Rocket Fuel Tank Capacity

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0. Problem Definition

A. *Problem Description*

There is a recent call for deep space, high payload exploratory missions. SpaceX is planning a manned mission to Mars around 2026, and NASA is planning a manned mission to Mars around 2030. The company, Orbital Assembly Corporation has announced their plans to open a hotel in space by 2027, named the Voyager Station (Street, 2021). However, it is undeniable that in order for these feats to succeed, rockets need better fuel tank capacity. Missions to Mars will require four to six astronauts living in a spacecraft the size of a recreational vehicle and will span roughly three years (Temming, 2020). Voyager Station will require all necessities of Earth hotels in addition to keeping a full-time staff aboard and transporting customers to and from the hotel. The current anatomy of rockets does not allow for long distance travel or sizable payloads that missions such as these are going to demand. Ninety percent of the mass of rockets are rocket propellants, six percent is the rocket's structure, and four percent is the payload which covers humans, equipment, miscellaneous storage, etc. (MIT, 2021).

B. *Problem Substantiation*

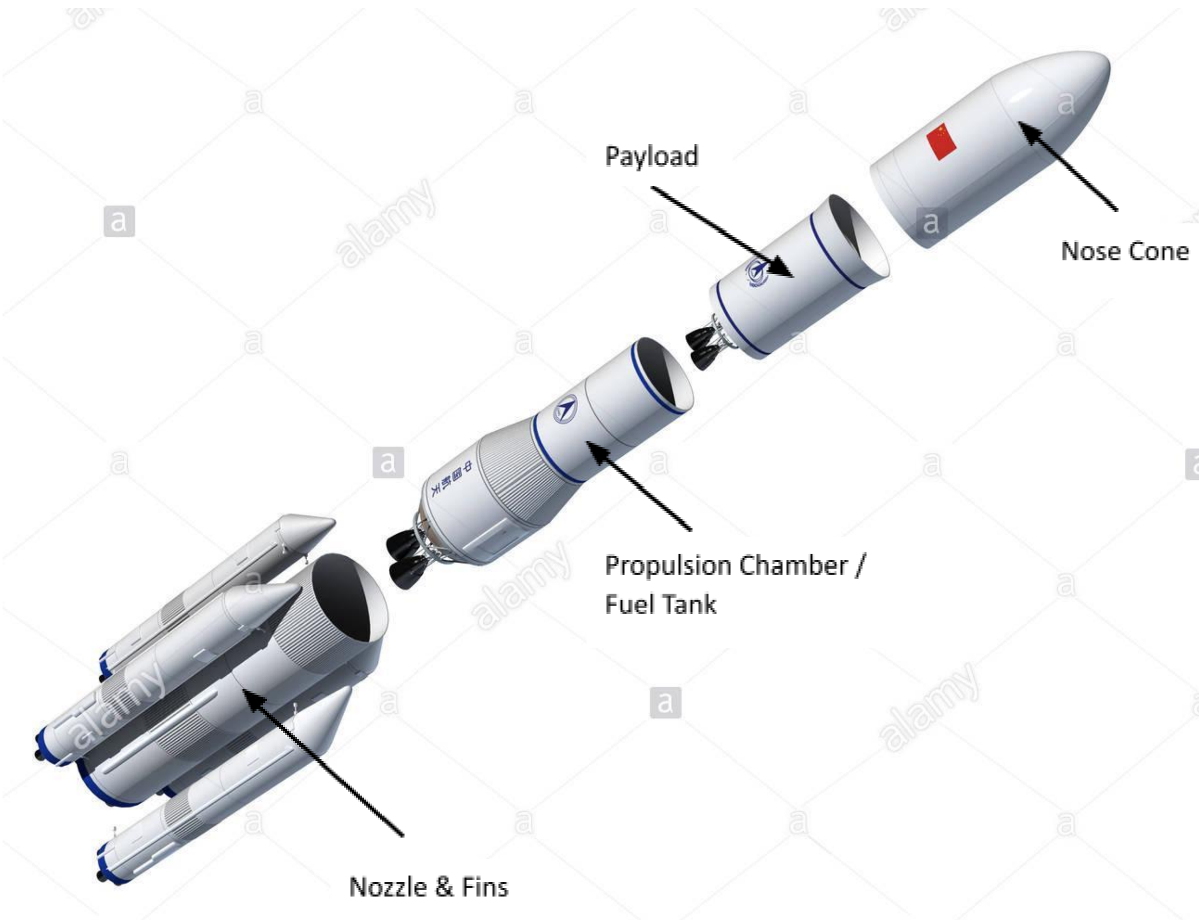
The only feasible way to increase the distance travelled, and the amount of payload that spaceships can hold is to cut down on the mass dedicated to rocket propellants. By engineering more efficient propulsion systems, less mass will be dedicated to propellants, and more can be dedicated to payload. Without finding ways to increase fuel tank capacity, humans will never be able to transport the massive payloads they wish to transport in their future. The furthest object humans have sent into space is NASA's Voyager 1, which launched on September 5th, 1977, and is 152.6AU away from Earth. The farthest humans have traveled in space is only 0.00267AU, which is along the moon's orbit used by Apollo 13 to return to Earth after a mission failure. Mars is 2.06AU from Earth so sending a manned mission to Mars is going to require significant improvement to current rocket technology.

