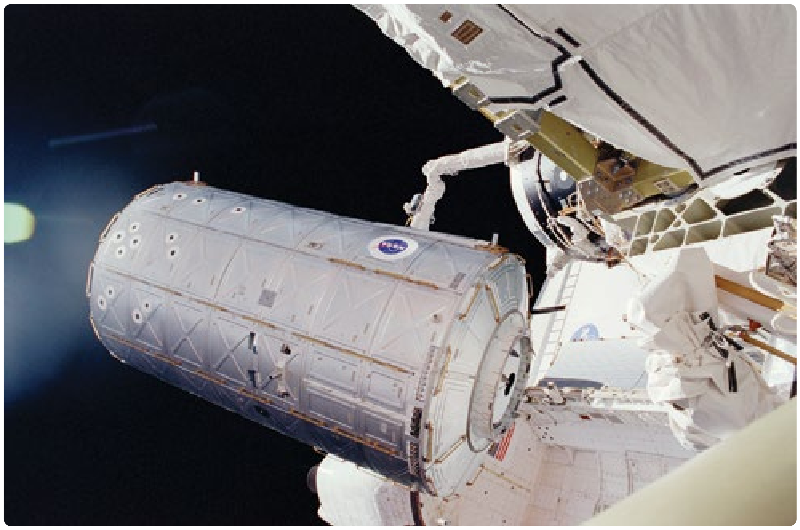
Larry Bell

Orion Multi-Purpose Crew Vehicle (MPCV) heat shield, 2014
The Orion spacecraft being equipped with the world's largest heat shield, measuring 4.87 metres (16.5 feet) in diameter. Made from a single seamless piece of Avcoat ablator, it will be tested on Orion's first flight in December 2014 as it protects the spacecraft from temperatures reaching 2,200°C (4,000°F).

Reaching Towards a New Era of Space Architecture

BRAVE NEW WORLDS

Space travel is on the brink of a new era. **Larry Bell**, Professor of Architecture and Space Architecture at the University of Houston, describes how new ambitions are being reached for, such as the exploration of distant Mars, which will require longer and ever more complex missions. At the same time Space is being opened up internationally, with the participation of China and India, and space tourism is introducing privatisation and new commercial players.



SpaceX, Dragon V2 unveiling ceremony, Hawthorne, California, 2014
The spacecraft is designed to carry people into earth orbit and was developed in partnership with NASA's Commercial Crew Program under the Commercial Crew Integrated Capability agreement.

International Space Station, NASA Destiny Laboratory, 2001
On 10 February 2001, the crews of the Space Shuttle Atlantis successfully installed the Destiny Laboratory onto the International Space Station.

Architectures in Space present new worlds of challenge and opportunity as nations join together to explore human destinations beyond Earth. This great exploration adventure began a half-century ago when a tiny orbiting capsule first carried a young Soviet cosmonaut named Yuri Gagarin around our planet on 12 April 1961. Within the next 11 years, 12 American citizens walked on the Moon as six of their crew companions orbited above.

The Russian Mir (1986–2001) and US Skylab (1973–9) space stations that soon followed demonstrated that people can live and conduct useful work under weightless conditions over prolonged periods. New generations of launch and return vehicles, including the reusable Space Shuttle that also saw service as a habitat and laboratory, made space travel routine from 1981 to 2011.

Beginning in 1998, construction of the International Space Station, the greatest collaborative enterprise and technological marvel since the dawn of mankind, has ushered in the era of a true global spacefaring community. Orbiting more than 300 kilometres (190 miles) above the Earth every 90 minutes, this epic development and assembly feat was accomplished with seamless cooperation involving professional teams from NASA, the European Space Agency (ESA), the Russian Space Agency and the Canadian Space Agency. Each government organisation, in turn, enlisted support from numerous corporate and institutional design, engineering and fabrication contractors – teams that included specially educated and experienced professionals with architectural backgrounds functioning in key roles.

Longer Missions Present Larger Architectural Challenges

As the international community extends human missions in terms of both distance and duration, the challenges to support future voyagers and settlers become ever more complex and daunting. Unlike, relatively, very short 'sprints' to the International Space Station's low earth orbit or even to the Moon and back, round-trip missions to Mars will require at least three years, with the majority of that time spent in transit under psychologically claustrophobic and physically deconditioning weightless conditions. Low gravity (one-sixth Earth gravity on the Moon, and one-third Earth gravity conditions on Mars) will add compensatory exercise requirements to retain muscular and cardiovascular health; exposures to life-threatening space radiation risks must be mitigated; intervention responses must be provided for an endless variety of equipment and medical emergencies; and satisfying nutritional and recreational requirements will be essential to sustain crew health, morale and performance under long periods of isolation, to mention but a few preparedness prerequisites.

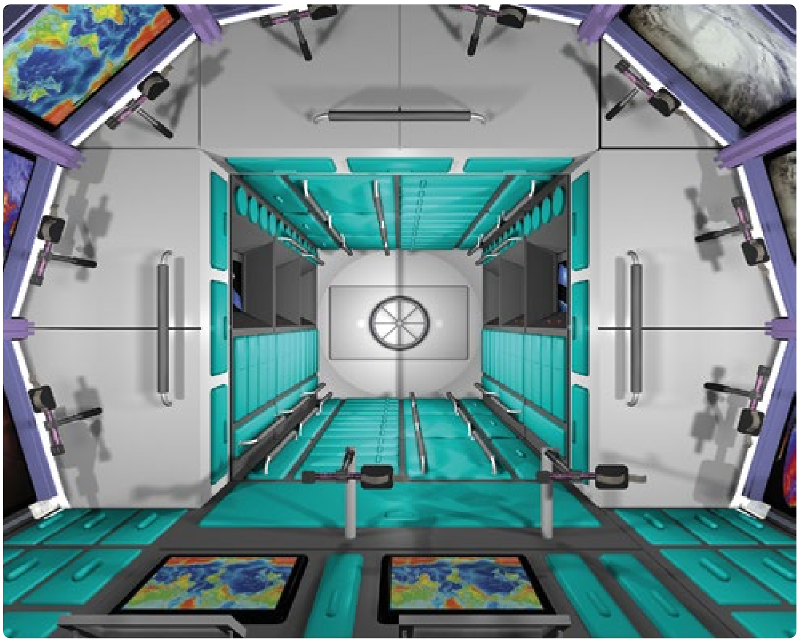
An evolution from 'right stuff' military pilot astronauts to ISS scientific specialists to future lunar/Mars explorers or settlers will also impact planning in profound ways. Each stage imposes priorities to accommodate greater inhabitant diversity and self-reliant autonomy. This will include comprehensive planning and design for multi-cultural crew mixes, specialised and multi-tasking roles, broader long-term age- and gender-related health factors, and cohabited marriage relationships.

Space: An International Market

In addition to an evolving privatisation of 'space citizenry', emerging commercial interest is opening up new entrepreneurial space markets. Sir Richard Branson plans to offer commercial Virgin Galactic space tours. Space Exploration Technologies Corporation (SpaceX), owned by PayPal cofounder

Sasakawa International Center for Space Architecture (SICSA), Commercial Space Development Project, University of Houston, Texas, 2002
below: Laboratory module. Space offers an unlimited vacuum and 'weightless' environment for a variety of laboratory experiments and production processes.

right: A large volume and variety of replacement parts and supplies must be made immediately available to maintain all commercial on-orbit operations at mature stages of development.



