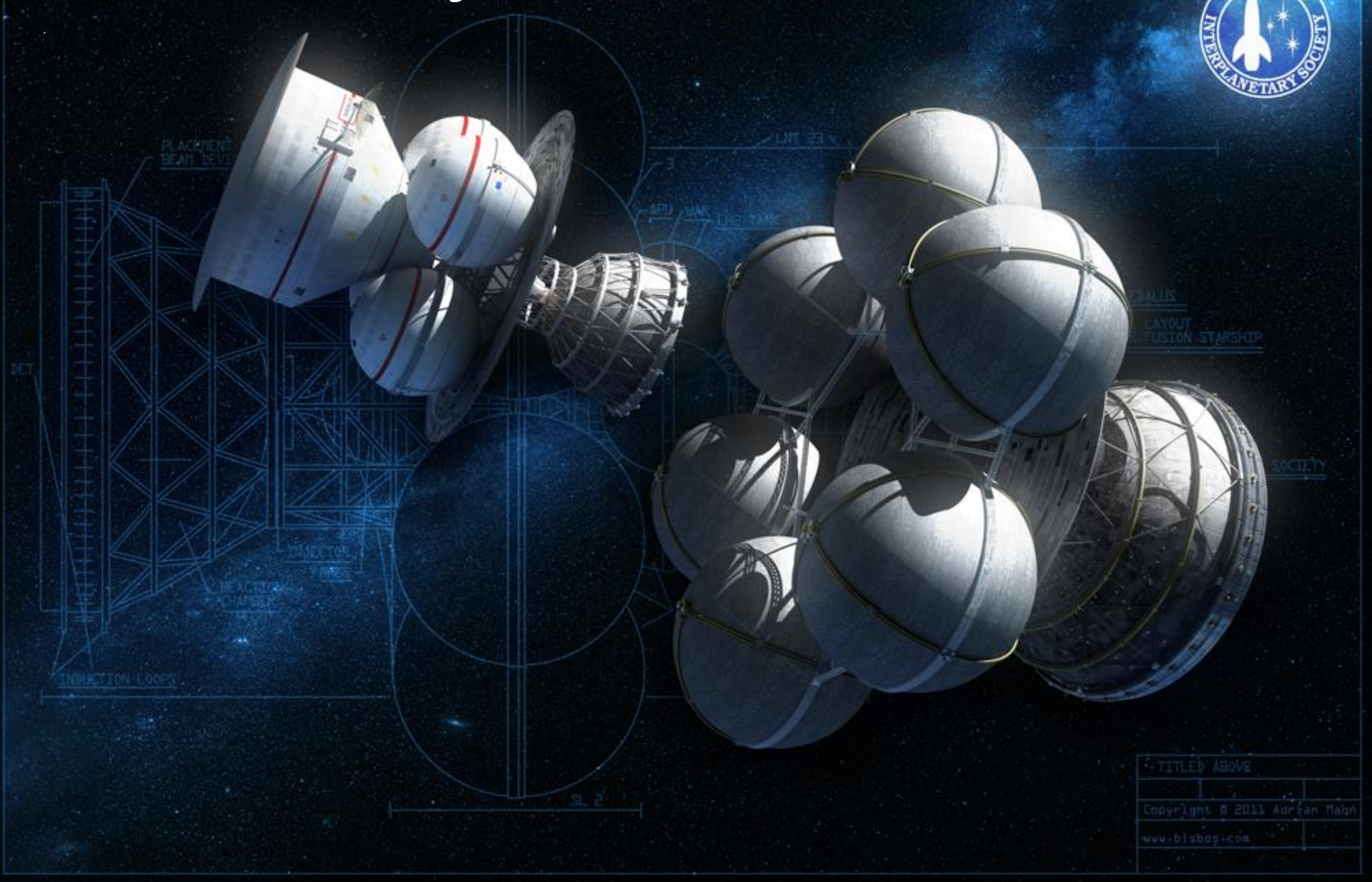
Bussard, R.W, *Galactic Matter & Interstellar Flight*, Astronautica Acta, 6, pp.170-194, Fasc.4,1960.

Bond, A. *An Analysis of the Potential Performance of the Ram Augmented Interstellar Rocket*, JBIS, 27, 9, pp.674-685, September 1974.





Project Daedalus

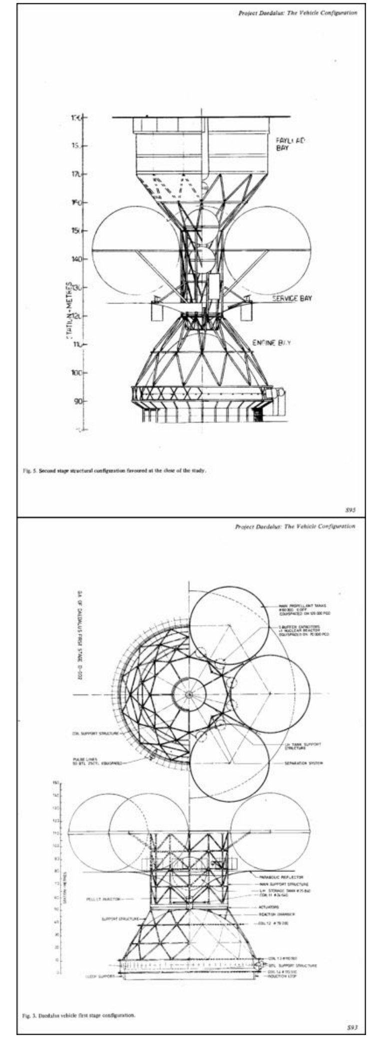


Adrian Mann (www.bisbos.com)

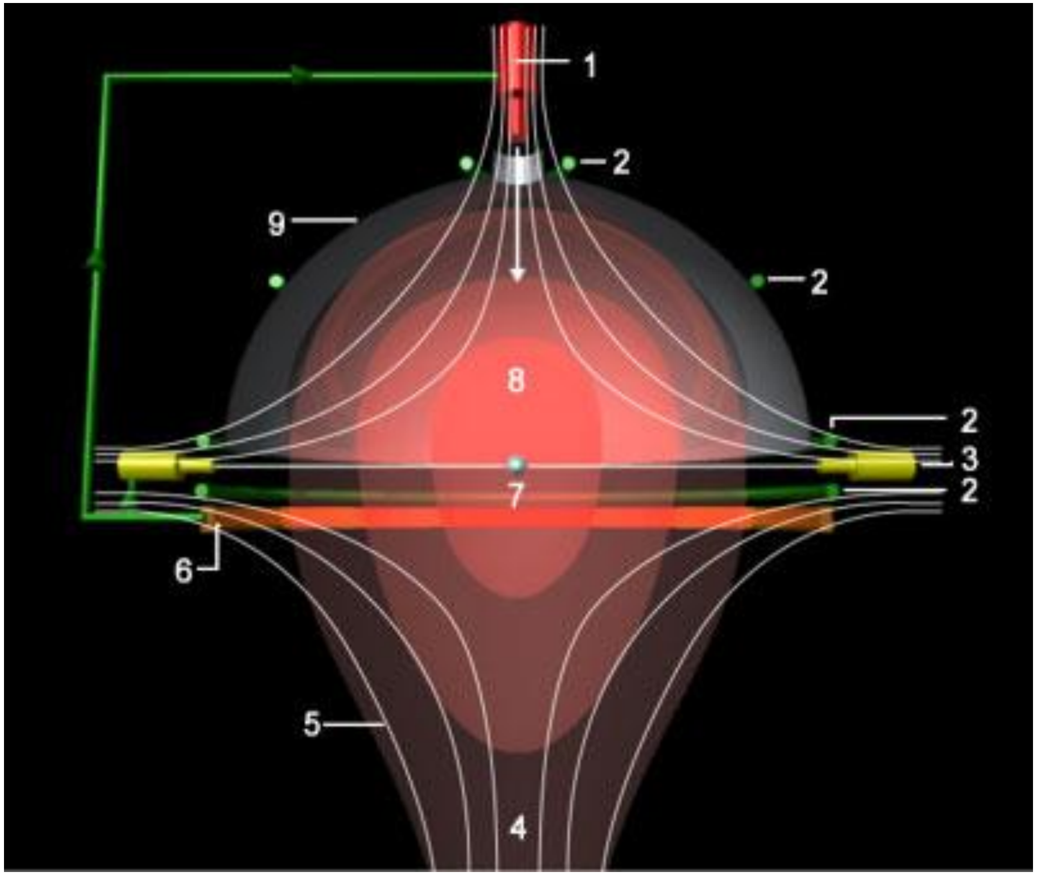
Project Daedalus

Fusion Spacecraft Design study

- Considered the challenges of interstellar travel
- Used current/near-future technology
- Reach destination within a human lifetime
- Allow for a variety of target stars



Inertial Compression Fusion – Daedalus style



1 Pellet injection gun
2 Superconducting field coils (4)
3 Electron beam generators
4 Plasma exhaust jet
5 Magnetic field
6 Energy extraction coils
7 Frozen nuclear pellet
8 Nuclear explosion
9 Reaction chamber

http://www.bisbos.com/space_n_daedalus_prop.html

Challenges for Daedalus

- Pellet trajectory
- Electron beams
- Tritium trigger
- Firing rate
- Pressurant Mass
- Fuel DHe3

Project Icarus

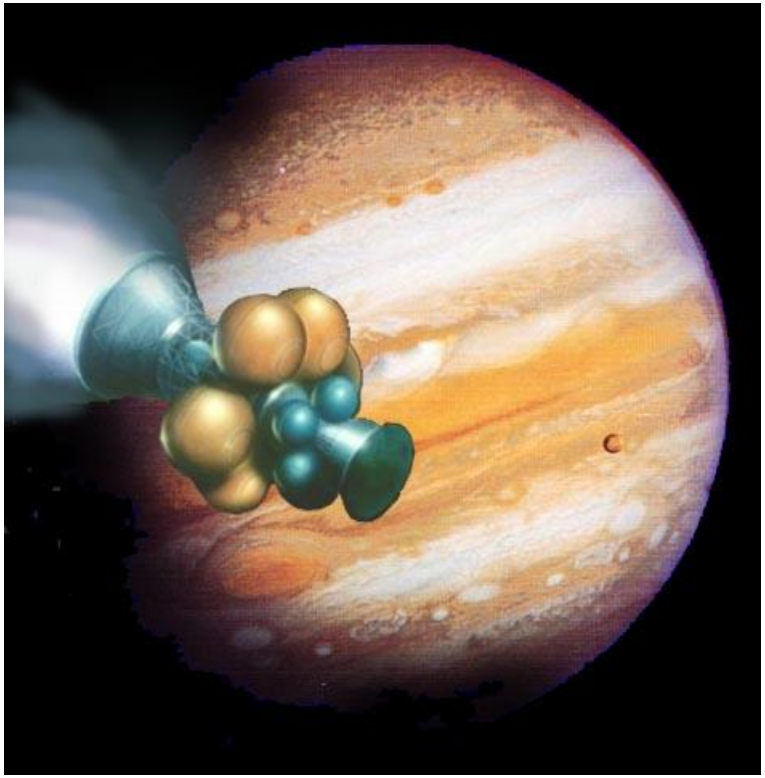
- British Interplanetary Society initiative originally in collaboration with Tau Zero Foundation

Purpose

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

Case Study: Fuel Acquisition

- Daedalus mission to mine He3 from the atmosphere of Jupiter
- Alternatives include
  - Solar wind
  - Asteroids
  - Comets
  - Accelerator
  - The Moon
  - Other planets or moons



Planet	Jupiter	Saturn	Uranus	Neptune
Distance (AU)	5.2	9.5	19.2	30.1
V_{escape} (km/s)	59.5	35.5	21.3	23.5
Atmosphere *	89%H, 10%He	95%H, 3%He	83%H, 15%He	80%H, 19%He

Early Thinking

- Daedalus and payload were too massive
- Jovian gas giant mining not ideal and would likely necessitate wide scale solar system economy first
- Pulse frequency too high
- Flyby not useful compared to future solar system based observations
- Also competing views
  - Eg Fast cruise (0.15-0.2c) versus slow cruise (<0.05c)
  - Eg Early design decisions versus late design decisions
  - Eg Massive space based infrastructure versus moderate infrastructure
  - Eg Flyby versus complete deceleration

Icarus Interstellar

Alaska Entity #: 133623

State of Alaska
Department of Commerce, Community, and Economic Development
Corporations, Business and Professional Licensing

CERTIFICATE OF INCORPORATION

RECEIVED
MAR 07 2011
PATTON BOGGS LLP

Nonprofit Corporation

THE UNDERSIGNED, as Commissioner of Commerce, Community, and Economic Development of the State of Alaska, hereby certifies that Articles of Incorporation duly signed and verified pursuant to the provisions of Alaska Statutes has been received in this office and have been found to conform to law.

