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A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach

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Chapter 1
Introduction

The world needs a new and better paradigm for long distance, long duration space travel. Look at almost any mission concept, and one will see a metal capsule launched atop a massive rocket. This approach enabled humans to reach the Moon (barely), but the type of craft is prohibitively expensive, not reusable, and uncomfortable.

What is needed is a spacecraft that has some of the features of the stagecoaches of the Old West—a spacecraft that is simple, durable, and that can be serviced and refueled in flight. The authors call them spacecoaches, as a nod to the stagecoaches of yesteryear (Fig. 1.1).

When the authors first wrote about spacecoaches in the *Journal of the British Interplanetary Society*[1] they asked the question, "What if a spacecraft were composed mostly of water?" This question is relevant because water is so essential to life support, is easily handled, and because of its potential to reduce the deadweight in a ship by replacing non-consumable structures and propellant with water.

This approach is not only viable but offers synergies that can reduce costs 10× or more compared to conventional spacecraft, because the water can be used for so many purposes in flight. Spacecoaches will be fully reusable interplanetary spacecraft that can be built and flown using technology available today, and that properly maintained and upgraded will fly for many generations.

The basic idea behind the spacecoach is simple; build a spacecraft whose mass is mostly water or water-rich material at the beginning of its journey. This water is used for many purposes throughout flight, such as radiation shielding, a heat sink, life support and for electric propulsion.

[1]"A Reference Design for a Simple, Durable and Reusable Interplanetary Spacecraft," *Journal of the British Interplanetary Society, Vol 63, pp 108-119, 2010*

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Fig. 1.1 "Stagecoach in Winter," painted by Nick Eggenhofer (1897–1985)

Several decades ago researchers measured the performance of microwave electrothermal engines that superheat water vapor to produce thrust. These devices are similar in principle to microwave ovens in that microwaves are used to heat water. Microwave engines use a large amount of energy to superheat a comparatively small flow of water, producing a plasma. More recent research shows that other types of electric engines, such as electrodeless Lorentz force thrusters, can operate efficiently with water, as well as carbon and nitrogen-rich fluids.

With a conventional spacecraft, consumable water and food rations are a dead weight, weight that must be pushed along by non-consumable propellant. In a spacecoach, the water itself is the propellant, offering the opportunity to use consumable water as useful propellant after consumption. Before the water is consumed by the engines, it can be used for many other purposes, from life support to radiation shielding, which eliminates even more dead weight. We calculate that more than 90 % of the ship's initial mass can be water or water-rich material, mass that is eventually used to push the ship toward its destination.

Using water in this way offers a radical conception for spacecraft design. What would have been cost prohibitive in a conventional rocket ship, like agriculture or aquaculture, becomes straightforward in a water-based ship. Water is also essential to life support, from radiation shielding, and temperature control to oxygen generation. These things that are also dead weight become working mass in a spacecoach.

Some spacecoaches will fly out to become permanent settlements at their destinations. Because they will never have to enter a planet's atmosphere, they can be any size or shape, and can continuously adjust their course using solar electric propulsion rather than high thrust chemical rockets. Smaller chemical rockets can be used for maneuvering and docking. Spacecoaches can be upgraded as they fly, for example, to add larger or more efficient solar power arrays, or to replace first generation engines with new and improved units. These ships can be built within a decade and launched using technology available today, yet be continually upgraded to improve performance and to replace worn or degraded components. Properly maintained, some of them might fly for generations.

These spacecraft will enable humans to reach interesting destinations throughout the inner Solar System, at costs far less than for conventional missions. The dwarf planet Ceres is an especially interesting destination and will be discussed in detail later in this book. But rather than build a ship around a specific mission, spacecoaches will be multi-mission ships. As they are upgraded with better power plants and engines, they will increase their range and capabilities to sail to new ports of call.

These spacecraft can be built using existing technology and launch platforms. The authors modeled missions using the SpaceX Falcon 9 Heavy to estimate payload capacity and overall costs. The first generation ships will not go straight to Mars. Most likely they will fly simulated missions much closer to home, and then once operators have gained experience and have upgraded key systems, they will venture further out to cis-lunar space and far beyond. Downscaled models will be used to inexpensively flight test spacecoaches before full-scale crewed versions are flown.

Beyond enabling humanity to venture past the Moon, spacecoaches will be the basis for a real world star fleet. It may start with just one or two modest ships, but because these ships can be upgraded incrementally, they may fly for generations. The fleet and the places it can reach will grow. That first prototype could be flying in just a few years, and perhaps it will still be sailing as a tourist destination, like the USS Constitution, centuries from now.

Assumptions

While researching the spacecoach concept, the authors made a number of assumptions to eliminate dependencies on not yet developed materials or technologies. All of the component systems and technologies exist today, and if not already flown in space, can plausibly be developed via low-risk, low-cost pathways.

Among the assumptions made:

1. No nuclear energy. While nuclear power for spacecraft is possible (see NERVA), this is not currently practical due to public apprehension and political resistance. The reader can assume large solar photovoltaic (PV) arrays are

the primary power source for early generation spacecoaches, and that solar PV technology will steadily improve in terms of efficiency and power density in coming years and decades.

2. No reusable rocket launchers. The reference design's modules are sized to fit within existing launch systems such as SpaceX Falcon 9 and Falcon 9 Heavy, which have known lift capacity and published launch costs. (SpaceX advertises delivery to low Earth orbit at $1700 per kilogram via Falcon 9 Heavy.) The authors use present-day published launch costs for economic models, and do not make assumptions about future reductions in ground-LEO launch costs.
3. No cryogenic fuels for chemical propulsion beyond LEO. The reference design eliminates the use of cryogenic fuels to simplify chemical propulsion systems as much as possible. Spacecoaches will use solar-electric propulsion with water and possibly waste gases as reaction mass for low-thrust, long-duration operation and non-cryogenic chemical propulsion for short duration maneuvers such as orbital capture, burns meant to exploit the Oberth effect, etc. Any chemical propellants should be stored at room temperature (e.g., kerosene, nitrous oxide, compressed gases).
4. Water-based solar electric propulsion. During cruise with solar-electric propulsion, the craft will process water in electrodeless engines. Microwave electrothermal engines are used as a baseline technology in the JBIS paper. It may also be possible to use similar engine types, such as RF arc jets, Electrodeless Lorentz force thrusters, or Hall effect thrusters. These engines will be developed and tested in ground-based vacuum chambers, a low-cost, low-risk development pathway prior to in-flight testing. Existing engines will also be tested with water, CO_2 and gasified waste to evaluate their suitability for spacecoaches. These engines are also small, and can be clustered in large arrays to increase thrust. Their small size makes them easy to repair, replace or upgrade, and also provides safety through redundancy.
5. Crew serviceable engines. The reference design calls for solar-electric engines to be mounted within a compartment that can be sealed and pressurized to enable the crew to service the engines in a shirtsleeve environment, for example to replace burned out units or ablated parts without conducting a spacewalk. Provided the wear/failure prone components are lightweight, this eliminates the need to design them for extreme reliability, as they can be periodically replaced, like light bulbs. The design also calls for standardized enclosures, electrical and propellant fittings so that as improved units become available, they can be installed easily within the existing engine enclosure.
6. Steam propulsion for low gravity sites. While steam rockets (hot water rockets) are not usable for high gravity sites, they are a simple way to generate thrust for landing on low gravity bodies such as the Martian moons. This doesn't rule out other types of engines, but for the purposes of this book, the authors want to explore the maximum extent to which water can be used.
7. No atmospheric operations. Spacecoaches are purely ships of space. These craft never enter a planet's atmosphere. They only travel between orbits, and

to low gravity sites such as the Martian moons (whose escape velocity is only a few meters per second). Landers and re-entry craft will be designed separately and coupled to spacecoaches on the missions where they are needed and left in parking orbits when not needed.

8. Minimal EVA (spacewalk) requirement. Once assembled, the spacecraft is designed to minimize the requirement for extravehicular activity. For example, high gain antennae and other communications gear might be located inside a compartment made of material that is transparent to microwave radiation. This would enable the crew to service this equipment without venturing outside, and would also permit the use of equipment that does not need to be hardened for the space environment.
9. Empty hull design. The craft are designed as bare bones vessels, with only the essential structural elements, power bus, etc., as permanent elements. This is done to maximize the ease of in-flight repair, incremental system upgrades, and mission specific configuration. All other elements are brought on board as needed, and when not needed are left at the terminus of the mission to minimize excess payload.
10. Passive/manual modes of operation. Wherever possible, system elements are designed with passive or manual modes of operation to provide fail-safe options. For example, spacecoaches will be loaded with a dilute mixture of water and hydrogen peroxide, which decomposes to water and oxygen. This provides a fail-safe, non-mechanical mode of oxygen generation, to enable the crew to survive a deep space equivalent of an *Apollo 13* scenario.

What are the benefits of a water-based design? The goal is to design ships that are durable, easily serviced, and simple enough that they are more like wagons to operate, small enough that they can be reached by existing launch platforms, and cheap enough that both spacefaring nations and private operators will be able to afford them.

Chapter 2
Water

Water is central to the design of spacecoaches. Conventional spacecraft based on the rocket and capsule paradigm treat water and other crew consumables as dead weight. In the spacecoach, water is the propellant, and because it is eventually used as propellant (we'll talk about propulsion in Chap. 3), it frees us to consider radically different, radically safer spacecraft concepts.

Water is a versatile material and can perform many functions prior to being consumed by the engines to produce thrust. Here are some of its other uses.

Radiation Shielding

Water is comparable to lead, on a mass basis, in terms of radiation shielding. Simply by storing water in compartments surrounding the areas where the crew spends the most time, spacecoaches will provide ample radiation shielding for their crews. In a radiation emergency, such as a solar flare event, additional water can be pumped into bladder-like shelters to provide additional shielding.

Heat Management

Due to the high thermal mass of water, it can also soak up excess heat when the engines or other systems are producing more heat than can be radiated away. This provides a stabilizing temperature regime compared to metal craft that must be rotated to relieve thermal stress. It can also soak up excess heat when the engines or other systems are producing more heat than can be radiated away. This heat management system will be mechanically simple and reliable.

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Life Support

It is the basis for a multiply redundant and fail-safe life support system, which will be discussed in detail in Chap. 5.

Consumables

It is a crew consumable, as both drinking water, and water-rich food. This water can be reclaimed via condensation, and from urine, subsequently to be consumed by the engines. In a spacecoach, even orange juice (or beer!) counts as propellant. In addition to human consumption, water is an important input for agriculture and biofuel generation.

Debris Shielding

It can be used for debris shielding, especially when frozen to form pykrete.[1,2] Pykrete is formed by freezing water and fibrous material. During World War II, the British investigated building an aircraft carrier out of ice mixed with wood pulp. This combination of water and fibrous material, once frozen, is as strong as concrete. Potentially, it is an excellent material for self-healing debris shielding. Gelatinous material, similar to ballistic gel, could also be incorporated into the design to further improve self-healing capability, at least for small debris strikes.

In a ship where water is abundant, agriculture and aquaculture both become possible, enabling crews on long journeys to grow at least some of their food *en route*, and also recycle carbon dioxide. The first ships probably will not be fully self-sustaining, but they'll be able to experiment with space agriculture and aquaculture early on, and gradually increase this capability with experience. Creature comforts that would be unthinkable in a conventional ship (hot baths anyone?) also become possible in a spacecoach.

Water is also important to the design because it is ubiquitous throughout the Solar System. There are many low gravity sites—the dwarf planet Ceres is an especially interesting place—that contain immense reservoirs of water-ice. Eventually it should become possible to extract water from sources like this and transport it to refuel spacecoaches wherever they fly. When spacecraft reach Jupiter, its icy moons offer a virtually inexhaustible source of water.

[1]Website (accessed April 6th, 2015), http://en.wikipedia.org/wiki/Pykrete.

[2]http://www.sciencedirect.com/science/article/pii/S0261306914008280.

And that is the ultimate goal of a system like this, to reach the point where we can scavenge most of the raw materials we need, especially water, to establish a continual supply chain and permanent settlements throughout the Solar System.

The Effect of Water on Crew Consumables

For a conventional spacecraft using cryo-propellants, the life support consumables are simply dead weight that must be accelerated and decelerated, requiring energy from the fuel or propellant. Given that deep space missions will require large quantities of materials for life support—e.g., water, food and oxygen—the spacecraft designer will try to limit their consumption to reduce the propellant required. An average person in the United States uses about 200 kg (440 pounds) of water per day, mostly for bathing and flushing the toilet.

When water is just a consumable, the mass cost is extremely large for deep space missions, and extremely costly if sourced from Earth using current rocket technology. NASA has determined that without recycling, drinking, water in foods and minimal toilet and bathing requires about 14 kg each day. The International Space Station reduces water demand by recycling water from bathing, waste recycling and respired water. This is about 85 % efficient in recreating water pure enough for drinking. This reduces the water demand to less than 2 ½ kg of water a day.[3]

For a 500-day Mars flyby mission that reduces the amount of water for an astronaut from 7 tons (7000 kg) to 1 ¼ tons (1250 kg). Even though this comes at a mass cost for the recycler, the overall saving in mass is very significant. There may be a certain "yuck factor" in drinking water recycled from the toilet, but in fact, properly treated, it can be purified to be cleaner than the water that comes from the municipal water supply.[4] In addition to water, the astronauts will need food and oxygen, estimated by NASA to require 1.8 and 0.84 kg per day, respectively. This would add 1.3 tons (1300 kg) for each astronaut on a roundtrip mission to Mars orbit and/or the Martian moons.

Ohio State University[5] recently estimated a mass budget for the proposed 2-person Mars flyby mission, Inspiration Mars,[6] estimating a 3-ton life support requirement of food, water and oxygen. This is broadly in line with a 5.1-ton requirement using NASA's guidelines, although it suggests even more minimal

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[3]National Aeronautics and Space Administration, "Closing the Loop: Recycling Water and Air in Space", (n.d.): n. pag. NASA. Web. http://www.nasa.gov/pdf/146558main_RecyclingEDA(final)%204_10_06.pdf.

[4]"Reclaimed Water." Wikipedia. Wikimedia Foundation, n.d. Web. 03 July 2014.

[5]Gilligan, R et al. "Inspiration Mars International Student Design Competition" (n.d.): Ohio State University Web http://members.marssociety.org/inspiration-mars/semifinalists/ARES-M.pdf.

[6]Inspiration Mars website, http://www.inspirationmars.org.

water use. As Mary Roach so graphically wrote in *Packing for Mars,* after just two weeks in the Gemini spacecraft the astronauts' undergarments were literally rotting.[7] A 500-day camping trip in a spacecraft with no way to wash would be extremely uncomfortable. Clearly having the ability to create special chambers for laundry or personal washing would be a morale booster.

Because the spacecoach uses water for propellant, this water can be used prior to expulsion for consumption by the crew. Depending on factors such as engine efficiency and length of engine burn, the crew can use far larger quantities of water than a minimal ration in a conventional spacecraft. Even consumables such as frozen food and beverages count as propellant in a spacecoach, as the water content can be reclaimed from condensation and urine. This conversion of dead weight to working mass, in combination with modestly improved engine efficiency, results in order of magnitude cost reductions compared to conventional spacecraft.

[7]Roach, Mary. Packing for Mars: The Curious Science of Life in the Void. New York: W.W. Norton, 2010. Print.

Chapter 3
Propulsion

The central premise of the spacecoach is to augment or replace conventional chemical rockets with solar electric engines that generate thrust by using water as reaction mass and are powered by a large solar photovoltaic array.

Advantages and Disadvantages of Spacecoach Propulsion

The spacecoach's mode of propulsion has several advantages and disadvantages relative to chemical rockets.

Dead Weight to Working Mass

As noted before, the first and most important benefit of an engine that uses water as propellant is that it turns dead weight (water, crew consumables, etc.) into working mass. This has a radical and positive impact on mission economics.

Safety

Solar electric engines are mechanically simple and inherently safe compared to chemical rockets. They can be built as an array of small units that work in parallel, providing redundancy, so the failure of one unit or one electric power bus has a negligible effect overall. They won't explode and, if designed properly, can be serviced by crews in flight without venturing outside the spacecraft. In addition, the huge amount of water on the ship provides for excellent life support safety margins.

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Fuel Efficiency

Solar electric engines are more fuel efficient than chemical rockets because they eject their exhaust at a much higher velocity. On the low end, these engines produce specific impulse of 800 s, and it's expected that performance in the range of 1500–3000 s, still well below that attained by ion drives, should be attainable by modifying other electric engine types, such as electrodeless Lorentz force (ELF) thrusters, to utilize water. This is an important point, as the authors do not assume performance anywhere near the upper end of the performance envelope for electric propulsion (e.g., VASIMR) (Fig. 3.1).

Refueling

Water is easily handled at room temperature and pressure, making it easy to design refuelable systems. It's much more complicated to design a refuelable chemical rocket, especially one that uses hazardous or cryogenic fuels such as liquid oxygen. With water, it is as simple as hauling plastic containers on board during a re-supply hookup if a hose bib is broken. An orbital fuel depot would be little more than a tank of water.

Upgradability

Spacecoaches will not be one-time, one-off ships, but will be designed with standard fittings and interchangeable parts so they can be upgraded over time. Engines, for example, might be upgraded periodically to improve their performance, while older units can be transferred to spacecoaches that do not need as much range or performance.

These are significant advantages, but solar electric engines have one big disadvantage compared to chemical rockets. They require large amounts of electrical power to generate useful amounts of thrust, and cannot be used for high impulse maneuvers where a large velocity change is needed in a short period of time, such as to exploit the Oberth effect (Table 3.1).

Solar electric propulsion makes the most sense when gradual acceleration or deceleration is required. Chemical propulsion makes the most sense when a large change in velocity in a short time is needed (for example, to quickly go from low Earth orbit to geostationary orbit to minimize time spent in the Van Allen radiation belts). The goal then is to minimize the need for chemical rockets, and rely on solar electric/water propulsion wherever possible. For an excellent comparison of electric and chemical propulsion, the authors recommend a paper ("Low Thrust

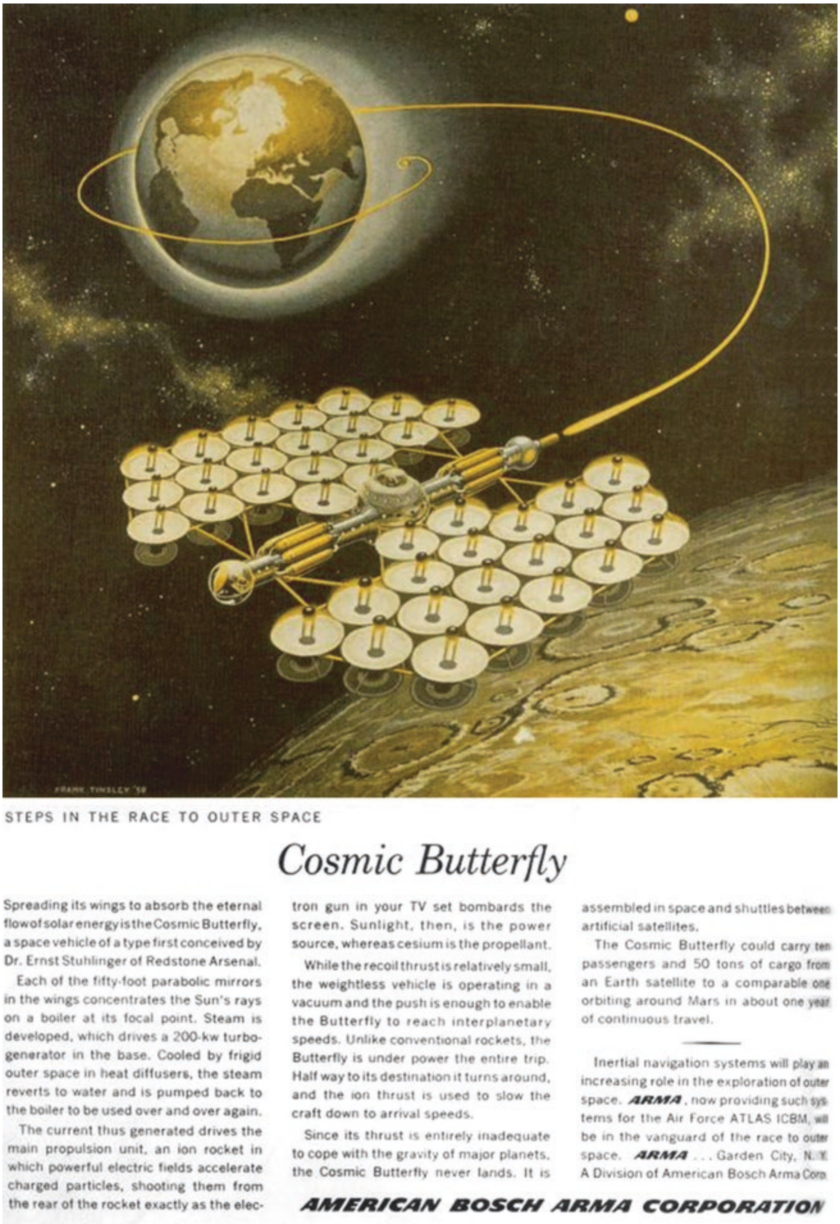

Fig. 3.1 An early concept for a crewed solar electric "sun-ship," proposed by Dr. Ernst Stuhlinger in 1954. The design used solar thermal collectors to power steam turbines that in turn powered ion drives that used cesium as propellant. Although the spacecoach differs in using photovoltaics as a power source and water as propellant, it is worth noting that the idea of crewed solar electric vehicles has been around since the beginning of space exploration. *Image credit* Frank Tinsley/American Bosch Arma Corporation ("A Reference Design for a Simple, Durable and Reusable Interplanetary Spacecraft," *Journal of the British Interplanetary Society* Vol 63, pp 108–119, 2010. Website accessed April 6th, 2015)

Table 3.1 Comparison of possible maneuvers by propulsion type

Type of maneuver	Chemical rocket	Electric engine
Efficient gradual orbit change (increase/decrease altitude)	N	Y
Gradually accelerate/decelerate over time	N	Y
Low energy orbit transfer (Hohmann transfer)	Y	It depends, but if the engine runtime is short relative to overall flight time, it can approximate the performance of an interplanetary Hohmann transfer
Orbit capture/escape	Y	Y, but requires greater delta-v compared to chemical burns that exploit the Oberth effect
Ascent/descent to surface	Y	N, except possibly very low gravity sites such as asteroids
Emergency course change to avoid debris	Y	It depends on how much time is available, probably a good idea to have some chemical propulsion capability for this reason

Transfer From LEO to GEO: Comparison of Electric To Chemical Propulsion") by Sarah Stansbury of the Colorado Center For Astrophysics Research.[1]

The Rocket Equation

The rocket equation enables spacecoach designers to calculate how much delta-v a ship can generate given just three parameters: the specific impulse of the rocket motor, the initial mass of the ship, and the final mass of the ship after the propellant has been consumed. The equation is expressed as:

$$\delta v = v_{exhaust} \times \ln\frac{m_0}{m_1} = 9.8 \times I_{sp} \times \ln\frac{m_{initial}}{m_{final}}$$

There are only two ways to improve the performance of a rocket in terms of delta-v. One is to increase the exhaust velocity from the rocket. Performance is directly related to this parameter, so doubling the rocket's specific impulse doubles the delta-v, all other parameters being equal. This is why electric engines are so attractive, because even the most inefficient engines have twice the specific impulse of chemical rockets, and many systems such as ion drives and Hall effect thrusters are ten times better.