C. Population(s) that Most Benefit

The population which benefits the most is subjective. Initially scientists, engineers, and astronauts will benefit as they will be able to launch missions that can reach further depth of space currently unexplored, and carry the necessary payload for large scale missions. Entrepreneurs involved with Voyager Station will also benefit rapidly as they will be able to complete and launch their business. The next phase is indirect yet is dependent nevertheless. While the target audience will most likely be the wealthiest population, the general public will have the opportunity to experience life outside of our planet. Additionally, with the increased effects of climate change, life on Mars may become a viable option in the near future for the human race. Moving society from Earth to Mars will require significant payloads and thus will call for rockets with more efficient fuels, so that the percent mass dedicated to payload can be higher.

1. Description of System Operation

A. Conceptual Model



In the figure above, a basic illustration of rocket anatomy can be seen. This can help visualize the relative size of each of the parts. It should be noted that the payload is the smallest section of the rocket, and the fuel chamber is the largest part. The fuel tank/chamber works by mixing an oxidizer with a propellant in a combustion reaction to create thrust for the rocket. Some rocket thrusters work differently, but on a general level, the fuel chamber becomes extremely hot as the reaction occurs, and the thrust lifts the rocket into the air, allowing it to leave the atmosphere and travel as far as it's fuel can take it. The materials are a big importance for the rocket. The rocket needs to be able to withstand massive amounts of heat from air friction and from the reaction taking place in the fuel chamber. Additionally, there also needs to be a temperature resistant storage unit for liquid hydrogen, the most common rocket fuel, where it can be kept at -423°F. Without this fuel being kept at the proper temperature, the rocket will not be able to burn the fuel to produce thrust, and it will be useless. The other parts of the rocket are designed with aerodynamic shapes and lightweight construction as the main factors. This rocket design will not be good enough to get humans and all of their equipment, food etc. to Mars, or to make it around the globe on commercial orbit trips. Unless fuel tanks and propulsion systems are made more efficient, this ratio of payload to rocket chamber size will not be feasible for future goals.

B. Key Challenges

The challenges associated with this dilemma are either knowledge-based or technological. Aside from Earth, the Moon, and a small understanding of Mars, we don't know what we don't know. There could be answering to questions about our solar system or the universe as a whole yet to be discovered at nearby locations that we cannot access yet. This is where our lack of knowledge meets our lack of technology. We do not have a rocket fuel efficient enough with our current storage capabilities to travel long-distance through space, nor can we have sizable payloads for these missions. While many alternatives to chemical based propulsion that is used now are being researched and tested, they each come with their own challenges.