Elon Musk, has already accomplished two unmanned flights to the International Space Station, and is focused upon readying a Dragon capsule to carry up to seven people. Boeing has progressed to final design stages for its CST-100 vehicle, a capsule that will fly atop a United Launch Alliance Atlas 5 rocket, and plans to launch its first International Space Station crew in 2016. Sierra Nevada's Dream Chaser features a winged vehicle design that will also fly on an Atlas 5, with a target first manned launch date in 2016 or 2017.

Las Vegas-based Bigelow Aerospace (see pp 68–9) has even more ambitious plans. The company intends to be the first to operate a commercial space hotel, and is scheduled to put an inflatable Sundancer module in orbit for operational status in 2015. The 180-cubic-metre (6,357-cubic-feet) facility is designed to accommodate up to six people for short-duration stays, and three for longer periods. Sundancer will serve as a test for a three-module commercial version that is currently under development. Bigelow has previously demonstrated two unmanned smaller-scale prototypes launched on Russian spacecraft.

China is progressing with ambitious space plans as well. The country sent its first astronaut into space in 2003, the third country after Russia and the US to achieve independent manned space travel. Then in June 2013, three Chinese astronauts spent 15 days in orbit and docked with an experimental laboratory, part of Beijing's plan to establish an operational space station by 2020.

President Xi Jinping has made it very clear he intends to have China establish itself as a space superpower. In December 2013, the Chinese launched and landed a robotic rover called Yutu (Jade Rabbit) in the northwest corner of the giant Imbrium Basin, the left eye of the 'Man in the Moon', to survey the surface. Zhao Xiaojin, director of aerospace for the China Aerospace Science and Technology Corporation, described the rover as a high-altitude 'patrolman' carrying the dreams of Asia.[1] The next stage in 2017 will likely land a lunar probe, release a moon rover and return a probe to Earth.

Yutu's lander design is far too big to have been designed for tiny rovers. Its size is larger than the one used for the NASA Apollo programme (1967–72), suggesting that it must have been engineered for the addition of a crew cabin module and return-to-orbit vehicle for lunar astronauts. The Chinese are also developing an Apollo-class moon rocket.

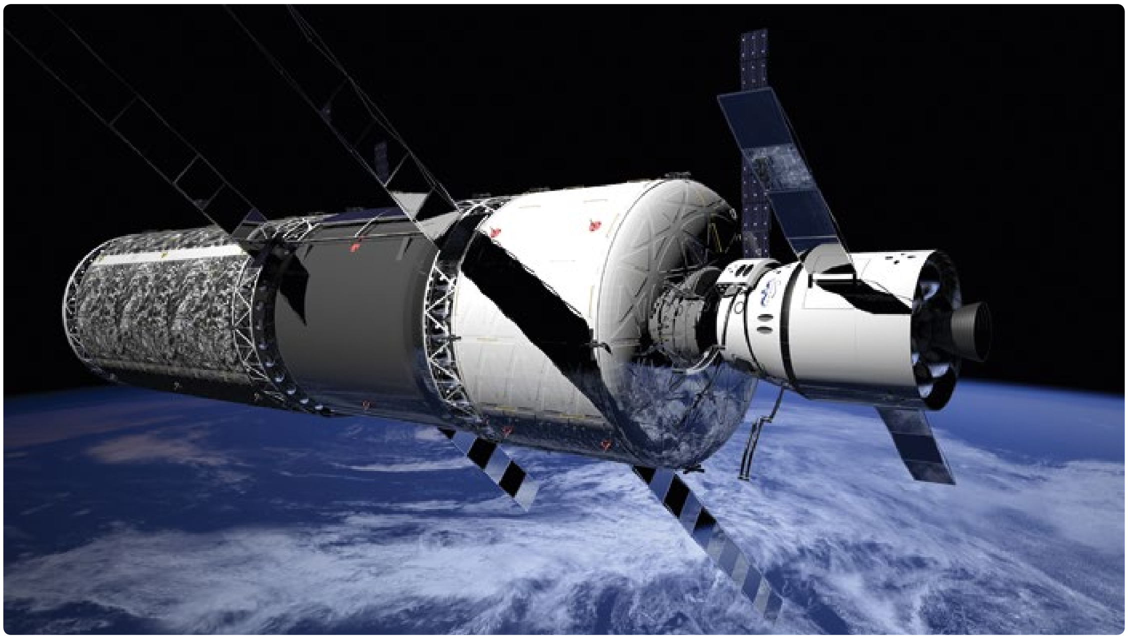
Russia is advancing towards several unmanned lunar landing missions, most likely in preparation for human Mars surface operations. Four of these, which will be launched between 2015 and 2020, will aim at the Moon's south pole. Their most logical goal is to explore ways to collect and process surface resources as an experimental laboratory for future human habitation on both the Moon and the Red Planet.

Not wanting to be left behind other spacefaring nations, India has dispatched an unmanned probe named Mangalyaan (Marscraft) to orbit Mars. Upon the probe's successful arrival, India's space agency becomes the fourth in the world to reach Mars following the US, Russia and Europe. Its Mangalyaan launch is broadly recognised as the first salvo in a burgeoning space race with China, Japan, South Korea and other emerging world powers. Like China, it will also include lunar rovers.

Brave New Worlds

Where and how far will our near-term international space future reach in these difficult and uncertain economic times? Given so many other urgent priorities, can we afford such costly programmes? When asked this question, Nisha Agrawal, chief executive of Oxfam in India, offered an answer during a BBC interview:

Sasakawa International Center for Space Architecture (SICSA), Minimalist mission to Mars, University of Houston, Texas, 2013
A minimalistic approach to a Mars mission using commercial space launch and habitat capabilities.



> India is home to poor people but it's also an emerging economy, it's a middle-income country, it's a member of the G20. What is hard for people to get their head around is that we are home to poverty but also a global power … We are not really one country but two in one. And we need to do both things: contribute to global knowledge as well as take care of poor people at home.[2]

K Radhakrishnan, chair of the Indian Space Research Organisation (ISRO), offered a similar reply:

> Why India has to be in the space programme is a question that has been asked over the last 50 years. The answer then, now and in the future will be: 'It is for finding solutions to the problems of man and society'.[3]

And what about American and European space futures? Having realised countless achievements and paybacks from our investments in space exploration that have driven new technological advancements, transformed our trade economies, and revolutionised global communications, it is unthinkable that progress will be allowed to stop. Just as India and China now recognise that they can and must make commitments to ensure their places in the high frontier, the US and Europe also cannot afford not to.

Sixteen years ago Neil Armstrong told BBC science correspondent Pallab Ghosh: 'The dream remains! The reality has faded a bit, but it will come back, in time.'[4] Thanks to cost-saving technology advancements, expanding entrepreneurial interest, and the successful International Space Station collaboration precedent, there is good reason to believe that time has now arrived. Accordingly, Space Architecture research and design can be expected to play important roles in making those resulting new worlds of opportunity livable and safe.