ACCORDINGLY, the undersigned, as Commissioner of Commerce, Community and Economic Development, and by virtue of the authority vested in me by law, hereby issues this certificate to

Icarus Insterstellar

and attaches hereto the original copy of the Articles of Incorporation for such certificate.

THE SEAL OF THE STATE OF ALASKA

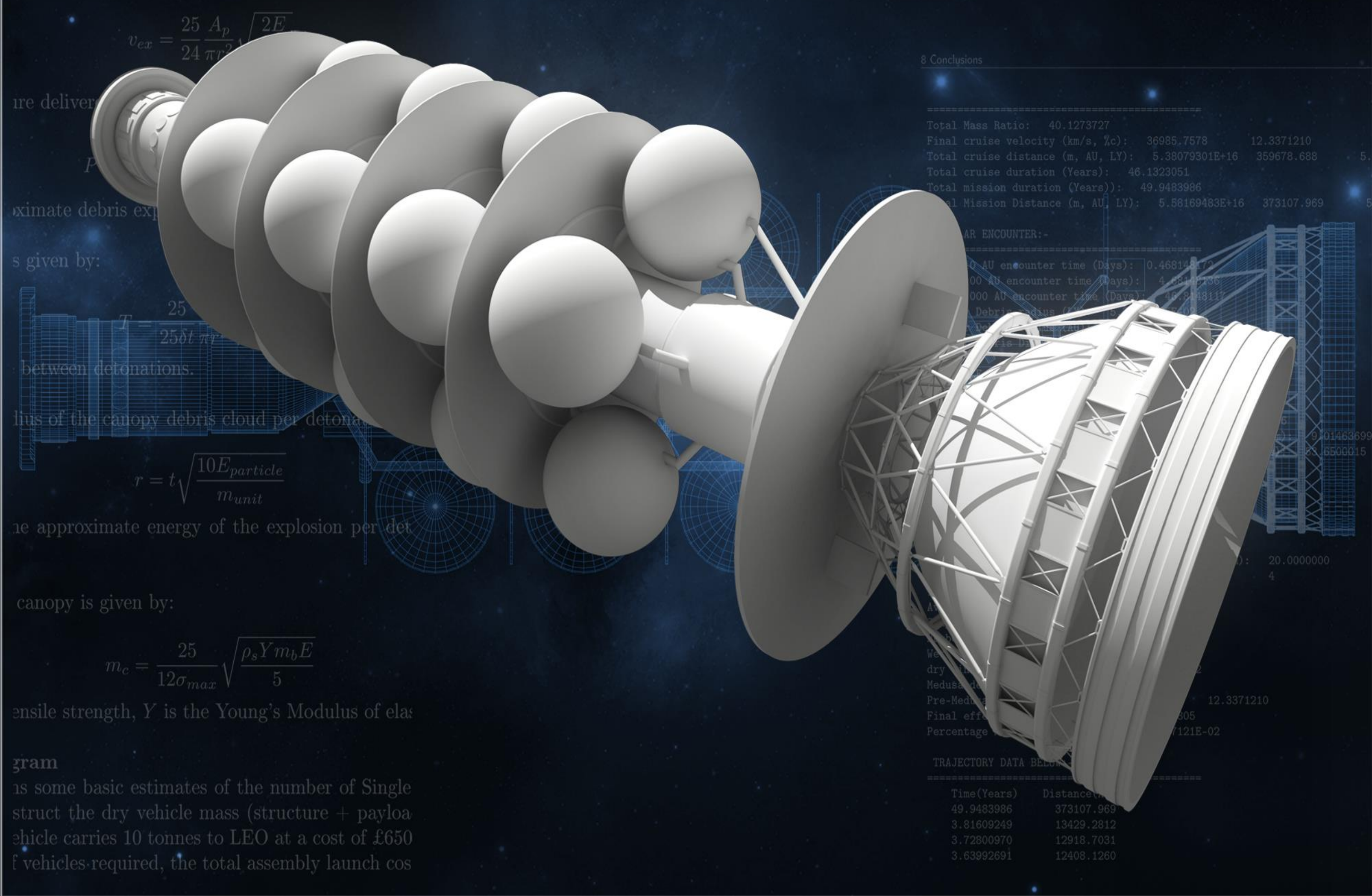
IN TESTIMONY WHEREOF, I execute this certificate and affix the Great Seal of the State of Alaska on **February 4, 2011.**

Susan Bell
Commissioner

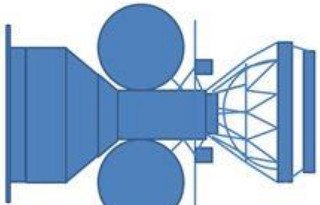
Concept Design Competition

- Key parameters – propulsion system and fuel
- Concept Design workshop 9 months later at the BIS HQ

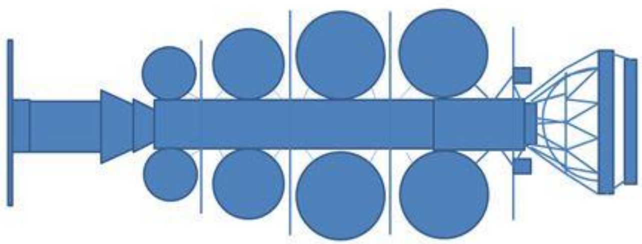
Project Icarus – Resolution



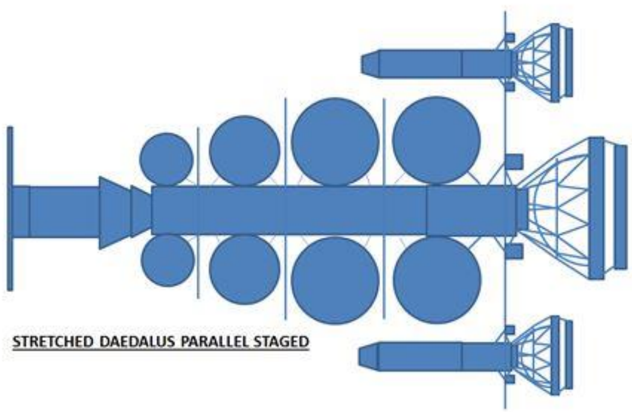
Resolution



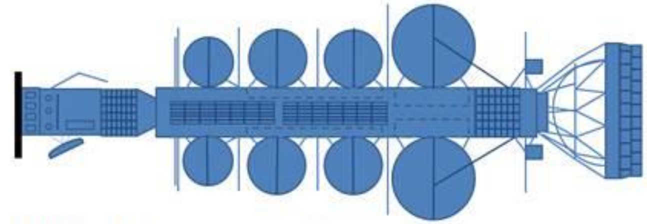
DAEDALUS SECOND STAGE



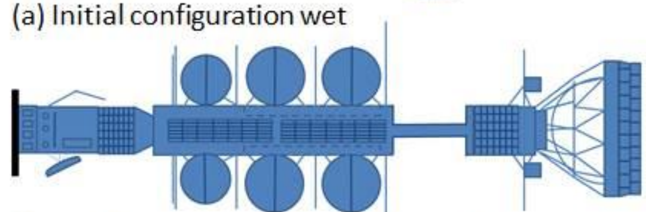
STRETCH DAEDALUS



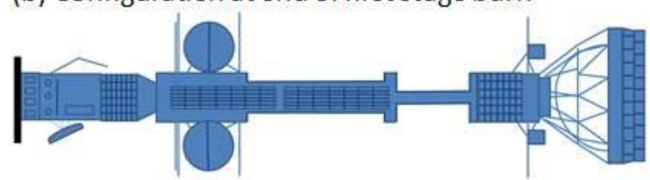
STRETCHED DAEDALUS PARALLEL STAGED



(a) Initial configuration wet

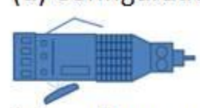


(b) Configuration at end of first stage burn



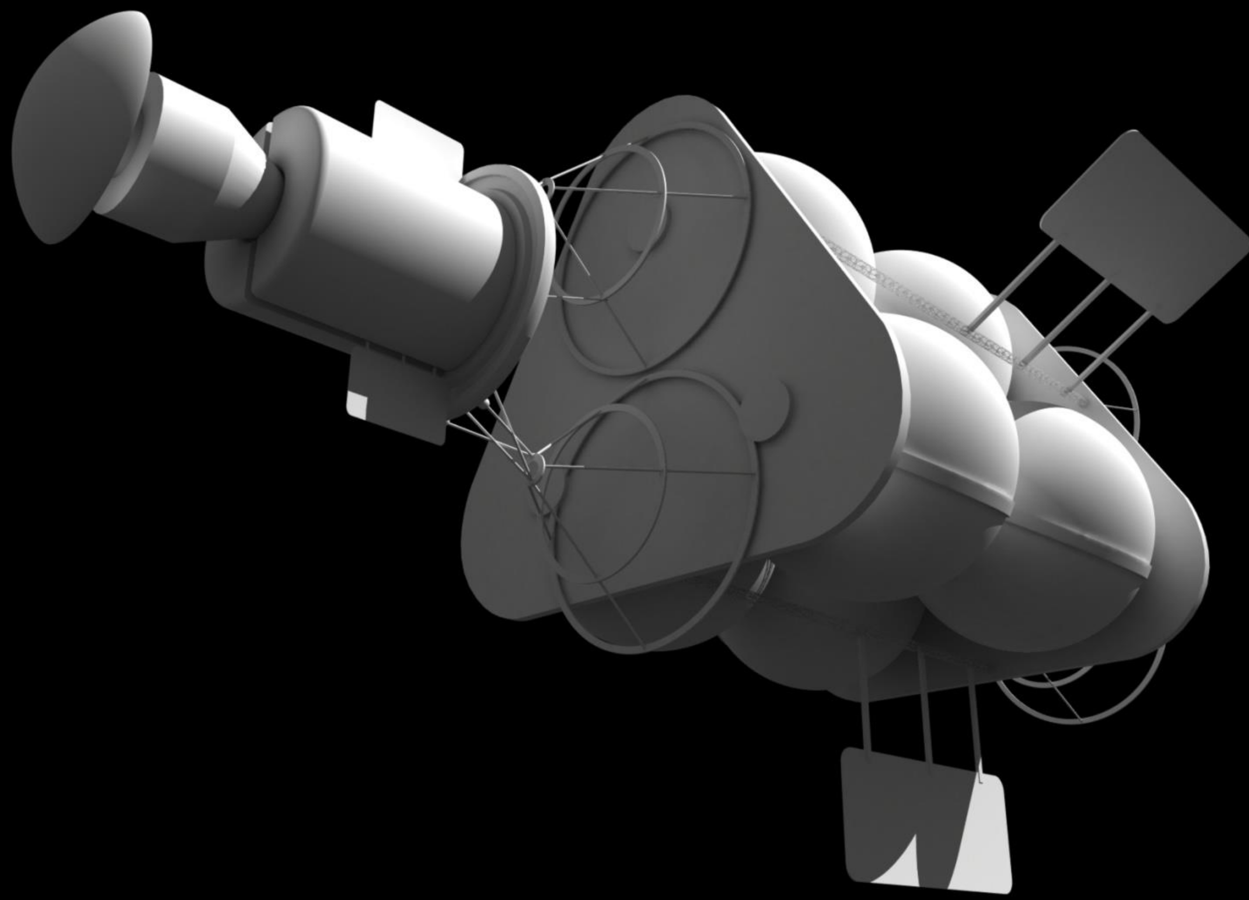
(c) Configuration at end if second and third stage burn

