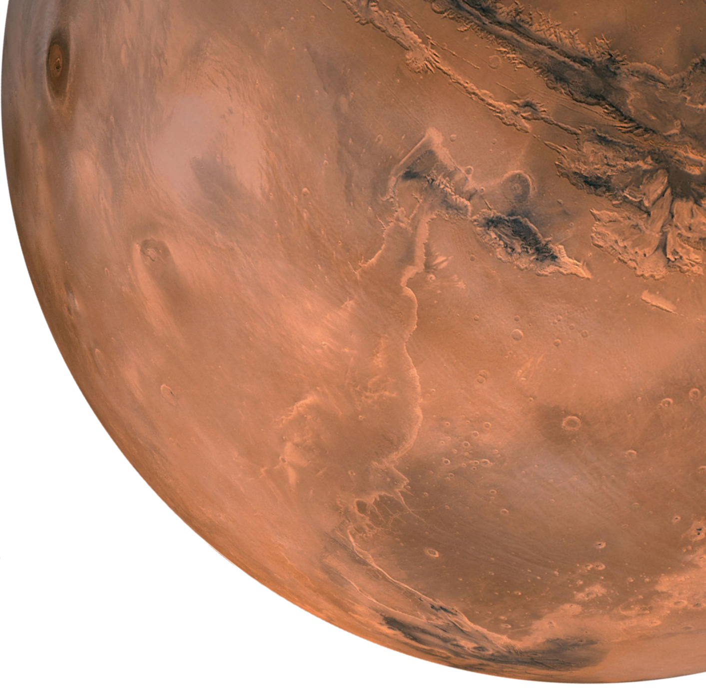
This documet is an abridged transcript of Elon Musk's presentation at the 68th International Astronautical Congress on September 28th, 2017 in Adelaide, Australia.



MAKING LIFE MULTIPLANETARY

> *"You want to wake up in the morning and think the future is going to be great - and that's what being a spacefaring civilization is all about. It's about believing in the future and thinking that the future will be better than the past. And I can't think of anything more exciting than going out there and being among the stars."*
>
> *Elon Musk, CEO and Lead Designer, SpaceX*

BECOMING A MULTI-PLANET SPECIES

This presentation will cover the updated design for what we are currently calling BFR. The most important thing that I want to convey in this presentation is that I think we have figured out how to pay for it. This is very important.

In last year's presentation, we were really searching for the right way to pay for this thing. We went through various ideas—Kickstarter, collecting underpants, etc. These didn't pan out, but now we think we have got a way to achieve this.

Our updated design leverages a smaller vehicle, still pretty big but a single vehicle that can do everything that's needed for greater Earth orbit activity. Essentially we want to make our current vehicles redundant. We want to have one system—one booster and one ship—that replaces Falcon 9, Falcon Heavy and Dragon. If we can do that, then all the resources that are used for Falcon 9, Falcon Heavy and Dragon can be applied to this system. That's really fundamental.

PROGRESS

DEEP CRYO LIQUID OXYGEN TANK

This giant deep cryo liquid oxygen tank is actually a twelve meter tank—you can see the relative scale of it in figure 1. It's a thousand cubic meters of volume inside. That is actually more pressurized volume than an A380, to put that into perspective. We developed a new carbon fiber matrix that is much stronger and more capable at cryo than anything before, and it holds 1200 tons of liquid oxygen.

We successfully tested the tank up to its design pressure and then went a little further. We wanted to see where it would break, and we succeeded in that effort. It shot about 300 feet into the air, landed in the ocean and we fished it out. At this point we have got a pretty good sense of what it takes to create a huge carbon fiber tank that can hold cryogenic liquid. That is actually extremely important for making a light spaceship.

Fig.1. Deep cryo liquid oxygen tank developed by SpaceX

RAPTOR ENGINE TESTING

The next key element is on the engine side. We have to have an extremely efficient engine; the Raptor engine will be the highest thrust-to-weight engine, we believe, of any engine of any kind ever made. We already have 1200 seconds of firing across 42 main engine tests. We have fired Raptor for as long as 100 seconds. It could fire for much longer than 100 seconds, this is just a reflection of the size of the test tanks. The duration of the firing for landing on Mars is about 40 seconds. The test engine currently operates at 200 atmospheres, or 200 bar, the flight engine will be at 250 bar, and then we believe over time we could probably get that to a little over 300 bar.

MAKING LIFE MULTIPLANETARY

Fig.2. Falcon 9 completing a successful propulsive landing

PERFECTING PROPULSIVE LANDING

The next key element is propulsive landing. In order to land on a place like the Moon where there is no atmosphere and certainly no runways, or to land on Mars where the atmosphere is too thin to land with wings even if there were runways, you really have to get propulsive landing perfect.

Propulsive landing is what we have been practicing with Falcon 9. As of the time of this presentation, SpaceX has had 16 successful landings and that is really without any redundancy. Falcon 9's final landing is always done with a single engine whereas with BFR, we will always have multi-engine out capability. You want minimum pucker factor on landing—you need to be able to essentially count on the landing. If you can get to a very high reliability with even a single engine, and then you can land with either of two engines, I think we can get to a landing reliability that is on par with the safest commercial airliners.

Falcon 9 can also land with very high precision. In fact, we believe the precision at this point is good enough that we will not need legs for the next version. It will literally land with so much precision that it will land back on its launch mounts.