Many large questions, however, remain to be answered. How far will those journeys to new worlds take humankind? Which nations will lead, which will join, and what will they contribute? What will those spacefaring nations discover, at what costs, and who will benefit most? Finally and most importantly, in what ways will fruits of international cooperation essential for success advance progress where it matters most – to benefit all voyagers on Spaceship Earth? ⌂

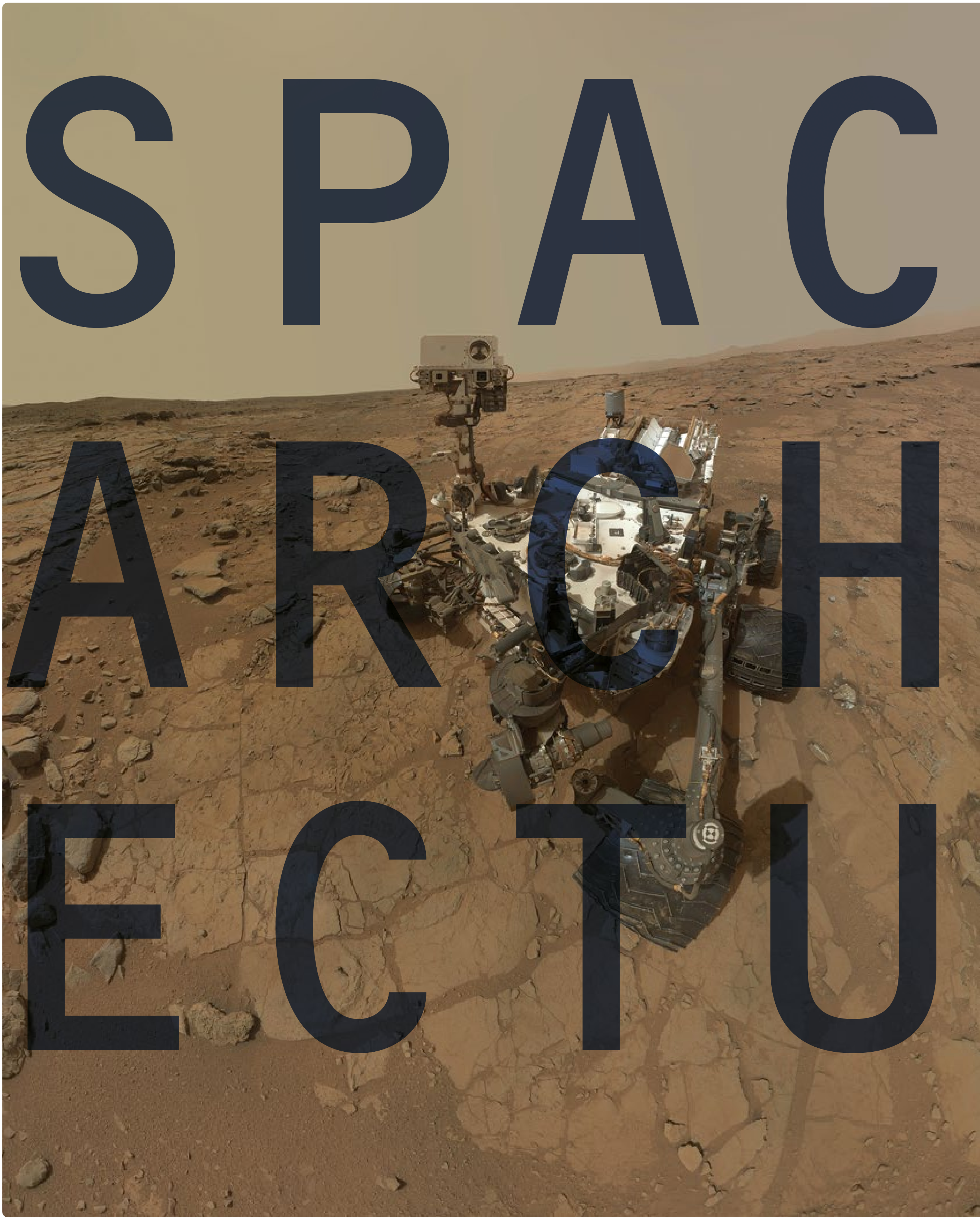
Notes

1. Xinhua English News: 'China Unveils its First and Unnamed Moon Rover', 25 September 2013: http://news.xinhuanet.com/english/china/2013-09/25/c_132750241.htm.
2. BBC News, 'India's First Rocket Blasts Off to Mars', 5 November 2013: www.bbc.com/news/science-environment-24729073.
3. Ibid.
4. BBC News, Paul Rincon, 'Neil Armstrong: "Diffident" Emissary of Mankind', 26 August 2012: www.bbc.com/news/science-environment-19383607.

INTRODUCTION

Neil Leach

Curiosity rover self-portrait, Mars, 3 February 2013
The self-portrait was taken on a patch of flat outcrop called John Klein, where the NASA rover was due to perform rock-drilling activities. The image is actually composed of dozens of exposures stitched together.



Space Shuttle Atlantis seen from the Mir space station, 29 June 1995
Fish-eye view of the Atlantis as seen from the Russian Mir space station during the STS-71 mission.

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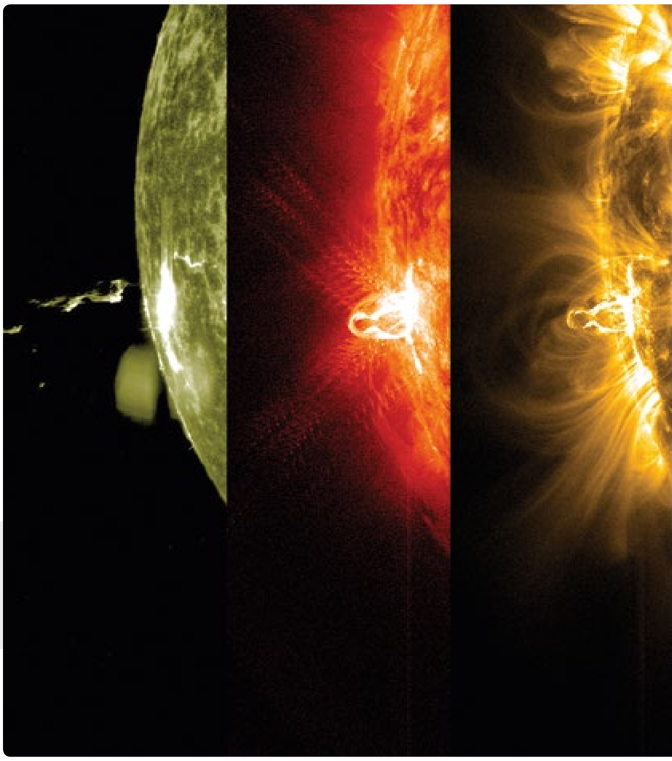
THE NEW FRONTIER FOR DESIGN RESEARCH

Architecture in Space is entering a new era. It is over 40 years now since the late Neil Armstrong became the first human being to set foot on the Moon. For many people space exploration has not advanced much since that historic moment, but in reality there have been numerous developments. Space exploration has taken on a collaborative international dimension through the International Space Station (launched in 1998) and other ventures. Likewise, the practice of one-off flights has given way to the introduction of reusable hardware such as NASA's Space Shuttle (operational 1981–2011). More recently, in 2011 the US sent the Curiosity rover, its most sophisticated robotic vehicle, to investigate the climate and geology of Mars. And other countries have joined the space industry, with China sending its first astronaut, Yang Liwei, into Space in 2003 and then landing its own lunar rover, Yutu (or Jade Rabbit), on the Moon in December 2013. Significant research has also been undertaken into harnessing energy from Space, and the space tourism industry is gearing itself up to send the first space tourists into low earth orbit.