[1]"Low Thrust Transfer From LEO to GEO: Comparison of Electric To Chemical Propulsion", Stansbury, Sarah, Colorado Center For Astrophysics Research, December 10th, 2009, http://ccar.colorado.edu/asen5050/projects/projects_2009/stansbury/.

Another way to maximize delta-v is to increase the ratio of propellant relative to the "dry" mass of the ship. This is not a very promising option because (1) it cuts into payload, and (2) the returns diminish dramatically, because this term in the equation is given by the natural logarithm of the initial mass divided by the final mass. Simply put, this means that increasing the propellant mass from 90 to 99 % of the total spaceship mass, the velocity would merely be doubled and not increase tenfold, as might be naively expected.

The Spacecoach Equation

When waste flows from consumables can be repurposed as propellant, one can re-write the rocket equation to calculate the engine performance required for a mission as a function of the ship's empty mass, crew size and mission profile. This equation is as follows:

$$\delta v = 9.8 \times I_{sp} \times \ln\left(\frac{m_{hull} + (n_{crew} \times t_{mission} \times m_{ration})}{m_{hull} + m_{waste}}\right)$$

Thus, the engine performance for a desired mission is given by:

$$I_{sp} = \frac{\delta v}{9.8 \times \ln\left(\frac{m_{hull} + (n_{crew} \times t_{mission} \times m_{ration})}{m_{hull} + m_{waste}}\right)}$$

This equation also predicts the minimum mass budget for a mission. If the engines perform at or above the required specific impulse, additional mass savings are not possible, as the consumables will need to be on board anyway. It is a bit counterintuitive, but the spacecoach architecture actually makes it easier to plan long duration, high delta-v missions with large crews because longer missions require more consumables, and therefore provide more propellant to work with. In a conventional mission architecture, long duration missions' consumable budgets force even larger propellant budgets, which lead to high costs.

Electric Engines

Electric engines use power provided by a photovoltaic array to superheat or accelerate the plasma flowing through them. There are a variety of engines that can potentially be used in a spacecoach design, among them:

- resistojets
- microwave electrothermal thrusters
- RF arcjets
- electrodeless Lorentz force thrusters
- Hall effect thrusters

Resistojets

The simplest type of electric engine, resistojets combine a resistive heating element with an exhaust nozzle. Gas flows into the device, is heated to a high temperature, and ejected aftward. These engines are not widely used primarily because their specific impulse is low, only about 200 s, about half of what chemical rockets are capable of. However, they are potentially useful in spacecoaches for use in situations where one needs to make a relatively small velocity change in a relatively short period of time, such as to avoid orbital debris, during rendezvous or docking, etc. Although this role may also be fulfilled by supplemental chemical rockets, resistojets merit a mention, as they can use the same water as propellant.

Microwave Electrothermal Engines (MET)

Microwave electrothermal engines are similar in principle to a microwave oven. Instead of burning fuel and oxidizer in a chemical reaction to produce heat and thrust, they use microwave radiation, powered by an external source such as a solar array, to heat a small flow of propellant to extremely high temperatures. This superheated plasma is vented aftward at great speed, producing net thrust in the process. A 2002 paper by John Brandenberg and John Kline[2] nicely summarizes the performance of MET engines (Fig. 3.2).

The MET engine consists of a few basic elements:

- A hollow, resonant cavity that reflects microwaves (so they are trapped and deposit all of their energy in the propellant gas, similar to the way a microwave oven is designed).
- A source of microwave radiation, powered by an external power plant (typically a solar photovoltaic array).
- A heat exchanger, to transfer waste heat from the engine to the cold water flowing into the unit (thereby enabling most waste heat to be used to pre-heat and vaporize water, although losses to ionization will not be recoverable).
- A intake nozzle that blows a steady stream of water vapor into the cavity.
- An exhaust port or nozzle that directs superheated gas aftward.
- Optional: mechanical or electrostatic gimbaling apparatus, to enable the exhaust to be vectored (this would enable spacecraft designs that allow for both constant engine operation and artificial gravity via rotation).

[2]The MET (Microwave Electrothermal Thruster) Using Water Vapor Propellant, Brandenberg, John; Kline, John, http://www.marspapers.org/papers/Brandenburg_2002_1.pdf.

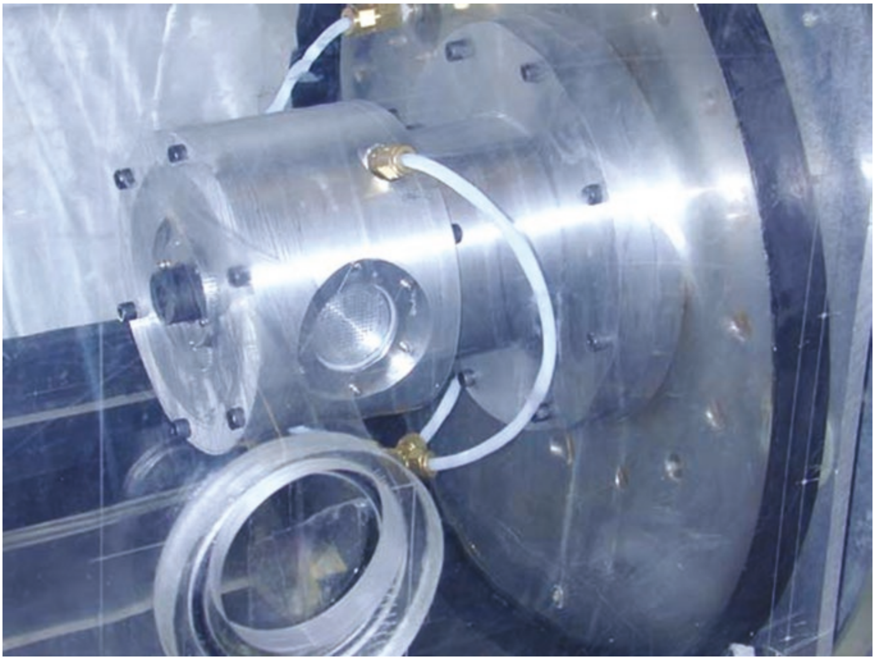

Fig. 3.2 A water-based MET engine is a relatively simple device. *Image credit* Electric Propulsion and Plasma Dynamics Lab, Princeton University, http://alfven.princeton.edu/projects/microwave_thruster.htm

RF Arc Jets

RF arc jets operate using a similar principle as METs, though the shape of the engine is somewhat different. In this design, a coil is wrapped around a hollow quartz chamber. The coil functions as an antenna, while the radiation emitted is absorbed by the propellant flowing through the chamber.

These engines have primarily been investigated for use in satellite station keeping, and have been tested with inert gases, hydrazine (to boost the performance of a conventional hydrazine motor) and ammonia. They should also work with water vapor, although this needs to be investigated further.

Electrodeless Lorentz Force Thrusters

Another promising candidate for a water-burning engine is the electrodeless Lorentz force (ELF) thruster. ELF engines have been tested with a variety of propellants, including both water and carbon dioxide. When tested with water, they generated a specific impulse of 1700 s, which, while on the low end of what

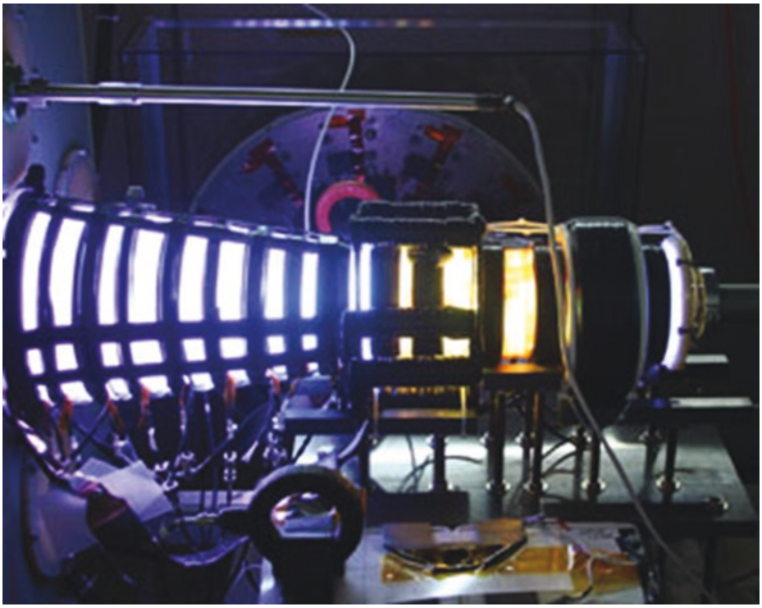

Fig. 3.3 Electroless Lorentz force thruster. (Image courtesy of Plasma Dynamics Lab, University of Washington, http://www.aa.washington.edu/research/plasmaDynamics/research.html)

electric propulsion systems are capable of, are several times more fuel efficient than chemical rockets (Fig. 3.3).

ELF thrusters are especially interesting because they can use a wide range of propellants.[3] They have been tested not only with water vapor but many other gases, including carbon dioxide. Omnivorous engines will be especially relevant to spacecoach design because they can process not only water but also waste gases, gasified solid waste, etc.

Helicon Double Layer Thrusters

Developed in Australia, helicon double layer thrusters are another promising engine technology that has specifically been tested with alternative propellants, including nitrogen, methane and ammonia.[4]

[3]"The Electrodeless Lorentz Force Thruster Experiment", Thomas E. Weber, A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, University of Washington, 2010.

[4]"An experimental investigation of alternative propellants for the helicon double layer thruster", C. Charles, R. W. Boswell, R. Laine, and P. MacLellan, Journal of Physics D: Applied Physics, Aug 21, 2008.

HDLTs are similar to microwave electrothermal thrusters, as they use RF energy to generate a plasma that is ejected aftward to produce thrust, although instead of producing thrust by heating the plasma, a strong electric field gradient is created within it to accelerate the plasma aftward, which results in significantly higher exhaust velocity (15–27 km/s, which equates to a specific impulse of 1500–2700 s). The engines are also mechanically simple, with no moving parts. In theory, they should work with virtually any propellant, and appear to be a good candidate for the spacecoach.

Hall Effect Thrusters

Hall effect thrusters produce thrust by accelerating ionized gas within a magnetic field. They have been used extensively for satellite station keeping and orbit changes, and can be considered a flight-ready technology. They typically produce thrust with a specific impulse ranging between 1500 and 3000 s (Fig. 3.4).

Although they have not been tested extensively with water vapor and other gases, there is no reason to assume they would not work with these propellants. If tests reveal that they do work reasonably well, they will be especially interesting due to their relatively high specific impulse, and the fact that they are a mature, flight-ready technology that is available more or less off the shelf.

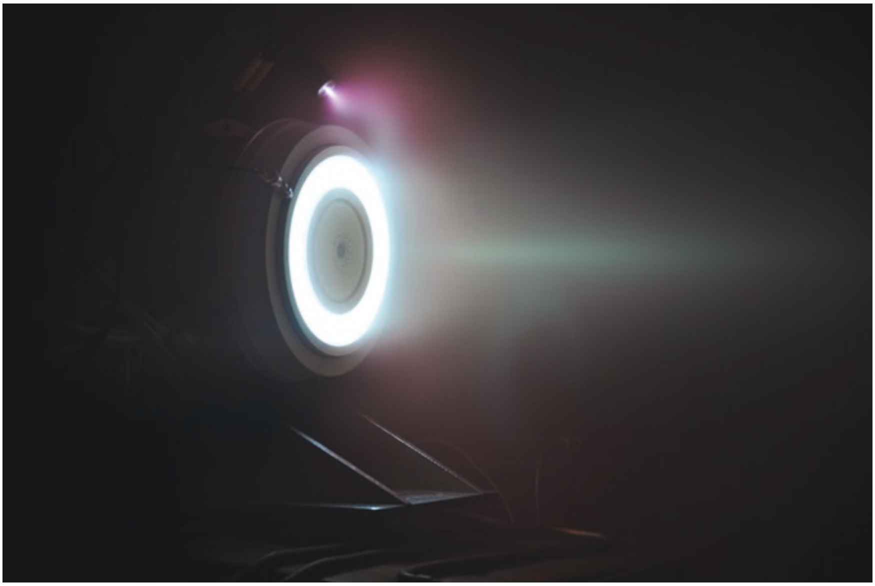

Fig. 3.4 T-140 Hall effect thruster test firing. (Image courtesy of High Power Electric Propulsion Laboratory ("T-140 Hall effect thruster test firing," High Power Electric Propulsion Laboratory, Georgia Tech, http://mwalker.gatech.edu/hpepl/thrusters/t-140-het/)

Table 3.2 Electric engine performance

Engine type	Specific impulse (s)	Tested w/Inert gases	Tested w/Water	Tested w/NH_3	Tested w/CO_2
Resistojet	200	Y	Y	Y	Unknown
RF arcjet	500–800	Y	Unknown	Unknown	Unknown
Microwave electrothermal	800–900	Y	Y	Unknown	Unknown
Electrodeless Lorentz force	1500–5000	Y	Y	Y	Y
Helicon double layer thruster	1500–2700	Y	Unknown	Y (and CH_4)	Unknown
Hall effect	1500–3000	Y	Unknown	Unknown	Unknown
VASIMR	Up to 30,000	Y	Y	Unknown	Unknown

An Overview of Electric Propulsion Systems

Available research shows that there are several types of engines that can be incorporated into a spacecoach. At this stage of the concept's development, it is premature to recommend a specific technology, but we can conclude that solar electric propulsion using water as the primary propellant should be feasible, and should deliver a specific impulse of 800 s (MET thruster) to 1700 s (ELF thruster), and possibly up to 3000 s (Hall effect thruster). All of the engine types below should be tested for their ability to process water vapor, ammonia, carbon dioxide and representative waste gases to determine current and near future performance bounds (Table 3.2).

One of the first action items in developing the spacecoach further will be to organize an X-Prize-style competition for engines, where engine developers will compete to develop an engine module that meets key requirements for form factor, multi-propellant capability, and performance criteria, or test already built engines with representative propellants (e.g., water, CO_2, gasified waste). This competition can be done quickly and inexpensively, and will give designers insight into the current and near-future capabilities expected for these components.

Combining Different Electric Propulsion Technologies

There is a wide range in performance, in terms of specific impulse, among electric propulsion technologies, from just 200 s for resistojets, to 20,000–30,000 s for VASIMR, with most falling somewhere in the middle. Although higher specific impulse seems like the best option, that's actually not the case because of the power requirements for ultra-efficient engines, and because of crew consumable requirements (see the spacecoach equation).

The overall goal of the spacecoach design pattern is to match the crew consumables budget with the propellant budget so that nearly all propellant is reclaimed from consumable waste streams. This leads to a cost minimum for a given mission because the consumables are, in effect, the propellant, and also need to be on board in any case.

Electric propulsion also requires more power to achieve higher specific impulse (and higher exhaust velocities), which is expressed as the power to thrust ratio (the amount of input power required to generate one unit of thrust). This is shown by the equation below:

$$\frac{P}{T} = \frac{v_e}{2 \times \eta} = \frac{9.8 \times I_{sp}}{2 \times \eta}, v_e\text{: } exhaustvelocity, \eta\text{: } engineefficiency$$

What this equation shows is that the amount of power required to generate a unit of thrust scales linearly with the specific impulse or exhaust velocity of the engine. For example, a resistojet with a specific impulse of 200 s (~2000 m/s exhaust velocity) will require one kilowatt of input power to generate a Newton of thrust (assuming 100 % electrical efficiency to keep the math simple). A Hall effect thruster with a specific impulse of 3000 s will require 15 kW of power (more when one factors in less than 100 % efficient conversion of electrical power to exhaust kinetic energy). A VASIMR engine operating at 30,000 s will require ten times more power again.

Since the mass of the engines relative to the propellant they process over the course of a mission will be small, ships could be outfitted with a mix of engine types, to enable high thrust, but less propellant efficient maneuvers where the ship needs to make a rapid change to its trajectory in a short period of time. When the ship needs to make a large velocity change, such as to spiral out from Earth to Mars, and has plenty of time to do this, higher specific impulse engines are better suited to this task since the distances involved allow a gradual buildup of velocity.

The optimal engines will depend primarily on a combination of the mission delta-v and consumables budget. High delta-v missions with relatively low consumables budgets will favor higher specific impulse engines. Provided the engines themselves do not carry a large mass burden it will make sense to have a variety that can operate across a range of exhaust velocities.

Using a combination of different engines will also enable the ship to optimize exhaust velocity by propellant. For example, one type of engine might work especially well with water, while another is better for carbon-rich propellants such as carbon dioxide or gasified waste. Since many small engines are clustered to form a large array, it will be straightforward to include propellant specific units in the array.

Combining Chemical and Electrical Propulsion

There are a number of situations where chemical rockets are the best option, which include:

- Descent/ascent to the surface of a moon.
- Short duration high impulse maneuvers that exploit the Oberth effect, although this can also be accomplished with timed solar electric propulsion.
- Crew transit through hazardous regions, such as from low Earth orbit to geostationary orbit, which involves transiting the Van Allen radiation belt.

It's important to note that while chemical rockets will play a role in spacecoaches, they needn't be especially large.

Another design goal, to improve safety and reduce complexity, is to eliminate the need for toxic or cryogenic fuels that pose safety, refueling and long term storage concerns. Fortunately, there are several candidates that are non-toxic and can be stored safely at room temperature.

Nitrous oxide functions both as an oxidizer, and as a monopropellant (reacts with itself under the right conditions to release heat and produce thrust). It can be stored as an inert compressed liquid at room temperature[5] (not unlike a carbon dioxide fire extinguisher), making long-term storage straightforward. When used as an oxidizer, nitrous oxide can produce thrust with a specific impulse of ~300 s. This is comparable to other chemical rockets. Though not as good as cryogenic rockets, the safety/simplicity tradeoff is compelling. Nitrous oxide is also safer to store versus high concentration hydrogen peroxide (which can auto-catalyze if exposed to contaminants).

Hydrogen peroxide (H_2O_2), like water, is liquid at room temperature, and can be stored safely for long periods of time in dilute solution with water (which is also very useful in life support; see Chap. 5). In high concentrations, hydrogen peroxide can be used as an oxidizer for a bipropellant chemical rocket. The British used hydrogen peroxide plus kerosene to fuel rockets in their Black Arrow program,[6] which successfully launched orbital rockets in the 1960s. It can also be used as a monopropellant, where hydrogen peroxide is blown over a silver metal catalyst that causes it to decompose, releasing heat and steam in the process (the jet packs popularized in the 1960s used hydrogen peroxide as their propellant). Although hydrogen peroxide is difficult to handle in high concentration, it is safely and easily stored in dilute form (up to 30 % concentration). That said, there are substantial safety issues with handling high test hydrogen peroxide, so in all likelihood, this will not be used as a propellant in spacecoaches. However, it deserves a mention because of the likelihood that water reservoirs could be loaded with dilute H_2O_2 (<10 % concentration) to provide for passive oxygen generation for life support, as well as a bacteriocide and for wastewater treatment (Table 3.3).

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[5]Website (accessed April 21st, 2015): http://www.spg-corp.com/nitrous-oxide-safety.html.

[6]Website (accessed April 8th, 2015): http://en.wikipedia.org/wiki/Black_Arrow.

Table 3.3 Fuel efficiency (specific impulse) for different engine and fuel combinations

Engine type	Propellant(s)	I_{sp} (s)	Approximate Ve (m/s)	Cryogenic?
Thermal	Steam: simple	45	~450	No
Thermal	Steam: complex	195	~2000	No
Monopropellant	Hydrogen peroxide	160	~1600	No
Monopropellant	Nitrous oxide	180	~1800	No
Bipropellant	H_2O_2 + HC fuel	300	~3000	No
Bipropellant	Nitrous oxide + HC fuel	300	~3000	No
Bipropellant	Oxygen + kerosene	350	~3500	Yes
Bipropellant	Oxygen + methane	360	~3600	Yes
Bipropellant	Oxygen + hydrogen	450	~4500	Yes
Electrothermal	Water (microwave electrothermal)	800–900	8000–9000	No
Electric	ELF thruster w/ Water	1700	17,000	No
Electric	Helicon double layer thruster	1500–2700	15,000–27,000	No
Electric	Hall effect	1500–3000	15,000–30,000	No
Electric	Gridded Ion thruster	2000–5000 s	20,000–50,000 m/s	No
Electric	VASIMR	3000–15,000 s	30,000–150,000 m/s	Yes, for cooling supercon-ducting coils

Research and Development Pathway

Much of the work needed to prove out electric engines, power arrays and other systems can be done in ground-based facilities.

- I_{sp} Prize, to develop promising engine designs and better understand performance characteristics and limits, broadly investigate the performance of electric engines using water as propellant. This competition would be modeled after successful design competitions like the X-Prize competition for the first private suborbital spaceflight (won by Burt Rutan and Scaled Composites in 2004 for the flight of their Spaceship One rocketplane).
- Simulated flight testing in ground-based vacuum chambers, to validate performance and estimate mean time before failure for critical components (also part of the I_{sp} Prize).
- Design sealable engine compartments, so crews can replace or service motors and parts without conducting an EVA. Design motors so failure-prone parts can be swapped out with lightweight replacements.

- Develop standard form factor for motors and their electrical and fluid interconnects, so that future generation modules can be swapped into replace older units.
- Investigate use of additive manufacturing (e.g., selective laser sintering) for manufacturing engine parts such as the resonant cavity, feed lines, etc., to allow for inflight manufacture of replacement or upgraded parts. SpaceX recently demonstrated the use of 3D printed rocket motors with their Super Draco thrusters for the Dragon 2 crew capsule and re-entry vehicle.

The key design criteria for the solar electric propulsion (SEP) engines is that they conform to a standard form factor, and also utilize standardized electrical and fluid interconnects. This will make replacing a unit, either for repair or for replacement with a future generation unit, a simple operation that is comparable to swapping out a server on a computer rack. We expect that individual motors will be relatively compact, low power devices. Although they may be assembled into large arrays that as a group consume a lot of power, the individual units will be small, modular and replaceable.

The emphasis on inflight serviceability is important for another reason. By designing units so that they can be easily fixed in flight (for example to replace a worn or corroded part), the units do not need to be engineered for extreme reliability. This will reduce costs, excess weight, and system complexity. The timeline for developing and perfecting these engines can be an aggressive one, because most of this work can be done in ground-based facilities long before actual spacecraft are flown.

Once spacecoaches are flying, they can also serve as testbeds for new engine designs. The distributed thrust architecture means that spacecoaches could be outfitted with a mix of mature and experimental engine designs, and by firing different engines at different times, could collect real world performance data in actual space conditions. This would not be unlike attaching a mix of engines to an airframe, as shown in Fig. 3.5.

Timeline

A design competition modeled after the successful X-Prize competition is a good place to start. This competition (I_{sp} Prize?) would offer a financial reward to the teams who produce engines that meet key design criteria for fuel efficiency (specific impulse), energy efficiency, and inflight servicing. With a combination of financial support from private or public sponsors, and access to facilities such as vacuum chambers, such a competition can be completed quickly and inexpensively, at a cost of a few million dollars.

Within two or three years, spacecoach designers will know what the performance characteristics of the first generation engines will be, and will probably have good insight into what second and third generation engines will be capable of. With this information, ship designers can incorporate this data into their

Fig. 3.5 Airbus A-340 outfitted with different engines. *Image credit* “A380 Trip Report”, Chui, Sam, http://samchuiphotos.com/A380TripReport/TLSD2215.jpg

parametric models, both to further develop the spacecraft design and to establish the ship’s exploratory capabilities when outfitted with the first generation engines.