(d) Configuration at end of fourth stage deburn

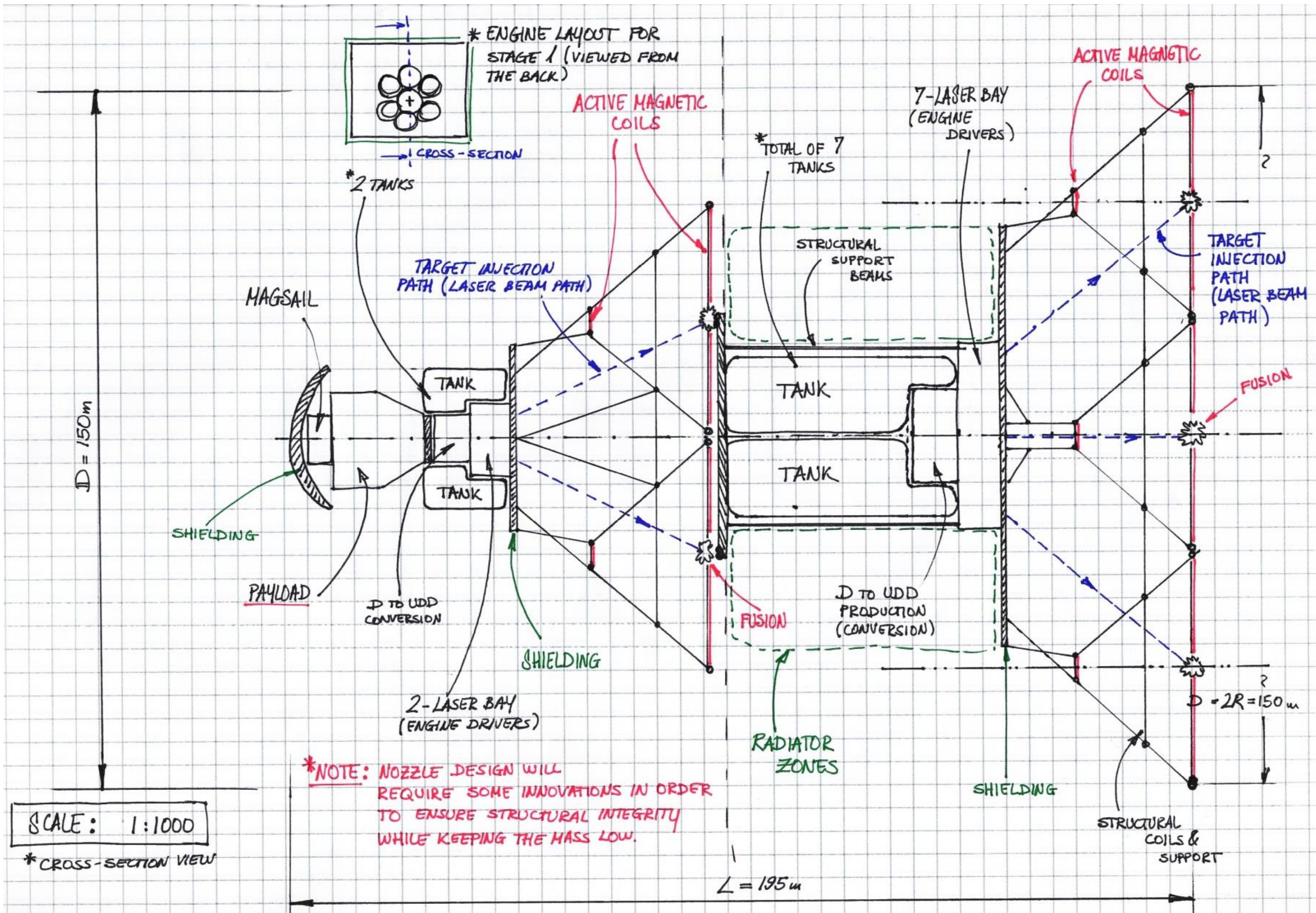


(e) Configuration at Stellar Exploration Phase

Project Icarus – UDD Concept



UDD Concept

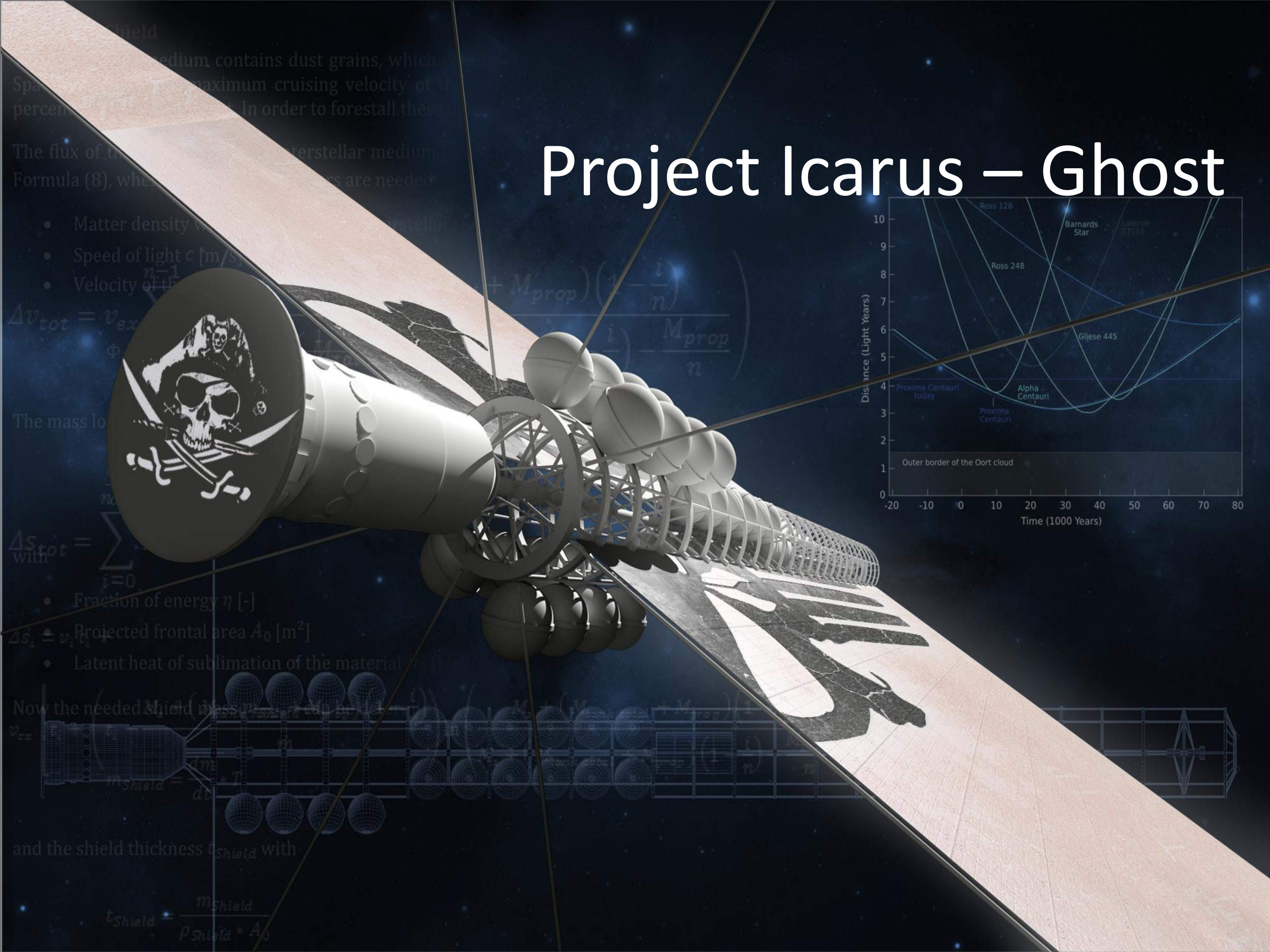


* ENGINE LAYOUT FOR STAGE 1 (VIEWED FROM THE BACK)
CROSS-SECTION
*2 TANKS
ACTIVE MAGNETIC COILS
*TOTAL OF 7 TANKS
7-LASER BAY (ENGINE DRIVERS)
ACTIVE MAGNETIC COILS
STRUCTURAL SUPPORT BEAMS
TARGET INJECTION PATH (LASER BEAM PATH)
MAGSAIL
TARGET INJECTION PATH (LASER BEAM PATH)
TANK
TANK
TANK
TANK
FUSION
D = 150m
SHIELDING
PAYLOAD
D TO UDD CONVERSION
FUSION
D TO UDD PRODUCTION (CONVERSION)
SHIELDING
2-LASER BAY (ENGINE DRIVERS)
D = 2R = 150 m
RADIATOR ZONES
SHIELDING
*NOTE: NOZZLE DESIGN WILL REQUIRE SOME INNOVATIONS IN ORDER TO ENSURE STRUCTURAL INTEGRITY WHILE KEEPING THE MASS LOW.
SCALE: 1:1000
*CROSS-SECTION VIEW
STRUCTURAL COILS & SUPPORT
L = 195 m

UDD Concept

- Advantages:
  - Circumvent compression stage, allows direct ignition (absence of hydrodynamic instabilities and reduced plasma-laser interaction consequences).
  - Single PW-scale laser ignition reduces the system complexity, mass.
  - Gains depend solely on the size of the target.
  - Uses D and converts it to UDD on-board; D is abundant, stable, non-toxic and magnitudes cheaper to produce than i.e. ^{3}He.
  - Allows for multi-engine, modular design which greatly increases overall system robustness and reliability,
- Disadvantages:
  - Is UDD real?
- **IF** it is: could be a winner.

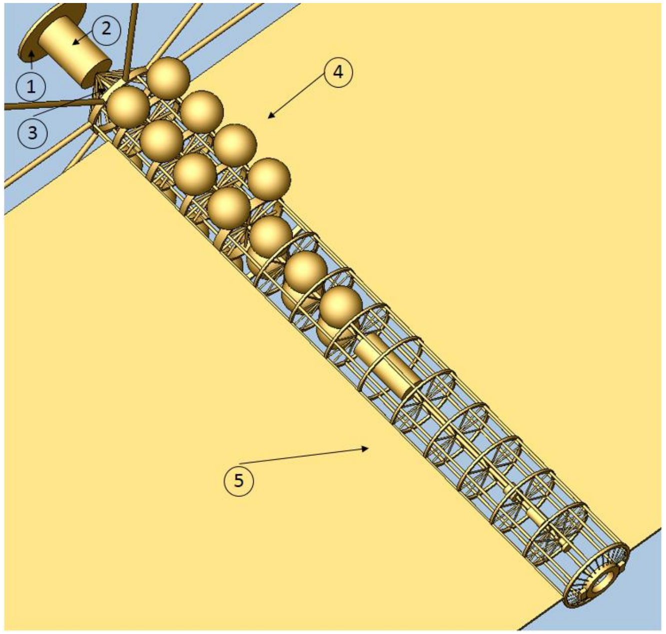
Project Icarus – Ghost




POINTS:
DESIGN: GHOST
BUS
BOTH GO ON
IN DETAIL
POWER CONVERSION
COMMUNICATIONS
POWER
THE BRITISH
INTERPLANETARY SOCIETY

Basic Characteristics

Characteristic	Selection / Value
Fusion stages	1 for acceleration & deceleration
Decelaration propulsion	Magnetic sail
Fusion scheme	Deuterium – Deuterium
Fusion Isp	540,240 s
Mission duration	100 years
Overall mass	153,940 tonnes
Payload mass	150 tonnes
Dry mass	3351 tonnes



Configuration
1. Dust Shield
2. Payload
3. Magnetic Sail
4. Tank Sections
5. Radiators

Revised Ghost Mission Design

- Optimum via Trade Space Analysis
- Duration = 118.5 years

	Acceleration	Cruising phase	Deceleration MagSail	Deceleration fusion	Target system operation
Distance	0.37 ly	3 ly	0.02 ly	0.0024 ly	-
End velocity	5% c	-	3470 km/s	150 km/s	-
Duration	25.63 y	56.43 y	36 y	0.229 y	-

Revised Ghost Mass Budget

Spacecraft element	Mass [mt]
Tank mass	**927**
Payload mass	**150**
Sub system mass	**4670**
Magnetic Sail	1785
Truss structure	200
Dust shield	15
Power	20
Communication	40
ADCS	40
Tritium production (deceleration)	95
D/T tanks, pellet manufacturing, transport	20
Radiators	2500
Fusion engine mass	**11144**
Laser system (Laser, Sphere, Light Tubes, Ampl.)	1000
Coils	500
UO2	*9537*
Neutron shield	82
Accelerator	25
Spacecraft dry mass	**7444**
Propellant mass	**247100**
Acceleration	242,500
Deceleration	4600
Spacecraft total start mass	**263991**

PROPULSION: PLASMA JET MAGNETO-INERTIAL FUSION - ZEUS

The PJMIF propulsion model is a 3 stage system without any moving parts, relying largely on magnetism to produce and direct a nuclear fusion reaction.