2. Alternatives to Be Considered

- Liquid Hydrogen

  Some of the recent advancements made in engineering better rocket fuels have included investigation into alternate storage methods, and methods of obtaining liquid hydrogen in an attempt to increase its candidacy as a fuel for the future. Hydrogen is the lightest element, and there is more research being conducted to perfect the use of this reliable fuel. Today, liquid hydrogen is the signature fuel of the American space program and is used by other countries in the business of launching satellites. Rocket engines of each shuttle flight burn about five hundred thousand gallons of liquid hydrogen with another two hundred thirty-nine gallons depleted by storage boil off and transfer operations (NASA,2021). Advancements in increasing rocket fuel capabilities have recently included construction of a supercooling tank which is attached to the rocket during take-off, as well as a "glass bubble". Both of these technologies help conserve fuel by reducing the amount of fuel which is lost due to boiling off during take-off. According to NASA, "With glass bubble insulation, liquid hydrogen losses through boil off can be reduced by as much as forty six percent". If the losses due to the boil-off of liquid hydrogen can be minimized near zero by the implementation of both of these technologies, liquid hydrogen could provide the necessary power and longevity needed for deep space missions. In the short term, finding better ways to store liquid hydrogen for use in rockets helps NASA test their rockets more often, as less fuel is wasted during testing. For the long term, to support their SLS rocket, NASA started construction of a new liquid hydrogen storage tank at Pad 39B. This rocket is designed to launch the Orion spacecraft, which is NASA's current shuttle candidate for the Moon and Mars missions. The shuttle will require seven hundred thirty thousand gallons of liquid hydrogen and oxygen. This is notably higher than the average rocket currently burns on its missions, providing for greater endurance on missions.

- Refueling Station

  Another solution related to liquid hydrogen research is the possibility of a moon refueling station. In an article by Neel Patel titled "Here's how we Could Mine the Moon for Rocket Fuel", Patel writes about the purpose and implications of a moon fueling station. The reason the moon is being considered, is that according to estimates by NASA, there is about six hundred million to a billion metric tons of lunar ice to be mined for water. This water could be separated into hydrogen and oxygen, which as mentioned before, are the respective propellant and oxidant for most rockets today. By establishing a moon refueling station, this allows rockets the ability to have to carry less fuel upon their take-off from Earth because they only need to get to the moon, and can fill up for the rest of the mission on the moon. This would be favorable, not only because launching from Earth would now be cheaper, but more people and equipment can be carried to the moon instead of fuel. Starting rockets on a path to Mars would be easier from the moon because the fuel would be sourced there, and because the moon's atmosphere and gravity is less, the rocket could carry more weight, which is essential to maximizing both fuel capacity and payload size. In addition, commencing missions from the moon would give spacecraft nearly a two hundred fifty-thousand-mile head start. As we reach further into space, refueling stations could become more common to continue extending how far we can travel.

- Metastable Metallic Hydrogen

  Another approach to the rocket fuel problem is investigation into other fuels entirely. One of these, according to the *Journal of Physics: Conference Series*, includes using metastable metallic hydrogen, which is a very light-weight, low volume, powerful rocket propellant (Cole & Silvera, 2010). One of the characteristics of a propellant is its specific impulse (Isp). Liquid molecular hydrogen-oxygen used in modern rockets has an Isp of ~460s, whereas metallic hydrogen has a theoretical Isp of 1700s. This is an increase of over 4 times to the current fuel. However, while it is one of the most efficient, lightweight and powerful propellants, it is limited by other design factors. If pure metallic hydrogen is used as a propellant, the reaction chamber temperature would be six thousand degrees Kelvin, too high for currently known rocket engine materials. The research suggests a dilution can decrease the temperature of the chamber significantly, at a little loss of efficiency and lightweight. By diluting metallic hydrogen with liquid hydrogen or water, the reaction temperature can be reduced, and there is still a significant performance improvement for the diluted mixture.

- Nuclear Propulsion

  An additional approach to the fuel problem is to ditch chemical based fuels and processes, and use nuclear propulsion systems. According to Jeff Sheehy, chief engineer of NASA's Space Technology Mission Directorate, an NTP (nuclear thermal propulsion) system uses a nuclear reactor to generate heat from a uranium fuel. This heat then burns a chemical propellant such as liquid hydrogen (Lewis, 2021). So, instead of the rocket being fueled by an oxidizer and liquid hydrogen, it will be uranium and liquid hydrogen. According to Sheehy, NTP rockets produce twice the thrust per unit of propellant than a chemical system. On the other hand, nuclear electric propulsion systems use propellants much more efficiently than chemical rockets but provide a low amount of thrust. These systems use a nuclear reactor to generate electricity that induces positive charge in gas propellants, which push ions out of a thruster in order to move the ship forward (NASA, 2021). The advantage of a nuclear electric propulsion system (NEP's) is that the amount of propellant needed by the rocket is cut drastically, at the cost of thrust. In essence, this makes the rocket have much more mass dedicated to payload, but will leave it with less ability to take-off successfully (due to less thrust power). A rocket with NEP is thought to be the ideal "long-distance" design of a spacecraft for these reasons.