Flight testing can be done using scaled down robotic craft that are launched into low Earth orbit as secondary payloads. These craft will simulate long distance, long duration operation by stepping up and down between orbital altitudes, to simulate the cumulative delta-V and duration associated with a deep space mission. This will allow component systems, including engines, power plant and other elements, to be thoroughly evaluated prior to advancing to full-scale crewed vessels.

Questions and Gating Factors

Spacecoach designers will need to address the following questions related to propulsion technology.

- Electric engine performance. What are realistic upper and lower limits for electric engines that use water as propellant? What are their specific impulse energy efficiency (how much energy is lost as waste heat or to ionization losses), and their thrust/mass ratio?
- How are electric engines likely to evolve over time? Is there a hard upper limit to specific impulse with water, or can we expect incremental improvements with future design iterations? What are realistic performance metrics today, 3–5 years out, 10+ years out?

- Non-cryogenic chemical rocket performance. What chemical propulsion system makes the most sense for the ship, and what are realistic performance metrics for it (specific impulse, thrust/mass ratio), etc.? Is it possible to build a non-cryogenic hydrogen/oxygen rocket? (If so, the fuel can be generated in flight by electrolyzing water, while the water itself can be used as a heat sink during engine operation.)
- Can water and/or non-cryogenic chemical propellant be pre-positioned at destinations to refuel spacecoaches for their return trips? If so, how does this affect the overall budget for missions?
- Can water be harvested from low gravity sites at the destination (e.g., Martian moons, Ceres)? This is a long-term challenge, but something operators should investigate early on because it will have a large impact on mission economics if water can be transferred inward to Earth orbit by spacecoaches returning from low gravity sites.
- Can electric engines be designed to process a variety of gases (water vapor, carbon dioxide, ammonia, etc.)? Or, does it make more sense to have an array consisting of a variety of propellant-specific engines?
- Can electric engines be designed to consume fine dust (regolith) harvested from low gravity sites such as the Martian moons? If so, this would open another path to in situ resource utilization.
- What is the safest configuration that combines electric and chemical propulsion? (For example, to allow for short duration maneuvers to avoid space debris)?

With this information, spacecoach designers and mission planners can accurately model the dimensions of their ships and predict their capabilities, as well as their likely evolution via future upgrades.

Chapter 4
Power Plants

Spacecoaches rely on electrical power, typically generated by a large solar photovoltaic array to provide electrical power for their engines. They will require large amounts of electrical power, from several hundred kilowatts to a few megawatts, meaning they will be fitted with large area solar arrays. Second and third generation ships destined for the outer planets may eventually rely on nuclear power plants, but the early generation ships will be solar powered, and can utilize technology that is readily available today. On a power to weight basis, solar outperforms nuclear by several orders of magnitude. If photovoltaics continue on their decades-long trend of incremental improvement, it should be possible to power future generation spacecoaches well beyond the Asteroid Belt via solar power. A nuclear electric power plant can be used in the spacecoach architecture, though space-ready solar photovoltaics are already in widespread use, and should continue to improve in terms of specific power, without the safety issues and engineering challenges associated with space-based nuclear electric power.

Calculating the size of the solar array required to generate a given amount of power is a function of a few basic parameters, including:

- power required.
- solar cell photovoltaic efficiency (this will typically range from 20 to 40 %).
- distance from the Sun.

The array area is given by the equation:

$$A = \frac{P \times d_{AU}^2}{1400 \times \eta}$$

Example: to generate 500,000 W (500 kW) when operating in the vicinity of Mars (d = 1.67 AU), with a 30 % efficient array, one will need a 3300 m^2 array (58 m

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on a side). To generate the same amount of power near Earth, all other factors being the same, a 1190 m^2 array will be required.

The required power plant capacity will be driven primarily by the engine power requirements, which in turn are determined by the overall size and payload capacity of the ship, engine efficiency and delta-v requirements. One of the key design tradeoffs for spacecoaches will be power plant capacity versus payload. One can increase power output by attaching a larger array to the ship, but the array must propel itself along with the ship, so extra power comes at the expense of added weight, which will cut into the ship's useful payload capacity. For this reason, designers will most likely opt for either ultrahigh efficiency solar cells to minimize array area or ultralight thin film material. (It is interesting to note that thin film PV materials, while they are less efficient per unit of area, are much less massive, and are also resistant to radiation damage.[1])

Another factor is the required specific impulse for the engines. Engines that use water operate at the low end of fuel efficiency for electric propulsion (e.g., I_{sp} 800–900 s for MET engines, 1700 s for ELF thrusters) and can generate useful amounts of thrust while operating at lower power compared to gridded ion drives, for example. Higher specific impulse engines, which will be needed for high delta-v missions such as a Ceres round trip, will require larger power plants, unless of course operators can allow the ship to take longer to build up the required delta-v.

Fortunately, solar power technology benefits from a slow motion Moore's law effect, known as Swanson's law, where manufacturers are learning to fabricate photovoltaic devices using less and less material. The key parameter spacecoach designers will be interested in is specific power, measured in kilowatts/kilograms for photovoltaic arrays.

Spacecoaches will be able to utilize solar power as their primary energy source from the inner planets out to the Asteroid Belt (and the dwarf planet Ceres). As solar photovoltaic technology improves in terms of power density, spacecoaches will be able to travel further yet.[2]

From a technology standpoint, space-based solar power is well understood. It is advancing rapidly, being closely related to the terrestrial solar power industry. The basic technology needed to build high efficiency, large area solar arrays already exists. The primary challenge for spacecoach designers will be to design structures that can support a large football field-sized array, while minimizing the need for trusses and other heavy structural elements to maximize the overall power density of the array. This is primarily a structural engineering challenge and is where solar power satellite designs might help, by reducing mass and increasing ease of deployment.

[1]"Super radiation tolerance of CIGS solar cells demonstrated in space by MDS-1 satellite," Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on, 18–18 May 2003, pp. 693–696, Vol. 1.

[2]"The case for space solar power", J. Mankins—Virginia Edition Publishing—2014.

As photovoltaic efficiency improves, and as designers learn to fabricate increasingly lighter structures, spacecoaches can be upgraded to raise their power output, reduce dead weight, or a combination of both (see Chap. 7).

Battery-Assisted Solar Electric Propulsion (Exploiting the Oberth Effect)

One disadvantage of solar electric propulsion is that it is difficult to exploit the Oberth effect. The Oberth effect, also known as a powered flyby maneuver, enables a ship to increase effective delta-v for a maneuver by applying thrust when flying close and fast to a massive body such as Earth.

A solar electric engine with no batteries is limited to slowly spiraling out from Earth. This results in a delta-v requirement that is roughly twice as great as a maneuver that exploits the Oberth effect. The effect is greatest when a ship is operating close in within a deep gravity well, and is negligible near low mass objects such as small moons and asteroids or near the edge of a gravity well.

There is a way to compensate for this, and that is to use batteries that are sized to store one orbital period's worth of power (about 1.5 h in low Earth orbit, longer periods as the orbit is raised).

The battery assisted engine then collects energy while it is orbiting high and slow, and then runs its engines at maximum power when the spacecraft is flying low and fast. With each orbit, it will increase the eccentricity of the orbit, and eventually end up in a highly elliptical orbit, and then gradually circularize this orbit. With this strategy, one can use solar electric engines to exploit the Oberth effect, although the maneuver takes much longer to complete compared to a short chemical burn. There is a mass penalty for the batteries, though battery energy density should improve with time. This is an optimization worth looking into, though probably something that will only prove attractive for second and third generation ships (allowing for continuing improvements in battery power density).

The batteries would also be useful as a backup system. In the event of an electrical system failure, critical systems could run on battery power (though the primary safety feature for the electrical system should be a highly decentralized design to eliminate central points of failure). Ship designers will probably want to include some amount of battery backup or alternate power generation methods for this reason (at least enough to run electronics and life support systems).

Note also that if the time required to complete the maneuver is long this also can be done without using batteries, and thus without their mass penalty. The ship would simply cycle its engines on and off, running them only for a few minutes per orbit while flying low and fast. This would increase the time required to transfer from a circular low Earth orbit to a highly elliptical orbit by roughly 5–10 times (assuming the engines are only running for 10–20 % of the time per orbit).

Questions and Gating Factors

Spacecoach designers and mission planners will need to answer the following questions to model ships and predict their capabilities.

- What are the best space-rated solar cells available off the shelf today? What terrestrial technologies can be adapted for the space environment (e.g., thin film solar)?
- What are realistic upper and lower bounds for specific power (kilowatts per kilogram) for an assembled solar array? Model this for a rigid, truss-based system, and also for a flexible, sail-like array that is lashed to a rigid frame created by the ship itself. Include ancillary materials such as cabling, inverters (if AC power is needed). How is this likely to improve over 3, 5 and 10 years?
- How can we maximize array size even further (for example by towing a free-floating array behind a spacecoach, or by hanging large sails off the rim of a spinning ship)?
- What are realistic near-term targets for battery energy density, and what trajectories are possible using battery augmented solar electric propulsion? How can these maneuvers be optimized, for example by leaving battery modules in a parking orbit for retrieval on return.
- What types of photovoltaic materials are resistant to radiation? Literature suggests that thin film (CIGS) material does not degrade substantially when exposed to radiation. If so, this will be a promising material for tugs that spiral in and out from low Earth orbit, and thus are exposed to the Van Allen radiation belt for longer periods of time.

With this information, designers can plug values into parametric models to calculate the ship's propulsion capability, power plant capacity, and dry weight, which in turn will define performance characteristics for the ship. This will also give them an idea of longer term trends in cost and performance.

Chapter 5
Life Support, Materials and Artificial Gravity

Water, of course, is the basis for life, and besides breathable air, the most important consumable required for crew survival. Life support is an integral part of a spacecoach, versus an extra complication and source of dead weight in a conventional spacecraft. Because of this we can design spacecraft that are capable of surviving extreme scenarios (think *Apollo 13* in deep space), while also providing crew comforts that would otherwise be unthinkable.

Besides its use as a source of drinking water for the crew, the water on board a spacecoach has many other life support related uses, which include:

- oxygen generation via electrolysis, or via decomposition from dilute water/hydrogen peroxide mixture.
- heat management, both for steady state temperature control and for soaking up excess heat during high power operations, which depending on the ship configuration could even be a non-mechanical process driven by convection.
- carbon dioxide elimination, via plant photosynthesis (aided by water).
- radiation shielding.
- debris shielding, especially when frozen in fiber to form pykrete.

Oxygen Generation

Oxygen generation from water can be done in two ways. When electrical power is available, water can be electrolyzed into oxygen and hydrogen. An even simpler way to generate oxygen will be to load spacecoaches with a dilute water/hydrogen peroxide mixture (which can be safely stored at up to 30 % concentration by weight). Hydrogen peroxide decomposes to water and oxygen in the presence of a metal catalyst or ultraviolet light, a simple, non-mechanical process for generating

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oxygen throughout the course of a mission. With a mixture of water and hydrogen peroxide, a spacecoach would be 2–25 % oxygen by weight, all of it easily accessible via decomposition. The safety implications of this are hard to overstate.

If this hydrogen peroxide reserve is depleted, oxygen can also be drawn from the remaining water using electrolysis. While this process requires electrical input, it is also simple and reliable, and is a space-rated technology that has been in use since 1987. The hydrogen generated in this process can be vented into the engines or combined with carbon dioxide to produce methane for chemical propulsion. (A Sabatier reactor that does just this is already in operation on the International Space Station.[1])

If the ship is equipped with a nitrous oxide-based chemical propulsion system, this can also be used as a backup oxygen generator, as nitrous oxide can be decomposed to nitrogen and oxygen. The gas is blown through a heated catalyst, and will decompose to a 50/50 mixture of nitrogen and oxygen. This process is somewhat more complex than decomposing dilute water/hydrogen peroxide, a room temperature process, but not greatly so.

If plants are grown on board, and the authors assume even the first ships will experiment with on board agriculture and biofuel production, they will generate oxygen via photosynthesis. Until there is more data about the success of these experiments, this should be treated as a supplemental source of oxygen, nice to have, but not the sole source of oxygen. That said, some plants do well in microgravity environments, and if well lit by LEDs tuned for each crop, and well irrigated, they should thrive on board spacecoaches.

Consumable Propellant

One of the most interesting aspects of a spacecoach is that most of the crew consumables eventually become propellant. Water and water-rich food all ultimately feed into the engines. In a conventional ship, everything the crew consumes is dead weight, and must be traded against payload and propellant. In a spacecoach, even orange juice counts as propellant (it may start the journey as orange juice, but after the water is recovered from dehumidifiers, urine collection, etc., it can later be sent off to the engines to generate thrust). This is especially important on a long journey because even a small crew will require significant amounts of food and water to survive the trip. Spacecoaches should also be able to support larger crews because of this ability.

[1] "Development and Integration of the Flight Sabatier Assembly on the ISS", Samplatsky, Darren, et al. 4th International Conference on Environmental Systems, 17–21 July 2011, Portland, Oregon, http://arc.aiaa.org/doi/abs/10.2514/6.2011-5151.

Carbon Supply Chain

Carbon and nitrogen-rich organic materials will be highly valuable at most destinations. So while spacecoaches may expend water as propellant along the journey, it will probably be desirable to hang onto carbon and nitrogen-rich materials. Urine, for example, can be mixed with potash to create a rich fertilizer (nitrogen-rich fertilizer's primary feedstock is urea). This material can be delivered on outbound journeys, and left in bulk at the destination for use in agriculture there. It is also a feedstock for protein synthesis in bioreactors (already used at a large scale to replace animal feedstock).

Similarly, spacecoach operators will probably want to retain dead plant/algal material, composted waste and trash. At the very least, it can be used as soil or fertilizer en route or at the destination site. If the excess weight is a burden, it can be burned off in an incinerator or gasified, and the exhaust gases fed into the electric engines to generate thrust. This will give planners extra flexibility in designing missions.

Solid human waste can be sterilized by mixing it with hydrogen peroxide. (Many wastewater treatment plants use hydrogen peroxide for this very purpose, another bonus of loading spacecoaches with dilute hydrogen peroxide at the beginning of their journey.) Then it can be re-used in fertilizer or stored for delivery to the destination site.

Thermal Management

Dealing with extreme temperature variations is something else water will be useful for, as it is an excellent heat sink. Water will be used in two modes for heat management, to smooth out temperature differences between sunlit and shaded regions of the spacecraft, and to soak up excess heat during high power operations, for example when all engines are running at peak output.

The water reservoirs in a spacecoach can be thought of as large thermal batteries. Water has a specific heat of 4.18 kJ/kg per degree, and a heat of evaporation of 2.2 MJ/kg. Since a spacecoach will typically be loaded with tens of thousands of kilograms of water, it will be capable of storing and releasing large amounts of heat as needed.

Spacecoaches will typically be oriented so their equilibrium temperature is below the optimum temperature. (It is easier to generate heat than to radiate excess heat away in space.) The interior temperature will be raised to the crew's desired temperature using resistive heating powered by the solar arrays. Note that thermal management may constrain missions close into the Sun, as it is more difficult to dump excess heat than to heat a well-insulated space. This is something to be studied closely in subsequent design and safety analyses.

Carbon Dioxide Elimination

A water-rich spacecraft offers many options for carbon dioxide elimination and recycling. Since this is a critical item, designers will likely employ several independent mechanisms for doing this on a long voyage.

Spacecoaches will use a variety of mechanical and biological processes to remove carbon dioxide from the atmosphere, including:

- Sabatier reactors. This is a space ready technology that converts hydrogen and carbon dioxide to methane (already flying on the International Space Station). The methane can either be vented off, or stored for use in chemical propulsion.
- Calcium hydroxide. This is for use in an emergency, a concentrated solution will suck up carbon dioxide and convert it to $CaCO_3$
- Fast growing plants and algae. While experience with space agriculture is currently limited, spacecoaches will have a large amount of interior space that can be allocated to growing crops, both to remove and recycle CO_2 and to produce fresh food. This will probably be a secondary carbon dioxide removal system in early spacecoaches, but as operators gain experience with space agriculture, they can rely on agriculture as a primary life support system.

The primary method for recycling carbon dioxide will be to use mechanical systems to remove CO_2, with agriculture as a supplemental process. Experimenting with different crops and growing methods will be one of the main areas of focus in early spacecoach missions since sustained space agriculture will have a significant positive impact on future missions. Gardening and agriculture will also be an enjoyable for crews on long journeys, even if the impact on mission economics is negligible.

Radiation Shielding

Water is an excellent radiation shielding material, comparable on a per kilogram basis to lead. A layer of water 18 cm (7 in.) thick will block about 50 % of the radiation passing through it, also referred to as the halving distance. Lead by comparison has a halving distance of just 1 cm, but is 11 times as dense as water (and is pure dead weight, as it can't be used for any other purpose). So the two materials are similar in terms of protection by weight, except astronauts can't drink lead. However, it should be noted that water, being proton-rich, will be better at blocking charged particle radiation, while lead will work better for gamma radiation. This is good, because charged particle radiation from solar flares will be the primary threat.

Water has the added benefit of being a fluid, so in a radiation emergency, it can be pumped into large temporary bladders that maximize the thickness of the water between the astronauts and a radiation source. During normal operations, water would be stored in reservoirs that wrap around areas where the crew normally spends a lot of time, or sleeping quarters, typically in the low/zero gravity central hub of the ship. The ship could also be oriented so that the thickest shielding faces known radiation sources.

There is always a benefit from at least some level of radiation protection beyond that provided by the skin of the pressure hull and other structural elements. While it will never be possible to completely eliminate radiation in the space environment, through careful positioning and temporary structures, it should be possible to reduce cumulative crew exposure by several orders of magnitude. This should effectively eliminate radiation exposure as a health concern for long duration missions.

One factor spacecoach designers will need to account for is the ship's "drying out" as it depletes its water reservoirs to generate propulsion during the course of a trip. One can think of the ships starting out like grapes and ending like raisins. For radiation shielding, designers will want to meet two goals. One is to minimize the cumulative radiation dose the crew receives, which they can do by draining the reservoirs where the crew spends the most time last. The other is to use variable geometry, for example tanks that are thicker viewed one way than another. The important factor in radiation exposure is the cumulative dosage the crew receives, so there will typically be many available adaptive responses throughout the mission.

It should also be noted that with a large power plant, a spacecoach may also be capable of active radiation shielding, by diverting electrical power from the engines to electromagnetic coils built into habitable structures to generate a large magnetic field around protected areas. For example, when coasting the ship might route electrical current from the solar array in loops around the perimeter of the ship to generate a magnetic field that diverts charged particles away from crew areas. The ships will not be lacking for electrical power, so this may be an attractive way to augment passive radiation protection.

Debris Shielding (Pykrete)

Water, when frozen into fibrous material such as wood pulp, forms a tough material known as pykrete. This material is similar in strength to concrete. (The British once experimented with building an aircraft carrier made of a mix of ice frozen into wood pulp.[2]) The strength of the material can probably be increased well beyond what the British achieved using high strength fibers such as silk, carbon fiber, and other materials that have been developed since then.[3]

[2]Perutz, M. F. (1948). "A Description of the Iceberg Aircraft Carrier and the Bearing of the Mechanical Properties of Frozen Wood Pulp upon Some Problems of Glacier Flow". *The Journal of Glaciology* **1** (3): 95–104.

[3]Website (accessed April 7th, 2015): http://en.wikipedia.org/wiki/Pykrete.

The use of pykrete is advantageous not only for debris shielding but also as a way to prevent liquid water from sloshing around, a potential issue in a ship that is rotating to generate artificial gravity. It will also be useful for creating reaction wheels, which can be used to re-orient the ship without consuming propellant. It additionally has good insulating properties.

For missions to Mars and beyond, it will probably be relatively easy to maintain water in a frozen state, and heat it to melt or vaporize it only as needed during a mission. In these missions, pykrete will be an easy way to reinforce the ship's structure, with almost no mass penalty since the fiber the water freezes into will weigh just a small fraction of what the water weighs. Pykrete is also an interesting material for use in surface base habitats, as crews could deliver very lightweight habs to the surface and then fill the outer shell with locally obtained water and freeze it to form pykrete.

Artificial Gravity

Long term exposure to microgravity, combined with exposure to radiation, is one of the main challenges in long duration deep space missions. As discussed earlier, water-based spacecraft will provide excellent radiation shielding, so that problem can be solved by spacecoaches, but what about gravity?

A spacecraft can generate artificial gravity via rotation, an idea that was best popularized in Stanley Kubrick and Arthur C Clarke's *2001: A Space Odyssey.* Artificial gravity has typically been imagined using ring-shaped structures that, when spun up, generate enough centripetal force to approximate gravity.

Another way to do this is via a kite-like design where a central module is connected to outboard modules via long inflated tubes that function as hollow tethers. These tubes, in addition to serving as passageways and storage areas, also function as masts for the solar arrays (Fig. 5.1).

This design pattern solves several problems concurrently, as it creates a large structure to which flexible (and thus lightweight) solar arrays can be tied down, while also enabling the craft as a whole to be spun to generate artificial gravity. It also eliminates the need for the solar array to be built with a rigid metal truss, which should reduce the overall mass of the solar array by an order of magnitude. This approach also minimizes the mass of the habitable areas compared to a classic ring configuration.

In the figure shown, the outboard modules are connected to the central hub by inflatable passageways 25 m in length. This creates a structure large enough for a 1250 m^2 solar array, which will be sufficient to generate several hundred thousand watts of power when operating in Earth's vicinity and oriented toward the

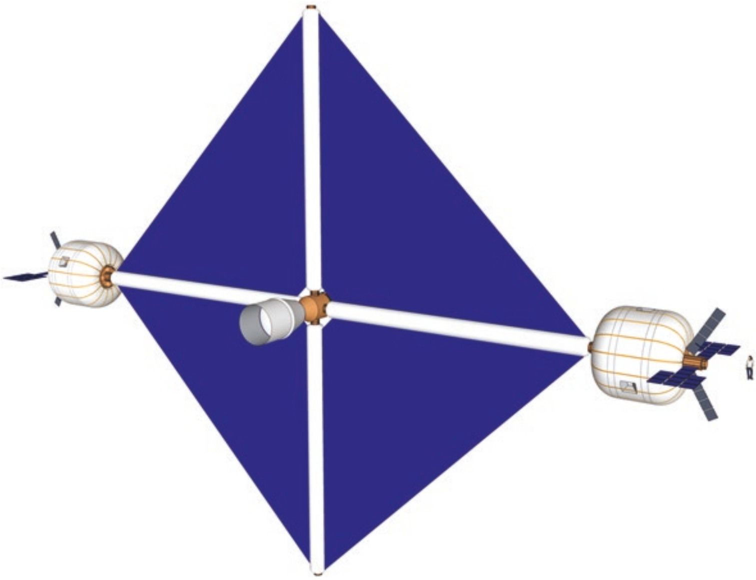

Fig. 5.1 "Kite" design that can be spun up to generate artificial gravity in the outboard modules, with two or four modules per ship, along with a central low/microgravity hub for docking and primary water storage. High-strength inflatable tubes connect the outboard modules to the central hub, and also serve as masts for the solar array. Bigelow Aerospace's Sundancer modules are shown as the outer habs. (*Image credit* Rüdiger Klaehn. Used with permission.)

Sun—in other words, large enough to generate significant amounts of power—and if a larger array is needed, designers can use longer passageways to create a larger frame. Note that the inflatable passageways can be scaled up as needed to increase array area, decrease angular velocity for crew comfort, or both. To generate artificial gravity, the craft will rotate around its central hub. For a ship of this size, this works out to about 2 or 3 revolutions per minute.

The main engineering challenges associated with this design will be to make the connecting passageways strong while minimizing mass per cubic meter of habitable space. Another issue, which may constrain the amount of artificial gravity that can be generated and require longer masts, will be crew discomfort due to tidal and Coriolis forces, since the apparent gravity will vary with the astronaut's distance from the central hub.