LAUNCH RATE

When you seriously consider the idea of establishing a self-sustaining base on Mars or the Moon or elsewhere, you ultimately need thousands of ships and tens of thousands of refilling operations. This means you need many launches per day. In terms of how many landings are occurring, you need to be looking at your watch, not your calendar.

So while SpaceX's launch rate is quite high by conventional standards, it is still a very small launch rate compared to what will ultimately be needed.

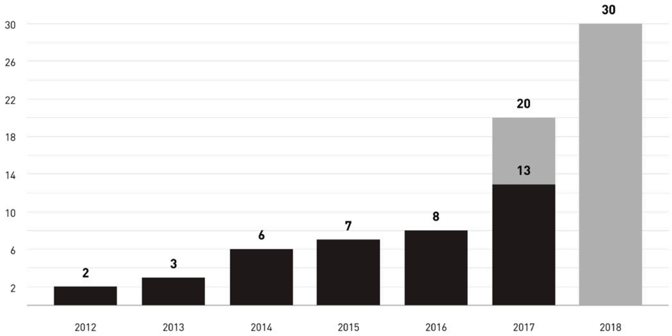


Fig.3. Launch rate to date and projected 2017/2018

RENDEZVOUS AND DOCKING

The next key technology is automated rendezvous and docking. In order to refill the spaceship in orbit, you have to be able to rendezvous and dock with the spaceship with very high precision and transfer propellant. That is one of things that we have perfected with Dragon. Dragon 1 will do an automated rendezvous and docking without any pilot control to the space station.

Dragon 1 currently uses the Canadarm for the final placement onto the space station. Dragon 2, which launches next year, will not need to use the Canadarm as it will directly dock with the space station, and it can do so with zero human intervention. You just press "go" and it will dock.

Dragon has also allowed us to perfect heat shield technology. When you enter at a high velocity, you will melt almost anything. The reason meteors do not reach Earth is they melt or disintegrate before they reach the ground, unless they are very big. You have to have a sophisticated heat shield technology that can withstand unbelievably high temperatures and that is what we have been perfecting with Dragon—also a key part of any planet colonizing system.

VEHICLE EVOLUTION

FALCON 1

Falcon 1 is where we started out. A lot of people really only heard of SpaceX relatively recently, so they may think Falcon 9 and Dragon just instantly appeared and that's how it always was—but it wasn't. We started off with just a few people who really didn't know how to make rockets. And the reason that I ended up being the chief engineer or chief designer, was not because I wanted to, it's because I couldn't hire anyone. Nobody good would join, I ended up being that by default. And I messed up the first three launches, the first three launches failed. Fortunately the fourth launch—which was the last money that we had for Falcon 1—the fourth launch worked, or that would have been it for SpaceX. But fate liked us that day. So the fourth launch worked and it's interesting—today is the ninth anniversary of that launch. I didn't realize that until I was told that just earlier today but this is a very emotional day, actually.

Falcon 1 was quite a small rocket. When we were doing Falcon 1 we were really trying to figure out, "What is the smallest useful payload that we could get to orbit?" We thought, okay, something that could launch around half a ton to low Earth orbit. And that is how we sized Falcon 1, but it is really quite small compared to Falcon 9.

FALCON 9

Falcon 9, particularly when you factor in payload, is roughly on the order of thirty times more payload than Falcon 1. And Falcon 9 has reuse of the primary booster, which is the most expensive part of the rocket. Hopefully, Falcon 9 will soon have reuse of the fairing, the big nose cone at the front. We think we can probably get to somewhere between 70 and 80 percent reusability with the Falcon 9 system.

FALCON HEAVY

Hopefully, towards the end this year we will be launching Falcon Heavy. Falcon Heavy ended up being a much more complex program than we thought.

It sounds like Falcon Heavy should be easy because it's two Falcon 9 first stages strapped onto a center first stage as boosters. It is actually not easy. We had to redesign almost everything except the upper stage in order to take the increased loads. Falcon Heavy ended up being much more a new vehicle than we realized, so it took us a lot longer to get it done, but the boosters have all now been tested and they are on their way to Cape Canaveral. And we are now beginning serious development of BFR.

