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JBIS CONTENTS

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OUR MISSION STATEMENT

The British Interplanetary Society promotes the exploration and use of space for the benefit of humanity, connecting people to create, educate and inspire, and advance knowledge in all aspects of astronautics.

SCORPION: a Design Study for a General Purpose Space Transportation System

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The Scorpion is a spacecraft concept that has the intended purpose of being a multirole human space transport system that supports high earth orbit, lunar and near interplanetary flight. The study objective was to explore what is possible with realisable technology to contrast with what we currently actually have, to illustrate the working of Martin's law within the Space industry. The spacecraft is 107 m long with a dry mass of 230 tonnes, it has a crew of 6 people and can be spun to provide artificial gravity. It has significant internal and external provisions for carrying payload, whether pure cargo or mission specific equipment. The prime propulsion is provided by a hybrid thermal/electrical fission nuclear propulsion system, called Serpent-H, which has a thrust of 200 tonnes and an exhaust velocity of 12.7 km/sec. As a result the Scorpion would create a capability significantly surpassing the infrastructure outlined in NASAs Post Apollo programme. A provisional parametric cost estimate suggests the implementation and operational costs would be comparable to other aerospace programmes that have been funded since the Apollo programme. This demonstrates that the failure to advance human space flight is about mankind's comprehension and motivation – not technical or financial constraints.

Keywords: Scorpion, Martin's Law, nuclear-thermal-electric propulsion, Serpent engine

1 INTRODUCTION

1.1 Study Objectives

The Scorpion is a multi-purpose crewed vehicle concept to extend the human Space infrastructure beyond low Earth orbit. It is the output of a study that had the objective of exploring what could be achieved with our current technical abilities. Since Apollo humanity's progress into Space has halted and indeed in many respects fallen back. After half a century there seems to be a belief that the reason for this lies with the technical and cost difficulties involved with adventurous human Spaceflight beyond low Earth orbit and there is nothing that can be done to improve things. In other words there is a perception that the Space industry is like the computing or aviation industries, in that it works on the borders of what is possible and is primarily constrained by its technical limitations. The premise of the Scorpion study is that the Space industry is not like other industries at all, but is in fact governed by Martin's Law:

"politics first – money second – technicalities last" [1]

At first hearing this might seem to be a trivial satirical throwaway reflection on the inevitability of real world societal constraints on major engineering projects. All industries have such societal constraints, for example the current lack of an operational supersonic airliner is clearly not due to any technical inability to make one, but due to insufficient market demand and environmental concerns – and engineers will always rail against such annoying impacts of reality. However in the case of the Space industry, Martin's Law is actually a reflection of a deeper malaise that prevents astronautics progressing to address clear societal needs. In other words the political needs and constraints imposed on the space industry are not reflections of genuine societal needs and constraints.

What constitutes "political" in this context requires defining. There is Political "with a big P;" that is the actions of politicians and civil servants that together form the government. And clearly the main immediate and obvious constraints are the directions and funding (or more often lack of both) given to space agencies. The scale of the engineering and hence funding required to reach and exploit space means that governments play the pivotal role in how space advances. A situation reinforced by the UN Outer Space Treaty [2] that requires all activity in Outer Space to be under the auspices of a sovereign state, i.e. with the knowledge and approval of a government that accepts liability for that activity.

However these direct government policies reflect a wider societal understanding of space and its role, so we have the more pervasive and ultimately more important politics with a small p. It is the perception that society as a whole has of space and humanity's role within it that determines what government's think. Politicians and civil servants are drawn from the wider population and hence very rarely have any special knowledge and understanding beyond the general population. Further governments tend to follow the popular opinion when it does not interfere with the wealth of the ruling elite. The result is nations have the space programme that reflects their culture.

And what the prevailing Post Apollo culture makes of Space is perhaps well summed up by Dennis Meadows. The comment was a specific response to O'Neill's space colony proposals but it reflects an attitude that many would apply to human spaceflight generally:

"I am not sure that we should want to have another frontier. It seems to me to block constructive response to the problems here on Earth" [3]

That is human space activity, particularly expansive activity, is not just an expensive waste of time, it is actually a dangerous diversion that threatens humanity's ability to deal with its existential problems. With this underlying societal view on space as an activity to expand humanity's horizons, it is no surprise that none of the objectives of the post-Apollo era have been even attempted let alone fulfilled. It is perhaps worth pointing out for the record that in the subsequent half century there has not been a great deal by way of "constructive responses" to the Earth's problems either, but at least no one can blame this on the distractive allure of human exploration of the Solar System.

In the post Apollo environment this malaise and misjudgement about what is technically possible in astronautics has extended to within the space industry itself. After all the space industry consists of people who are just as influenced by the zeitgeist as the government. In some areas Space technologies have improved since the time of Apollo, almost all due to "spin in"; that is Space-qualifying general technical advances. However these improvements have not led to any significant change in actual capability, indeed by any measure mankind has less capability now than it had in 1970.

The Scorpion study's objective was to illustrate the impact of Martin's law by providing a contrast between what mankind could have had by way of space capability and what it actually has. It reverses Martin's law and places technical constraints first, that is to outline concepts that while still limited by technical reality are on the boundary of what is demonstrably possible. The study then explored the cost implications. Assuming the costs were found to be viable in terms of overall magnitude and cost effectiveness (and they were), then the difference between what this study has produced, and what currently exists in reality is a measure of the impact of the political constraints on the development of human spaceflight. That is a measure of humanity's failure to realise its potential.

1.2 Technology Constraints

For the Scorpion study to be valid, all the technology used in the concept designs must be demonstrably achievable. To meet this requirement one of two criteria must apply. Either:

1) the technology used must be currently at a high enough Technology Readiness Level (TRL) that a contract could be currently placed for the components.

or:

2) the technology was outlined before 1985 and realisable before 2000, but a failure to engage in a full development programme means it is not at a high Technology Readiness Level. If a full development programme was undertaken and difficulties found then the technology is excluded.

The first criterion is easily established and uncontroversial. The second criterion is more a matter of judgement as to whether the technology has had sufficient development work to demonstrate its potential viability if further development work was conducted. This depends upon a combination of the level of the advance and the amount of development work conducted – a bigger advance needing a greater amount of work. The key areas to which the second criteria has been applied are:

- thermo/electric hybrid nuclear engines,
- inflatable liquid hydrogen tanks,.
- unpressurized assembly of habitats,
- in-orbit cooling of cryogens.

And the argument for their technical viability will be considered in this paper at the appropriate points.

1.3 Supporting Launch Infrastructure

The Scorpion study concerned itself with the in orbit infrastructure and that requires a complimentary launch infrastructure to connect it to the Earth. For this purpose the study assumed Skylon D1 [4] with the performance and interfaces defined in its Users' Manual [5]. The launch cost assumed by the study were derived from the most comprehensive exploration of Skylon's operational costs which was conducted during the ESA funded "SKYLON Based European Launch Service Operator" study [6]. This work showed a large range of costs and prices (which are not the same things) dependent on assumptions of the launch and launcher market size (which are not the same things), the business model employed by the Skylon builders and operators, and the level of state aid. For the Scorpion study a set cost of $20 million a launch to low Earth orbit was used. This was within the optimistic range in the context of the European Launch Service but arguably pessimistic in the context of the scale of activity envisaged by the Scorpion study.

Skylon [7] was the direct follow on from the BAe/Rolls Royce HOTOL project [8]; the name change reflecting the concept's move to Reaction Engines Limited; which was a company set up with the sole purpose to preserve, improve and pursue the work and knowledge from the HOTOL study. Over the over thirty year history of the HOTOL/Skylon project it has had many formal external reviews. Every one of these reviews judged the concept technically and economically viable and thus worth progressing. The detailed level of technical maturity of the Skylon concept was demonstrated in reports to the International Astronautical Congress [9, 10]. Further it was shown to be ready for full development against the specification for the next generation European Launcher in the ESA funded "SKYLON Based European Launch Service Operator" study [11].

Thus Skylon meets the second of the study's criteria to be judged technically viable. It was conceived in the early 1980s and only funding constraints, imposed by continuous political failure to appreciate its viability and potential impact, has prevented its realisation by 2000 (or indeed any time since). The history of Skylon is in and of itself a pure and perfect example of Martin's law operating in the post-Apollo world.

2 REQUIREMENTS AND OBJECTIVES

2.1 Approach

A starting point for consideration of where mankind's domain in space could have been in 2020 is the NASA's Post Apollo programme [12, 13]. It was a plan proposed by NASA in 1969 to continue the momentum of the Apollo Moon landings and secure a permanent and significant human presence in the inner Solar System. There were three options offered and if either of the first two options had been followed we would now have over a hundred people in space with bases in Earth orbit, lunar orbit and surface and Mars orbit and surface.

As the core overall vision of the NASA post-Apollo Programme was in essence the same as the Scorpion study, it follows they have very similar overall objectives in terms of transport requirements. That is to create an inhabited space infrastructure that includes all of Earth Space (including the Moon) and could reach to Venus and Mars. The NASA programme also recognised the cost and reliability problems of continually designing new mission specific systems and adopted an approach of assuming common building blocks (a chemical stage Space Tug, a habitation module, a nuclear stage using the NERVA engine, and a Mars Lander) which could then be assembled in different configurations to make up the systems required for specific missions.

This approach of developing major building block elements that can be combined to create habitats and transport systems (sometimes known as "Space Lego"), has merit and this author has advocated it in the past [14], including at the "Three Ways to Mars" event held at the BIS a decade ago [15]. The three advantages argued for this approach are:

(i) cost savings in development and learning curve production effects
(ii) safer more reliable systems
(iii) faster system development

While this has superficial attractions it assumes that the systems created by the collection of standard modules have minimal extra development to achieve efficient, verified and certified safe systems. However in reality this is not the case, the complex interactions between the elements in a space system means that producing a new one – even if made from existing elements remains a considerable enterprise. That is not to say the "Space lego" approach does not have advantages and in the context of the technology available in the late 1960's it was a sensible approach.

However; with technology that is currently available there is an alternative approach which is to develop single complete system that has a multi-role capability. This approach can only be used where there is a performance margin which is sufficient to allow the inefficiency of carrying equipment that is not required for many of the missions the system would undertake. An analogy would be the difference between a racing car where the system has solely intended to go round a circuit as fast as possible and a family saloon car that has seating, luggage area, and performance which is rarely fully used on the journeys it undertakes. In the context of the Scorpion this approach is illustrated by the provision of landing legs which enable it to land on the Moon, this undercarriage is carried on every other mission even though they have no purpose.

2.2 System Purpose and Constraints

The Scorpion's system purpose was –

To be a single human transport system that supports high earth orbit, lunar and near interplanetary flight.

Near interplanetary" being taken to mean the solar system Space scoped by Venus, Mars and near Earth asteroids.

This purpose was intended to support the use of a functional requirement generation process (as opposed to the more normal mission requirement generation process) [16] which is a more appropriate methodology for multi-role systems. In this approach feasibility designs are produced to explore the boundaries of what is technically possible and then the performance of these designs on the various missions of interest is established. That is there are no mission performance requirements fixed before the technical assessment, they are defined by the discovered performance of the feasibility study concept system.

Although this objective was intended to focus on a transport role, the inclusion of interplanetary flight led to an extensive habitation system capable of supporting the crew for the years such flights would take – what in effect is a small space station. This gives the Scorpion a functionality beyond the simple transportation of crew and equipment to a location, it can also fulfil an operational role once at the destination. In this regard it can be seen as a deep space equivalent of the role the Space Shuttle had in low Earth orbit, in that it cannot only deliver a payload to an orbital location but can support it with power, data handling and crew intervention over an extended period of time. Thus in most cases it can carry out a complete mission without any other systems such as human bases, robotic support spacecraft or other propulsion stages.

The study worked with a small list of constraints on the Scorpion system that effectively acted as a definition of what would constitute a safe and viable "single human transport system"

- one vehicle design does all missions – strictly no special versions
- meet the technical and infrastructure constraints outlined in Section 1
- have viable radiation protection and artificial gravity provisions
- the crew to include non-flight crew mission specialists (passengers)
- have a viable escape system (with some operational caveats)

The first of these constraints could benefit from some amplification. It is envisaged that the Scorpion would be stored in orbit between its missions, it being impractical to disassemble and return the spacecraft to Earth for modifications. Storage in low Earth orbit is the Scorpion equivalent of being in the hanger ready to be fuelled and equipped for its next flight. Thus each new mission can only add fuel, supplies and payload (using the designated payload carrying capability), the core Scorpion cannot be modified mission to mission.

The other constraints, while obvious, represent an addressing of the issues involved with human space fight without compromise. For example the insistence on artificial gravity – normally avoided in human Mars proposals and the requirement for an escape system, normally only considered as a requirement for space stations. The intention is to make the Scorpion a robust transport system suitable for safe, long term general use.

3 SCORPION DESCRIPTION

3.1 Overview

The Scorpion (Fig. 1) is a concept intended to demonstrate the feasibility of meeting the broad requirements of an effective general purpose human orbital transport system with lunar landing and Martian orbit capability within the assumed constraints of technical viability. The primary propulsion system uses a nuclear powered engine called Serpent-H that combines direct thermal heating with arc jet augmentation. There is also a secondary hydrogen/oxygen chemical propulsion system. It has a large pressurised habitat suitable to act as a living envi-

Fig.1 **The Scorpion General Purpose Space Transport System.**

ronment for the crew for months or even years. There are significant provisions for carrying cargo and equipment, both internally and on six payload connection ports, enabling the Scorpion to be configured for a wide variety of missions.

The key parameters of the Scorpion system are given in Table 1. The actual flight masses would alter considerably from mission to mission; as there is not really a fixed maximum payload mass (which could be as much as several hundred tonnes). The propellant load shown are the maximum the tanks can carry, in practice most missions would carry less propellant than this – particularly oxygen for the secondary propulsion system.

This specification enables a wide range of missions. For example the cargo delivery capability from low Earth orbit to geostationary orbit is over 500 tonnes and around 450 into a lunar orbit. From low Earth orbit to the lunar surface it can carry around 20 tonnes of payload, stay on the surface for around six months than then return to Earth orbit [17]. With an Earth departure boost it can carry a crew of 6 and two Martian landers to a Mars orbit and return the crew.

3.2 External Configuration

Fig. 2 overleaf shows the exterior arrangement of the Scorpion. The main structure is a combination of a truss beam and the structure of the pressurised habitat, which form a central spine. The truss frame is composed of struts made of carbon fibre reinforced titanium, a technology proven on the Skylon programme [7]. At the forward end the truss is used to stiffen the primary load bearing structure, which is the pressurised transfer tube. The habitat's Hub Module forms the main structure at the centre and then a truss forms the rear end structure to support the Serpent engine and rear hydrogen tanks.

The hydrogen tanks and the chemical Propulsion Pods that contain the ACRE chemical engines are attached to the side of the spine. The ACRE engines fire orthogonally to the Serpent,

TABLE 1: SCORPION KEY SPECIFICATIONS	
End of mission mass*	240 tonnes
Liquid Hydrogen	400 tonnes
Liquid Oxygen	110 tonnes
Length	107 m
Width	50 m
Height (legs retracted)	13 m
Pressurised volume	622 m^3
Main prop. thrust	2,000 kN
Chemical prop. thrust	2,400 kN
Electrical power	120 kW
Operational crew	3 people
Total personnel	6 people

** detailed in Table 3*

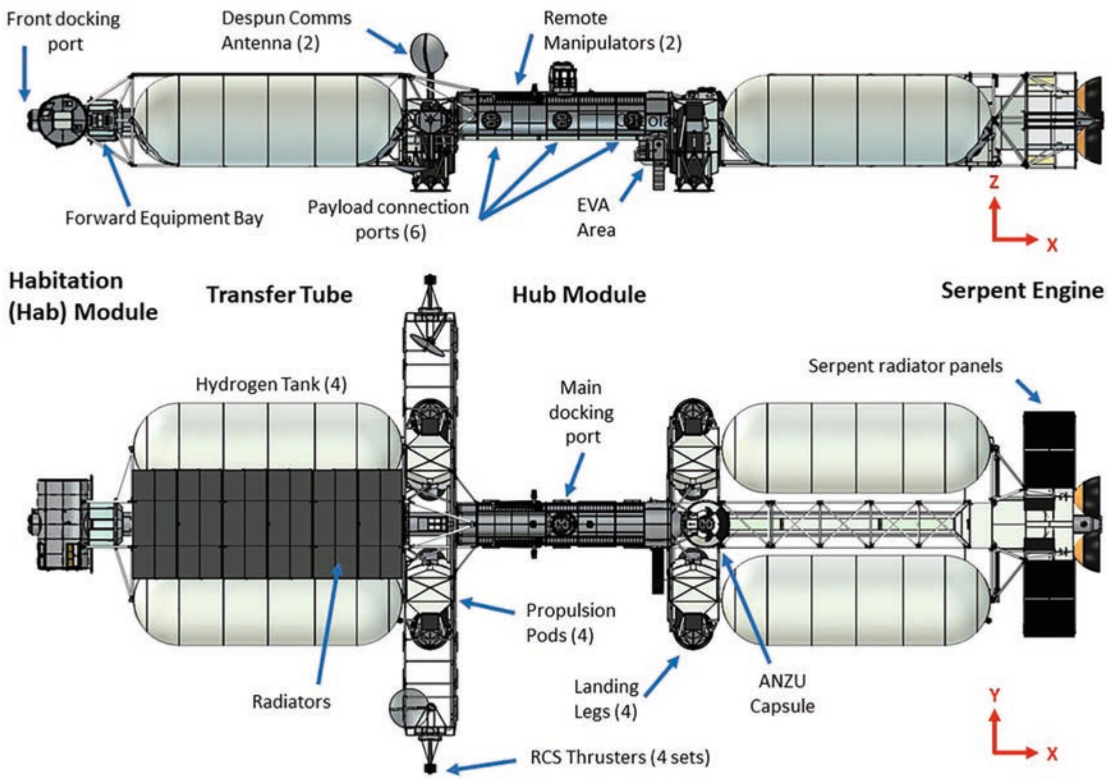

Fig.2 Orthogonal Views of the Scorpion.

and enable lunar landings. The landing legs attach to these pods exploiting the same structural load paths.

There are also two truss "wings" that hold the main communication antennas (mounted on de-spin tables) and the Y thruster clusters. This arrangement of equipment was selected to maximise the inertia ratio about the intended spin axis (along the Z axis centred on the main docking port) when generating artificial gravity.

The two thrusters clusters on the wing give roll and yaw rotational control, and X and Z linear motion control. They are supplemented by two further clusters, one contained in the Forward Equipment Bay and the other in front of the Serpent engine. These supplement yaw and Z control and add pitch and Y control. Each of these clusters is supplied by a set of two hydrogen and one oxygen gas storage tanks except the Forward Equipment Bay that has four hydrogen and two oxygen tanks. These tanks act as a buffer store for the gas supplied from the tanks and water management system. Each tank is 1m in diameter and with a working pressure of 100 bar giving a storage capacity of 9.4 kg of hydrogen and 54 kg of oxygen. There is also a 0.5 m diameter water tank with a capacity of 65 kg – allowing the fuel cells to operate for a day as an isolated system.

The forward equipment bay also contains an independent open loop life support system for emergency use. There are six 1m gas tanks of common design with the gas propellant tanks which carry 54 kg of oxygen (sized for a crew of six for seven days) and 270 kg of make-up air for any cabin leakages. There is also another independent life support system by the airlock to support the EVA preparation area role as a safe haven for 2 days.

3.3 Payload Provisions

The Scorpion's main provision for carrying payloads are six USIS berthing ports [18]. These open into the Hub area so the payloads can be pressurized modules that extend the Scorpion's habitable volume or they can be used simply as unpressurised attachment points. The ports are spaced 7m apart but the safe payload envelope is 6.2 m by 9 m high, although on a case by case basis payloads could go beyond that. The distance out from the port is determined only by the payload's Centre of Mass and the moment it creates. However beyond 18 m the rear pointing thrusters (-X) would have to be disabled to prevent plume impingement which creates a constraint on the control of linear motion in the X direction, but in most applications this should not be an issue.

The side mounting orientation means that when either the ACRE chemical engines or the main Serpent engine are fired the linear loading on the port is in shear and a moment is created. The moment limit on the USIS connection is 500 kN m and the shear limit is 200 kN values that are derived from the USIS role as a launch vehicle interface [19]. The limitation this puts on payload mass is a multi-parameter problem. As the mass attached to the port increases so the shear load and moment increases, another factor is that larger masses also tend to have a centre of mass further from the port, also increasing the moment. However with a larger total payload mass the acceleration drops due to the fixed thrust of the Serpent engine, reducing the loads.

In practice these strength limits are unlikely to prove an issue in orbital flight. For example the Scorpion has the capability to deliver around 550 tonnes to geostationary orbit; during this mission a payload of 100 tonnes attached to a port would experience a maximum shear load of 23 kN (a Reserve Factor of 8.7) and the centre of mass must not exceed 20 m to stay within the moment constraint. For this mission a far bigger constraint is simply packing the payload into the space available between the two propulsion pods.

Another in orbit example would be the return of Scorpion (i.e. empty tanks) with two 300 tonnes payloads. This produces a shear force of 72 kN (a Reserve Factor of 2.8) and a 7 m centre of mass limit. This is not probably a realistic scenario, as such large payloads are more likely to be spread over all six ports, but is shows that the USIS connection strength is unlikely to prove a constraint for orbital missions.

The lunar landing case is different, here the design case is the touch down impact. The undercarriage is designed to take out a 12.4 m/s velocity with 1.5 m movement and a maximum acceleration of 0.5 g. The design case was taken as 1 g as a contingency to cover uncertainties. The shear constraint limits the payload to 20 tonnes per port with a 2.5 m centre of mass constraint. This means for some potential Moon landing missions it is the USIS port's strength rather than the Scorpion's propulsive capability that determines the practical maximum payload.

The Scorpion has two manipulators (port and starboard) that run along body mounted rails over the payload ports. These handle the port mounted payloads, including acting as cranes to take the payloads from the ports to the lunar surface. The manipulators also enable the berthing operations for the Anzu capsule and other spacecraft and space stations that attach to the main docking port.