Research done with rotating room experiments from the 1960s through the 1980s suggests that a spacecoach with a mast radius of 25–50 m should be able to provide a comfortable environment while generating at least partial artificial gravity. (A full 1 g environment may not be necessary to offset the worst health effects of microgravity.[4,5,6,7])

In a spacecraft that is always spinning to generate artificial gravity, it will be necessary to vector the thrust from the engines as they rotate. The electric engines can be gimbaled, for example using a simple mechanical apparatus driven by linear actuators, so their thrust vector can be adjusted as the ship rotates. In this case, the crew will only be exposed to brief periods of microgravity, which along with radiation shielding will solve the health problems that make long-duration space missions dangerous.

Water is heavy. Therefore to minimize structural requirements as well as the ship's moment of inertia, designers will probably situate most of the water in or near the central hub, where there is a near weightless environment. The crew, meanwhile, would spend most of their time in the outboard modules when radiation flux is low, but would retreat to the heavily shielded, low gravity hub during periods of elevated radiation exposure, as well as to rest or sleep.

Artificial gravity offers more than just health benefits, it will also mitigate one of the most difficult and least talked about issues in space travel, the toilet. On the Apollo missions, the zero gravity "toilet" was a bag and plastic glove. The space shuttle and ISS toilets were not much better. They can charitably described as purpose-built vacuum cleaners. As you can imagine, they break, and when they do, someone gets the unpleasant job of fixing them. Spacecoaches could instead be fitted with composting toilets that are basically no different than what one finds on Earth and also are very low tech and easily repaired. More important is the use of artificial gravity to aid defecation and urination, avoiding the need for suction and failure-prone components. This benefit extends to other interior elements and appliances, as spacecoach designers can use ordinary (and much cheaper) products designed for use on Earth.

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[4]Connors, Mary M.; Harrison, Albert A.; Akins, Faren R. (1985). *Living Aloft: Human Requirements for Extended Spaceflight* (NASA SP-483, pp. 35–51). NASA Scientific and Technical Information Branch.

[5]Cramer, D. Bryant (1985). Physiological Considerations of Artificial Gravity. In A. C. Cron (Ed.), *Applications of Tethers in Space*, Williamsburg, Virginia, USA, 15–17 June 1983 (NASA CP-2364, vol. 1, pp. 395–3107). NASA Scientific and Technical Information Branch.

[6]Graybiel, Ashton (1977). Some Physiological Effects of Alternation Between Zero Gravity and One Gravity. In J. Grey (Ed.), *Space Manufacturing Facilities (Space Colonies): Proceedings of the Princeton/AIAA/NASA Conference, May 7–9, 1975*, (pp. 137–149). American Institute of Aeronautics and Astronautics.

[7]Lackner, James R.; DiZio, Paul A. (2003). Adaptation to rotating artificial gravity environments. In, *Journal of Vestibular Research* (vol. 13, pp. 321–330). IOS Press.

Questions and Gating Factors

The following must be taken into consideration:

- How much oxygen will each crewmember consume, on average, per day?
- How much carbon dioxide will each crewmember exhale, on average, per day?
- How much carbon dioxide can be taken up by plants or algae grown on board? Is this sufficient to absorb crew output?
- If not, how much scrubbing equipment is required to remove excess carbon dioxide?
- How much carbon-/nitrogen-rich material (e.g., compost, fertilizer, plant material) can be deposited at the terminus, to reduce mass on the return leg and provide supplies for permanent bases or stations?
- How much water and water-rich food will each crewmember consume per day?
- How much of this water be recovered and used for propulsion? (e.g., via condensers, urine collection, etc.)
- Can MET engines consume "gray water," urine or carbon rich gases?
- What types of stresses will a spinning kite design be exposed to when artificial gravity is applied?
- What are the safety implications of the design? Can connecting passageways be configured such that there are multiple paths between each module, in the event that one is rendered impassable?
- What is the minimum radius for a kite design that provides *comfortable* artificial gravity?
- What level of radiation shielding is possible for various ship/reservoir configurations?
- What level of shielding can be achieved with temporary, bladder-type structures?
- Can fertilizer such as urine plus potash mix be used in space agriculture?
- What toilet designs will work best in partial artificial gravity environments (e.g., 1/3 g)?

The basic goals here are to maximize the percentage of crew consumables that are ultimately converted to propellant, to maximize the percentage of life support that can be provided by plants or algae, and to maximize the amount of excess carbon-/nitrogen-rich material that can be dropped off at the terminus of the mission.

Chapter 6
Upgradability

Spacecoaches are based on an empty hull design where the habitation areas are little more than pressure vessels lined with reservoirs to store water or pykrete. Nearly all equipment is brought onboard as needed, and can be upgraded with each mission. Electrical and communication wiring will be similarly exposed and readily accessed. This differs from a conventional spacecraft design where most equipment is permanently installed, and is often shipped pre-installed at launch. This is important because of year after year improvements in component technologies, so being able to upgrade them with each resupply mission will enable spacecoaches to enjoy a long life in service.

Solar Arrays and Electrical Bus

Solar photovoltaic technology benefits from a slow motion version of Moore's law called Swanson's law.[1] The performance metrics we are most interested in for space-based solar power are specific power (the amount of power generated per unit of mass) and conversion efficiency. The former refers to the mass required to generate a given amount of power, while the latter governs the array area required to generate a given amount of power. Of the two, we are most concerned with specific power, as the goal is to minimize the mass of the solar array while maximizing the amount of power produced.

Increasing specific power is primarily a matter of using less photovoltaic material per unit of array area. Thin film photovoltaics that, rather than using rigid, glass-coated panels, are made of thin films with PV material sprayed onto them,

[1] "Swanson's Law." Wikipedia. Wikimedia Foundation, n.d. Web. 21 April 2015. http://en.wikipedia.org/wiki/Swanson%27s_law.

B. McConnell and A. Tolley, *A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach*, SpringerBriefs in Space Development,
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will enable spacecoach designers to construct very large and lightweight photovoltaic sails. While their conversion efficiency is significantly lower than for conventional silicon panels, they will enable order of magnitude reductions in mass per unit area, and thus far outperform silicon in terms of specific power. It's also worth noting that thin film PV materials appear to be more resistant to degradation due to radiation exposure, another reason to seriously consider their use in spacecoach design. Concentrating mirrors and lenses could also be used to trade weight for heat dissipation. Quantum dot solar photovoltaics are another promising technology that could potentially be used in spacecoach solar arrays.

Because the spacecoach will normally be rotating to produce artificial gravity, the same rotation can be used to extend the solar array. The inner array would most likely be fixed to the main ship structure, very much like a sail, which would eliminate the need for a rigid backplane or truss. To extend the array beyond the main ship structure, designers could exploit the ship's rotation so that even larger outer arrays would hang off the ship as it spun.

Using techniques like this, it should be possible to design lightweight arrays that have a collecting area of tens of thousands of square meters, and an electrical generating capacity measured in megawatts. There are many potential configurations like this that can be explored in ship design competitions.

Electric Engine Arrays

The electric engines can likewise be upgraded over the course of a ship's lifetime. It is reasonable to expect that first generation engines will have moderate performance, with a specific impulse of 800–1700 s when using water as propellant. This is significantly better than chemical rockets, but is on the low end of what is possible with electric propulsion systems. Ship designers will be interested in three performance metrics for electric engines: specific impulse, omnivorous operation, and thrust/power ratio.

Specific impulse, of course, relates directly to exhaust velocity. Higher exhaust velocity directly translates to higher change in velocity. Ultra high specific impulse, as is attainable with technologies such as VASIMR, is actually not desirable for most missions. This is due to the fact that the power required to drive the engine at a given thrust level increases in proportion to specific impulse. This forces tradeoffs between power plant size, the time required to complete maneuvers, and specific impulse. The authors' analysis found that the ideal specific impulse for water-burning engines will be between 1500 and 3000 s, which is well within reach of systems such as Hall effect thrusters and electrodeless Lorentz force thrusters.

Omnivorous operation, especially the ability to vaporize surface materials such as lunar regolith, is another area for improvement. Although it is unknown if there is accessible water-ice under the soil of the Martian moons, there is an essentially unlimited supply of soil. If this material can be vaporized in engines similar to microwave electrothermal engines, it may be possible to excavate propellant that can be used by returning spacecoaches. An example engine design might be a two-stage thruster in which regolith is vaporized by a short-duty cycle laser in the first stage, while the vapor is superheated via microwaves in the second stage. One can think of these motors as miniaturized mass drivers. It will also be good if engines can use carbon- or nitrogen-rich gases as propellant, as this would enable gasified waste to be used for propulsion.

Lastly, thrust/power and thrust/mass ratios are another set of metrics to watch. Engine designers will seek to minimize the mass of the engine relative to the thrust it generates, and relative to the power it consumes. One of the easiest ways to boost engine performance will be to minimize the mass of its components, for example by using the lightest possible metals, and by using techniques such as laser sintering to minimize the amount of metal required to generate a given shape. Each individual design iteration won't necessarily yield breakthrough results, but many minor improvements when combined will lead to steadily improving performance.

Because the spacecoaches will be designed around standardized component form factors, improved engines can be installed to replace early generation units, as they become available and as future missions require. Older units can either be discarded or transferred to spacecoaches that do not require upgraded performance. It may even be possible to manufacture some engine parts inflight, such as an improved nozzle design or resonant cavity, using selective laser sintering. Meanwhile, damaged or unused components could be melted down in an electric kiln, and then reused for other purposes.

Life Support and Agricultural Systems

Life support and agricultural systems can similarly be brought on board as needed, for example based on the crew size for a given mission. These components would be packaged as modular systems that can be manually loaded onto the spacecraft, not unlike fixtures in a commercial airliner, then removed when they are obsolete or no longer needed.

Spacecoach designers can probably leverage work that is underway in containerized urban agriculture, where plants are grown in modular hydroponic racks with LED lighting tuned to maximize the growth of each crop.

Avionics and Communications

Anything related to computing and communication technology is going to be out of date before it flies.

In spacecoaches, crews will carry handheld computers that can serve as multifunction devices. These devices, iPads basically, will be lightweight, inexpensive, and software upgradable. The spacecoach itself may be permanently equipped with a local wireless network and long range communication gear, but otherwise most gear will be brought on board as needed. One doesn't need much imagination to see that this is an easy place to improve things with each trip out. Standardizing around a low voltage direct current electrical system for these systems will also largely eliminate the need for DC/AC conversion devices such as inverters. (Solar photovoltaic arrays provide DC power that would otherwise need to be converted to alternating current.)

Long range, high gain communication equipment will be placed in a special part of the ship's hull, whose skin is transparent to optical or electromagnetic radiation, or in a compartment that can be sealed to allow shirt-sleeve maintenance. By placing this equipment in sealable compartments inside the spacecoach, designers can eliminate the need for crews to engage in spacewalks to service them, and enable them to easily replace or upgrade them while inside the spacecraft, similar to the way the engine compartment will be designed.

In general, designers should move as much equipment as possible into the pressurized interior or into mini airlocks so that it is accessible for servicing and replacement without an EVA. Although one can't eliminate all potential reasons for an EVA (such as a damaged solar array), it will be possible to eliminate most of them, and therefore most of the risk associated with it.

Navigation Equipment

Spacecoaches will be able to navigate autonomously via several methods. The spacecraft will be outfitted with high resolution external cameras or telescopes that are used to image the background star field, planets and known asteroids. This will enable crews to precisely determine their location and trajectory, both via automated systems and, in an emergency, via manual observations. (See chapter on safety and autonomy.)

Habitable Modules

The habitable modules themselves will probably not be replaced as frequently, since they form part of the ship's permanent structure, but if placed appropriately, it should be straightforward to replace them at the end of their service life, or when significantly lighter units become available. The habitable modules' permanent structure will be an important source of dead weight in the ships, so for example, if new high strength fiber materials become available that allow a 10–20 % reduction in mass, while providing the same levels of strength and protection, it may make sense to swap these units out, as that will enable the ship to travel further, carry more payload or some combination of both.

Using available specifications from Bigelow Aerospace, which specializes in inflatable/expandable habitats, the authors estimate that the habitable areas of the ship will weigh in at about 60 kg/m^3 of inhabited space,[2] and that this should decrease over time as new materials are incorporated into these structures. Bigelow already has two scaled-down expandable habs in low Earth orbit, and is preparing to fly BEAM, an expandable module that will be attached to the International Space Station.[3]

Perpetual Supply Chain

Spacecoaches will also create a near perpetual supply chain that continuously delivers rare and valuable materials to destinations wherever they fly, as well as refurbished ships and hardware. Every ship component will be designed for modularity and reuse, so for example, a solar array that is no longer needed on one ship might be dropped off at a permanent base on Phobos or Deimos to expand the power plant there. (Both Martian moons are interesting because of their low gravity and low communication latency with the Martian surface.) If designers pay careful attention to designing components for modularity and second-hand use they can minimize the amount of material that is “thrown overboard.”

Carbon- and nitrogen-rich material can similarly be deposited at destinations such as the Martian moons for use at bases there. If it has no immediate use (for example because they’re still experimenting about how to do space agriculture efficiently) it can be dropped off for future use, which will still reduce the amount of propellant needed for the return trip.

As operators become more and more proficient at using these materials for on board food and resource generation, they can also reduce consumable and propellant requirements for outbound trips while expanding crew capacity, another source of gradual and compounding improvement in the overall system’s capability.

The ultimate goal of the spacecoach program will be to discover and exploit low gravity sources of water and other materials. In situ resource utilization will reduce or eliminate the need to launch large amounts of water from earth’s surface. Instead it can be towed to wherever it is needed by robotic barges (essentially little more than a solar array, engine cluster, and water tank).

[2]Bigelow Aerospace, BA330 module specifications, (accessed April 6th, 2015) http://bigelowaerospace.com/b330/.

[3]Website (accessed April 6th, 2015): http://bigelowaerospace.com/beam/.

Upgrade Costs

The cost of upgrading spacecoaches, relative to other supply costs, will be minimal, because for any long range mission, most of the Earth to orbit launch costs will be to deliver water or water/hydrogen peroxide for consumables and propulsion. Equipment will constitute only 10–20 % of the initial mass, and will comprise a proportional share of overall costs. This can be further reduced as a percentage of mission cost if equipment can be used for several missions before it is replaced.

As of 2015, SpaceX charges about $1700 per kilogram[4] to deliver material to low Earth orbit, meaning the cost to replace several thousand kilograms of solar array or engine units will be a few million dollars, a small amount relative to the cost to deliver tens of thousands of kilograms of water. This is especially true if these components can be used for several missions prior to replacement.

Surface Launcher Reusability

SpaceX's progress toward developing reusable booster stages suggests that it should be possible to further reduce surface launch costs, especially for the water that comprises the bulk of the spacecoach's initial mass. The materials cost of fresh water is negligible on the ground, but valuable in the orbit where it is needed, making it an ideal payload for a heavily reused booster, which can then be flown until it fails.

This is potentially an ideal arrangement for both spacecoach and launch operators. Water, food, etc., can be launched via previously used boosters, with only the upper stage needing to be built per flight. This should significantly reduce launch costs for the water and other low value payloads. Only high value components would need to be launched via newer, lower-risk vehicles.

The launch operator will likewise benefit from being able to fly reusable components until they fail, and thus acquire valuable knowledge about reusability limits, as well as manufacturing techniques that provably extend equipment life.

[4] Website (accessed April 7th, 2015): www.spacex.com.

Chapter 7
Landers

Spacecoaches are not intended to enter a planet's atmosphere or land on a high gravity site. However, there are many low gravity sites, such as the Martian moons, near Earth asteroids, and Asteroid Belt objects, whose surface gravity is so low that landing on them is more akin to docking with a space station. Spacecoaches will be able to visit these destinations without requiring dedicated landers such as the LM (lunar module).

For missions to higher gravity sites, such as Earth's Moon and the dwarf planet Ceres, spacecoaches would be coupled with purpose-built landers that are capable of reaching the surface. (Spacecoaches will be not be designed to survive high g maneuvers.)

Low Gravity Moons (Phobos and Deimos) and Asteroids

The Martian moons Phobos and Deimos, unlike Earth's Moon, are very small objects, thought to be asteroids that were captured in Mars orbit. In fact, the delta-v required to land on these moons is just a few meters per second, about as fast as one might ride a bicycle. These sites are interesting because they are essentially ready-made space stations, and may also be rich in material that can be scavenged for a variety of purposes.

The advantages of using these sites as bases of operation are numerous, and include:

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- Communication delays due to the speed of light are minimal (less than 20 ms), allowing astronauts to teleoperate surface equipment and robots as if they were physically present using virtual reality gear. Deimos in particular is just above Mars synchronous orbit and will maintain a direct line of sight to a given point on the surface for over 2 1/2 days per overhead pass.[1]
- Potential to scavenge surface material for metals, organic material and possibly sub-surface ice for refueling ships for return trip.
- Minimal energy required to land and take off from these bodies, with the ability to land one or more habitable modules on the surface instead of purpose-built landers.
- These will become forward bases of operation for future Martian surface expeditions. Think of them as the Martian equivalent of McMurdo Station in Antarctica.

The kite design shown earlier, in addition to serving as a spaceship, can also be used to deliver two habs to the lunar surface with each sortie. The ship would leave with four habs attached, and then detach the habs on one mast. The habs would be fitted with small steam or chemical rockets that would enable them to descend to the surface and land on their bellies. Once there they would function as a permanent base.

It turns out that a crude steam rocket is sufficient for the maneuver. To make it to the surface of Phobos and back, a spacecoach would need to consume just 2 % of its mass to get to and from the surface. A one-way descent would require just 1 % of its mass; therefore, it would need about 100 kg of water for every 10,000 kg delivered to the surface.

Steam rockets may seem a bit retro, but they fit naturally into the spacecoach concept, as they are water-based, refuelable, and can be powered by the same solar arrays that drive the microwave electrothermal engines in cruise flight. The electricity is used instead to power electric heaters that turn water in the tanks to high pressure steam at several hundred degrees in the hours or days prior to powered descent. In this context, a steam rocket is essentially a thermal battery.

Chemical rockets are also an option. As discussed earlier, nitrous oxide plus hydrocarbon fuel will be an attractive option, as both can be stored at room temperature and low pressure.

Ceres

Mars is the most often cited destination for human exploration. However, the dwarf planet Ceres, in the Asteroid Belt, is a small world, but contains an enormous amount of water, possibly up to 50 % of the dwarf planet's mass. Yet its

[1] Anzaldua, Al; Dunlap, David, "Moon to Moon to Mons", The Space Review, April 6th 2015, http://www.thespacereview.com/article/2725/1.

surface gravity is just 1/35th that of Earth. It has enough gravity that it should be possible to work on the surface, but little enough that it will be easy to launch huge amounts of water and other materials into space. With its rich water reserves and its location, it could be the Saudi Arabia of water for space exploration.

To get from the surface of Ceres to local orbit will require a change of velocity of about 360 m/s. This, combined with the low surface gravity, puts it well within the reach of steam rockets, including crude designs that are little more than a pressure vessel attached to exhaust nozzles. This velocity change should also be achievable with steam cannons or mass drivers. Steam launchers will be able to deliver large amounts of water to local orbit, and from there be towed to wherever needed by electric tugs (most likely uncrewed drones).

High Gravity Moons

High gravity moons, such as Earth's Moon, require a large enough delta-v that only chemical rockets are practical. Getting to and from our Moon's surface requires a delta-v of 1870 m/s to and from low lunar orbit. What type of lander would make sense for a spacecoach, where the goal is to generate propellant on site or in flight as much as possible?

Methane + oxygen will be an attractive option, as methane can be produced on board via a Sabatier reactor that converts hydrogen generated via life support electrolysis and carbon dioxide into methane and oxygen. Biofuels generated by algae or bacteria may be another good option. In both cases, waste streams can be converted into fuel for surface operations, or at least partially offset the need for pre-stocked fuel supplies.

Hydrogen peroxide in combination with kerosene or kerosene-like biofuel could be an attractive alternative. Dilute hydrogen peroxide can be generated in flight via an electrolytic process, using technology developed for wastewater treatment plants (or pre-loaded in dilute form at the beginning of the trip). When needed for propulsion, it would be converted to high concentration via a low temperature vacuum distillation process. Hydrogen peroxide is a potent oxidizer, and when used in combination with hydrocarbon fuel, generates a specific impulse in the mid-300s, more than adequate for descent to and from large moons.

As discussed previously, high concentration hydrogen peroxide is dangerous to handle, so nitrous oxide might be a safer oxidizer, though not possible to manufacture in flight.

Another way to optimize the design of landers for high gravity moons is to rethink their basic design. Readers may remember the lunar landers from the Apollo missions, so it is easy to assume that designers would build updated versions of them. Conventional wisdom has crews don their spacesuits and then board an encapsulated vehicle, like the Apollo lunar lander, for their descent to the surface. In effect they are boarding a spacecraft within a spacecraft, which adds a lot of complexity and weight.

Table 7.1 Propellant (as % of overall mass) required for ascent/descent each way

Destination/delta-v	Steam (190 s) (%)	H2O2/RP1 (350 s) (%)	LOX/H2 (450 s) (%)
Phobos/Deimos (5 m/s)	0.26	0.14	0.11
Ceres (360 m/s)	17.5	9.99	7.83
Moon (1870 m/s)	63.3	42.0	34.5

Why not have crews simply don their spacesuits and then ride down on an open platform? This would eliminate the complexity and weight associated with a pressurized cabin, life support equipment and other gear. If the purpose of the trip is to explore the surface, they will be venturing outdoors anyway. If it is to travel to a base on the surface, they will probably need to walk from the lander to the base, so either way they will be going outside, and the view from a lunar stander will be spectacular. Conservatively this would cut the weight of the lander by half or more, and reduce the fuel budget proportionally.

These "open air" landers could also be highly versatile machines. They would consist of a bare platform with tie down points and sit atop the engines and landing gear. They'll be autonomous vehicles that require little or no input from human pilots, a capability that is already well along in development and should be mature by the time these fly. SpaceX's Grasshopper and F9R and NASA's Morpheus programs are both examples of this developing capability.

Summary

The choice of propellant for higher thrust engines will depend on the delta-v required to reach the destination. For low gravity sites such as the Martian moons and Ceres, electrically heated steam rockets will be sufficient, with the benefit of being easily refueled, potentially with locally harvested water. For higher gravity sites, such as Earth's Moon, chemical propulsion will be a better option unless water can be obtained cheaply enough that the cost benefits outweigh the use of chemical propellants (Table 7.1).

One thing that has become apparent is that Earth's Moon is not a very attractive site either for either a base or for a staging area for missions further afield. It requires a lot of energy to reach, its dry except possibly at the north and south poles, and it's a costly detour on the way to Mars and other destinations. Compared to the Martian moons it is also resource poor from the standpoint of in situ resource utilization. Operators may instead be better off testing their equipment in orbit, and then venture onward to the Martian moons and beyond.

Chapter 8
Safety and Autonomy

Conventional spacecraft, as well as the International Space Station, are largely controlled from the ground. Spacecoaches, on the other hand, will require little or no ground support after they depart, and will also be safe by default. Deep space *Apollo 13* scenarios, which would be totally unsurvivable in a conventional spacecraft, will be manageable in a spacecoach.

Although a detailed safety analysis is beyond the scope of this book, one can anticipate the types of safety features spacecoaches will have versus conventional spacecraft. This analysis would most likely be done as part of detailed ship designs, which will be possible to develop once data from engine competitions is available. What is described in this book is intended as a reference design, or design pattern, as many configurations are possible.

