IMPROVING THE SPACEX MARS COLONIZATION PLAN

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ABSTRACT

Elon Musk of SpaceX has proposed a bold and visionary plan to colonize Mars, "Making Humans a Multi-Planetary Species" [1] (Fig. 1). Just as Robert Zubrin's "The Case For Mars" [2] will always be a fundamental description of how 1970s technology is sufficient to land and return from Mars, the SpaceX vision lays out the fundamental description of the technology sufficient to colonize Mars.

From an engineering point of view, this vision, while necessary, is not sufficient, as its scope overlooks several important practical considerations key to implementation of the plan. The Musk plan assumes launching (and re-launching) the Mars transport vehicle from Earth (with orbital fuel-up) and returning it back into the Earth gravity well. Compared with the concept of a cycler (e.g., Aldrin Cycler [3], Fig.2) which, once launched, stays in orbit periodically encountering Earth and Mars, this is colossally wasteful. A much more efficient scheme would be to use dedicated vehicles ("trucks") for surface-to-orbit transfers and cyclers for orbit-to-orbit transportation. Musk's proposal effectively relies on using the Earth truck as a cycler, which is grossly inefficient. Mars trucks can be much smaller than Earth trucks. Moon trucks can be smaller still. The size of the gravity well determines the truck size – and given the rocket equation (an exponential tax on payload weight by increasing fuel required), bigger rockets are not the solution: if anything, they will exacerbate fuel waste. Moreover, given the facts that no craft flies with 100% safety and failure probability scales non-linearly with complexity, smaller and more numerous trucks can provide better odds of Mars settlers arriving to their destination. Additionally, space trucks will give the settlers a system similar to air travel that they can understand.

Smelters are fundamental features of bases. Cooking rocks to get the oxygen out really isn't necessary on Earth, but quite important on the Moon and Mars. The leftover sand becomes bricks and windows, the leftover metals are powdered and fed into 3D printing. Building vehicles, e.g., Moon trucks, on Earth is much more expensive than building them on site. Converting CO_2 into methane works, but using a full gas-to-liquid process to make kerosene or similar fuels is better, and the same process turns coal fired power plants into carbon neutral fuel sources on Earth. Going to Mars will save the Earth, if we do our homework.

Stay and Die or Go and Die?

There are numerous threats to life on Earth, such as Coronal Mass Ejections (CMEs), asteroids/comets, local gamma ray bursts, nearby supernovae, and wandering brown dwarfs (pretty much in decreasing likelihood of encountering them in our lifetime). Mankind of course has created its own threats, such as nuclear war, bio-warfare, rogue nanotechnology, and pollution. There are plenty of ways to die, and most of them apply just as well on Mars as they do on Earth, with Mars having no air, no food, and very little protection against radiation of all kinds. A CME that would bounce right off Earth's magnetosphere would completely fry the people and equipment on the Martian surface. What is important is that the most likely extinction-level natural events (the first two) would only affect one planet or the other. The other three could pretty much kill everybody no matter where we are, until we can expand to another solar system.

The Sword Over Our Heads

Every summer, we risk the end of life on Earth. Methane hydrate bubbles frozen in the tundra of Siberia are already popping, releasing a greenhouse gas twenty five times more powerful than CO_2, while temperatures in the arctic are ten degrees higher than average [4]. But even larger methane hydrate bubbles are trapped within the continental shelf of the arctic ocean [5,6]. Fortunately, we have brave humans willing to pop the methane bubbles for their own enrichment [7], risking releasing 800 years of equivalent CO_2 consumption at 25x potency, which might lead humans in the next few years to try to move to Venus to cool off. Carbon poisoning our planet has been bad enough, but now some people in positions of power appear desperate to prove our species is suicidal.

Shortage of Materials

Figure 3 shows a periodic table which reveals we are running out of key elements we use in our modern technology [8]. Our technology will either have to evolve to use the substitutes, or we will have to find new sources. Titanium is quite prevalent on the Moon and magnesium is quite prevalent on Mars. Mars has a land area equivalent to all of Earth, implying mining will be important long term. Given that Martian water (in the form of water ice) will have to be mined, mining will become important on Mars before the earliest settlers are even comfortable in their new home.

Do We stay or Do We Go? We Don't Know HOW!

Fortunately, we have many people "protecting" us from going to Mars. For 45 years, all manned programs to Mars have been canceled before they could produce the hardware to go there. This has led to a huge amount of unproven technology which could get us there but we can't be "sure" will get us there. In short, for almost 50 years, mankind has not had the will to go to Mars, even though (as demonstrated by Dr. Zubrin [2]) we have had the means. Into this vacuum of will, Elon Musk has stepped forward and announced we will figure it out.

Not Just a City – A Civilization

Despite this, moving not just a city, but a civilization to Mars is a daunting undertaking. Digital libraries make moving the information and history fairly compact, but as anyone who has learned how to tap dance can tell you, there is more to the performance than you might think. We have built up a huge infrastructure over the past couple of thousand years, and that infrastructure is not adapted to the Moon or Mars environments, much less to microgravity environments. But given the ability to 3D print "free" spaceships from the lunar dust, would you do it, if it meant we could settle Mars within a decade?

Approaches and terminology

The Musk plan [1] relies on several components (Fig. 1): the Mars vehicle (Mars Colony Ship) comprised of the interplanetary spaceship and the rocket booster, and the tankers that fuel the interplanetary spaceship in orbit. One reusable component – the spaceship – travels all the way from Earth surface to Mars surface and back. The Aldrin Mars cycler (Fig. 2, [3]) is fundamentally different: the interplanetary ship (hereon referred to as cycler) is launched from Earth once, but travels on an elliptic heliocentric orbit with regular close approaches to Earth and Mars. Travel between planetary surfaces (e.g., Earth to Mars) requires three trips with two transfers: Earth surface to Earth orbit, transfer to cycler, Earth orbit to Mars orbit, transfer from cycler, and Mars orbit to Mars surface. In this paper, we shall refer to the surface-to-orbit vehicles as Earth trucks and Mars trucks. Not incidentally, the original Aldrin concept also includes the cislunar cycler for Earth-Moon trips.

Moon vs. Mars? Not either/or – BOTH!

One way that small businesses succeeded prior to the invention of the Internet was to market locally. The Moon will always be closer to the Earth than Mars, and has many of the same challenges. It has useful resources, including aluminum, titanium, iron, silicon, oxygen, and sunlight. It also has no atmosphere, wide temperature swings, two weeks of daylight and two weeks of night, and a scarcity of readily available water (potentially useful amounts of water have been detected near the poles [9] even more in some rocks[10]). But in a risk averse world, building a cycler system between the Earth and the Moon (as Aldrin originally proposed) would allow us to evolve the technology while building a fleet of trucks and cyclers. Establishing a station in Mars orbit would then make full colonization of the planet a foregone conclusion. With the first manned missions paired with the station construction in areosynchronous orbit, Mars would be open to mankind at last. But unless a lunar base and station are built first, Mars will remain out of reach. We must become a space-faring society, building our muscles on the short day hikes to the moon, before we start building a civilization in the far cold and dark.

Affordability

As engineers, we must ask about the difference between two designs to be something beyond aesthetics. In this case, we use the two metrics of cost and time. A system that costs more is less efficient than one that costs less. A system that risks fewer lives also costs less, and a system that avoids lawsuits also costs less. A system that gets more people to Mars in less time is more efficient. A system that gets people to Mars in a timely manner that risks fewer lives is also more efficient.

This leads us to question some of the design choices in comparing the SpaceX Mars Colonization System Architecture (SMCSA) and the Buzz Aldrin Mars Cycler Colonization Concept (BAMCCC). The first leg of the journey is identical between the two systems (from Earth surface to Earth orbit). In SMCSA, the colony ship is refueled in orbit and then launched, presumably while the colonists are still on board, while many rocket related accidents happen during fueling/refueling procedures. In BAMCCC, the fuel used by the cycler can be completely different from that used by the Earth trucks. The possibility that was originally considered by Aldrin was a gravity-driven loop around the sun with a 146-day transfer time between Earth and Mars orbit. The total cycle duration would be 2.1 years, with about 16 months spent beyond Mars orbit (and not carrying passengers). Variations of this approach with more eccentric orbits can yield faster transfer times (possibly down to 75 days), but at the expense of longer total cycle durations (more than 10 years) and the necessity to expend more fuel during transfers. The fuel use to maintain the cycler on such an orbit is minimal – only for corrections. A possibility of both shorter cycles and shorter transfer times is opened by using continuous propulsion for the cycler. This option is not feasible with a traditional chemical propulsion (reaction mass will run out quite fast), but several low-thrust options make sense, including a solar sail or Solar Electric Propulsion (SEP) coupled with a magnetic sail. Were such a magnetic sail able to harvest only 1% of the velocity of the solar wind, it could cut the trip to Mars during the closest approach to 81 days, allowing at least three trips (or more) during the most advantageous time for travel between the planets. Of course, the challenge here is relatively low harvest-able energy density, especially near the cycler orbit aphelion, but the faster and "inhabited" parts of the cycler orbit are closer to the Sun. Cyclers between the Earth and Moon can serve as testbeds for a variety of continuous thrust technologies, which in the limit case could reduce the commute from several days to eleven hours. But even if the magnetic sail doesn't work that efficiently, it still protects the crew from radiation, and in terms of specific impulse I_{SP}, SEP is three to thirty times more efficient than chemical rocket propulsion. The high fuel mass flow and high total mass thrust of the chemical engine may be necessary to get in and out of the planetary gravity wells, but in interplanetary space, there are more graceful ways to travel. A design which uses the least efficient engine for a given environment is poorly factored, which is the conclusion for SMCSA versus BAMCCC.