Over the last decade there has been a fundamental shift in the space industry from short-term pioneering expeditions to long-term planning for colonisation and new ventures such as space tourism. Architects are now involved in designing the interiors of long-term habitable structures in Space, such as the International Space Station, researching advanced robotic fabrication technologies for building structures on the Moon and Mars, envisioning new 'space yachts' for the super-rich, and building new facilities such as the Virgin Galactic Spaceport America in New Mexico designed by Foster + Partners (2011). Meanwhile, the mystique of Space remains as alluring as ever, with architects including Greg Lynn (see his article on pp 82–8 of this issue) involved in design fictions set in Space, and educators such as Michael Fox of the California Polytechnic State University (Cal Poly – see pp 100–101), Larry Bell of the Sasakawa International Center for Space Architecture (SICSA) at the University of Houston (pp 118–21) and Lynn running design studios drawing upon ever more inventive computational design techniques.

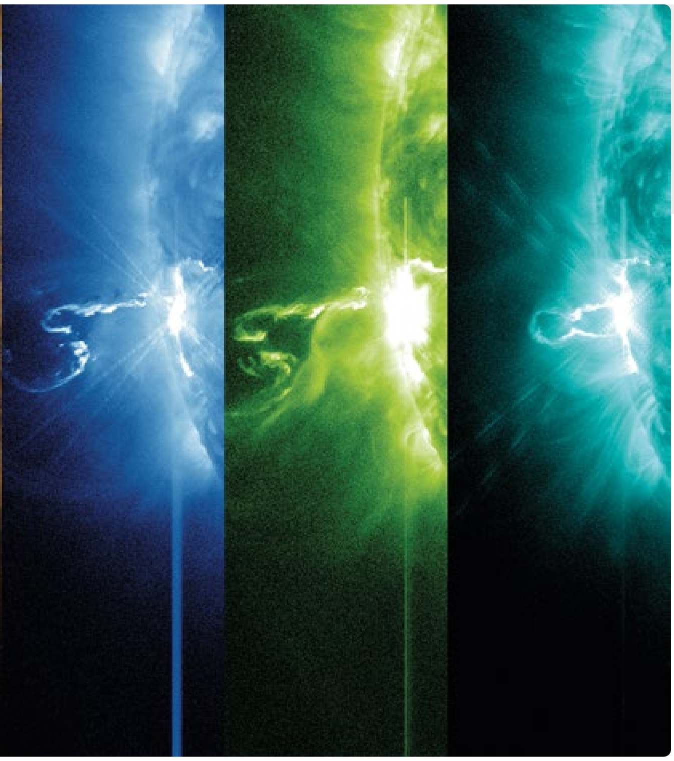
OVER THE LAST DECADE THERE HAS BEEN A FUNDAMENTAL SHIFT IN THE SPACE INDUSTRY FROM SHORT-TERM PIONEERING EXPEDITIONS TO LONG-TERM PLANNING



This issue of AD features the most significant of projects currently underway and highlights key areas of research in Space, such as energy, materials, manufacture and robotics. It also looks at how this research might be realised in outer space and the potential for applying it to conventional architectural design and construction. It is structured along the lines of the four key domains of Space Architecture: space colonisation, habitable artificial satellites, space tourism and terrestrial space-related industries.

Space Settlement

Space settlement remains one of the most contested topics. Should humankind continue to explore the potential of sending a handful of human beings to planets such as Mars and other celestial bodies, or should the emphasis be placed instead on relatively large-scale settlement programmes on the Moon? Contributors to this volume remain divided. Space architect Madhu Thangavelu (pp 20–29) favours the potential settlement of the Moon, as does fellow space architect Brent Sherwood (pp 16–19), who sets out the various future options in terms of space developments. Designer Andreas Vogler's MoonCapital proposal (pp 30–35) offers an architectural vision of such a project. Meanwhile, former astronaut and the second man to set foot on the Moon, Buzz Aldrin (pp 40–45), argues that the next important milestone is surely to send a human being to Mars, despite the unlikelihood of being able to bring that person back. Aerospace engineer and author Robert Zubrin (pp 46–53), himself a long-time passionate advocate of missions to Mars, agrees with Aldrin that we should be investing our energies in settling Mars, although his vision is slightly different.



NASA Solar Dynamics Observatory, Solar flares, 24 February 2014
The harvesting of solar energy remains a further potential opportunity in Space. These images show the first moments of an X-class flare in different wavelengths of light.

Space architects have also been involved in researching other concerns related to space settlement, exploring ways of constructing habitats and other infrastructural facilities on the Moon and Mars, which has developed considerably in the past few years, and devising novel rovers for traversing their surfaces, such as the ATHLETE moon rover developed by A Scott Howe (see pp 36–9). For example, a series of consortia are now exploring the potential of robotic fabrication technologies for printing structures on the Moon and Mars that echo the growing interest in 3D printing in general. These technologies can also be deployed in habitable artificial satellites for printing replacement parts and even for printing food. My own article on pp 108–11 of this issue offers an overview of developments in 3D printing in Space.

Habitable Artificial Satellites

In terms of habitable artificial satellites, despite the many speculative ideas promoted by a variety of designers, the International Space Station (or 'Alpha', as it is known in the space industry) remains the only actual human habitat that has been deployed in Space to date. In her article (co-authored with Rod Jones), Constance Adams, who was involved in the design and fabrication of Alpha, recounts the process (see pp 70–77).

While research has been conducted into other possible space habitats – some of which are featured in this issue – the experience of astronauts actually inhabiting the International Space Station has itself generated a valuable new field of research into the physiological and psychological problems of keeping human beings in Space for extended periods. What has become clear is that human beings face considerable obstacles if they are to survive in Space, given the recurrent problems of radiation, weightlessness and diet. In his article on pp 90–95, Ondřej Doule (chair of the Space Architecture Technical Committee at the American Institute of Aeronautics and Astronautics (AIAA)), considers the issue of gravity, which he considers to be the fundamental challenge in space exploration, not only in terms of the problems of weightlessness in space habitats such as Alpha, but also in launching rockets in the first place. Likewise, space architect Sandra Häuplik-Meusburger (pp 114–17) looks at the potential of different greenhouse systems in Space in which to not only grow vegetables, but also to provide some visual relief to the monotony of life on board. Equally, space architect Marc M Cohen (pp 78–81) describes his vision of a Water Wall whereby waste fluids are redeployed as a radiation shield for spacecraft.

NASA Mars Reconnaissance Orbiter, Proctor Crater, Mars, 9 February 2009
Photo taken by the orbiter's High Resolution Imaging Science Experiment (HiRISE) camera showing one of the many dunes composed of fine sand.

SpaceX Dragon capsule grappled by the International Space Station's Canadarm2 Mobile Servicing System (MSS), 20 April 2014
Private enterprise has emerged as one of the most important drivers within the space industry, with companies such as SpaceX playing an increasingly prominent role. Here, a SpaceX Dragon craft is grappled by Canadarm2 as it delivers supplies.