The key structural components are a near-parabolic nozzle, 150 plasma jet rail guns, 2 theta pinch guns, and a system of superconductor coils.

PJMIF uses these components to form a plasma pellet, pressurize it with a liner until fusion occurs, and evacuate the reacted particles by means of a magnetic field.

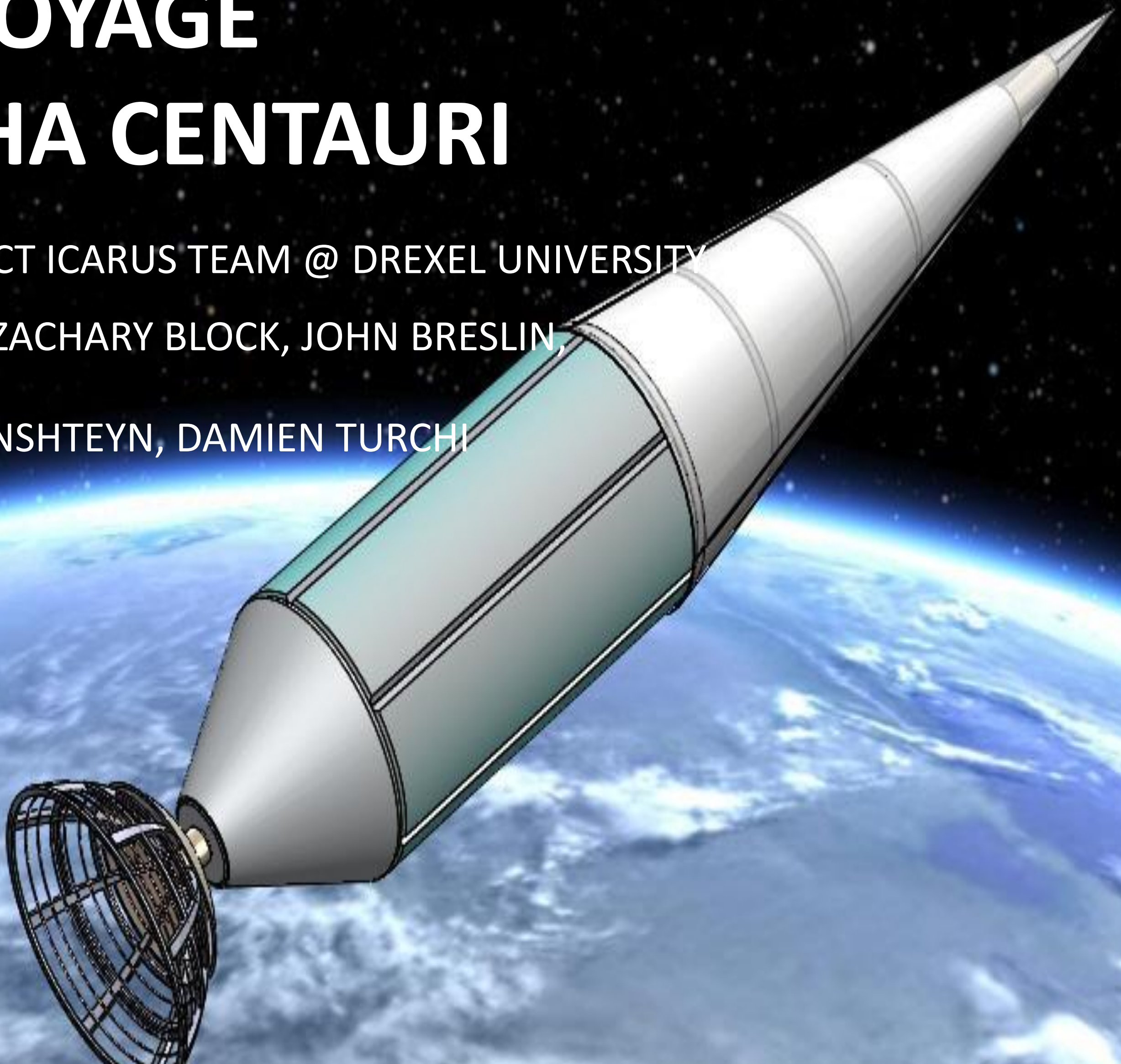
This process has the potential to produce unprecedented amounts of thrust.

AN INTERSTELLAR VOYAGE TO ALPHA CENTAURI

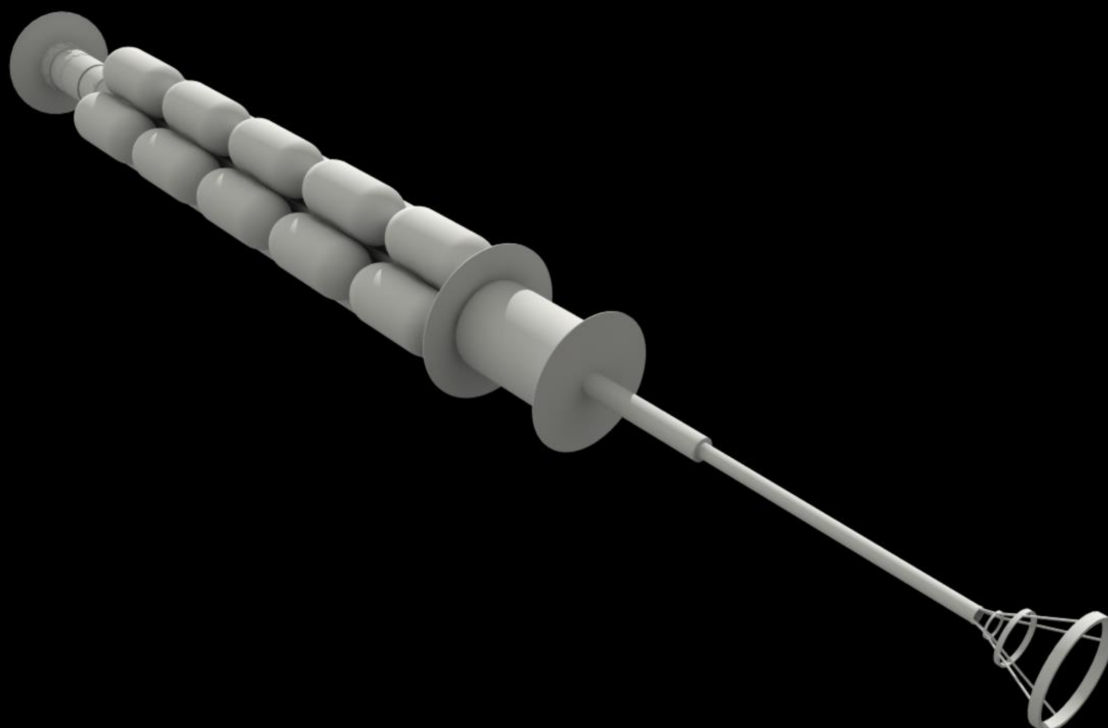
CREATED BY: THE PROJECT ICARUS TEAM @ DREXEL UNIVERSITY

PRESENTED BY: ZACHARY BLOCK, JOHN BRESLIN,

DAVID EVINSHTEYN, DAMIEN TURCHI



Project Icarus - Firefly



Natural Pinches

Pinches occur naturally, with the most familiar being lightning.

The copper tube at the right (currently on display at the School of Physics, University of Sydney, Australia) was studied by Pollock and Barraclough in 1905 after it was struck by lightning.

Shumlak's ZaP Experiment

The ZaP Experiment was constructed in Shumlak's lab at the University of Washington to confirm that sheared flow really does stabilize a Z-pinch.

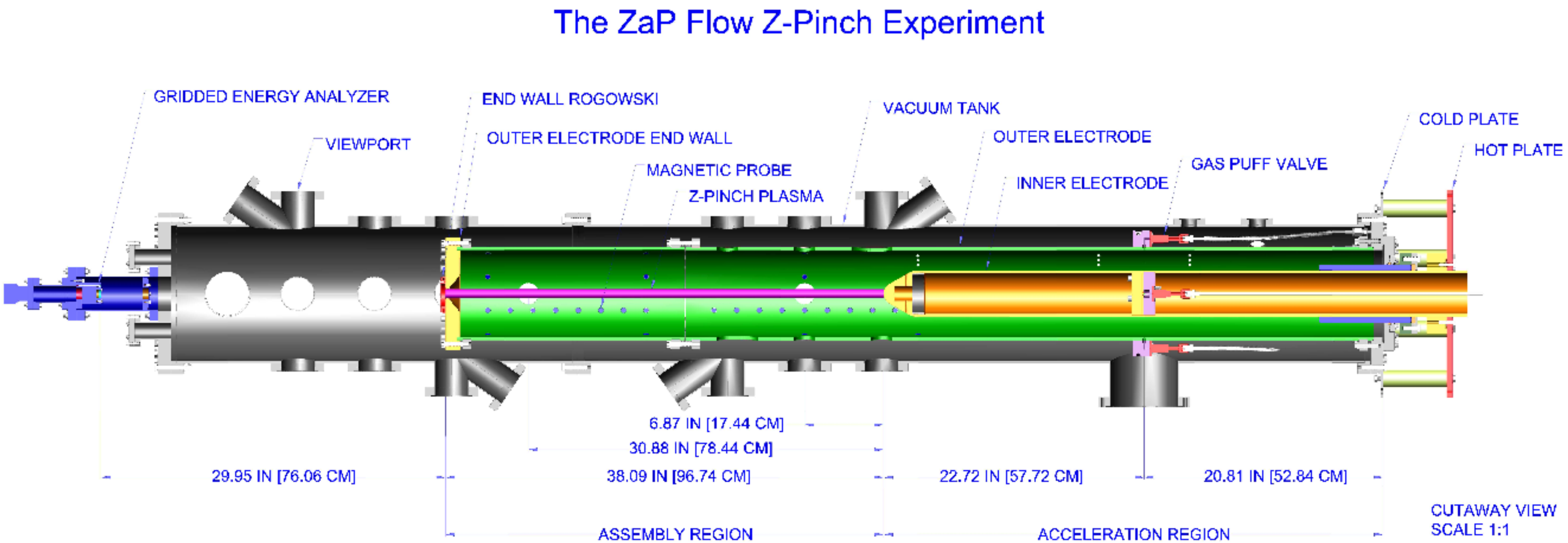
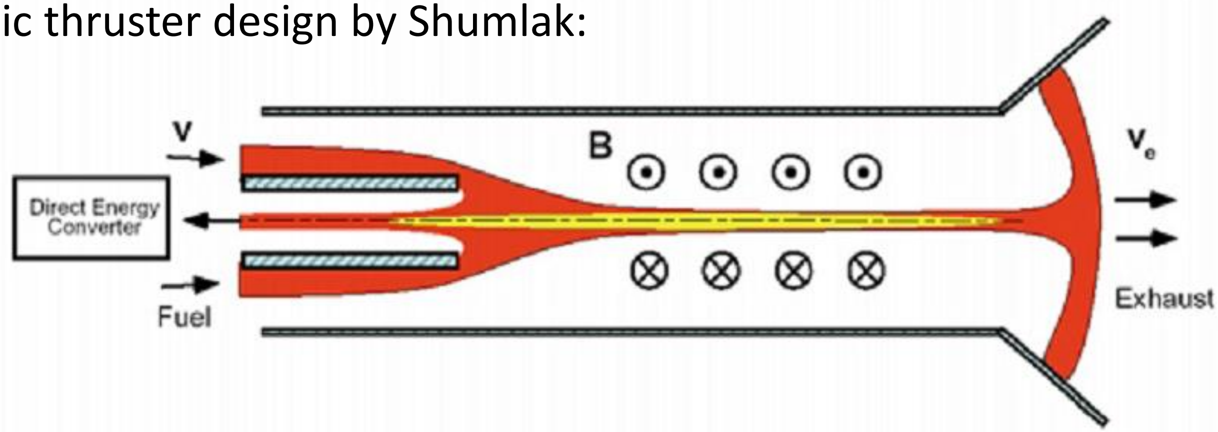


Image courtesy of Sean Knecht, UAW (2008)

Basic Z-Pinch Thruster Designs

Simplistic thruster design by Shumlak:



Slightly different design from NASA's Marshall Space Flight Center:

