Three Ways to Mars

Three related talks by Bob Parkinson, Alan Bond and Mark Hempsell
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Report by Stephen Ashworth

Chairman Rodney Buckland introduced the speakers with a quote from George W. Bush: "The American way of life is non-negotiable." To him, this suggested that Earth would not be able to support a growing population aspiring to a modern American level of affluence, and that therefore many of us would need to move to Mars. (Memo to RB: have you considered the possible impact of space-based solar power?)

Talk 1
Bob Parkinson, "You need a little magic to get to Mars"

Bob Parkinson teaches engineering at Queen Mary College, London (give or take a few changes of name at that college). He is Vice-President of the IAF, and is very involved with preparations for the IAC in Glasgow in 2008.

He originally did the work he's talking about today in two consultancy contracts, one for ESA and one for a Canadian organisation. Neither client took his work any further.

A graph shows the drop over the years in the size of proposed Mars missions:

60,000 tons in LEO	– Von Braun, 1950
5,000 tons in LEO	– Von Braun amended, 1956
2,000 tons in LEO	– NASA, 1970
< 1,000 tons in LEO	– Parkinson, 1980

He discusses conjunction class vs opposition class missions. Parkinson concludes: the first mission is likely to be opposition class with Venus flyby, for the shortest possible total mission time. Once it has been established that people can survive on Mars, subsequent missions will be lower-energy conjunction class (3-year missions), and using the same hardware for both means that later missions will therefore have extra payload capacity.

He is talking from here on about short-stay missions which use the Venus flyby trajectory.

The crew will number 5 or 6. Their ship will be assembled in LEO within about a year, to keep cryogenic boiloff losses within bounds. First mission: a 40-day stay at Mars. The ship will not use cryogenic propellants after Earth orbit departure, and will not use nuclear propulsion.

Parkinson's key point is this: you need a little magic, and the magic might be one of five things:

– nuclear thermal propulsion;
– nuclear electric propulsion;
– solar electric propulsion;
– aerobraking at Mars;
– in-situ resource utilisation (ISRU) at Mars.

It is very difficult to tell which of these is best, but each one is "magic", in the sense that each involves a technology which cannot be considered immediate state of the art at present.

Nuclear-thermal rockets were partially developed in the 1970s (the NERVA programme), but like the other concepts still demand some serious technology development before they can be considered flight ready.

The problem with nuclear electric and solar electric is that the mass of the power generation system needs to come within 5 kg/kW. Current technology can only manage around 50 kg/kW (though supporters of these systems claim that they can get down close to the lower value).

Robert Zubrin's approach in his Mars Direct plan is to employ both ISRU and aerobraking at Mars. Like the other technologies, Zubrin's choices would need demonstrating on representative sizes and timescales before one could confidently base a mission on them. Avoiding Mars orbit rendezvous, Mars Direct substitutes Mars surface rendezvous, which its supporters offer as an improvement in mission safety. But the corollary is that it loses the abort option in Mars orbit (i.e. a decision to go home without landing), and in Parkinson's judgement on balance that worsens the overall safety of the plan.

Parkinson himself plumps for aerocapture into Mars orbit as his key "magic" technology.

An inflatable aerobrake/heat shield made by the Babakin space centre in Russia in collaboration with Astrium in Germany has been actually demonstrated on an orbital recovery. This would be a good design, but needs to be scaled up for a manned Mars ship. A Mars entry aeroshell would have to carry about 120 tonnes and have a diameter of about 36 metres.

In LEO, the resulting Mars ship has an Earth Departure Stage (EDS) consisting of three cryogenic rockets, an aerobrake for martian aerocapture, a Mars Excursion Vehicle (MEV; initially assumed to be cone-shaped like an Apollo CM – this later turns out to need modifying to a bent conic), a Transfer Habitation Module and an Earth Return Capsule (also Apollo CM-shaped). Three-quarters of the mass in LEO is the EDS, including propellants.

The ship is put together on an assembly truss, with a robot arm to join the pieces together. There is one heavy lift (e.g. Energiya) launch to orbit the truss, and five more to orbit the parts of the Mars ship. Two more smaller launches are required to orbit firstly a checkout crew, then the flight crew.