Another type of affordability must be considered. In Figure 4, costs and performance characteristics of various rockets are summarized. We can see that a booster/colony ship pair has an initial cost estimated to be over 2B$. Tanker/boosters will have a similar cost, shown as four per ship/booster, for a cost of 10B$ per 100 colonists. This puts the basic cost of a base with 1000 colonists at 10B$ for two orbital stations, 10B$ for a base, and 100B$ for ten ship/boosters/tanker/booster sets, giving an initial cost of 130B$ for the SMCSA. A fleet of such ships has to have an equivalent economic value on the other end which is never described. In the BAMCCC, the tanker ships are not necessary, where the re-usability of ten launches brings all the colonists to the station. We observe that a crewed SpaceX Dragon ship launched on a Falcon Heavy is more cost effective when launching to a station (such as Johnson Prime)[8] which is capable of holding several hundred people, due to fat rockets being potentially less cost effective and more risky than several launches of smaller rockets. The entire initial shipment of colonists could be launched in 142 crewed Dragons, for a cost of 13B$. There are still costs for cyclers, a station in Earth orbit, a station in lunar orbit, and a station in Mars orbit (10B$ each for three stations). Add 10B$ each for at least two bases, and a cost close to 100B$ is not unreasonable for the effort (given cyclers, Moon and Mars trucks, rovers, etc.). In this concept, the lunar station and base are the economic engines driving space colonization. Costs for trucks, cyclers, and other components can be less than a sixth the costs of Earth manufacture and launch, leading to a lower total cost (even with majority Earth manufacture). Given the flexibility to use Falcon Heavy, Falcon 9, or Mars Colony Ship launches, it would also make much better sense to integrate the "plant the flag" mission which precedes full colonization into the general colonization plan. The U.S. and other governments will happily spend that much to develop the International Space Station, but not for a better, more functional replacement, or to build the foundation to go to Mars. So the bases must have smelters, and algae farms, and 3D printers with automated manufacturing so they can make real products and produce real value. BAMCCC is based on the premise that commercial space is exactly that, and the governments will be of limited assistance.

A third type of affordability – mass – must also be considered. In the SMCSA, we estimate a budget of 6,600 pounds per person – total water, food, air, body mass, clothing and possessions. In BAMCCC stations, bases, and cyclers (every habitable component that stays in a low- or microgravity environment) have aeroponic gardens incorporated into the design to provide fresh food, possibly allowing a lower mass launch cost and definitely providing a higher standard of living. Also, rather than being the "spam in a can" designs prevalent in the industry, structural aerogel, foams, and hybrid structural sandwiches build life support into the walls while increasing comfort. Doing things the way we did fifty years ago would be acceptable if newer technology did not exist. Doing the internet the same way as 1967 would not be tolerated today, nor should the space missions beyond Earth be done the same way. NASA has done great work on preparing a bulldozer for use on the Moon, or teleoperation from Mars orbit. Figure 5 schematically depicts a lunar bulldozer, with graphics based on a functionally equivalent Caterpillar Base Track Loader (BTL). A versatile, autonomous or semi-autonomous lunar/Martian bulldozer should use solar power to drive its electric motors, with batteries, electronics, and possibly solar panels installed on a lightweight body using β-Ti_3Au or similar materials for heavy duty components and aerogel structural or CFRP for lighter-duty components to reduce launch mass. Tanks in the back can spray the runway or landing pad. Presently no NASA project partners with industry to actually build low mass bulldozers or other construction vehicles (track loader, material handlers, etc.) that would be required to build bases. We think Tesla and SpaceX might be interested in forming such joint ventures. Low mass washing machines, dishwashers - in essence, anything we think we would ship to the Moon or Mars to live - will also need to be built, tested, and evolved. Mass costs affect how heavy the spacecraft are, and how much must be shipped to orbit, so if we really want to go, we must be serious and address this issue in depth.

Reuse – Refuel – Right Propellant

SpaceX rockets (Falcon) use RP-1 (kerosene). SMCSA rockets (Raptor) use methane. Chemistry is destiny for rockets, it determines limits on the specific impulse I_{SP}, which confines either type of rocket to I_{SP} of about 360 to 384 s. For contrast, the NSTAR thrusters used on Deep Space 1 and the Dawn mission typically produce I_{SP} between 1000 and 3100 s, using xenon gas for propellant. These designs are better suited for deep space, but thrust limitations preclude the use of ion drive for getting in and out of planetary gravity wells (which is essential for implementing the SMCSA scheme). The BAMCCC implementation would not be handicapped with the need for different types of propellant, since each segment of the trip would use technology optimized for that segment. SpaceX will continue to drive down cost through re-use, since a rocket which flies ten times is ten times cheaper than one that only flies once (not considering the refurbishment costs – fuel costs remain the same). High re-use targets are in place for SMCSA, and BAMCCC would seek to obtain similar numbers, with craft optimized for each segment having to deal with a smaller range of stresses. Cyclers need never enter an atmosphere, while trucks need never spend weeks in space (during normal operations).

Stations and bases are the places in both architectures where refueling occurs. Bases make propellant and oxidant (or working fluid in the case of xenon/nitrogen), using trucks to deliver it to stations, just like tanker trucks deliver gasoline to your local filling station. How they make that propellant and how they make that oxidant are key questions, and SMCSA is rather vague in terms of answers to them. The Sabatier process converts CO_2 and water into methane (and also free oxygen). Adding a Fischer-Tropsch Gas-to-Liquid (GTL) process allows the same input materials to be processed into kerosene and free oxygen. Water requires either mining (abundant on Mars, limited on the Moon) or a source of supply. One could imagine an economy developing between Mars and the Moon for shipments of water, given efficient means of doing so. Given its valuable nature on both the Moon and Mars (plus the lower general availability of xenon), the use of nitrogen as SEP working fluid could easily result in another basis for trade. The use of algae ponds to grow fuel, plastic precursors, and food provides yet another basis for trade.

System Architecture

SMCSA is colonization oriented, seeing the purpose of colonizing Mars as sufficient in itself to justify the expenditures. BAMCCC is commercially oriented, seeing the purpose of human colonization of space as the potential to add value to the entirety of human existence while paying its own way to get there. SMCSA sees a big enough rocket to go all the way to Mars, BAMCCC sees a system of interrelated parts, which adapts to the local conditions to help mankind adapt to space. SMCSA sees the Moon as an obstacle to the true destination of Mars, BAMCCC sees it as a catalyst in the cost reduction and technological evolution required to colonize the Solar System. SMCSA sees orbital stations as the main infrastructure, while stations and bases are equally important in BAMCCC, where stations link cyclers and trucks, and bases provide the resources to support them.

Today there is no such infrastructure. Five or six Falcon Heavy launches will be required to build the initial lunar base. A comparable number of launches will be required to build the lunar station (Luna Prime) and the Earth station (Johnson Prime). With the arrival of the crews for the base and stations, production will begin. Roughly 1/3 of each station or base is set aside for food production, similar to land use on Earth, with the difference being aeroponic and hydroponic robotic technologies. Both mechanical and biological life support systems are used to reduce the life support cost for people, which is true for cyclers as well. With the smelters coming online, the advanced manufacturing of cyclers, trucks, and other components big and small can begin. As the routine transport from the surface of the Earth, to Johnson Prime, then on to Luna Prime, travel to the Moon's surface becomes commonplace, and the equivalent of six Falcon Heavy launches from the Moon to Mars will build Ares Prime. The Mars base will be built, and the routine transport from the Earth and Moon to Mars will commence.

Cycler Architecture

Cyclers are not built for routine atmospheric entry, despite most of them being designed to handle an emergency landing on Earth or Mars. One example design is shown in Figure 6 (derived from an X33 variant called "BigStar" [11]), another in Figures 3 and 4 from our previous paper [12]. Most cyclers will use a combination of SEP and magnetic sails, simply because power harvesting from the magnetosphere and heliosphere will always be available to them. Another advantage is constant, gentle acceleration / deceleration. The X33 variant shown here has a HIAD-derived (HIAD - hypersonic inflatable aerodynamic decelerator) decelerator in the nose for emergency un-powered reentry. The six MHD enhanced NSTAR derived engines are tuned for nitrogen, each providing over 6,000 s I_{SP} (final thrust determined by mass flow), over fifteen times the efficiency of a Raptor engine.

Another engine is buried in the body of the spacecraft, under the skin. Figure 7 shows the magnetic field around the Mars cycler. Three separate fields are required to be able to slow down (either N-S-N or S-N-S), depending on whether the craft is sunbound or outbound. These fields allow power to be extracted (as long as the spacecraft is in motion) from the coils (typically located towards the rear of the craft), while the Lorentz force contributes propulsion from the coils located throughout the body. Another benefit of this arrangement (potentially even outweighing its contribution to shortening the trip) is the creation of a synthetic magnetosphere, preventing charged radiation from entering the craft or endangering the passengers. Neutral radiation is blocked by an ice wall located in the outer skin of the craft.

