REPURPOSING THE INTERNATIONAL SPACE STATION

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ABSTRACT

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The International Space Station serves today as a research platform for the effects of microgravity and cosmic radiation on a myriad of objects. The ISS has served as the primary source of our understanding of the effects of large amounts of cosmic radiation, particularly on humans. The ISS, however, is nearing the end of it's lifespan, and it is likely that within the next decade, the US government will cease funding operations on board. This raises the question of what to do with the ISS afterwards?

This paper will suggest several potential uses for the International Space Station following government withdrawal. The ISS can either be turned into a hotel, serving as a once-in-a-lifetime destination for those that can afford passage, or a microgravity manufacturing facility for a variety of products. These include human organs for transplant, foodstuff, metal alloys, advanced fiber optics, and crystals.

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1. The Background of the International Space Station

The International Space Station was launched into Low Earth Orbit in late November of 1998. The ISS is the result of a collaborative partnership between the United States, Canada, Russia, Japan, and several member countries of the European Space Agency (ESA). Over the course of its 22 year life, the ISS has seen over 240 astronauts from 19 different countries stay on board the station. The ISS serves as a valuable research platform, allowing the study of the effects of microgravity on humans, plants, as well as the physical properties of materials such as crystals.

Much of the research done on board the International Space Station focuses on the impacts of space travel on the human body. Much of this research is vital for making future space travel, such as NASA’s Artemis mission to the Moon, as safe as possible. Research on subjects from the effects of cosmic radiation on DNA telomeres to hair, which reflects the metabolic environmental conditions of the subject. The ISS can also be used to survey the surface of the Earth; it passes over 90% of the world’s population over the course of its orbit.

The International Space Station is comprised of individual pressurized modules connected together on a steel truss. The truss itself is 357.5 feet long, almost as long as a standard football field. On each end of the truss are the solar panel arrays that provide between 75 and 90 kilowatts of power to the station. Currently, the ISS is comprised of sixteen pressurized modules: nine US modules, four Russian modules, two Japanese modules, one European module, and the Canadian robotic arm. All together, the modules have a pressurized volume of 32,898 cubic feet, which is equivalent to the pressurized volume of a Boeing 747 airliner. The entire structure is connected via the Integrated Truss Structure (ITS). The ITS is a series of 10 aluminum truss structures that contain the cooling and electrical systems that keep the ISS working properly. The iconic solar panel wings of the ISS are connected at both ends of the ITS, and provide power to the entire station. Figure 1 is a schematic of the International Space Station showing the location of each module, as well as the country of origin.

However, the ISS is an aging structure. Many component parts have become outdated as they are technology from 22 years ago. Additionally, the station has to be continuously boosted back to a higher orbit to ensure that it doesn’t fall into the atmosphere due to gravity. The cost of maintaining the station, about $1.4 billion USD per fiscal year from the US alone, is an astronomical cost. According to an internal audit run by the Inspector General of NASA in 2018, direct US funding for the International Space Station is scheduled to end in the 2024 fiscal year, pending the conclusion of ongoing research experiments. Thus, with the US government more or less washing their hands of direct involvement with the ISS, an enormous opportunity arises for the private sector to explore the opportunities presented by the lack of station control.