NOT ONLY DO CERTAIN TECHNOLOGIES USED ON EARTH OWE THEIR ORIGINS TO DEVELOPMENTS IN THE SPACE INDUSTRY, BUT ALSO THE WHOLE OF THE SPACE INDUSTRY IS ULTIMATELY CONDITIONED BY TERRESTRIAL CONCERNS.

Michael Maltzan Architecture, New building for NASA's Jet Propulsion Laboratory (JPL), Pasadena, California, 2010
In this proposal for the new JPL building, the upper courtyard, with its reflecting fenestration, gives the impression of endless space.

Cosmonaut Sergey Ryazanskiy conducts a spacewalk outside the International Space Station, 9 November 2013
The Russian cosmonaut shown during a session of extra-vehicular activity (EVA).

Another great challenge facing the space industry is that of funding. At one stage, especially around 1964–6 when the Apollo programme was in full swing, the US space industry was the best resourced in the world. However, recent cutbacks and hiatuses in developing a viable replacement for the now retired Space Shuttle have led to the seemingly absurd situation where US astronauts are forced to hitch a lift with Russian rockets in order to reach the International Space Station. In his article, space architect Larry Bell (pp 118–21) laments the situation, and contrasts the heavy investment on the part of the Chinese space industry to the relative stagnation in the US.

JUST AS SCIENCE FICTION OFTEN INFORMS DEVELOPMENTS IN SCIENCE ITSELF, SO THE REALM OF 'DESIGN FICTIONS' CAN ALSO INFORM DESIGN.

Space Tourism
If, however, there is one area that has developed more rapidly than others it has been the private space industry. Not only have we witnessed the meteoric rise of private companies such as Space Exploration Technologies Corporation (SpaceX) in designing, manufacturing and launching advanced rockets and spacecraft to resupply Alpha, the emergence of space tourism as a viable commercial venture has also changed the game. In his article on pp 64–9, Ondřej Doule charts the emergence of this new industry that seems to hold so much promise for the future.

Terrestrial Space-Related Industries
Another aspect of the space industry is, of course, the design and construction of space industry buildings on Earth. This issue of AD features two recent terrestrial buildings.

Crew members in the Japanese Experiment Module (JEM), International Space Station, 8 November 2013
Nine crew members gather for a group portrait in the JEM, known as the Kibo laboratory. Russian cosmonauts are joined by astronauts from NASA, the European Space Agency (ESA) and Japan Aerospace Exploration Agency (JAXA).

Spaceport America (pp 56–9) , designed by Foster + Partners and constructed in the desert of New Mexico, services the Virgin Galactic space tourism initiative, and is the first of a series of such spaceports that will soon be offering paying tourists the opportunity of going into low earth orbit. And the Cultural Centre of European Space Technologies (KSEVT) (pp 60–63) was designed by a consortium of Slovenian architects, and constructed in the Slovenian town of Vitanje. Other notable projects include the – albeit unbuilt – design of Michael Maltzan Architecture for a new building for the Jet Propulsion Laboratory (JPL) in Pasadena, California.

Indeed the whole relationship between Earth and the space industries is an interesting and complex one. In my article on pp 54–63, I offer an overview of this connection. Not only do certain technologies used on Earth owe their origins to developments in the space industry (and here one can also imagine the potential of 3D printing techniques designed for the Moon being used for arid places on Earth, such as the desert), but also the whole of the space industry is ultimately conditioned by terrestrial concerns. Space, as such, becomes a mirror that reflects human concerns on Earth, and it is important not to overlook the significance of terrestrial ambitions in determining the course of the space industry.

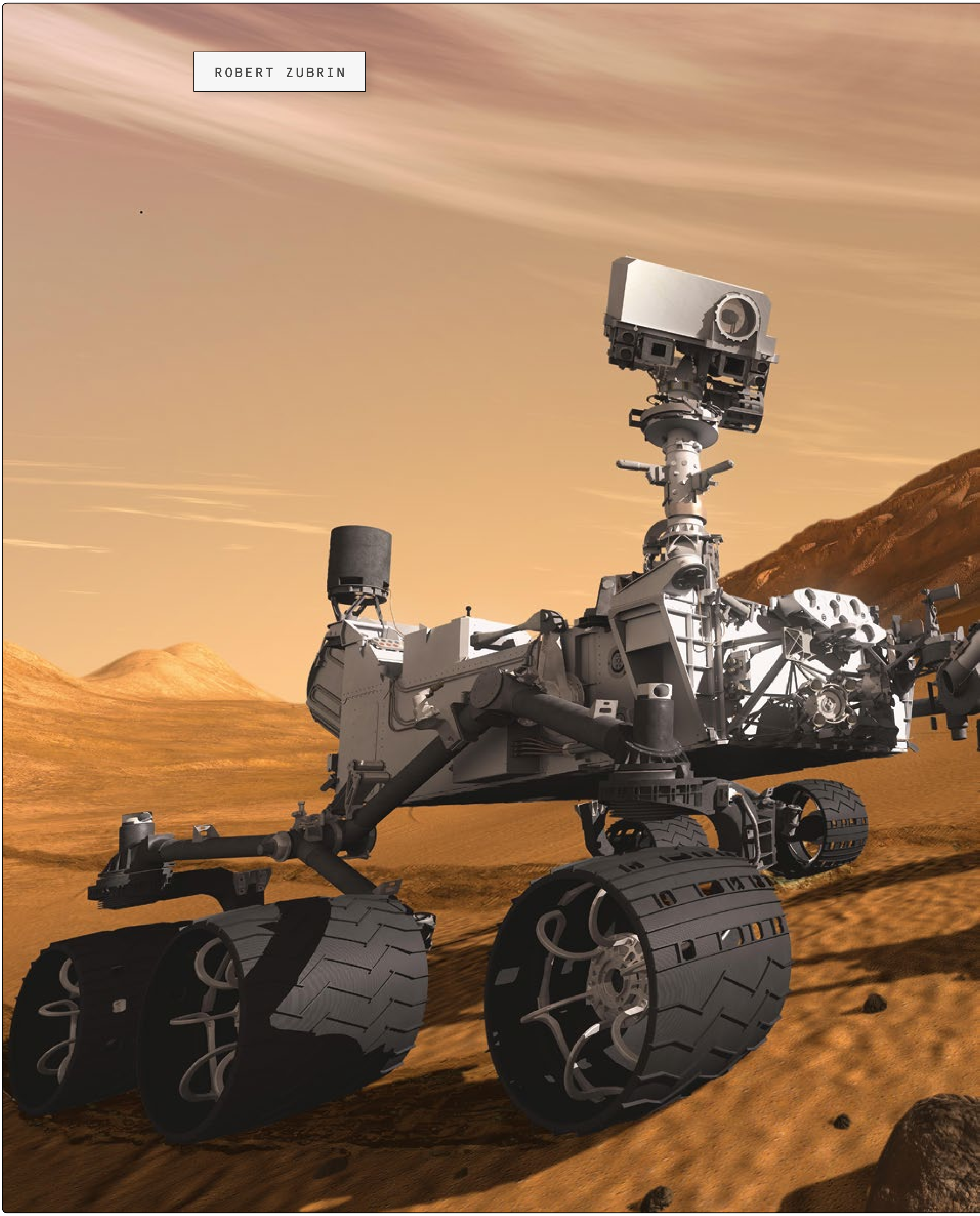
Space Fantasies

Finally, no overview of developments in any field is complete without a degree of fantasy. Just as science fiction often informs developments in science itself, so the realm of 'design fictions' can also inform design. Included in this issue are the speculative projects of Greg Lynn (pp 82–9), completed in association with Alex McDowell, a designer for the Hollywood movie industry, and Peter Frankfurt, founding partner of the Imaginary Forces design agency. Equally, a number of space fantasies are included among the student projects featured on pp 96–107, which range in outlook from purely speculative design fictions to relatively serious attempts to operate realistically within the testing constraints of Space Architecture.