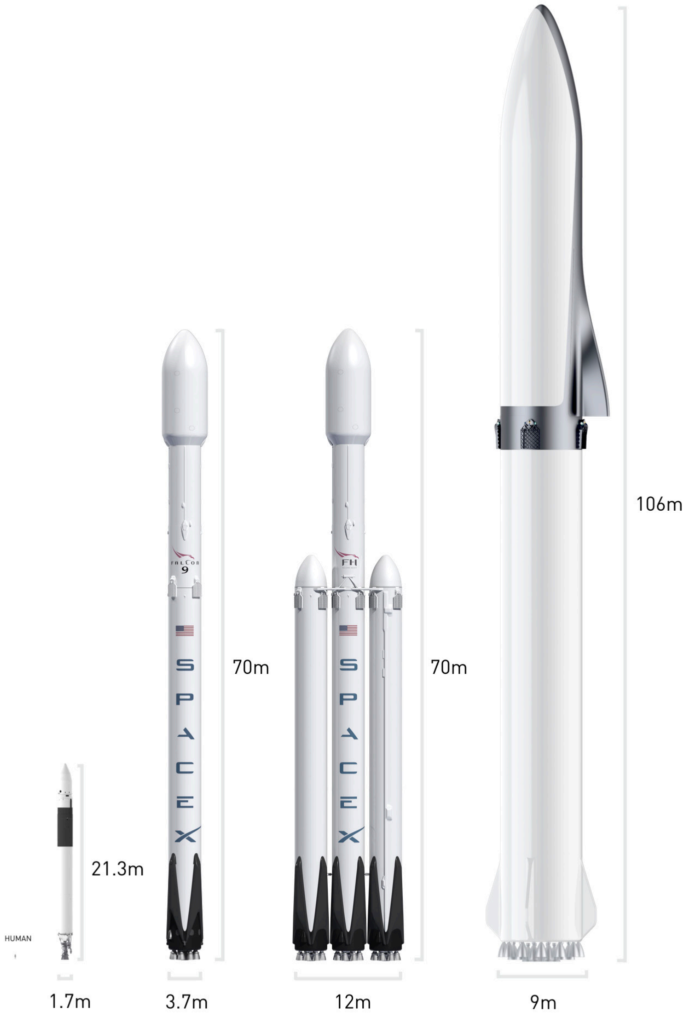


Fig.4. Vehicle overview: Falcon 1, Falcon 9, Falcon Heavy and BFR

MAKING LIFE MULTIPLANETARY

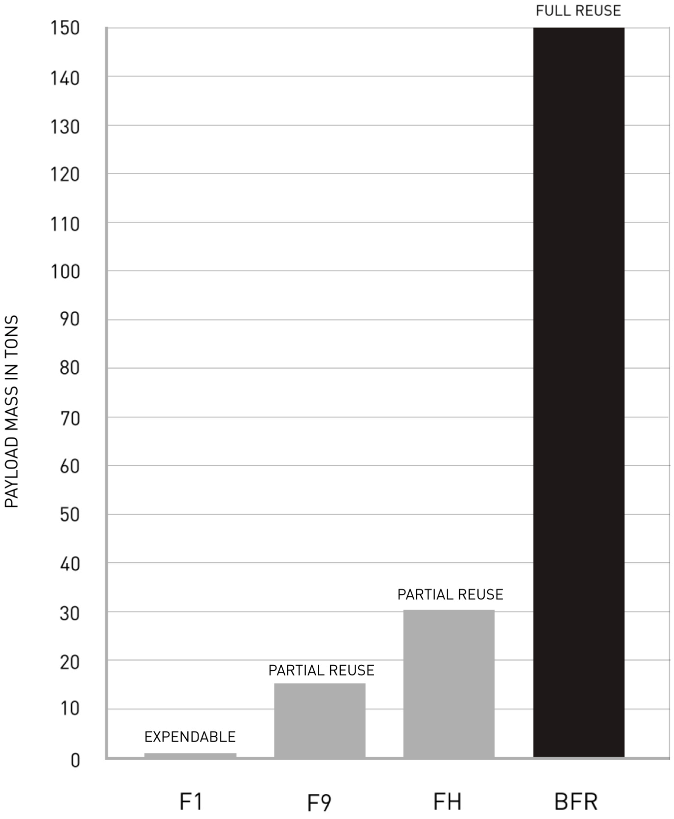


Fig.5. Vehicle payload comparison in tons

BFR

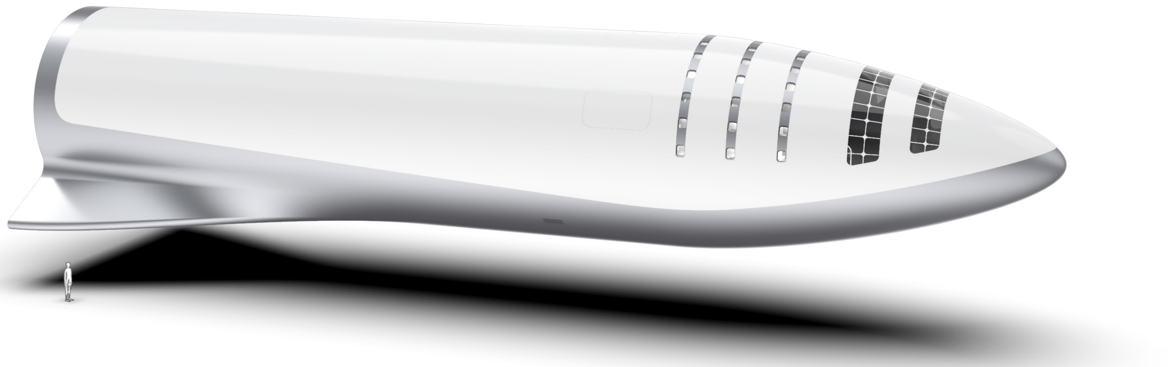
From figure 5, you can see that the payload difference between BFR and the other vehicles is quite dramatic. With BFR in fully reusable configuration, without any orbital refueling, we expect to have a payload capability of 150 tons to low Earth orbit. That compares to about 30 tons for Falcon Heavy, which is partially reusable. Where this really makes a tremendous difference is in the cost, which will be discussed later in the presentation.

With BFR, you can get a sense of scale by looking at the tiny person in the image below. It is really quite a big vehicle. Main body diameter is about 9 meters or 30 feet and the booster is lifted by 31 Raptor engines that produce a thrust of about 5,400 tons, lifting the 4,400 ton vehicle straight up.