One of the primary design goals for spacecoaches is to make them highly autonomous and easy to operate, much more like a stagecoach, and to design them so that they can be repaired in flight, and to remain habitable even in the event of a major system's failure.

The single greatest safety feature is the amount of water available. A well-designed ship will have multiple, distributed reservoirs, so that even if the ship is partially destroyed, useful amounts of water will remain available to continue providing life support, and thermal and radiation shielding, which are the key things the crew will need to survive long enough to be rescued or complete a return trajectory.

Space Debris

A spacecoach should already be highly resistant to debris, through the use of layers of Kevlar-type material, and possibly also pykrete. Provided the outer layers are well compartmentalized, the typical result of a partial hull penetration will be

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the loss of a few kilograms of water as it boils off into space. It's also worth noting that space debris will be less of a problem in high orbits and on interplanetary orbits compared to low Earth orbit. A spacecoach that is outfitted with supplemental chemical propulsion, for example hydrazine thrusters, will also be able to make short duration, low delta-v maneuvers to avoid oncoming debris.

But what happens if an impact is serious enough to compromise the pressure hull? A well-designed spacecoach will be compartmentalized so a compromised module can be sealed off from the remainder of the ship, assuming a repair to patch the leak is not possible. Ship designers should also look at ways to design multi-path configurations, where every module is connected to at least two others, or is compartmentalized such that if a unit is punctured, part of the space can be sealed off without blocking access to other parts of the ship. There should be many possible configurations to explore in spacecoach design competitions.

Electrical Power and Propulsion

When most people think of a spaceship, they think of a big ship with one or two big engines. Spacecoaches will have dozens or hundreds of small engines.

This is an important design feature because it eliminates a central point of failure in the ship's main power and propulsion systems, and prevents a small failure in one system from cascading to its neighbors, similar to the way an electrical blackout can trigger a "domino effect" in neighboring power grids. If part of a spacecoach's engine array or electrical bus is damaged, it will merely experience a fractional degradation in performance.

Spacecoaches will be exposed to sometimes violent space weather, coronal mass ejections in particular. It takes several hours or days for these to reach the inner planets, so in most cases, the crew will have adequate warning to throw switches to put the solar array and electrical bus in a safe configuration. The main danger with solar electrical storms is they can cause a large electrical current in long cables. This is another area where the spacecoach's distributed thrust architecture is advantageous, as the electrical bus can be subdivided into many smaller subsystems that operate independently and are not interconnected. Meanwhile, the availability of large water reservoirs provides radiation shielding for the crew and delicate electronics.

Attitude Control

The spacecraft's attitude can be controlled by gimballing the engines, as well as by modulating their thrust to produce an off-axis thrust or torque. If pykrete is used on the ship, it may also be possible to use it to form large momentum wheels that can be melted down at the end of a trip.

Oxygen Generation and Life Support

Spacecoaches will provide crews with extremely good safety margins for life support, especially oxygen generation. Oxygen is easy to generate from water via electrolysis, and from hydrogen peroxide by running it over a catalyst, similar to a contact lens cleaner. Both processes are simple, and in the case of hydrogen peroxide, non-mechanical.

Ships will be fueled with a dilute mixture of water and hydrogen peroxide, probably between 3 and 10 % concentration, comparable to what you will find at your local drug store. Each ton (1000 kg) of solution will generate about 50 kg of oxygen at 10 % concentration. A typical spacecoach will leave with at least 50,000–100,000 kg of water/hydroxide solution, enough to generate 2500–5000 kg of oxygen. This is enough for 2500–5000 crew-days, or enough to support a 5 person crew for 500–1000 days, without recycling carbon dioxide.

Additional oxygen can be generated via electrolysis, where electricity is passed through water to generate hydrogen and oxygen. The hydrogen can be stored for future use or vented overboard. This process will convert 1000 kg of water into 890 kg of oxygen. It does require electrical power, so a properly designed spacecoach should include portable units that can run on main or backup power.

An added benefit of using hydrogen peroxide as a precursor for oxygen is the extreme simplicity of the oxygen generating process. It is non-mechanical and requires no power source, while dilute hydrogen peroxide can be safely stored just like water. It can also be used as a disinfectant and can be used to treat solid waste.

Removing carbon dioxide can likewise be done in a number of ways, as discussed in the chapter on life support, which will provide the crew with multiple options in a long duration *Apollo 13* type of emergency. These will include Sabatier reactors (which convert hydrogen and CO_2 to methane), fast-growing plants, and chemical scrubbers (for use in an emergency).

In a long duration emergency, the crew would be able to survive almost indefinitely as long as plants can be adequately lit and irrigated. The basic strategy would be to use agriculture, and possibly also algae, to soak up CO_2, and rely on Sabatier reactors and scrubbers only when needed, and if the plants are edible much of that biomass offsets food requirements. Short of the complete destruction of the ship, it is hard to foresee a scenario where a crew runs out of oxygen before other systems fail.

Food

Spacecoach crews will likewise have multiple options for food if stranded. A typical mission will be stocked with a variety of frozen foods for daily use (the water will be reclaimed for propulsion), plants or seedlings, and dehydrated food for emergencies.

The most attractive option for long-term survival will be to cultivate fast growing plants that are mostly edible, so most of the biomass can be reclaimed as food. It will never be possible to make this a perfect closed loop system, but even if a fraction of the crew's exhaled CO_2 is converted into edible material, that will offset withdrawals from the bank of pre-stocked food.

Another technology that will likely become important is synthetic biology. Also in development are engineered bacteria that produce useful chemicals, such as milk fats and proteins. It's not hard to imagine bioreactors that produce ingredients like sugars, milk proteins, etc., that likewise cycle CO_2 back into edible matter.

Communication

Situating communication gear inside the spacecraft, in a protected but microwave transparent enclosure, will enable crews to repair communication systems without conducting an EVA. This will also enable the use of off-the-shelf equipment that is cheap, lightweight, and does not need to be hardened for the space environment. One consideration unique to an interplanetary craft will be the need for communication relays to enable spacecoaches to communicate with Earth when on the opposite side of the Sun.

This equipment should also be extremely lightweight, thanks to advances in computing technology, so a typical spacecoach will be stocked with many spare components that in turn are stored in well-protected areas. Even in the wake of a damaging solar flare event, the crew should be able to replace damaged components and quickly re-establish communication. Taken together these safety features mean that even extreme scenarios will be survivable, and survivable in relative comfort.

A detailed study of safety features will be a logical part of ship design competitions, which should be feasible once more engine performance is available.

Chapter 9
A Spacecoach Reference Design and Timeline

The Spacecoach Design Philosophy

The most important point to understand about the spacecoach is that it is an integrated system based on modularity, extensive re-use and incremental improvement. It borrows heavily from the lessons of the information technology industry, whose development has been propelled mostly by many small improvements (slightly faster chips, slightly better memory performance) that compound year over year into the dramatic advances of the past 30 years. We're now seeing a similar Moore's law effect in solar power, which will soon be as cheap or cheaper than coal power in many parts of the world.

Also important is the emphasis on autonomy, ease of use and serviceability. The authors envision spacecoaches being a lot like oceangoing sailboats. They will be durable, simple to operate, and designed to allow in-flight repairs and maintenance. They will operate largely independently of ground support. Maintenance using engines that can be cleaned or replaced in flight will reduce the need to design components for extreme mean time before failure. If replacing an engine module is similar to replacing a rack mounted computer, it will be easy to carry spare components, or even manufacture them in flight via additive printing processes. (Selective laser sintering could be used to make the type of metal and ceramic components one would need in an electric engine.)

The Crewed Ship

The ship described here is intended as a realistic and conservative starting point for detailed ship designs. (We look forward to the spacecoach design competitions in the coming years.) Where possible, the authors have used specifications taken

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from existing space-flown or space-ready hardware, and where available, have used reasonable extrapolations from existing systems or components. The intent at this point is to understand the overall economics, and to anticipate where further development will produce the best returns.

The reference design is a 40,000 kg (40 ton) ship by dry weight, including the ship's hull, engines, solar array, equipment brought on board, and non-consumable material. This is about 1/10th the mass of the International Space Station, still a significant ship, yet light enough that the Falcon 9 Heavy could lift the entire spaceship to LEO with a single launch.

Using a "kite" design, the ship will have five inflatable habs, most likely derived from Bigelow Aerospace technology. There will be one central hab (also fitted with water reservoirs, docking port and airlock) that, in turn, would be connected via long inflatable passageways to the four outer habs. (These will rotate around the central hab to generate artificial gravity during most of the flight.) The ship's hull will comprise half of the total empty weight, or 20,000 kg. Estimating from published specifications for Bigelow's habitable modules, they will weigh about 50–100 kg per cubic meter of usable space. That yields an interior volume of 200–400 m^3. For comparison, the International Space Station has a pressurized volume of 900 m^3. As inflatable/expandable module technology improves, it should be possible to further increase habitable space, reduce empty weight, or some combination of the two. Of the remaining 20,000 kg, this would be divided among engines and related equipment, solar arrays and power buses, equipment, and non-consumable items (clothes, chemicals, and so on).

The spacecoach will need between 500 kW and 1 MW of peak electrical power. This will requires a solar array with a total area of 1700–3500 m^2 at 1 AU (using 20 % efficient PV material). One of the advantages of this kite design is that the solar array can be rigged like a sail using the passageways like inflatable masts, which eliminates the need for a rigid truss in most areas. The array could, for example, be made of flat solar panels that unfold, accordion-style, as they are pulled tight. If a larger area is needed, the ship's rotation can be used to extend outer solar sails that hang off the ship as it spins. A design like this can be very lightweight, a few kilograms per square meter at most. So even at the high end of the requirements, the array should weigh less than 5000 kg.

The engine compartment will most likely be a small hab that is attached to the central hub, and is designed so that it can be sealed and pressurized to allow shirt-sleeve maintenance when the engines are not running. Overall the engines and associated equipment are calculated to weigh in at 5000 kg. This can probably be optimized further, but this is a conservative estimate for now.

That leaves another 10,000 kg (about 20,000 pounds) for equipment, instrumentation, and non-consumable items and chemicals to be used during the trip. Because every ounce of water and water-rich food eventually becomes propellant, the economics of spacecoaches are exceptional. The only dead weight is the ship itself and non-consumable material, while everything else helps push the ship along on its journey. This also means the ships can support larger crews compared to a conventional ship because crew consumables and life support don't have to be traded against propulsion.

Cargo Ships

Cargo ships will have a different set of design criteria, and since they will be uncrewed, designers don't have to build in features such as radiation shielding and artificial gravity into them, nor will they require a large pressurized volume. These ships will be designed to haul cargo and water cheaply, and will basically be a giant solar array attached to some engines and cargo compartments.

One can picture something like a barge, with a row of sausage-like cargo compartments, many of them unpressurized, flanked on both sides by large rectangular solar arrays. These ships will probably also use inflatable structures, but since they are mostly not for habitation, they can be lighter, less rugged and only weakly pressurized to hold their shape. As a result, designers can discard most of the hull from the crewed ship resulting in a solar array, engines and frame weighing roughly 20,000 kg when empty. Another feature of these ships is that they will generally deliver material one way. A typical ship will fly outbound loaded with cargo, water and equipment, and then return nearly empty except for return samples and propellant needed for the return leg.

Cargo ships will probably be fitted with engines that are designed to run at higher specific impulse, between 3000 and 8000 s. Hall effect thrusters can easily operate in the low end of this range using inert gases, and should be able to do so using water. The only tradeoff is that higher specific impulse engines accelerate more slowly given the same input power (longer overall trip time), but since these ships are uncrewed, the slower transit times are acceptable, and they would just fly out ahead of the crewed ships. Using a combination of crewed and cargo ships, there will be many ways to optimize logistics and operating costs.

Landers

Spacecoaches are not designed to land on a planetary surface, although at low gravity sites such as Phobos, and possibly even Ceres, it will be possible to detach inflatable habs and fly them down as one piece using low-thrust chemical rockets. The energies involved are small (just a few meters per second), making this a potentially safe and economical way to transfer people and light equipment. For higher gravity sites, such as like Earth's Moon, crews and equipment would be flown down via separately designed landers.

Development and Construction Timeline

Spacecoaches embrace the philosophy of iterative design, not unlike the software industry where the manta "release early, release often" is often used. Designers can build first generation ships in just a few years, and upgrade them incrementally as new technologies come online.

Ground-Based Research (What's in the Works Now)

Most of the spacecoach research and design work can be done in ground-based facilities. Among the key things designers will need to nail down:

- Water-based electric engine dimensions and performance: Program managers will define standard form factors and interconnects, while teams compete to build the best performing engines that meet these specifications. This is a key item since engine performance drives the rest of the system and economic models.
- Solar array designs: There can be competitions to design large array solar arrays that can be lashed to a rigid frame, are easy to assemble or (ideally) self-assemble and maximize power density. This is another key metric since thrust is limited by power, and in turn will determine vehicle size, payload capacity, etc.
- Investigate available inflatable/expandable structures to evaluate the possibility of adapting them for use in spacecoach designs: Bigelow Aerospace is already flying two inflatable habitats in Earth orbit, and will soon add the BEAM module to the International Space Station. Determine realistic mass/volume parameters for system design and modeling.
- Life support and agriculture systems: Based on crew size, calculate consumable budgets and determine how much can be generated via regenerative systems, on board agriculture, algal bioreactors, etc., and if that's not feasible, what the budget looks like for non-regenerative systems.

This phase of the program will be low cost and low risk, consisting of several engineering competitions that run in parallel (one for engine designs, one for solar array designs, and one for life support/ag systems designs). This phase would conclude with a design competition for a complete spacecoach design that utilizes the best component technologies found in the first round of competitions. The winning designs would be evaluated via numerical simulations, to develop accurate forecasts of their performance. Most of this work could be completed in 2–3 years.

Small Satellites (Near Future)

To save money, designers could launch a satellite that is small enough that it can be launched on a small rocket, or as a secondary payload on a larger launch.

This would essentially be a remote-controlled model, which though scaled down could validate key aspects of the design pattern, specifically the ability to reliably generate thrust using water in solar-powered electric engines in actual space conditions.

This mini-ship would be launched to low Earth orbit, where it would perform a long series of altitude and plane change maneuvers to build up delta-v to simulate a lunar or Martian mission. While it probably would not be possible to simulate the full ship's operation, operators could use this strategy to test engine and solar array performance in actual spaceflight conditions, and then proceed to a larger unmanned vehicle that could later be incorporated into crewed ships.

This satellite will also be an ideal secondary payload. There are no flammable fuels or pressurized tanks that would pose a risk to the primary payload. This should substantially reduce the cost of flight testing spacecoach elements in actual space conditions.

Scaled Down Uncrewed Ship (3–5 Years)

In phase two, a scaled down and uncrewed ship will be launched into Earth orbit, where it will simulate a long duration, high delta-v mission such as a round trip to the Martian moons. It will simulate high delta-v by stepping up and down between orbital altitudes or by making plane changes, to accumulate a large total delta-v while remaining in low orbit. This will allow the ship and its systems to be teleoperated from the ground with minimal communication latency.

These test flights will be used to validate engine and power plant performance, ship systems and avionics without putting a crew at risk. Ideally, the uncrewed ship will be a segment, such as inflatable hab, that can re-used in the first crewed ship, to reduce initial construction costs somewhat.

The USS Roddenberry

The first crewed ship, which could be assembled in part using elements of the uncrewed test bed, would be assembled by crews in low Earth orbit, and then flown uncrewed using electric propulsion to the EML-2 Lagrange point, where it will be parked to await its first supplies and long-duration crew.

The first crewed proving flight would likely remain in cis-lunar space. From EML-2, the delta-v to low lunar orbit is just 600–800 m/s. The ship could simulate a Mars mission by descending to lunar orbit and then executing a series of orbital altitude and plane changes, like the uncrewed simulation, to accumulate delta-v and trip times comparable to a Mars mission, or least collect enough data to validate performance and safety criteria for the first trip outside the Earth-Moon system.

Life support, hygiene, shielding and artificial gravity would all be thoroughly tested with a human crew on board, providing the data and confidence mission planners would need before sending a crew out to the Martian system. The ship would then return to EML-2, where it would rendezvous with supply ships carrying water, consumables and equipment for the next voyage, and then with the first Martian crew.

Mars Orbital Mission

The first mission beyond the Earth-Moon system will likely be a Mars orbital mission with several goals:

- Teleoperating surface robots and rovers on the Martian surface. In low Martian orbit, telecommunication delays will be just a few thousandths of a second, enabling astronauts to teleoperate robots using virtual reality gear.
- Surveying the Martian moons Phobos and Deimos from close orbits. This would be to determine what surface materials are available, and to identify the best landing sites for future missions to the Martian system.
- Exploration of the lunar surface, including sample collection. This would be to determine the available and extent of materials that are suitable for in situ resource utilization (water/ice, organics, soil, etc.).
- Flight test regolith burning engines on return leg. This would be to compare actual performance against ground-based tests (assuming regolith burning engines are feasible). Even if only a small amount of regolith is used as propellant, it will be possible to determine the actual performance of the engines.
- Further proving out ship systems. This would focus on life support and agriculture, during a long-duration flight with crew on board.

Taking a human crew all the way to the Martian surface and back is a much greater challenge, and much riskier from a safety standpoint. Contamination, especially forward contamination, is also a real risk. For these and many other reasons, it may make sense to use the Martian moons as forward bases and space stations, as south pole McMurdo stations of a sort, to build up the infrastructure and operating confidence needed to proceed onward, then go to the surface when ready.

The Fleet Grows

Spacecoaches will be the foundation for a real world star fleet, a fleet that will eventually be able to reach destinations throughout the Solar System. Their lower cost and declining value with age will also make them accessible to smaller nations and perhaps even private operators (much as the Pilgrims were able to charter the Mayflower for their journey in 1620).

Because spacecoaches are refuelable and upgradable, there will rarely be a good reason to dispose of one entirely. Older ships can be repurposed as space stations, or disassembled to recycle their components into orbital and surface bases. The number of them in operation, and the number of sorties in progress at any time, will steadily grow.

As permanent settlements are built, and as operators learn to extract resources locally, spacecoaches will open much of the Solar System to human exploration, as well as form the basis for small space-based colonies.

Chapter 10
Mission Templates and Cost Estimates

These ships will not be mission specific. Even first generation spacecoaches will be capable of reaching a variety of interesting locations. In this section of the book, the authors provide mission templates and economic models. These templates will give mission planners a good idea of the resources and budgets needed for a given route. The authors would like to acknowledge Rüdiger Klaehn here, who works as a software engineer at the German Space Operations Center, and assisted with calculations for low thrust delta-v figures to destinations throughout the inner Solar System.

The authors were intentionally conservative when preparing these models, and assumed that only low-thrust electric propulsion is used. This results in higher delta-v requirements for many routes, although this is more than offset by the increased efficiency of electric engines. Missions also did not include other cost-saving maneuvers, such as gravitational slingshot or the more recently discovered ballistic capture method.

The following process was used in calculating mission profiles (delta v, resupply costs, etc.):

1. EML-2 is defined as the standard starting point for missions. Spacecoaches will start their missions at, and return to, EML-2. This makes direct comparisons between different mission profiles easier.
2. Most equipment and material is launched to low Earth orbit (cost $1700/kg via SpaceX Falcon 9 Heavy), and is spiraled up to EML-2 using solar electric propulsion. Assuming ~7 km/s in delta v from LEO to EML-2, this results in a cost to EML-2 ranging from $2150/kg ($I_{sp} = 3000$ s) to $2750/kg ($I_{sp} = 1500$ s). The higher figure is used for resupply cost estimation.
3. The entire trajectory from EML-2 to the destination and back is flown via low thrust propulsion.
4. Economizing maneuvers such as high thrust burns to exploit the Oberth effect, Hohmann transfer, gravity assist, or low energy transfers are not utilized.

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5. Water-rich material, such as frozen food, is counted as propellant. The amount of water required is calculated using Eq. 10.2 below (2). This figure is divided by 40,000 kg and rounded up to yield the number of Falcon 9 Heavy launches to deliver water to orbit. (We assume that 40,000 kg of the 53,000 kg LEO payload capacity is water, and the remainder is budgeted for engines, solar panels and other equipment.) This, in turn is multiplied by $100,000,000 (Falcon 9 Heavy launch cost).
6. The ship fabrication cost is estimated by using SpaceX Falcon 9 Heavy as a proxy for the initial cost to fabricate the dry hull (~$100–200 M), and then amortizing this across the expected number of missions the ship will fly. Amortized over 5–10 missions, the fabrication cost is approximately $10–$20 million per mission.
7. The cost to deliver the dry hull to EML-2 is estimated by multiplying 40,000 kg by the EML-2 delivery costs (2), and is amortized over 5–10 missions. This yields an amortized ship delivery cost of $8.6–$22 million per mission.
8. The crew, delicate equipment, perishables, return vehicle and last minute cargo travel directly to EML-2 via a Falcon 9 Heavy launch, at an approximate cost of $100 million per mission.
9. (5), (6), (7) and (8) are summed to yield a rough estimate of the per mission cost, including ship fabrication, delivery, crew launch and consumable resupply costs. (5) is dependent on mission delta v and engine specific impulse, while cost factors (6), (7) and (8) should be approximately the same for different missions.
10. No assumptions are made about launch cost reductions due to booster reusability. If it becomes possible to reuse boosters for water delivery, substantial cost reductions may be possible. However, cost estimates are made using current, published LEO launch costs.

Because consumables and waste streams *are* the propellant in the spacecoach architecture, mission planning is simplified. One can simply budget the amount of consumables required to support a crew of a given size for the duration of the mission, and from that calculate the engine performance required to achieve the delta-v for the mission.

$$
\begin{aligned}
I_{sp} &= \frac{\delta v}{9.81 \times ln\left(\frac{m_{initial}}{m_{final}}\right)}, \\
m_{initial} &= m_{hull} + m_{consumables}, \\
m_{final} &= m_{hull} + m_{waste}
\end{aligned}
\tag{10.1}
$$

$$
P = \frac{0.5}{\eta} \times \dot{m} \times (9.81 \times I_{sp})^2 \tag{10.2}
$$

Equation 10.1 above gives the minimum specific impulse required to achieve the delta-v for a mission as a function of the hull's empty mass and the consumable budget for the trip (also accounting for waste that cannot be processed by the engines). For example, let's use a 500-day Phobos roundtrip from EML-2, with a 40,000 kg dry hull and 6-person crew requiring 15 kg per person-day in consumables, 90 % of which can be reclaimed for use in engines. (If engines can be made to work with gasified waste, near 100 % reclamation will be possible.) This works out to 45,000 kg of consumables (water, frozen food, etc.), 40,500 kg of which is reclaimed and used for propulsion. According to the spacecoach equation, engines operating at a specific impulse of about 2850 s or better will be sufficient. (Hall effect thrusters operate in this range.)

It is interesting to note that delta-v capability scales with crew size and trip duration. This is counterintuitive, but it makes long duration, high delta v missions with larger crews easier because the consumable budget is large to begin with, and thus provides a large amount of propellant to work with during the course of the mission. This is the exact opposite of conventional mission architectures, where large consumable budgets force even larger propellant budgets, a problem that is avoided when the consumable waste streams are the propellant.

When engine performance is well matched to the planned consumable budget, the approximate cost to resupply a spacecoach will be the cost to deliver the crew, gear and consumables to the EML-x starting point. No extra propellant is required, although planners will presumably build reserves into mission plans.

$$m_{propellant} = e^{\frac{\delta v}{9.8 \times I_{sp}}} - 1, \textit{ yields kilograms of propellant per kilogram of dry hull} \tag{10.3}$$

Equation 10.3 can be used in a more conventional mission planning approach where one starts with the required delta-v for the mission and known engine performance. This equation yields the propellant mass required per kilogram of dry hull.