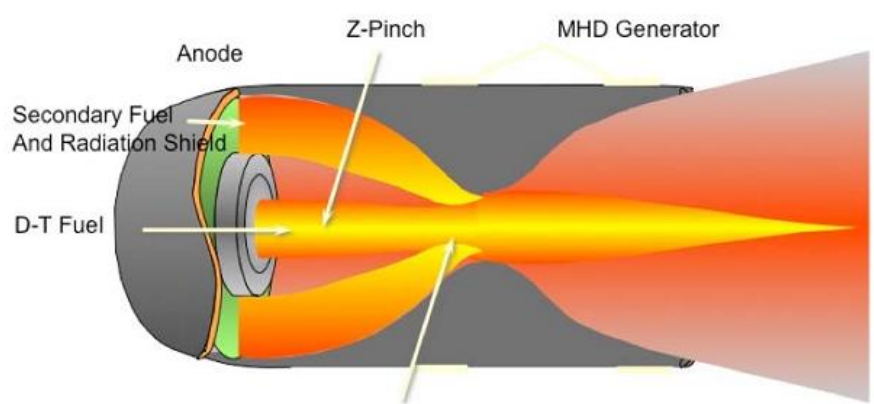


Image courtesy of Marshall Space Flight Center (2000)

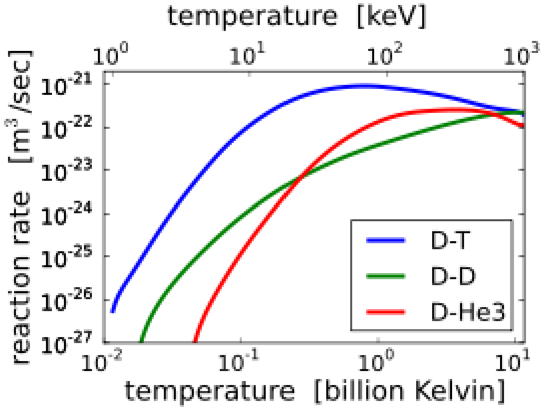
Most Updated is Firefly

Fuel Selection: DT vs. DD vs. DHe3

The three most commonly studied fusion reactions are as follows, ranked in order of difficulty:

D2	+	T3	?	He4	(3.49 MeV)	+	n^0	(14.1 MeV)
D2	+	D2	?	He3	(0.82 MeV)	+	n^0	(2.45 MeV)
			?	T3	(1.01 MeV)	+	p^+	(3.02 MeV)
D2	+	He3	?	He4	(3.6 MeV)	+	p+	(14.7 MeV)

DT is the easiest, but it releases most of its energy in fast neutrons that aren't usable for thrust. Tritium has a very short half-life anyway.



DHe3 is often considered as an alternative because it releases only charged particles, but unavoidable DD reactions generate neutrons anyway. And we can't get He3 here on Earth.

So Firefly uses **DD** fusion.

Waste Energy: Neutrons & X-Rays

DD Fusion generates a LOT of waste energy:

- Half of DD fusion reactions release a 2.45 MeV neutron.
- The other half of DD fusion reactions release a Tritium, which immediately reacts with Deuterium in the plasma to produce a 14.1 MeV neutron.
- Shielding these fast neutrons typically spawns energetic EM rays.
- Heating of electrons in the plasma produces Bremsstrahlung radiation, which is released in the form of X-rays.

Shielding any significant portion of this radiation would add prohibitive mass to the vessel, but an alternative is to **design the vessel so that most of this radiation escapes directly into space**.

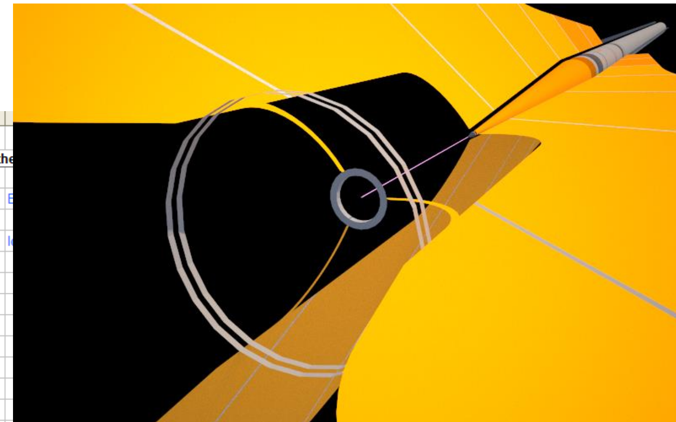
The challenge is that X-rays easily penetrate low-Z materials (which lack the large electron clouds), while neutrons easily penetrate high-Z materials (in which the nuclei are widely spaced by their electron clouds).

Firefly Engine

Time-Lapse Z-Pinch Fusion

Describes the mathematics of the Z-pinch fusion, and calculates radiation fluxes on various parts of the

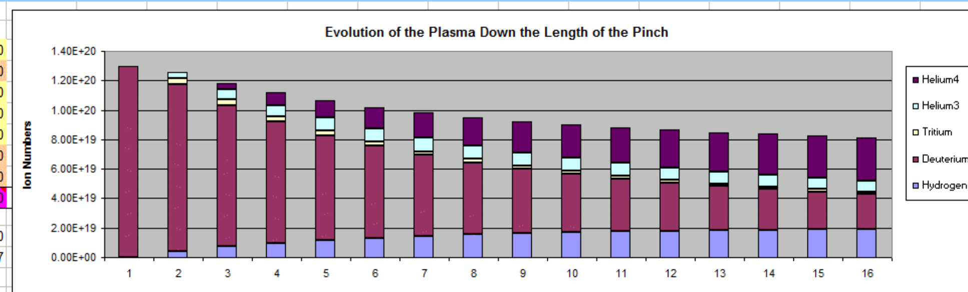
Row	B	C	D	E	F
4	**Assembly Region**				
5	Assembly Region Length	L_a	L	5.00	m
6	Inner Electrode Tip Radius	R_{et}		0.25	m
7	Inner Electrode Base Radius	R_{eb}	$R_{et} + L_a/10$	0.75	m
8	Slope of Electrode Wall	α_{ew}	$\mathrm{atan}((R_{eb}-R_{et})/L_a)$	5.71	degrees
9	MPD Thruster Plume Divergence	β_{MPD}		55.00	degrees
10	Input Plasma Layer Thickness	h	$(L_a^2+(R_{eb}-R_{et})^2)^{1/2} \tan(\beta_{MPD}/2)$	2.62	m
11	Height of Truncated Tip of Plume	x_1	$R_{eb} / \tan(\beta_{MPD}/2-\alpha_{ew})$	1.88	m
12	Height of Truncated Tip of Electrode	x_2	$R_{et} / \tan(\alpha_{ew})$	2.50	m
13	Input Plasma Volume	V_a	$(\pi/3)((L_a+x_1)(h^2-R_{eb}^2)-x_2(R_{eb}^2-R_{et}^2))$	43.91	m^3
14	Input Plasma Temperature	T_a		10,000	K



KEY RESULTS		
Debris Velocity	11,728	km/s
Exhaust Velocity	10,010	km/s
Specific Impulse	1.020	million s
Thrust	0.435	MN
Waste Energy	201.4	GW
Mass	1,557	tonnes
Thrust:Weight Ratio	280	N/tonne
Charged Particle Q	2.16	

Row	B	C	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
16	**Pinch Segment Length**	L	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	m
17	**Distance Down the Pinch**	D	0.00	5.00	10.00	15.00	20.00	25.00	30.00	35.00	40.00	45.00	50.00	55.00	60.00	65.00	70.00	75.00	m
18	**Burnup Fraction Achieved**	f_b	0.128	0.263	0.368	0.453	0.522	0.578	0.625	0.663	0.696	0.724	0.748	0.769	0.787	0.803	0.817		

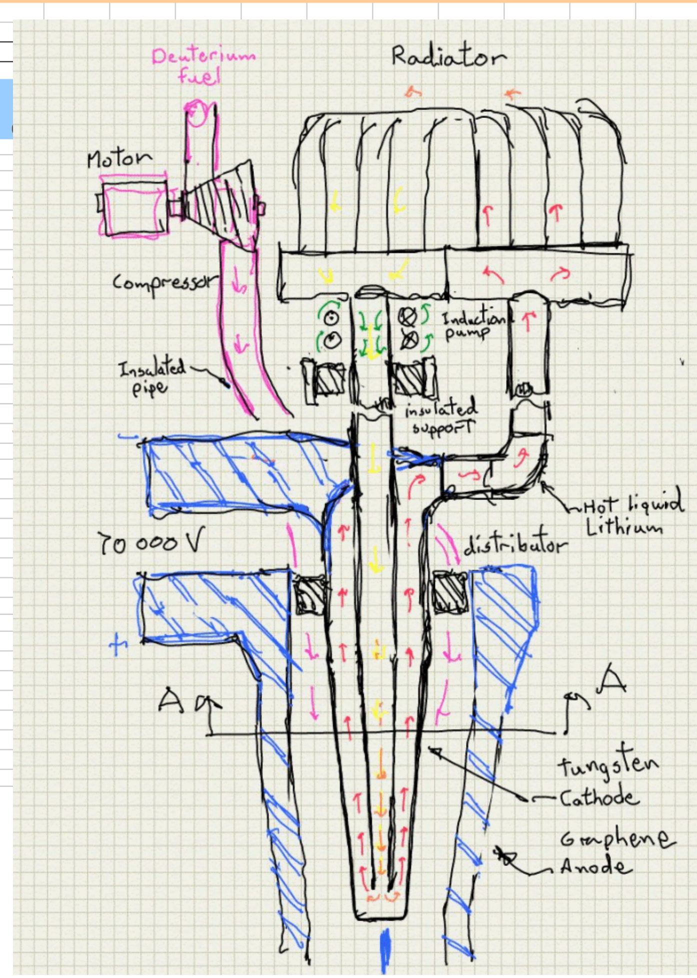
Row	B	C	D	E	T	U
20	**Plasma Species**					
21	Hydrogen Ions	N_H		0.00E+00	1.92E+19	
22	Deuterium Ions	N_D		1.30E+20	2.38E+19	
23	Tritium Ions	N_T		0.00E+00	1.47E+18	
24	He3 Ions	N_{He3}		0.00E+00	7.58E+18	
25	He4 Ions	N_{He4}		0.00E+00	2.94E+19	
26	Li6 Ions	N_{Li6}		0.00E+00	0.00E+00	
27	Li7 Ions	N_{Li7}		0.00E+00	0.00E+00	
28	Total Ions	N_t		1.30E+20	8.14E+19	
30	Average Atomic Number	Z	$\Sigma_i (Z_i N_i) / N_t$	1.00	1.45	
31	Average Ion Mass	m	$\Sigma_i (m_i N_i) / N_t$	3.34E-27	4.33E-27	kg



Row	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
33	**Pinch Region**																			
34	Linear Number Density	N		2.60E+19	2.52E+19	2.36E+19	2.24E+19	2.13E+19	2.04E+19	1.97E+19	1.90E+19	1.85E+19	1.80E+19	1.76E+19	1.73E+19	1.70E+19	1.67E+19	1.65E+19	1.63E+19	ions/m
35	Axial Flow Speed	v_z		500,000	508,222	524,169	538,215	550,469	561,135	570,424	578,531	585,626	591,859	597,357	602,227	606,559	610,429	613,899	617,025	m/s
36	Particle Flow Rate	n_d		1.30E+25	1.28E+25	1.24E+25	1.20E+25	1.17E+25	1.15E+25	1.12E+25	1.10E+25	1.08E+25	1.07E+25	1.05E+25	1.04E+25	1.03E+25	1.02E+25	1.01E+25	1.00E+25	ions/s
37	Mass Flow Rate	m_d		0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	0.043	kg/s
39	Pinch Current	I		4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10	MA
40	Pinch Temperature	T_p	$\mu_0 I^2 / (8\pi N k_B(1+Z))$	100.9	102.5	106.0	109.3	112.4	115.1	117.6	119.8	121.8	123.6	125.2	126.7	128.0	129.2	130.3		keV
42	Pinch Volume	V_p	$V_a [C_p N T_a(1+Z)]^{3/2} / I^3$	1.10E-06	1.07E-06	1.02E-06	9.72E-07	9.33E-07	8.99E-07	8.71E-07	8.47E-07	8.26E-07	8.08E-07	7.93E-07	7.79E-07	7.67E-07	7.56E-07	7.47E-07		m^3
43	Pinch Cross-Section	A_p	V_p/L	2.19E-07	2.14E-07	2.03E-07	1.94E-07	1.87E-07	1.80E-07	1.74E-07	1.69E-07	1.65E-07	1.62E-07	1.59E-07	1.56E-07	1.53E-07	1.51E-07	1.49E-07		m^2
44	Pinch Radius	a	$(A_p/\pi)^{1/2}$	0.264	0.261	0.255	0.249	0.244	0.239	0.236	0.232	0.229	0.227	0.225	0.223	0.221	0.219	0.218		mm
45	Pinch Volume	V_p	$\pi a^2 L$	1.10E-06	1.07E-06	1.02E-06	9.72E-07	9.33E-07	8.99E-07	8.71E-07	8.47E-07	8.26E-07	8.08E-07	7.93E-07	7.79E-07	7.67E-07	7.56E-07	7.47E-07		m^3
46	Number Density	n_p	$N/A_p = N_t/V_p$	1.19E+26	1.18E+26	1.16E+26	1.15E+26	1.14E+26	1.13E+26	1.13E+26	1.12E+26	1.12E+26	1.12E+26	1.11E+26	1.11E+26	1.11E+26	1.11E+26	1.10E+26		ions/m^3