- Solar Electric Propulsion

  Another alternative is Solar Electric Propulsion (SEP). Engineers at NASA's Glenn Research Center are researching how to effectively use SEPs for deep space missions that require large payload. Spacecraft equipped with SEPs would not entirely abandon the current chemical-based rocket propulsion system that is currently in use as it would be used to move the spacecraft out of the atmosphere. However once in space, the SEP system would become available. The SEP system is powered by on board solar arrays which power an electrically propelled system that uses ten times less propellant than current chemical propulsion systems. NASA collaborated with two companies, ATK Systems Inc. and Deployable Space Systems Inc. to design the solar arrays. The arrays were designed to be held in the spacecraft until it had left the atmosphere, then exit the spacecraft in a folding motion similar to a fan, and a rolling motion comparable to blinds in a window. These arrays can survive long periods of time in orbit and can withstand radiation belts. The energy harnessed from the arrays is fed to electrostatic Hall thrusters, which are used to provide thrust (Mohon, 2021). The Hall thrusters trap electrons from the magnetic field and ionize them using a propellant gas, creating an exhaust plume which initiates acceleration (Reckart, 2020). This process uses significantly less propellant than the current chemical-based system, which could optimize storage and payload while increasing endurance. Unfortunately, sunlight is not an infinite resource. The equation for sunlight intensity is 1r2, where r is the distance from the Sun (Nagaraja, 2021). As you move further away, the intensity exponentially decreases and more arrays would be required to produce the same amount of power. Under current conditions, we could utilize sunlight four astronomical units (AU) from the Sun which is roughly 1AU from Jupiter. As solar technology improves the outlook on our capabilities is that we will be able to harness solar energy further into the solar system. According to the most recent test results of SEP, at 13.5kW of input power, the SEP provides 57% efficiency, 589mN of thrust, and a specific impulse of 2600s at a mass of only 123kg (Barber & Cassady & Jackson & Miller & Peterson & Soendker & Welander, 2019).

3. Metrics of Comparison

- Cost (USD)
  If the cost of producing the spacecraft, rockets, hiring astronauts, equipment, acquiring rocket fuel, or creating a new propulsion system is beyond a certain threshold it may not be worthwhile. Although space exploration is an interesting topic that could answer our questions about the universe, there is not access to free resources and labor so there are still monetary restrictions.
- Specific Impulse (s)
  Specific Impulse measures how efficiently a rocket makes thrust from its propellant. The higher the specific impulse, the higher the efficiency of the rocket in terms of fuel use. If a rocket has a high specific impulse, it requires less fuel to travel distances compared to that of rockets with low specific impulse. It also suggests that with large amount of fuel, the rocket could travel long distances.
- Endurance / Range (AU / km / mi)
  Range can be measured using the Breguet equation (Range = $Vt_f = V \times \frac{L}{D} \times I_{sp} \times ln\frac{W_i}{W_f}$). The maximum range of a rocket can give insight on how many rockets to use and where missions can take place. This metric should be compared alongside other metrics such as velocity and payload as it does not matter how far you can go if the time it takes to get there is not feasible or if you cannot bring sufficient equipment.
- Thrust (mN)

Thrust is a vital metric for space travel. Escape velocity is roughly 11.2km/s, and once you have left the atmosphere, your destination could be days to months away. If you can travel faster the time it takes to complete these missions could be cut significantly. Thrust should be compared with acceleration when comparing metrics considering that even if there is a high maximum velocity, it is most efficient to have a high acceleration as well so it does not take long periods of time to gain speed.

- Feasibility

  This metric is based upon the technology currently available and how efficient it is. The amount of research already conducted on an alternative and the planned missions using that alternative give insight on the reliability and feasibility of future use of the alternative.

