Human asteroid exploitation mission
Blue team - Space Vehicle

Jeremy BEK, Clément BORNE, Anton KÅBJÖRN and Filippo POZZI

***Abstract*—Asteroid rendez-vous and mining is one step towards deep space exploration and interplanetary journeys, and it could prove to be a very lucrative endeavour. This paper tackles the space vehicle design associated with the hypothetical mission. It presents background, challenges and solutions linked with spacecraft design. The structure, mass, cost and technology readiness level (TRL) of the different systems composing the space vehicles are described in the report.**

***Index Terms*—Spacecraft design, Asteroid, Mining, Technology Readiness Level.**

I. INTRODUCTION

Designing a space vehicle for a certain mission is a complicated task that contains many parameters and variables. Even more so, for a particularly ambitious mission like asteroid mining. However, this paper constitutes a preliminary study of what could resemble such a mission, from a vehicle point of view.

The study tackles various topics, such as trajectory calculations, launcher considerations, or spacecraft design. The latter including descriptions of key systems such as power, thermal control or communication systems.

Finally, some off-nominal scenarios have also been imagined to highlight important challenges and ways to overcome them.

II. THE ASTEROID

469219 Kamo'oalewa (originally *2016 HO*$_3$) is a fairly small asteroid (40–100 m in diameter), first discovered in 2016. As it can be seen in Figure 1 it orbits the sun in a way that it stays pretty close to the Earth, and is therefore referred to as a quasi-satellite of Earth [1]. Its distance with Earth varies from 38 to 100 times the distance to the moon. The sphere of influence of the Earth is defined as below:

$$r_{SOI} = a\left(\frac{M_\oplus}{M_\odot}\right)^{2/5} = 925\ 000\ \text{km}$$

Where a is one astronomical unit, $M_\oplus$ the mass of the Earth and $M_\odot$ those of the Sun. The lunar distance LD is 384 400 km so the asteroid is outside of Earth's sphere of influence. The orbital period is one year, just like Earth, and so its seen period around Earth is also one year. This means that whichever trajectory is chosen, there is a launch window every year at the same period.

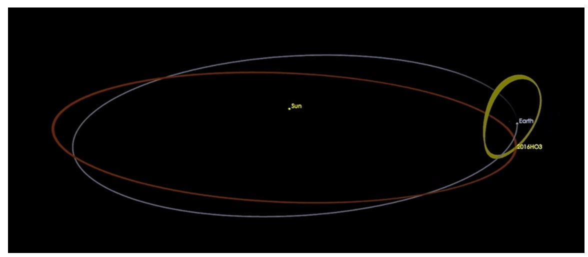

Fig. 1. Orbit of 469219 Kamo'oalewa

III. LAUNCHERS

The launch is the first part of a spaceflight. For the purpose of our mission several launchers have been analyzed but only three have been selected: SLS, Falcon Heavy and Falcon 9. The aspects compared are both price and payload capacity to LEO. Values have been found on the website of the launch providers [2] [3], as shown in Table I.

TABLE I
LUNCH VEHICLE COMPARISON

	Payload to LEO	Price (million $)
Falcon 9	22.8	63.8
Falcon Heavy	60	90
SLS	130	800-900

Fairing dimensions have also been taken into account, as well as the launch abort system for the crewed launch. SLS, in the configuration block 2, will be used because of its huge capability, but the main drawback is the price, very high compared to other launchers. Moreover, since our mission is to proceed with a new cargo vehicle launched every year, Falcon Heavy is the best alternative thanks to its re-usability. Fairing, first stage and lateral booster can be used several times, decreasing the launch price from 150 M$ to 90 M$.

IV. Trajectory

To rendez-vous with the asteroid, there are two options. The first optimizes travel time while the second optimizes the total ΔV. To complete the space trip, assuming that the spacecraft is in a Low Earth Orbit, a total of three burns are required. The first one, done in LEO, is needed to leave the Earth's sphere of influence and reach the asteroid. Once arrived at the asteroid, the spacecraft will decelerate in order to maintain the same orbit as the asteroid. After staying on the asteroid's surface, the spacecraft will come back to Earth with a relatively low ΔV. The reentry speed is about 12 km/s. The spacecraft will slow down using the drag force from the atmosphere and finally a parachute.