BFR SHIP OVERVIEW

The ship is 48 meters in length. Dry mass is expected to be about 85 tons. Technically, our design says 75 tons but inevitably there will be mass growth. The ship will contain 1,100 tons of propellant with an ascent design of 150 tons and return mass of 50 tons. You can think of this as essentially combining the upper stage of the rocket with Dragon—it is as if the Falcon 9 upper stage and Dragon were combined.

In figure 7, you have the engine section in the rear, the propellant tanks in the middle and then a large payload bay in the front. That payload bay is actually eight stories tall. In fact, you can fit a whole stack of Falcon 1 rockets in the payload bay. Compared to the design I showed last time, you will see that there is a small delta wing at the back of the rocket. The reason for that is to expand the mission envelope of the BFR spaceship. Depending on whether you are landing or you are entering a planet or a moon that has no atmosphere, a thin atmosphere, or a dense atmosphere, and depending on whether you are reentering with no payload in the front, a small payload, or a heavy payload, you have to balance the rocket out as it is coming in. The delta wing at the back, which also includes a split flap for pitch and roll control, allows us to control the pitch angle despite having a wide range of payloads in the nose and a wide range of atmospheric densities. We tried to avoid having the delta wing but it was necessary in order to generalize the capability of the spaceship such that it could land anywhere in the solar system.



MAKING LIFE MULTIPLANETARY

BFR CARGO/CABIN AREA

The cargo area has a pressurized volume of 825 cubic meters—greater than the pressurized area of an A380. BFR is capable of carrying a tremendous amount of payload. In a Mars transit configuration, since you would be taking three months in a really good scenario but maybe as much as six months, you probably want a cabin, not just a seat. The Mars transit configuration consists of 40 cabins. You could conceivably have five or six people per cabin if you really wanted to crowd people in, but I think mostly we would expect to see two to three people per cabin, or about a hundred people per flight to Mars. And then there is a central storage area and galley and a solar storm shelter, entertainment area, and I think probably a good situation for at least BFR version one.

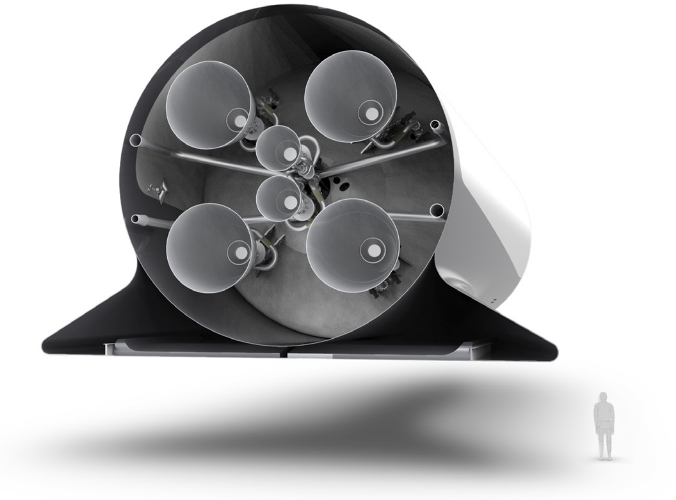


Fig.6. BFR engines

BFR MAIN BODY

In the center body of the vehicle, this is where the propellant is located—sub-cooled methane and oxygen. As you chill the methane and oxygen below its liquid point you get a fairly meaningful density increase. You get on the order of 10 to 12 percent density increase, which makes quite a big difference for the propellant load. We expect to carry 240 tons of methane (CH4) and 860 tons of oxygen. In the fuel tank are header tanks; when you come in for landing, your orientation may change quite significantly, but you cannot have the propellant just sloshing around all over in the main tanks, you have to have the header tanks that can feed the main engines with precision. That is what you see immersed in the fuel tank on figure 7.