In terms of mass, the operation is bigger than building the ISS. But in terms of the assembly procedure, very much simpler. One of the problems with the ISS is that, when a new piece is added on, you have to have spacewalks to make external connections between the modules manually. This could be avoided in Mars ship assembly.

The basic mission architecture is Mars Orbit Rendezvous. The MEV goes back to Parkinson, 1970.

But there is a problem: the conical MEV is 11 metres wide at the base, which is probably too wide to fit on a launch vehicle. A new idea is therefore to scrap the CM-shaped MEV and replace it with a bent conic, which is longer and thinner (wizard's hat-shaped, with a slight kink halfway along). It is a little more difficult to fit the crew cabin and ascent vehicle within this shape. The ascent vehicle has two stages, and needs to be mounted with its long axis at right angles to the long axis of the overall MEV.

The martian air is so thin that you can't decelerate to subsonic speed on the lander's aeroshell alone. You need to jettison the aeroshell while still flying supersonic, then deploy parachutes to slow you down to subsonic, then use rockets to land.

Another new idea occurred to Parkinson while musing on the idea: "How the Chinese got to Mars first." The ship has already used a large inflatable aerobrake for capture into Mars orbit, so why not reuse the same piece of kit to land on the surface? (Another factor would be that, while Western astronauts are given a mass allowance of 90 kg each, including clothing and personal belongings, the Chinese only allow 67 kg for each of their astronauts.)

The inflatable aerobrake for orbit capture is much larger than is needed to get the MEV down to the surface, and is therefore highly effective. It is so large that the relatively small lander/ascent vehicle behind it needs very little extra protection, sitting comfortably in the wake of the large aerobrake.

We move on to consider the interplanetary voyage. An analysis of the inert masses reveals that the largest single item being carried is hygiene water, even allowing for 90% recycling. As Parkinson put it, you are expending a great deal of effort on trucking bathwater round the solar system. Furthermore, another unexpectedly large proportion of the mass is accounted for by the docking units holding the various modules together.

Other matters were discussed: surviving extended exposure to zero-g, cosmic and solar radiation; the psychology of living in a confined environment; the comms lag with Earth; using multiple vehicles (offering a lifeboat capability); and mission abort options (none of which, however, gets you home much quicker).

An example was given of a landing site in Dao Vallis (in the eastern rim of Hellas). This offers varied terrain in one region, but even so a tiny Apollo-style radius of exploration would only allow you to explore one type of terrain during the mission (still talking about the initial brief 40-day stay). The limit to the range of exploration is set by the need for the astronauts to be able to walk back home after a rover failure. To relax this constraint they would need a back-up or rescue capability and some confidence about operating on the surface of Mars.

One important unanswered question is whether the martian surface is toxic. Viking demonstrated that it is biochemically active.

The mission is dogged by a dilemma: will robotic precursor missions such as ExoMars find life on Mars? If they don't, then people will lose interest and there won't be funding for a manned landing. If they do, then Mars will be declared off-limits to people and astronauts won't be allowed to land.

Parkinson emphasises that the timescale cannot be as fast as was Apollo (here again disagreeing with Zubrin). A test mission (perhaps fully robotic) would need to be flown, which adds two years. From starting a programme to actually getting there will take 15 years. But before a programme can even start it first needs to develop whichever "magic" technology it has chosen.

Parkinson is sceptical about Zubrin's sums. It seems that Zubrin has slanted his calculations to support his own case, and that therefore he may not be able to carry out a full manned mission with only two heavy lift launches, as he claims. The five "magic" formulae listed above are about equally good, and need a lot more study before one can call between them.

The concluding discussion raised the question of what the Chinese might achieve in manned spaceflight. Parkinson believes that they are a long way from the Moon. Their programme is slow and steady, and there is no chance of a race to the Moon developing with them. Similarly, a decade or two ago people feared that the Japanese would race ahead of the West, but this didn't happen.