For the manned spacecraft the first option has been chosen i.e. the total duration has been minimized for safety reasons and to reduce the mass of the life support systems. The different ΔV and transfer time can be seen in Table II.

TABLE II
TRAJECTORY DATA - MANNED SPACECRAFT

State	**ΔV**	**Transfer time**
Earth departure	3.61 km/s	120 days
Asteroid arrival	-2.85 km/s	20 days
Asteroid departure	448 m/s	190 days
Earth arrival	-11.95 km/s	
Total	6.91 km/s	330 days

Considering the unmanned spacecraft, the total change in velocity ΔV has been minimized, since the travel time is less critical and a lower ΔV means less fuel, so less mass, and finally, lower cost. The different ΔV and transfer time can be seen in Table III.

The different ΔV and transfer time have been determined using NASA trajectory browser [4].

TABLE III
TRAJECTORY DATA - UNMANNED SPACECRAFT

State	**ΔV**	**Transfer time**
Earth departure	4.08 km/s	310 days
Asteroid arrival	-1.27 km/s	395 days
Asteroid departure	425 m/s	200 days
Earth arrival	-11.97 km/s	
Total	5.77 km/s	905 days

V. Propulsion

For the manned spacecraft, because of the travel time and TRL constraints, a chemical propulsion system has been chosen.

For the unmanned spacecraft, even if electrical propulsion is more efficient in terms of fuel consumption (higher I_{SP}), the thrust is too low, and the transfer time would be to long. So chemical propulsion has also been selected.

After comparing different existing engines, it has been decided to use the Vinci [5]. It is designed to power the upper stage of Ariane 6, it is currently under development but it is supposed to be ready in time for our timeline. It is fed with liquid oxygen (LOX) and liquid hydrogen (LH2) with a mixture ratio of 5.8 and this type of propellant is currently the most efficient combination in terms of I_{SP}. However it has a low density which implies larger fuel tanks. Moreover it has to be cooled down to cryogenic level to be stored. Today there remain some difficulties to store it for long periods, but it is assumed that an efficient solution will be found before 2030.

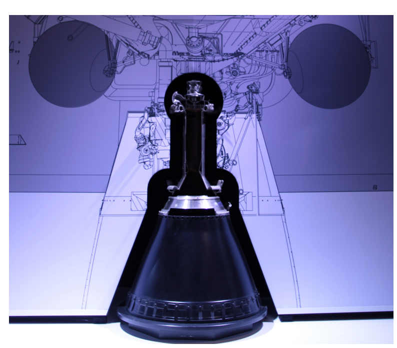

Fig. 2. Vinci rocket engine

Table IV reassume the main characteristics of the Vinci engine.

TABLE IV
VINCI ROCKET ENGINE CHARACTERISTICS

Thrust	180 kN
I_{SP}	465 s
Propellant	LOX/LH2
Density	973 kg/m^3

Given a spacecraft mass of approximately 20 tons, the acceleration is given by

$$a = \frac{T}{m} = \frac{180}{20} \simeq 1\text{g}$$

Thus, the engine is not too rough on the human body.

VI. Communication

Human and robotic long term deep-space expeditions need fast, efficient and available communication means. The higher the data rate, the more information can be transmitted (high definition imagery, videos). Today, mainly radio and microwave portions of the electromagnetic spectrum are used.

A new system called Deep Space Optical Communications (DSOC) is currently being developed by NASA, with its first planned test in space in 2026 aboard Psyche mission. It should improve performance 10 to 100 times over the current state of the art (for the same mass, volume and power) [6].

This technology will use lasers with near-infrared wavelength ($1.55\mu m$), which allows for a higher rate compare to actual technologies.

As Figure 3 shows, the project includes three main segments:

- Ground Uplink Station
- Flight Laser Transceiver
- Ground Receiving Station

The TRL of the different subsystems varies from 4 to 6.

In case of failure of this main system, two small deep space transponders have been added.