Lifting body designs like our cycler are similar to blended wing body designs, which have been investigated as the basis for near term jet aircraft designs [13]. Figure 8 shows how such a design for a large capacity jetliner could be implemented. The seats would need to be equivalent to Business Class or above seats, as shown in Figure 9, due to the long duration of the flight (80 to 180 days). It has a major disadvantage for our cycler, the thrust force would be horizontal, through the backs of the chairs, requiring walking "up" the walls to go anywhere. Our design treats the nose as "up", and the tail as "down", dividing the craft into 17 decks, roughly 3 meters (~9ft) each, as shown in Figure 10. The width of each deck is shown on the left side of the schematic, passenger capacity on the right. Lower decks ("Coach") are dominated by the airliner derived seats (64 per deck), while four "cabins" provide 16 berths per deck, as shown in Figure 11, for a total of 480 passengers. Eight access tubes provide ladders to ascend and descend between decks. While the comfort level is not exactly that of a cruise ship, it's far superior to accommodations for paying customers traveling, say, from England to Australia a century and a half ago on a trip of similar duration (up to four months).

Figure 12 shows the middle decks, which carry no passengers, but instead focus on life support and recreation. Deck 6 includes food grown by hydroponics, and biological water recycling. Deck 7 includes food grown by aeroponics, and biological air recycling. On deck 8, food is grown using automation with mechanically processed air and water. Deck 9 is used for food preparation and consumption, doing double duty as a center for card games and board games. Deck 10 is used for the mechanical Environmental Control and Life Support System (ECLSS), which are dually redundant, plus the food storage for the trip – think pallets of Meals Ready to Eat (MREs) or possibly some more appetizing options. Deck 11 is the local fitness center, designed to help compensate for the low gravity (10% Earth Normal) in a 30 × 8 m space. Deck 11 is also where the main airlock is located.

Figure 13 shows Deck 2, typically reserved for the crew due to the proximity to the command deck (or "Cockpit"). Cabins on Decks 3, 4, and 5 are larger on each lower deck, thus commanding the highest prices. Figure 14 shows the upper decks, with 8 berths on four of the decks, which when combined with the 480 total passengers and crew of the coach class, gives a maximum occupancy of 512 passengers and crew.

Vehicle Design – 3.1x Saturn V

The Mars Colonial Transport of SMCSA has at least three times the thrust of a Saturn V, thus paying a higher tax to lift its own weight. This is seven times the thrust of a Falcon Heavy, but delivers less

payload to LEO, while costing more than ten times more. This is to be expected because the payload is the Mars Colonial Ship, a full spacecraft and rocket in its own right. In BAMCCC, the seven Falcon Heavy launches, or the equivalent Falcon 9 cost launches, can be used to ship colonists, fuel, supplies – whatever the mission requires at that day and time. Falcon Heavy boosters would then land to be reused and refueled, Crewed Dragon capsules likewise. The flexibility in scheduling can produce cost savings all by itself.
The 42 engines of the Mars Colonial Transport Booster have 332 s I_{SP} at sea level and 384 s I_{SP} in vacuum. The three nine-engine cores of the Falcon Heavy have 282 s I_{SP} at sea level and 311 s I_{SP} in vacuum. This indicates that upgrading the Merlin engines to Raptor engines could provide a ~20% boost in performance (and payload). This implies that a Heavy version of the Crewed Dragon – perhaps with 15 to 20 passengers - could be designed fairly easily, cutting the launch costs in half. Some versions of the SNC Dream Catcher and the Boeing X-37C have been designed with similar capacity, so like Commercial Crew, we predict several "Earth Truck" providers will evolve to fill the demand.

Booster – Interplanetary Spaceship vs. Cycler
Even with the SMCSA design, there is no reason why the station could not be equivalent to the BAMCCC design, giving the colonists time to adjust to their new lifestyle, while the spacecraft is refueled, even if it takes days for the fuel to arrive (due to four launches and weather conditions at the launch site). This provides greater logistical flexibility, as the Mars Colonial Ship does not have to launch with all the supplies on board, instead loading them (just like the fuel and oxidizer) in orbit. Using coach and cabin designs from the cycler, the floating hotel/airport in space can reduce the logistical headaches of surface to orbit transport, interplanetary launch, interplanetary return and orbit to surface return.

One important detail of the interplanetary trip is not mentioned in the original Musk plan, which can easily be forgiven as there are millions of details to be sorted out, but since it is common to both designs, it deserves to be discussed. It is unclear given the description we are provided whether the Mars Colonial Ship runs at full burn and then coasts, or whether a lower, slower, continuous burn is planned. Either way, at some point before reaching Mars and with enough time to slow down, the ship must turn around and reverse the burn, otherwise the craft will pass right by Mars at too high a velocity to enter orbit. Variations of this become obvious, burn as hard as you can (roughly 2 *g*) until at maximum velocity to reduce trip time, coast as long as you can, then burn as hard as you can to still be able to enter orbit; or continuous burn for customer comfort (somewhere between 1/10 and 1/3 *g*) which allows you to provide the equivalent of gravity for 6 to 20 times longer without any other assistance. The ramifications of the amount of time in simulated gravity and in microgravity/zero-*g* heavily influence the mass cost of the two ship designs. Admittedly, the BAMCCC design has dramatic advantages in this regard, with higher fuel efficiency, electromagnetically harvested propulsion (the equivalent of sails on a sailing ship), and the possibility of full year access to Mars (with longer travels times depending upon distance). Even the longest route, Earth to Mars on opposite sides of the Sun, would take no more time than the unpowered Earth to Mars travel at opposition (roughly six months in current plans).
Hybrid designs
One possibility we would be remiss not to suggest is that the SpaceX hardware described in the Musk Mars colonization plan [1] can be adapted to the cycler/truck scheme, potentially resulting in

substantial savings. For example, several Mars colony ships can be used for surface-to-orbit transfers (and configured to accommodate shorter trip durations and more acceleration/maneuvering), while differently configured ships using the same basic hardware will serve as cyclers. This approach has the advantages of using the investment already put into the development of the plan and of having a unified hardware platform.

Propellant Manufacturing

Regardless of what fuel burn profile is chosen, fuel and oxidizer, or working fluid, has to be provided. It is fairly safe at this point to assert there will be no oil reserves on the Moon or Mars, no dinosaurs that died for our sins so that we might live. We can create them with algae ponds [14], just as we do on Earth (although they may need to be sealed, have artificial lighting, etc.) as shown in Figure 15. This gives settlers on the Moon and Mars direct access to the hydrocarbon chain, the ability to make fuels and plastics off world.

Mars of course, has another option, direct atmospheric compression and processing, combined with ice mining. For over a century, the Sabatier reactor [2,15] has combined CO_2 with hydrogen to make methane, and further processing by steam reforming and the Fischer-Tropsch process can be used to produce synthetic fuels such as diesel, kerosene, and gasoline, in addition to hundreds of other traditionally petrochemical products.

CO_2 is a problem child (chemically speaking) on Earth. Output from power generation plants in the billions of tons produces carbon poisoning, which results in deleterious environmental consequences. Solving the fuel production problem for Mars also solves a large part of the carbon poisoning problem on Earth. The only significant difference is a means of filtering the power plant exhaust to isolate the carbon dioxide, which can be achieved in a couple of different ways. One way, used at the Petra Nova Carbon Capture plant [16], uses an amine process. Another way is to directly filter the CO2 through a selective membrane, such as the Memzyme process recently patented by UNM and Sandia National Laboratories. A power plant which creates carbon neutral fuel from what would otherwise become pollution is shown in Figure 16. This gives us an opportunity to perfect the technology on Earth while preparing to deploy it on Mars. We note that AABT, one of our partners on the ArmorHab paper [12], is working on bioreactor technology to replace the Fischer-Tropsch process, which would be much more mass cost efficient.

Cost Per Trip

The launch of seven Falcon Heavys at 100M$ each only provides half the colonists that the launch of a Mars Colonial Transport does at 2B$, so full equivalence must come from fourteen launches (1.4B$), and to fill a cycler takes seventy-four launches, at a cost of 7.4B$. The tankers required add 8B$ to the SMCSA, fuel and supplies for the Cycler another 7.4B$. So the SMCSA ships 100 people at 10B$ (100M$/person) to orbit, while BAMCCC ships 500 people to orbit at 15B$ (30M$/person). Fortunately, both designs can reuse launchers to reduce costs for future passengers.

The BAMCCC design requires three stations, at 10B$, and two bases at 10B$, for a basic cost of 50B$. SMCSA implies there is only one station (at Earth), and there are no bases for the colonists to live in when they arrive (BAMCCC Bases are robotically assembled). The SMCSA design has certain risks for the first colonists, including uncertainty regarding the arrival of the supplies (unless these are sent before their arrival). Additionally, without a source for the hydrogen used in the fuel production process, the colonists will remain stranded on the surface, unable to ever return. Presuming they land well within the shoreline of the Great Northern Ocean and are provided with shovels, they should be able to reach the ice at depths of a meter to a few meters. They will then find out that the colder the ice, the harder the ice. Without ice mining tools and equipment, they will be unable to extract the water, then split it to make fuel and oxidizer.