Talk 2

Alan Bond, "Project Troy: A strategy for a mission to Mars"

Alan Bond is Managing Director of Reaction Engines Ltd and promoter of the Skylon single-stage-to-orbit spaceplane, which is based on a revolutionary new design of combined jet/rocket engine (called SABRE).

The underlying question which Bond addressed was this: how could Skylon influence the cost of a mission to Mars? His "Helen" is colleague Helen Webber, and Project Troy is aimed at using a Mars programme as a Trojan horse to get Skylon into development (assuming that greater political support exists for a Mars programme than for Skylon itself).

Skylon is designed to carry a payload of 12 tonnes into very low Earth orbit, or 10 tonnes to the ISS (at around 350 km altitude). It has a 4.6 metre diameter payload bay with a volume of 200 cubic metres. Launch costs should be around one fiftieth of those of the Space Shuttle (i.e. around $20 million/launch).

Bond briefly discusses nuclear rockets. A hundred years from now, the nuclear pulse fusion rocket (described in the BIS *Daedalus* starship study as long ago as 1978) will be the dominant propulsion system.

But he disagrees that nuclear fission rockets are necessary for the first missions to Mars. Chemical propulsion wins hands down on cost. Of course, when venturing further out to Jupiter or beyond, then nuclear rockets will become indispensable.

For the present, if we use ISRU on Mars, a 100 kW(e) nuclear reactor could provide 330 tonnes of carbon monoxide/oxygen propellants for a plant mass of 25 tonnes, processing the martian atmosphere at 4 g/s. Reaction Engines and its colleagues are continuing to study this.

The Troy spacecraft has a recoverable Earth Departure Stage. Aerobraking is not allowed for capture into martian orbit, because the atmosphere is highly variable. The return to Earth requires an Apollo CM-style capsule. The interplanetary spacecraft rotates to provide 0.4 g of artificial gravity, about the same as that on the martian surface.

Could Skylon contribute to the construction of such a spacecraft?

Bond has long been a fan of robotic precursor missions. The precursor lands a base on the surface of Mars for use by a subsequent crew: this is an essential part of the scheme.

The timeline might run as follows:

2026-2027 – fly robotic precursor mission
2028-2029 – fly manned mission
2031 – crew return to Earth

The time the crew are away from Earth is then comparable with Magellan's first European circumnavigation of the Earth (1519-1522). (A more inspiring comparable voyage might be the second European circumnavigation, by Drake, 13 Dec. 1577 to 26 Sept. 1580, for Magellan was killed en route while Drake was knighted on his return. A more poignant example would be the first ever circumnavigation of the globe, now believed to have been carried out by Zheng He's fleet in 1421-1423, just before China entered its period of isolation.)

The 2028 window has been chosen for the manned mission because it falls during a quiet period of the solar cycle. The more dangerous radiation risk is from solar flares, rather than from galactic cosmic radiation. During a quiet sun, two solar flares might be expected during a three-year Mars mission, while during an active sun four might be expected. (Anders Hanson, present in the audience, has written on the GCR risk.)

This particular window also allows the expedition to return to Earth with a relatively low departure delta-V at Mars. The Earth encounter velocity is relatively large, but this can be handled with aerobraking, not a propulsive manoeuvre, Earth's atmosphere being more reliable than that of Mars.

The Troy spacecraft is assembled in LEO. The operations base is not a simple truss, but a "Kew Gardens arrangement" rather like a large cylindrical greenhouse, in order to prevent the assembly operations generating dangerous orbital debris. The internal temperature is controlled. Four Skylons can dock with it at any one time. It orbits at 367 km altitude and at a 28.5 degree inclination to the equator. At this altitude, it completes 46 orbits every three rotations of Earth, keeping it in phase with one or more launch sites on Earth.

Note that any inclined LEO precesses 7 degrees/day due to Earth's equatorial bulge, complicating the departure geometry for interplanetary flights.

The assembly of Troy takes hundreds of Skylon flights (see below).