4. Decision Matrix Analysis

	Liquid Hydrogen	Moon Fuel Station	Metastable Metallic Hydrogen	Nuclear Propulsion (thermal/electric)	Solar Electric Propulsion
Cost (USD)	$3.26/kg	$100,000/kg equipment $35,000/kg lunar deployment	Years of RnD in materials and high-pressure physics	$2,000,000,000 / flight	
Specific Impulse (s)	460s	460s	1700s	850-950s (t) 4000-8000s (e)	2600s
Endurance (AU / km / mi)	0.00267AU	N/A			
Thrust (mN)	1250mN	1250mN		240mN (e) 400mN (t)	589mN
Feasibility	Feasible	Feasible	Not Currently Feasible	Feasible	Feasible

<u>Storage of Liquid Hydrogen</u>

When analyzing the storage of liquid hydrogen using the metrics shown in Figure 1.2, cost was found to be very low (hence the green), at 3.26/kg (Schwing, 2008). The specific impulse of liquid hydrogen is 460 seconds, which is good, but compared to the other alternatives in the matrix is a yellow quantity. The thrust is noted to be 1250 mN, which is impressive and ranked green. Lastly, as mentioned earlier, liquid hydrogen is a very common fuel, and there have been numerous projects, some being adopted by NAS currently, which seek to help liquid hydrogen become more viable (by optimizing storage). This makes liquid hydrogen an overall extremely feasible alternative, so it was ranked green for this metric. However, the farthest distance a human has ever reached using liquid hydrogen was around the moon, which is noted as yellow because the distances being considered when discussing alternative rocket fuels are far more like the distance to Mars. For comparison, the distance to Mars is approximately 1.5 AU, and the farthest humans have ever been (using liquid hydrogen) is approximately .002 AU.

Moon Fuel Station

When considering a rocket fueling station on the moon, the specific impulse, thrust and distance can be assumed to be around the same as in the liquid hydrogen storage row, however they will vary depending on how much more fuel can be added into the rocket due to the moon having weaker gravity, and less atmosphere. In reality, these values will be higher, so the specific impulse is ranked yellow, while the distance and thrust are both ranked green. The metric which is most consequential when considering a moon fueling station is the cost, and with estimates like $100,000/kg of equipment, and $35,000/kg for lunar deployment (Shishko, 2019), the cost of transporting materials to the moon, construction, testing, transportation of humans, etc., the cost becomes extremely high. Also, this has never been done before, or tested, and Americans have not been to the moon since 1972. If the money is not a problem, then a moon fueling station is an extremely feasible alternative. However, cost is important, so a moon fueling station was ranked somewhat feasible because it is a large-scale project, and extremely large amounts of planning and money would be needed to make it happen.

Metastable Metallic Hydrogen

Metastable metallic hydrogen has not yet been tested as a fuel yet. Metallic hydrogen has not been produced on Earth. However, according to calculations, it would have a specific impulse of 1700, which is nearly 4x the specific impulse of the current fuel, liquid hydrogen. Atomic metallic hydrogen, if metastable at ambient pressure and temperature could be used as the most powerful chemical rocket fuel (Silvera, 2013). This fuel would have one of the highest possible distances and thrusts imaginable. Exact figures have not been predicted, but its high specific impulse implies this. Therefore, these three metrics are all green. However, on top of metallic hydrogen never being produced on Earth, using it as fuel would create temperatures in the fuel chamber which exceed the limit of currently used rocket engine materials. When weighing the cost of this alternative, the cost of creating metallic hydrogen, the cost of creating new materials which can withstand the heat from metallic hydrogen, and all of the research and development which comes with it need to be factored in. However, when comparing this cost with the potential cost of a moon fueling base, or the billions of dollars it is currently estimated to send humans to Mars, the cost of metallic hydrogen as an alternative fuel is rated yellow. If metallic hydrogen becomes the fuel of the future, trips to Mars and the moon will be much less costly. In conclusion, although metallic hydrogen is an amazing, exciting fuel in theory. It is still “in theory”, and until the research and development allows it to be tested, this fuel will not be feasible. It earns a red rank for the feasibility metric.

Nuclear Thermal Propulsion

Nuclear thermal propulsion (NTP), has been researched before, and is one of the systems currently being considered for NASA’s future missions. It should be noted that the cost of a manned Mars mission using NTP, would cost about $20B and $2B per flight. This is an extremely consequential cost, and is thus denoted red. While NTP has been researched by NASA since 1972, there isn’t much data on distance estimates. However, the specific impulse and thrust provided by NTP are about 850-900 seconds and 400 respectively (Houts, 2021). This specific impulse is respectable, especially when compared to our current specific impulse of 460 seconds (liquid hydrogen). It is denoted green. The thrust is on the average side, ranked yellow, and falls below the thrust provided by liquid hydrogen. The ability of NTP to make chemical propellant fuel span large amounts of time certifies that NTP is one of the best fuel options for long-distance manned missions. Its distance metric is green for this reason. NTP has only become more and more feasible as more research is being done, and designs are being tested. NTP is a real option being considered by NASA, and doesn’t have any limitations other than research and development costs attached to its use. Its feasibility runs green.