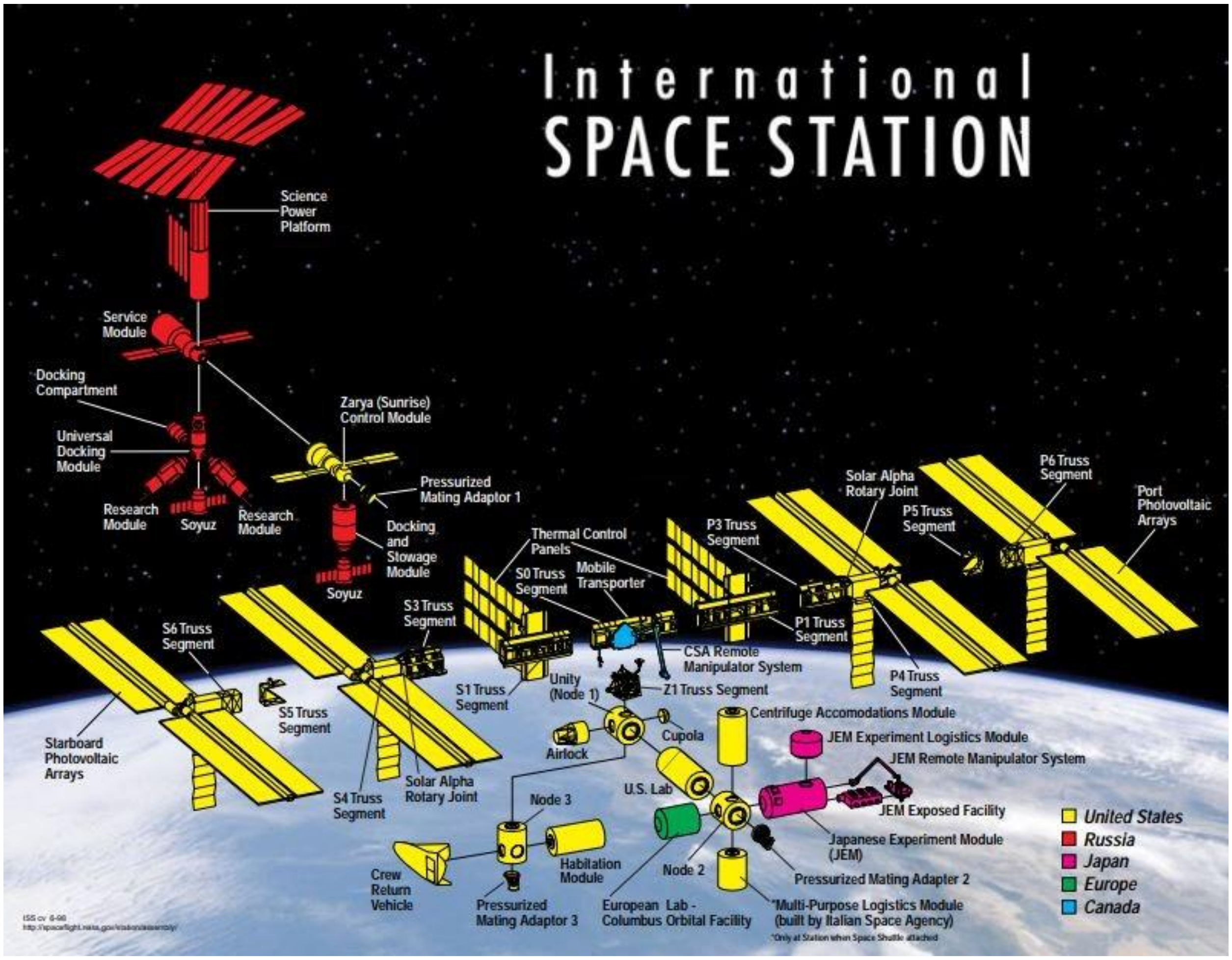


Figure 1: ISS Assembly and Ownership Diagram

2. Future Uses of the ISS

There are a myriad of potential futures for the International Space Station. However, several of them will not be considered in this paper due to their trivial nature. These trivial solutions include extending funding beyond the expiration date, and simply letting the ISS reenter the atmosphere and burn up on reentry, thus being destroyed. The future paths that will be considered are, as mentioned above, are the conversion of the International Space Station into a hotel, as well as conversion into a manufacturing facility, or a combination of the two.

There are several assumptions that have been made for all following designs for the sake of simplicity. First, there is some private entity or entities capable of and willing to take on the cost of maintaining the International Space Station. Secondly, that once the US government abandons the ISS, all involved countries will follow simultaneously. Third, launch cost will remain constant. Finally, the current hardware onboard the ISS is assumed to be compatible with any technology needed for the options discussed.

3. Space Hotel

First, the space hotel. Space tourism is a growing interest in the travel industry, and the ISS itself has a history of tourism. In 2001, Dennis Tito, a businessman based in the US, became the first tourist to visit the ISS, at the cost of around $20 million USD paid to Russia for a round trip to the station. Today, it is possible to visit the ISS as a civilian, however, the cost of such a trip would be prohibitively expensive to the majority of the world’s population, including a $60 million USD “taxi fare,” as well as a $35,000 nightly fee to stay on board.