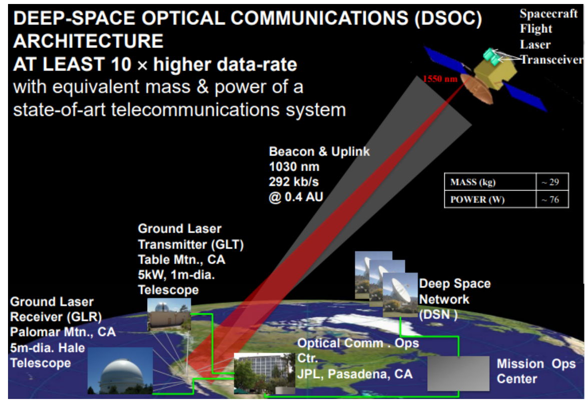

Fig. 3. Operational architecture for DSOC

VII. Power

To power the communication systems, the engine and the life support systems, electrical power has to be produces on board. To achieve this, solar arrays are needed: they convert solar radiation into electrical energy. These solar panels have to be efficient, but also lightweight. Considering the whole power system, wires, power control system, batteries, deployment system and a rotation system are needed.

A. Photovoltaic effect

The photovoltaic effect was first discovered in 1839 by Edmond Becquerel. It generates electricity without moving parts, chemical effects or heat, only using sunlight.

A solar cell is composed of two doped semiconductors (one p-type and the other n-type) joined together in a p-n junction. The electrons of the n-side can wander across the junction, leaving behind them static positive charges. On the other side, they join up with holes causing both to disappear. At the same time, holes of the p-side can wander across the junction, leaving behind them negatives charges. On the other side, they join up with electrons causing both to disappear. Then across the border there is an accumulation of positive charges on the n-side and negative charges on the p-side, creating an electric field. A schematic view of the process is shown in Figure 4.

When absorbing a photon, the electrons reach a higher energy level and jump in the conduction band. Then they are free to move freely in the material. Because of the electrical field created by the junction, these new electron-hole pair will move, but in the opposite direction as those stated before. Instead of being attracted to the p-side, the freed electron tends to move to the n-side. This motion of the electron creates an electric current in the cell which can be directly utilized or storage in batteries.

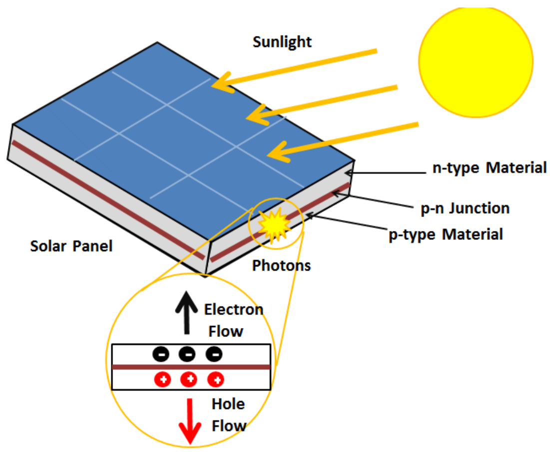

Fig. 4. Photovoltaic effect

The ISS power consumption is about 80 kW. To find the required solar arrays surface, this values have been scaled down to correspond to our needs. The mass of the wires, and power control station have also been added.

VIII. Thermal Control

The Thermal environment of the various spacecraft will need to be controlled to some degree. Solar radiance, power consumption and crew all contribute to heating the spacecraft and this heat needs to somehow be rejected via dissipation or reflection. The Sun radiates at about 1360 W/m^2 at a distance of 1 AU, Assuming a perfect black body this alone would lead to a average spacecraft temperature of several hundred degrees. Clearly this radiance must be rejected. The standard method of more or less eliminating both heat loss and solar heating is by using Multi-Layer Insulation(MLI) sheets. By stacking thin layers of low emissivity sheets between two layers of high emissivity and high reflectivity this method can achieve close to total heat rejection, for analysis purposes we assume on average that 99% of solar radiance is rejected.

Heat generated aboard the spacecraft must be rejected by active cooling systems. The External Active Thermal Control System (EATCS) on the ISS has a total heat rejection capability of 70 kW and it achieves this by extracting heat from the station by pumping liquid ammonia through external coolant loops. The EATCS then radiates this heat away through radiator panels. The envisioned thermal control system for the spacecraft is adopted from the EATCS, scaled to the required heat rejection capability of the spacecraft.

IX. Manned Vehicle

A. Requirements

The main purpose of the manned spacecraft is to safely bring the crew to the asteroid and then back to Earth. The presence of the crew implies several requirements. Some life support system is then needed, and needs to be constantly powered.
Moreover, the crew cannot survive in vacuum, that is why the spacecraft has to be pressurized. Furthermore, the pressurized volume has to be large enough to host the astronauts for the nearly 1-year mission. After some discussions with the team responsible for life support systems, is was decided that the total pressurized volume had to be of at least 100 m^3.