So the prudent course of action is to make a Mars station and Mars base at 20B$ part of the SMCSA, because otherwise the design fails. Colonists have a place to arrive, with sufficient food, and an operable base on the surface, with bulldozers, material handlers, smelters, and tools. The equivalent cost is at least 30B$, sufficient to say only the cost associated with colonizing the Moon. All that is left to equalize the designs is some method of transport from Mars surface to orbit, and from orbit to surface. We now encounter a cost never seen in either of the designs. Presuming the use of Crewed Dragons, colonists will need space suits to leave the capsule and enter the base, plus the manufacture of some number of Falcon Heavy equivalents somewhere, and towing them to Mars for them to retro-repulsively land. Then the colonists are also going to need a ladder. A really big, long ladder.

An alternative solution is to make the Mars truck based upon the cycler design, with fuel tanks in place of the middle decks, for a tail based landing, and a docking collar that comes out from the base like the docking jetway at modern airports. This mechanism could also be modified for the Falcon Heavy solution. The point of the whole exercise is that colonization requires preparation, and with some forethought, a more cost effective solution is available. The SMCSA tells us a great deal about one way to get to Mars, almost nothing about what to do when we get there, and even less about how to get back. The BAMCCC tells us even more about how to get to Mars, using the path that leads through the Moon, gives us stations and bases that are functional the day we arrive, and make it easy to get home again. It does more for 1/3 the cost per person, and is the better engineering solution.

Timeline

No battleplan survives unmodified the first encounter with the enemy. No space program survives its the first contact with reality on schedule and within budget. SpaceX has delayed milestone after milestone, but it has also accomplished milestone after milestone. Every time they faced setbacks, they have persevered. At one time, six Falcon Heavy launches would be more that all the Falcon Heavy launches of all time. This time is today. But if we go by Falcon 9 launches, it is less than the Falcon 9 launches so far this year. So within two years, we could launch the rockets to build the lunar base (Luna Actual), if we knew how to build one. Call it 2020. Two years after that, we could build a station in Earth Orbit (GEO), directly over Houston, Texas (thus Johnson Prime). Call it 2022. Two years after that, we could build the lunar station, Luna Prime. Call it 2025. Two years after that, we could build a Station in areosynchronous orbit (Ares Prime). Call it 2027. Two years after that, we could build the martian base (Ares Actual). Call it 2029. Two years after that, we could begin colonizing Mars. Call it 2031. Note that the first humans on Mars could arrive in 2027, a full decade before NASA gets there.

FIGURES

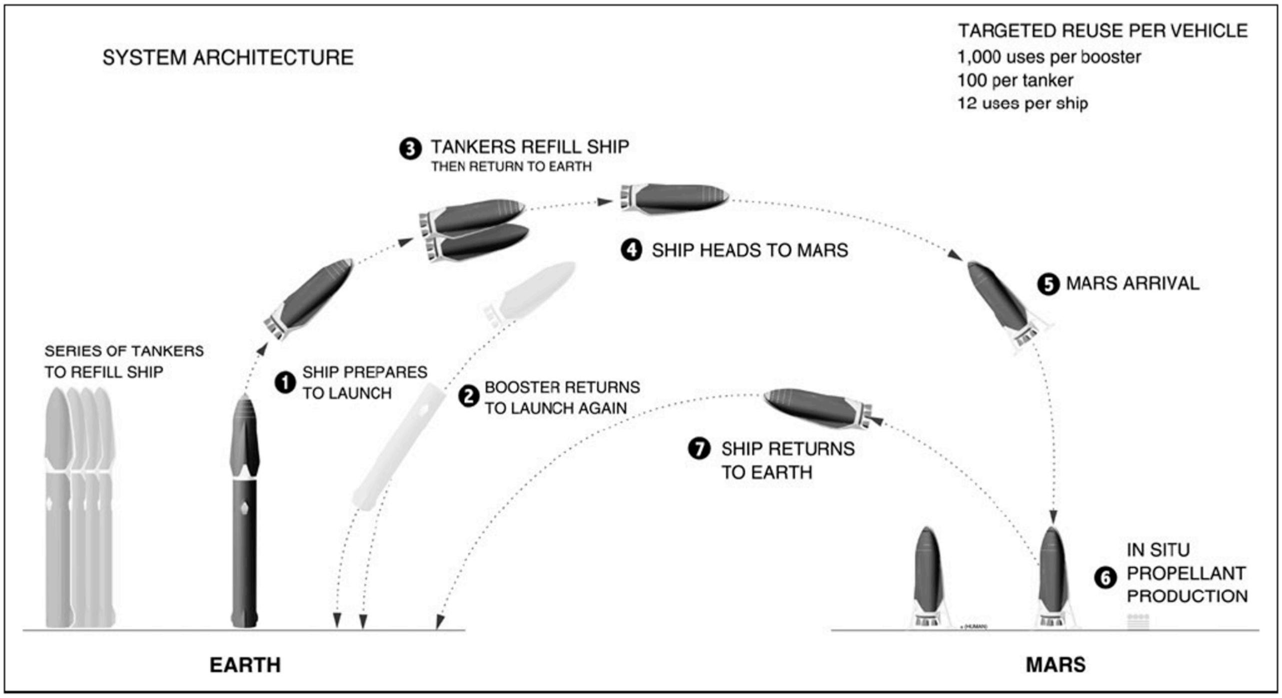

Figure 1: SpaceX Mars Colonization System Architecture (figure 5 in original text)