Nuclear Electric Propulsion

Much like NTP, nuclear electric propulsion (NEP) uses nuclear power to create thrust. The costs will be around the same, because NEP and NTP are both being constantly researched and tested the same, and will be used for the same missions. The cost metric runs red. However, as mentioned earlier, NEP works differently and doesn’t require chemical propellant. Instead, NEP only requires electricity which would be produced by the nuclear reactor in the rocket engine. This process yields a significant range of specific impulses, and depends on which ions are utilized for thrusting in the order of magnitude of 1,000 to 10,000 seconds (Black, 2003). While these values are extremely high, the thrust provided by NEP is very poor, and technological advancements need to be made on battery storage and power in order to fix this downfall. NEP earns a green specific impulse rank, and a red thrust rank. There is much more distance to go with this technology, and NASA is still investigating it for the future. This makes NEP extremely feasible, as it has potential to send humans long distances in relatively short times by utilizing high speeds (NASA, 2021). NEP is assigned a green rank in distance and feasibility. NEP technology has a long way to go, but faces no direct limitations (such as materials), and instead just needs research and development.

Solar Electric Propulsion

According to the most recent tests by NASA scientists, SEPs are proving to be a reliable alternative propulsion system. The price of producing the arrays and the mechanisms for SEPs has not been disclosed, however the latest tests used nearly $40,000 in solar panels alone. SEPs would also require the use of another propulsion system to leave the atmosphere, increasing cost. The specific impulse of SEPs is over five times as much as liquid hydrogen, which is the current rocket fuel. It does however have roughly half the thrust in comparison to the current model, however as the number of panels increases along with higher sunlight intensity, specific impulse and thrust are expected to increase. Additionally, spacecraft equipped with SEPs would have the longest range of any manned vehicle due to its reliance on sunlight. As mentioned previously, with today's technology the furthest usable sunlight reaches nearly to Jupiter. This is a feasible option due to its success in NASA trials and the expectation that it will be used so send a manned mission to the lunar surface by 2024, which is why it is marked green.