Put together, what we have is a snapshot of the latest developments in Space Architecture. What becomes clear is that there have been considerable activities going on in recent years that demonstrate that the space industry is alive and well. But they also reveal the versatility of the architectural imagination. No longer constrained by the limitations of terrestrial architecture, space architects are now exercising their imagination within the space industry, designing not only habitats for Space, but also working on other aspects of habitation – methods of building structures and ways of inhabiting them afterwards.

Rumours of the death of the space industry are greatly exaggerated. ᗪ

ROBERT ZUBRIN



COLONISING THE RED PLANET

HUMANS TO MARS IN OUR TIME

Astronautical engineer and President of the Mars Society **Robert Zubrin** explains why a human exploration of Mars is preferable to the Moon and now within our grasp, despite being an average of 225 million miles away. He advocates how missions might be realised through a Mars Direct approach that employs relatively small spacecraft launched directly to the Red Planet via boosters.

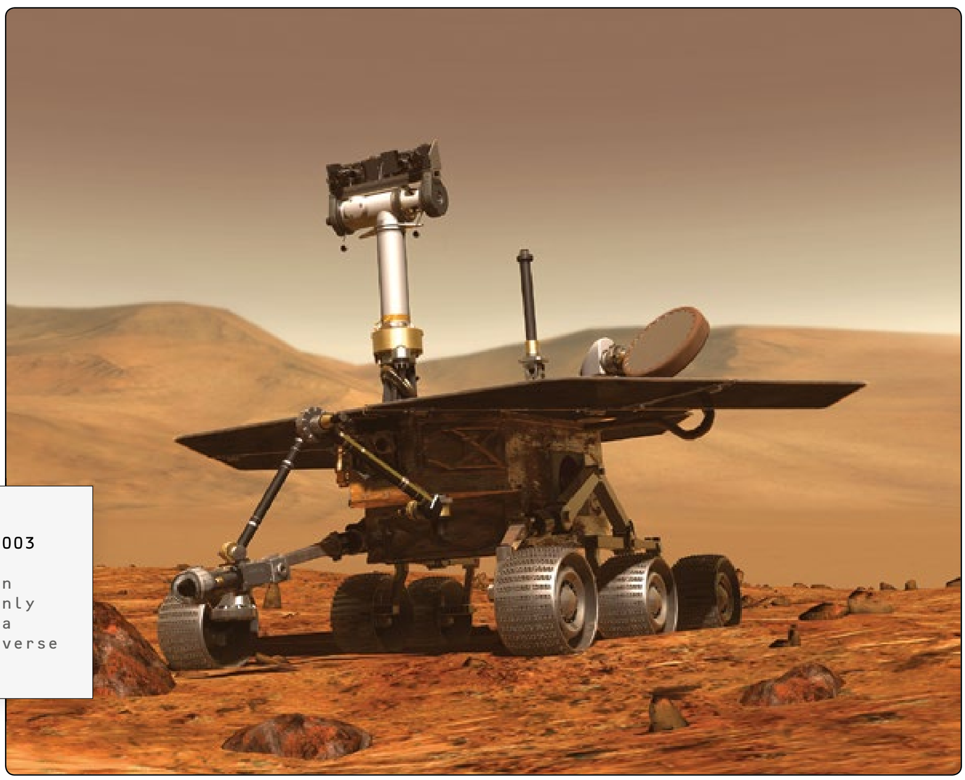
NASA, CURIOSITY MARS ROVER, 2012
Artist's concept. While packing 10 times the payload of Opportunity, Curiosity's average speed is still less than 30 metres (100 feet) per hour, and it cannot dig, drill or do any of the lab analysis required to discover or characterise life on Mars.

Many people believe that a human mission to Mars is a venture for the far future, a task for 'the next generation'. Such a point of view has no basis in fact. On the contrary, the US has in hand, today, all the technologies required for undertaking an aggressive, continuing programme of human Mars exploration, with the first piloted mission reaching the Red Planet within a decade. We do not need to build giant spaceships embodying futuristic propulsion technologies in order to go to Mars. We do not need to build a lunar base, a grander space station, or seek any other way to mark time for further decades. We can reach the Red Planet with relatively small spacecraft launched directly to Mars by boosters embodying comparable technology as that which carried astronauts to the Moon almost a half century ago. The key to success comes from following a 'travel light and live off the land' strategy that has well served explorers over the centuries that humanity has wandered and searched the globe. A plan that approaches human missions to the Red Planet in this way is known as the Mars Direct approach.[1] Here is how it would work.

The Mission

At an early launch opportunity, for example 2022, a single heavy lift booster with a capability equal to that of the Saturn V used during the Apollo programme (1967–72) is launched off Cape Canaveral and uses its upper stage to throw a 40-tonne unmanned payload onto a trajectory to Mars. Arriving at Mars eight months later, it uses friction between its aeroshield and Mars's atmosphere to brake itself into orbit around Mars, and then lands with the help of a parachute. This payload is the Earth Return Vehicle (ERV), and it flies out to Mars with its two methane/oxygen-driven rocket propulsion stages unfuelled. It also has with it 6 tonnes of liquid hydrogen cargo, a 100-kilowatt nuclear reactor mounted in the back of a methane/oxygen-driven light truck, a small set of compressors and an automated chemical processing unit, and a few small scientific rovers.

As soon as landing is accomplished, the truck is telerobotically driven a few hundred metres away from the site, and the reactor is deployed to provide power to the compressors and chemical processing unit. The hydrogen brought from Earth can be quickly reacted with the Martian atmosphere, which is 95 per cent carbon dioxide gas (CO_2), to produce methane and water, and this eliminates the need for long-term storage of cryogenic hydrogen on the planet's surface. The methane so produced is liquefied and stored, while the water is electrolysed to produce oxygen, which is stored, and hydrogen, which is recycled through the methanator. Ultimately, these two reactions (methanation and water electrolysis) produce 24 tonnes of methane and 48 tonnes of oxygen. Since this is not enough oxygen to burn the methane



NASA, OPPORTUNITY MARS EXPLORATION ROVER (MER), 2003
Artist's concept. Though a great technical success, in 10 years Opportunity has only travelled a distance that a human explorer could transverse in one day.

at its optimal mixture ratio, an additional 36 tonnes of oxygen is produced via direct dissociation of Martian CO_2.