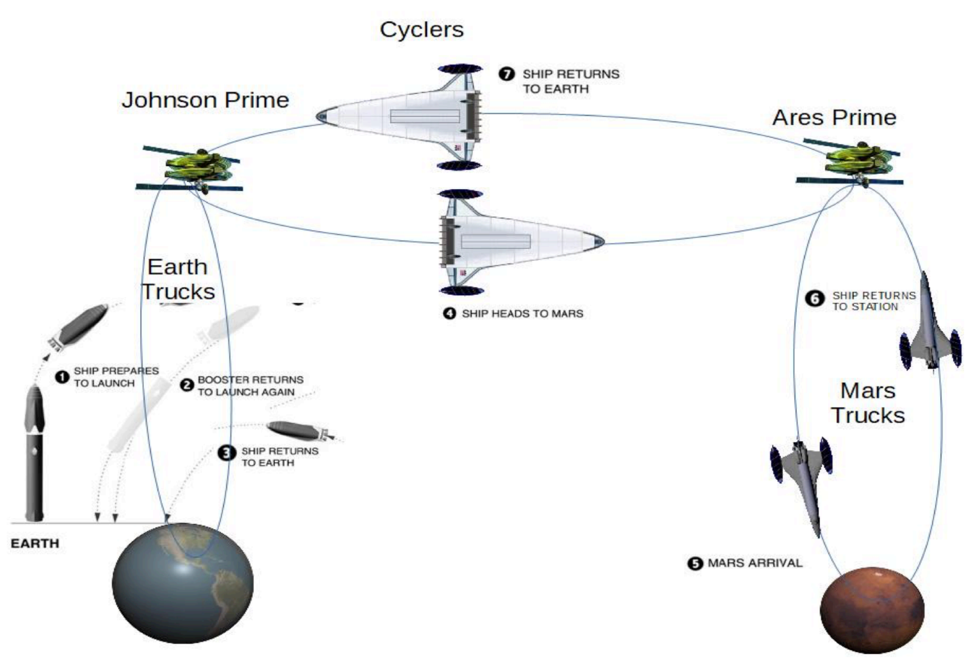

Figure 2: Buzz Aldrin Mars Colonization Cycler Concept

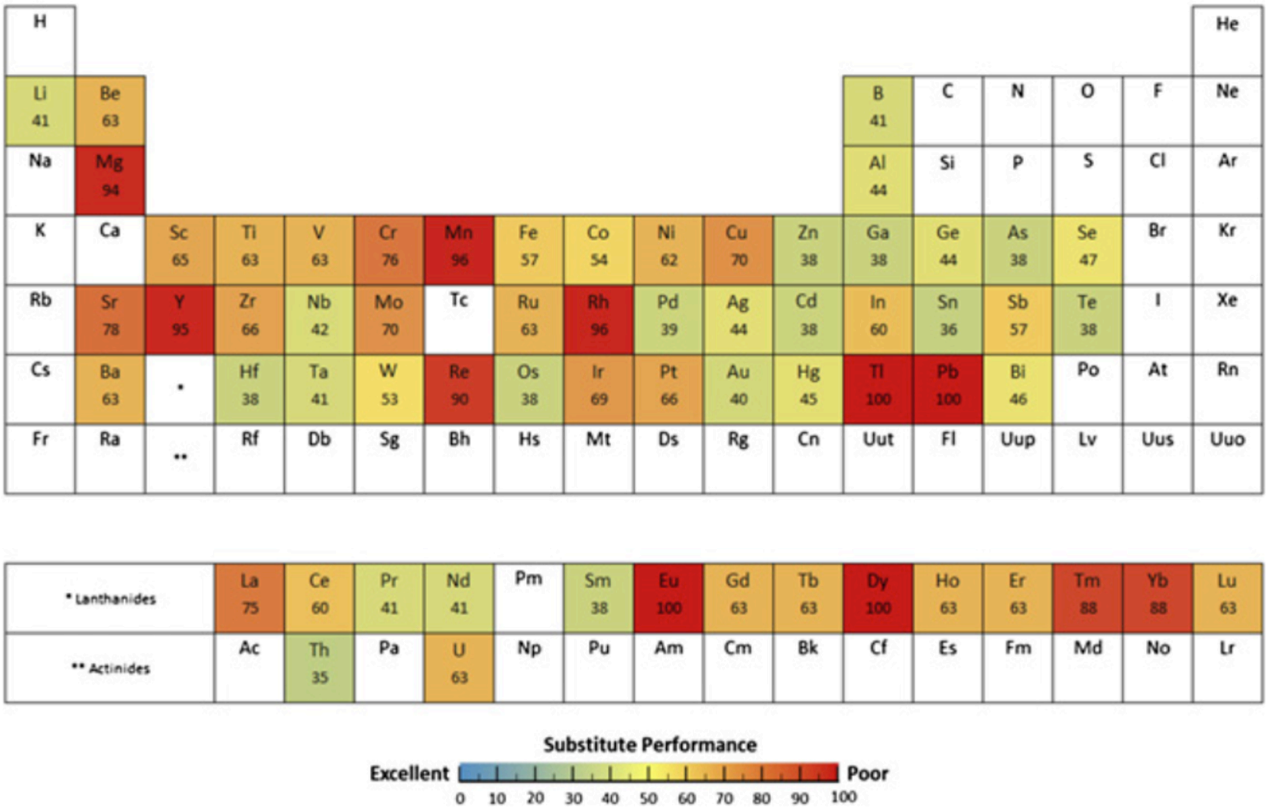

Figure 3: Periodic Table of Substitute Performance

Rocket	Launch	LEO Prison	Moon	Mars	M$	$/lb	$/LEO
Falcon 9	1116984	50265	18300	8860	62	$6,997.74	$1,233.46
fraction	100.00%	4.50%	1.64%	0.79%			
Falcon Heavy	3125735	140660	58860	37040	180	$4,859.61	$1,279.68
fraction	100.00%	4.50%	1.88%	1.19%			
9x Falcon 9	10052856	452385	164700	79740	558	$6,997.74	$1,233.46
fraction	100.00%	4.50%	1.64%	0.79%			
3x Falcon Heavy	9377205	421980	176580	111120	540	$4,859.61	$1,279.68
fraction	100.00%	4.50%	1.88%	1.19%			
SLS	6118064	290000	110771	69707	500	$7,172.88	$1,724.14
fraction	100.00%	4.74%	1.81%	1.14%			
Saturn V	6540000	310000	107100	67396	1160	$17,211.70	$3,741.94
fraction	100.00%	4.74%	1.64%	1.03%			
Mars Heavy	20625000	928125	389813	247500	2050	$8,282.83	$2,208.75
fraction	100.00%	4.50%	1.89%	1.20%			