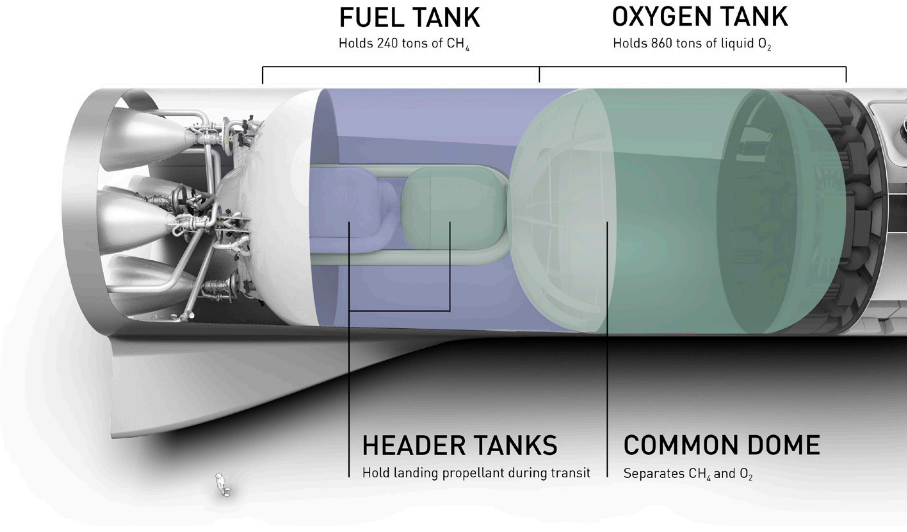


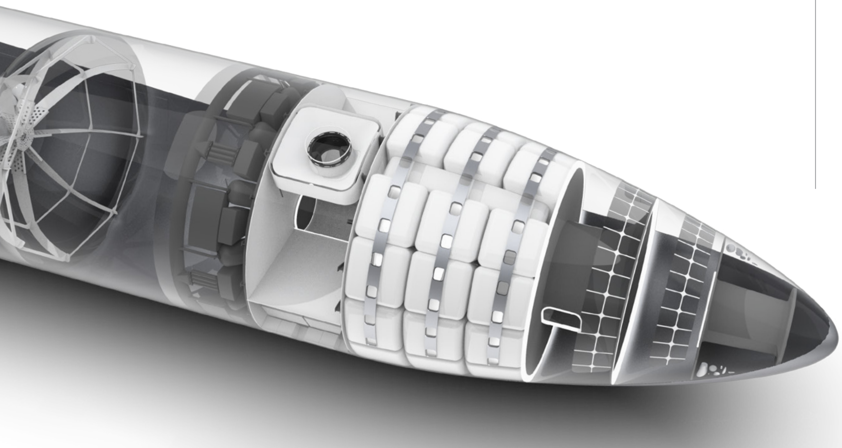
Fig.7. BFR main body

BFR ENGINES

The ship engine section consists of four vacuum Raptor engines and two sea-level engines. All six engines are capable of gimbaling. The engines with the high expansion ratio have a relatively smaller gimbal range and slower gimbal rate. The two center engines have a very high gimbal range and can gimbal very quickly. And you can land the ship with either one of the two center engines. When you come in for a landing, it will light both engines but if one of the center engines fails at any point, it will be able to land successfully with the other engine. Within each engine there is a great deal of redundancy as we want the landing risk to be as close to zero as possible. The sea-level engines are about 330 ISP at sea level. The upper stage engine is 375 ISP. Over time there is potential to increase that specific impulse by 5 to 10 seconds and also increase the chamber pressure by 50 bar or so.

BFR REFILLING

For refilling, the two ships would actually mate at the rear section. They would use the same mating interface that they used to connect to the booster on liftoff. We would reuse that mating interface and reuse the propellant fill lines that are used when the ship is on the booster. To transfer propellant, it becomes very simple—use control



MAKING LIFE MULTIPLANETARY

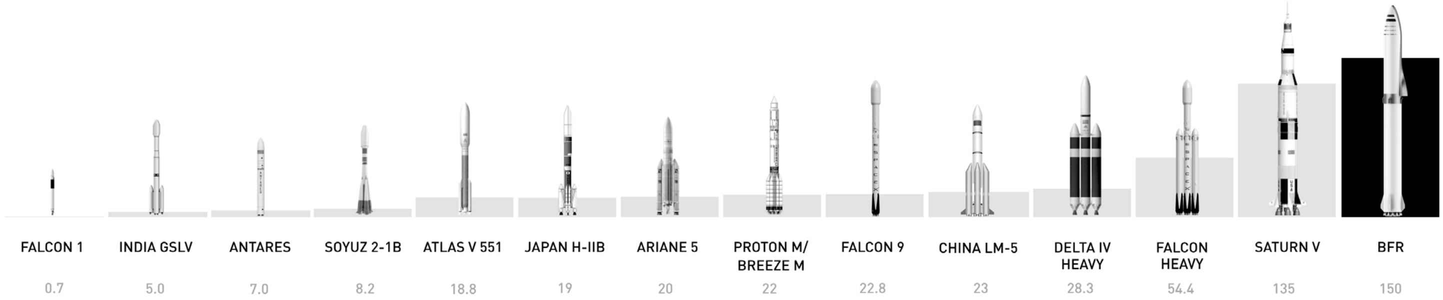


Fig.8. Rocket capability: Payload to low Earth orbit in tons. BFR has larger payload capacity than Saturn V, while being fully reusable.

thrusters to accelerate in the direction that you want to empty. If you accelerate in this direction, propellant goes that way, and you transfer the propellant very easily from the tanker to the ship.

ROCKET CAPABILITY

Figure 8 gives you a rough sense of rocket capability, starting off at the low end with the Falcon 1 at a half-ton and then going up to BFR at 150 tons. I think it is important to note that BFR has more capability than Saturn V even with full reusability. But here is the really important, fundamental point—let us look at the launch cost.

When you look at the vehicles against marginal launch cost, the order reverses. I know at first glance this may seem ridiculous but it is not. The same is true of aircraft. If you bought a small, single-engine turboprop aircraft—that would be one and a half to two million dollars. To charter a 747 from California to Australia is half a million dollars, there and back. The single-engine turboprop cannot even get to Australia. So a fully reusable giant aircraft like the 747 costs a third as much as an expendable tiny aircraft. In one case you have to build an entire aircraft, in the other case you just have to refuel something. It is really crazy that we build these sophisticated rockets and then crash them every time we fly. This is mad. I cannot emphasize how profound this is and how important reusability is. Often I will be told, "but you could get more payload if you made it expendable." I say "yes, you could also get more payload from an aircraft if you got rid of the landing gear and the flaps and just parachute out when you got to your destination. But that would be crazy and you would sell zero aircraft." So reusability is absolutely fundamental.