Accommodations on the ISS currently are rather spartan, with crew members sleeping in small berths only large enough for one person, their sleeping bag, a laptop computer, and a few personal items. Currently, there are 6 sleeping spaces available for the crew of the ISS, four of which are the small berths discussed above. All four berths are located within the Harmony module, which also serves to connect laboratory modules. The other two sleeping spaces are located in one of the Russian modules. On top of limited sleeping space, there are only two lavatories on board the ISS, one in the Tranquility module and one in the Zvezda module. Given the current arrangement of accommodations, to turn the ISS into a hotel would require some serious renovations.

There are additional challenges besides simply the internal layout. The life support system of the ISS also would need upgrades. The life support of the ISS can currently only support 9 crew members at maximum, however this places increased stress on the life support system. Crew size is limited to 6, even though it is designed for 7 astronauts. This limits the number of guests that can visit the station at any given time. Furthermore, if there are any staff members that must work on the station, the guest list under current limitations decreases even further.

4. Manufacturing in Space

Low earth orbit presents a unique opportunity for manufacturing. Microgravity produces very beneficial effects on a large variety of products, from artificially grown meats to metal alloys. Some manufacturing does already take place on board the ISS, however, the manufacturing capability is small in scale, and largely focused on exploring methods for manufacturing in microgravity.

Research experiments on the International Space Station are housed in what are called EXPRESS Racks, which stands for EXpedite the PRocessing of Experiments to the Space Station. EXPRESS racks are basically a shelving unit that supports and stores experiments on board, and provides power, cooling, and exhaust functions to the stored experiment. There are 8 EXPRESS Racks on board the ISS, and while they are a little dated, would serve as an excellent base from which to build out a manufacturing facility.

So what would that look like? What would be manufactured on the ISS? There are limitless possibilities. As mentioned above, microgravity provides excellent conditions in which to manufacture organic material, as well as inorganic material. Additionally, there is space enough to perform it all. The first potential items are actually human tissue.

4.A. 3D Bioprinting

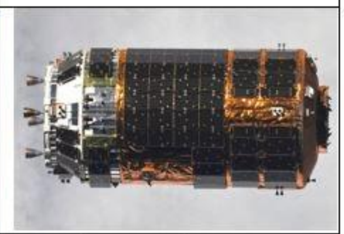
Human organs can be 3D printed using bioinks consisting of gel and human stem cells. However, due to the fragility of the material, during the printing process most specimens collapse under their own weight unless certain chemicals are injected into the mix. In space, this problem would not occur. The printed layers would not have to fight against gravity, chemical strengtheners would not have to be added, and the tissue would be able to strengthen properly on its own, producing a viable transplant organ in 45 days or less. According to statistics from the US government, there are over 109,000 people waiting to receive an organ transplant, and approximately 17 people die each day waiting to receive a transplant. The average cost of a heart transplant is northwards of $1.4 million USD. Utilizing the resources of the International Space Station, all those numbers could decrease significantly.

Increasing the capacity of the International Space Station to house 3D bioprinters is extremely viable. Not only would the transplant waiting list decrease, there is the possibility that transplant success rate could increase as well. Techshot, one of the companies behind 3D bioprinting, has done research into printing organs using the transplant recipient's own stem cells, which would lower chances of rejection. Currently, transplant rejection drugs must be taken for the remainder of life following an organ transplant, and cost around $1500-$1800 a month for at least the first year. With an organ printed from your own cells, the body would no longer try to reject the new organ, and anti-rejection drugs would no longer be necessary.

4.A.1 Mission Limitations

There are several cargo vehicles available to serve as transport for the purpose of bringing our supply of printers and ink to the ISS and are shown in Table 1, below. Demonstrably, the ideal craft is the SpaceX Cargo Dragon spacecraft. Not only does it have much larger available volume for cargo, it is also, most importantly, reusable, and can carry cargo back into the ground, whereas both the Russian Progress MS and Japanese HTV-X cannot reenter the atmosphere, and at the compression of their mission are jettisoned to burn up in the atmosphere. The Cargo Dragon capsule contains storage space for both pressurized and unpressurized payloads; the capsule itself is pressurized, and has a volume of 9.3 cubic meters. The trunk has a volume of 37 cubic meters, and is unpressurized. The trunk remains attached to the Dragon capsule until shortly before reentry, at which time it detaches, and