5. Engineering Recommendation

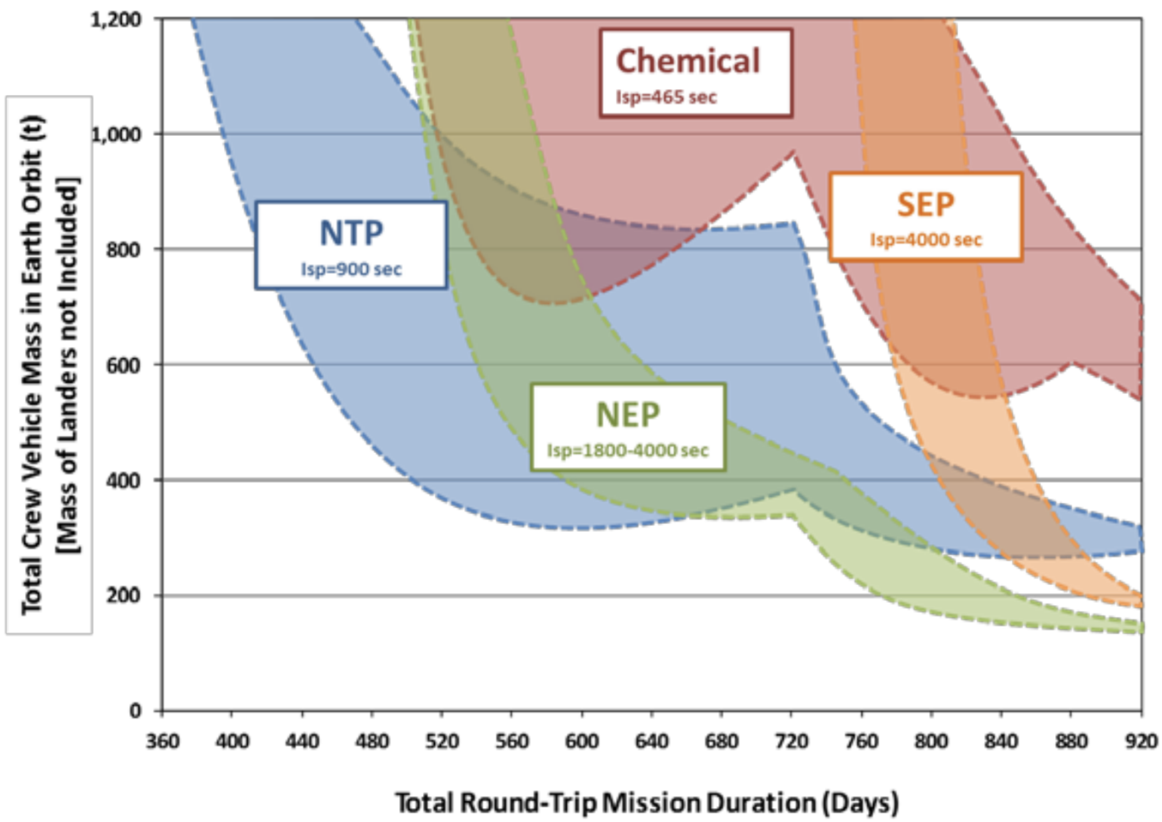


Figure 1.3: Comparison of 4 Types of Rocket Fuel Systems
Source: NASA (Houts)

After analysis of multiple rocket fuels across multiple metrics, the case for liquid hydrogen remains strong. Specifically, the case for liquid hydrogen is strong if its storage can be improved, and is especially strong in the event that a moon fueling station is affordable. This is a multilateral conclusion, but is supported by the estimate that there is about six hundred million to a billion metric tons of lunar ice to be mined for water, and the fact that that water, combined with effective storage could prove liquid hydrogen to be the key to interplanetary travel. As mentioned earlier, new storage technologies for liquid hydrogen could see “boil-off” percentages drop to 0. In this case, the estimated 730,000 gallons of liquid hydrogen needed for a Mars mission, would be much easier to accommodate, considering that the current shuttle receives about 500,000 gallons of fuel, with 239,000 boiling off. By reducing this boil off to zero, it allows liquid hydrogen to become more efficient than it has ever been. In figure 1.3, the chemical rocket fuel systems section of the graphic spans a large area. However, as the graphic represents the fuels' abilities to get large payloads (vertical axis) in short amounts of time (horizontal axis), the top left of the graph is where the (currently) reliable fuels will lie. In the event of optimized, advanced storage techniques which minimize boil-off, and/or a moon fuel station, the section which represents chemical propellants will undoubtedly shift even higher left. In other words, liquid hydrogen has a distance to go. Feasibility is also high because research is already underway, and two possible approaches to the storage and efficiency problem have been mentioned previously. These new possibilities breed an amazing case for a moon fueling station. And combining the increased efficiency of liquid hydrogen, the new technology which allows increased storage, and the moon's low gravity and lesser atmosphere, and liquid hydrogen along with a moon fueling station becomes a very feasible, impactful alternative to the current model of rocket fueling.

Nuclear thermal propulsion is the future of deep space and interplanetary exploration. It produces twice the specific impulse of liquid hydrogen rockets and through further testing will also provide high thrust. As represented in figure 1.3, mission duration is significantly decreased using nuclear propulsion, which decreases cost and allows for more trips through space to be made. Nuclear propulsion also requires less fuel than chemical propulsion, allowing for a greater percentage of payload to be assigned to necessary equipment. This also implies that through the use of more fuel, spacecraft using nuclear propulsion systems could reach unexplored depth in our solar system. Although there has yet to be significant research into nuclear propulsion systems, we are familiar with nuclear energy. In 2020, the United States budgeted the Department of Energy $31.7 billion to fund nuclear energy. As NASA continues to research the possibilities of utilizing nuclear propulsion, it becomes more likely that nuclear propulsion will be relied on for missions of great distance and payload. Considering the bright future and high efficiency of this propulsion system, it should continue to be researched as it could replace the current chemical-based, liquid hydrogen system used today.