It is actually simpler to use Eq. 10.1, as it defines the minimum amount of propellant that will be available for a given mission based on its duration and crew size. This material needs to be on board in any case. One attractive feature of this approach is that it leads with crew support requirements, while the required performance factors (engine specific impulse, power requirements, etc.) are outputs.

The resulting cost estimates do not reflect potential savings due to a number of factors, which include:

- The possibility of using chemical propulsion for certain maneuvers, to exploit the Oberth effect when in a deep gravity well.
- The possibility of using timed electric propulsion to gradually transition to a highly elliptical orbit, which is then circularized. This will allow a solar-electric craft to exploit the Oberth effect to reduce overall delta v, although the maneuver takes significant time to complete.

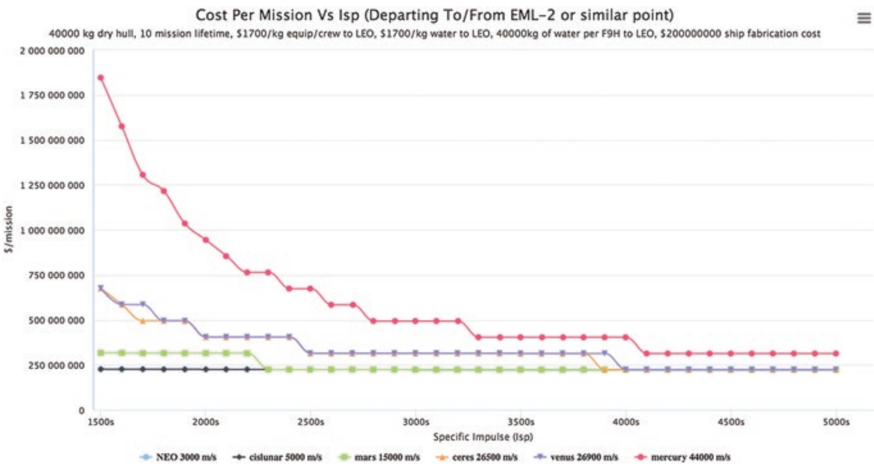

Fig. 10.1 Mission cost versus specific impulse for selected destinations within inner solar system

- The use of maneuvers such as aerobraking, gravitational assist or ballistic capture to reduce propulsive delta v requirements.
- The possibility to leave equipment, waste, or part of the ship itself at the destination, for use as a space station or surface base, which lightens the ship for the return leg.
- In situ resource utilization to harvest water at the destination for the return trip.
- Bulk delivery and storage of water and consumables at EML-2 depots, to allow for economies of scale across multiple missions.

In most cases, there will be numerous ways to reduce costs well below the baseline estimates, either via technological improvements or logistics. However, for the purposes of introducing the spacecoach reference design the authors present simplified missions that also represent worst-case scenarios in terms of the delta v budgets, and therefore resupply mass budgets (Fig. 10.1).

We used these rules to build a parametric model in Python which, in turn generates graphs illustrating how mission cost factors vary in relation to specific impulse, as shown in Fig. 11.1. Notice that mission cost steps down as a function of specific impulse (as specific impulse increases, the number of surface launches to deliver water to LEO decreases). Readers can obtain a copy of the source code at https://github.com/worldwidelexicon/spacecoach.

Chapter 11
Missions to the Cis-Lunar Environment, the Martian Moons, and the Asteroids

Cis-Lunar Space

The first spacecoaches will probably spend their first proving runs in cis-lunar space. There it will be possible to shake them down and simulate long-duration interplanetary missions while remaining close to Earth in the event of an emergency (Fig. 11.1).

The following mission template depicts a lunar proving run, starting at the Earth-Moon Lagrange Point 2, venturing to low lunar orbit, lunar polar orbit, low lunar orbit and back, with an optional surface sortie if the spacecoach is equipped with a lander. Lagrange points are points in space where Earth's gravity and the Moon's gravity cancel each other out. These are good places to park interplanetary spacecraft, as they are near the edge of Earth's gravity well.

Leg 1: *Resupply From LEO → EML-2 (7 km/s)*
The bulk of the material for the mission will be launched into low Earth orbit (cost $1700/kg via Falcon 9 Heavy), and from there, will spiral out via electric propulsion to the EML-2 parking orbit, where spacecoaches normally depart for deep space missions. This substantially reduces the cost of launching the bulk of the ship's mass and water directly to EML-2 via chemical propulsion.

Assuming a specific impulse of 1500 s, 0.62 kg of material can be shipped to EML-2 for every kilogram launched to low Earth orbit, resulting in an effective cost per kilogram at EML-2 of $2700/kg.

Leg 2: *EML-2 → LLO (0.8 kms)*
At EML-2, the spacecoach is refueled and resupplied, and from there descends to an equatorial low lunar orbit, with a delta-v of approximately 0.8 km/s.

Leg 3: *LLO ← → LPO (3.4 km/s), repeat as desired to accrue delta-v*
From an equatorial low lunar orbit, the ship then changes its plane to a low polar orbit and back to low equatorial orbit, for a combined delta-v of 3.4 km/s.

B. McConnell and A. Tolley, *A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach*, SpringerBriefs in Space Development,
DOI 10.1007/978-3-319-22677-4_11

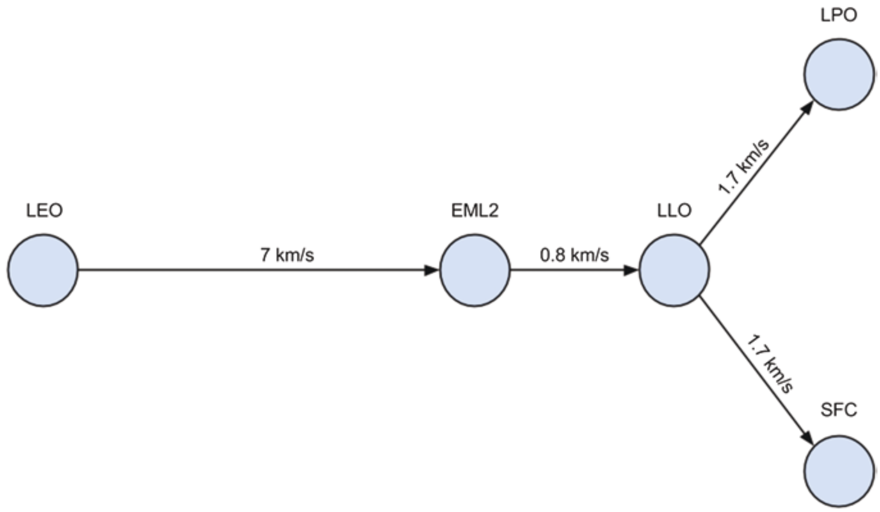

Fig. 11.1 A delta-v "subway map" for cis-lunar space using low thrust propulsion

This maneuver may be repeated multiple times to achieve a delta-v comparable to an interplanetary mission.

Leg 4 (Optional): LLO ← → Surface via Lander (3.4 km/s)
If equipped with a crewed or robotic lander, the ship may dispatch it to the surface. The lander is treated as part of the ship's payload for mission budgeting purposes since it will be powered by chemical rockets, whose propellant cannot be counted as consumable as water can.

Leg 5: LLO → EML-2 (0.8 km/s)
The craft then returns to EML-2, where it meets up with the next outbound supply delivery spiraling up from low Earth orbit, the crew returns to Earth via a crew return vehicle, and the next crew arrives for the next mission.

This mission has a total delta-v of about 5 km/s, although if the objective is to simulate a Mars-Phobos expedition the plane change maneuver can be repeated to accrue delta-v similar to that expected for a Martian expedition.

Moon Mission Economics

Initial Ship Delivery to EML-2

As noted earlier, by using solar electric propulsion to deliver material from low Earth orbit to EML-2, it is possible to significantly reduce costs. With a dry mass of 40,000 kg, the estimated costs to launch the hull to the staging location will be approximately $110 million in current U. S. dollars. This cost should be amortized across the number of missions the ship is expected to fly before retirement. Since the ship will not be exposed to extreme forces or vibration, it is probably reasonable to expect that it can complete 5 or 10 missions during its useful life, resulting in an amortized delivery cost of $10,000,000 to $20,000,000 per sortie, with similar costs for materials and fabrication prior to delivery.

Per Mission Supply Costs

The mission delta-v will range between 5 and 15 km/s depending on how many times the plane change maneuver is repeated. Let's consider two scenarios to get a sense of per-mission costs. One scenario will be a relatively short 6-month mission with a 5 km/s delta-v, while the other will be a full Mars simulation, with a 500-day duration and 15 km/s delta-v. In both scenarios there is a six-person crew.

The short duration mission will require about 16,000 kg of consumables (15 kg per person—day for water, food, and oxygen), while the long duration mission will require 45,000 kg. Water, liquid waste and carbon dioxide are reclaimed for use by the engines, while solid waste is not. If the engines can process gasified waste then solids can be pyrolized, and nearly 100 % of consumable waste streams can be utilized, but assume for now 10 % of the consumable mass is not usable (adjust this factor as desired). This yields a propellant mass of 14,400 and 40,500 kg, respectively.

With these inputs, Eq. 10.1 yields the engine performance required to achieve the desired delta-v. For the short duration, 5 km/s mission, the engines must perform at an I_{sp} of just under 1600 s. For the long duration, 15 km/s mission, the engines must perform at an I_{sp} of just under 2400 s. Both figures are well within the performance envelope for electric propulsion technologies.

The cost to deliver the consumables to EML-2 ranges from $43 to $122 million at $2700 per kilogram.

Crew Launch and Return

The crew, radiation sensitive equipment and perishables will be launched directly from Earth to EML-2 via a Falcon 9 or Falcon 9 Heavy at a per mission cost of approximately $100,000,000.

Total

Summed together, the per mission cost for this type of flight is estimated to be approximately $200–$300 million with amortization across 5–10 missions during the ship's useful life. This is inexpensive by the standards of human spaceflight, and probably cheaper on a per person basis than it currently costs to launch crew to the ISS.

The primary goal of these missions will be to fully validate spacecoaches, identify remaining problems, and upgrade components. This phase of development will last several years, and should lead to technical and operational improvements that will reduce the cost of BEO (beyond Earth orbit) missions.

The ability to operate economically even at low specific impulse means that planners need not wait for more advanced engines to become available. The first ships can fly extended missions in cis-lunar space, giving operators the ability to prove out all ship systems, and crews the opportunity to rehearse for trips beyond Earth orbit.

The Martian Moons

The first spacecoaches will probably spend their first proving runs in cis-lunar space. There it will be possible to shake them down and simulate long duration interplanetary missions while remaining close to Earth in the event of an emergency (Fig. 11.2).

Many of the envisioned missions to Mars are focused on sending humans all the way to the surface. For a number of reasons, operators may want to stop short

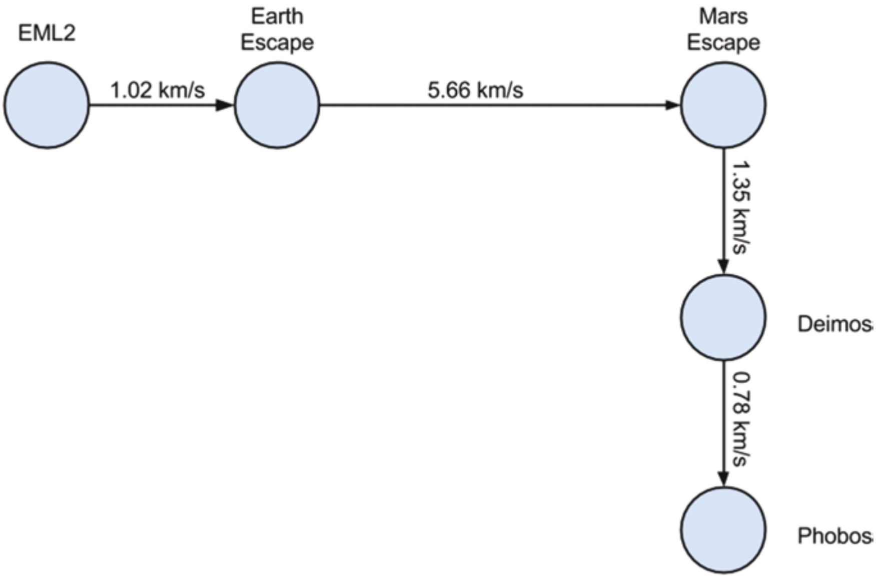

Fig. 11.2 Delta-v "subway map" for a mission from EML-2 to and from the Martian moons

of putting astronauts on the surface, at least during early trips to the Martian system, for these reasons:

- Physical danger. Landing and ascending to and from the Martian surface is dangerous. About a third of the probes sent to Mars have been lost or crashed.
- Difficult working environment. It is difficult to work in a pressurized suit with a limited field of view.
- The equipment, propellant and additional supplies needed to reach and return from a surface base will increase costs greatly. This may be by an order of magnitude or more.
- Probes can be sent to multiple sites and teleoperated concurrently. This increases the odds of a good science return.
- Probes can be designed to optimize investigational capability. For example, operators can switch from eye level to "ant level" views depending on what they are looking for.
- Protection from microbial contamination in both directions.

The better near-term option may be to have astronauts in low Martian orbit, or on one of Mars' moons, teleoperate surface-based robots and rovers using virtual reality gear. This technology has improved dramatically in recent years. The Oculus rift system, for example, solves the usability issues associated with previous systems and gives its users the feeling of being fully immersed in a virtual environment. This technology will only improve in the years ahead, and with the minimal communication delays from Martian orbit (about 20 ms) will enable astronauts to control robots with human levels of dexterity and haptic (sensory) feedback. They will have the sensation of being on the surface while working in a shirtsleeve environment, and none of the physical risk associated with a trip to the surface.[1]

The crews will be able to control surface robots in many locations around the world as they orbit, effectively teleporting from site to site as they fly overhead. This will enable mission planners to flexibly plan the science returns by sending landers down to many sites, whereas a crewed surface mission will be limited to a single site. Meanwhile, astronauts get to virtually explore a diverse variety of surface sites.

By proceeding incrementally, operators can build up a base of operations, not unlike Antarctica's McMurdo Station, from which they can set off on surface expeditions when they are sure they are ready, and when they have positively identified sites worth visiting. Equally importantly, future Martian surface expeditions will have a safe harbor they can go to within less than a day if they need to, much as the Apollo astronauts could retreat to Earth.

Leg 1: EML-2 → Earth Escape (1.02 km/s)

EML-2, being situated near the outer boundary of Earth's gravity well, is a good starting point for space coach missions. As with lunar proving runs, the

[1] "Moon to Moon to Mons: Synergies for Moon and Mars Development," Anzaldua, Al, and Dunlap, David, *The Space Review,* April 6, 2015, http://www.thespacereview.com/article/2725/1.

spacececoach will be resupplied by unmanned ships spiraling up from low Earth orbit using electric propulsion, with a per mission resupply cost of $2700 per kilogram of material shipped up, including water. From EML-2, the spacecoach will spiral out of Earth's gravity well, a maneuver that requires 1017 meters per second in velocity change.[2]

Leg 2: *Earth Escape → Mars Escape (5.66 km/s)*
Once out of Earth's sphere of influence, the spacecoach will spiral out from Earth's orbit to Mars' orbit, which will require a delta-v of 5.66 km/s, possibly less if the spacecoach can fly an approximately Hohmann trajectory and coast most of the way between Earth and Mars. It is assumed that this was the more conservative case of a spiral trajectory, where delta-v is equivalent to the difference in Earth and Mars' orbital velocities.[3]

Leg 3: *Mars Escape → Deimos (1.35 km/s)*
Once the spacecoach reaches Mars' sphere of influence, it will spiral into Deimos, the outermost Martian moon, and enter local orbit around it. There it may optionally detach and land part of the ship on the moon for use as a permanent base.

Leg 4: *Deimos → Phobos (0.79 km/s)*
From Deimos, the spacecoach will spiral further into Phobos, which is effectively in low Martian orbit, and may optionally transfer components or material to its surface as well.

Leg 5: *Phobos → Mars Escape (2.14 km/s)*
After orbiting and optionally exploring the surface of the Martian moons, the spacecoach will spiral back out of Mar's sphere of influence, which will require a delta-v of 1.35 km/s.

Leg 6: *Mars Escape → Earth Escape (5.66 km/s)*
From there it will return from Mars' orbit to Earth orbit, with a delta-v of 5.66 km/s

Leg 7: *Earth Escape → EML-2 (1.02 km/s)*
Finally, it will spiral into EML-2 for crew exchange and resupply.

Martian Moons Mission Economics

Initial Ship Delivery and Amortization

As with the lunar mission, it is estimated that a EML-2 delivery cost of about $110,000,000 for a 40,000 kg ship, using solar electric propulsion to spiral it out

[2]Calculations courtesy of Rüdiger Klaehn.

[3]Calculations courtesy of Rüdiger Klaehn.

to EML-2. This will be amortized across 5–10 missions, as will the initial fabrication costs, with an amortized per mission cost ranging between $20 and $40 million.

Per Mission Refueling and Resupply Cost

Because the delta-v for this mission is greater than for a lunar proving run, approximately 8.82 km/s each way, more water and water-equivalent material is needed to load the spacecoach. However, this is also a long duration mission, minimum 500 days, so the crew consumable budget will be larger.

For a 500-day mission with 100-day reserve supplies, the consumable budget will be 54,000 kg. If 90 % of the consumable waste streams, mostly water and carbon dioxide, are reclaimed for propulsion, this yields 48,600 kg of propellant, 5400 kg of unusable waste, and a 40,000 kilogram dry hull. Using these inputs Eq. 10.1 yields a required specific impulse of 2450 s. If this is greater than what currently available engines are capable of, planners can load more water onto the ship than the crew will consume to reduce the specific impulse required (by increasing the ratio of $m_{initial}$ versus m_{final}).

At $2700/kg the cost to deliver the consumables to EML-2 will be approximately $150 million. If more water is required, in order to operate with less efficient engines, this delivery cost will be higher. It's interesting to note in this case, that the ship will also be capable of supporting a larger crew as it will be overloaded with consumables.

Crew Launch and Return

As with the lunar proving runs, the crew, sensitive electronics and perishables would fly directly from Earth's surface to EML-2 via chemical propulsion, at a cost of approximately $100 million.

Total

Summed together, this type of mission will cost approximately $300 million per sortie, or around $50 million per crew member assuming a six-person crew.

Since this is a higher delta-v mission (18 km/s roundtrip), mission costs are more tightly linked to specific impulse. At the low end of the electric propulsion performance envelope (<1500 s), the cost of delivering water and water-equivalent material is dominant. However, even with modest improvement (in the range of

2000–2500 s), this cost drops off sharply, leading to per-mission costs for a 40-ton ship well under $300 million, a price that is affordable to many nations.

Cost Reduction Strategies

Readers will notice that the spacecoach equation (Eq. 10.1) predicts the engine specific impulse required to match engine propellant requirements to the crew consumable budget. Since crew consumables cannot be reduced much below a fixed limit without impairing crew comfort, this represents a cost minima for a given crew size and mission duration. Spacecoach designers will want to improve engine performance so it meets or exceeds this requirement, as otherwise ships will need to be overloaded with more water than the crew really requires. On the other hand, overloading ships may be desirable from a safety perspective (e.g., radiation shielding, oxygen generation during an extended emergency, etc.).

Once engines improve to the point that they meet or exceed the requirements given by the spacecoach equation, planners can look to other cost optimization strategies, which will include:

- Delivering and storing water and consumables in bulk at the EML-2 starting point. Instead of delivering supplies to EML-2 on a per mission basis, they would be delivered in aggregate, for use by many missions. This will reduce cost inefficiencies due to using mission specific launches.
- Developing engines that work well with gasified waste. Once this capability is developed, solid waste and trash can be pyrolized and used as propellant, enabling near 100 % consumable waste stream reclamation. Special-purpose units may need to be developed for this, where some modules process water and/or CO_2, while others just process gasified waste.

Leaving part of the ship in Mars orbit or on the Martian moons is another way to reduce costs, and will make it possible to reduce propellant requirements by an additional 30–50 %. Operators will see the best improvements as a result of improving engine performance, so that is where attention should be focused when upgrading ships.

Even with the baseline scenario, the per mission costs are still low by the standards of human spaceflight.

Asteroid Interception and Mining

Spacecoaches will be useful in space mining operations, which due to the high potential value of metallic asteroids, may be one of the more attractive uses for them. Space mining experiments would also be a proxy for asteroid interception and diversion missions, and enable operators to gain experience with different techniques.

The baseline mission scenario would be as follows:

A spacecoach would depart EML-2 and sail to an NEO (near Earth asteroid) that requires a low delta-v to reach it. Once there, the crew would harvest regolith rich in the desired materials. Some of this regolith would be used as propellant. For example, a regolith-based electric engine would vaporize the regolith first using a pulsed laser, and then feed this vapor into an electrothermal or electromagnetic second stage to achieve high exhaust velocities. This would enable a spacecoach to return with a substantial amount of cargo, while minimizing the amount of material that needs to be launched from Earth's surface.

Consider, for example, an NEO that can be reached with a low delta-v. Some can be reached with delta-v's well under 1 km/s each way.[4] Let's use 1 km/s as a baseline value. The spacecoach has a dry hull mass of 40,000 kg, a six-person crew, and a one-year mission duration. This leads to a consumables budget of approximately 32,000 kg. Even engines operating at the low end of the electric propulsion envelope will be capable of delta-v well in excess of the required amount, meaning that even with no regolith-based propulsion, the ship should be capable of returning a significant amount of surface material to the starting point. Since the initial missions would likely be focused on characterizing the material to determine its economic value, returning very large quantities would not be necessary.

If engines can be developed that use regolith as propellant, it will become possible for the spacecoach to return tens of metric tons of material with each round trip without using large amounts of Earth-launched propellant for the inbound leg back to EML-2. As many rare metals trade at prices in excess of $10,000/kg, a space mining operation that returns material to EML-2 could potentially operate at a profit if valuable materials can be extracted from bulk material.

While it may take time to develop this capability, it will make sense to explore NEOs both for scientific and financial reasons. These missions will also enable spacecoach operators to experiment with a variety of asteroid deflection techniques, and in the process of developing space mining capability also develop techniques to be used in planetary defense scenarios. A study of how a spacecoach might be applied to planetary defense against potentially hazardous asteroids is just one of the many elements that would be considered as studies of such systems are pursued going forward. See Joseph N. Pelton's and Firooz Allahdadi's *Cosmic Hazards and Planetary Defense*, (Springer, 2015).

[4]Delta-v required to reach near earth asteroids, website: http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html.

Chapter 12
Ceres and In Situ Resource Utilization

Why Ceres?

Ceres is a rarely mentioned destination for human space exploration, yet it is a potentially interesting resource. It is an enormous water reservoir, thought to contain much more water than Earth, and it is positioned mid-way between Earth and the outer planets. It is in a shallow gravity well, with surface gravity of just $0.028g$, and an orbital velocity of just 360 m/s, meaning it will be possible to launch water into orbit at low velocities. Yet, it has enough surface gravity that it should be possible to work on the surface (Figs. 12.1 and 12.2).

Ceres will require a fairly large delta-v to reach on a direct trip from Earth, with an expected delta-v from low earth orbit to Ceres of about 13 km/s each way. The primary challenges in reaching Ceres, compared to a trip to Martian orbit, will be the increased delta-v (higher impulse engines will be very useful), and the development of high power density solar arrays, as sunlight is roughly 1/10th as intense at that distance. The first expeditions would yield little or no water for the return trip, so they would need to be designed to fly a full roundtrip (total delta-v of about 26.5 km/s).