Figure 4: Table of Rocket Performance for Heavy Rockets

Figure 5: Modified Caterpillar D6N for off-world use

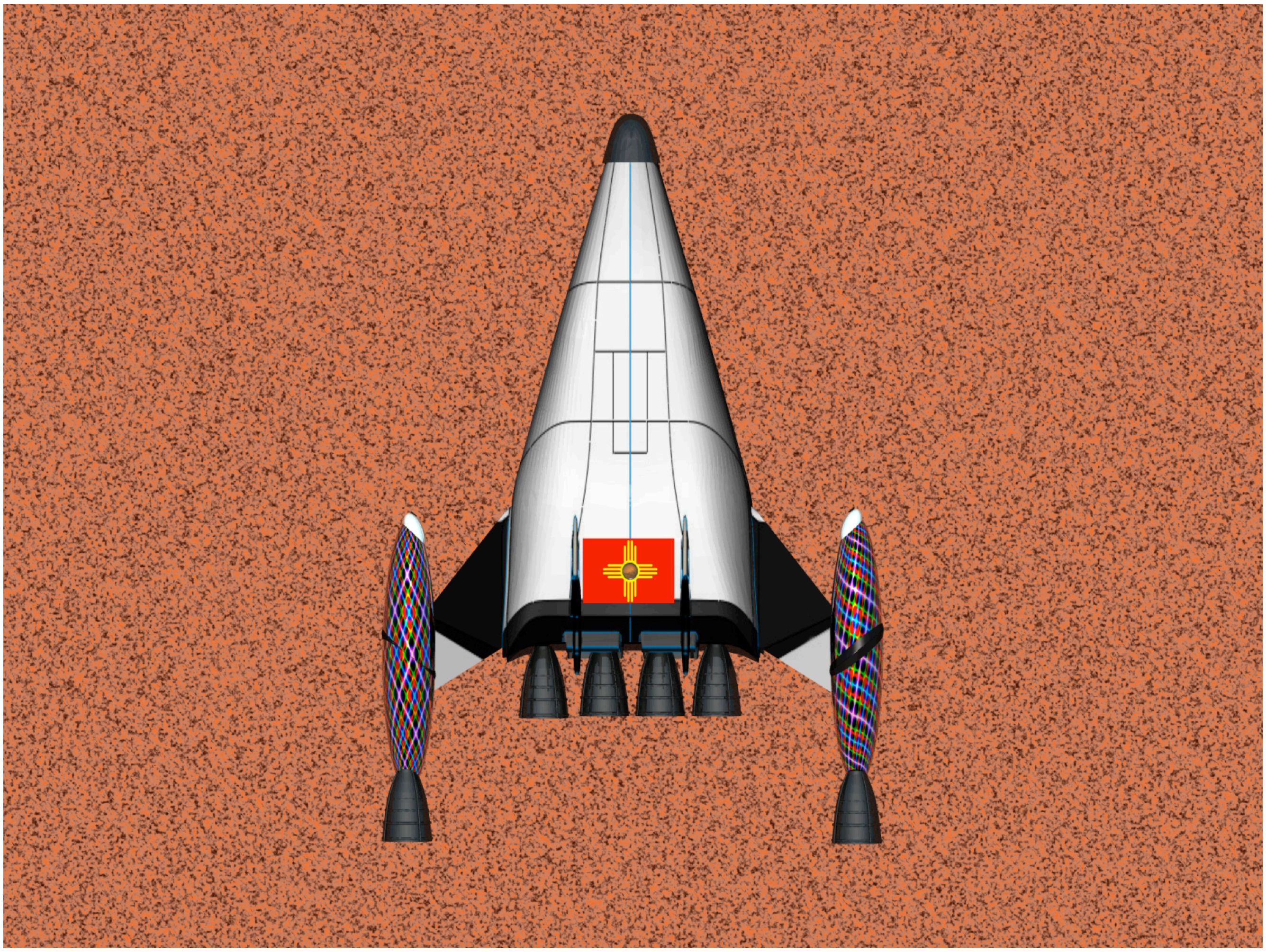

Figure 6: X33 VentureStar derivative Cycler in Low Orbit over Mars

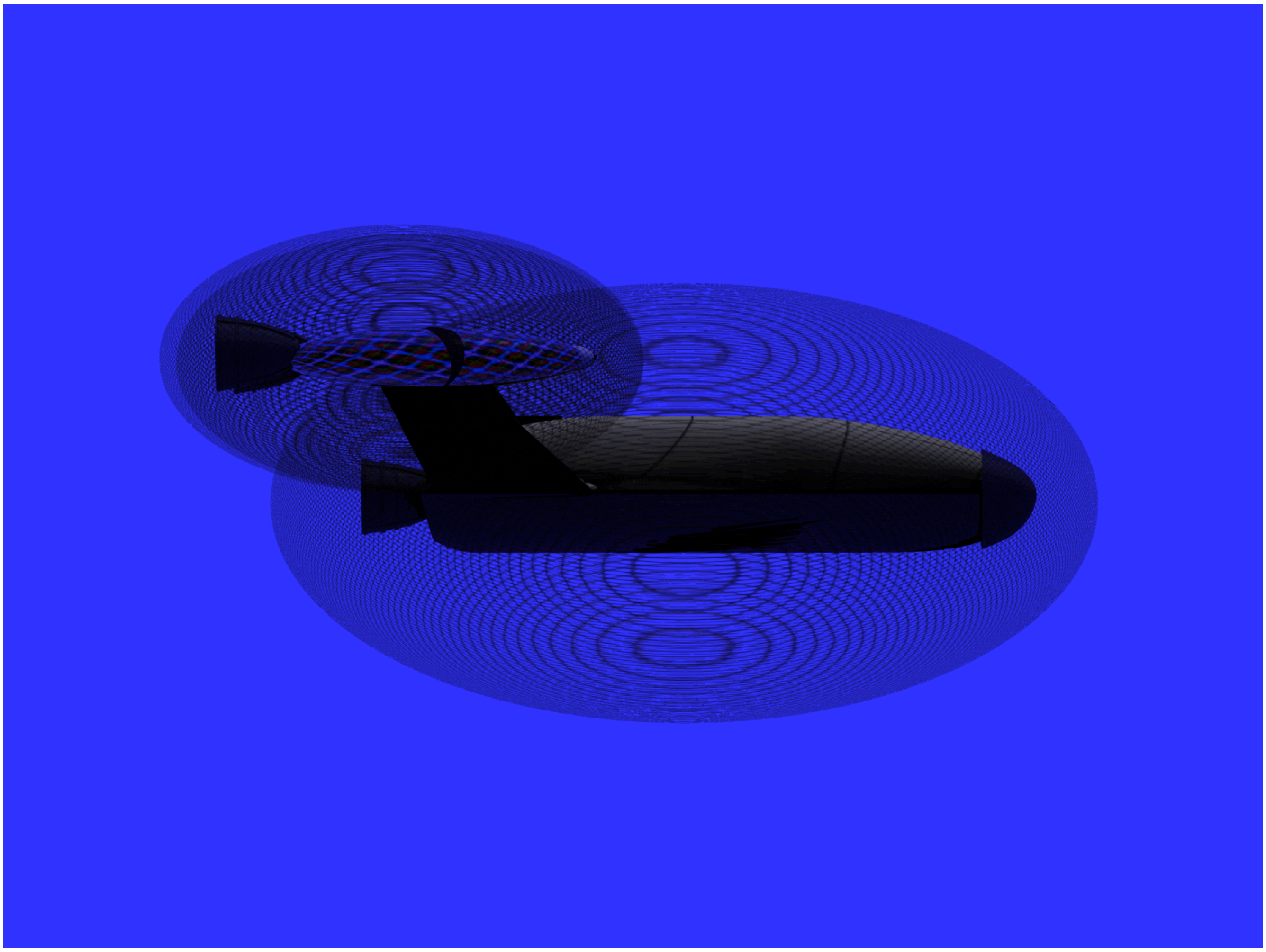

Figure 7: Magnetic field around Mars Cycler

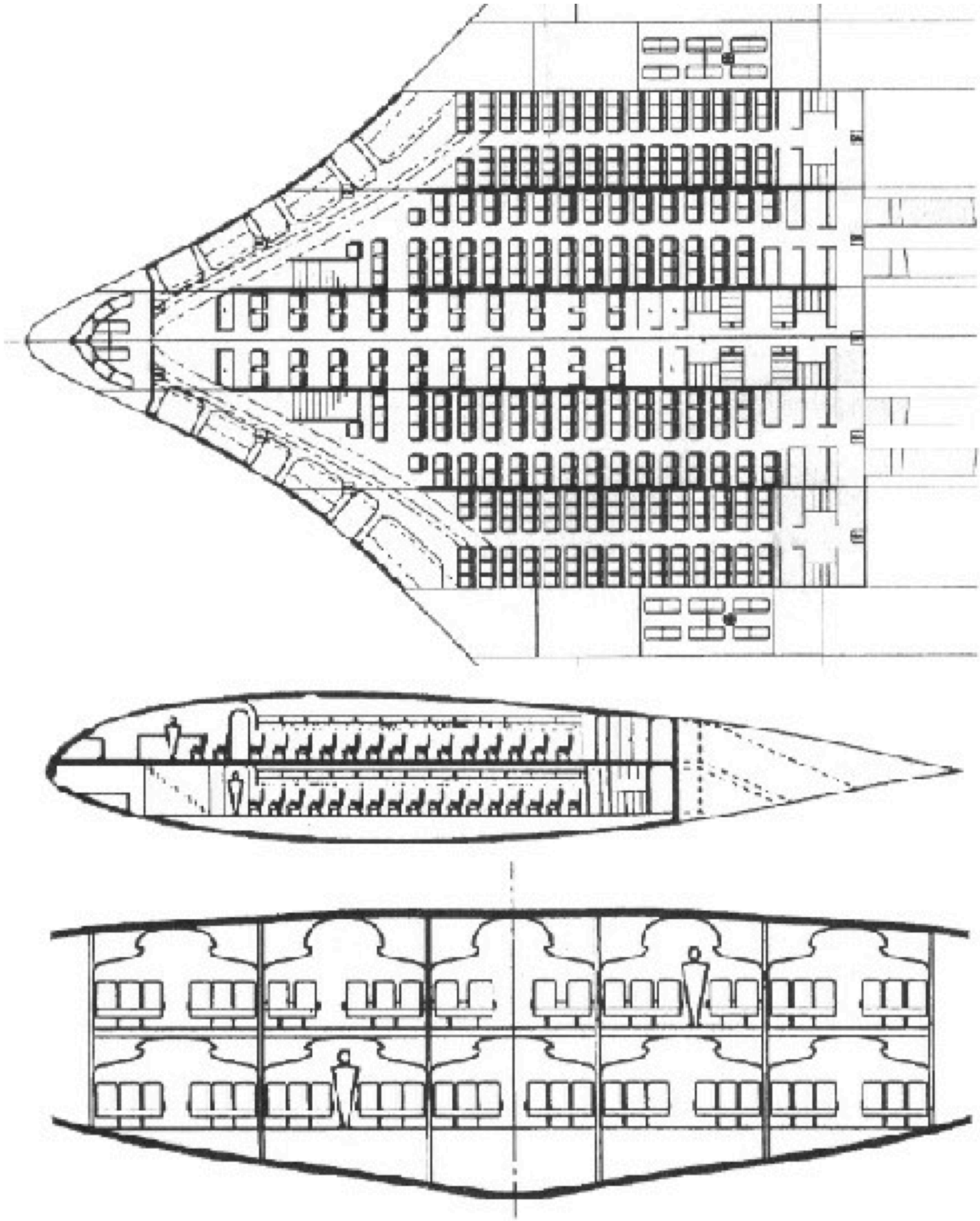