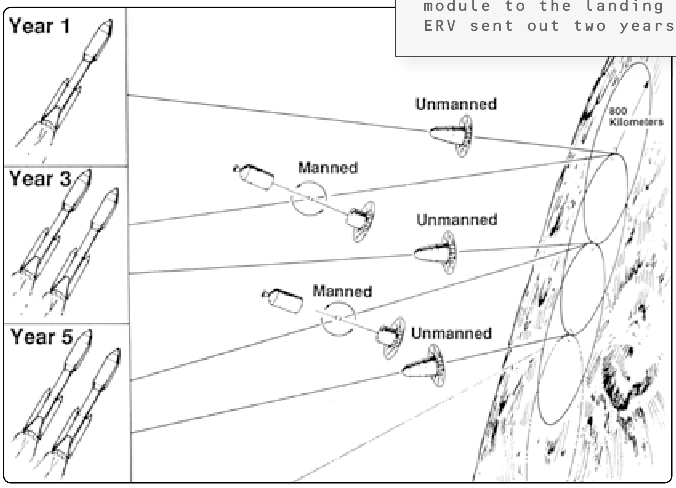
The entire process takes 10 months, at the conclusion of which a total of 108 tonnes of methane/oxygen bipropellant will have been generated. This represents a leverage of 18:1 of Martian propellant produced compared to the hydrogen brought from Earth needed to create it. Ninety-six tonnes of the bipropellant will be used to fuel the ERV, while 12 tonnes are available to support the use of high-powered, chemically fuelled long-range ground vehicles. Large additional stockpiles of oxygen can also be produced, both for breathing and for turning into water by combination with hydrogen brought from Earth. Since water is 89 per cent oxygen (by weight), and since the larger part of most foodstuffs is water, this greatly reduces the amount of life-support consumables that need to be hauled from Earth.

The propellant production having been successfully completed, in 2024 two more boosters lift off the Cape and throw their 40-tonne payloads towards Mars. One of the payloads is an unmanned fuel-factory/ERV just like the one launched in 2022; the other is a habitation module containing a crew of four, a mixture of whole food and dehydrated provisions sufficient for three years, and a pressurised methane/oxygen-driven ground rover. On the way out to Mars, artificial gravity can be provided to the crew by extending a tether between the habitat and the burnt-out booster upper stage, and spinning the assembly. Upon arrival, the manned craft drops the tether, aero-brakes, and then lands at the 2022 landing site where a fully fuelled ERV and fully characterised and beaconed landing site await it.

With the help of such navigational aids, the crew should be able to land right on the spot; but if the landing is off course by tens or even hundreds of kilometres, the crew can still achieve the surface rendezvous by driving over in their rover; if they are off by thousands of kilometres, the second ERV provides a backup. However, assuming the landing and rendezvous at site number 1 is achieved as planned, the second ERV will land several hundred kilometres away to start making propellant for the 2026 mission, which in turn will fly out with an additional ERV to open up Mars landing site number 3. Thus every other year, two heavy lift boosters are launched: one to land a crew, and the other to prepare a site for the next mission, for an average launch rate of just one booster per year to pursue a continuing programme of Mars exploration. This is clearly affordable. In effect, this pioneer approach removes the manned Mars mission from the realm of mega-fantasy and reduces it to practice as a task of comparable difficulty to that faced in launching the Apollo missions to the Moon.

ROBERT MURRAY/MARS SOCIETY, MARS DIRECT MISSION BASE, 1998
The hab module is shown on the left, and the Earth Return Vehicle to the right.

ROBERT MURRAY/MARS SOCIETY, MARS DIRECT MISSION SEQUENCE, 1998
Every two years, two boosters are launched to Mars. One sends an unmanned Earth Return Vehicle (ERV), the other sends a crewed hab module to the landing site of the ERV sent out two years earlier.



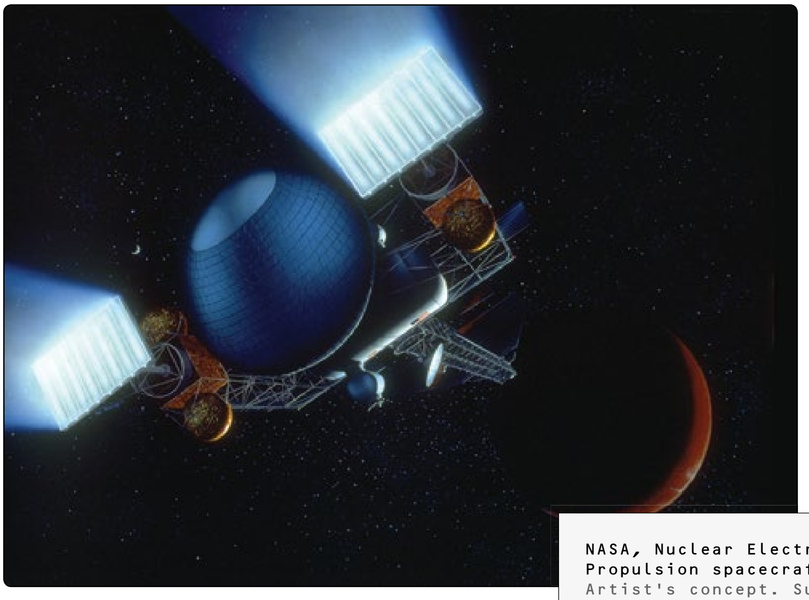
The crew will stay on the surface for one and a half years, taking advantage of the mobility afforded by the high-powered chemically driven ground vehicles to accomplish a great deal of surface exploration. With a 12-tonne surface fuel stockpile, they have the capability for over 24,000 kilometres' (14,900 miles') worth of traverse before they leave, giving them the kind of mobility necessary to conduct a serious search for evidence of past or present life on Mars – an investigation key to revealing whether life is a phenomenon unique to Earth or general throughout the universe. Since no-one has been left in orbit, the entire crew will have available to them the natural gravity and protection against cosmic rays and solar radiation afforded by the Martian environment, and thus there will not be the strong driver for a quick return to Earth that plagues conventional Mars mission plans based upon orbiting mother ships with small landing parties. At the conclusion of their stay, the crew returns to Earth in a direct flight from the Martian surface in the ERV. As the series of missions progresses, a string of small bases is left behind on the Martian surface, opening up broad stretches of territory to human cognisance.

Colonising Mars

Mars is not just a scientific curiosity, it is a resource-rich world with a surface area equal to all the continents of Earth combined.[2] As hostile as it may seem, the only thing standing between Mars and habitability is the need to develop a certain amount of Red Planet knowhow. This can and will be done by those who go there first to explore.

Among extraterrestrial bodies in our solar system, Mars is singular in that it possesses all the raw materials required to support not only life, but also a new branch of human civilisation. This uniqueness is illustrated most clearly if we contrast Mars with the Earth's Moon, the most frequently cited alternative location for extraterrestrial human colonisation.[3]

In contrast to the Moon, Mars is rich in carbon, nitrogen, hydrogen and oxygen, all in biologically readily accessible forms such as carbon dioxide gas, nitrogen gas, and water ice and permafrost. Carbon, nitrogen and hydrogen are only present on the Moon in parts-per-million quantities. Oxygen is abundant on the Moon, but only in tightly bound oxides such as silicon dioxide (SiO_2), ferrous oxide (Fe_2O_3), magnesium oxide (MgO), and alumina oxide (Al_2O_3), which require very high-energy processes to reduce. Current knowledge indicates that if Mars were smooth and all its ice and permafrost melted into liquid water, the entire planet would be covered with an ocean over 100 metres (330 feet) deep. This contrasts strongly with the Moon, which is so dry that if concrete were found there, lunar colonists would mine it to get the water out. Thus, if plants could be



NASA, Nuclear Electric Propulsion spacecraft, 2002
Artist's concept. Such gigantic futuristic concepts are unnecessary to send humans to Mars.