The Earth departure rocket of Troy has two stages. The first stage pushes the ship into a highly eccentric Earth orbit (HEEO), after which it can return to LEO for reuse. The second stage fires at apogee of the HEEO to take the ship on a trans-Mars trajectory. A plane change is necessary, and, by including that plane change in the apogee burn, the fuel required for it can be kept to a minimum.

If we assume hydrogen/oxygen propellants, the total mass at ignition in LEO is 782 tonnes for the unmanned precursor ship. This mass would be doubled if methane fuel were used. This is such a big difference that the problems of using hydrogen fuel must be grappled with in order to keep the total mass within reasonable limits.

The payload which ends up in Low Martian Orbit is then 137 tonnes.

The design philosophy is based on the fact that the development cost of a small module is less than that of a large one. So building lots of small modules and stacking them is an efficient solution.

Bond has always liked the Columbus philosophy of setting out with three ships. So his manned Troy will have three ships, each with a crew of 6, giving a total of 18 crew members for his first manned mission, which will have a 15-month stay on Mars.

Carbon dioxide will be removed from the cabin atmosphere by LiOH canisters. Parkinson has proposed a more advanced technology for this (not described at this meeting), but Bond can manage using the older system. Fuel cells provide power, and their associated tanks of oxygen, hydrogen and water provide mass for radiation shielding. Space suits require a significant mass allowance: if each crew of 6 astronauts (weighing 0.45 tonnes together) has between them 6 space suits plus one spare, the mass of the 7 suits will be 1.54 tonnes.

The payload which ends up on a return to Earth trajectory is 50 tonnes. This is chosen as the basic design constraint to which the various other masses are bound.

The martian dust storm season coincides with the northern autumn, and lasts 2-4 Earth months. This creates embarrassment for the plan presented here, as the second, manned, Troy mission then arrives in LMO just before the start of the dust storm season.

Bond adopts the Zubrin philosophy of using long-range land trucks to bring huge areas of the surface within range of the explorers. If the three ships land at widely separated points, then most of the planet comes within range.

The ascent vehicle has a single stage, not the traditional two-stage design. It is called a Ferry, weighs 50 tonnes and is fuelled with carbon monoxide and oxygen drawn from the martian atmosphere by a nuclear-powered chemical plant landed earlier. Given the plentiful supply of propellants, the Ferry can transport crews all over Mars and make visits to and from orbit as required. Its propulsion unit is the Seraph engine, currently being researched by Victoria Reed at Kingston University. As well as burning carbon monoxide and oxygen, propellants which make use of the nitrogen in the martian atmosphere (with an abundance of 2.7%) are also under investigation. Some of these, like cyanogen, are excellent compounds for storing energy for rocket propulsion.

Certainly the methane/oxygen combination favoured by Zubrin is better than carbon monoxide/oxygen in terms of specific impulse, but it is also harder to manufacture. Since the lower energy combination is adequate for the job, the extra expense on the higher energy propellants is not justified.

How many Skylon flights will be required to assemble Troy in LEO? The Earth Departure Stage tanks are sized to fit in the Skylon cargo bay. The precursor mission, like the later manned mission, will consist of three independent ships. Each ship requires 174 Skylon loads. The fleet of three ships requires a total of 522 Skylon flights. 390 of these, almost 75% of the total, are pure oxygen and hydrogen propellant. Extra flights will be required to assemble the orbital hangar in the first place, and to carry construction workers to and fro.

The bottom line is as follows:

Skylon development: $11.7 bn

Total cost of Mars programme: $70-100 bn

The cost of developing Skylon is therefore swamped by the development cost of the other Mars hardware.

Skylon could begin development in 2010. There is hope that this might happen. It would then be ready to enter service in 2019.

The Troy project would be over by 2032. Bond did not discuss any possible follow-on.

Talk 3

Mark Hempsell, "To Mars using space lego"

Mark Hempsell teaches aerospace engineering at Bristol University, is a past president of the British Interplanetary Society and is currently editor of the Society's *Journal*.

Hempsell begins, like a preacher with holy writ, with chapter 5 of Zubrin's *The Case for Mars* ("Killing the Dragons, Avoiding the Sirens"). He agrees with Zubrin that human factors, dust storms and back contamination are not the dragons they appear to be.