The manipulators were required to load and unload 20 tonnes in lunar gravity and to berth systems weighing 1000 tonnes these two factors means that these manipulators need to be stronger that the Space Station Remote Manipulator System installed on the ISS. The assumption was that the grapple points would follow the ISS standard [20], although a stronger version of this interface maybe required in some applications. To compensate for the higher loads the Scorpion manipulator was designed to have roughly half the reach and the load path was made symmetrical and strengthened. A comparison between the two systems is shown in Table 2.

TABLE 2: COMPARISON OF SCORPION AND ISS MANIPULATORS

	Scorpion	ISS RMS
Mass	2200 kg	1497 kg
Design zero G payload	1000 tonnes	116 tonnes
Reach	10.3 m	17.6 m
DoF	6 (including rails)	7

3.4 Internal Configuration

The pressurised habitable volume has three main areas. At the front is the Habitation (Hab) Module and in the spacecraft centre is the Hub Module and they are connected to each other by a 2.2 m diameter 36 m long Tube.

The Hab Module has all the provisions that provide the crew of six with living space but not the life support equipment which is housed in the Hub Module for mass balance, reduction in secondary radiation generation and to reduce cabin noise. It is sheathed in 90 mm plastic panels which with the structural pressure hull ensures there is 100 kg/m2 of radiation shielding for the whole Hab Module so it can be used a solar storm shelter. The whole module interior can rotate by ninety degrees, one orientation being required for Serpent engine firings and lunar operations the other when the Scorpion is spinning for artificial gravity. There are two sets of windows so the bridge has an external view in both orientations.

This area has an internal diameter of 4.75 m and is 8.65 m long. It is divided into three floors (Fig. 3). The lower floor houses a medical facility, a work area and secondary storage area for cargo transfer bags. The centre floor is split; the forward

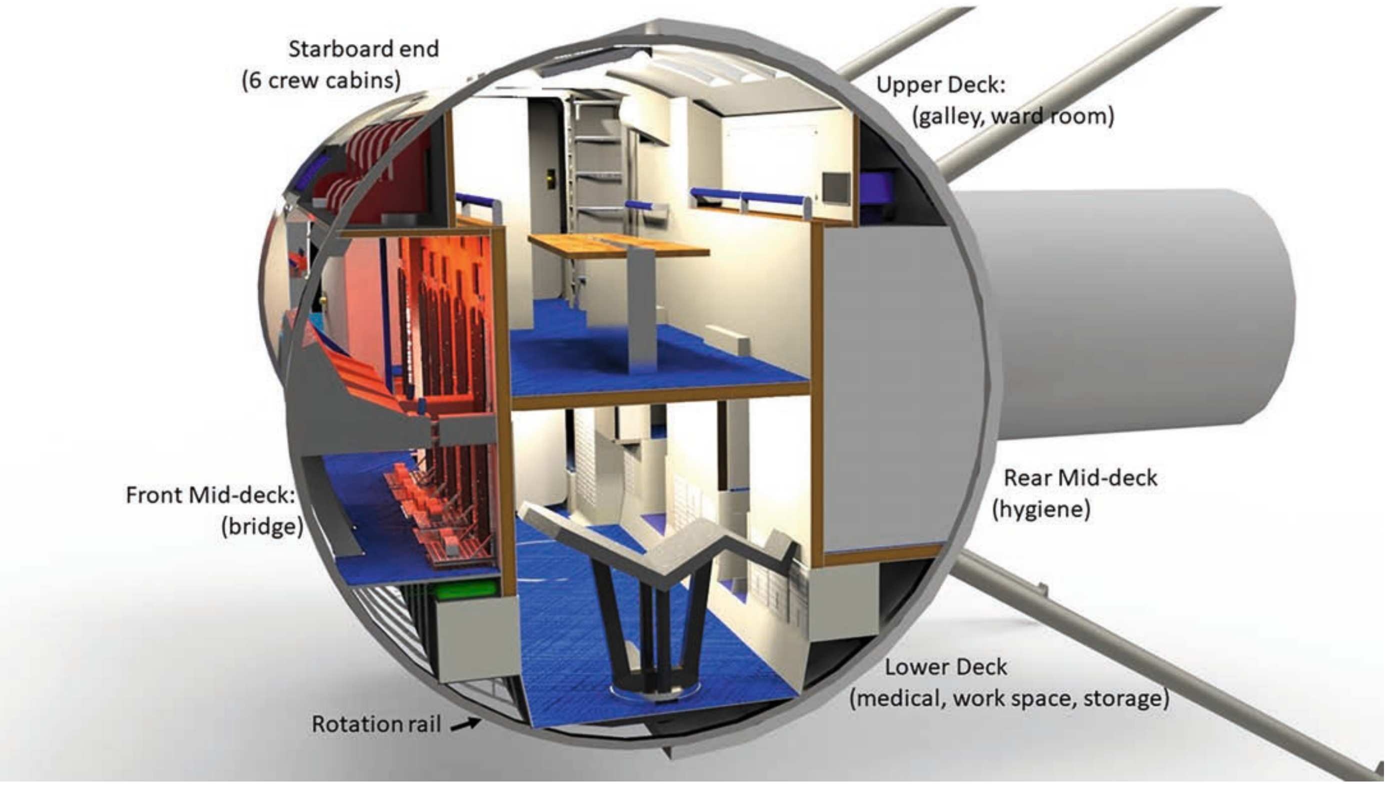

Fig.3 Habitation Module.

Fig.4 Scorpion Main Control Console.

section is the location of the Bridge and the rear the crew hygiene facilities. The upper floor has the galley and wardroom. At the starboard end there are six individual cabins (two per floor).

The bridge area has six couches in a line three of which are for the operation crew and have the control console in front of them and the main cabin windows (Fig. 4) the other three couches are for the mission specialist crew who are not involved in flying the vehicle. Each flight crew station centres on two 70 cm screens; the upper one being primarily the computer output display to the crew whereas the lower screen is used as the control input. The primary method of input is soft menu, using protected press switches on either side of the screen. The lower screen is also touch sensitive for secondary inputs – such as a soft QWERTY keyboard – but this would not be used for any critical functions. Between the stations are two electronic check lists. Above the windows are screens with fixed functions including clock and warning/alarm displays.

Fig.5 Tube Looking Towards the Hub.

The Hab Module is linked to the central Hub Module by the Tube (Fig.5). It creates the radius arm for the spin induced artificial gravity and is configured so the crew can use it, when spinning, when in lunar gravity and when in microgravity. The Tube is launched in four 9 m segments. The first segment has an airtight door enabling it and the Hab Module to be sealed from the rest of the pressurised area in the event of a hull breach. This segment also includes a back-up open loop life support system as a contingency for the event it is being used as a safe haven (during a solar storm shelter or hull depressurisation event) and the primary life support fails, as this is located in the Hub Module and thus is unreachable.

The main Hub Module (Fig. 6) is devoted to logistics storage which is assumed to use ISS cargo transfer bags and their carrier packaging. There are 312 possible supply bag locations along the Hub's walls which can carry enough supplies for 240 days for a crew of six. In the centre area are mounting provisions for eight ISS Equipment racks; either to carry them as cargo or connected up to provide additional functionality for specific missions. If the hub internal provisions are insufficient for a mission, the logistics or mission specific equipment capacity can be increased with the addition of modules on the six payloads ports.

The Cupola is located on top of the Hub above the nominal centre of mass. It acts as a docking tunnel and a control centre for using the two manipulators mounted on the Hub's roof.

At the front of the Hub Module is a utility area where the life support, main power and data equipment are located. The life support includes air revitalization system that is one of three methods of supplying oxygen. A second is the water recovery system that both purify recovered water and also electrolyzes it to produce hydrogen and oxygen gas to feed the four sets of gas propellant tanks that feed the RCS thrusters, fuel cells, and the oxygen feed for cabin use. Decomposing CO2 and water electrolysis all have high power requirements, but, due to the Serpent engine, power is plentiful, ameliorating the system impact of these close cycle approaches. The third source of oxygen is the liquid oxygen tank which is fed via the gas propellant tanks.

At the back of the Hub is an EVA preparation area which is separately pressurised and environmentally controlled. It primary role is analogous to the "Equipment Lock" in the ISS's Quest Airlock module, that is to store the EVA equipment and to provide space to prepare for space walks. This includes housing the EVA crew for during any pre-breathing periods. As this can mean many hours separated from the main habitation areas a third hygiene facility is included. The area has provision to store four space suits and the equipment to support them. A further two suits are assumed to be stored in the ANZU capsule, so all the crew have space suits.

The EVA preparation area is also expected to act as the primary safe haven, in all emergencies excepting solar storms (when the Hab Module acts as the safe haven). To support this function, in addition to the separate ECLSS, and hygiene facility, the area has a minimal control point for the whole ship. The area also includes the port connecting to the ANZU capsule which acts as the escape system. The logic being that in a contingency situation the crew can use the safe haven area to assess and manage the situation, and if this fails they have access to the means to abandon the ship.

A hatch in the floor of the EVA preparation area leads to the airlock which is 3.1 m high and has an internal diameter of 2.46 m. It is located below the main pressurised structure to facilitate reaching the lunar surface. A side door gives access to Space and this opens onto a balcony platform which has lockers to house EVA equipment. Fixed stairs lead from the balcony to the surface for lunar landing missions.

3.5 Mass Budget and Properties

The summary estimated mass budget for the Scorpion is given in Table 3. The mass estimates are created on a construction launch by construction launch basis and these contain an allocated margin at the launch level rather than subsystem by subsystem. The total "hidden" margin contained in these figures is 10.7 tonnes.

The calculated centre of mass for the dry vehicle is:
X = –90 mm Y = 12 mm Z = –72 mm

TABLE 3: SCORPION SYSTEM MASS BUDGET

Item	Subtotals (tonnes)	Totals (tonnes)
External equipment		**43.2**
Truss Structure	4.9	
Thermal System	9.7	
Front Equip. Bay	2.4	
Wing Equipment	2.0	
Landing Legs	15.0	
Manipulators	4.4	
Other	4.8	
Habitation		**59.3**
Habitation Module	28.0	
Tube	5.4	
Hub Module + airlock	23.5	
Cupola	2.4	
Propulsion		**98.1**
Tanks	33.8	
Serpent	45.5	
Propulsion Pods	17.6	
Other	1.2	
Anzu		11.1
Fluids		17.4
He Pressurisation	16.2	
Cabin air	0.8	
Water/Gas LH-LOX	0.6	
	TOTAL	**229.3**
Build Mass	**rounded up to**	**230.0**
Mission Additions		**9.1**
Propellant residuals	2.6	
Crew + effects	1.6	
Support Supplies	4.9	
	TOTAL	**239.1**
Typical End of Mission	**rounded up to**	**240.0**

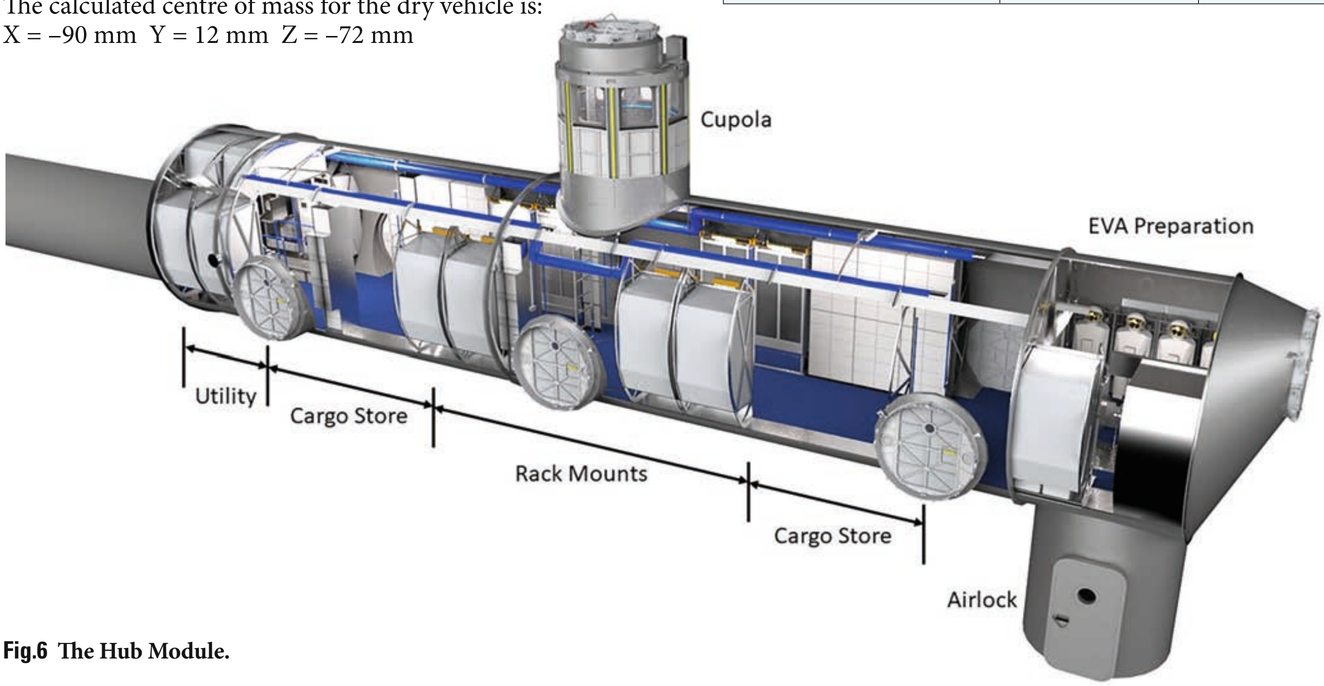

Fig.6 The Hub Module.

TABLE 4: SCORPION MASS PROPERTIES

	Payload (tonnes)	X (mm)	Y (mm)	Z (mm)	I_{XX} (kg m^2)	I_{YY} (kg m^2)	I_{ZZ} (kg m^2)	Inertia Ratio
Dry	0	-57	13	-34	7.35×10^6	2.66×10^8	2.72×10^8	1.023
Fuelled	0	-17	4	-10	3.42×10^6	6.33×10^8	6.66×10^8	1.052
Dry	60	-45	10	-27	1.08×10^7	2.68×10^8	2.77×10^8	1.035
Fuelled	60	-16	4	-9	3.76×10^7	6.34×10^8	6.71×10^8	1.057
Dry	240	-13	3	-8	2.10×10^7	2.74×10^8	2.94×10^8	1.072
Fuelled	240	-20	3	-16	4.78×10^7	6.41×10^8	6.87×10^8	1.072

Which is close enough to the desired location to demonstrate feasibility. There is no value in further refinement of the dry position as it would suggest a certainty in the mass estimates that does not exist. In any case adding the payload this creates comparable movements; so precise balancing would need to be on a mission by mission basis. The system provides a degree of active mass properties control through moving the manipulators along the rails giving +136 mm to + 347 mm movement along the X axis and +/- 40 mm along the Y axis. Raising and lowering the landing legs gives a centre of mass movement of 46 mm along the Z axis.

The centre of mass and the inertias about the main axis vary with fuel load and payload carried. Table 4 gives the calculated values with empty tanks and fully fuelled (510 tonnes in total) for three payload cases, assuming the payloads are perfectly balanced on the six ports. This gives the range of inertias required for the attitude control system. Another point is that the inertia ratio between I_{ZZ} (the spin axis) and I_{YY} (the intermediate axis) are sufficient for controllable stable spin.

The Scorpion is designed to be spun about the Z axis to provide artificial gravity in the Habitation Module which can rotate its internal equipment to create an appropriate architecture, as already in Section 3 (Fig. 7).

The radius arm is a nominal 50 m, but actually varies from 49 m to 52.5 m over the Habitation module. For a spin rate of 24 seconds this gives g levels of between 0.34 and 0.38 a close equivalent of Martian surface gravity. The design assumed a maximum spin of 20 seconds giving a half earth gravity. There is great uncertainty as to how fast people can be spun in zero g for long periods with free movement without adverse medical symptoms in particular nausea [21], but 20 seconds was judged to be the fastest safe level although this is a little slower than the conclusions of Hall [22]. The g level versus spin is given in Fig. 8 opposite.

Fig. 8 also shows the acceleration in the extremes central Hub Area (10 m from the spin axis) which reaches a tenth g at the maximum spin rate. This should be low enough for the crew to move around, although the overall architecture is not generally designed to be suitable, however local work stations are orientated to acknowledge this residual acceleration.

The spin is achieved using the reaction control thrusters. Fig. 9 shows the range of propellant required to achieve different spin rates for different propellant loads. The Scorpion was assumed to be carrying a payload suitable for a Mars landing mission - the most likely mission to use this capability. If the Scorpion has been spun up, it will later be required to de-spin

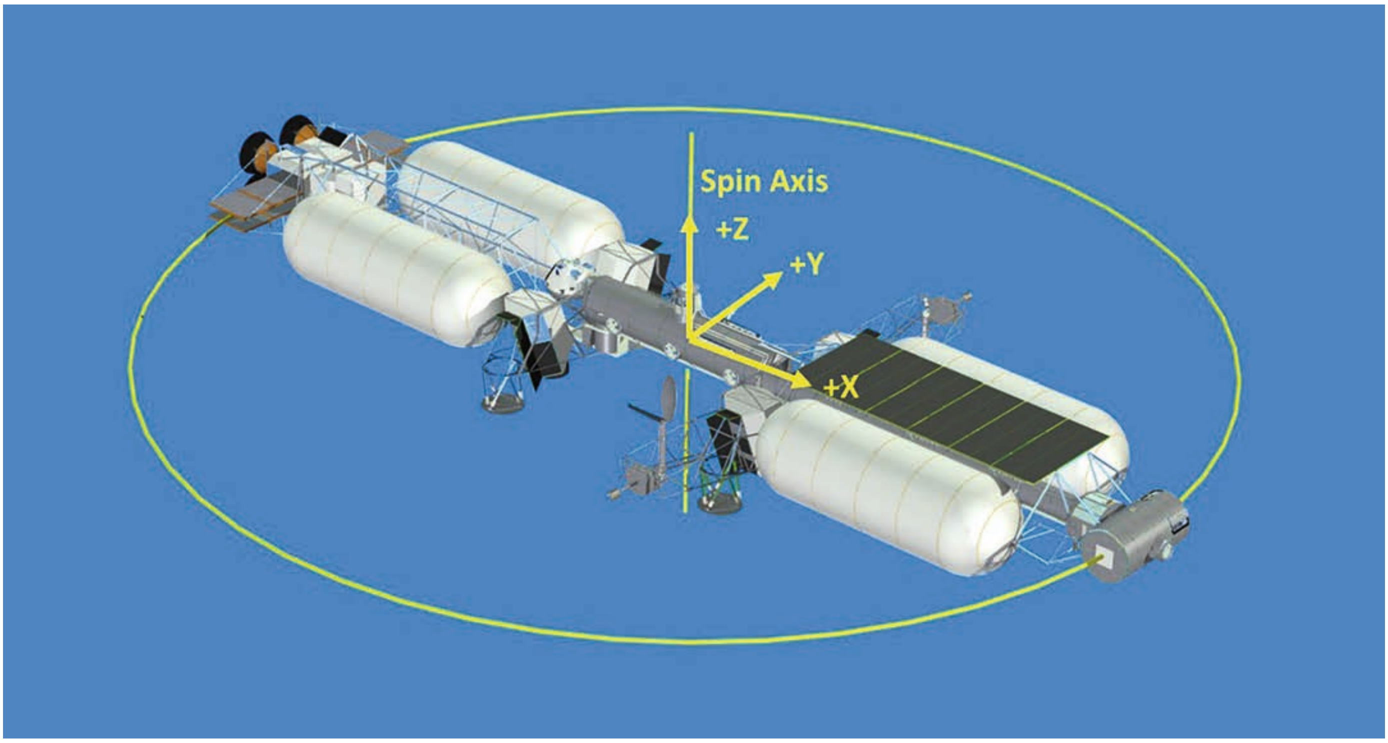

Fig.7 Scorpion Spin Orientation.

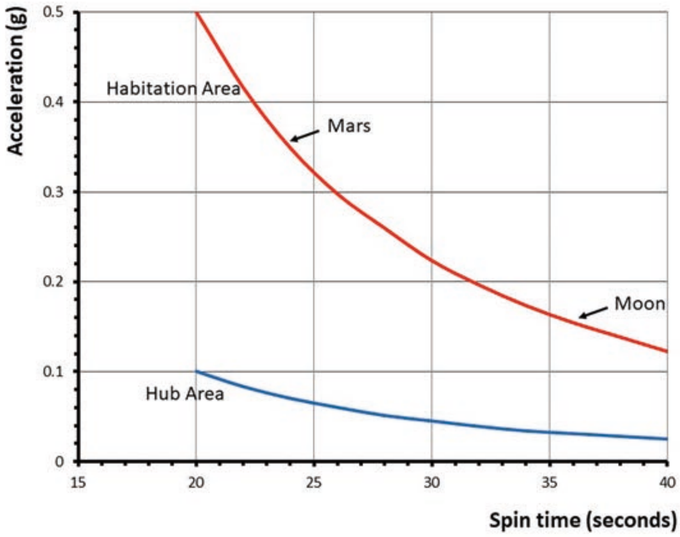

Fig.8 Spin against Acceleration.

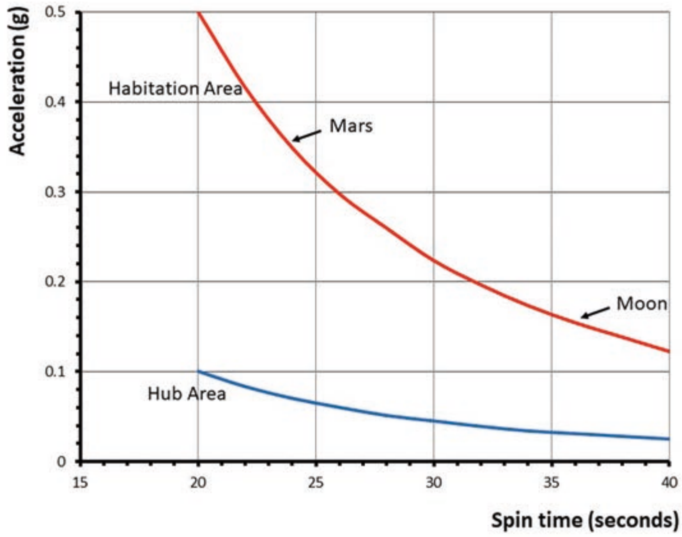

Fig.9 Propellant Required for Spin Up.

so the masses shown in Fig. 9 would need to be doubled for mission planning purposes.