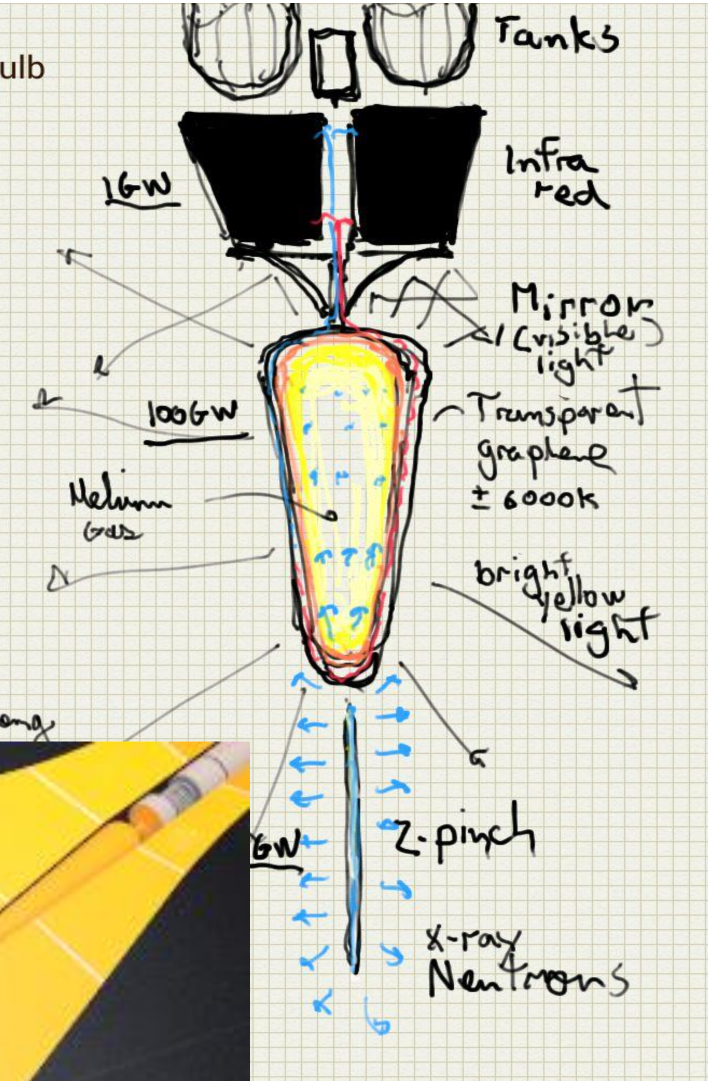
Firefly Engine

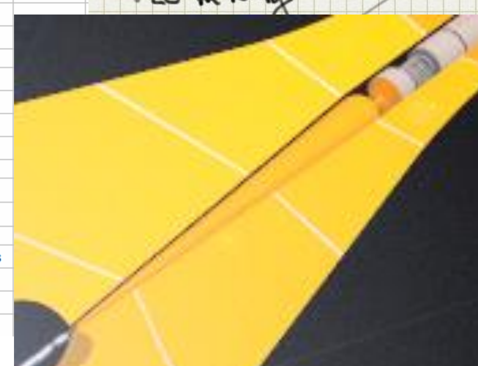
	A/B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	**Time-Lapse Z-Pinch Fusion**																				
2	**Describes the mathematics of the Z-pinch fusion, and calculates radiation fluxes on various parts of the vessel.**																				
101																					
102	Ionization Power	P_Ω	$I^2 \eta L / \pi a^2$	12	13	13	14	15	15	16	16	16	17	17	17	17	18	18	234	GW	
103	Thermal Power	P_{th}	$3n k_B T v_z \pi a^2$	630	10	21	19	17	15	13	12	10	9	8	24	22	20	18	849	GW	
104	Flow Power	P_{flow}	$0.5 m_d v_z^2 = 0.5 m n v_z^3 \pi a^2$	5															5	GW	
105	Radiative Power	P_{rad}	$(1.69e\text{-}38) \Sigma_i(Z_i^2 N_i) n_e T_e^{1/2}$	83	91												183	186	2,190	GW	
106	Input Power	P_{in}	$P_{th} + P_{flow} + P_{rad}$	719	101												202	203	3,044	GW	
107																					
108	Charged Particle Gain	Q_{ch}	P_{ch} / P_{in}	0.5	6.9												1.2	1.1	2.2		
109	Fusion Gain	Q	P_f / P_{in}	0.7	16.4												1.8	1.6	3.9		
110	Burnup Fraction	f_b	$E_f / E_{fmax} = 0.5 n <\sigma v>_{DT} L / v_z$	0.128	0.263												0.803	0.817	0.817		
111																					
112	**Radiation Fluxes**																				
113	Distance Segment to Assembly	D_a		2.5	7.5												67.5	72.5		m	
114	Distance Segment to Hot Tank	D_t	D_a+L_a	7.5	12.5												72.5	77.5		m	
115	Distance Segment to Shield	D_s	D_t+L_t	187.5	192.5												252.5	257.5		m	
116	Distance Segment to Nozzle1	D_{n1}	$((D-D_a)^2 + R_{n1}^2)^{1/2}$	72.7	67.7												9.0	5.6		m	
117	Distance Segment to Nozzle2	D_{n2}	$((D-D_a+D_{n12})^2 + R_{n2}^2)^{1/2}$	100.7	95.8												41.0	37.2		m	
118	Distance Segment to End of Fin	D_f	$(D-D_a)+D_{n12}+D_{tail}$	137.5	132.5												72.5	67.5		m	
119																					
120	Angle Subtended by Electrode Tip	α_{et}	$atan(R_{et}/D_a)$	5.7	1.9												0.2	0.2		degrees	
121	Angle Subtended by Electrode Base	α_{eb}	$atan(R_{eb}/D_t) - atan(R_{et}/D_a)$	0.0	1.5												0.4	0.4		degrees	
122	Angle Subtended by Hot Tank	α_t	$atan(R_{tb}/D_s) - atan(R_{tt}/D_t)$	0.0	0.0												1.6	1.6		degrees	
123	Angle Subtended by Shield	α_s	$atan(R_s/D_s) - atan(R_{tb}/D_s)$	0.1	0.1												0.1	0.1		degrees	
124	Angle Subtended by Nozzle1	α_{n1}	$atan(D_{nr}/D_{n1})$	0.5	0.5												3.9	6.2	86.2	degrees	
125	Angle Subtended by Nozzle2	α_{n2}	$atan(D_{np}/D_{n2})$	0.3	0.4												0.8	0.9	31.0	degrees	
126	Angle Subtended by Radiator Fin	α_{rx}	$\pi\text{-}atan(R_{n2}/D_f)$	169.7	169.3												161.0	159.7		degrees	
127																					
128	Neutron Power on Electrode Tip		$P_n * (\alpha_{et}/\pi)$	5.2	10.3												0.1	0.1	29.3	GW	
129	Neutron Power on Electrode Base		$P_n * (\alpha_{eb}/\pi)$	0.0	8.2												0.3	0.2	27.3	GW	
130	Neutron Power on Hot Tank		$P_n * (\alpha_t/\pi)$	0.0	0.0												1.1	0.9	25.9	GW	
131	Neutron Power on Shield		$P_n * (\alpha_s/\pi)$	0.1	0.4												0.0	0.0	2.0	GW	
132	Neutron Power on Nozzle1		$P_n * (\alpha_{n1}/\pi)$	0.4	2.8												2.6	3.6	28.4	GW	
133	Neutron Power on Nozzle2		$P_n * (\alpha_{n2}/\pi)$	0.3	2.0												0.6	0.5	13.7	GW	
134	Neutron Power on Radiator Fin		$P_n * (\alpha_{rx}/\pi) * (\alpha_{ry}/2\pi)$	0.5	3.2												0.4	0.3	16.8	GW (x3)	
135																			**177.1**	GW	**Waste**
136																					**Energy**
137	Radiative Power on Electrode Tip		$P_{rad} * (\alpha_{et}/\pi)$	2.6	1.0												0.2	0.2	8.1	GW	37.4 GW
138	Radiative Power on Electrode Base		$P_{rad} * (\alpha_{eb}/\pi)$	0.0	0.8												0.4	0.4	7.7	GW	35.0 GW
139	Radiative Power on Hot Tank		$P_{rad} * (\alpha_t/\pi)$	0.0	0.0												1.6	1.7	15.9	GW	3.5 GW
140	Radiative Power on Shield		$P_{rad} * (\alpha_s/\pi)$	0.0	0.0												0.1	0.1	0.8	GW	3.7 GW
141	Radiative Power on Nozzle1		$P_{rad} * (\alpha_{n1}/\pi)$	0.2	0.3												3.9	6.4	22.0	GW	50.4 GW
142	Radiative Power on Nozzle2		$P_{rad} * (\alpha_{n2}/\pi)$	0.2	0.2												0.9	1.0	7.3	GW	21.0 GW
143	Radiative Power on Radiator Fin		$P_{rad} * (\alpha_{rx}/\pi) * (\alpha_{ry}/2\pi)$	0.3	0.3												0.6	0.6	7.0	GW (x3)	16.8 GW
144																			**45.8**	GW	**201.4** GW
145																					