But, according to Hempsell, Zubrin does not win the radiation argument. Zubrin asserts that stacked provisions will provide a solar storm shelter. But in practice it is very difficult to package stores in such a way as to provide that protection.

Hempsell gives the amount of protection needed as 100 kg/square metre, though Bond would prefer 300 kg/square metre (i.e. 10 and 30 g/sq cm respectively; for comparison, Zubrin offers 5 g/sq cm round the periphery of his spacecraft, and 35 g/sq cm around his storm shelter). These shielding masses are acceptable provided that astronauts can be permitted to experience radiation levels up to ten times those found on the surface of Earth. To reduce the radiation exposure all the way down to Earth surface levels would require 30 tonnes/square metre, which in any conceivable near-future spacecraft is impossible.

(Of course, the desired shielding masses also depend on the shielding substance used, as that affects both the efficiency with which incoming particles are intercepted and the amount of secondary radiation produced which then also has to be soaked up. This was not discussed on this occasion.)

Hempsell offers a generic space habitat design. It is a cylinder about 10 metres wide, which could be launched on a heavy lift rocket or assembled from several segments launched separately by Skylon.

The microgravity problem is more intractable than the radiation one. At present, astronauts on long tours of space station duty have to accept permanent bone damage. The calcium loss in orbit is made up after the flight, but imperfectly, and the bone never recovers completely. (Zubrin, on p.121 of his book, claims that the recovery is "near total", but he is wrong here: the bones do re-grow, but the bone material is of a different type and not as strong.)

Therefore a long interplanetary voyage must use artificial gravity (Zubrin fully agrees, of course). But before that can be done two unknowns must be resolved:

– what is the minimum acceptable g level to avoid bone damage?

– what is the maximum acceptable spin rate to avoid dizziness?

In particular, we have no idea how different levels of gravity affect health. We know what happens at 1 g and at 0 g, but not anywhere inbetween (the lunar missions having been far too short to provide any relevant experience). We don't know the shape of the curve that connects these two data points: if we are lucky, a little gravity will do a lot of good, and as we approach 1 g a law of diminishing returns kicks in; if we are unlucky, a little gravity is almost as bad as none at all, and you have to be close to 1 g to avoid damage to health; or the relationship could be linear; or it could be some other shape altogether.

The only way to resolve this is with a variable gravity space station. The design proposed is 250 metres long, has a mass of 200 tonnes and draws 25 kW continuous power. Tethers are rejected in favour of a rigid spoke, 77 metres long, weighing 10 tonnes and enclosing an access tunnel 0.8 metres wide. The spoke is launched in segments in a single Skylon. The remaining 173 m of the station is accounted for by the habitat module and the counterbalance, which includes a rather heavy solar array and batteries to provide the 25 kW of power.

The complete variable gravity station would take 20 Skylon flights to build (costing $400 million, or about 1.5 times the cost of an Ariane 5 launch). This station has to be built and flown with various crews before the design of a Mars spacecraft can even begin.

But, in order to proceed with considering a Mars ship, Hempsell plumps for one third of a g, with a spin rate of one rotation per 30 seconds – while emphasising this is a pure guess. (Zubrin, on p.8 of his book, suggests the same rotation rate for two modules connected with a 330 m tether, giving martian gravity (0.38 g) for the trip.)

The greatest problem, however, is one that was not mentioned by Zubrin at all: reliability. This issue has been highlighted by the failures of the Shuttle programme and the resulting delays to the ISS construction schedule. But if a reusable spaceplane such as Skylon is in widespread use for other purposes, then it will have the necessary reliability, and this is assumed from here on.

As an interesting historical perspective: exploration vessels of the past have usually been tried and trusted long before they set sail on voyages to unknown lands. The *Santa Maria*, *Endeavour* and *Beagle* were not even new. If you're exploring the unknown, you want to be doing so in a reliable ship, to reduce the risk as much as possible. Of the exploration ships shown on Hempsell's slide, only the *Endurance* was specially built for exploration, and this is the one that didn't come back. The *Santa Maria* also didn't return, but the rest of the fleet did, which is why Columbus took three ships in the first place – he knew what their reliability was like.