VALUE OF REFILLING

Now I want to talk about the value of orbital refilling. This is also extremely important. If you just fly BFR to orbit and do not do any refilling, it is pretty good—you'll get 150 tons to low Earth orbit, and have no fuel to go anywhere else.
However, if you send up tankers and refill in orbit, you can refill the tanks all the way to the top and get 150 tons all the way to Mars. And if the tanker has high reuse capability, then you are just paying for the cost of propellant—the cost of oxygen and the cost of methane is extremely low. If that is all you are dealing with, the cost of refilling your spaceship on orbit is tiny and you can get 150 tons all the way to Mars. So automated rendezvous and docking and refilling are absolutely fundamental.

PAYING FOR BFR

Getting back to the question of "How do we pay for this system?" This was really quite a profound—I would not call it a breakthrough but a realization—that if we can build a system that cannibalizes our own products, makes our own products redundant, then all of the resources, which are quite enormous, that are used for Falcon 9, Falcon Heavy and Dragon, can be applied to one system.

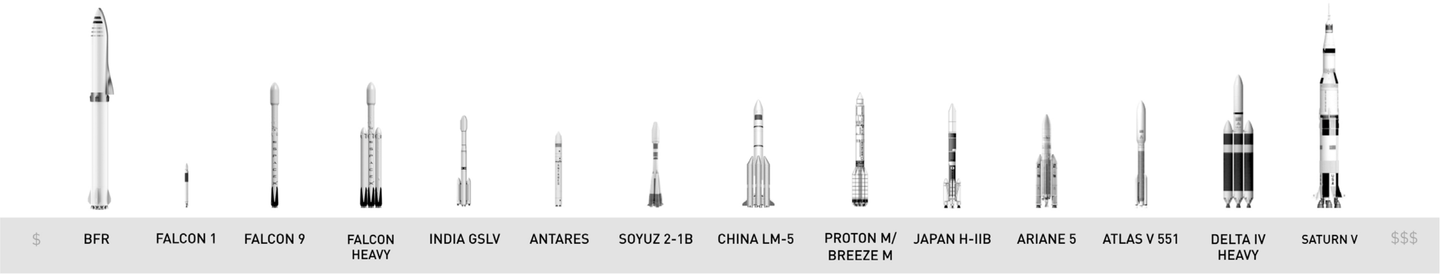


Fig.9. Launch cost: Marginal cost per launch accounting for reusability. Due to full reusability, BFR provides lowest marginal cost per launch, despite vastly higher capacity than existing vehicles.

MAKING LIFE MULTIPLANETARY

Some of our customers are conservative and they want to see BFR fly several times before they are comfortable launching on it, so what we plan to do is to build ahead and have a stock of Falcon 9 and Dragon vehicles so that customers can be comfortable. If they want to use the old rocket or spacecraft, they can do that because we will have a bunch in stock but all of our resources will then turn towards building BFR; we believe that we can do this with the revenue we receive for launching satellites and for servicing the space station.

SATELLITES

The size of this being a nine meter diameter vehicle is a huge enabler for new satellites. We can actually send something that is almost nine meters in diameter to orbit. For example, if you want to do a new Hubble, you could send a mirror that has 10 times the surface area of the current Hubble, as a single unit that does not have to unfold. You could send a large number of small satellites. You can actually go around and, if you wanted to, collect old satellites or clean up space debris—that may be something we have to do in the future. The fairing would open up, retract and then come back down, enabling launching of Earth satellites that are significantly larger than anything we have done before or significantly more satellites at a time than anything that has been done before.

INTERNATIONAL SPACE STATION

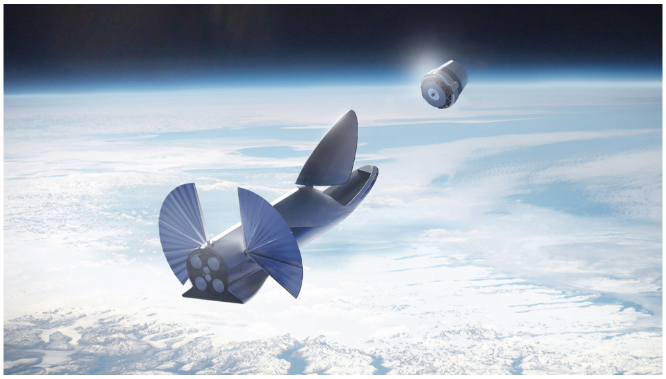


Fig.10. Satellite delivery in Earth orbit

It is also intended to be able to service the space station. I know it looks a little big relative to the space station but the Shuttle also looked big—so it will work. It will be capable of doing what Dragon does today in terms of transporting cargo and what Dragon 2 will do in terms of transporting crew and cargo. It can also go out to much further than that, like for example, the Moon.

Fig.11. Docking with the International Space Station

MOON MISSIONS

Based on our calculations, we can actually do lunar surface missions with no propellant production on the surface of the Moon. If we do a high elliptic parking orbit for the ship and retank in high elliptic orbit, we can go all the way to the Moon and back with no local propellant production on the Moon. I think that would enable the creation of Moon Base Alpha or some sort of lunar base. It is 2017. We should have a lunar base by now.