Each of the wings have a despin mechanism on which is mounted a steerable 4m diameter communications antenna and on the obverse a 280 mm aperture Cassegrain telescope in a fork mount. Both antenna and telescope have an almost hemispherical field of view and the mountings arrangements are reversed on the other wing giving the Scorpion a complete almost unrestricted field of view for high data rate communications and long range visual observation. Having two mechanisms also provides degraded redundancy.

4 PROPULSION

4.1 Overview

The Scorpion has three propulsion systems; a single thermo/electric nuclear main engine, four secondary chemical engines and a set of reaction control thrusters. While the engine systems are independent, the propellant supply system is to some extent common.

4.2 Serpent Nuclear-Thermal-Electric Engine

Scorpion's main propulsion system is a version of the Serpent engine cycle devised by Alan Bond. The cycle uses electrical augmentation of a nuclear thermodynamic rocket; a basic concept that goes back to at least Goldsmith in 1959 [23]. The third edition of Sutton [24] devotes a paragraph to the idea, citing Goldsmith, and also Berry [25] and Rester and Rott [26]. Later editions of Sutton removed this paragraph, presumably to make room for more detailed discussion of the NERVA development work that had been undertaken between editions. But the concept was not forgotten and in 1972 Bond outlined a detailed, elegant and realisable variant on this basic principle [27].

While the Serpent cycle follows the basic principles published by Bond in this paper, it has been updated using the experience gained during the SABRE engine development pro-

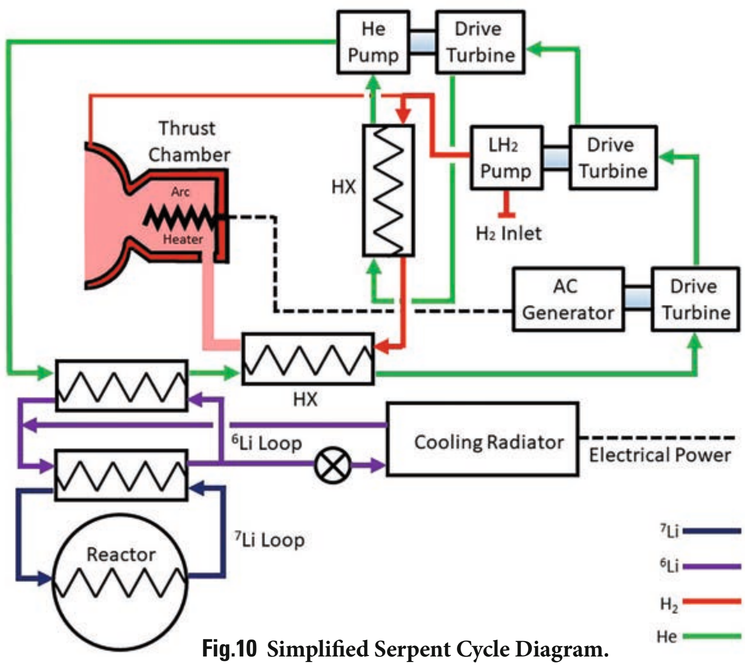

Fig.10 Simplified Serpent Cycle Diagram.

gramme [9] and as a consequence the specific details of the cycle are commercially confidential. However the basics can be described and are shown in a simplified cycle diagram (Fig 10). A reactor heats lithium in a loop which transfers the heat into a stack of heat exchangers which heat the hydrogen propellant and a helium power loop that drives the turbines which in turn power the hydrogen feed pump and an electrical generator. The electrical energy produced by the latter is then used to power arc heaters in the exhaust system. This augmentation heating of the hydrogen raises the effective exhaust velocity well beyond the 8 km/sec that could be expected from a conventional nuclear thermal engine, to above 12.5 km/sec.

While the Serpent uses a solid core fission reactor, this specific impulse is approaching what could be expected of a gas core fission engine. In 1970 Bussard uses 10 km/sec as an indicative example [28] (but this was not a performance prediction) while in the same volume Preston-Thomas and Evvard suggested that exhaust velocities in the range of 15 – 25 km/s could be achieved [29]. More typical estimates for gas core fission rocket performance are around double this range; for example Taylor outlines a concept for a 44 km/sec gas core [30] and Parkinson assumed 35 km/s as a realistic expectation for such an engine [31] based on work by Ragsdale [32]. Sutton and Ross [33] were more optimistic, suggesting a range between 50 km/s to 100 km/s. This wide range of performance estimates reflect the uncertainties in its technical implementation; particularly plasma control and the separation of propellant and core material. The technology has largely remained static since the 1970s, and these remain as technical issues with many ideas but no developed solutions. Thus a gas core engine is not a currently available technology.

While the Serpent is clearly moving into gas core performance territory, unlike a gas core fission engine, it is realisable with available technology and meets the Scorpion study's second criteria for technical viability. As the references already quoted demonstrate, the concept was envisaged and theoretically developed well before 1985. Indeed there had already been a decade of stagnation and neglect by that date.

At the same time as Bond's paper outlined realisable cycles; fission reactors suitable for Space propulsion use were largely proven on the NASA programme leading to the NERVA XE [34] with the test of near flight configuration reactors. However; NERVA was cancelled as a development programme in 1972, after seventeen years of work. There are significant differences with the Serpent, both in scale (Serpent is an order of magnitude larger in power terms) and technical approach. The key technical difference is that the Serpent does not run the propellant through the core, but uses a liquid lithium heat transfer system. This is a common technology for terrestrial reactors and was receiving serious and detailed consideration for a general purpose space power systems by NASA in 1971 [35] – a programme that was also abandoned at the same time as NERVA.

The hydrogen and helium heat exchangers require a mass performance outside what was available in the 1970s, but have subsequently been proven by Reaction Engines on the SABRE engine development programme [9]. All but one of the turbines and compressors are within available flight proven technology - the exception is the generator drive turbine that pushes the envelope a little. The generator itself is using modern (but currently available) technology. Which leaves the arcjet thrusters; these are another old concept (e.g. Reference 24) and at a basic kilowatt level arcjets using hydrazine propellant have been flight proven since 1993 [36] placing the overall technology at the highest technology readiness level. However, as with Space

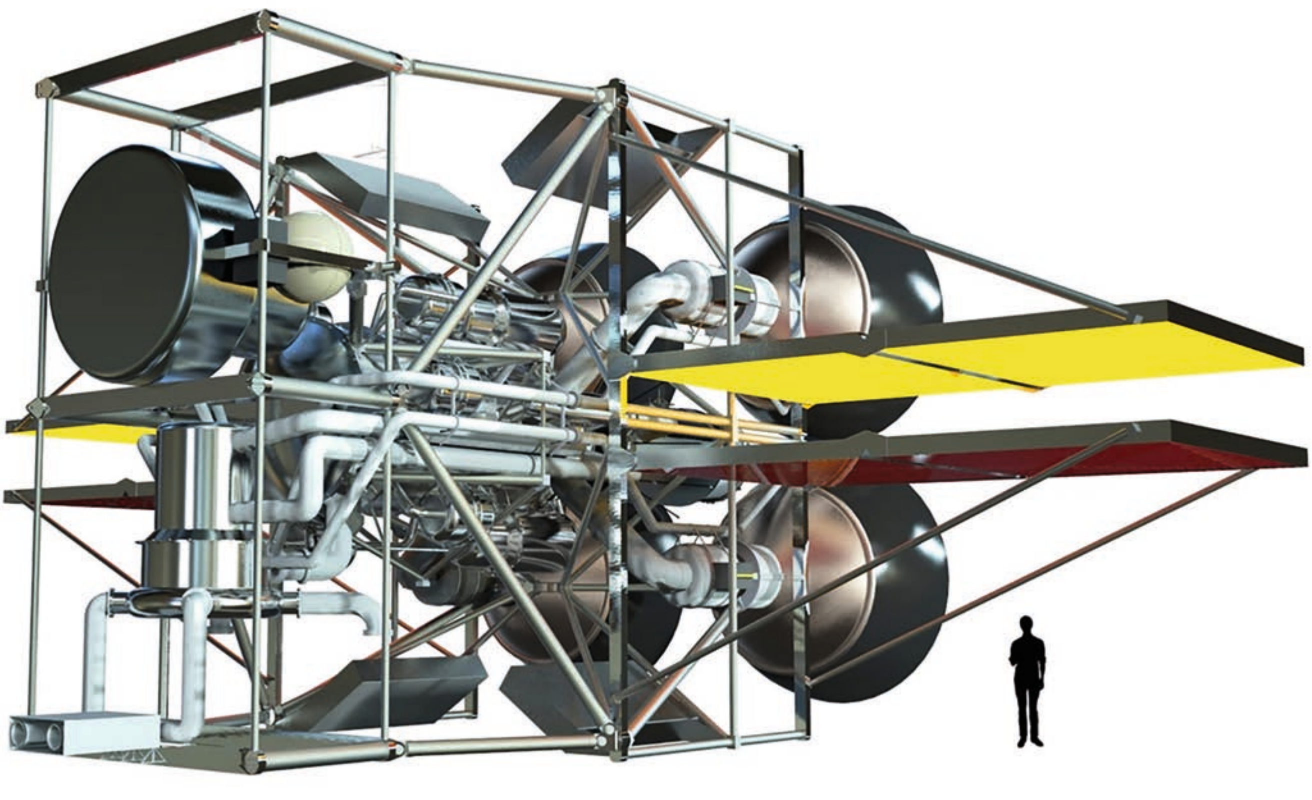

Fig.11 **An impression of the Serpent H.**

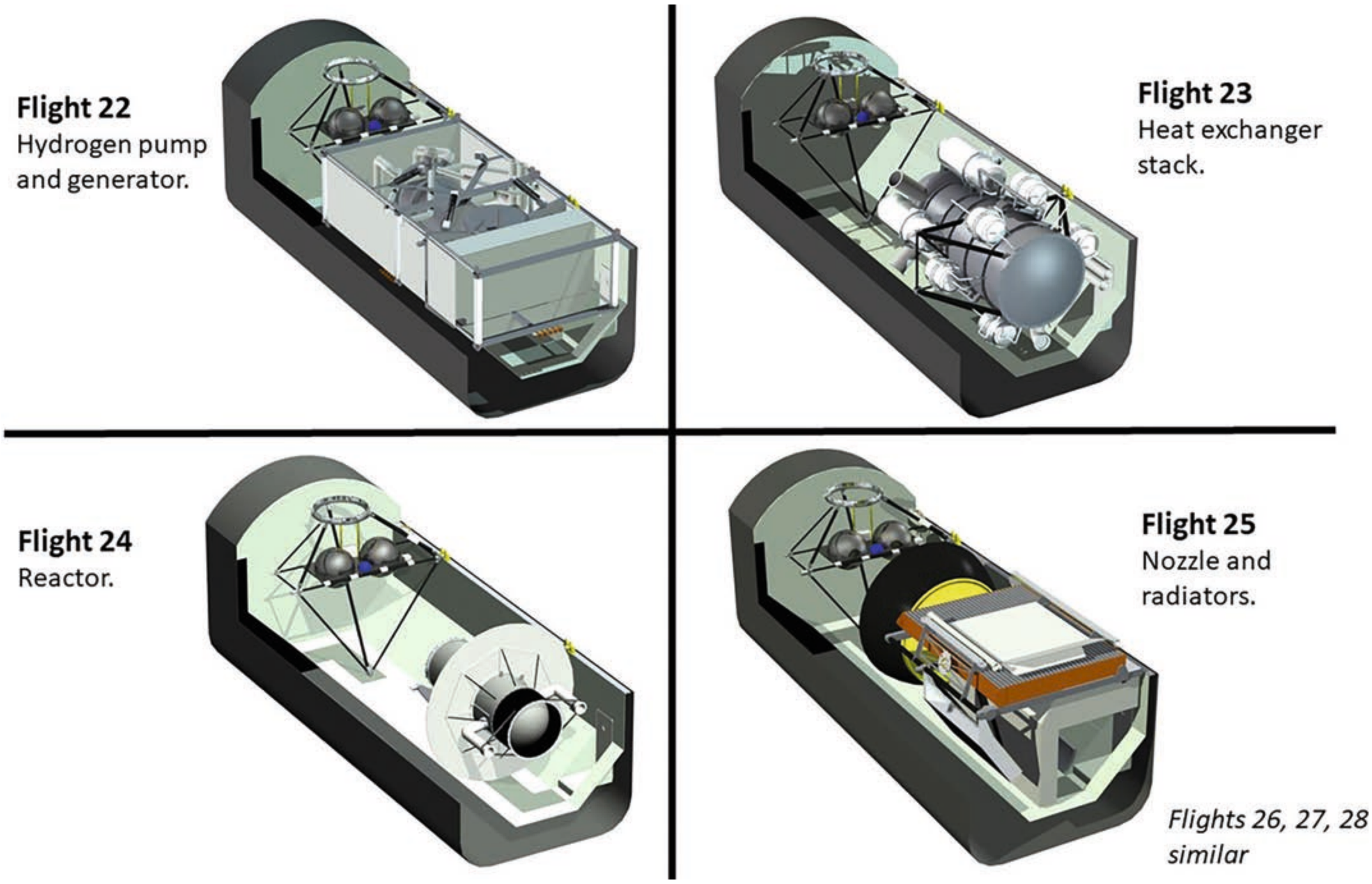

Fig.12 Serpent Assembly Flights.

nuclear systems, work on large thrust arcjet engines using hydrogen propellant largely stopped in the 1970s, as no application seemed likely.

From these considerations it is argued that, had development started on Bond's engine concepts before 1985, such an engine would have been available before 2000. This engine may have been a little heavier than the Serpent, which incorporates more modern technologies in the electrical generation area, but in all other respects it would match the Serpent's specification.

The version of the Serpent used in the study has been specially designed for it and is called the Serpent-H (Fig. 12). The reactor, which is fuelled by enriched uranium 235, is rated at 14.6 GW and the engine produces 200 tonnes thrust through 4 exhaust nozzles. The specific impulse is 12,746 Ns/kg, so 86% of the reactor energy ends up as kinetic energy in the exhaust. In its flight configuration, including the thrust structure and the outer panels, the engine has a mass of 40 tonnes. It is packaged so that it can be launched by seven Skylon flights for in-orbit assembly (Fig. 12).

As noted in Section 3.2: an attractive bonus feature of the Serpent is that, for a considerable time after a burn, the reactor cooling system can provide electrical power for the overall system using thermocouples embedded in the radiators - effectively a large radioisotope thermal generator.

The Serpent features three separate radiation protection shields. During engine operations the heat exchangers, and in particular the 6Li loop, together with additional shielding to fill the gaps, provide a "shadow" shield for the crew and equipment of the spacecraft, reducing the dose to 1 REM/hour. A second tungsten shield acts as a "manoeuvre" shield to reduce the external radiation in one direction, so that the dose at 50 km in open space is 1 REM/hour. This means that, when the engine is fired, care must be taken as to the location of nearby personnel or radiation sensitive equipment. When the engine is not operating the fissionable material is stored in a tungsten storage locker providing all round shielding.

4.3 Advanced Chemical Rocket Engine (ACRE)

The Serpent engine has several operational constraints. The start-up and even more significantly the power down procedures mean that the engine has a high minimum impulse per "burn." It has a fixed thrust and so cannot be used for manoeuvres such as a hot helicopter lunar landing. Also the radiation produced while firing means the Serpent cannot be operated close to human habitations. Thus systems employing Serpent engines will need to also have a secondary propulsion system for manoeuvres where these constraints make the use of the Serpent engine impractical.

In the case of the Scorpion this secondary propulsion is required to undertake the final landing and take-off manoeuvres of a lunar surface mission. It means the force produced by the system must be sufficient to perform this manoeuvre – with an engine out - and have the range of thrust needed to perform a hot helicopter landing. Further the chemical system must undertake all the manoeuvres when the altitude is under 50 km of the lunar surface to ensure the Serpent reactor is not active within the potential range of danger to the inhabitants of any surface bases. It is this mission that drives the required total

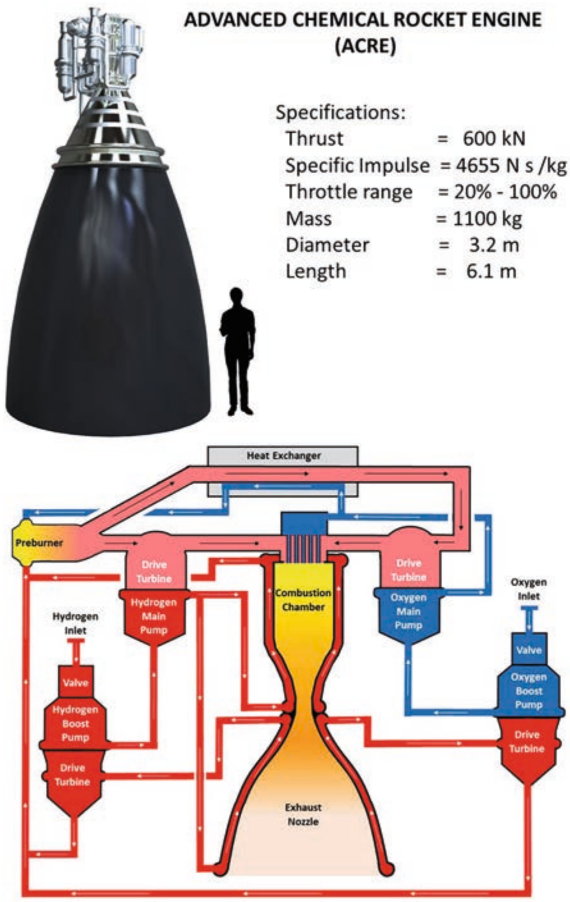

Fig.13 The ACRE Chemical Engine.

impulse, thrust level and degree of throttling.

To meet these requirements the Scorpion's secondary propulsion is provided by four hydrogen/oxygen chemical engines called the Advanced Chemical Rocket Engine (ACRE) (Fig. 13). This engine is a concept scaled from the throttleable version of the NASA/Rocketdyne Advanced Space Engine (ASE) [37]. Together these four ACRE engines deliver between 2.4 and 240 tonnes of thrust, and provide the secondary propulsion capability required to fill the capability gaps created by the Serpent engine's operational constraints.

4.4 Reaction Control Thrusters

Reaction control on the Scorpion is achieved by thirty 1kN gaseous hydrogen/oxygen thrusters arranged in banks of five to vary the thrust level between 1 and 5kN in kN steps (Fig.14).

In using gaseous hydrogen/oxygen thrusters the Scorpion follows the Skylon spaceplane which also assumed this technology for its reaction control thrusters [4]. The Skylon project gained a wide experience with gaseous hydrogen/air rocket engines [10] in this thrust range particularly with the development of reliable reusable electrical ignition. An alternative with gaseous hydrogen/oxygen propellants, that may prove both simpler and even more reliable, is catalytic ignition.

4.5 Propellant Supply System

The 400 tonnes liquid hydrogen is stored in four inflatable cylindrical tanks with a diameter 9 m and length 17.8 m. Inflatable tanks were assumed so that they can be packaged for launch; it was not assumed they would be lighter than conventional ridged tanks. This was a solution to launch system volume constraints proposed by von Braun in his 1953 Mars Project [38], who assumed "fabric reinforced plastic" collapsible tanks (and habitats), although he assumed this technology would exclude cryogenic propellants like hydrogen.

As space flight became a reality and progressed the technology of inflatable structures was not pursued until the 1990s and then in the context of habitats rather than propellant tanks. This was the Transhab development, which set a goal of creating a module that had a suitable volume for a Mars Mission that could be carried within the Space Shuttle payload bay [39]. The Transhab came from NASA's Johnson Spaceflight Center in Huston with its specialism in human spaceflight. Had it come from the Marshall Spaceflight Center in Huntsville with its propulsion specialism, it is more likely that it would have concentrated on the bigger volume problem for missions to Mars, which is the hydrogen tanks.

Transhab development at the Johnson Spaceflight Center was stopped by an act of Congress [40] – a clear example of Martin's law where big P Politics prevents an economical and technically promising approach from proceeding. The technology was taken up by Bigelow Aerospace and successfully brought to flight readiness for habitation roles. The company that makes the structural skins - the key technology involved - has recently been involved in a study to explore its use with cryogenic propellants [41] although the results from this work are unknown.

Thus inflatable propellant tanks are argued as technically viable using the second criterion. They were envisaged well before 1985 and although serious technology assessment started much later and was slightly off target. There is nothing to suggest it is not an easily realisable approach to large liquid hydrogen tanks that could have been developed at any time after Apollo.

The tanks have two outlets, in the X and Z axis so they can be used when either the Serpent or the ACRE engines are firing. These outlets feed four 1 m diameter spherical tanks for propellant management during engine start up, housed in the four propulsion pods. The propulsion pods (Fig. 15) also house

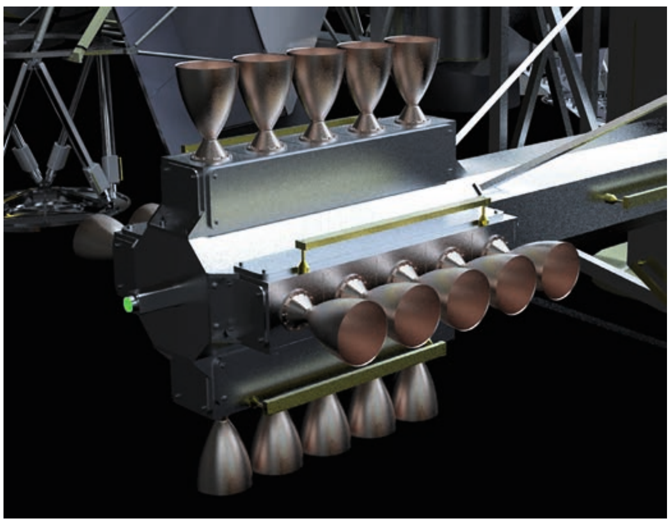

Fig.14 Starboard Wing RCS Thruster Cluster.

the four spherical oxygen tanks, each 4m in diameter and able to carry 27.5 tonnes of liquid oxygen. The pods also provide the mounting for the ACRE engines and the propellant pumps and cooling systems. Thus a large amount of the complexity of the propellant management systems are contained in these pods that are integrated and tested on the ground before flight, minimising the orbital assembly operations.