Figure 8: Blended Wing Body layout of future airliner

Figure 9: Seat styles of modern aircraft

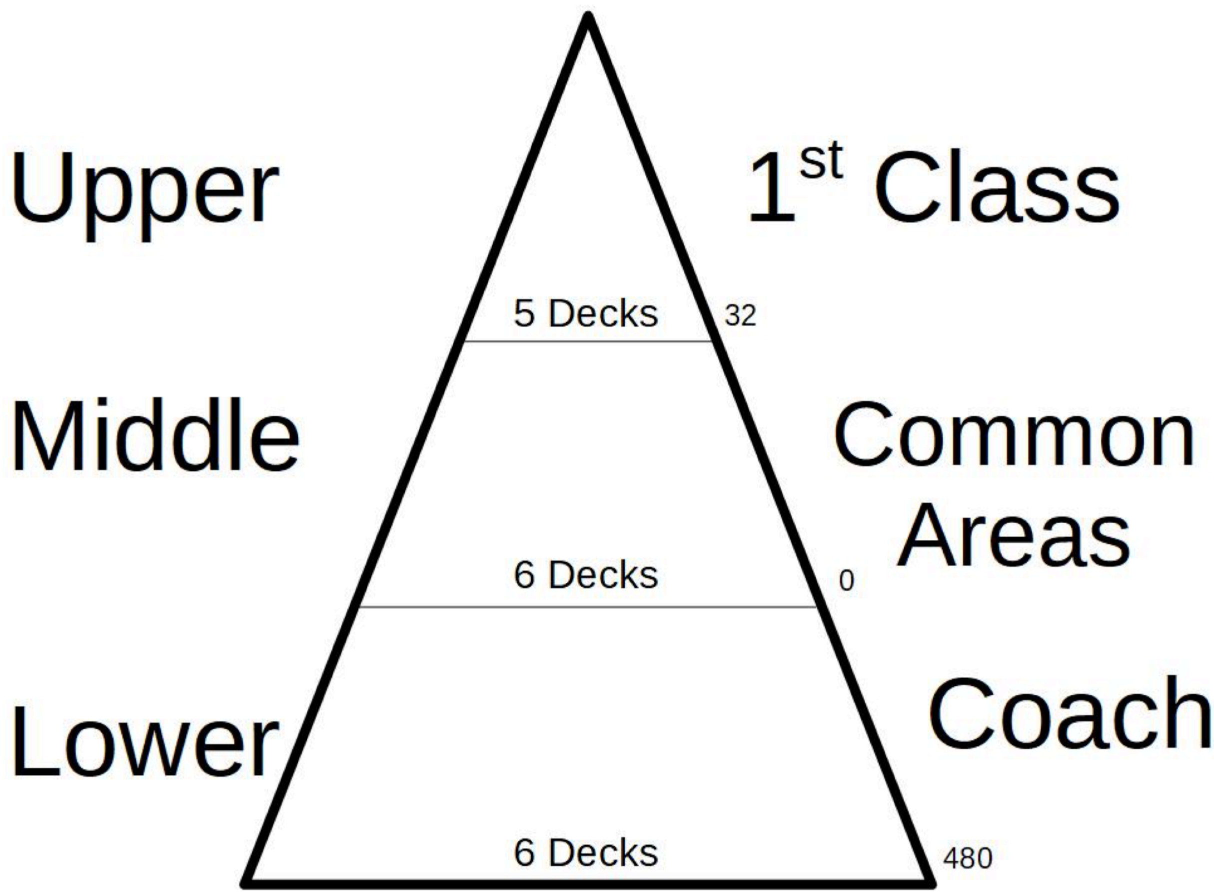

Figure 10: Cycler deck layout

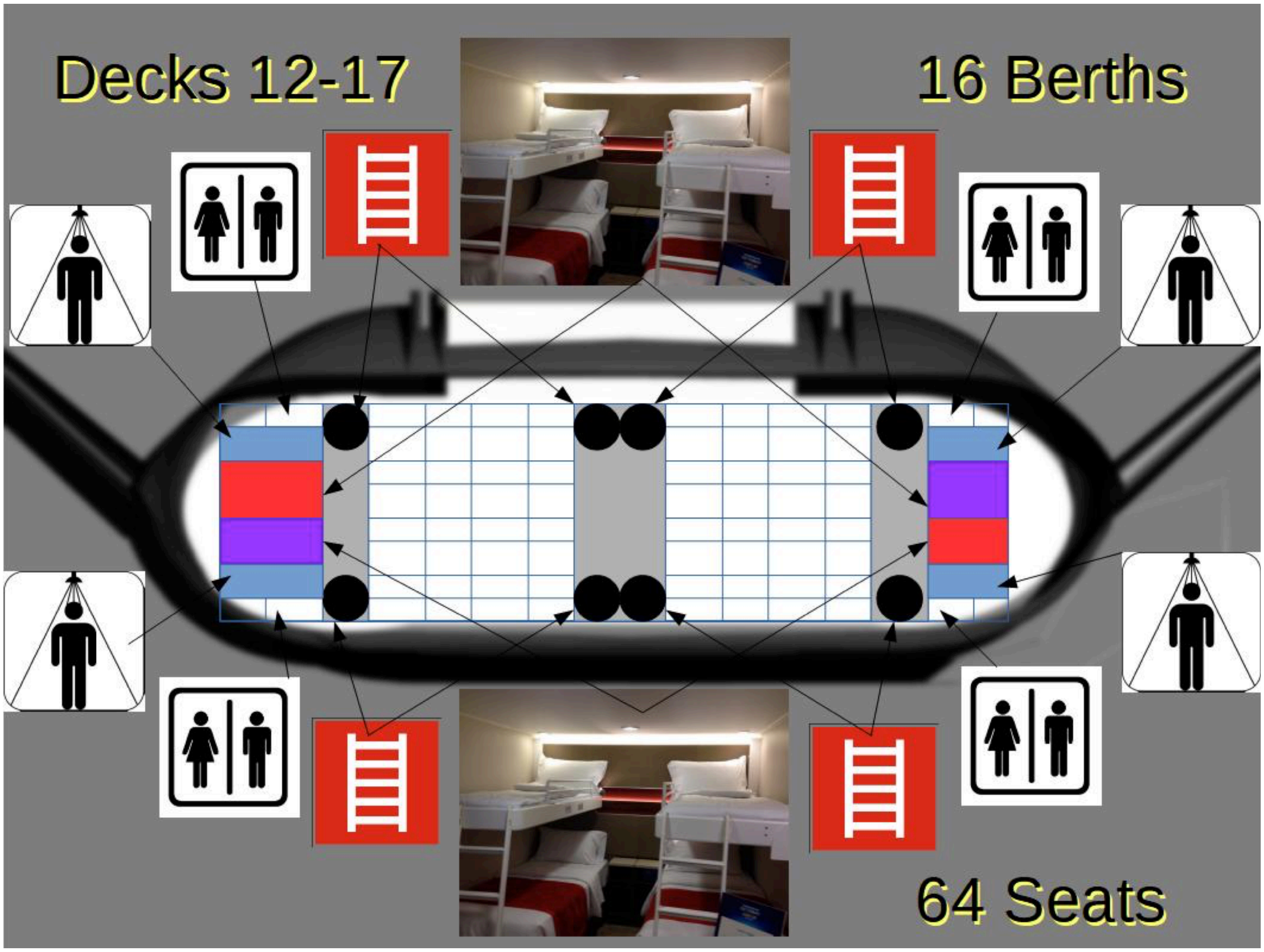

Figure 11: "Coach" class Cycler decks

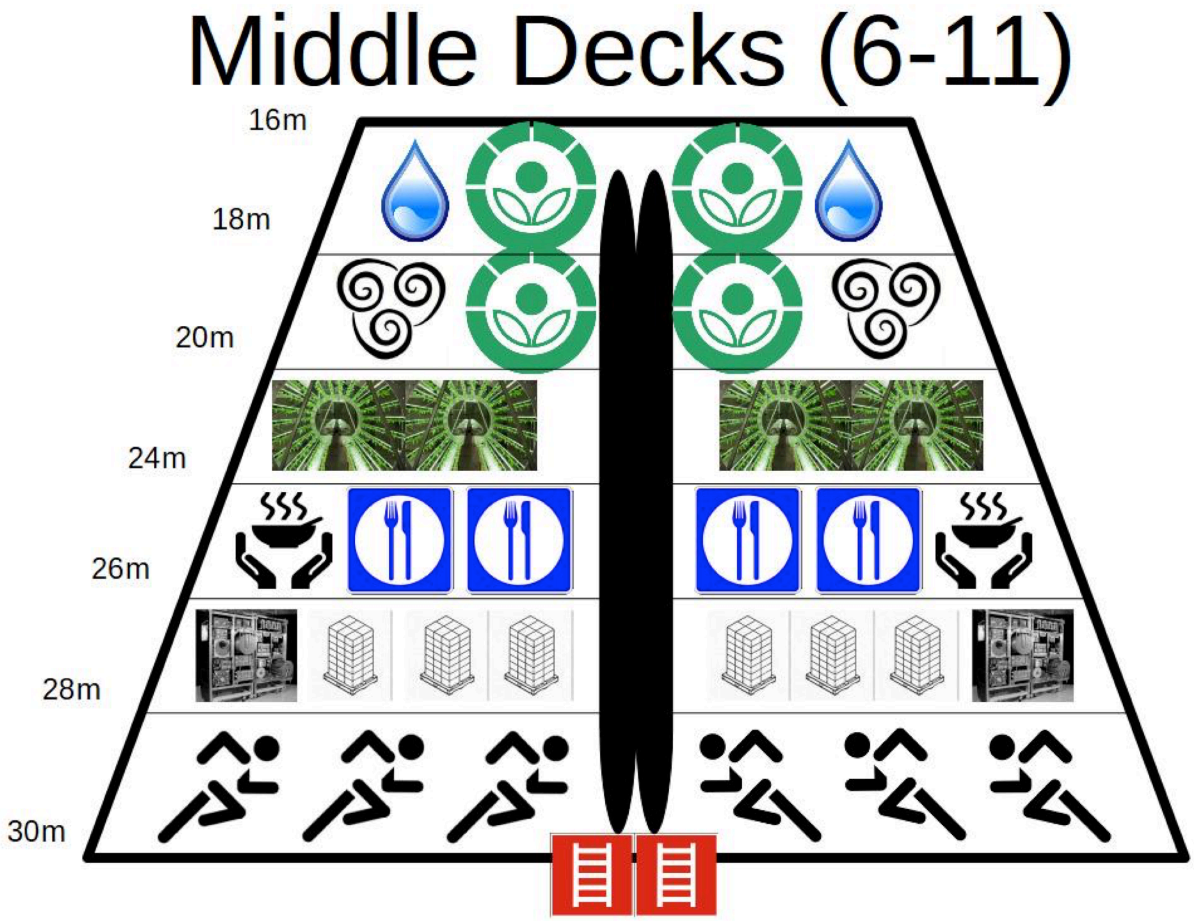

Figure 12: Cycler Middle Decks