Citations:

Ashish, A. (2020, August 21). What's the Farthest Humans Have Travelled in Space? Retrieved May 05, 2021, from https://www.scienceabc.com/nature/universe/farthest-humans-have-gone-space-apollo-13-moon-254-km.html

Berger, E. (2021, February 12). Report: NASA's only realistic path for humans on Mars is nuclear propulsion. Retrieved May 05, 2021, from https://arstechnica.com/science/2021/02/report-nasas-only-realistic-path-for-humans-on-mars-is-nuclear-propulsion/

Brown, K. (2020, October 14). NASA announces partners to advance 2020 'tipping POINT' TECHNOLOGIES. Retrieved May 05, 2021, from https://www.nasa.gov/press-release/nasa-announces-partners-to-advance-tipping-point-technologies-for-the-moon-mars

Brown, K. (2020, October 14). NASA announces partners to advance 2020 'tipping POINT' TECHNOLOGIES. Retrieved May 05, 2021, from https://www.nasa.gov/press-release/nasa-announces-partners-to-advance-tipping-point-technologies-for-the-moon-mars

Fearon, R. (2021). Reusable rockets: Expanding space Exploration possibilities with Retrievable Spacecraft. Retrieved May 05, 2021, from https://www.discovery.com/technology/Reusable-Rockets

Granath, B. (2018, December 19). Innovative Liquid Hydrogen Storage to Support Space Launch System. Retrieved May 05, 2021, from https://www.nasa.gov/feature/innovative-liquid-hydrogen-storage-to-support-space-launch-system

Herr, P. (1973). NASA Technical Reports SERVER (NTRS). Retrieved May 05, 2021, from https://ntrs.nasa.gov/citations/19730023888

Houts, M. (n.d.). NASA's Nuclear Thermal Propulsion (NTP) Project. Retrieved 2021, from https://ntrs.nasa.gov/api/citations/20170003378/downloads/20170003378.pdf

Jackson, J. (2019). NASA Technical Reports SERVER (NTRS). Retrieved May 05, 2021, from https://ntrs.nasa.gov/citations/20200000505

Journal of Physics: Conference Series, July 2009, Volume 215, International Conference on High Pressure Science and Technology. Retrieved March 03, 2021, from https://iopscience.iop.org/article/10.1088/1742-6596/215/1/012194

Landis, G. (n.d.). The Edge of Sunshine. Retrieved May 05, 2021, from https://science.nasa.gov/science-news/science-at-nasa/2002/08jan_sunshine

Lewis, N. (2021, February 10). Nuclear-Powered Rockets Could get Astronauts to Mars faster. Retrieved March 03, 2021, from https://www.cnn.com/2021/02/03/world/nuclear-powered-rocket-scn-spc-intl/index.html

MIT. (2021). 13.3 Aircraft Range: The BREGUET Range Equation. Retrieved May 05, 2021, from https://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node98.html

MIT. The Rocket Principles. Retrieved March 03, 2021, from http://web.mit.edu/16.00/www/aec/rocket.html

Mohon, L. (2015, July 13). Solar Electric Propulsion (SEP). Retrieved May 05, 2021, from https://www.nasa.gov/mission_pages/tdm/sep/index.html

Patel, N. (2020, May 19). Here's how we could mine the moon for rocket fuel. Retrieved May 05, 2021, from https://www.technologyreview.com/2020/05/19/1001857/how-moon-lunar-mining-water-ice-rocket-fuel/

Schwing, A. (2008). Costing Methods. In 1357526162 993574923 Purdue University (Author), *Project Bellerophon* (pp. 806-859). Indianapolis, IN: Purdue. doi:https://engineering.purdue.edu/AAECourses/aae450/2008/spring/report_archive/reportfinaluploads/pdfs/Report_Section_12.pdf

Shishko, R. (2019). Business Case Analysis of Lunar Thermal Mining. Retrieved 2021, from https://www.nasa.gov/sites/default/files/atoms/files/33_lunar_thermal_mining_for_cost_symposium_reduced.pdf

Silvera, Isaac F. and John W. Cole. 2010. Metallic hydrogen: The most powerful rocket fuel yet to exist. In International Conference on High Pressure Science and Technology, Joint AIRAPT-22 & HPCJ-50 : [proceedings] : 26-31 July 2009, Tokyo, Japan. Journal of Physics Conference Series 215(1): 012194. Retrieved from https://dash.harvard.edu/bitstream/handle/1/9569212/Silvera_Metallic.pdf

Skelly, C. (2021, February 04). Nuclear Propulsion Could Help get Humans to Mars Faster. Retrieved May 05, 2021, from https://www.nasa.gov/directorates/spacetech/nuclear-propulsion-could-help-get-humans-to-mars-faster