A dominating operational problem in using cryogens, particularly liquid hydrogen, is boil off. There is only a limited degree to which tank insulation can resolve this issue, it adds to the system's dry mass and can never prevent substantial propellant loss on long missions. For systems like the Scorpion, where the propellant is delivered piecemeal over many flights, there is an additional concern over significant loss during the mission preparation phase due to the extended refuelling operations.

The substantive secondary power that the Serpent engine generates gives the Scorpion an alternative strategy to deal with heat soak into the tanks. Each of the pods has an active cooling system (Fig. 16) which using 20 kW to extract 750 W from the hydrogen propellant. The cooled hydrogen is then passed through a heat exchanger to take 75 W from the liquid oxygen tanks. The majority of the heat is dumped into the main Scorpion cooling system but a substantial amount is also lost in radiators mounted on the propulsion pod itself. This secondary cooling loop is optimised to lower the coolant temperature rather than radiate power.

The system also has a second cooling system using triple point evaporators. These are used both to control the tank temperature when the Serpent power is not available, and to be a source of gaseous propellants for the reaction control thrusters which is additional to supply from the electrolysed water produced by the life support system.

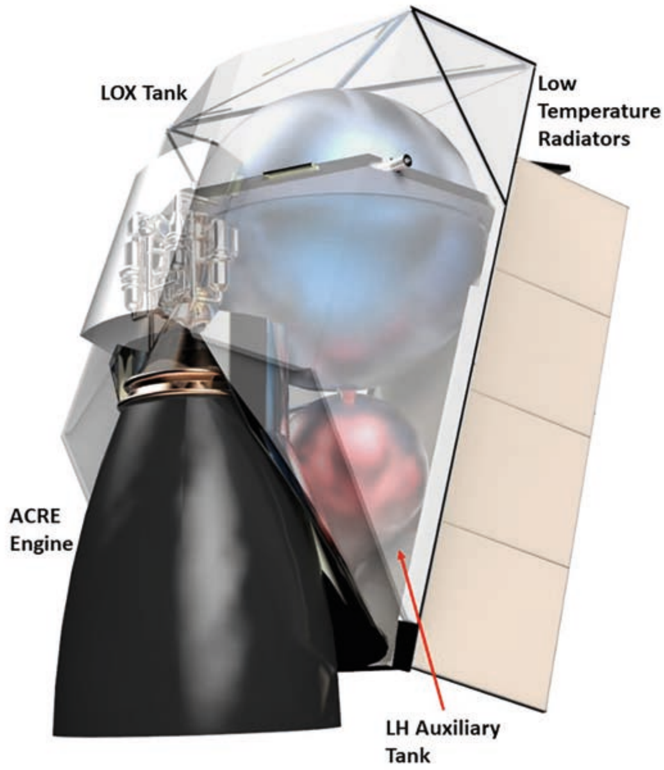

Fig.15 Propulsion Pod.

5 KEY SUBSYSTEMS

5.1 Overall Philosophy

The other subsystems on the Scorpion have followed conventional approaches, in large part drawn from the Space Shuttle

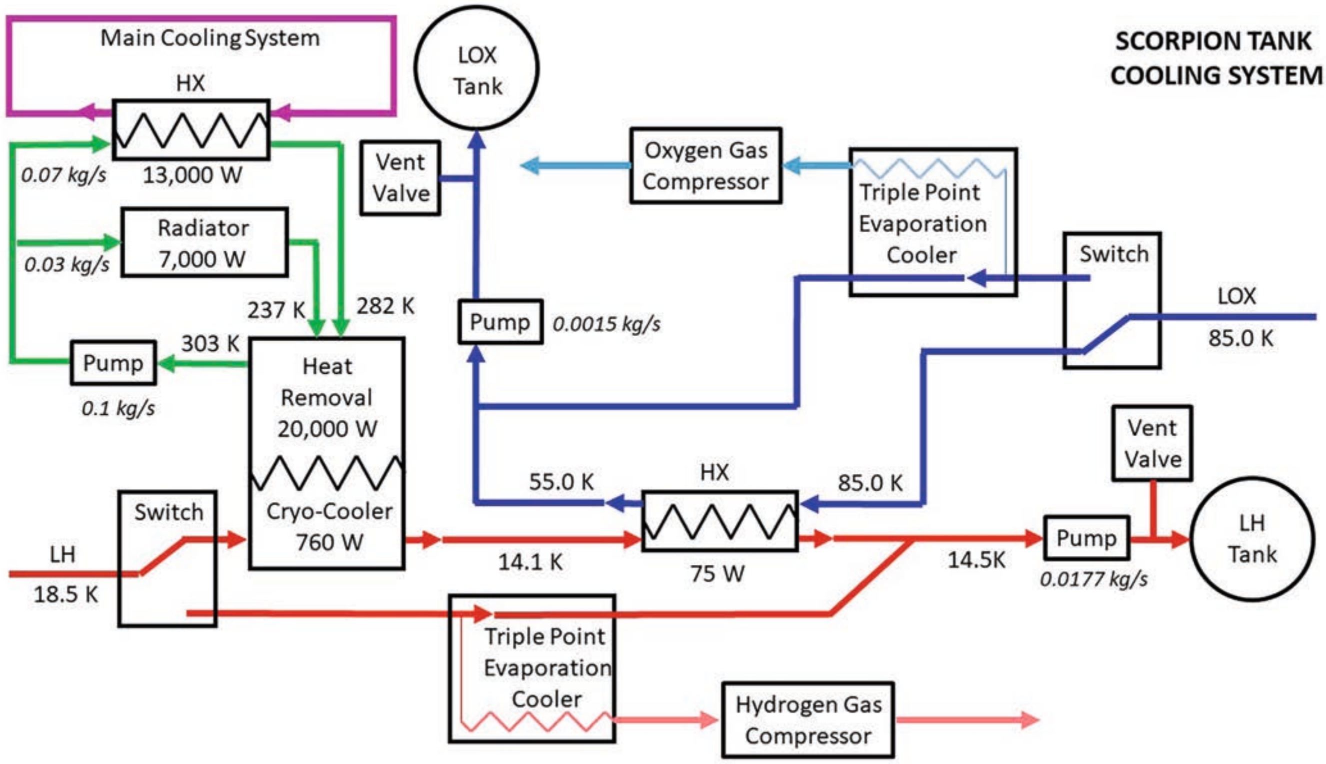

Fig.16 Propellant Cooling System.

and the ISS. Thus they represent technologies of twenty year maturity, and demonstrate that outside of the propulsion no part of the Scorpion design requires technologies that are not at Technology Readiness Levels 7 to 9.

The exceptions are some of the sensors and electronics. For example early in the study the main docking and landing sensors was the Neptec Tridar (Triangulation and LIDAR Automated Rendezvous and Docking} which had flown on the Space Shuttle in 2009 [40] and still used on the ATK Cygnus supply spacecraft. In the final version of the Scorpion describe in this paper this was replaced by the Tridar successor called LEIA (LIDAR for Extra-terrestrial Imaging Applications) [42]. This unit has superior performance to the Tridar and will have demonstrated the ability support lunar landings on the Luna 27 LunaResurs lunar lander planned for a 2024 landing.

Another area where the design used modern systems not yet space qualified was the data bus architecture which assumed an AFDX (Avionics Full-Duplex Switched) bus, compliant with ARINC 664 which is an aviation implementation of IEEE 802.3 (commonly called Ethernet) for the long distance communications between data nodes. This databus standard has been used on aircraft such as the Airbus A380 and Boeing 787 but not in space.

It is argued none of these exceptions affect the overall judgment of feasibility within the constraints set by the study. The electronics required by the Scorpion could have been achieved with the technology levels of the Space Shuttle and the higher mass and power requirements would not have a significant impact on the overall system budgets.

TABLE 5: ESTIMATED TYPICAL POWER LOAD

Item	Basis	Power kW
Payloads	6 x 3 kW	18
Tank cooling	3 x 20 kW	60
ECLSS		10
Serpent engine	Dormant	4
Other loads		12
	TOTAL	**104**

5.2 Power

The Scorpion's normal power load is estimated to be a little over 100 kW as shown in Table 5. The power loading is dominated by the propellant tank cooling system. It was thought unlikely all tanks would have the maximum design heat input at the same time, however even with only three systems operating it accounts for 60% of the power demand.

From this analysis the power system was specified at 120 kWatt. The primary source of power for the Scorpion are the thermoelectric panels built in to the reactor radiators. Each of the four panels generating 30 kW which is fed through a regulator to supply four power buses at 160V DC to reduce likeli-

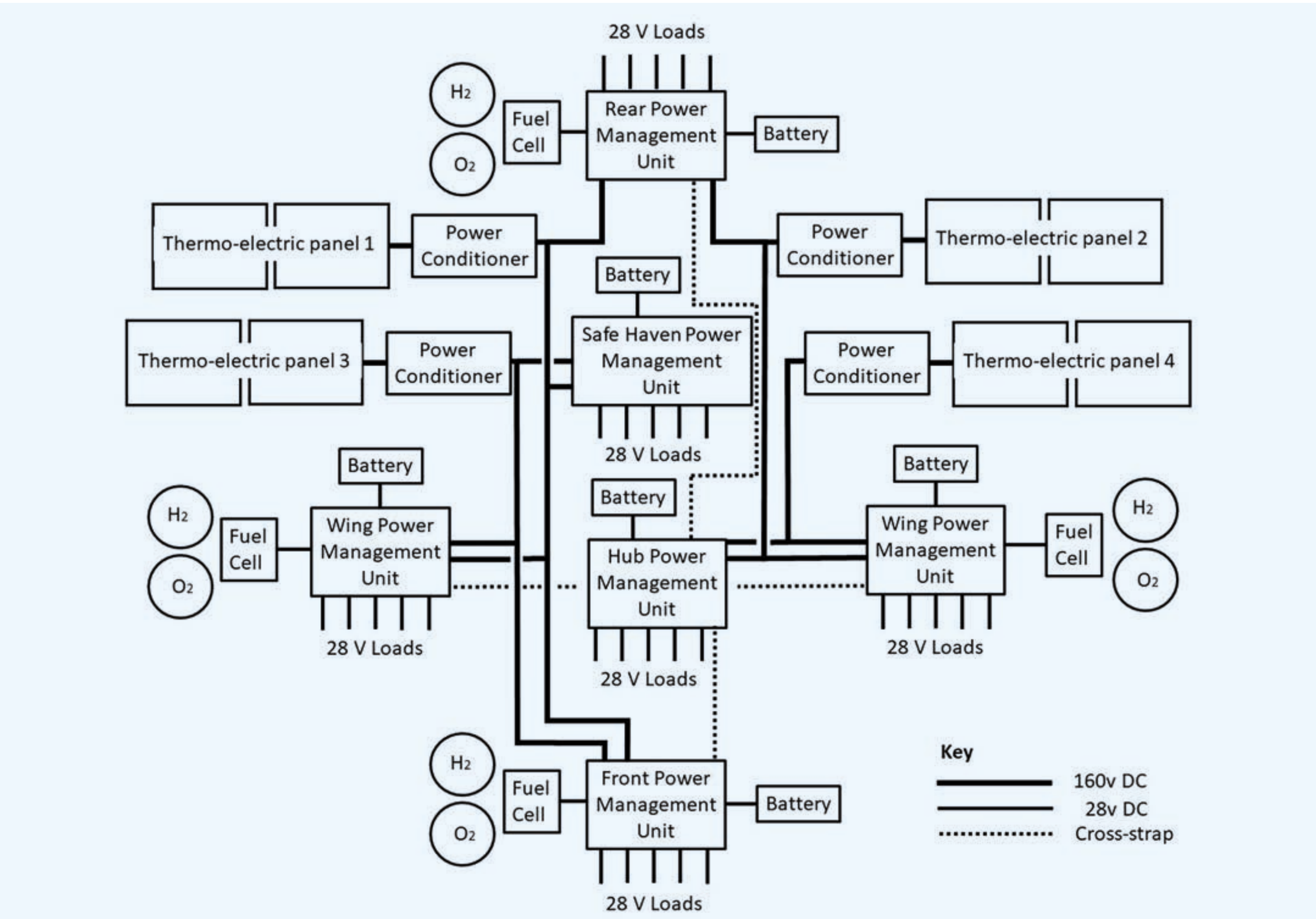

Fig.17 Power Distribution Architecture.

hood of arcing while creating a current of 187.5 amps which is easily handled by conventional 200 amp cabling.

Fig. 17 shows the assumed architecture of the power distribution system. The 160 V lines are fed to six power management units distributed around the vehicle. These house the switching, circuit breakers and conversion to the aircraft standard 28 V DC to feed to the spacecraft's equipment. Each Power Management Unit is supported by two nickel hydrogen batteries (except the safe haven unit which has only one battery) and four of them also have fuel cells. The unit also contains the conditioning and management systems for these secondary power sources.

The batteries have a nominal 28 volts and a capacity of 5 kWhr with a 60% depth of discharge. Thus the total capability of all eleven batteries is 55 kWhr. These batteries are intended to provide an hour of power to initiate the system before either the fuel cells or the thermoelectric panels are operating. It also provides 80 kWhr with 100% discharge which is sufficient to give two hours of last resort power in emergency situations.

The fuels cells also have a nominal voltage of 28 volts and a design power of 5 kW (where it operates most efficiently) and 6 kW peak power where it can operate if the extra power needed. This gives a total power output between 40 kW and 48 kW which is sufficient to power the Scorpion without the active tank cooling, which is not required n this operational mode as the alternative triple point evaporation cooling system is the source of the gaseous hydrogen and oxygen to power the fuel cells. The Scorpion can be powered from fuels cells indefinitely so long as there is hydrogen and oxygen in the propellant supply system.

5.3 Utility Area

Most of the Scorpion's non-propulsion subsystems are located in a Utility Area at the front of the Hub module (Fig. 18).

The environmental life support system was assumed to centre on two systems; one to handle water and the other the cabin atmosphere. The water processing was assumed to recover water from the atmosphere and hygiene facility and then processing it into clean usable water and also a secondary supply of oxygen and hydrogen using electrolysis. The oxygen production is through a Sabatier process breaking down cabin carbon dioxide.

This system is very close to the requirements and technology of the American sector of the ISS [43]. This uses a Water Processor Assembly housed in two standard equipment racks and an Oxygen Generation System housed in one rack. Evaluation of the real operational performance of this system on the ISS compared with a long duration mission, such as human flight to Mars, suggests that, broadly speaking, it is suitable for such applications [43 and 45].

Although there are some differences in requirement from the ISS it is close enough to make it the basis of the provisions in the Scorpion feasibility design. The utility area has four racks with a 2500 kg and 10 kW locations allocated to water and cabin atmosphere. Two further racks house the ECLSS controls, and air quality monitoring. These racks also house the cabin power management, data bus controllers, and servers.

There is an independent open loop life support system located in the Habitation module and the EVA preparation area has access to the life support system in the Anzu, in support of their roles as safe haven.

5.4 Thermal control

The Scorpion has an active cooling system. The main thermal control system is a Freon loop located in the front end using a technological approach very similar to that employed by the Space Shuttle [46] and the ISS [47].

The heat is collected from a set of heat exchangers. Each of the propulsion pods active cooling systems has a 13 kW Freon/helium heat exchanger. The Hub houses all the main power consuming equipment (ECLSS, data handing and payload) housed in ISS standard racks that require a water cooling loop. To support this are a pair of 10 kW Freon/water cooling loop rejecting the heat from the ECLSS. The final heat exchanger is a 7 kW Freon/air in the front equipment taking heat from the Hab module, which has a low thermal load and relies on air cooling.

Fig.18 Utility Area.

The heat collected by the Freon is rejected in three hot redundant radiator systems. Each has a pump unit which powers and controls the Freon flow and a Freon Supply Unit that contains top up fluid and maintains pressure. The heat is rejected by radiators mounted on the upper face of the forward truss. There is a total of 212 m^2 surface area nominally operating at 295 K and intended to radiate up to 80 kW of heat.

Additional radiators that are not connected to the Freon loop are mounted on the forward equipment bay, as part of a separate secondary cooling system for the Habitation area which can radiate around 7 kW, and on the propulsion pods, as part of the tank cooling system which again can radiate around 7 kW when the tank cooling system is operating. The Serpent engine controls its temperature through its own internal systems.

The batteries and fuel cells have radiators built in and they are mounted to expose these radiators to Space.

6 ANZU CAPSULE

A requirement the study placed on the Scorpion is that it should have a viable escape system for the crew. To meet this requirement the system has an independent capsule capable of Earth return from most places in Earth orbit. This multirole capsule is a complete spacecraft in its own right and has a full mission capability. Its development could be justified without its role supporting the Scorpion, nevertheless its full development cost has been included in the Scorpion's acquisition budget.

This capsule (Fig. 19) was based on the Excalibur Multirole capsule described in three papers published between 2004 and 2007 [48, 49, 50] which itself was a revision of the BAe Multi-Role Capsule; a study conducted in 1989 [51]. The concept has been slightly revised for the Scorpion study and the name altered to avoid confusion with the Excalibur-Almaz capsule [52]. The new name is Anzu, after the Sumerian mythical bird, a name that could be read to mean "acquainted with the heavens" or "have knowledge of the heavens."

Although it has provisions for a nominal crew of four, it can carry six people on an emergency basis – matching the full crew compliment of the Scorpion. It cannot only be used as an escape system but also as a general purpose small transport tender. However it is required to be on its port if the Scorpion is spinning to create artificial gravity and when using the ACRE engines for a lunar descent to ensure the correct mass properties.

There are several changes between the Excalibur and the Anzu. The physical shape has changed to a circular conic with 4.8m diameter base (the Excalibur had a 5.6m by 4.5m elliptical base). The Anzu uses of the USIS docking port as opposed to the Androgynous Peripheral Attach System used on the Excalibur, and the addition of a side USIS berthing port in place of a simple airlock door. There are an additional four propellant tanks raising the usable propellant load to 6.1 tonnes (from 5.1 tonnes).

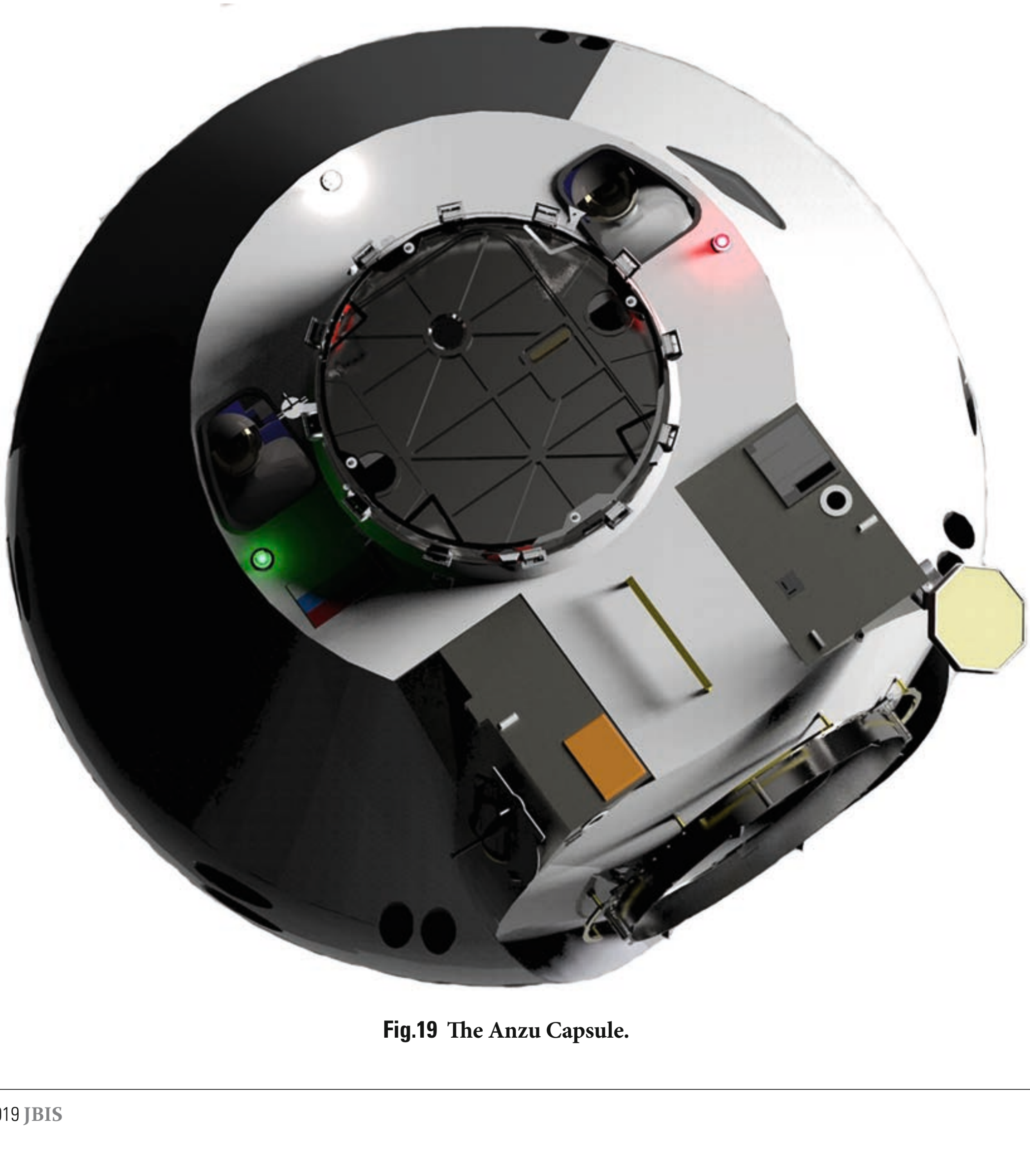

Fig.19 The Anzu Capsule.

SANGRAIL ENGINE

Fuel	Hydrazine (N_2H_4)
Oxidiser	Nitrogen Tetroxide (N_2O_4)
Mixture ratio	1:1.2
Max. thrust	31.8 kN
Throttle range	7% to 100%
Specific impulse	3141 N s / kg
Mass	14 kg
Dimensions	445 mm height, 150 mm diameter

Fig.20 The Sangrail Engine.