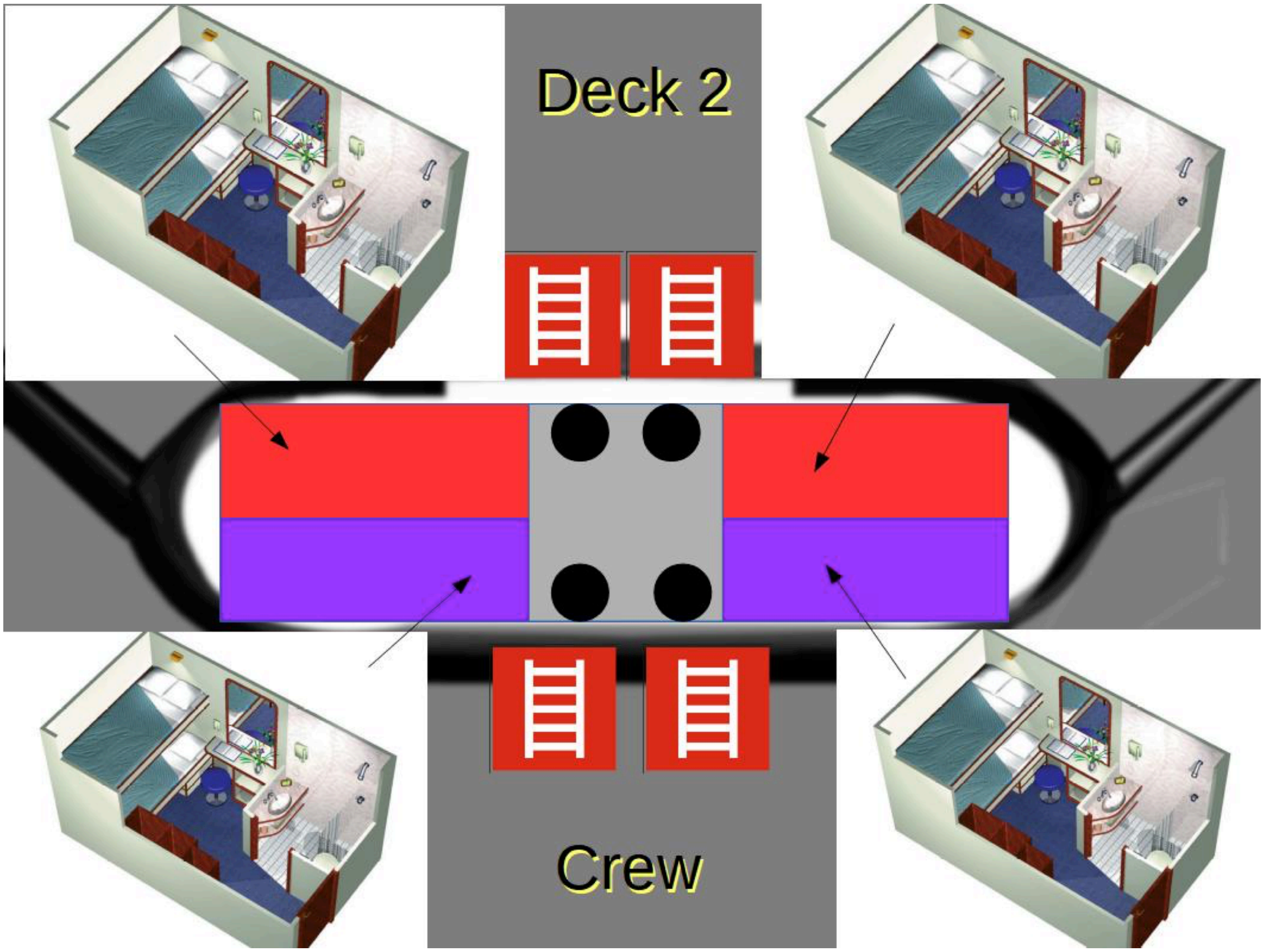

Figure 13: Cycler example upper deck layout

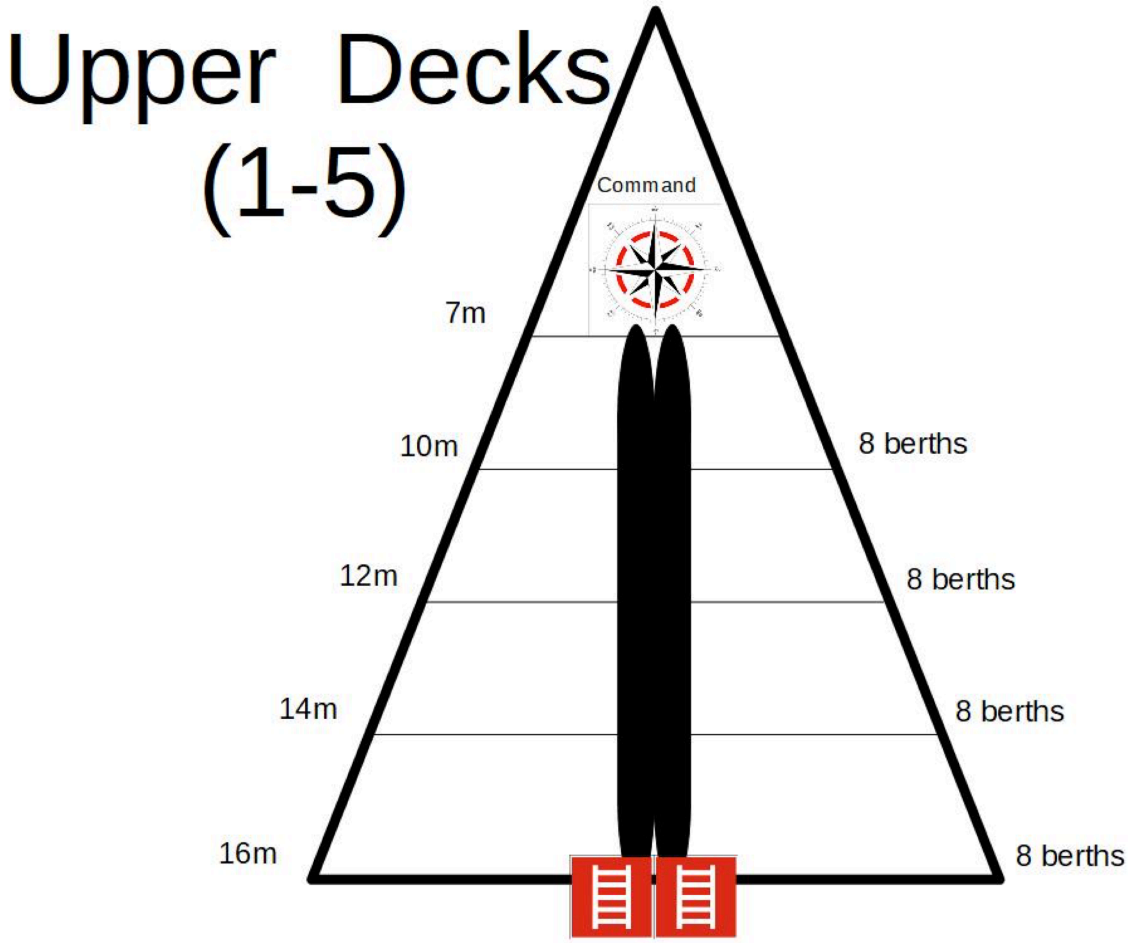

Figure 14: Cycler Upper Decks

Figure 15: Algae biofuel ponds on Earth

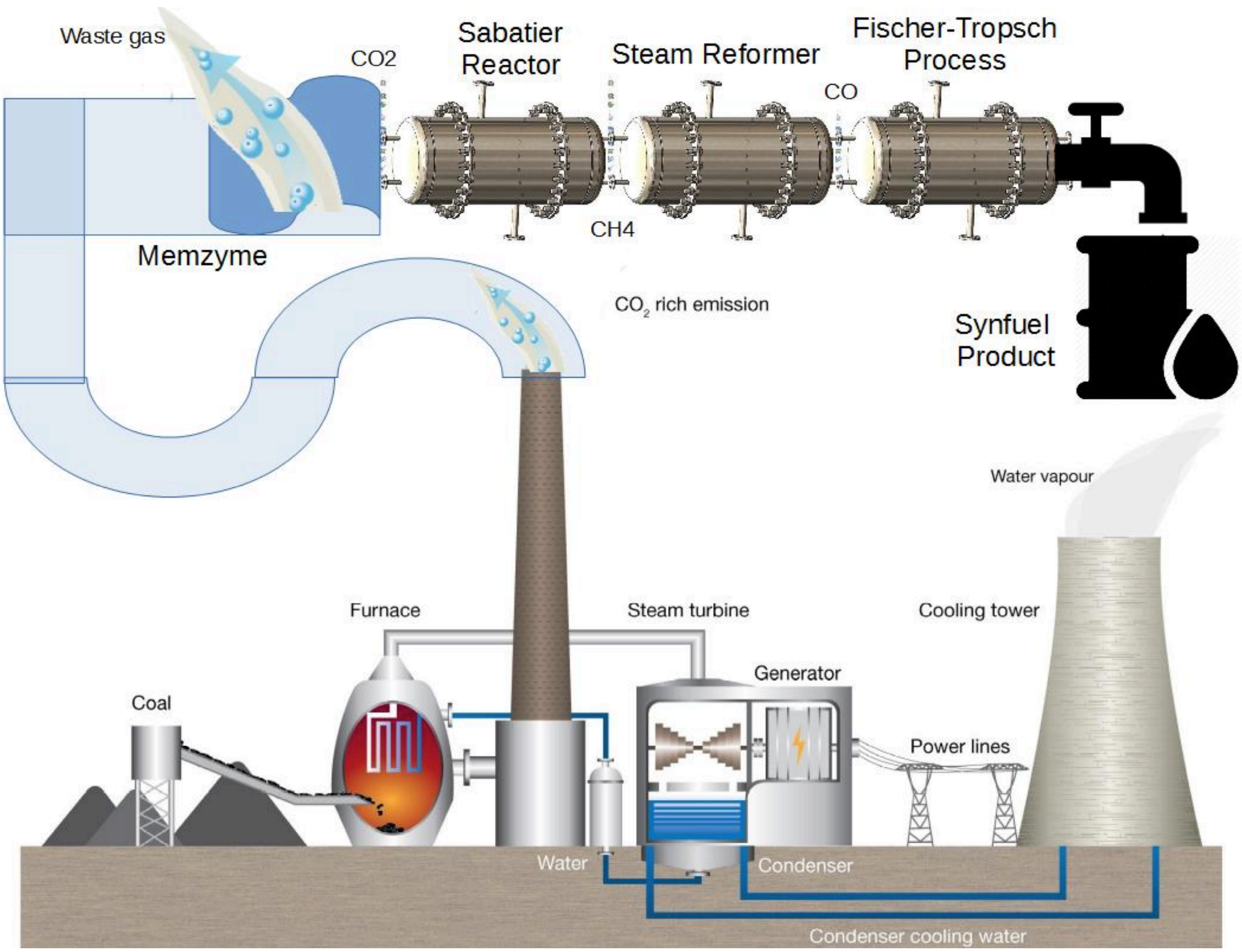

Figure 16: Carbon pollution converted to carbon neutral fuel

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