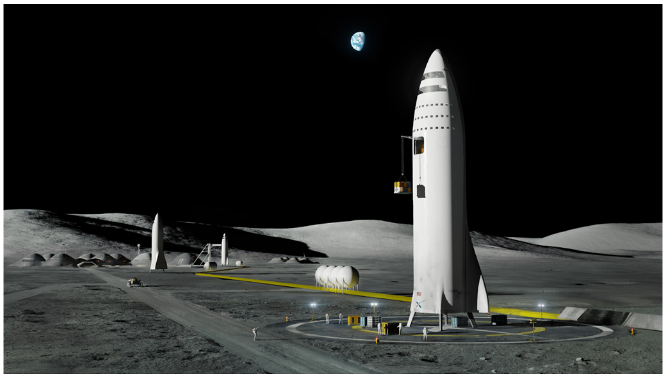


Fig.12. Establishing a Moon base

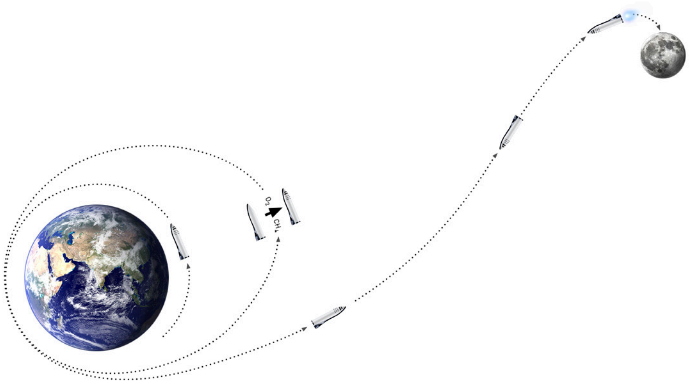


Fig.13. Lunar surface missions

MAKING LIFE MULTIPLANETARY

MARS

Becoming a multi-planet species beats the hell out of being a single planet species. We would start off by sending a mission to Mars where it would be obviously just landing on rocky ground or dusty ground.

MARS TRANSPORTATION ARCHITECTURE

It is the same approach that I mentioned before, which is to send the spaceship up to orbit, refill it until it has full tanks, and then it travels to Mars and lands. For Mars you will need local propellant production. But Mars has a CO2 atmosphere and plenty of water ice. That gives you CO2 and H2O, so therefore you can make CH4 and O2 using the Sabatier Process. I should mention that, long term, this can also be done on Earth. Sometimes I get some criticism along the lines of: "Why are you using combustion in rockets and you have electric cars?" Well there is no way to make an electric rocket, I wish there was, but in the long term you can use solar power to extract CO2 from the atmosphere, combine it with water and produce fuel and oxygen for the rocket. The same thing that we're doing on Mars, we could do on Earth in the long term.

Similar to the Moon, you land on Mars, but the tricky thing with Mars is we do need to build a propellant depot to refill the tanks and return to Earth. Because Mars has lower gravity than Earth, you do not need a booster—you can go all the way from the surface of Mars to the surface of Earth just using the ship. You need a max payload number of about 20 to 50 tons for the return journey to work, but it is a single stage all the way back to Earth.

MARS ENTRY

For Mars entry, you are entering very quickly, going seven and a half kilometers a second. For Mars, there will be some ablation of the heat shield, sort of like a brake pad wearing away. It is a multi-use heat shield, but unlike for Earth operations, it is coming in hot enough that you really will see some wear of the heat shield.

MARS LANDING

Because Mars has an atmosphere, albeit not a particularly dense one, you can remove almost all the energy aerodynamically. And we have proven out supersonic retropropulsion many times with Falcon 9, so we feel very comfortable about that.

MARS MISSION GOALS

We are targeting our first cargo missions in 2022—that's not a typo, although it is aspirational. We've already started building the system—the tooling for the main tanks has been ordered, the facility is being built and we will start construction of the first ship around the second quarter of next year. In about six to nine months we should start building the first ship. I feel fairly confident that we can complete the ship and be ready for a launch in about five years.