Firefly – Shielding

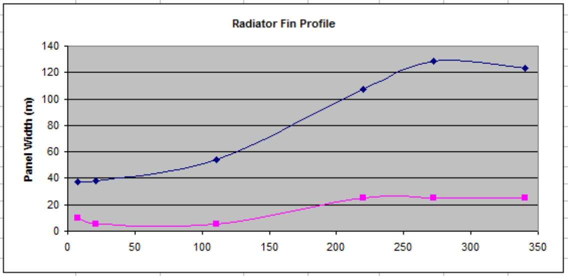
	A	B	C	D	E	F	G
1	**Firefly Shielding**						
2	**Describes the neutron and X-ray shielding.**						
8							
9	**Hot Deuterium Tank**						
10		Length of Hot Deuterium Tank	L_t		180	m	
11		Outside Radius of Hot Tank Tip	R_{tt}		0.75	m	
12		Outside Radius of Hot Tank Base	R_{tbo}	$R_{tt} + L_t/20$	9.75	m	
13		Slope of Outside Hot Tank Wall	α_{two}	$\mathrm{atan}((R_{tbo}-R_{tt})/L_t)$	2.862	degrees	
14		Height of Truncated Tip of Outer Tank	x_o	$L_t\ R_{tt}/(R_{tbo}-R_{tt})$	15.00	m	
15		Outside Volume of the Tank	V_{to}	$(\pi/3)\ ((L_t+x_o)R_{tbo}^2 - x_oR_{tt}^2)$	19,403	m^3	
16		Outside Surface Area of the Tank	A_{to}	$(2\pi/3)((L_t+x_o)R_{tbo} - x_oR_{tt})+\pi(R_{tbo}^2+R_{tt}^2)$	4,259	m^2	
17							
18		Spread of Deuterium at Base of Tank	w_d		1.00	m	
19		Inside Radius of Hot Tank Base	R_{tbi}	$R_{tbi} - w_d$	8.75	m	
20		Height of Truncated Tip of Inside Tank	x_i	$L_t\ R_{tt}/(R_{tbi}-R_{tt})$	16.88	m	
21		Inside Volume of the Tank	V_{ti}	$(\pi/3)\ ((L_t+x_i)R_{tbi}^2 - x_iR_{tt}^2)$	14,482	m^3	
22		Inside Surface Area of the Tank	A_{ti}	$(2\pi/3)((L_t+x_i)R_{tbi} - x_iR_{tt})$	3,581	m^2	
23							
24		Molecular Mass of Deuterium	m_D		4.028	g/mol	
25		Heat of Vaporization per Kg	ΔH_v		322	kJ/kg	
26		Heat of Vaporization	ΔH_{vap}	$\Delta H_v\ m_D$	1.298	kJ/mol	
27		Boiling Point @ 101kPa	T_0		23.32	K	
28		Operating Pressure	P		1,000	kPa	
29		Boiling Point @ Operating Pressure	T_B	$1/(1/T_0 - (R\ \ln(P/P_0)/\Delta H_{vap}))$	35.44	K	
30		Operating Temperature	T_t		50.00	K	
31		Deuterium Gaseous Density	ρ_g	$m_DP\ /\ RT_t$	9.69	kg/m^3	
32							
33		Volume of Deuterium Between Shells	V_d	$V_{to} - V_{ti}$	4,921	m^3	
34		Mass of Deuterium Gas in Tank	M_{tc}	$V_d\ \rho_g$	47,687	kg	
35							
36		Outer Tank Wall Thickness (SiC)	h_{two}		1.0	mm	
37		Outer Tank Wall Stress	Īƒ$_{two}$	$P\ R_{tbo}\ /\ h_{two}$	9.8	GPa	
38		Outer Tank Wall Volume	V_{two}	$A_{to}\ h_{two}$	4.26	m^3	
39		Outer Tank Wall Mass	M_{two}	$V_{two}\ \rho_w$	13,671	kg	
40							
41		Inner Tank Wall Thickness (SiC)	h_{twi}		1.0	mm	
42		Inner Tank Wall Stress	Īƒ$_{twi}$	$P\ R_{tbi}\ /\ h_{twi}$	8.8	GPa	
43		Inner Tank Wall Volume	V_{twi}	$A_{ti}\ h_{twi}$	3.58	m^3	
44		Inner Tank Wall Mass	M_{twi}	$V_{twi}\ \rho_w$	11,496	kg	
45							
46		Total Mass of Hot Deuterium Tank	M_t		72,854	kg	
47							
48	**Neutron Absorption in Deuterium Tank**						
49		Maximum Incident Angle of Radiation	α_{tr}	$\alpha_{tw} - \mathrm{atan}(R_{tt}/(L_a+L_p))$	2.325	degrees	
50		Maximum Depth at Tank Base	w_M	$L_t\ \tan(\alpha_{tr})$	7.31	m	
51		Average Distance Neutrons Travel in D2	x_n	$L_t\ w_d/w_M$	24.63	m	
52							





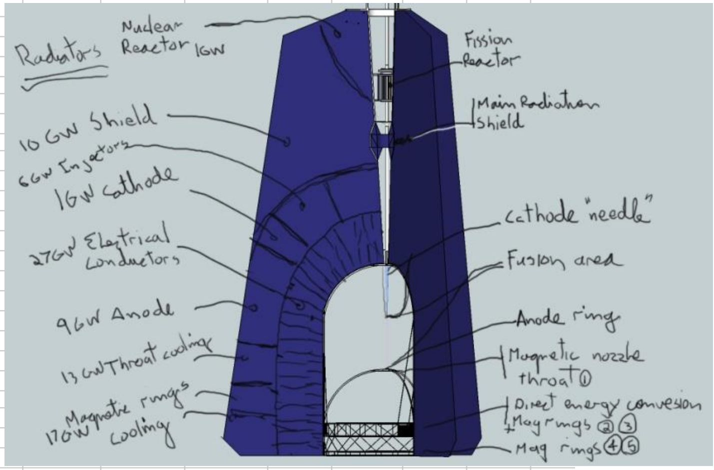
Firefly - Radiators

	A / B	C	D	E	F	G	H	I	J	K	L	M
1	**Firefly Radiators**											
2	**Describes the radiator system.**											
45												
46	**NOTE:** Based on the table above, the decision was made to use Zirconium Carbide for the electrodes & main piping. Pure Carbon is used for the radiators themselves.											
47												
48	**Radiator Fins**											
49	Number of Radiator Fins	N_r		3								
50	Distance of Radiator Fin from Axis	D_r		25	m							
51	Diameter of Fin Structural Element	d_{rp}		0.5	m							
52	Angle Subtended by Radiator Fin	α_{ry}	$\mathrm{atan}(d_{rp}/D_r)$	1.2	degrees							
53	Distance Fin Sticks Out Past Last Ring	D_{tail}		40	m							
54												
55				**Neutron Shield**	**Hot D2 Tank**	**Central Electrode**	**Radiator Fins**	**Nozzle Ring #1**	**Nozzle Ring #2**			
56	**Waste Heat Loads**											
57	Proportion of Fin Load Taken Here	σ					72.4%		27.6%			
58	Waste Power	W		3.7	3.5	72.4	36.5	50.4	34.9	GW		
59	Safety Factor	ω		1.2	1.2	1.2	1.2	1.2	1.2			
60	Power to Radiate	Q	ωW	4.4	4.2	86.9	43.8	60.5	41.9	GW	241.7	GW
61	Mass Flow Rate	f_M	$Q / \Delta H_r$	131	125	2,597	1,311	1,808	1,252	kg/s		
62												
63	**Overall Radiator Dimensions**											
64	Radiant Temperature Reduction	T_x		50	50	50	50	50	50	K		
65	Average Radiator Temperature	T_r	T_a-T_x	2,500	2,500	2,500	2,500	2,500	2,500	K		
66	Total Radiator Area	A_r	$Q / 2eB(T_r^4-T_s^4)$	1,240	1,181	24,519	12,374	17,068	11,819	m^2		
67	Average Power Density	φ_r	Q / A_r	3,544	3,544	3,544	3,544	3,544	3,544	kW/m^2		
68	Radiator Panel Length	L_r		15	12	168	50	55	40	m		
69	Radiator Panel Width	w_r	$A_r / N_r / L_r$	28	33	49	82	103	98	m		
70												
71	Distance Along Axis From Front	X		8	21	111	220	273	340	m		
72	Profile of Fin's Inner Edge	Y_1		10	5	5	25	25	25	m		
73	Profile of Fin's Outer Edge	Y_2	$Y_1 + w_r$	38	38	54	107	128	123	m		
74												
75	**Radiator Tubing**											
76	Number of Radiator Tubes per Meter	N_t		125	100	70	50	45	45	m^{-1}		
77	Radiator Tube Wall Thickness (CC)	h_{tw}		0.25	0.25	0.50	0.50	0.50	0.50	mm		
78	Corrosion Barrier Thickness (ZiC)	h_{tc}		0.20	0.20	0.20	0.20	0.20	0.20	mm		
79	Inside Radius of Radiator Tubes	r_t	$(1/N_t)/2 - (h_{tw}+h_{tc})$	3.55	4.55	6.44	9.30	10.41	10.41	mm		
80	Tube Wall Stress	Ïƒt	$P_2\, r_t / h_{tw}$	0.7	0.9	0.6	0.9	1.0	1.0	MPa		
81	Cross-Sectional Area of Radiator Tubing	A_t	$N_t\, L_r\, \pi r_t^2$	0.07	0.08	1.53	0.68	0.84	0.61	m^2		
82	Volumetric Flow Rate (Gaseous Side)	f_{Vg}	f_M / ρ_g	6.38	6.08	126.23	63.71	87.87	60.85	m^3/s		
83	Coolant Velocity (Gaseous Side)	v_g	f_{Vg} / A_t	86.0	77.9	82.3	93.8	104.3	99.3	m/s		
84												
85	Cross-Sectional Area of Tube Wall	A_{tw}	$\pi\,((r_t+h_{tc}+h_{tw})^2-r_t^2)$	6.09	7.66	21.65	30.63	34.12	34.12	mm^2		
86	Volume of Tube Wall Material	V_{tw}	$N_t\, L_r\, w_r\, A_{tw}$	0.31	0.30	12.39	6.32	8.74	6.05	m^3		
87	Cross-Sectional Area of Tube Coating	A_{tc}	$\pi\,((r_t+h_{tc})^2-r_t^2)$	4.59	5.84	8.22	11.81	13.21	13.21	mm^2		
88	Volume of Tube Coating Material	V_{tc}	$N_t\, L_r\, w_r\, A_{tc}$	0.24	0.23	4.70	2.44	3.38	2.34	m^3		
89	**Radiator Mass per Fin**	M_r	$\rho_{rw}V_{tw}+\rho_{rc}V_{tc}$	2.26	2.19	58.86	30.26	41.93	29.03	tonnes	165	tonnes
90												



Firefly - Radiators

	A/B	C	D	E	F	G	H	I	J	K	L	M
1	**Firefly Radiators**											
2	**Describes the radiator system.**											
91	**Radiator Piping**											
92	Supply Pipe Length per Fin	L_{ps}	L_r +…	15	180	168	105	106	197	m		
93	Supply Pipe Cross-Sectional Area	A_{ps}	A_t	0.07	0.08	1.53	0.68	0.84	0.61	m^2		
94	Supply Pipe Inside Major Radius	r_{ps1}	$(3A_{ps}/\pi)^{1/2}$	0.27	0.27	1.21	0.81	0.90	0.77	m	These determine the minimum cross-section of the structural members.	
95	Supply Pipe Inside Minor Radius	r_{ps2}	r_{ps1} / 3	0.09	0.09	0.40	0.27	0.30	0.26	m	With round pipes, the radiation loads become unbearable. We need oval pipes.	
96	Supply Pipe Wall Thickness (ZiC)	h_{ps}		1.00	2.50	6.00	4.00	5.00	4.00	mm		
97	Supply Pipe Wall Stress	Ïƒ$_{ps}$	$P_2\ r_{ps1} / h_{ps}$	13.1	5.4	10.0	9.9	8.9	9.4	MPa		
98	Supply Pipe Wall Volume per Fin	V_{ws}	$L_{ps}\ (\pi(r_{ps1}+h_{ps})(r_{ps2}+h_{ps}$	0.02	0.52	5.13	1.42	2.01	2.54	m^3		
99	**Supply Pipe Mass per Fin**	M_{ps}	$V_{ws}\ \rho_w$	0.11	3.40	33.64	9.33	13.17	16.64	tonnes		
100												
101	Volumetric Flow Rate (Liquid Side)	f_V	f_M / ρ_c	0.08	0.08	1.65	0.83	1.15	0.79	m^3/s		
102	Coolant Velocity (Liquid Side)	v_c		15	15	15	15	15	15	m/s		
103												
104	Return Pipe Length per Fin	L_{pr}	$L_r + w_r$ +…	43	213	217	187	178	138	m		
105	Return Pipe Cross-Sectional Area	A_{pr}	f_V / v_c	0.01	0.01	0.11	0.06	0.08	0.05	m^2		
106	Return Pipe Inside Radius	r_{pr}	$(A_{pr}/\pi)^{1/2}$	0.04	0.04	0.19	0.13	0.16	0.13	m		
107	Return Pipe Wall Thickness (ZiC)	h_{pr}		0.25	0.50	1.00	0.75	0.75	0.75	mm		
108	Return Pipe Wall Stress	Ïƒ$_{pr}$	$P_2\ r_{pr} / h_{pr}$	8.3	4.1	9.2	8.7	10.3	8.5	MPa		
109	Return Pipe Wall Volume per Fin	V_{wr}	$L_{pr}\ (\pi(r_{pr}+h_{pr})^2-A_{pr})$	0.00	0.03	0.26	0.12	0.13	0.08	m^3		
110	**Return Pipe Mass per Fin**	M_{pr}	$V_{wr}\ \rho_w$	0.02	0.18	1.67	0.77	0.86	0.56	tonnes		
111												
112	**Coolant Mass**											
113	Cycle Time in Radiator	t_r	w_r / v_g	0.32	0.42	0.59	0.88	0.99	0.99	s		
114	Total Volume of Radiator Tubing per Fin	V_r	$w_r\ A_t$	2.05	2.56	74.61	56.04	87.18	60.37	m^3		
115	Mass of Coolant in Radiator per Fin	M_{cr}	$V_r\ \rho_g = f_M\ t_r$	0.04	0.05	1.53	1.15	1.79	1.24	tonnes		
116												
117	Cycle Time in Supply Pipe	t_{ps}	L_{ps} / v_g	0.17	2.31	2.04	1.12	1.02	1.99	s		
118	Supply Pipe Volume per Fin	V_{ps}	$L_{ps}\ A_{ps}$	1.11	14.05	257.65	71.33	89.69	120.80	m^3		
119	Mass of Coolant in Supply Pipes per Fin	M_{cps}	$V_{ps}\ \rho_g = f_M\ t_{ps}$	0.02	0.29	5.30	1.47	1.85	2.49	tonnes		
120												
121	Cycle Time in Return Pipe	t_{pr}	L_{pr} / v_c	2.84	14.19	14.44	12.50	11.90	9.23	s		
122	Return Pipe Volume per Fin	V_{pr}	$L_{pr}\ A_{pr}$	0.24	1.13	23.81	10.40	13.65	7.34	m^3		
123	Mass of Coolant in Return Pipes per Fin	M_{cpr}	$V_{pr}\ \rho_c = f_M\ t_{pr}$	0.37	1.77	37.51	16.38	21.51	11.56	tonnes		
124												
125	Total Cycle Time in Radiator System	t	$t_r + t_{ps} + t_{pr}$	3.33	16.92	17.08	14.50	13.91	12.21	s		
126	**Coolant Mass per Fin**	M_c	$M_{cr} + M_{cps} + M_{cpr}$	0.44	2.12	44.34	19.00	25.14	15.29	tonnes	106	tonnes
127												
128	**Radiator Pumps**											
129	Reynolds Number	R_e	$\rho_c\ v_c\ d_p / \mu$	883,343	862,201	3,928,335	2,790,691	3,277,588	2,727,438			
130	Pipe Roughness	ε		0.000015	0.000015	0.000015	0.000015	0.000015	0.000015	m		
131	Darcy Friction Factor	f_D	1/(4(log((ε/7.4r)+(5.74/F	0.01464	0.01471	0.01105	0.01174	0.01141	0.01179			
132	Pressure Drop (Head Loss)	h_f	$f_D\ (L_{pr}/r_{pr})\ (\rho_c v_c^2)$	5,249	27,030	4,536	5,873	4,623	4,457	kPa		
133	Pressure Drop (PSI)			761	3,920	658	852	671	646	psi		
134	Typical Pump Efficiency	η		60%	60%	60%	60%	60%	60%			
135	Pump Power	P_h	$f_v\ h_f / \eta$	729	3,578	12,463	8,144	8,844	5,904	kW		
136	Pump Power (HP)			544	2,669	9,297	6,075	6,597	4,404	hp		
137	**Pump Mass per Fin**	M_u	Ph / 500	1.09	5.34	18.59	12.15	13.19	8.81	tonnes	59	tonnes
138												