The Anzu retains the Excalibur's use of a Unified Fluid System [53] whereby the nitrogen tetroxide and hydrazine propellants is also used in fuels cells to provide electrical power and life support water, decomposed to give oxygen and nitrogen for the cabin atmosphere and pressurised nitrogen for a cold gas secondary reaction control system. The main propulsion consists of four Sangrail engines (Fig. 20), devised by Alan Bond [54] which give a potential mission velocity of 2.5 km/s. Sufficient for a return to Earth from all of Earth orbit space and a lunar surface to orbit mission in event a Scorpion is stuck on the Moon.

The Anzu attaches to the Scorpion using its side berthing port to connect to a dedicated USIS berthing port on the Scorpion that leads into the EVA preparation area. The Anzu is orientated so it can perform a take-off from the lunar surface.

7 CONSTRUCTION

7.1 Construction Facility

The International Space Station is the only system that has been constructed that is comparable to the Scorpion in terms of construction complexity. It was constructed from components that were assembled without any orbiting supporting infrastructure, but it should be born in mind that the Space Shuttle, which conducted many of the assembly flights, incorporated what was effectively a small space station enabling the complex build operations that were necessary. This capability is not available with Skylon so the Scorpion does require a facility (an orbiting shipyard) for its construction. This construction facility needs to have:

– provisions for Skylon to attached and its cargo off loaded,
– manipulators and EVA capability and other provisions to enable assembly,
– construction crew habitability provisions.

The construction facility can be based around existing space station elements such as those flying on the International Space Station. For the study the concept assembly facility was based around the Post ISS Architecture (PIA) station [55], because the full design details and the detail of the cost estimation were available to the study. A further consideration is that Skylon (the study's assumed launch system) was specifically included as a module carrier in the study, which enhanced consistency. However the use of the PIA is not an inherent requirement to demonstrate feasibility, rather it is a matter of convenience for the study.

PIA Station consists of three modules (Core, Habitation and Laboratory) that are connected to create a working station with a pressures volume of 185 m^3 for a crew between three and four. It has a dry mass (i.e. without stores, payload or crew) of around 30 tonnes and its power system can supply 14 kW continuous electrical power. The acquisition cost of the three modules (without launch) was estimated to be $3.2 billion.

To turn the basic PIA station into a Scorpion construction facility requires the addition of an Anzu capsule to act as an escape system, a construction spine, and a crew and supplies delivery flight. The construction spine allows work on the entire length of the Scorpion and is delivered in two flights which makes a total of seven Skylon flights to construct the facility. Table 6 gives the total facility acquisition cost which is estimated to be $6 billion.

7.2 Construction Sequence

The assembly was assumed to take place in a low inclination (sub 30 degrees) orbit around 300 km altitude to which Skylon

TABLE 6: CONSTRUCTION FACILITY ACQUISITION COST

Item	$ Billion
PIA Core	3.20
Anzu	0.69
Spine	2.00
7 Skylon launches	0.14
TOTAL	**6.03**

can launch 14 tonnes of payload. All assembly flights (Fig. 21) require the Skylon Orbiting Facility Interface (SOFI) to connect to the Construction Facility, this was assumed similar to the one described in the Users' Manual [5] but has the addition of water ballast tanks that can carry up to 1.8 tonnes of water. This enables the spare mass capacity on the assembly flights to deliver 30 tonnes of water to prime the ECLSS and propellant supply systems. The SOFI mass was taken as 1 tonne which is higher than the 750 kg quoted in the Skylon Users' Manual [5] to account for the ullage water system. This leaves 13 tonnes per assembly flight for the Scorpion's parts and associated carrying structure and support equipment (called ASE -Airborne Support Equipment).

The Scorpion requires twenty eight assembly flights as shown in Table 7, this includes the first flight to deliver the assembly crew and their supplies. The item masses are the rounded up values from the estimates and so incorporate the equipment uncertainty margin. The ASE masses are similarly rounded up; with a 200 kg minimum in cases where trunnions and grapple points attach directly to the flight structure. The ullage water is calculated from the remaining mass capability up to the 1800 kg limit, with a check that the complete payload centre of mass lies within the envelope defined in the Skylon Users' Manual [5]. The volume requirements of the Scorpion components mean that the mass capability of Skylon cannot be fully exploited on every flight; the average mass utilisation is 78%.

The Scorpion construction is assumed to be undertaken nose to tail, which means starting with the pressurised area that creates both a habitable space and the main structural element of the front of the spaceship. The construction does not follow the route of previous space habitats that were assembled in orbit where modules are launched pressurised and then docked together via berthing or docking ports. The Scorpion's pressure sections are launched unpressurised and joined by ring interfaces that are bolted together. Pressurisation is then undertaken in orbit once the assembly is complete using air in the forward equipment bay tanks. This takes place in two stages; the first three flights construct the habitation module and the first segment of the tube that can then be pressurised. Subsequent six flights complete the Tube and Hub, which is followed by a flight with a pressurised supply module and the two forward landing legs. This flight has the air to pressurise the remainder of the habitable areas, it remains attached for the remainder of the construction process and is used as the means to return some of the ASE to Earth once assembly is completed.

The remaining assembly flights then launch the external equipment starting with the four propulsion pods. The truss structure elements having been already launched with previous flights mostly with the Tube segments. Finally the Serpent engine components complete the construction process, and the Scorpion is ready for free flight.

8 COSTING

The preliminary nature of the Scorpion combined with its unique role and technological approach makes parametric costing less precise than can be expected from more conventional design studies. However it was felt that such an exercise would give a scoping rough order of magnitude estimate to indicate the scale of the investment required. Table 8 shows the development and unit build cost estimate from Parkinson [56] from the Scorpion mass budget. The result is around $40 billion (mid 2010s). The estimate includes the Anzu development,

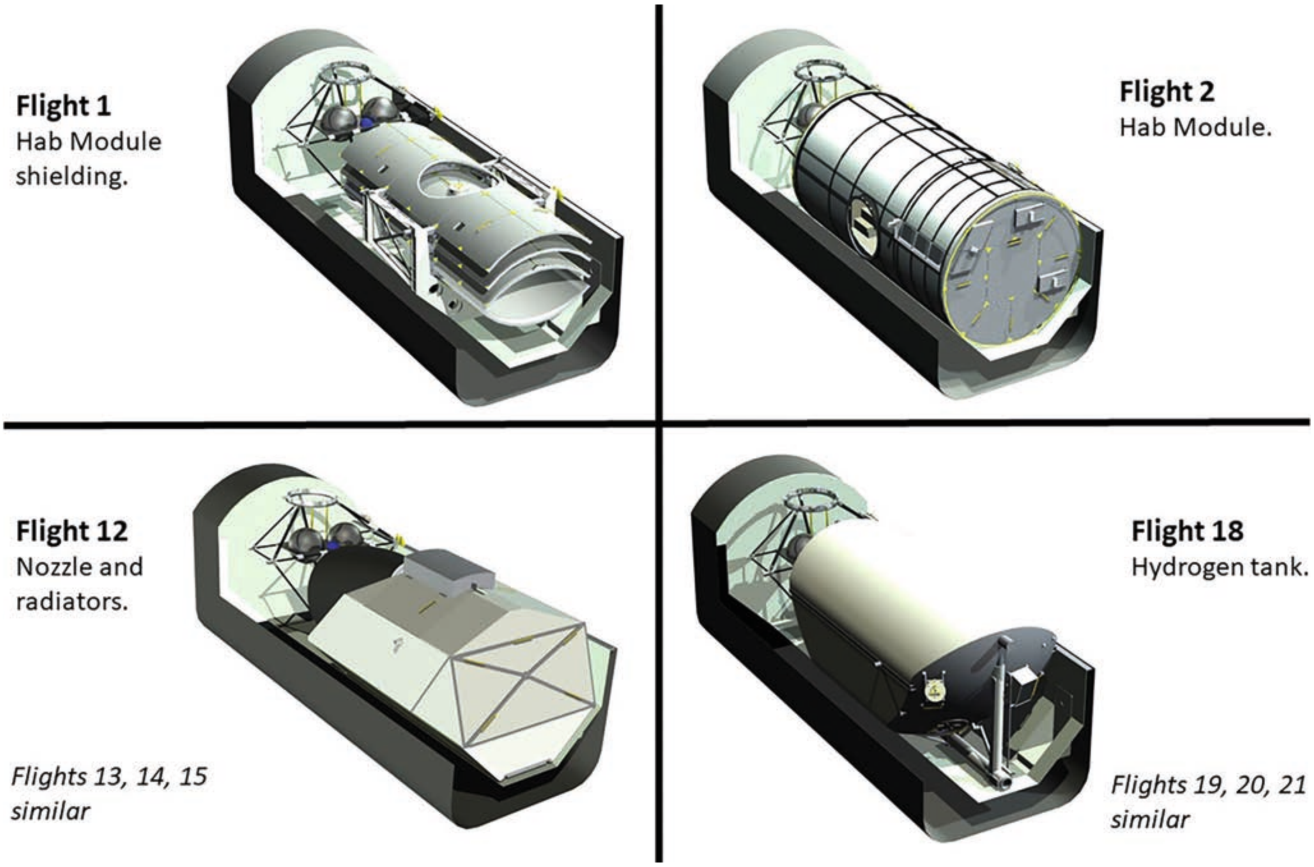

Fig.21 Example Assembly Flights.

TABLE 7: SCORPION CONSTRUCTION FLIGHTS

Flight	Item	Item Mass (tonnes)	ASE (tonnes)	Water (tonnes)	Unused (tonnes)
1	Assembly Crew				
2	Habitation Shielding	12.0	1.0	0	0
3	Habitation Module	12.0	0.2	0.8	0
4	1st Tube	11.0	0.2	1.8	0
5	2nd Tube	6.9	1.2	1.8	3.1
6	3rd Tube	6.0	1.2	1.8	4.0
7	4th Tube	7.3	1.2	1.8	2.7
8	Forward Hub	12.8	0.2	0	0
9	Middle Hub	12.0	0.2	0.8	0
10	Rear Hub/Airlock	5.5	0.2	1.1	6.2
11	Fwrd Legs + Supplies	7.0	4.0	1.8	0.2
12	Fwrd Strbrd Prop. Pod	4.4	0.2	1.8	6.6
13	Fwrd Port Prop.. Pod	4.4	0.2	1.8	6.6
14	Rear Strbrd Prop. Pod	4.4	0.2	1.8	6.6
15	Rear Port Prop Pod	4.4	0.2	1.8	6.6
16	Wing Equipment	12.0	1.0	0	0
17	Anzu Capsule	11.1	1.2	0	0.7
18	Fwrd Strbrd Tank	12.5	0.2	0.3	0
19	Fwrd Port Tank	12.5	0.2	0.3	0
20	Rear Strbrd Tank	12.5	0.2	0.3	0
21	Rear Port Tank	12.5	0.2	0.3	0
22	Generator and LH Pump	7.3	0.2	1.8	3.7
23	Heat Exchanger Stack	12.0	0.2	0.8	0
24	Reactor	12.2	0.8	0	0
25	Strbrd Upper Nozzle	3.5	0.5	1.8	7.2
26	Strbrd Lower Nozzle	3.5	0.5	1.8	7.2
27	Port Upper Nozzle	3.5	0.5	1.8	7.2
28	Port Lower Nozzle	3.5	0.5	1.8	7.2
	TOTALS	**228.7**		**29.9**	**75.8**

although this might not be a valid assumption given the Anzu is an independent system and could have been developed with a different purpose for roles outside Scorpion support.

The non-nuclear elements are conventionally costed using established space station and rocket engine parametrics. The main uncertainty being the preliminary nature of the mass estimates used as the inputs. The highest single contribution is the ACRE chemical engine which is shown as a separate item.

TABLE 8: SCORPION COST ESTIMATE

	Development ($ billion)	Unit Build ($ billion)
Non-Propulsion elements	5.0	0.90
ACRE chemical engine	2.5	0.12
Serpent Nuclear Engine	20.5	0.68
Anzu	9.5	0.69
System Eng & Integration	0.5	0.12
TOTAL	38.0	2.51

Reference 47 discusses the development cost of the Excalibur multi-role capsule which is in essence the same as the Anzu. This derived two estimates dependent upon whether the system was treated as a re-entry system ($4 billion) or a planetary lander ($9 billion). The paper considered one estimate too low and the other too high. For this estimate we have taken $7 billion as an intermediate estimate and factored by 15 years of inflation to give $9.5 billion.

The dominant development item is the Scorpion nuclear engine, but without a prior development as a suitable basis for precise a parametric the estimation this figure must we taken as an indicative figure. The cost estimate was actually derived from marine nuclear parametrics.

The sort of programme that a Scorpion fleet would undertake is entirely speculative. But for comparison purposes the study considered a fleet of five vehicles, each of which undertakes twenty missions making a total of a hundred missions. This is comparable to the fleet size and mission count of the

Space Shuttle programme.

In this scenario the estimated acquisition cost for each Scorpion, including a development payback component, is given in Table 9.

The acquisition cost is dominated by the non-recurring costs. Without development and facility payback the repeat build is $3.2 billion without any allowance for learning factors which would further reduce this estimate.

The flight's operational costs are completely dominated by the Skylon flights to fuel the vehicle and vary due to different propellant loads and payload masses. A typical flight requires 400 tonnes of hydrogen and 30 tonnes of oxygen, which require 43 Skylon flights. Once payload and crew delivery flights are included the total flights required is around 50. At $20 million per Skylon flight that is a billion dollars per Scorpion mission. To reach a total flight cost, $600 million in acquisition payback ($12 billion/20 flights) needs to be added. Thus in this scenario the cost per typical mission is $1.6 billion.

With the assumption of a hundred flights in the total programme a total Scorpion programme cost would be $160 billion.

TABLE 9: INDIVIDUAL SCORPION ACQUISITION COST ESTIMATE

	$ billion	Basis
Development Payback	7.60	$38 billion /5
Unit Build	2.51	Table A.
Launch flights	0.56	28 x $20 million
Assembly Facility	1.30	Section 7
Total	**11.97**	**Call it $12 billion**

9 ASSESSMENT AND CONCLUSIONS

9.1 Technical

In the Apollo period there was an expectation that by the end of the Twentieth Century humanity would have extended its reach at least to Mars and maybe beyond. This was not just the vague vision of serious science fiction such as '2001: A Space Odyssey' [57, 58], it was a proposed plan from NASA that was backed up by Phase B level studies. [12, 13]. Just a decade later the "failure of nerve" that afflicted humanity's progress into space was clear and discussed by Parkinson [59]. Yet at no point was the technical viability of the Post-Apollo plan open to question, and its annual costs, while high, would have been below that required and spent by the Apollo programme. So its failure to produce anything except a compromised Space Shuttle - that has now been abandoned without any effective replacement - is solely a matter of politics; that is the operation of Martin's law.

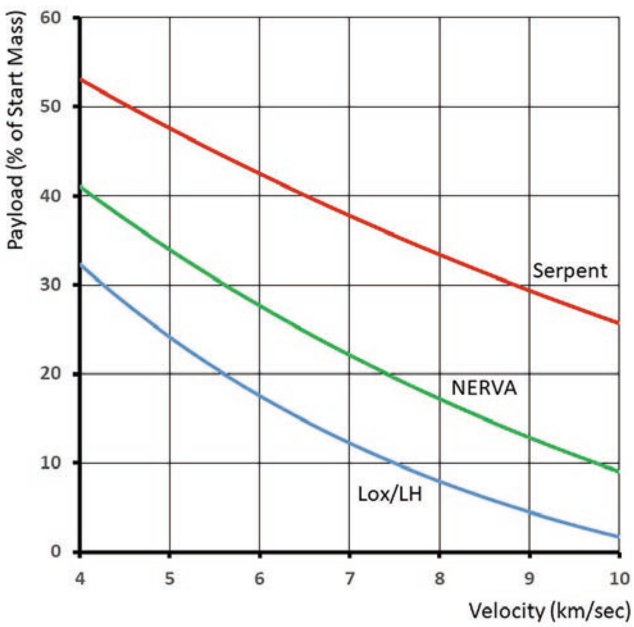

Fig.22 Performance Comparison of Engine Technology.

Although at first sight there may appear little difference in the resulting transport infrastructure of the post-Apollo programme and the Scorpion, and therefore all that this study achieved is to restate that mankind could have easily have achieved the post-Apollo goals by 2020. This impression is deceptive and fundamentally incorrect. Yes; the post Apollo exploration goals could have been achieved, but the Scorpion study shows they could have been achieved with systems that had a far greater scope for the subsequent exploitation of those locations after they have been reached.

The Post Apollo transport infrastructure was based on chemical and NERVA nuclear stages. The performance of both these engine technologies when matched against the mission velocities required for exploration beyond Earth orbit mean the transport systems have to be highly optimised to achieve the necessary mass ratios. For although the NERVA almost doubles the specific impulse over chemical engines, the heavier engine and larger tanks required when all the propellant is liquid hydrogen blunt the impact by doubling the achievable dry mass. The performance of the Serpent engine makes a dramatic difference, for although the specific impulse is only 50% greater than NERVA, the mass ratio is about the same and all the extra performance becomes extra payload.

This can be seen in Figure 22. This shows the payload of three generic orbital transfer stages over the range of typical mission velocities required to support the objectives of Post-Apollo and Scorpion studies. These three stages use Lox/LH (as exemplified by the Advanced Space Engine [37]), the NERVA engine [34] and the Serpent, with specific impulses of 4,655, 8,093, and 12,746 Ns/kg respectively. The minimum mass ratio (i.e. without any payload) was taken as 10% for the Lox/LH stage and 20% for both the NERVA and Serpent stages. The figure readily shows that, over most of the velocity range of interest, the Serpent engine almost doubles the payload over the NERVA and triples it over a chemical stage. It is this extra capacity that allows the Scorpion to incorporate features such as radiation shielding, landing legs, and a configuration capable of spin while remaining a viable transport system.

Another very significant difference between the Post-Apollo and Scorpion study is the assumptions on the launch infrastructure that connects the Earth with Space. The Post-Apollo Plans assumed a two stage Saturn 5, and a fully reusable two stage Space Shuttle. The Saturn 5 would be modified so that it is optimised for low Earth orbit delivery, and in some studies (e.g. [60]) it was uprated by enlarging the first stage and the addition of four solid propellant boosters to give a capability of up to 250 tonnes. The Space Shuttle was foreseen as a two stage fully reusable system with a payload capability around 10 tonnes (a third of the planned payload - but never achieved - of the Shuttle actually built). This combination of an expendable heavy lift system for launching large infrastructure elements and a smaller reusable system to launch everything else, including crew, can be effective [62]. The scale economy and the efficiency of launching large systems in larger units which reduces in orbit assembly off-setting the impact of the expendability of the heavy lift system. So the launch infrastructure NASA assumed would have been a significant improvement over what existed then or indeed at any time since.

Both Saturn 5/Shuttle and Skylon launch infrastructures could support a technically Scorpion programme. However Skylon's single stage operation meant its reliability, operational availability and launch costs would be far superior to the fully reusable two stage Shuttle configuration NASA was assuming for the post Apollo programme. So it is unlikely that Saturn 5/Shuttle would be able to deliver a realisable programme with hundreds of flights at affordable costs.

However a Scorpion programme with hundreds of flights as outlined in the paper does not actually indicate the full potential of the Skylon/Scorpion combined infrastructure. As shown in Section 8, Scorpion acquisition costs are two thirds development payback so with this cost written off and accounting for the impact of production learning effects subsequent Scorpions could be a quarter the cost. The flights costs are dominated by the Skylon launch costs and those also have a capability to reduce if a higher launch rate is assumed.

The build and operation of the Scorpion, as outlined in the paper, does not actually indicate the full potential of a Skylon based space infrastructure. Other work conducted by the study has looked beyond the hundred flight programme to examine at what could be achieved with a combination of Skylon and Scorpion. The combination is more than enough to make the utilisation of in-space resources economically viable, and thereafter the generation of an in-space economy with hundreds of millions of people, well beyond that envisaged in Parkinson's 2050AD economic model [31]. Such space activity could be solely supported by a fleet of a few thousand Skylons (below the current fleet size of civil airliners) around half dedicated to passenger flight and the other half dedicated to cargo. From this perspective Skylon is the last launch system humanity needs to fully become a complete spacefaring species. That is not to say it could not, or would not, be improved upon, it just means it would not need to be in order to achieve the complete and permanent conquest of Space.

It is argued that this comparison with the Scorpion illustrates that if the push to advance human exploration had been pursued after Apollo, then the vision outlined by the NASA post-Apollo planning, however ambitious and advanced it appears now given the context of the real subsequent history, probably falls well short of the limit technical capability would have imposed. This underestimates not only the effects the raw performance; what the Scorpion study shows is that this late 1960s NASA vision underestimated the degree to which an orbital infrastructure can incorporate reusability and multirole systems to create a sustainable exploitation infrastructure, rather than one solely limited to exploration and reliant on a continuing state political and financial support.

It is to be expected that in half a century technical improvements would surpass what was predicted in the 1960's. Mankind has a long history of underestimating the rate of technical advance in the long term. But this advance has been achieved even though the area of human space exploration was not actively invested in. An example is the heat exchanger technology developed by Reaction Engines for the SABRE engine, which also enables the Serpent engine, and in turn enables both Skylon and Scorpion systems. But this is not the only example; general improvements in electronics and computers far exceed general 1960's expectations, also composites materials, pressurised structures and the International Space Station experience in space assembly all go beyond what NASA had assumed. All of which shows there was an inherent technical potential for the Scorpion, but also leaves open the question how much further technology would have progressed if there had been a major space exploration initiative in the late Twentieth Century. In this light; the film and book "2001: A Space Odyssey" and this Scorpion study could both be significant under-prophecies if something like the post-Apollo programme and follow up activity, with the character of the Scorpion, had been vigorously pursued.

9.2 Economics

The second aspect of Martin's law is money. The cost estimates of the Scorpion are not accurate, not only due to the conceptual nature of the design but also due to the lack of any reliable parametric for developing nuclear engines, but they do give a good indication of the scale of the project and is considerably under the \$55 billion cost of developing the F35 Lightning II fighter [63].

Of course the Scorpion depends upon the development of Skylon. The development cost for this system was estimated to be around €16 billion [6], which does not alter the overall investment picture. Furthermore, a large part of this acquisition costs are included in the Skylon launch cost assumptions used in Section 8.