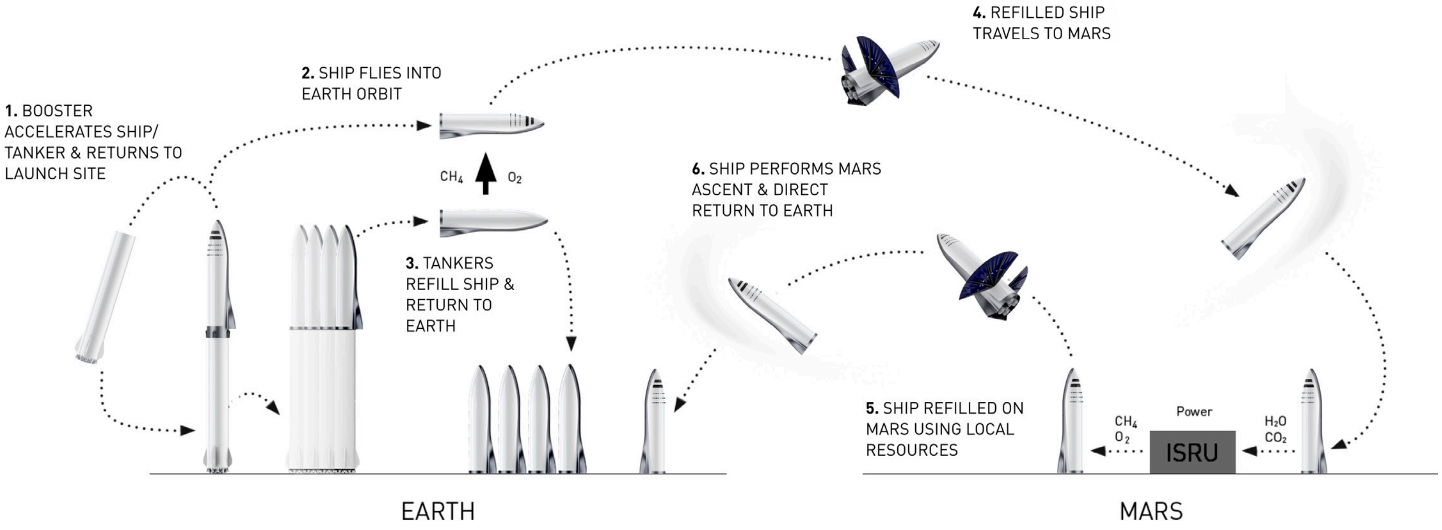


Fig.14. Mars transportation architecture

MAKING LIFE MULTIPLANETARY

Five years seems like a long time to me. The area under the curve of resources over that period of time should enable this time frame to be met, but if not this time frame, I think pretty soon thereafter. But that is our goal, to try to make the 2022 Mars rendezvous. The Earth-Mars synchronization happens roughly every two years, so every two years there is an opportunity to fly to Mars.

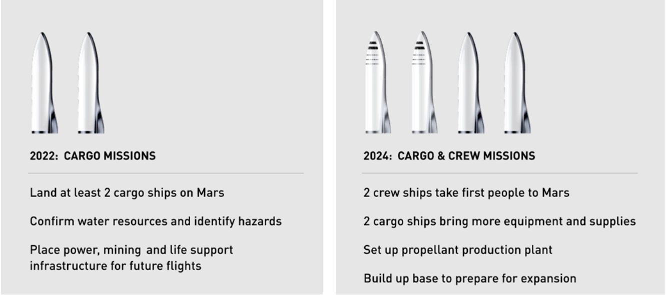


Fig.15. Initial Mars mission goals

Then in 2024 we want to try to fly four ships—two cargo and two crew. The goal of the first mission is to find the best source of water, and for the second mission, the goal is to build the propellant plant. We should—particularly with six ships there—have plenty of landed mass to construct the propellant depot, which will consist of a large array of solar panels, and then everything necessary to mine and refine water, draw the CO2 out of the atmosphere, and then create and store deep cryo CH4 and O2.

MARS BASE

The base starts with one ship, then multiple ships, then we start building out the city and making the city bigger, and even bigger. Over time terraforming Mars and making it really a nice place to be.

It is quite a beautiful picture. You know that on Mars, dawn and dusk are blue. The sky is blue at dawn and dusk and red during the day. It’s the opposite of Earth.

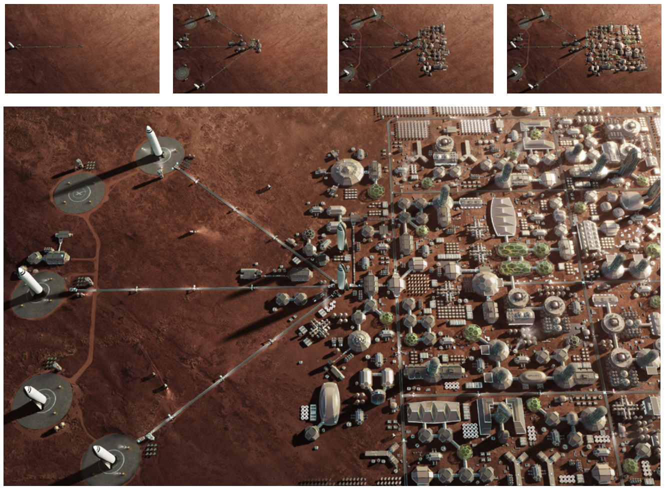


Fig.16. Mars base buildup progression

Fig.17. Mars colony

EARTH TO EARTH TRANSPORT

But there is something else. If you build a ship that's capable of going to Mars, what if you take that same ship and go from one place to another on Earth? We looked at that and the results are quite interesting.

With BFR for Earth to Earth transport, we are traveling at 27,000 kilometers an hour, or roughly 18,000 miles an hour. During the final descent is where propulsive landing becomes very important. Most of what people consider to be long-distance trips would be completed in less than half an hour. The great thing about going to space is there is no friction, so once you are out of the atmosphere, it will be smooth as silk. No turbulence. If we are building this thing to go to the Moon and Mars, then why not go to other places on Earth as well? Thank you.

TIME COMPARISONS TO MAJOR CITIES

ROUTE	DISTANCE	COMMERCIAL AIRLINE	TIME VIA BFR
LOS ANGELES TO NEW YORK	3,983 km	5 HOURS, 25 MIN	**25 MIN**
BANGKOK TO DUBAI	4,909 km	6 HOURS, 25 MIN	**27 MIN**
TOKYO TO SINGAPORE	5,350 km	7 HOURS, 10 MIN	**28 MIN**
LONDON TO NEW YORK	5,555 km	7 HOURS, 55 MIN	**29 MIN**
NEW YORK TO PARIS	5,849 km	7 HOURS, 20 MIN	**30 MIN**
SYDNEY TO SINGAPORE	6,288 km	8 HOURS, 20 MIN	**31 MIN**
LOS ANGELES TO LONDON	8,781 km	10 HOURS, 30 MIN	**32 MIN**
LONDON TO HONG KONG	9,648 km	11 HOURS, 50 MIN	**34 MIN**

Fig.18. Earth to Earth time comparisons