B. Spacecraft design

The spacecraft is built to be modular and is composed essentially of six parts. To complete the design, power and thermal systems have also been considered. Table V shows dry mass, volume (or surface) and price estimates of the different subsystems.

A modular spacecraft design has been selected because of the limited launch capability. Three launches in total will be needed to bring the spacecraft and its propellant to LEO.
First, the SLS will put the dry spacecraft without Dragon 2 in orbit. Afterwards, an in-orbit refuelling will be performed, the propellant being launched with a Falcon Heavy. Lastly the crew, inside the Dragon 2, will be launched with a Falcon 9.
This strategy also takes into consideration a possible launch abort of the dragon 2, using the eight side-mounted SuperDraco engines.
Once in orbit, the Dragon 2 will dock with the main spacecraft. Just after the first burn the solar panels will be deployed and the spacecraft will look

TABLE V
MANNED SPACECRAFT DATA

	Dry mass (tons)	Volume (m^3)	Price (million $)
MPLM	4.4	77	80-100
Dragon 2	9.5	9.3	160
BEAM	1.4	17.2	2
Shuttle Airlock	1	4.2	2
Vinci engine	0.7	-	30-40
Fuel tank	1-2	109.4	10-15
Power system	3	66 m^2	15
Thermal Control	2.5	115 m^2	15
Total	23.5-24.5	107.7	300-335

like in Figure 5. At this point also, the radiators can be deployed.
The spacecraft is 20 meters long and has a maximum diameter of 6 meters. Taking into account solar panels, it becomes 26 meters wide.

Regarding the re-entry phase, the "dry" spacecraft (MPLM, BEAM, Airlock, Fuel tank, solar panels and radiators) will burn in the atmosphere while the Dragon 2 will survive the high temperature due to its heat shield and safely land on the Earth surface with parachutes.

The MPLM (standing for Multi-Purpose Logistics Module) is a large pressurized container. It was used on Space Shuttle missions to transfer cargo to and from the ISS. In our case the MPLM is the central part of the spaceship, linking all modules together. It provides the majority of the needed volume for experiments and life support systems.
The BEAM (Bigelow Expandable Activity Module) is an expandable module currently in use on the ISS. During launch it will be folded but after its expansion it provides more livable volume.
Since during the mission a lot of EVAs will be performed, the spacecraft is fitted with an airlock. The shuttle airlock has been selected due to its small size and weight, and its TRL.
The deployable solar panels will produce 15 kW, enough for the spacecraft's system and life support system. They are mounted on a gimbal so that they can rotate and always face the sun with the best angle.

To control the thermal environment aboard the human spacecraft, we adopt a variant of the EATCS. Two liquid ammonia coolant loops will extract heat from the spacecraft subsystems and radiate from four 33 m^2 radiator panels, two radiators per loop. The radiator panels will be mounted radially on the MPLM at 90 $^\circ$ to the solar panels. The radiators will not be orientable but will instead rely on the spacecrafts attitude control to maintain optimal cooling. This decision was made in order to reduce the mass of the system. The total heat rejection capability of the thermal control system is estimated at 17 kW. In conjunction with the active cooling system the spacecraft will be covered in highly reflective MLI sheets to provide close to total rejection of solar heat.

The spacecraft will have harpoons to tether to the surface of the asteroid, this will enable the astronauts to descend to the surface safely. Similar in design to those on the Philae lander on the Rosetta mission, however some testing and development is required to ensure their functionality.

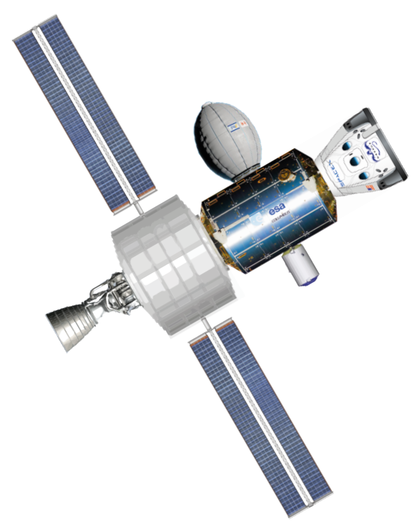

Fig. 5. Human spacecraft design

C. Mass budget & cost

To design the fuel tank, the total mass of propellant needed has to be known. For that the Tsiolkovsky rocket equation (Equation 1) is used.