Swamee–Jain Friction Factor Equation

$$f = 0.25\left[\log_{10}\left(\frac{\varepsilon}{3.7D}+\frac{5.74}{\mathrm{Re}^{0.9}}\right)\right]^{-2}$$

Haaland Friction Factor Equation

$$\frac{1}{\sqrt{f}} = -1.8\log_{10}\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11}+\frac{6.9}{\mathrm{Re}}\right]$$

Haaland explicit solution for Colebrook equation

Pressure Drop Calculation

In order to keep pressure within pipe strength parameters, the pumping pressure required (pressure drop) must not be too high.

$$h_f = f_D \cdot \frac{L}{D} \cdot \frac{V^2}{2g} \qquad \Delta p = f_D \cdot \frac{L}{D} \cdot \frac{\rho V^2}{2}$$

FIREFLY THERMAL CONTROL

- A liquid metal evaporates in the hollow structure capturing heat in its phase change
- The gas moves to the radiators, where it cools and condenses, expelling the heat. The liquid metal is pumped back to the main structure where the cycle begins again

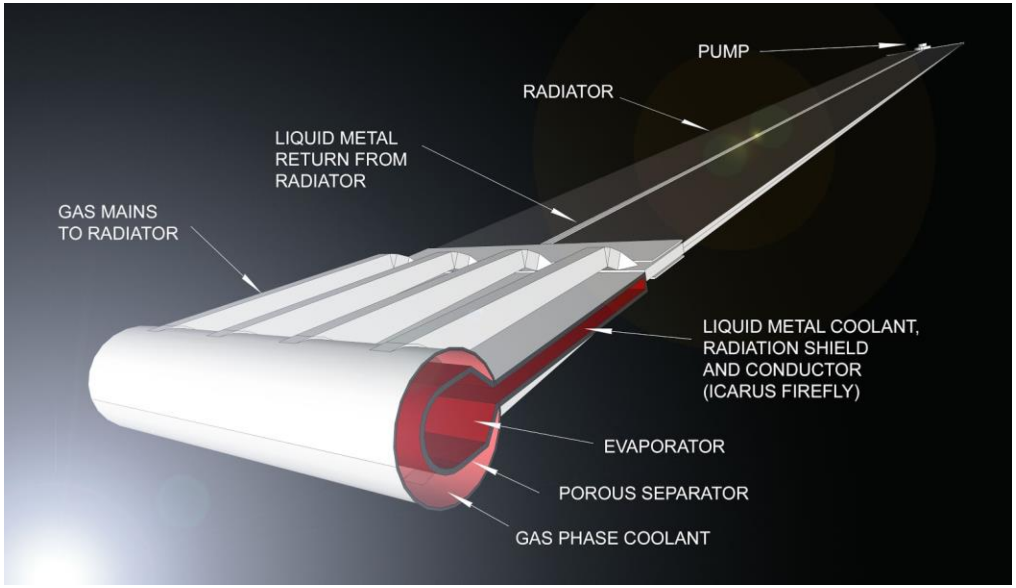


Image: M Lamontagne

FIREFLY THERMAL CONTROL

- A superconducting magnetic coil and its shielding:
- The liquid metal coolant absorbs neutrons, the high density metal absorbs x-rays, heating up
- The coolant evaporates, the gas carries away heat
- The multilayer insulation protects the superconductors from the thermal radiation from the hot shield
- Liquid nitrogen coolant

removes any leftover heat to be radiated away at low temperature radiators

In the image the fusion reaction is to the right

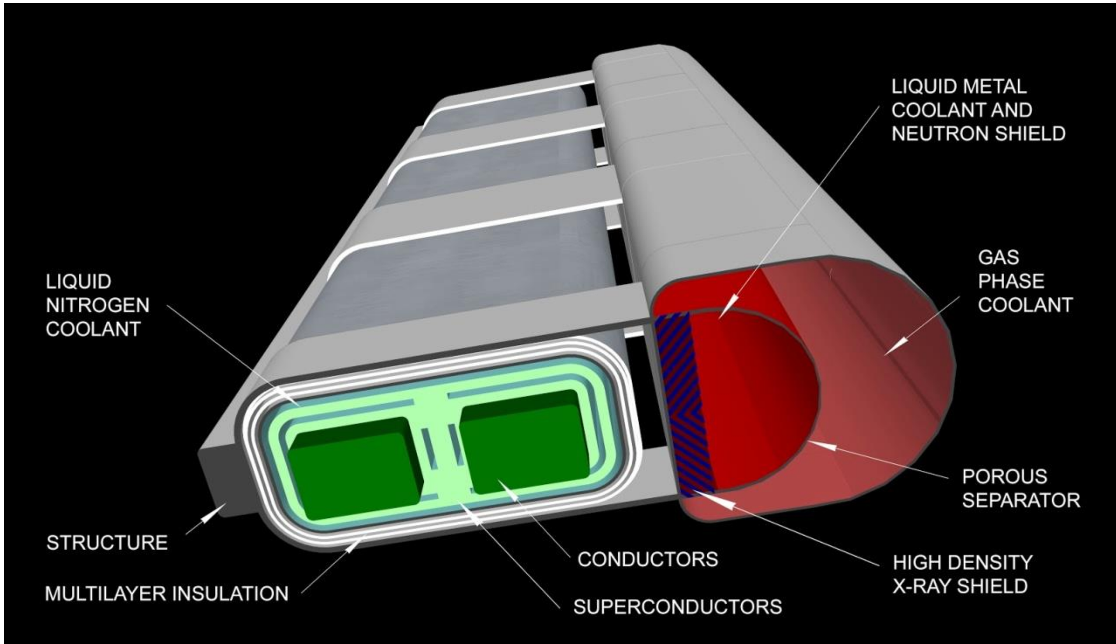


Image: M Lamontagne

Updated Firefly

Freeland II, R.M. & Lamontagne M, “Firefly Icarus: An Unmanned Interstellar Probe using Z-Pinch Fusion Propulsion”, JBIS, 68, pp.68-80, 2015.

Other fusion options

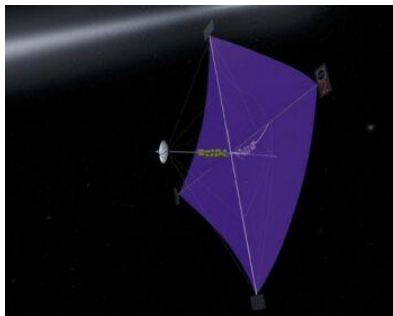
- NIF, HIPER

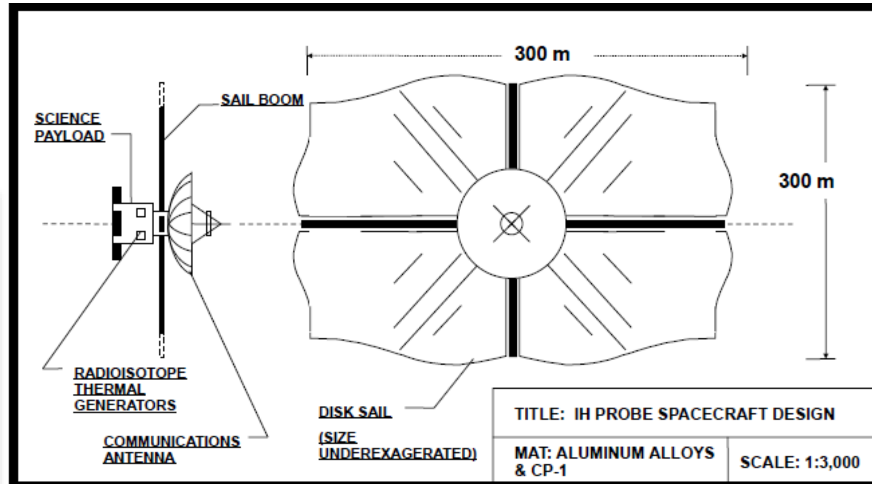
- MCF
- FRC
- MTF
- Various…and tipping point – private investment?

MCF - ITER in build

Other Near future - Solar Sails?

Uses solar pressure to push ultra-thin thin sail to high speeds.





JAXXA

- IKAROS: Interplanetary Kite-craft Accelerated by Radiation Of the Sun
- Launched May 2010
- 315 kg
- Square sail, 20 m diagonal
- 75 micro-m sheet of polymide
- Spun at 20-25 rev/min to unfurl
- Propelled onto Venus.
- The first Solar Sail in history

BREAKTHROUGH STARSHOT

12 April, 2016

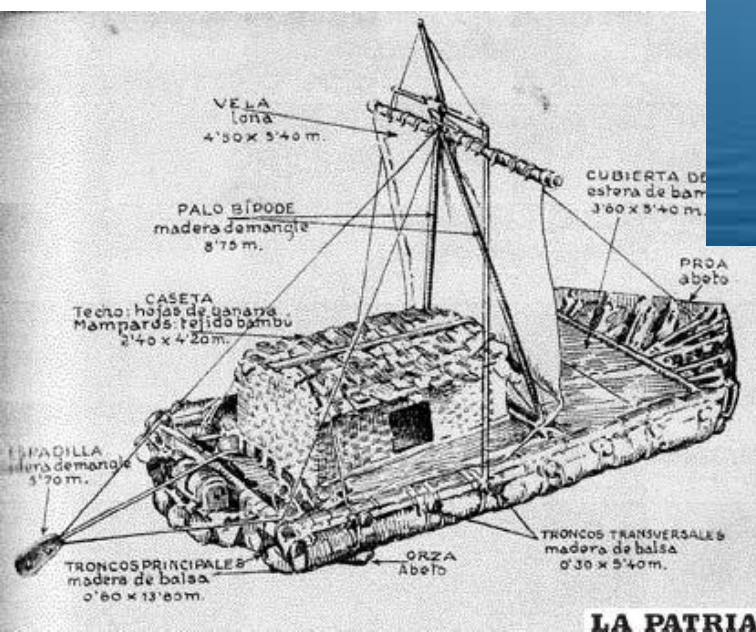
One World Observatory

New York, NY

USA, Earth

So this may take a little while:

A few hundred years...?



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THE BRITISH INTERPLANETARY SOCIETY

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