The estimated total programme cost of \$160 billion is comparable with programmes that were funded in the post-Apollo period. The Space Shuttle total programme cost in inflation -adjusted terms to 2010 was \$209 billion [64]. The International Space Station was estimated to cost about \$150 billion up until 2015 [65], including all the international partners' contributions, but also some double accounting with the Shuttle Programme as the Shuttle flights to the ISS are counted in both estimates.

It is therefore concluded that the financial requirements of the Scorpion do not place it in a special category over other major space infrastructure initiatives, and that it is an economically feasible system.

9.3 Politics

Given the technical and financial feasibility of the Skylon/Scorpion infrastructure or something like it, the premise of the study is that it is politics that is the reason humanity has not progressed into Space to continue the human exploration initiative started by the Apollo programme.

It is concluded that when considering how far and how fast humanity uses its skills and resources to expand out into Space the question is really solely political, just as the positive out-come of the Apollo Moon landings was pre-eminently political. The lack of progress in the last half century has really nothing to do with technological capability or available financing, rather it is failings within the core of humanity; in part failures of desire and motivation, but more importantly failures of understanding and vision.

These failures are not only external to the astronautics community but pervasive within it. This community has not only failed to follow up on the base the Apollo programme left, but failed to make launch systems reusable and economic, failed to provide space access to the general public, failed to open up space applications beyond data services to include power and material goods, and failed to deal with the growing space debris population (a problem of its own making). All these are reasonable and desirable challenges that have been repeatedly raised in the last 50 years and should have been met. Yet all are challenges that have repeatedly eluded the space industry, leading to a defeatist attitude that it is the technical difficultly and lack of finance that is responsible. It is not - it is only Martin's law.

The Scorpion study's object was to highlight the operation of Martin's law – to show how far the current space goals and achievements fall short of what they could be and could have been. It is expected to generate a strong response, but that response is intended as a route to self-examination of what we as individuals, and Society as a whole, really want from Space.

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This paper reports on early experiments to design a functional microstrip antenna for one face of a 10 cm x 10 cm Cubesat. The objective is to design an antenna with no moving parts and a minimum of soldered components. Microstrip antennas are printed circuit boards where the copper track acts as a radiating element. A literature search suggests that most microstrip antenna designs are resonant for either RFID circuits around 900 MHz or for microwave frequencies at 2.4 GHz or above. This means that no design is readily available for the popular bands for satellite telemetry, the 145 MHz and 435 MHz amateur bands. Small circuit boards can be ordered online, relatively inexpensively, from production companies in China, thus making it possible for further experimentation to take place. This paper is written to encourage such experimentation.

Keywords: Microstrip antenna, Microsatellite communications, 144Mhz microstrip, pcb antenna

1 INTRODUCTION

There are one or two examples in real life of antenna malfunction in small satellites, either as a known fault or as a presumption when the satellite is presumed to have been deployed but its signal has not been detected. A first consideration therefore is to create an antenna which does not need a kinetic energy (e.g. a spring) to deploy it, whether by moving parts or by melted restraining wire, or cannot serve as a carrying handle.

A secondary consideration is that soldering expertise varies considerably in electronics enthusiasts and a minimum of soldered components will maximise the chance of creating a successful board.

Most radio amateurs who receive satellite telemetry are equipped for the two amateur bands 145 and 435 MHz with availability tailing off in the higher bands.

Finally, advanced designs – beyond the scope of this article – can employ phase switching of antenna beams by electronic means, once the basic antenna element has been designed effectively.

For all these reasons, it is worth examining the potential for a workable printed microstrip antenna for the 145 and by extension the 435 MHz frequency bands.

2 LITERATURE REVIEW

Fundamental design determines the length of a monopole as a function of the radiating frequency, preferably a quarter of the wavelength, derived from Equation 1:

$$\textit{Velocity of light} = \textit{frequency} \times \textit{wavelength} \qquad (1)$$

where the velocity of light = 300 x 10^8 m/s, the frequency is in MHz and the wavelength is in metres.

Thus a 150 Mhz antenna is approximately equal in length to one quarter of two metres = 0.5 m.

The published literature considers both RFID (radio frequency identifying) devices at around 900 MHz [1]; and Wireless LAN devices at 2.4 GHz and 5 ghz, the frequencies used in domestic WiFi installations [2], (Fig. 4) [3] (Fig. 2 and Fig 3) Characteristically, such printed antennas are composed of a top monopole circuit printed in a distinctive shape, a fibreglass dielectric (standard dielectric is FR4) and a ground plane against which the monopole acts.

The monopole circuits are folded in their design, i.e. the continuous pole loops back in adjacent but continuous tracks. Here the literature divides between "Meander lines" [4] which are just a continuous nested line, and lines which form a sawtooth [5], (Fig. 1), a nested square wave [4], (Fig. 1 and Fig. 6) text [6]; varying multiples of wavelength [1] (Fig. 9) and even a fractal or version of another mathematical model (the Minkovsky Monopole). All seem to radiate effectively.

3 DESIGN HISTORY

This project considers that what matters is not necessarily the mathematical nature of the pattern of the printed monopole but its length and nested character by reference to the frequency (and thereby capacitance and inductance).

This paper takes a practical "hands-on" approach to antenna design because readily available RF simulation software did not show resonance at the design frequency but implied resonance at a frequency above 250 MHz.

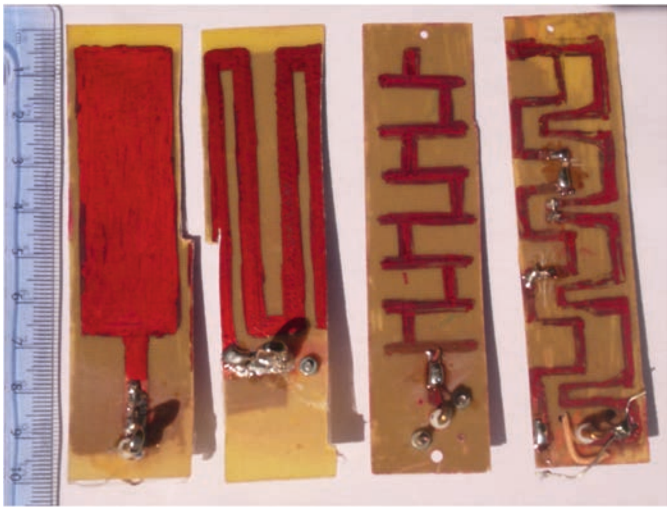

Fig.1 **Early designs etched onto a copper board with a ground plane on rear.**

It started with monopoles and then changed its direction to balance two monopoles as a dipole, against the standard practice in the literature.

In Figure 1 early monopoles were etched on double-sided copper boards in a variety of configurations. These include (from left to right) a blade, two main loops, a jagged monopole and a nested jagged monopole, each etched onto one side of a copper PCB with a ground plane connected at the rear.

The designs in Fig. 1 were not found to radiate effectively. But it was found (Fig. 2) that a length of approximately 0.25 of wavelength could be wound on perforated board and used as a monopole with no ground plane for a hand-held radio. Operationally, this served to open a repeater some 10 km away with distinct linear polarisation.

At this point it was decided to make a reproducible design of a monopole using a CAD programme (Eagle) which generated industry standard files known as Gerber files. These files were then sent to two companies in China for manufacture; they arrived back in about ten days and cost approximately $2 per board.

Fig. 3 shows the main design for this experiment. The track is a nested monopole of 59 centimetres total length which at 146 MHz is slightly more than a quarter wave, but which can be cut back. Each board is 16.1 cm long x 5 cm wide; thus a dipole

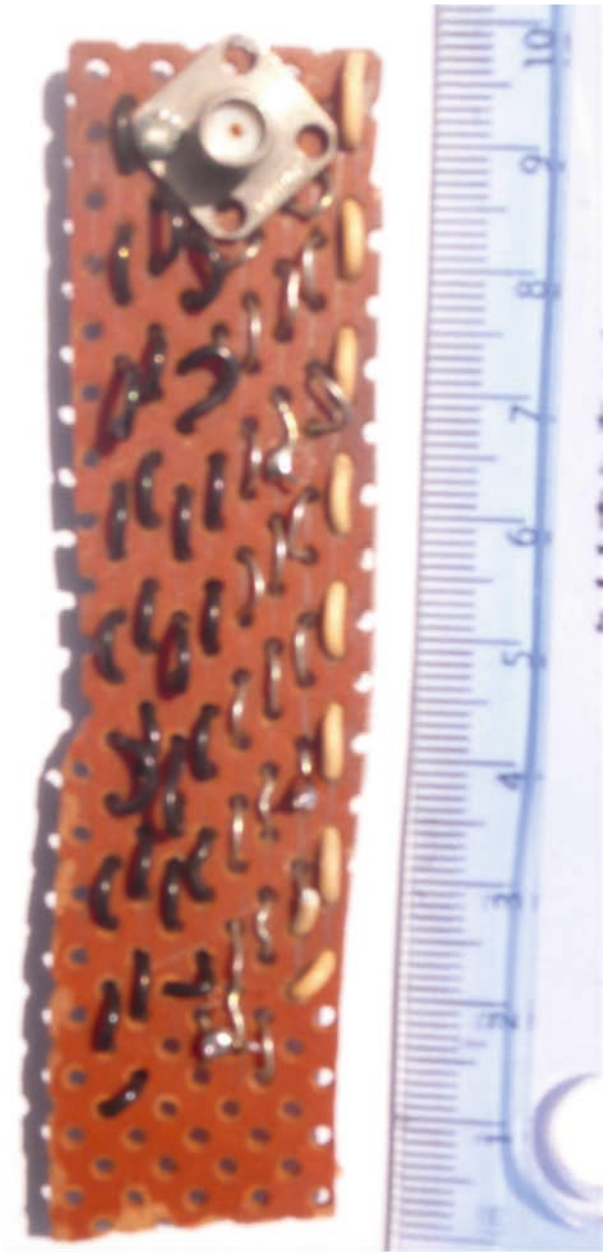

Fig.2 **Continuous wire wound monopole.**

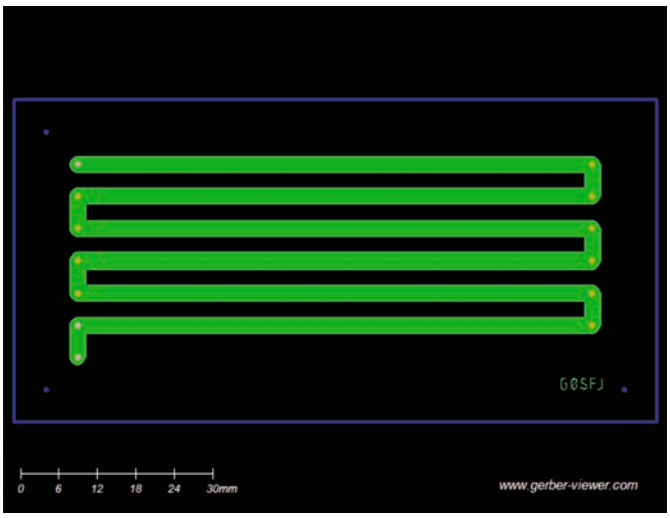

Fig.3 **The Microstrip Monopole Board as viewed online through www.gerber-viewer.com.**

will cover the 10 cm x 10 cm face of a cubesat.

Two of these monopoles were connected as a dipole as in Fig. 4. Measurements of efficiency were made by comparing forward with reflected power, i.e. a Standing Wave Ratio, where ideal efficiency tends towards 1.0. The meter used was a home-built unit based on the AD8307 module.

Operationally, this antenna was again successful in opening the repeater, and again exhibited linear polarisation. However, as Table 1 shows, the dipole did not have an acceptable standing wave ratio. To improve this the back of the board was covered with thin sticky copper foil, of the type used in electric guitars. Table 1 shows the improvement in SWR by using this backing. The copper, which is found commonly as an outer plate to the satellite, was not connected to either pole of the dipole.

Tests of top-loading (or base loading) each monopole by printing a nested coil at one end of the design as shown in Fig. 5 and Fig. 6 below show that using one of each in the installation in Fig. 7 has a SWR of approximately 1.7 or better, i.e. a relatively efficient antenna.

Options for further research include base or centre loading by printing a coil in the middle of the thick track. Boards may be produced with a back partially covered in copper.

Printed boards may also be designed into the outer fabric of the Cubesat as Fig. 7 suggests.

The 435 MHz band has not yet been considered but it ought to be relatively easy to design a dipole for this band on a board 10 cm x 5 cm.

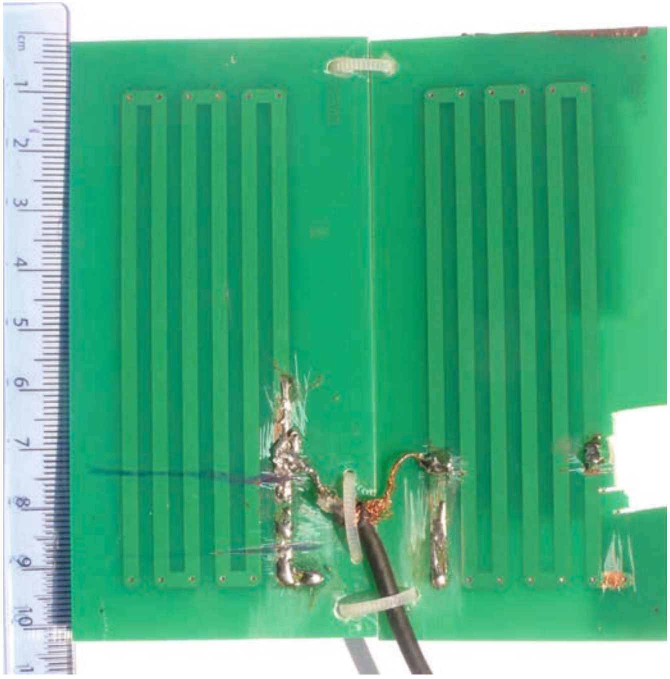

Fig.4 A 10 cm x 10 cm pcb dipole under test.

TABLE1: EFFECT OF COPPER BACKING ON PRINTED DIPOLE	
Coverage	**Measured SWR**
Without copper back	7.99
Cover whole back	4.86
Cover one half of back	3.81

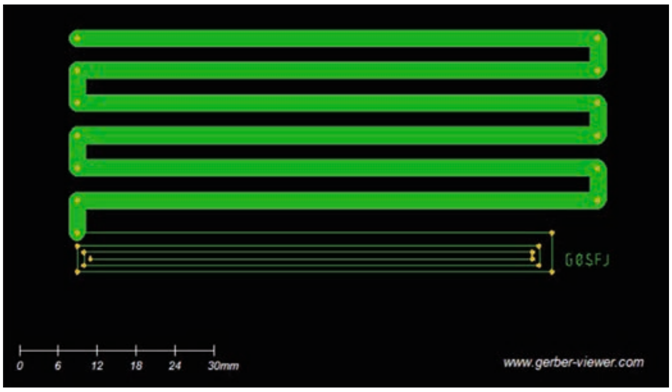

Fig.5 An inductance "top load" on the pcb antenna.

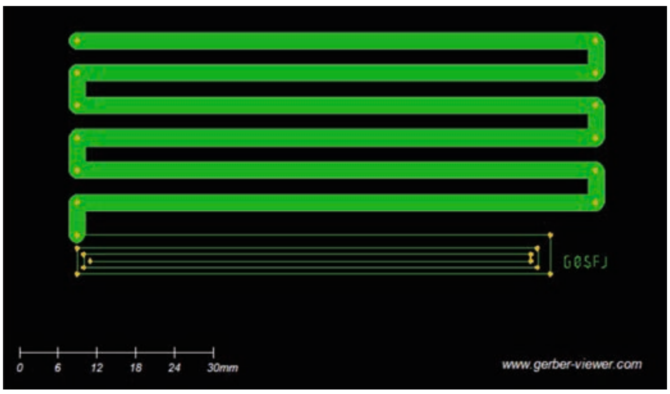

Fig.6 An inductance "top load" in a different design on the pcb antenna.

Fig.7 Another possible orientation if antenna is weaved into the corner of the cubesat.

4 DISCUSSION

In testing the antenna "at the kitchen sink" there were sometimes slight variations in the measurements but they stay in relative order of Figure 1. This suggests that the integration of the antenna in the structure of the satellite may be quite important in its efficiency. However the SWR figures are not yet particularly impressive, although a good RF lab ought to be able to improve on them.

Radiation from a satellite will be polarised linearly and facing perpendicular from the antenna, thus the antenna should face Earth.

5 CONCLUSION

It is possible to design a reproducible printed circuit (microstrip) antenna for the two metre amateur band to dimensions suitable for one face of a cubesat. Although currently its efficiency is low, this antenna is worth further investigation.

The strength of this paper is that it shows that there is a way forward in design for such simple microstrip designs.

The inexpensive reproduction of the final design will encourage the development of satellite kits.

Acknowledgements

I am grateful to Mark Hempsell and Fabrizio Bernadini for their encouragement in this project, to Tim Simmons G8JFX, for his modelling and the design of the AD8307 power meter, and Colin Lowe G1IVG for his testing my results. All errors and omissions are my own responsibility.

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NOTES ON A TITAN SUBMARINE

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Titan has now long been known to possess lakes of liquid hydrocarbons, and submersibles have been proposed for their exploration. The hydrostatic and hydrodynamic properties of liquefied natural gas (LNG, a close approximation to the methane believed to comprise the bulk of these lakes) are briefly investigated, along with the phenomenon of cavitation therein. Suggestions are made for means of saving energy in propulsion and hull design in light of the limitations imposed by available power sources.

Keywords: Titan Maria, Submarine, Cavitation, Comparative Hydrodynamics, Radioisotope Power

1 INTRODUCTION

Not long after Cassini entered orbit around Saturn, observations with its Synthetic Aperture RADAR confirmed that there were, as had long been hypothesised, lakes of liquid hydrocarbons on Titan's surface [1], participating in a methane cycle very similar to Earth's own water cycle [2]. The potential for comparative planetology thus became even greater (as is often the case with Titan), and NASA began to entertain the idea of a marine craft for Titan, eventually funding a submarine study utilising the Advanced Stirling Radioisotope Generator [3]. Given the recent selection of the Dragonfly mission to Titan [4] to explore the surface and atmosphere, the submarine concept seems worth revisiting with a view to confirming some of its assumptions as well as drawing some engineering hydrological comparisons. As it seems that we do not have an advanced radioisotope power source which is likely to be available in the immediate future, improvements to the energy efficiency of such a machine may be useful.

2 LAKE ENVIRONMENT

Reynolds' eponymous number describes the ratio of inertial to viscous forces in a fluid, defining the flow conditions for a given geometry, velocity and fluid viscosity:

$$Re = \frac{\vec{u}\,x}{\nu} \tag{1}$$

where $\boldsymbol{u}$ is fluid velocity, $\boldsymbol{x}$ is a characteristic length and $\boldsymbol{\nu}$ is kinematic viscosity, the ratio of absolute viscosity ($\boldsymbol{\mu}$) to density ($\boldsymbol{\rho}$), i.e.:

$$\nu = \frac{\mu}{\rho} \tag{2}$$

For the same velocity at the same scale in two different fluids, we can thus compare the kinematic viscosities to determine the ratio of the Reynolds numbers. The kinematic viscosity of water at room temperature in $\mu(m^2/s)$ is approximately 1, whilst that of methane is about 0.43 [5]- thus we would have to be moving approximately twice as fast in Lake Ontario (Earth) as in Ontario Lacus (Titan) to generate the same flow conditions. At similar speeds flow would conform more closely to the surface of a moving body in Titan's lakes, just as in its atmosphere. Hydrostatically, a lake of LNG on Titan under the influence of $1/7^{th}$ Earth gravity would experience a rate of pressure increase about $1/15^{th}$ of that in a terrestrial ocean- so ~640 Pa/m rather than ~10,000 Pa/m.

3 PROPULSION

Nautical hydrodynamics studies the motion of bodies which generate strongly turbulent flows (Re>4,000) in which the phenomenon of cavitation is an issue under normal operating conditions. The cavitation number $\boldsymbol{S}$ (representing the probability of occurrence in the fluid [6]), is given:

$$S = \frac{Q}{dP} \tag{3}$$

where the pressure differential $\boldsymbol{dP}$ is between the hydrostatic and vapour pressures of the fluid and Q is the dynamic pressure generated by the body, defined as the second integral of density with respect to velocity:

$$Q = \int\int \rho (d\vec{u})^2 = \frac{\rho \vec{u}^2}{2} \tag{4}$$

The vapour pressure in LNG at Titan lake temperatures is about 17kPa (versus around 2kPa for Earth water at ambient conditions), and at a depth of 1m in Ligeia Mare the hydrostatic pressure would only be 1% higher than Titan atmospheric. We thus expect the factor in (3) to reach unity close to the lake surface at velocities of about 25 m/s, and around 32m/s near its bed (it having been found by Cassini to reach a depth of only 160m [7]). Considering LNG to be an incompressible fluid, we can relate limiting blade surface velocity to propeller angular velocity with a simple equation:

$$\vec{v}_b = \frac{r\omega_p}{\cos(\theta)} \quad (5)$$

where $\boldsymbol{\omega_p}$ is the angular velocity of the propeller, $\boldsymbol{r}$ its radius and $\boldsymbol{\theta}$ the angle of twist of the blades from the rotation plane. A terrestrial marine propeller 0.1m in radius with twist of roughly 30 degrees would be limited to ~20 rad/s (191 rpm), whilst the same configuration in a Titan lake would not experience similar cavitation until three halves to twice the speed. A different approach suggested for a submarine intended for use on Europa [8] is that of jets. The use of a radioisotope power source to thermally pressurise fluids for propulsion (akin to the "poodle thruster" devised by the TRW corporation in the late 1960s [9]) would allow for the replacement of rotary motors with solenoid valves – as the fastest moving surfaces relative to the fluid become the nozzle walls rather than propeller blades, proportionally greater speeds are possible before the probability of cavitation damage outweighs acceptable material design risk.