$$\begin{aligned} \Delta V &= g_0 I_{SP} \ln\left(\frac{m_f + m_p}{m_f}\right) \\ m_p &= m_f \left(\exp\left(\frac{\Delta V}{g_0 I_{SP}}\right) - 1\right) \end{aligned} \tag{1}$$

Where m_f is the dry mass, m_p the propellant mass, and $g_0 = 9.81$ m·s^{-1} is standard gravity. In total the fuel tank will carry 125 tons of propellant, both LOX and LH2 with a mixture ratio of 5.8.

All the prices are rough order-of-magnitude estimations since most of the parts are still on development or are part of old spacecraft with very few data available. The final price will be around $300 - 335$ millions of dollars, without considering development cost and propellant cost, as shown in the last column of Table V.

X. Equipment Vehicle

A. Requirements

The main requirement for the equipment vehicle is to be able to transport 35 tons of unpressurized equipment payload to the asteroid. Once the vehicle has reached its destination and the equipment has been unloaded, its mission is considered accomplished. That means that the vehicle does not need to return to Earth.
The vehicle also needs to fit inside the fairing of an SLS launcher and have a basic communication, thermal control and power system.

B. Spacecraft design

To accomplish its mission, a fairly simple design has been selected for the spacecraft. It is composed of a cargo bay, a fuel tank and an engine, as can be seen in Figure 6.

The cargo bay is designed to fit all the equipment as well as the electronics, thermal control and communication systems.
The Vinci engine has been selected for propulsion, as it fits the requirements for the mission.

Table VI shows mass and price estimates as well as the volume of the different components of the spacecraft.

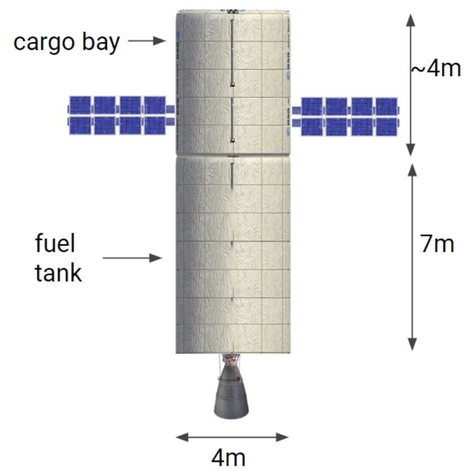

Fig. 6. Equipment spacecraft design

TABLE VI
EQUIPMENT SPACECRAFT DATA

	Dry mass (tons)	Volume (m^3)	Price (million $)
Vinci engine	0.7	-	30-40
Fuel tank	1-1.5	88	8-10
Cargo bay	1.5	50	2
Power system	0.2	-	1
Thermal Control	0.3	-	1
Total	4.5	140	42-52

XI. Cargo Vehicle

A. Requirements

The main requirement for the cargo vehicle is to be able to transport back to Earth 50 tons of unpressurized cargo payload. This means that the vehicle travels to the asteroid empty, is then filled-up with payload, travels back to Earth, and reenters the atmosphere with the payload. Because of the large mass of payload, the reentry ability of the spacecraft has been our main concern.
The vehicle also needs to fit inside the fairing of a Falcon Heavy and have a basic communication, thermal control and power system.

B. Spacecraft design

The cargo vehicle is composed of a cargo module, a fuel tank and an engine, as can be seen in Figure 7. The fuel tank and engine are very similar to the equipment spacecraft with a Vinci engine powering the vehicle. The spacecraft will directly dock to the canopy of the mining process, where it can be filled up with the cargo material.

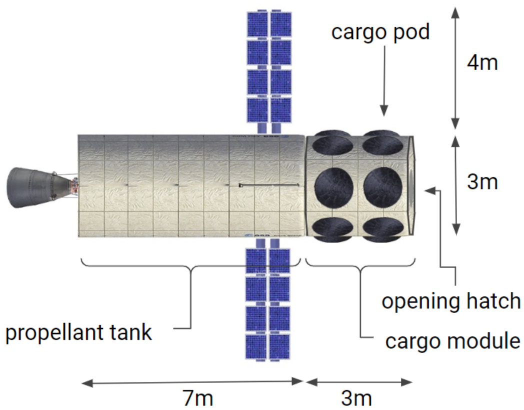

Fig. 7. Cargo spacecraft design

To reenter the atmosphere, because the payload is extremely dense, is was decided to divide it into smaller quantities stored in different cargo pods. As displayed in Figure 8, each cargo pod is essentially a reentry capsule fitted with a heat shield, a payload bay, parachutes and a control system with electronics and avionics.