Leg 1: *EML-2 → Earth Escape (1.02 km/s)*
As with the lunar and Martian runs, the spacecoach will spiral out from EML-2 to leave Earth's sphere of influence.

Leg 2: *Earth Escape → Ceres Escape (11.88 km/s)*
The ship will then spiral out from Earth's orbit to Ceres.[1]

Leg 3: *Ceres Escape → Low Ceres Orbit (0.35 km/s)*
Once in Ceres' sphere of influence, the ship will spiral in to low Ceres orbit, and from there may optionally fly landers to the surface.

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[1]Calculations courtesy of Rüdiger Klaehn.

B. McConnell and A. Tolley, *A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach*, SpringerBriefs in Space Development,
DOI 10.1007/978-3-319-22677-4_12

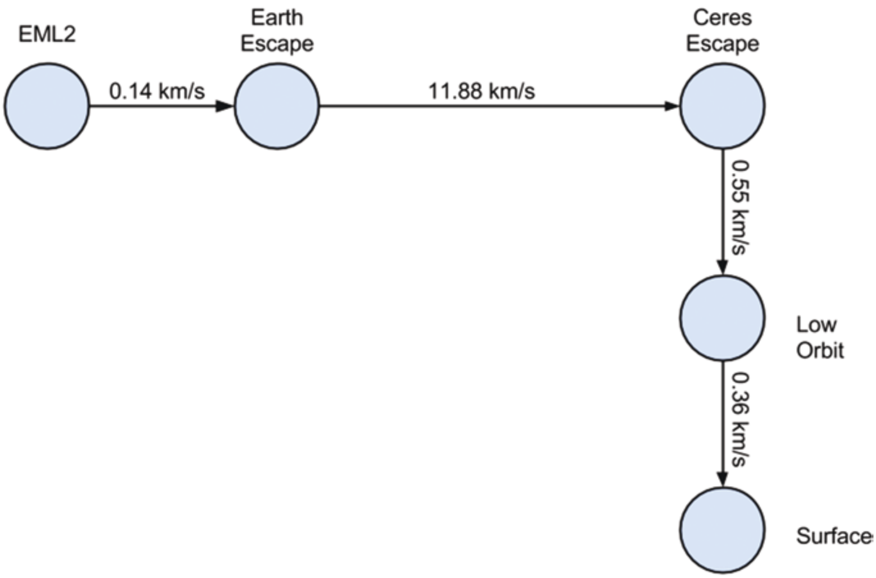

Fig. 12.1 A delta-v “subway map” for a mission from EML-2 to and from Ceres

Legs 4, 5, 6: *Low Ceres Orbit → EML-2 (13.25 km/s)*
The ship will then fly back to EML-2, with a total delta-v of 12.57 km/s each way.

Surface Operations

Ceres is thought to contain a huge ice reservoir, and possibly subsurface oceans. The presence of water and other materials makes this a prime candidate for finding life, and thus not only of interest for resource utilization but also as a science destination. The only similar destinations are the Jovian and Saturnian moons that are much harder to reach, not only in terms of delta-v to get there but the deep local gravity well and extreme radiation environments.

The shallow gravity well at Ceres will make it easier to transport large amounts of equipment and material to and from the surface. The delta-v from the surface to low orbit is 360 m/s, potentially reachable via steam rockets and mass drivers.

Ceres is an attractive enough science location that it will might make sense to fly part of the spacecoach down to the surface where it will remain as a permanent base. To do this, one or two of the habs could be detached from the main ship, coupled together, and flown down to the surface using relatively low thrust rockets attached to the exterior. This is a one way trip for these components, which will reduce propellant costs for the return trip.

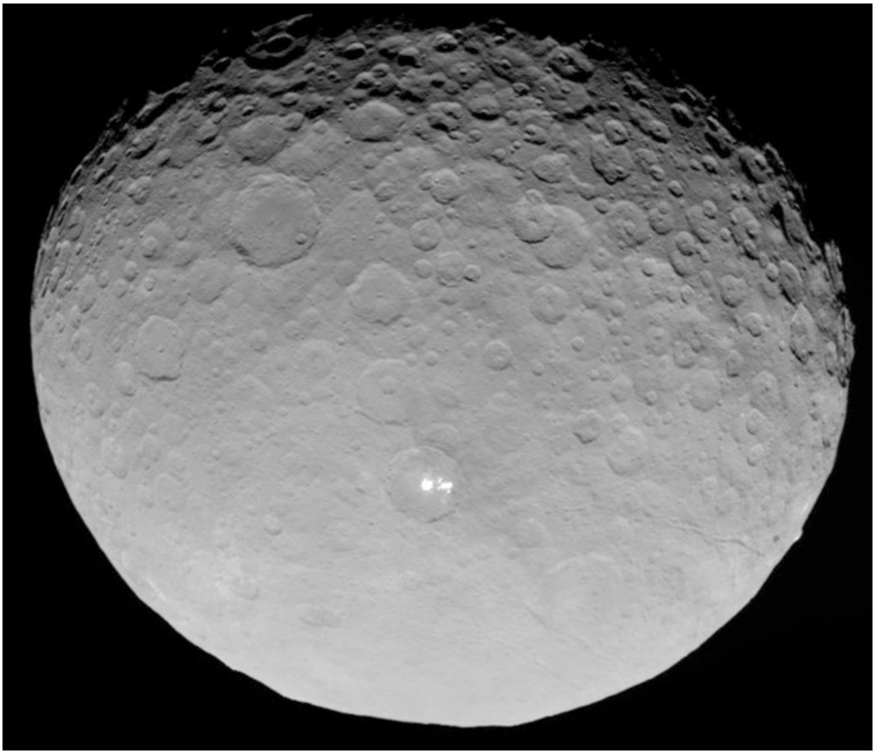

Fig. 12.2 Ceres, imaged by the Dawn spacecraft on May 4, 2015 (*Credit* NASA/JPL)

Table 12.1 Propellant required for one-way descent to Ceres surface

Rocket type	Specific impulse (s)	Propellant ratio (kg propellant/kg ship)
Steam	190	0.21
Hydrazine	240	0.17
LOX + RP1	350	0.11

Table 12.1 shows that one can fly entire habs down to Ceres without using much propellant, even when using simple steam rockets or hydrazine motors. Cryogenic rockets don't offer much of an advantage, and for a long trip like this, are probably not worth the extra complexity and risk.

Assuming approximately half of the hull mass remains at Ceres (plus equipment that isn't needed for the return trip), about 20,000 kg must be transferred to the surface, with a propellant budget of 0.17–0.21, or 3400–4200 kg. This has the added benefit of reducing the mass of the returning ship, which reduces the amount of water needed overall and proportionally reduces costs.

Mission Economics

This mission has a similar delta-v as the round-trip from EML-2 to low Venusian orbit. The large delta-v makes the mission economics especially sensitive to engine performance.

Initial Ship Delivery and Amortization

As with the lunar and Martian runs, the amortized cost of delivering the dry hull to EML-2 should work out to between $20 and $40 million per mission, assuming 5–10 missions per ship. It is important to note that spacecoaches are not mission specific ships, so the same ship may fly all of these routes throughout its life.

Per Mission Resupply Cost

Due to the large delta-v (13.25 km/s each way), resupply costs are especially sensitive to the engine specific impulse. Assuming engines rated to run at 1500 s, the cost to load the spacecoach with water-equivalent material will be $550 million per sortie. By increasing engine performance to 2000 s, this cost is reduced by 50 % (to $280 million per sortie), and by increasing it to 3000 s, at the high end of Hall effect thruster performance, by over 75 % (to $125 million per sortie). Clearly investing in better electric propulsion technology will be an important focus for Ceres missions.

On the other hand, missions to Ceres will be longer than to Mars, probably closer to three years overall. Using the spacecoach equation (Eq. 13.1) to calculate the resupply cost minimum for a six-person, 1000-day mission, the ship will require engines that operate at about 2800 s specific impulse to optimize the use of consumable waste streams as propellant. This is within the performance envelope for many electric engines, such as Hall effect thrusters, which suggests that a cost optimized trip to Ceres should be possible. If so, the consumable budget for the crew will be roughly 90,000 kg (15 kg/person-day). With an EML-2 delivery cost of $2700/kg, this works out to about $250 million per mission.

Crew Launch and Return Cost

As with the lunar and Martian runs, the crew, delicate equipment and perishables will fly direct to EML-2 via chemical propulsion, at an approximate cost of $100 million per sortie.

Total

Summed together, the per mission cost for a Ceres mission will range between \$265 and \$700 million per sortie, with clear opportunities for cost reduction by investing in improved electric propulsion technology.

Ceres, being a high delta-v location, will require more advanced engines in combination with lightweight PV arrays. Even so, engines that operate at the low end of the electric propulsion envelope (2000–3000 s), will bring overall mission costs down to parity with other destinations. This is one of the most compelling aspects of the spacecoach concept, as relatively small improvements to the engines will enable ships to upgrade their operating range. The engine performance required is easily within reach of existing technologies such as Hall Effect and Lorentz force thrusters.

Meanwhile, the longer trip duration means that the consumable budgets for these missions will be larger, so the ships will have more propellant to work with in any case. The authors' analysis shows that ships capable of traveling to the Martian system should also be capable of travel to Ceres.

In Situ Resource Utilization

One of the primary long-term goals in spacecoach development will be to enable them to scavenge local resources for consumables, construction and propulsion. This will reduce the need for Earth launched materials and will reduce mission costs proportionally, and as off-Earth resupply sites become available, will enable spacecoaches to venture off on truly deep space missions.

Water (for Consumables and Propulsion)

Finding and learning to extract accessible water, especially from low gravity sites, will be one of the primary objectives as the spacecoach supply chain is built out. Even locations that are thought to be arid, such as the Martian moons, may have extractable water or ice bound in their regolith. This water could be harvested by placing regolith in a drying oven that in turn vents into a chiller or condenser. While early spacecoach missions would be fully supplied via Earth-launched material, a primary research goal for early missions will be to determine how accessible water is at these locations, and to experiment with different extraction methods.

The ability to extract useful amounts of water at low gravity sites for inbound transport would reduce the need to launch water and water-rich materials from Earth's surface, and would lead to substantial cost reductions in mission resupply costs. Because of this there will be substantial financial incentives to extract water from low gravity sites versus launch it from Earth's surface.

Regolith (for Shielding, Propulsion and Tools)

While water may be difficult to access at some locations, there will be an essentially unlimited supply of regolith that can be used for shielding and possibly also for propulsion. A number of solid fuel electric engines have been proposed, so it should be possible to design an engine that vaporizes regolith as its means of propulsion.

For example, regolith mixed with filler could be molded into a cylindrical form, not unlike a pencil lead, that is fed into a device that ablates the tip of the lead with a short duty cycle laser, the vapor from which is fed into a second stage that superheats and vents the exhaust. This would be a mechanically simple engine, and one that could be scaled up as an array of small motors. Candidate engines can be tested during the engine design competitions, using simulated soils to determine their likely performance characteristics.

Additive manufacturing techniques, such as selective laser sintering, will enable crews to transform fine grain regolith into virtually any shape. This should be useful for manufacturing a wide range of parts and tools, and should also enable mission planners to reduce their dependence on Earth-delivered material as this technology matures.

Regolith will also be useful as a shielding material for surface habitats, providing excellent debris and radiation shielding. The primary challenge will be learning how to manipulate useful amounts of it in very low gravity environments.

Pykrete (for Surface Construction)

In locations where water or water-ice is abundant, as Ceres is thought to be, water can also serve as a primary construction material. Although ice is brittle and fractures easily, water frozen into fibrous material is as strong and durable as concrete.

This will also be a simple construction method, as water can pumped into inflatable forms packed with low density fiber, then allowed to freeze to form a durable, rigid structure.

Chapter 13
Venus and Mercury

Venus

Spacecoaches will be able to fly directly to Venus's orbit, using a mission profile similar to the Mars/Phobos mission. The overall delta-v requirements are roughly similar, meaning spacecoaches equipped to travel to the Martian system will be able to travel to Venus without major modifications, although the refueling costs, all other parameters being equal, will be somewhat higher (Fig. 13.1).

Venus is an interesting destination, as it is thought to have started out as Earth's twin before it became the victim of a runaway greenhouse effect. Among the science opportunities there are:

- Probes designed to float in the upper atmosphere (Earth air is buoyant in Venus's carbon dioxide rich atmosphere) could be remotely operated by crews in orbit, and could conduct a range of meteorological and chemistry experiments.
- One of the more interesting ideas for human colonization the authors have seen is to place floating sky cities in the Venusian atmosphere. While surface conditions are hellish, at altitude temperatures are much more moderate, and breathable air is buoyant.
- Gain operational experience in environments where sunlight, and available solar power, is more intense.
- Rehearsal for a future trip further inward to Mercury.

Leg 1: EML-2 → Earth Escape (1.02 km/s)
As with lunar and Martian missions, the spacecoach would depart from EML-2 to escape the Earth's sphere of influence.

B. McConnell and A. Tolley, *A Design for a Reusable Water-Based Spacecraft Known as the Spacecoach*, SpringerBriefs in Space Development,
DOI 10.1007/978-3-319-22677-4_13

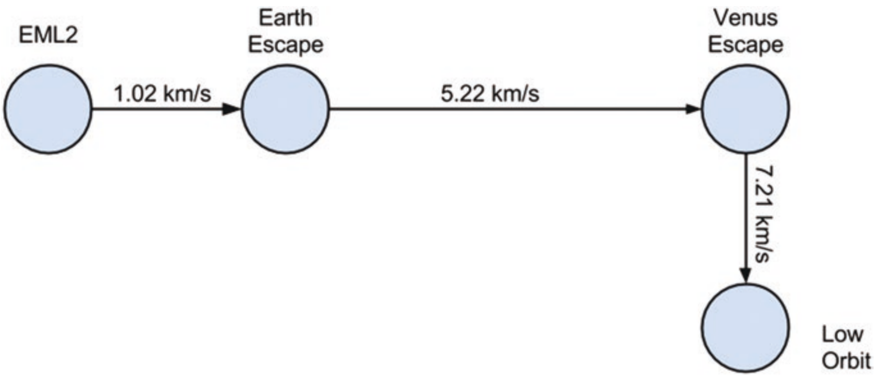

Fig. 13.1 A delta-v “subway map” for a mission from EML-2 to and from low Venusian orbit

Leg 2: Earth Escape → Venus Escape (5.22 km/s)
From there, the ship will spiral in from Earth’s orbit to Venusian orbit.[1]

Leg 3: Venus Escape → Low Venus Orbit (7.21 km/s)
Once in Venus’s sphere of influence, the spacecoach will spiral in toward low orbit. Because this maneuver requires a fairly large change of velocity, mission planners may decide not to spiral too close in, or may opt for a highly elliptical orbit that allows for close passes while requiring less delta-v. There should be many opportunities for cost reduction here.[2]

Leg 4, 5 and 6: Low Venus Orbit → EML 2 (13.45 km/s)
The spacecoach then flies back to EML 2, with a total delta-v for the roundtrip of 26.9 km/s.

Mission Economics

With a worst-case delta-v of just under 13.5 km/s each way, a Venusian roundtrip will also be a dry run for a mission to Ceres, whose delta-v is similar.

Ship Delivery and Amortization

As with the lunar and Martian runs, the amortized cost of delivering the dry ship to EML-2 should work out to between $20 and $40 million per mission, assuming 5–10 missions per ship.

[1]Calculations courtesy of Rüdiger Klaehn.

[2]Calculations courtesy of Rüdiger Klaehn.

Per Mission Resupply Costs

Because the delta-v for a Venusian return mission is significantly greater than the Martian expedition, the resupply costs are greater. Assuming engines rated to run at 1500 s, the ship will require 5.23 kg of water-equivalent mass per hull kilogram, which works out to a resupply cost of $565 million per sortie, roughly twice that of the Martian expedition.

Using the spacecoach equation to estimate the minimum cost, assuming a 600-day mission duration, six-person crew, and 15 kg/person-day consumable budget, the required engine specific impulse will be just under 4000 s. While this is potentially achievable, it is likely ships flying these missions will be overloaded with water to allow the use of engines that perform at lower specific impulse. (Meanwhile the availability of more water will allow the option of expanding the crew.)

There will be many opportunities to reduce this cost. Among the options available:

- Skip the descent to low Venus orbit, remain in high orbit, to reduce delta-v by up to 5 km/s each way, making the delta-v requiring comparable to a Mars-Phobos trip.
- Opt for a highly eccentric orbit around Venus that allows for low passes, to reduce delta-v by about 2.5 km/s each way.
- Leave part of the ship in Venusian orbit as a permanent space station.

With some combination of these strategies, it should be possible to limit per mission resupply costs to $200 million per sortie.

Crew Launch and Return

As with the lunar and Martian missions, the crew, delicate equipment and perishables will fly direct to EML-2 via chemical propulsion, at a cost of approximately $100 million.

Total

The total per mission cost for a Venusian roundtrip via a 40,000 kg spacecoach should range between $300 and $700 million per sortie.

Because Venus is a higher delta-v destination, the economic model is especially sensitive to specific impulse. Such a trip is probably not economically feasible with low end electric propulsion (I_{sp} < 1500 s), but with performance above 1500 s, the cost of water-equivalent material drops off sharply to bring overall mission costs in line with what a Mars lunar trip would cost.

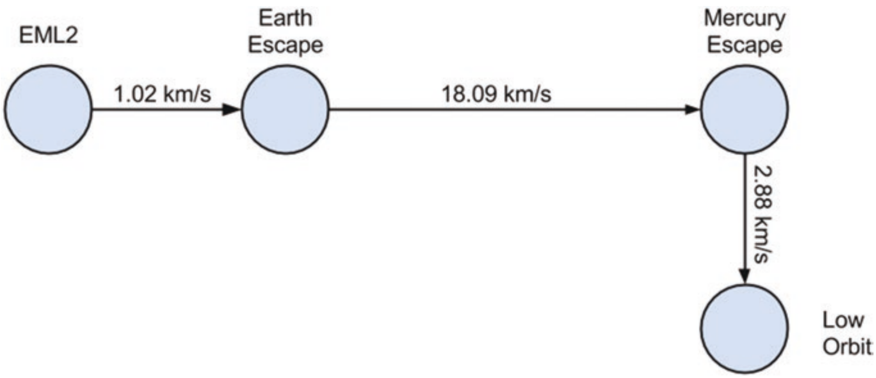

Fig. 13.2 Delta-v "subway map" for a mission from EML-2 to and from low Mercury orbit

Mercury

While Mercury may not be a high priority for human exploration, at least initially, it is interesting to run the economic model for a roundtrip from EML to low Mercury orbit. Being in a tight orbit around the sun, it requires an even greater delta-v to reach. On the other hand, solar insolation is roughly 7 times that at 1 AU, so a ship would be able to utilize higher specific impulse engines at higher power levels, which makes the increased delta-v less of an issue. Obviously the heat and radiation environment will be a challenge, but this is also the basis for an interesting design competition, to see if early spacecoach configurations can be adapted incrementally to operate there (Fig. 13.2).

The primary rationale for a Mercury expedition would be to teleoperate robots in the polar craters to search for surface or thinly buried ice in cold traps. A spacecoach parked in a polar orbit would, like a ship in Martian orbit, have low latency telepresence capability and would enable astronauts to operate surface robots with dexterity and haptic feedback not possible with Earth-controlled equipment.

Leg 1: EML-2 → Earth Escape (1.02 km/s)
As with other missions, the ship starts at EML-2 and spirals out of Earth's gravity well.

Leg 2: Earth Escape → Mercury Escape (18.09 km/s)
The spiral transfer from Earth's solar orbit to Mercury's requires a delta-v of 18.09 km/s each way.[3]

[3]Calculations courtesy of Rüdiger Klaehn.

Leg 3: Mercury Escape → Low Mercury Orbit (2.88 km/s)
A transfer to low orbit from there will require an additional 2.88 km/s each way.[4]

Legs 4, 5, 6: LMO → EML-2 (21.99 km/s)
For a full round-trip, the delta-v budget works out to 44 km/s.

Mission Economics

Getting to Mercury without using Venus for a gravity assist (which is probable) will require a one way delta-v of 22 km/s. Right away, one can see that this is significantly more than a trip to Venus, and will drive propellant requirements up significantly. On the other hand, solar power is abundant as the ship travels inward, so it will be possible to use higher specific impulse engines operating at higher power levels.

It should be clear that higher specific impulse engines dramatically reduce propellant requirements. At an I_{sp} of 2000 s, a fully fueled spacecoach will require about 8.4 kg of water and water-equivalent material for each kilogram of dry mass. This level of performance is right in the middle of the performance of Hall effect thrusters. At 3000 s, this is reduced to 3.46 kg of water per hull kilogram, which works out to a per mission resupply cost of $300 million. If EVGA can be used to reduce the delta-v, the resupply cost can be further reduced.

Using the spacecoach equation to calculate the minimum cost mission using only crew consumable waste streams as propellant, one can determine the engine performance needed to make a cost-optimized trip. Let's assume a 500-day mission and six-person crew to enable direct comparison to other missions. This will require a significantly higher specific impulse, approaching the 7000 s. This is well above the performance envelope for engines such as Hall effect thrusters and suggests that ships flying these missions will be significantly overloaded with water to enable the use of lower specific impulse engines. These missions will almost certainly incorporate economizing maneuvers, EVGA in particular. If so, it should be possible for early generation ships to make this sort of high delta-v trip. (While the thermal and radiation environments may be show stoppers, the high delta-v should be achievable.)

[4]Calculations courtesy of Rüdiger Klaehn.

Chapter 14
A Vision of the Future

Spacecoaches will be the foundation for a real world star fleet, an ever expanding fleet of ships and ships recycled as space stations and bases that will be capable of reaching more destinations as they are upgraded. They will start by exploring nearby destinations: Venus, Mars and perhaps Ceres, but as electric propulsion and photovoltaic technologies improve they will open up much of the Solar System to human exploration.

The spacecoach architecture deliberately borrows from the computing and communication industries, whose progress is based not on radical breakthroughs but rather the combined effect of many incremental improvements in component technologies. The upgradable nature of the system will incentivize improvements to engines, solar arrays and inflatable structures, and while year after year improvements in individual components may appear small, they will compound over long time scales.

How are these technological improvements likely to pan out over the next 20 to 30 years, and what are the likely implications for the system as it evolves?

The capabilities of these ships are governed by just a few factors, which include:

1. The cost to launch materials from Earth's surface to low Earth orbit.
2. Electric engine performance, most importantly specific impulse and efficiency.
3. Solar photovoltaic power density (also known as specific power).
4. Expandable structure density (mass per unit of habitable volume).

Surface to LEO Launch Costs

Surface to LEO launch systems are a mature and well understood technology. In recent years SpaceX in particular has made great progress in bringing costs down (currently at $1700/kg for Falcon 9 Heavy's published cost as of June 2015).

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If they succeed in achieving partial reusability, it is possible these costs will decline even further, especially for low value payloads (such as water), where launcher reliability may be less of a concern. That said, it seems unlikely, absent an unforeseen technological breakthrough, that these costs will decline by orders of magnitude. For this reason, the authors chose to treat surface to LEO launch as a fixed cost that is unlikely to decline much in the future. If launch costs do decline further, the overall systems and mission costs for spacecoaches will decline proportionally.