4 RTG HYDRODYNE

Though propulsion systems might be designed to minimise the use of servo motors, the ballast system would still require a pump for pressurisation of atmosphere before a dive. In order to reduce the duty cycle on this part, our submarine might be designed as a hydrodyne (Titan's low gravity more than compensating for the decreased density of the lake fluid), using hydrostatic lift only to *stop* whilst surfaced or doing science. Such streamlined geometry (akin to a cartilaginous fish like a ray for example) would also enable a much larger area of the lake bed to be accessed passively by the vehicle for sampling, via unpowered, gliding descent – meaning more power for scientific instrumentation (an issue for long as NASA's only available radioisotope generator technology is of the low-efficiency thermoelectric type).

5 CONCLUSION

The hydrodynamic environment of a Titan lake is more favourable for a submersible than that of a terrestrial lake. Whilst it is well understood that reduced density means less drag, higher Reynolds number means greater flow fortification whilst increased pressures mean a reduction in cavitation, thus less concomitant damage to wetted surfaces for the same propulsive flow conditions. In common with flight in the atmosphere of Titan, reduced gravity means less weight for lift to counteract, making the operation of a hydrodyne more energy efficient than a purely hydrostatically buoyant machine. Additionally, the use of "waste" heat from the only currently available radioisotope technology for propulsion would afford additional energy efficiency.

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ORBITAL CIVIL ENGINEERING: Waste Silicates Reformed Into Radiation-shielded Pressure Hulls

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In addition to solar power the extra-terrestrial resource most likely to be utilized in future space manufacturing is near earth asteroids (NEAs) for volatiles and metals. Methods are proposed for reforming the waste stream from metal extraction into strong anhydrous glass (AG) to make radiation shields half the thickness of water-based shielding as well as pressure hulls for spacecraft. Power for vitrification is half that for cement production. Benefits include maximum utilization of expensively shipped raw materials and the avoidance of a potential hazard and waste disposal problem. One-piece monocoque shells are strong, avoid radiation shine paths, and are robust enough to last for centuries. Much construction mass is provided by the shielding and material processing is minimized. Simple methods and minimal materials processing will enable largely autonomous construction of basic components although high-tech equipment must come from Earth until it can be manufactured in space. Further development should enable very large structures to be built from reinforced AG using additive manufacturing techniques as detailed in later SPACE Project papers. Using such methods, it is estimated that an O'Neill Island 1 class orbital habitat could be constructed in 10 years.

Keywords: Waste stream vitrification, Anhydrous glass, Orbital civil engineering, Space habitat, Radiation shielding, Monocoque hulls, Concrete surrogate

1 SCOPE

This paper is part of the "BIS SPACE Project" revisiting O'Neill's concept of orbital construction and his design for the Island 1 habitat [1, 2]. It precedes the main study concentrating on methods for reforming waste streams from metal extraction into strong anhydrous glass (AG). Benefits include maximum utilization of expensively shipped raw materials and the avoidance of a potentially hazardous and costly waste disposal problem. Orbital construction methods utilizing AG are then discussed for making massive radiation shields and pressure hulls for spacecraft. This leads to methods and designs for building habits similar in size to Island 1 and thereby laying the foundations for more detailed work described in later SPACE Project papers.

2 INTRODUCTION

Work in the 1970s [1, 2] showed that the construction of kilometre scale orbital habitats should be possible using lunar materials and 20th century bridge and ship building technology. They should therefore be regarded as civil engineering not aerospace projects. The traditional designs were located away from Earth, typically at L5 [1], because of the enormous amounts of lunar materials required, mainly for radiation shielding. (For convenience, L5 is retained as a notional location for large orbital construction projects although other orbits may also be suitable.)

The main engineering constraints for large habitats are the requirements for

a) atmospheric pressure containment,
b) rotation to impart ~1g of pseudo-gravity (In the absence of data on safe levels for gravity and air pressure for long-term occupation by a mixed population with pregnant women and children this conservative approach is adopted)
c) the ability to mitigate the effects of micrometeoroid and debris impact.
d) outside the protection of the Earth's magnetic field a further, perhaps dominant, engineering constraint is the need to provide sufficient radiation shielding.

To justify the enormous investment in time money and resources habitats must be designed to last for centuries if not millennia [1].

2.1 Radiation risk

Outside the protection of Earth's magnetosphere, the hazard from ionizing radiation is severe, especially from galactic cosmic rays (GCRs) or solar mass ejections (SMEs). Structural components are relatively immune whilst electronics and especially living organisms, including humans, are vulnerable requiring protection or (in the case of electronics) hardening.

Some kinds of radiation are inherently more dangerous to biological tissue, even if their "energy deposition" levels are the same. Consequently, the absorbed dose, Gray (Gy) is multiplied by a radiation weighting factor. To determine the equivalent radiation dose (Sv), the absorbed dose (Gy) is multiplied by a radiation weighting factor that is unique to the type of radiation. The radiation weighting factor (WR) takes into account that 1 mSv is the dose produced by exposure to 1 mGy/yr of radiation. The annual limit for US astronauts is 500 mSv/year with a lifetime cap of 10,000–30,000 mSv for women and a higher limit for men. The US standard annual permissible dose for adult radiation workers is 5 rem/yr (50 mSv/yr). For the general population, especially children and developing fetuses, the standard is <0.5 rem/yr (5 mSv/yr). This is about twice that at sea level but much lower than the levels (>20 mSv/yr) found in a few populated areas on Earth. The International Commission on Radiological Protection (ICRP) recommends a 20 mSv/yr limit for occupational radiation exposure which seems reasonable for a space habitat [3]. The value of WR is unknown for developing fetuses so the unit of radiation dose, Gy, is used instead. However, there is some uncertainty about the dose acceptable for pregnant women so a more conservative approach is recommended [3] to limit exposure to <6.6 mGy/yr.

The US 50 mSv/yr occupational limit has been adopted here for construction workers whereas mixed populations in permanent habitats enjoy the additional protection afforded by a limit of 20 mSv/yr. During pregnancy, women may need to spend much of their time inside additional shielding.

Until active shielding methods, possibly electric and magnetic fields against charged particles, are developed passive shielding is the only viable option. However, the situation is complex and requires much work to accurately determine the risks with different materials [4].

2.2 Impact Risk

The probabilities of impact by meteoroids of particular sizes are known but the probability of a collision increases with time together with the risk. The risk for spacecraft with lifetimes of a few decades is relatively low but much higher for habitats lasting for centuries. In addition, many more people are at risk in a habitat compared with the relatively few passengers in near future spacecraft. Consequently, risk mitigation is much more important for large habitats than for spacecraft and other first-generation structures.

From the size and frequency distributions it is estimated that micrometeoroids of about milligram mass will strike a lunar base (or orbital habitat) almost yearly [2] while strikes by larger objects are much less frequent, Table 1. Meteoroids of ~1×10^{-6} g and 1 g, produce craters of 0.5 mm and 20 mm diameter, respectively, in metal. In most materials, crater depth is comparable to diameter but fracturing effects in brittle materials extend the damage to greater depth [5].

Fortunately, the effects of small meteoroid damage can be mitigated whilst, as Table 1 shows, impacts from larger asteroids are extremely unlikely. By the time space habitats are being constructed, technology to detect and deflect large objects in hazardous orbits should be well established leaving an even smaller residual risk.

Impacts from manmade debris represent a further potential hazard, limited mainly to Earth orbit. There is also the small risk of collision with visiting spacecraft but impact speeds should be relatively low causing local damage only.

3 MAIN CONSTRUCTION MATERIALS

Although the early work proposed utilizing lunar regolith as the main raw material launched into orbit with electromagnetic catapults [1, 2], attention has recently turned to near earth asteroids (NEAs) as a source of materials already in orbit [6]. The proposed exploitation of NEAs not only makes economic sense but their removal as a potential hazard to Earth is often also given as justification [6]. Much less is known about asteroid compositions compared to lunar regolith [7] but most also contain materials suitable for construction as well as the all-important volatiles [6].

Maximum utilization of all parts of the raw materials expensively transported to L5 must be an important economic aim. Furthermore, material not used becomes co-orbiting waste and, as a potential impact hazard, must be dealt with. Waste disposal requires either ejection on a safe trajectory and/or consolidation and storage in the construction orbit; either option is an unwanted expense. Silicates form the bulk of most asteroids and will remain as waste after volatiles and metals have been extracted. This provides an economic incentive for utilizing large amounts of silicates, a problem recognized by O'Neill [1] who proposed using them for radiation shielding. If this can be achieved, an important side benefit of building habitats is that silicates become important construction materials so there should be no, or very little, waste for disposal.

Taking this approach, a modest delivery rate of ~10 kt per year of rocks for shielding should be sufficient for most simple structures described in section 7. This mass is within reach of near future technologies and would require ~20 of the 7 m (500 t) asteroids that were recently being considered for recovery [8] to high lunar orbit.

The much greater quantities needed to shield large habitats (~120 Mt section 7.4.5) will not be available until much later.

Automated asteroid mining methods have been described elsewhere [6] and are not included here. This paper is mainly concerned with utilizing the waste stream after extraction of volatiles but important construction materials are identified and discussed briefly.

3.1 Steel for main load bearing structures

While the composition of meteorites has been studied extensively, far less is known about their strengths [9]. The little information available indicates that even the strongest nickel

TABLE 1 Frequency of meteoroid impact and damage estimates

Mass of meteoroid (g)	Occurrence/km^2 (yr)	Diameter of crater (m)	Damage estimate
1×10^{-6}	1×10^{8}	0.5×10^{-3}	Surface etching
1×10^{-3}	2000	1×10^{-2}	Deep etching
1	10	0.02	Minor structural
10	1	0.09	Significant structural
1×10^{6}	0.005	2	Major structural

iron meteorites are not very strong (tensile strength 43 MPa) [9] but are ideal for making maraging steels. These are iron-cobalt-nickel alloys that offer high strength (>1,200 MPa), high ductility and a low coefficient of thermal expansion. Vacuum melting, easy in space, minimizes contamination and ensures a consistent product [10].

3.2 Materials for external support structures

Aluminium is abundant in lunar regolith and titanium in significant amounts. Both are also found in asteroids but require complex multistep processing so not readily available until a later stage of industrialization.

At high temperatures (200–250°C) aluminium alloys become weaker but at sub-zero temperatures their strength increases while retaining ductility [11]. This makes aluminium alloys extremely useful at low-temperatures such as those experienced by external support structures permanently in shade and especially when they must be light in weight. A tensile strength of 340 MPa is expected.

3.3 Materials for radiation shielding

Radiation shielding requires the most mass so should utilize the most abundant materials already in orbit, silicates or water.

Water is best for shielding in terms of mass needing 7 $t.m^{-2}$ compared to 11 $t.m^{-2}$ for lunar regolith [3]. However, liquid water is a poor construction material because it requires containers needing additional support in pseudo-gravity. Containers are also vulnerable to penetration by meteorites leading to water and therefore shielding loss. Dissolved additives such as gel-forming polymers may mitigate water loss through small punctures and antifreeze prevent freezing but make pumping out and re-use more difficult. Also, polymers are likely to degrade under prolonged exposure to ionizing radiation. Water used as ice avoids these problems but expands on freezing so thin layers must be added [12] to build-up the 7 m thickness necessary for shielding [3]. The strongest forms of ice are very cold so radiation shields would need protection from excessive warming from internal waste heat or solar input. Water also has many other uses whereas silicates are adequate for shielding [3] but have little other utility and present a significant waste disposal problem. (These arguments apply in the inner solar system, beyond Mars orbit the greater abundance of water and lower temperatures make ice much more attractive for shielding.)

Traditional shield designs with unprocessed lunar regolith, or slag, held between metal shells shielding thin walled pressure vessels [1, 2] are structurally weak. In contrast, the principal civil engineering construction material on Earth is bonded aggregate, or concrete. Roman buildings such as the Pantheon in Rome demonstrate its longevity as a construction material even in earthquake prone Italy. Built by the Emperor Hadrian in 126 AD it has been in continuous use for 1,890 years and at 43.3 m diameter remains the largest unreinforced concrete dome in existence.

Concrete is strong in compression but weak in tension so modern structures are designed accordingly. Reinforced with steel or pre-stressed with steel cables to bear large dynamic and static loads they can be very big. Stresses from loading by Earth's gravity and pseudo-gravity in orbital habitats are practically equivalent so conventional structural designs should be equally capable when rotating in space. Apart from its own static weight the stresses on a bridge from moving traffic and wind are challenging dynamic loads. In orbital habitats pseudo-gravity, air pressure and floor loads are all mostly static and so less problematic.

Concrete is widely used in the nuclear industry not only for construction but also for pressure containment and radiation shielding. If it were readily available in orbit reinforced concrete would almost certainly be used to build radiation-shielded habitats. Alternatively, however, instead of being used for concrete silicates can be fused to produce ceramics (bricks, pottery) or vitrified for glass, all important construction materials. The absence of hydrolytic weakening processes in the very dry space environment makes vitrified silicates, or anhydrous glass (AG), ten times stronger [11, 13] than if made on Earth with great potential as radiation shielding.

4 PROPERTIES OF AG

AG has a similar density to aluminium but a much lower coefficient of thermal expansion. It will probably be coloured brown or green by Fe^{2+} and other metal ions. Table 2 (from [13]) reveals the effect of flaws with the average bending strength of unflawed bars being more than double that of flawed samples. Glass fibres are much stronger still because the weakening effects of cracking are averaged over many elements.

4.1 Strength of AG

Although weak compared to the metals and alloys available (average bending strength for flawed bars is 100 $N.mm^{-2}$, Table 1), AG is 50 times stronger than concrete (bending strength 2 $N.mm^{-2}$) and much stronger than other abundant potential shielding materials. As a superior substitute for concrete AG offers new possibilities for constructing orbital habitats. Spaceborne structures built using civil engineering methods should be robust and capable of working lifetimes of many centuries.

For maximum strength, the melt must be cooled rapidly to make AG rather than a weaker partially crystalline material; artificial basalt AB (tensile strength 34.5 $N.mm^{-2}$ compression strength 538 $N.mm^{-2}$ [13]). The introduction of flaws in manufacture and during the working lifetime of the product must be minimized. Even so, the average bending strength of flawed AG bars (100$N.mm^{-2}$) is about a quarter that of structural steel (~400 - 450$N.mm^{-2}$) and this value is used here.

No value for the compression strength of AG is available but, assuming it is proportionally similar to AB, it is probably ~15 times the tensile strength. Therefore, like concrete, load-bearing AG (or AB) structures are much stronger in compression than tension. Also, monolithic glass structures although strong, are brittle, requiring careful design to minimize the risk of catastrophic failure.

4.2 Radiation shielding with AG

Recent work with NASA's OLTARIS 2014 radiation dose modelling software [3] shows that, to meet the 50 mSv/yr limit with lunar regolith, 4 $t.m^{-2}$ (1.3 m of AG) is necessary. For the 20 mSv/yr and <6.6 mGy/yr limits between 10 and 11 $t.m^{-2}$ is required, or 3.25 m and 3.55 m, respectively, of AG. The actual value is closer to 10 than 11 $t.m^{-2}$ so the average thickness of 3.4 m, half that necessary for water, can be used safely. However, in a large habitat with children and pregnant women additional

TABLE 2 TYPICAL PROPERTIES FOR AG

Property	Unit	Flawed glass bars	Unflawed glass bars	Glass fibres
Max bending strength	$N.mm^{-2}$	125	360	630
Av. Bending strength	$N.mm^{-2}$	100	205	630

shielding from soil, air, water in storage/hydroponic tanks and construction materials means the occupants should receive <20 mSv/yr for a 3.4 m thick shield-hull.

Shielding made in one piece entirely avoids any possibility of gaps and shine-paths for ionizing radiation.

4.3 Impact mitigation for AG shielding

The outer surface of an AG shell is vulnerable to minor damage, which, while not immediately hazardous, makes it less able to resist heavier impacts or other stresses. However, unpressurized non-rotating radiation shields could sustain significant damage without compromising effectiveness so need no protection from minor impact and could be made entirely from AG.

Long-stay pressurized habitats must be stronger and protected, perhaps by concentric iron shells, from moisture on the inside and micrometeorite abrasion on the outside. A tough composite material 2-3 mm thick is effective against damage by micrometeoroids in the mg range whereas a few cm should protect against those <1g [14]. An outer sacrificial layer of armour, separated from the main hull by a gap (Whipple shield) or fragile porous layer, is very effective at dissipating the effects of impacts whilst minimizing the transmission of shockwaves to the underlying structure.

Using local materials, an outer covering of waste tarry residues from processed carbonaceous asteroids over an iron sheath separated from the AG hull by foamed glass provides effective ballistic protection from most meteoroids. A tarry layer 10-15 cm thick would suffer continuous abrasion from small dust particles so need occasional refreshment. It would also protect the underlying structure against the less frequent strikes by meteoroids <1 g. Intervals between strikes by even larger meteoroid are measured in hundreds or thousands of years so are unlikely even in the life of habitats designed to last for several centuries. Even so, in the unlikely event (once every 2,000 y) of an impact by an object of 10 g, the tarry layer should dissipate most of the energy with some repairable damage inflicted on the armour and underlying foamed glass. The AG radiation shell should therefore be protected against all but very low risk impacts by much larger objects. However, even in the event of major structural damage from a severe impact, the steel shells and reinforcement matrix should hold the AG shell together sufficiently to provide radiation protection and contain air pressure during evacuation of the occupants.

The outer organic layer also attenuates incident radiation and reduces the production of secondary ions by the inner structure. It also insulates and prevents differential thermal expansion between the iron sheath and underlying glass.

5 LARGE SCALE PRODUCTION OF AG

First-generation radiation shields will likely be made from undifferentiated waste silicates forming AB, less strong but still adequate, until materials processing methods can produce suitable feedstock for AG. Such first-generation shields from undifferentiated material will later be re-cycled to recover valuable metals.

In the microgravity of the energy rich orbital environment it should be possible to vitrify sufficient material for very large structures.

5.1 Power availability

Some 1.37 kW of sunlight pass continuously through each square meter of space normal to the sun in Earth orbit, nearly twice the maximum of 0.747 kW available at the Earth's surface during daytime.

5.2 Power requirements and heating methods for AG

The power requirement for melting soil by resistance heating has been published [15] at $675 kWh.t^{-1}$. 20% improvement is expected under anhydrous conditions expected in large orbital rocks. However, some power is needed to evaporate volatiles in the asteroids of interest, so the published figure is retained. Experience on Earth shows that 1,000 t (1 kt) melts are achievable in ~10 days and should easily be duplicated in orbit. Using these figures, 675 MWh is needed to melt 1 kt which averaged over 10 days implies a supply of 2.8 Mw but power input varies and a peak value of 5 Mw must be budgeted for. The power required is half that for cement production [16].

Multi-junction gallium arsenide and silicon layered solar cell arrays have an efficiency of ~29%, and can generate ~400 $w.m^{-2}$ in orbit. For the 5 MW needed to vitrify significant amounts of rock, using microwaves [17] or resistance heating [15, 16] ~12,500 m^2 of solar panels are required.

Solar furnaces on Earth are very efficient compared to electric heating methods with a separate electricity-generating step. In orbit with a higher and continuous solar flux similar high efficiencies should be achievable and may prove best for large-scale vitrification. Ignoring losses due to focusing errors, reflection and IR radiation from the target, ~3,600 m^2 of mirror (near Earth orbit) could collect 5 MW.

6 POTENTIAL ORBITAL CONSTRUCTION METHODS UTILIZING AG AS REQUIRED FOR THE SPACE PROJECT

Even the simplest orbital construction requires a framework, or jig, to hold equipment and components in their correct positions and prevent drift during assembly. A jig augmented by an array of different types of manipulator, including robot arms, is termed a jig-factory (concept credit John Strickland). Most importantly, it enables the electrically powered manipulators to move on rails to perform rapid and smooth operations on multiple objects simultaneously. It must be sized and shaped to match the structure it is building or the robot arms either will not be able to reach the work-piece or not have room to work. Although much construction and processing work will use the mobile manipulators, operators may need to use spacecraft equipped with servo-operated arms, Space Construction Vehicles (SCVs), for more complex tasks. Both robot arms and SCVs are powered from an accompanying electrified rail that also supplies the manipulators and power-tools. Furthermore, a robot or SCV can clamp itself rigidly to the rail as necessary during engineering tasks to allow the entire jig-factory to provide reaction mass.

6.1 Simple low tech, low precision methods for first generation radiation shielding

Glass making has a long history and modern methods of melting and forming glass, supported on a basic jig-factory, have the potential to be adapted for use in orbit. Initially at least, the raw material would be waste rock left over from volatile extraction, not ideal for glass making but suitable for relatively small items in simple shapes. Starting with basic, low-tech methods such as glass blowing and casting it should be possible to make cups and hollow spheres for radiation shelters. As the technology develops, habitat and spacecraft hulls should also become feasible using scaled up versions of the same basic methods and equipment.

Such simple methods lend themselves to remote operation and it is conceivable that orbiting radiation shelters for spacecraft could be made before astronauts are required for more intricate work.

6.1.1 Glass blown shells

An uncontained mass of molten glass in orbit held together by gravity, surface tension and viscosity, suggests a number of manipulation methods. Selective heating and cooling, rotational forces, inertia, and gas pressure are all potential methods.

The viscosity of molten glass increases smoothly as temperature falls without discontinuities caused by phase changes. Consequently, when molten glass is stretched any parts that start to thin cool more quickly than the rest become more viscous and resist further thinning. This ensures glass blown hollow spheres have walls of uniform thickness.

These techniques could probably be adapted and used on a large scale in orbit to make hollow glass spheres. Once the glass has cooled to optimum viscosity, refractory blowpipes introduced into the centre of the mass use gas pressure to blow hollow spheres. Blowing stops at the requisite wall thickness for shielded structures, storage tanks, mirrors, sunshades and other items.

Gases suitable for blowing are dry oxygen or carbon dioxide, available in large quantities from iron smelting.

Blown spheres penetrated while soft at the point opposite the blowpipe and spun, perhaps with additional heating, open the structure to make cup or dish shapes. After forming the required shape and cooling rapidly to make AG, annealing by reheating and cooling slowly relieves residual stresses.

6.1.2 Casting

Casting should enable large hollow products such as shielded hulls for spacecraft or small habitats to be made. On Earth, gravity allows molten glass to flow and it is likely that casting in orbit will require pseudo-gravity from rotating furnaces paired with moulds supported together by the jig-factory.