The post-Apollo programme (rejected by Nixon in 1969) had the right idea: build a space infrastructure from six versatile basic elements (including the Saturn rockets). We therefore need a kit of generic modules which can be applied to many different types of missions, hence the term "space lego" in the title of this talk.

We need a reusable launcher (Skylon), an in-space boost stage, and a capsule for return from interplanetary space. Hempsell has designed an Earth return capsule called Excalibur; superficially it resembles an Apollo/Orion capsule, but is in fact very different from them, as the *JBIS* papers describing it illustrate.

In Bob Parkinson's terms: yes, you need some magic, but that magic has to work right across the infrastructure, not just be a fix for Mars. Hempsell's preferred choice of fix is thermal nuclear. Such a rocket would resemble the US NERVA rocket of the 1960s, but could now be built considerably better and achieve an exhaust velocity of 10 km/s.

For the sorts of missions we are now considering, a nuclear thermal boost stage can be one third the mass of a hydrogen/oxygen stage. The nuclear rocket would be launched by Skylons. It would have a spherical inflatable tank, 13 metres diameter when inflated, and a total mass of 100 tonnes (i.e. 20 tonnes = two Skylon launches for engine and tank, plus 80 tonnes = eight further Skylon launches for hydrogen). It could boost a payload of 100 tonnes to GEO, 110 tonnes to lunar orbit (4 km/s) and 140 tonnes to an Earth escape trajectory (3.6 km/s; e.g. onto a transfer orbit directed towards Mars).

One major problem which must be addressed before this can become reality is how to transfer liquid hydrogen from one tank to another in zero-g. (Hempsell did not discuss the option of attaching the hydrogen tanks used for transport from Earth to orbit directly to the nuclear thermal stage.)

The interplanetary (not specifically Mars) spacecraft which emerges consists basically of the rotating space station propelled by two nuclear rockets. It would take 75 Skylon launches, and the launch cost would therefore be around $800 million, approximately equivalent to a single Shuttle launch. (Of course there are a number of different Shuttle cost figures doing the rounds, depending upon whether one has in mind the recurring cost, the full operational cost or the cost including development payback. Cost figures are also complicated by inflation, which has made a big difference over the nearly 30 years of Shuttle flights. At the current launch rate of only three or four flights per year, a figure of around $1 billion is probably close to the mark.)

The Mars lander is not included on this interplanetary spacecraft. We launch three (roughly Apollo CM-shaped) landers together separately on a single nuclear rocket (25 Skylon launches). Each lander opens out its aeroshell in petals like a daisy to expose solar panels on the inside when in space, and also when on the martian surface. They aerobrake into martian orbit. This lander contains the author's Excalibur capsule with a drop tank for return to orbit. The capsule will have long been used for return from the Moon, so will be known to be reliable (very important).

Finally, the siren. Zubrin is right that you don't need to go to the Moon before you go to Mars. But he is wrong, because Mars is the siren, not the Moon. The Moon is valuable for many reasons on its own account. The Moon is also potentially relevant to solar power satellite schemes, which would be very useful if meanwhile civilisation on planet Earth is to survive.

Like the other two speakers, Hempsell expects an extended timeline. Starting immediately, a Mars landing in 2025 is the earliest conceivable, but in practice would probably be later.

In conclusion, there are three important points to remember:

(1) Mars should not be conceived of as a special objective in isolation. Rather it should be part of the overall expansion of human civilisation into space.

(2) Space infrastructure needs to be based on generic multi-role elements ("space lego").

(3) This saves money, development time and lives because of the reliability issue when developing a new piece of infrastructure.

In general, systems need to be consciously engineered to be flexible and applicable to many different roles. It would not be good engineering to build a specialised system and hope that it could be used for something different later on (despite the arguable counter-example of Apollo-Saturn).

And it is an urban myth that the voyages of Columbus and others were in their day as expensive as spaceflight is to us now. Spaceflight is more difficult and expensive.