Robert Murray/Mars Society, Building the Base, 2001
As landings continue, multiple hab modules can be connected to create a base.

grown in greenhouses on the Moon (an unlikely proposition, as we have seen), most of their biomass material would have to be imported.[4]

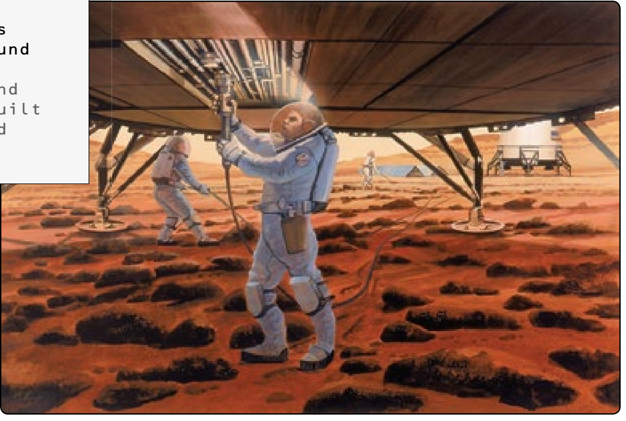
The Moon is also deficient in about half the metals of interest to industrial society (copper, for example), as well as many other elements such as sulphur and phosphorus. Mars has every required element in abundance. Moreover, on Mars, as on Earth, hydrologic and volcanic processes have occurred that are likely to have consolidated various elements into local concentrations of high-grade mineral ore. Indeed, the geologic history of Mars has been compared to that of Africa, with very optimistic inferences as to its mineral wealth implied as a corollary. In contrast, the Moon has had virtually no history of water or volcanic action, with the result that it is basically composed of trash rocks with very little differentiation into ores that represent useful concentrations of anything interesting.

You can generate power on either the Moon or Mars with solar panels, and here the advantages of the Moon's clearer skies and closer proximity to the Sun than Mars roughly balance the disadvantage of large energy storage requirements created by the Moon's 28-day light/dark cycle. But if you wish to manufacture solar panels, so as to create a self-expanding power base, Mars holds an enormous advantage, as only Mars possesses the large supplies of carbon and hydrogen needed to produce the pure silicon required for photovoltaic panels and other electronics. In addition, Mars has the potential for wind-generated power while the Moon clearly does not. But both solar and wind power offer relatively modest potential – tens or at most hundreds of kilowatts here or there. To create a vibrant civilisation, a richer power base is needed, and this Mars has both in the short and medium term in the form of its geothermal power resources, which offer potential for a large number of locally created electricity-generating stations in the 10 MWe (10,000 kilowatt) class. In the long term, Mars will enjoy a power-rich economy based upon exploitation of its large domestic resources of deuterium fuel for fusion reactors. Deuterium is five times more common on Mars than it is on Earth, and tens of thousands of times more common on Mars than on the Moon.

However, the biggest problem with the Moon, as with all other airless planetary bodies and proposed artificial free-space colonies, is that sunlight is not available in a form useful for growing crops. A single acre of plants on Earth requires 4 MW of sunlight power, a square kilometre needs 1,000 MW. The entire world put together does not produce enough electric power to illuminate the farms of the state of Rhode Island, that agricultural giant. Growing crops with electrically generated light is just economically hopeless. But you cannot

Robert Murray/Mars Society, Mechanics on the Red Planet, 2001
top: Servicing equipment at a Mars base.

Robert Murray/Mars Society, Underground Vaults, 2001
bottom: Underground vaults could be built to create expanded habitation space.



On Mars there is an atmosphere thick enough to protect crops grown on the surface from solar flares. Therefore, thin-walled inflatable plastic greenhouses protected by unpressurised UV-resistant hard-plastic shield domes can be used to rapidly create cropland on the surface.

use natural sunlight on the Moon or any other airless body in space unless you put walls on the greenhouse thick enough to shield out solar flares, a requirement that enormously increases the expense of creating crop land. Even if you did that, it would not do you any good on the Moon, because plants will not grow in a light/dark cycle lasting 28 days.

On Mars there is an atmosphere thick enough to protect crops grown on the surface from solar flares. Therefore, thin-walled inflatable plastic greenhouses protected by unpressurised UV-resistant hard-plastic shield domes can be used to rapidly create cropland on the surface. Even without the problems of solar flares and a month-long diurnal cycle, such simple greenhouses would be impractical on the Moon because they would create unbearably high temperatures. On Mars, in contrast, the strong greenhouse effect created by such domes would be precisely what is necessary to produce a temperate climate inside. Such domes up to 50 metres (160 feet) in diameter are light enough to be transported from Earth initially, and later on they can be manufactured on Mars out of indigenous materials. Because all the resources to make plastics exist on Mars, networks of such 50- to 100-metre domes could rapidly be manufactured and deployed, opening up large areas of the surface to both shirt-sleeve human habitation and agriculture.

Robert Murray/Mars Society, Farming on Mars, 2001
Greenhouse agriculture will serve to help make the base self-sufficient.

And that is just the beginning, because it will eventually be possible for humans to substantially thicken Mars's atmosphere by forcing the regolith to outgas its contents through a deliberate programme of artificially induced global warming. Once that has been accomplished, the habitation domes could be virtually any size, as they would not have to sustain a pressure differential between their interior and exterior. In fact, once that has been done, it will be possible to raise specially bred crops outside the domes.

The point to be made is that unlike colonists on any other known extraterrestrial body, Martian colonists will be able to live on the surface, not in tunnels, and move about freely and grow crops in the light of day. Mars is a place where humans can live and multiply to large numbers, supporting themselves with products of every description made out of indigenous materials. Mars is thus a place where an actual civilisation, not just a mining or scientific outpost, can be developed. And significantly for interplanetary commerce supporting operations in the resource-rich asteroid belt, Mars and Earth are the only two locations in the solar system where humans will be able to grow crops for export.

The New World

Mars is the New World. Someday millions of people will live there. What language will they speak? What values and traditions will they cherish, to spread from there as humanity continues to move out into the solar system and beyond? When they look back on our time, will any of our other actions compare in value to what we do today to bring their society into being?

We now have the opportunity to be the founders, the parents and shapers of a new and dynamic branch of the human family, and by so doing put our stamp upon the future. It is a privilege not to be disdained lightly.

Notes

1. Robert Zubrin with Richard Wagner, *The Case for Mars: The Plan to Settle the Red Planet and Why We Must*, Free Press (New York), 2nd edn, 2011.
2. Hugh H Kieffer, Bruce M Jakosky, Conway Snyder and Mildred Shapley Matthews, *Mars*, University of Arizona Press (Tucson and London), 1992.
3. John S Lewis, Mildred S Matthews and Mary L Guerrieri, *Resources of Near Earth Space*, University of Arizona Press (Tucson and London) 1993.
4. Grant Heiken, David Vaniman and Bevan M French, *Lunar Sourcebook*, Cambridge University Press (Cambridge), 1991.

Robert Murray/Mars Society, New Life on a New World, 2001
Over time, the Mars base will grow into a true settlement, the beginning of a new branch of human civilisation.