Iron melts at ~1,535°C compared to rock which ranges from 1,200 to 2,000°C depending on composition [16]. Casting using iron moulds requires a glass mixture that melts at a temperature below that of iron so some selection of ingredients may be necessary. To make a pressure hull, pre-formed inner and outer moulds can have glass cast between them. The inner mould then forms the inside wall of the vessel, supported during casting by internal gas pressure while the outer skin contains the pressure from the flowing glass.

6.2 High precision construction with additive manufacturing (3D printing).

Additive manufacturing, or 3d printing, is now widely used and is improving dramatically in terms of resolution, number of printable materials (including different, simultaneously printable materials), size, cost and complexity. Over 25 different materials can now be printed, including aerospace grade metals and glass at architectural scale [18]. Concrete is also being used and, notably, a 4-story apartment block was recently 3D printed in China and a small bridge in Madrid.

The versatility of 3D printing makes it ideal for making a wide range of (often one-off) structures in space [19, 20]. However, printing techniques for microgravity environments are necessary and plastic printing was recently tested on the ISS [21]. The printed structures were indistinguishable from those printed on Earth although there were some minor technical issues. Printing, especially of reactive metals or when bubbles must be avoided, is often done inside vacuum chambers with severe limits on size. There is no such size limitation in the high-vacuum space environment.

It is expected that 3D printers capable of simultaneously utilizing different materials will become important components of a jig-factory. A multifunctional printer head, or heads, moving around the jig-factory in three dimensions could build very large complex structures to high accuracy. Indeed, an advanced jig-factory utilizing these technologies has the potential to promote the degree of precision in large-scale orbital construction from civil engineering levels towards mechanical engineering standards.

7 TYPES OF ORBITAL STRUCTURE MADE FROM AG

In addition to its potential for radiation shielding, AG is strong enough that it can be considered for several types of space borne structures.

7.1 Spacecraft shielding

For SCV operators working for years outside the Earth's magnetosphere, shielding from ionizing radiation and micrometeorites is essential. A simple solution, available at an early stage of development, employs a cup shaped shield of AG into which the SCV reverses like a hermit crab into a snail shell leaving sensors and manipulators facing outwards. An inflatable spacecraft with a rigid front section incorporating radiation shielding, tool platform and docking hatch is one possible option.

A cup derived from a sphere with internal diameter 2 m and 1.3 m wall thickness, has a mass of ~145 t. A hermit crab can carry its heavy shell because it is supported in water. Similarly, in space, although inertia tends to damp rapid accelerations, relatively little energy is needed for the shielded SCV to maneuver at low speed over short distances. Such independent movement will be exceptional, however, since they will normally travel economically and safely along the jig-factory rail system.

The shell shields the SCV from most cosmic rays and micrometeorites and, if always facing away from the sun, completely from solar radiation. As a radiation shield, the shell is not subject to significant stress so does not require protection or reinforcement. Different types and generations of spacecraft could occupy a range of standardized designs.

For longer journeys in cis-lunar space, transit times are sufficiently short that radiation exposure is acceptable, except during SMEs, so shielding mass could be minimized. Storm shelters made from large cups could be placed at strategic locations for use by visiting spacecraft. Orbiting with the open end facing out of the plane of the ecliptic, the inside is always dark and fully shielded against the sun and the orbits of most micrometeorites. GCRs are omnidirectional so will penetrate the open end whatever the orientation. Nevertheless, full shielding from SMEs is provided and exposure to GCRs significantly reduced by the partial shielding. The cups rotate slowly to average heating effects from solar radiation but are not significantly stressed so could be made entirely from AG.

A cup derived from a sphere with an internal diameter of 20 m should provide space for visiting spacecraft and weigh ~5.8 kt or ~18.3 kt, for 1.3 m and 3.4 m thickness, respectively, depending on the level of radiation protection required. Such a cup could also provide a shaded location for a cryo-fuel depot.

7.2 Shielded orbital workshops

Very large structural components made in jig-factories could be worked on using robots, ROVs and SCVs as described above. However, the various high-tech components for such structures require more delicate work by astronauts so the jig-factory soon needs a large shielded microgravity workshop. Vacuum suits used inside a shielded, heated and floodlit space are simpler and cheaper than full spacesuits. A pair of cups 20 m internal diameter similar to storm shelters attached at their rims could be separated as necessary to allow large components to enter and assembled structures removed. Workers and small items enter through smaller access ports/docking stations. Airtight seals could enable a pressurized "shirtsleeve" environment.

7.3 Small habitats

It is likely that the first temporary habitats beyond the Earth's magnetosphere will be relatively small and, like the International Space Station (ISS), non-rotating and unshielded. These first habitats will be made on Earth, assembled in orbit and be self-contained. Indeed, NASA's proposed "Lunar Gateway" is such a habitat destined soon for lunar orbit.

If a small carbonaceous asteroid could also be brought into lunar orbit then it could be utilized, not only for water and other volatiles but also to make a simple radiation shield like the SCV and storm shelter cups described above. One possibility for such hybrid structures would use inflatable liners [22].

As the technology matures it may progress to non-rotating clusters of larger pressurized spheres without prefabricated liners. These would need protection from moisture on the inside and abrasion by micrometeorites on the outside. Simple AG radiation shields therefore evolve into monocoque pressure hulls, much stronger than alternative complex designs.

7.3.1 Stress on small AG spheres from air pressure

The radial stress (σφ) from pressure (p) on a hollow sphere is proportional to its radius (r) and thickness (b).

$$\sigma_\varphi = pr/2b \qquad (1)$$

For a constant wall thickness, the stress increases with radius so smaller spheres are the strongest. For a pressurized shell of 5 m internal radius, and 1.3 m thickness the stress from atmospheric pressure (100 MPa) is ~20 $t.m^{-2}$.

Assuming a value of 100 $N.mm^{-2}$ (10.2 $kg.mm^{-2}$) for the bending strength of AG, the strength of a 5 m radius shell 1.3 m thick is ~13,000 $t.m^{-2}$. It is therefore clear that AG is many times stronger (factor 670) than required to contain atmospheric pressure. However, it is likely that good AG will not be possible in the initial stages of space industrialization and AB (1/3 weaker) is produced instead. Even so, it is still more than strong enough to contain atmospheric pressure with such a small sphere with a huge safety factor of 230.

A similar calculation for a much larger 250 m radius sphere of 3.4 m wall thickness shows the stress to be 372 $t.m^{-2}$. The strength of the AG shell is 35,000 $t.m^{-2}$; a safety factor of 93~ which is substantial when compared to factor 5 used for bridges. It is clear that relatively small monocoque habitat shells constructed of AG of sufficient thickness to provide the necessary radiation shielding are more than strong enough to contain air pressure. Nevertheless, experimental work in orbit should be conducted to confirm that such a brittle material can safely be used for a pressure hull without re-enforcement.

7.4 Construction in a jig-factory of the large habitats envisaged in the SPACE Project

Printing low melting AG reinforced with embedded steel wires and cooling pipes around an axial armature supported by the jig-factory should allow large reinforced hulls to be built-up. The reinforcing wires (which double as heating elements), cooling pipes and protective shells would be formed in situ by printing molten steel. To avoid problems with cooling very large masses of AG and to limit the effects of stress cracking relatively thin hoops of AG laid down by the rotating printer heads would cool partially before the next layer is added. The freshly printed AG/iron composite must be re-heated evenly using the embedded resistance wires to ensure the glass fuses properly before being annealed to avoid stress cracking during final cooling. This internal melting system remains available throughout the lifetime of the shield-hull to fuse together any cracks, from impact or other stresses that weaken the hull and/or produce radiation shine-paths.

In principle, very large spheres and cylinders (or more complex shapes such as a torus, Figure 1) could be constructed by such automated methods. However, rotating spheres are unstable and for cylinders to be stable the radius to length ratio is limited to 1.3 [23]. In addition, the shape determines the ratio of hull surface area to size of 1 g living area [23], a requirement for mixed populations as outlined in the introduction. For a sphere, an internal deck is required to achieve a flat 1 g living space which in effect forms a cylinder within a much larger than necessary pressure/shield hull resulting in high hull area / 1g

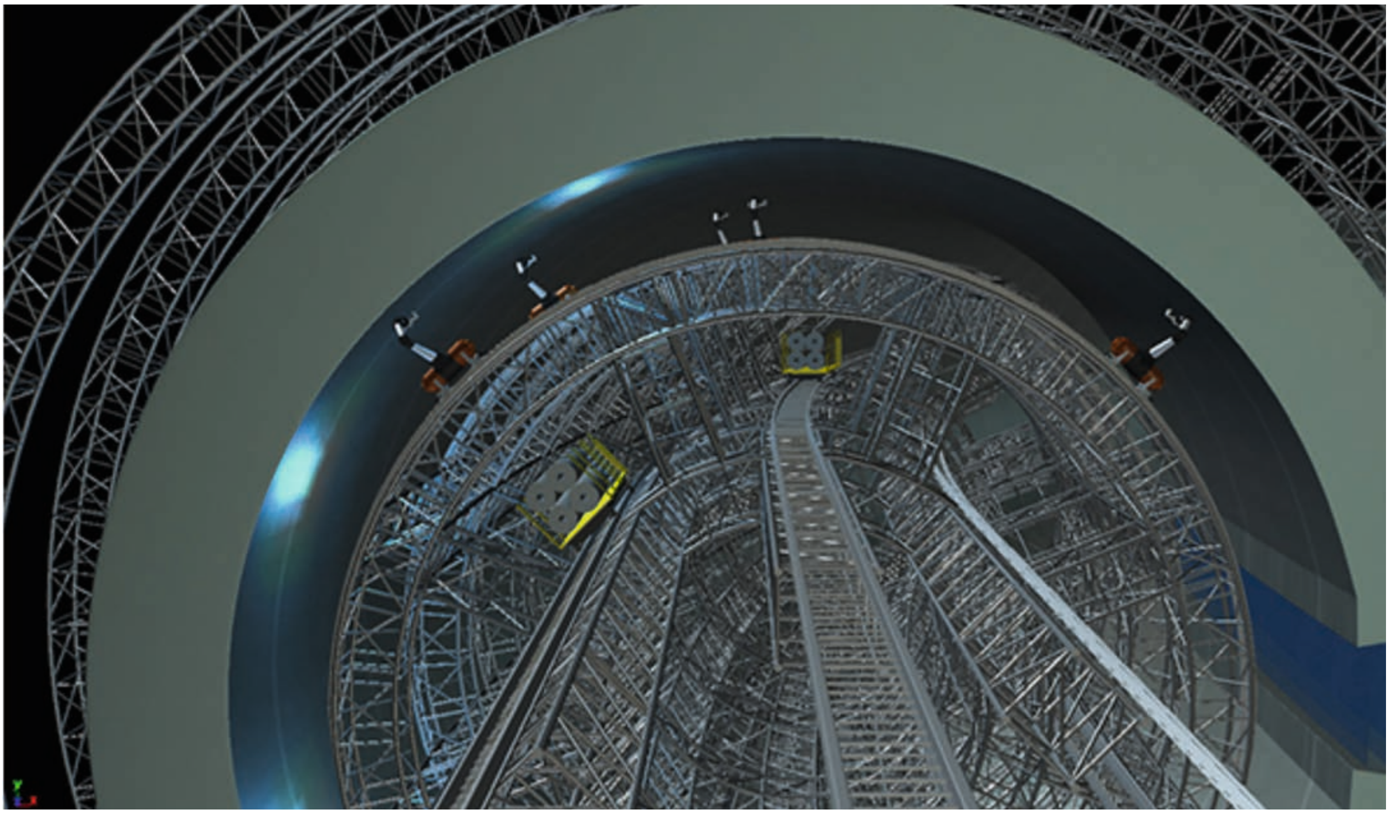
CONCEPT: JOHN STRICKLAND / IMAGE CREDIT: ANNA NESTEROVA

Fig.1 **Torus under construction in a jig-factory.**

living area ratio. For a cylinder within the rotational stability limit the ratio is ~1.77 whereas the corresponding value for a torus is 3.14. The cylinder is therefore the most economical shape for maximum 1 g living space and for a habitat the size of Island One with sufficient growing space to support 10,000 people [1, 2] a cylinder of radius ~500m and length ~650 m is required.

Construction of such a large cylindrical habitat might start with polar spaceports / airlocks mounted like wheel hubs at the ends of an armature. They could be pressurized to provide temporary shielded workshop space and accommodation for construction workers needed for delicate work. Paired printers would then build both end-caps simultaneously by extending the spaceports to form the end-caps including supports for solar panels and radiators. When the end-caps are complete the sides of the half-cylinders would be printed until they meet and fuse at the equator.

The precision afforded by rotating print heads within the rigid framework of the jig-factory ensures mass is distributed evenly and structures are radially symmetrical avoiding any built-in tendency for rotating habitats to wobble.

7.4.1 Design of very large AG hulls

The various stresses on pressurized rotating hulls become significant for very large structures. These are now investigated in respect of the properties and likely performance of AG and how this impacts design.

7.4.1.1 Stress from air pressure on large, pressurized, rotating AG hulls

Equation (2) shows that for a cylinder, the hoop stress is twice the radial stress for a sphere of the same diameter (cf equation (1)).

$$\sigma\varphi = pr/b \qquad (2)$$

In a cylindrical habitat, the stress due to air pressure is therefore twice as much for the body as for the hemispherical ends. The hoop stress on a pressurized AG cylinder 500 m radius is ~1,500 $t.m^{-2}$ and, for 3.4 m thick AG to provide radiation shielding, the safety factor is ~23, much more than 5 (used for bridges).

7.4.1.2 Stress from pseudo-gravity inside a rotating cylinder

For a cylinder rotating to give 1 g on the inner surface, if the wall thickness (t) is small compared to the radius (as it is in an orbital habitat), the stress (σz) is given by

$$\sigma z = \rho t \ N.m^{-2}$$

For a cylinder of 500 m radius the load equates to 0.1054 N.mm-2 (10.54 $t.m^{-2}$), coincidentally very similar to the air pressure. Floor loading from internal structures is estimated to be 0.05 $N.mm^{-2}$ (5 $t.m^{-2}$) while the load from non-structural elements is 0.1 $N.mm^{-2}$ (10 $t.m^{-2}$) [20].

A pressurized habitat of 500 m radius and 3.4 m wall thickness, rotating to give 1 g of pseudo-gravity on the internal surface and carrying an additional floor load of 15 $t.m^{-2}$ needs a wall thickness of 1.9 m to just support the total load. The extra thickness required for radiation shielding (3.4 m) provides a barely adequate safety factor of ~2 (Table 3) but when steel reinforcement is taken into account it should be more than strong enough.

7.4.1.3 Stress on rotating flat end caps

Habitat end caps also induce stress due to centripetal acceleration when rotating.

TABLE 3 Minimum wall thicknesses (b) required in a cylinder of 500 m radius to balance various loads. Thicker walls needed for radiation shielding provide a safety factor (sf)

Load	Load $N.mm^{-2}$	Tensile Strength of AG $N.mm^{-2}$	r m	b m	3.4m thickness sf
Air Pressure	0.1	100	500	0.50	6.8
Floor Load	0.15	100	500	0.75	4.5
Self load	0.1054	100	500	0.53	6.5
Total load	0.3554	100	500	1.9	1.8

Stress in a rotating disc can be expressed as

$$\sigma z = \omega^2 r^2 \rho / 3$$

where; σz = stress (Nm^{-2}), ω = angular velocity ($rad.s^{-1}$), r = radius of disc (m) and ρ = density ($kg.m^{-3}$)

A 500 m radius disc rotating at 0.138 $rad.s^{-1}$ (1.32 RPM) has a self-load of 0.005 $N.mm^{-2}$ compared to 100 $N.mm^{-2}$ for the strength of AG. This gives a safety factor of 20,000 so stress in the end caps due to rotation is so small it can be ignored.

7.4.2 Design features for large habitats

Designs that keep the structural elements in compression are intrinsically stronger because the compression strength of AG is ~ 15 times higher than the bending strength (section 2). For example, for a bobbin shape the concave end-caps are always under compression as are the curved cylinder sides, which are narrow at the equator and flared out towards the end-caps. Flanged steel collars supported by pre-tensioned steel (or glass fiber) cables running parallel to the axis and tensioned spokes between each flange and the corresponding hub resist stress translated to the end-cap rims (Figure 2). Such designs could, in principle, be very large approaching O'Neill's vision for large vista habitats [1, 2].

A separate steel pressure hull within an unpressurized AG shell is more complicated but has advantages. The unpressurized AG hull can have flat end caps, saving mass, and needs only support itself, and hull mounted equipment, whilst rotating. As a consequence, the maximum radius of an unreinforced cylinder of AG with 3.4 m thick walls can be increased from 500 to 2,000 m for a safety factor of 1.6. A cylinder of this radius could have a length of 2,600 m, within the rotational stability limit, and a circumference of 12.5 km yielding a surface area at 1 g of 32,700,000 m^2 (32.7 km^2). However, this safety factor is insufficient for large AG (i.e. brittle) rotating structures which therefore need reinforcement and must be protected against the weakening effects of damage (section 3.4). Such a reinforced unpressurized AG shield hull in a bobbin shape (Figure 2) could be even bigger than the above example, the exact size depending on the type and degree of reinforcement.

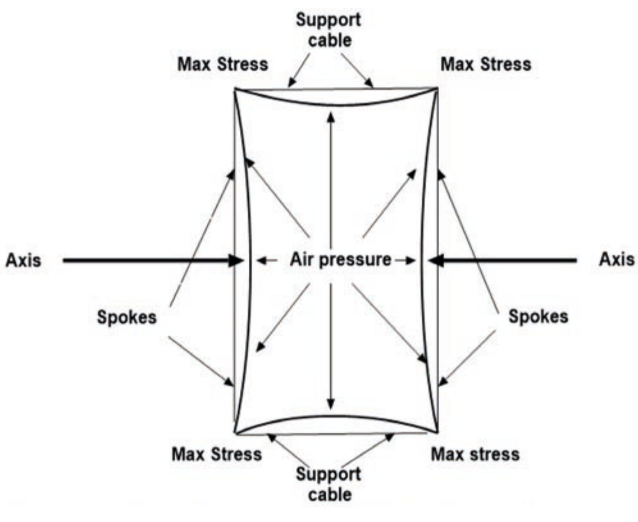

Fig.2 Showing points of maximum stress with bobbin shape with support cables and spokes.

For a double hull, an armoured shield hull protects the pressure hull, not only from ionizing radiation, but also from abrasion by micrometeorites. Also, the gap and necessary suspension system between the hulls prevents shock waves propagating to the inner hull protecting it from quite severe impact from larger meteorites. Cracks in the outer hull can be repaired as convenient.

If robust and reliable bearing systems can be contrived so the two hulls can counter-rotate, they can each provide reaction mass for the other during spin-up [2]. The more massive shield hull rotates more slowly than the pressure hull, pseudo-gravity is proportionally less so stresses from self and floor loads are also reduced. The pair also have no net angular momentum so can be moved easily with no external effects of precession.

7.4.3 Quantities of construction materials and power requirements for large habitats

There is enough information for a rough quantitative estimate of the main construction materials for an O'Neill Island 1 class double-hulled cylindrical habitat 500 m in radius and 650 m long. The shield hull needs the most mass at 43 Mt of silicates (or glass) while steel for the pressure hull amounts to 17 Mt. Reinforced concrete beams contain ~250 $kg.m^{-3}$ of steel and, assuming the same proportions for AG, an additional 3 Mt of steel is required giving a total of 20 Mt. Although not discussed here, aluminium for external structures is estimated at ~500 kt.

Steel production uses, on average worldwide ~20 MJ/kg (5.6 MWh/t) [24] so the 20 mt needed for a habitat requires 110,000 GWh. However, much of this is chemical energy released by smelting ore with coke. Also, much power is consumed for heating for which a solar furnace would be 5 times more efficient. It should therefore be possible to reduce the electric power requirement for steel making from this rather pessimistic estimate but the value is retained for the following discussion to allow for other uses that have not been identified.

For glass production 675 MWh is needed to melt 1 kt [15] of unrefined rock (or slag from steel production) so 29,000 GWh is needed for the 43 MT radiation shell.

Aluminium production uses a huge amount of electricity; the theoretical minimum being ~ 13 MWh/t. In practice production in the US requires much more at ~90 MWh/t but with huge scope for improvement [25]. Assuming that the most efficient technologies are used in the orbital facility, close to the theoretical minimum at 15 MWh/t, then production of 500 kt of Al would require ~7,500 GWh.

Total power required for the industrial complex to build a habitat this size is therefore 146,500 GWh, which, rounded up to 150,000 GWh and averaged over a 10-year construction period, needs a power supply of 1.7 GW.

Multi-junction gallium arsenide and silicon layered solar cell arrays have an efficiency of ~29% and can generate ~400 $w.m^{-2}$ in orbit. Therefore, to generate 1 GW ~2,500,000 m^2 (2.5 km^2) of solar panels are required so the area for the industrial complex will be 4.25 km^2, a ~1.2 km radius disc.

For a total mass of 120 Mt raw carbonaceous asteroid, and assuming an annual delivery rate of 12 Mt and timely materials processing, the habitat would take 10 years to build. During the build, each set of 3D printers must melt and print 7.7 $t.h^{-1}$ of steel and 57 $t.h^{-1}$ of AG using ~2.4 MW (~300 $kWh.t^{-1}$ melts steel) and 70 MW of solar power, respectively. The cross-sectional area of the cylindrical shell is 10,650 m^2 so an AG layer ~125 mm deep must be deposited every day onto the pre-printed iron framework for each of the growing half-cylinders. These rates of delivery may seem daunting but they are not much different from the routine pouring of concrete in large civil engineering projects like dams.

8 CONCLUSIONS

AG radiation shielded hulls for spacecraft and habitats could be made from vitrified waste silicates using solar energy. Power required is half that for cement production. Reinforced one-piece monocoque shells are strong, avoid radiation shine paths, and are robust enough to last for centuries. Much construction mass is provided by the shielding and material processing is minimized. With remote, and/or, autonomous operation, first generation orbiting radiation shelters could be made before astronauts arrive although high-tech equipment must come initially from Earth. Building on this basic capability, further development should enable very large structures to be built as envisaged in the SPACE Project. Using such methods, it is estimated that an O'Neill Island 1 class orbital habitat could be constructed in 10 years.

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