Electric Engine Performance

There will be many opportunities to optimize electric propulsion for crewed vehicles. As the authors have noted, increasing specific impulse (exhaust velocity) is useful up to a point. It is counterintuitive, but when consumable waste streams are the primary source of propellant, it is not necessary to achieve extreme performance in terms of exhaust velocity. For most destinations out to the Asteroid Belt, engines that have exhaust velocities similar to Hall effect thrusters will be sufficient. Increasing exhaust velocities well above that range, as VASIMR engines do, drives up power requirements, and since the consumables budget cannot be reduced without reducing the crew size or mission duration, the ships will have to fly with that consumables mass anyway.

Where electric engines can be improved is in terms of density, specifically thrust to weight ratio, and in terms of efficiency. Engines should be as lightweight relative to the thrust they generate as possible. This is an example of where dematerializing manufacturing techniques will lead to continual improvement. Many of these engines are mostly empty space, so it should be possible to fabricate units that are lightweight, and thus can be scaled up in large arrays that collectively do not add much deadweight to the hull. Every kilogram that can be shaved off the engine mass will be an extra kilogram of consumables/propellant or an extra kilogram of payload.

Efficiency is the other major area for improvement. Electric engines never convert 100 % of the input electrical power to kinetic energy. Input power is lost to waste heat, radiation (light) escaping from the engine, ionization losses, and so forth. Reducing these losses, or reclaiming lost energy (for example, converting light radiating from the engine back into electricity via solar cells, or by using waste heat to pre-heat incoming propellant) will increase the engine's thrust to power ratio, and will reduce the size of the solar array needed to power the engines, and thus passive hull weight, all else being equal.

Omnivorous operation is another area to focus on. The ability to use mixed or adulterated propellants, as well as gasified solid waste, will enable nearly all consumable waste streams to be used as propellant, and will increase the ships operating capabilities.

Solar Photovoltaic Technology

Solar photovoltaics are probably the most important component technology in terms of the potential for long-term improvement. This is already a mature and well understood technology that is now used on virtually all spacecraft. (Nuclear power has only been used on probes traveling to the outer planets, and even then only at low power levels nowhere close to that required for a crewed ship.)

Solar power technology benefits from a slow motion Moore's law known as the Swanson effect. This is due to year by year improvements in the amount of material needed to yield a given power output. Thin film (CIGS) materials, which are also radiation resistant, offer considerable promise in the development of very lightweight, large area arrays that will be capable of generating large amounts of electrical power. Quantum dot photovoltaics, which can be tuned to absorb a broad range of wavelengths, are also a promising technology to be considered.

This is important because solar insolation drops off as a function of the square of the distance from the Sun. A spacecoach traveling in the vicinity of Jupiter will require an array 25 times the size of its equivalent at Earth's distance. Using a 1 MW power plant as a baseline, a spacecoach at 1 AU will require a 3570 m^2 array, or 60 m on a side (assume 20 % conversion efficiency). At Jupiter, this area swells to almost 90,000 m^2, or 300 m on a side. Even if the array only weighs a fraction of a kilogram per square meter, one can see that it carries a large mass penalty.

This is where thin film materials will be important (lightweight solar reflector/concentrator units will also be attractive) because they will enable the fabrication of arrays whose mass will be measured in grams per square meter, which will keep the hull mass within acceptable limits.

Using a 40,000 kg dry hull as a baseline, with no more than 10 % of the hull mass (4000 kg) being budgeted for solar photovoltaic arrays, one can calculate the maximum allowable array density (kg/m^2) as a function of distance from the Sun.

Table 14.1 clearly shows the relationship between the maximum allowed array density versus the distance from the Sun. At Earth's distance and inward, the array can weigh 1 kg/m^2 or more without taking up an unreasonable percentage of the dry hull mass. At Jupiter's distance, the array or a reflector/concentrator that concentrates light on a smaller photovoltaic array, will need to weigh in at less than 40 g/m^2 (about an ounce per square meter). These are attainable numbers, and as

Table 14.1 Maximum solar array density (kg/m^2) assuming 20 % conversion efficiency

Distance (AU)	Array area (m^2)	Max array density (kg/m^2)
1 (Earth)	3571	1.120
1.67 (Mars, aphelion)	9959	0.401
2.97 (Ceres, aphelion)	31,500	0.126
5.46 (Jupiter, aphelion)	106,460	0.037
10.11 (Saturn, aphelion)	365,000	0.010

materials improve over the next 20–30 years, it should be possible to design spacecoaches that can operate using solar power in the outer Solar System.

Inflatable/Expandable Structures

Inflatable/expandable structures feature prominently in the spacecoach architecture, as they can be used to create large habitable spaces that can be deployed easily and can be compacted into standard launch fairings. This technology is still at an early stage of development, with two unmanned habitats currently on orbit, and one unit slated for launch to the International Space Station in summer 2015.

The primary performance factor spacecoach designers will be interested in is their mass density (kilograms per cubic meter of habitable space). Bigelow Aerospace's planned BA330 unit is expected to have a density of 60 kg/m^3. This figure should also decrease over time as manufacturers such as Bigelow gain experience with fabrication techniques and incorporate more advanced materials into these structures.

The primary benefit of decreasing habitat density will be the ability to accommodate larger crews. This in turn leads to a virtuous (as opposed to a vicious) cycle because crew consumable waste streams are utilized as propellant, where the larger propellant budget translates into a combination of larger delta-v (increased operating range) and/or increased payload. One would also expect more elaborate and comfortable structures to become possible as fabricators gain experience with their craft.

High Speed Transit

Spacecoaches will also be able to achieve shorter flight times as their engines and power plants are upgraded. They will do this by building up more delta-v than is required for a Hohmann-like trajectory, and will be able to reduce travel time by doing so. One can think of this strategy as "VASIMR Lite." As engines are upgraded, mission planners will be able to emphasize economy (fly the lowest energy trajectory to minimize propellant) or speed (overfuel the ship to maximize delta-v).

With their ability to provide both radiation shielding and artificial gravity, spacecoaches will not need to achieve short flight times due to health considerations. However, one can imagine that once the novelty of going where no human has gone before begins to wear off, crews will want to reach their destinations more quickly.

Faster flight times will also allow spacecoaches to fly more missions during their service life, and will enable operators to reduce development and construction costs via amortization.

Space Stations and Bases Everywhere

Spacecoaches are also readymade surface bases and space stations. It is easy to imagine missions that will drop off substantial parts of the ship at their destinations, especially habitats. This will enable them to run light on the return trip while also building up permanent bases and stations with each trip out. The authors didn't factor this into most of the mission templates, in order to keep the examples simple, but this will reduce mission operating costs by an additional 30–50 % depending on the amount of the hull mass left at the destination. However, these savings are offset somewhat by the need to replace that mass in subsequent missions.

Once out of Earth orbit, there's really no reason not to re-use components when you get to your destination. A beat up hab might be dated for flight service, yet be perfectly adequate as sleeping quarters or as a bar at a future Mars or lunar base. Until something becomes dangerous or breaks down completely, there will be little reason to throw things away. So with every outbound mission, the traveling and carrying capacity of the fleet will grow.

Chapter 15
Research Priorities

Spacecoaches will be based on existing technologies and launch platforms. Most component systems are well understood, and if not already spaceflight ready, can be developed on an aggressive timescale. In this chapter, the authors highlight the important topics that need to be researched to fully understand the near-term costs and capabilities of first generation spacecoaches.

Electric Engine Performance and Reliability

Ground-based vacuum chamber tests need to be done to determine performance characteristics of early water-burning electric engines (i.e., specific impulse, power/thrust ratio, power/mass ratio, mean time before failure for key components). There should be investigations into whether Hall effect thrusters and other electric propulsion technologies can be used as-is or can be adapted to use water for propellant, and if so, what their performance characteristics are like.

Technology readiness: The technology is developed and is well understood, but it needs to be developed into flight ready components that have been extensively tested in ground facilities, so ship designers know key performance metrics and operators can service the components in flight. An engine design competition will be very helpful in generating this data.

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Adapting Electric Engines to Vaporize Soil or Regolith for Propulsion

There must be investigation into whether electric engines such as METs can be adapted to vaporize and superheat simulated surface material or regolith to generate useful thrust. If so, we know there is an essentially unlimited supply of this material in the Martian moons.

Technology readiness: Unknown, but if this can be made to work, it is a potential game changer, as it will enable a faster path to in situ resource utilization.

Non-cryogenic Chemical Rockets

This is already a well understood topic. Spacecraft designers will have a number of propulsion systems to choose from, including monopropellant systems using hydrogen peroxide or nitrous oxide, bipropellant systems such as nitrous oxide and hydrocarbon fuel, and hypergolic systems such as hydrazine. The performance characteristics, risks and tradeoffs are well known, so not much additional research is required early on.

Technology readiness: Already built, many options to choose from depending on mission needs.

In Situ/in Flight Fuel Generation for Chemical Rockets

Hydrogen peroxide can be generated onboard via an electrolytic process that is already used in wastewater treatment, and combined with low temperature vacuum distillation could be processed to high enough purity that it can be used as an oxidizer with hydrocarbon fuel. It will be interesting to investigate the possibility of using algae to generate hydrocarbon fuel, while using H_2O_2 as an oxidizer.

Hydrogen-oxygen rockets, their fuels generated via water electrolysis, should also be investigated. While cryogenic fuel storage may be problematic, if the required impulse per burn is relatively low, it may eventually be possible to use a non-cryogenic, compressed gas design without adding excessive dead weight to the ship.

Technology readiness: Component technologies are understood, but not flight ready. However, even in early missions, it will be possible to run scaled-down tests to estimate production capacity and gain operational experience. Also, while nice to have, it is not necessary for most missions.

Solar Array Mass/Area/Power Density

It is important to determine realistic near-term mass/power density figures for a solar array that is lashed to a rigid frame, similar to a sail. (See the "kite" design for an example of what such an array may look like.) Solar photovoltaics are a well understood technology, so this is primarily an electrical and structural engineering exercise to determine realistic upper and lower bounds for this parameter using components that will be available in a 3–5 year time frame. This research will be followed by actual fabrication of prototype materials to validate these numbers.

Technology readiness: Space-based solar power is well understood. Designers will need to determine what realistic bounds are for power density in watts per kilogram of array. Similarly need to calculate area power density, which will be determined by the photoelectric efficiency of the solar cells used in the densest power/mass arrays.

Artificial Gravity Designs

The reference design features a dumbbell or kite-like configuration that can be rotated to generate artificial gravity. In this configuration inflatable passageways linking the modules double as hollow tethers. Other configurations should be studied to see if there is a more mass efficient arrangement that also provides multiple paths between modules, so in the event a passageway is rendered impassable, alternate routes are available.

Oxygen Generation via Hydrogen Peroxide Decomposition

We must test various mechanisms for hydrogen peroxide decomposition using metal catalysts, ultraviolet light (simulating levels expected in near-Earth and near-Mars space), and also simulated cosmic radiation. These tests will help determine expected decomposition rates in various conditions, and will be used to decide what concentration of hydrogen peroxide/water mixture will work best. This is already a well understood process, so there should not be big surprises.

Technology readiness: Already developed and well understood, need additional research to better understand edge cases such as behavior in high UV or cosmic radiation environments.

Oxygen Generation via Water Electrolysis

Hydrogen generation via electrolysis is already a well understood phenomenon, and much research is underway to find more efficient electrolysis methods because of its utility as an energy storage mechanism here on Earth. This research can be leveraged to identify the most lightweight and energy efficient electrolysis units for use on spacecoaches.

Technology readiness: Already developed, just need to identify best off the shelf options at the time of ship re-supply.

Carbon Dioxide Uptake via Plants and Algae in Closed Loop Systems

We should grow plants and algae in simulated closed loop environments with artificial (LED) lighting tuned to maximize growth. We can simulate most aspects of the space environment except high energy radiation and microgravity in ground tests. We can then leverage published results from space-based tests dating back several decades, and can probably also utilize research done for biofuel production since that's a related process. Containerized urban agriculture research can also be leveraged for this data.

Technology readiness: Growing plants and algae to generate oxygen and hydrocarbons is to be explored; designers will need to determine the performance characteristics of a closed or semi-closed loop system and what size crew it can support and where it will need to be supplemented. This capability is not necessary for the first missions but rather is nice to have.

Carbon Dioxide to Methane Generation

Sabatier reactors, already flying on the International Space Station, convert carbon dioxide and hydrogen (generated from electrolysis) into methane and oxygen. This is a well understood, spaceflight ready technology.

Technology readiness: Already flight ready, though operators will need to design a methane storage system or, better, an efficient process to convert methane into a hydrocarbon that is liquid at room temperature for easy, lightweight storage.

Inflatable/Expandable Habitats

There must be consultations with organizations such as Bigelow Aerospace to determine weight and volume of inflatable/expandable habitats it plans to fly in near-term (3–5 years). Also we must determine likely fabrication costs associated with these units, and likely advances in terms of materials and habitat density.

TECHNOLOGY READINESS: Bigelow has two uncrewed but active habitats that have been in orbit for years. BEAM is due to fly to the ISS in mid-2015. Technology is flight ready, but needs to be adapted to spacecoach dimensions and specifications.

Pykrete Strength and Material Requirements

We must test different formulations of pykrete with various fibrous materials, fiber densities, and temperatures. They will be tested for structural strength (compression, tensile strength and fracture resistance), and for debris impact resistance using high velocity air guns. This research can be done inexpensively in ground-based test facilities. High-velocity impact tests will require specialized facilities, but basic material strength testing can be done in any materials science or civil engineering lab. We'll also want to investigate the extent to which pykrete can be used to offset other material requirements, to further reduce the deadweight in a ship.

TECHNOLOGY READINESS: Need current data about pykrete strength using newer fiber materials since most recent research dates back to World War II.

Potential Applications in Space Mining and Planetary Defense

Spacecoaches can be used in a number of space mining and planetary defense scenarios. Designers should anticipate how spacecoaches can be configured to accommodate these types of missions, especially missions to explore and characterize asteroids for the suitability of various deflection techniques as well as their mineral value.

Surface to LEO Launch Costs and Payload Capacity

We must update LEO/GEO launch costs on per kilogram basis as they change. SpaceX's published rate is currently \$1700/kg to low Earth orbit. Since this information is publicly available it can be readily kept up to date. Note that if reusable boosters become available, the cost of delivering water and water-equivalent material to orbit could decline significantly.

System-Wide Safety Analysis

A detailed safety analysis will be applied to attractive designs to identify single points of failure, dependences between interlinked systems, and backup systems or strategies. This will most likely take place once a short list of detailed designs are under consideration.

Appendix A
Equations and Supporting Data

Readers can use the following equations to develop parametric models to calculate the performance of spacecoaches, using different assumptions about engine efficiency, mass budgets and other parameters. Also included are references to additional research, software for modeling missions and other resources you can use in developing alternative designs.

Rocket Equation

Use this to calculate the maximum delta-v a ship can achieve, given the specific impulse of the engine, combined with the initial and final mass of the spacecraft.

$$\delta v = I_{sp} \times 9.8 \times \ln \frac{m_{initial}}{m_{final}}$$

Use this to calculate the amount of propellant needed to achieve a specific change in velocity, given the initial mass of the ship and the engine's specific impulse (I_{sp}) . Example: You want to descend from local orbit to the surface of Ceres (delta-v: 360 m/s) using a high efficiency steam rocket (I_{sp}: 190 s). You'll need a mass ratio of 1.21.

$$\frac{m_{initial}}{m_{final}} = \mathrm{e}^{\frac{\delta v}{9.8 \times I_{sp}}}, \quad m_{propellant} = m_{final} - m_{initial}$$

Spacecoach Equations

Use this to calculate the engine specific impulse required to achieve a given delta-v, using only crew consumable waste streams as propellant. This also results in the minimum cost for a mission given a specific crew size and consumable budget since the consumables must be on board anyway.

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$$I_{sp} = \frac{\delta v}{9.8 \times \ln\left(\frac{m_{hull} + (t_{mission} \times n_{crew} \times m_{ration})}{m_{hull} + m_{waste}}\right)}$$

Use this to calculate the average power required to run the engines, where m is the mass of the consumable waste streams processed by the engine, $t_{runtime}$ is the engine runtime in days, η and I_{sp} is the engine specific impulse. For example, a ship that consumes 45,000 kg of consumables as propellant over a period of 400 days at a specific impulse of 2500 s and 50 % efficiency will require 800 kW of electrical power.

$$P = \frac{m_{consumables}}{t_{runtime} \times 24 \times 3600} \times \frac{0.5}{\eta} \times (9.8 \times I_{sp})^2$$

Steam Rocket Energy Budget

Use this equation to calculate how much energy will be required to heat a mass of water to power a steam rocket (use the rocket equation to calculate the mass of propellant required to achieve the necessary delta-v). Example: To generate 400 kg of steam, heated from 0 to 300 °C, we will require 1,400,000,000 J, or 390 kWh, of electricity.

$$E = \left(m_{H_2O} \times 2{,}260{,}000\right) + \left(m_{H_2O} \times (4{,}179 \times \delta T)\right)$$

Data About Electric Engine Performance

The authors' paper in the *Journal of the British Interplanetary Society,* "A Reference Design for a Simple, Durable and Reusable Interplanetary Spacecraft," summarizes research on electric engines from the 1960s to the recent past. This data suggests that water-based engines should be capable of specific impulse (I_{sp}) of at least 1500 s, and with present-day technology, may be capable of significantly better performance.

Engine Power Budget

Use this to calculate the power required per unit of thrust as a function of engine specific impulse and efficiency. This equation shows that the power required increases in proportion to specific impulse, which is why ultrahigh I_{sp} engines, such as VASIMR, are not attractive for most missions. Example: a 50 % efficient engine rated to run at 1000 s will require about 20 kW/N of thrust, while an engine rated to run at 10,000 s will require 200 kW/N of thrust.

$$\frac{P}{T} = \frac{9.8 \times I_{sp}}{\eta}$$

Use this to calculate how much power your electric engine will require to generate a specific amount of thrust, given its specific impulse (I_{sp}), propulsion efficiency, and overall electrical efficiency. Example: to generate 100 N of thrust with an engine that has a specific impulse of 800 s and 50 % overall efficiency, you will need approximately 780,000 W of electrical power.

$$P = \frac{9.8 \times I_{sp} \times F}{2 \times \eta}$$

$$P = \frac{\rho}{2 \times \eta} \times \left(9.8 \times I_{sp}\right)^2$$

Engine Run Time

Use this to calculate how long the engines will run over the course of a mission. For ships that are underpowered, the engines will need to run longer to expend all of the propellant, which may result in a longer overall trip time. What this equation shows is that increasing the amount of power available or increasing engine efficiency will decrease runtime proportionally. On the other hand, increasing the amount of propellant on board, or increasing engine specific impulse, will increase the runtime.

$$t = \frac{m_{water} \times (9.8 \times I_{sp})^2}{2 \times P \times \eta}$$

Cost Per Kilogram to EML-2 (Via Electric Propulsion from LEO)

Use this equation to calculate how much power your electric engine will require to consume an amount of propellant in a specific time frame. If your engine is underpowered, it may take an inordinately long amount of time to burn off enough propellant to achieve your desired change in velocity. (You can calculate the amount of propellant required to achieve a given delta-v using the inverse rocket equation.) This power versus thrust tradeoff is an important element of spacecoach design. You want a solar array that is big enough to power your engines, but not so big that the mass of the solar array starts to undermine the ship's delta-v performance. Example: To burn 10,000 kg in 10 days (11.574 g/s) at an I_{sp} of 900 s and 50 % efficiency, you'll need approximately 900,000 W of power.

$$\frac{C_{LEO}}{e^{\frac{7000}{9.8 \times I_{sp}}}}$$

Cost per kilogram to EML-2 is calculated by dividing the published cost per kilogram to low Earth orbit by the mass fraction needed to achieve a 7 km/s delta-v. Thus, with a cost to LEO of $1700/kg and a specific impulse of 1500 s, the cost to EML-2 will be $2736/kg. Note this assumes that the tug is incorporated into the spacecoach waiting at EML-2 (e.g., its engines are transferred over to the spacecoach).

Solar Array Power Budget

Use this to calculate how much power your solar array will generate given its surface area, photovoltaic efficiency and distance from the Sun (in astronomical units, where Earth-Sun distance = 1 AU).

$$P_{\max} = 1400 \times A_{array} \times \eta \times \frac{1}{d_{AU}^2}$$

Oxygen Supply: Dilute Hydrogen Peroxide

Use this to calculate the amount of oxygen that can be extracted from dilute hydrogen peroxide loaded onto a spacecoach, given the total propellant mass and the percentage concentration by volume. Example: 10,000 kg of 10 % H_2O_2/water by mass would yield 470 kg of oxygen.

$$m_{O_2} = m_{mixture} \times \rho_{H_2O_2} \times \frac{8}{17}$$

Oxygen Supply: Electrolysis

Use this equation to calculate the amount of oxygen that can be extracted from pure water (for example, after hydrogen peroxide has been decomposed). Note that this method requires electrical energy, whereas hydrogen peroxide decomposition requires no input energy and is a fail-safe, non-electrical, non-mechanical process.

$$m_{O_2} = m_{H_2O} \times \frac{8}{9}$$

Carbon Budget

Use this equation to calculate the amount of carbon dioxide that will be generated by the crew throughout the course of a mission, and thus, how much carbon dioxide must be scrubbed from the atmosphere and/or taken up by plants or algae.

A typical person exhales about 1 kg of carbon dioxide per day, so in rough numbers, you can estimate the crew's carbon dioxide output as the number of people times mission duration in days. Example: A six-person Mars mission lasting 600 days would generate 3600 kg of carbon dioxide.

$$m_{CO_s} = n_{crew} \times days \times emissions/day$$

Appendix B
Recommended Reading

1. Tolley, Alexander; McConnell, Brian "A Reference Design For a Simple, Durable and Refuelable Interplanetary Spacecraft", Journal of the British Interplanetary Society, Vol 63 No 03—March 2010
2. "Living off the land in space: green roads to the cosmos" Gregory L. Matloff - L. Johnson - Constance Bangs - Springer - 2007
3. "Mining the sky: untold riches from the asteroids, comets, and planets" John S.Lewis - Addison-Wesley Pub. Co. - 1996
4. "Homesteading space: the Skylab story" David Hitt - Owen K.Garriott - Joe Kerwin - University of Nebraska Press - 2011
5. "Space: the free-market frontier" Edward LeeHudgins - Cato Institute - 2002

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Appendix C
Glossary of Terms

AC	Alternating current
au	Astronomical unit
BEAM	Bigelow expandable activity module
BEO	Beyond Earth orbit
$CaCO_3$	Calcium carbonate
CIGS	Copper indium gallium selenide
CO_2	Carbon dioxide
DC	Direct current
delta-v	Change in velocity
ELF thruster	Electrodeless Lorentz force thruster
EML-2	Earth Moon lagrange point 2
EVA	Extra vehicular activity
EVGA	Earth and Venus gravity assisted maneuver
G	Gravity
HC	Hydrocarbon
HEO	Highly elliptical orbit
HDLT	Helicon double layer thruster
H_2O_2	Hydrogen peroxide
Isp or I_{sp}	Specific impulse
ISS	International Space Station
JBIS	Journal of the British
LED	Light emitting diode
LEO	Low earth orbit
LH_2	Liquid hydrogen
LLO	Low Lunar orbit
LMO	Low Mars orbit
LOX	Liquid oxygen
LPO	Low polar orbit
LVO	Low Venus orbit

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MET	Microwave Electrothermal Thruster
MJ	Megajoule
NEO	Near earth object
NERVA	Nuclear Engine for Rocket Vehicle Application
PV	Photovoltaic
RF	Radio frequency
RP1	Rocket Propellant-1
SEP	Solar electric propulsion
SpaceX	Space Exploration Technologies Corporation
VASIMR	Variable Specific Impulse Magnetoplasma Rocket

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