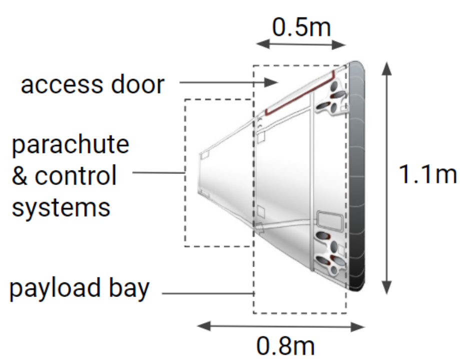

Fig. 8. Cargo re-entry pod

The goal of the spacecraft is to manoeuvre itself into a reentry trajectory using the Vinci engine. The cargo pods are then ejected as shown in Figure 9 and orient themselves with their onboard systems. The cargo spacecraft then burns-up through the atmosphere as the pods reenter safely, using parachutes. They then eventually land on the ground, without particularly high requirements for the touchdown velocity, considering the nature of the payload which is essentially rocks.

Table VII shows mass and price estimates as well

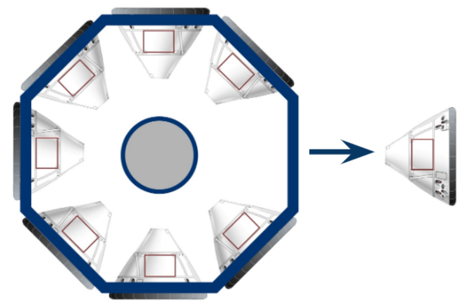

Fig. 9. Cargo module, side view

TABLE VII
CARGO SPACECRAFT DATA

	Dry mass (tons)	Volume (m^3)	Price (million $)
Vinci engine	0.7	-	30-40
Fuel tank	1-2	50	5-6
Cargo Module	10	22	166-198
Cargo pods (x16)	0.5	0.2	10-12
Structure	1.5	-	4
Power System	0.2	-	1
Thermal Control	0.3	-	1
Total	11.7-12.7	72	201-244

as the volume of the different components of the spacecraft.

The data for the cargo pods, and especially the size and mass of their heat shields, has been computed from SpaceX's cargo dragon and other re-entry capsules.

It should be noted that the distribution of the reentry pods inside the spacecraft was selected to assure that they could be filled from their access doors, thanks to the opening hatch at the end of the cargo module.

XII. Off-nominal Scenario

One of the worst possible scenarios regarding the different spacecraft is a main engine failure on the manned spacecraft.

This failure could happen during one of the four different parts of the mission.

- If the failure happens around Earth orbit, one should abort the mission and re-enter the crew safely. Then, one can try to fix the failure into orbit, or send a new spacecraft.
- If the failure happens once the asteroid is reached, an equipment spacecraft should be launched with food and supplies for the crew,

and if necessary, also some spare parts to repair the engine.

- If the failure happens during the journey back, the crew should manoeuvre the spacecraft with maneuvering thrusters to reach LEO and re-enter safely.
- If the failure happens on the way to the asteroid, a rescue mission should be sent to rescue the crew. It is the toughest case, because if nothing is done, the spacecraft is going to cross Earth orbit again, but 20 days too soon.

To avoid such an issue, a solution would be to add smaller engines around the main Vinci engine, to create redundancy.

XIII. Conclusion

An asteroid's mining mission would provide knowledge and skills in building spacecraft for long journeys in deep space. Through this report, it has been shown that such a mission is feasible. The rough price estimate for this is 2.5 billion dollars.
However, this is just an overview. To really design such spacecraft thousands of people and tens of thousands of working hours would be needed, generating development costs.
Moreover some aspects of the design can be improved, for instance it might be possible to fit the mining equipment inside the cargo vehicle, increasing the diameter of the spacecraft. This will lead to less spacecraft to be developed and launched, i.e. saving money.

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