Spacecraf | Cargo Dragon | Soyuz (Progress MS-15) | H-II Transfer Vehicle

Spacecraf t	Cargo Dragon	Soyuz (Progress MS-15)	H-II Transfer Vehicle
Image			
Payload Mass	Launch: 6000 kg Return: 3000 kg	Launch: 2540 Return: 0 kg	Launch: 5850 kg Return: 0 kg
Volume	46.3 m^3	7.6 m^3	14 m^3

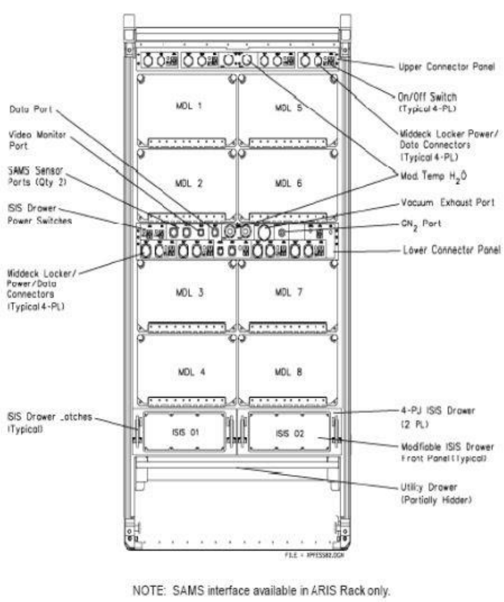
burns up in the atmosphere.

Table 1: ISS Cargo and Resupply Vehicles

The next step is to perform a cost analysis of 3D printing organs in space. The present cost to lift an item to space on a Falcon 9 rocket, the current rocket used to resupply the ISS, is $2720 per kilogram of weight. Due to the reusable function of the Falcon 9, cost to return to the surface of the earth per kilogram is assumed to be a quarter of the cost to go up, approximately $680 USD. A typical bioprinter weighs approximately 18 kilograms, and it's the dimensions (Length, Width, Height) are 0.477m, 0.441m, 0.365m. It takes up a volume of 0.0768 cubic meters. Thus, the cost to send up each bioprinter is $48960. Not only is cost a launch limitation, the payload weight capacity of the Falcon 9 rocket is as well. The maximum payload weight to Low Earth Orbit is 22800 kg. This weight must be budgeted between all supplies needed to begin printing organs. There is ample room for all equipment needed. For example, if only printers are sent up, then in one trip, 602 will fit in the capsule and the trunk of the Cargo Dragon. If all available space is used, and the maximum weight is reached, the launch cost of the trip comes to $62 million USD. This leads to the next limitation of the mission: printing stations on board the ISS. Sending only the 24 printers would cost $1175040 USD.

As mentioned previously, there are 8 EXPRESS racks on board the ISS. They are shown in Figure 2. The EXPRESS racks are roughly the size of a commercial refrigerator, capable of supplying up to 8 experiments with electricity as well as climate control in the individual lockers. These are labeled 1-8 on the figure below, and can all be removed to accommodate larger experiments. With the dimensions of the bioprinters, four can be fit into each EXPRESS rack. The utility draw on the bottom of each rack can be used to store the spools of bio-inks necessary to print each heart.

Figure 2: EXPRESS Racks



Once each heart is printed, it needs time to cure and develop enough mass and structure that the cells can survive reentry. In order to maintain production, at least two racks should be used for storing manufactured hearts until they can be shipped back to the surface of the earth. With six EXPRESS racks housing four printers each, twenty-four printers can be put to work. A heart viable for transplant can be grown in around a month and a half. In the first operational cycle, allowing for a failure rate of 25% to account for malfunctions or other errors, 18 hearts can be created. In order to return the hearts to the Earth's surface, precautions must be taken on the reentry journey to ensure that the gravitational and vibrational forces do not destroy them during transit. The average weight of an adult human heart is 0.35 kg; using the return journey cost estimated above, each heart costs $204 USD to bring down from orbit. The total cost of the return journey is $3672. Once on the ground, they can be provided to waiting transplant patients.

4.B. Foodstuffs

It may seem a little grisly to follow a section of growing human organs with a section on food, growing food, and specifically meat, could be revolutionary for long-term human missions in space. Using a similar process to the printed organs, any meat can be grown in space from tissue cultures. Rather than print the meat from bioinks, meat can be grown using the natural regenerative processes that exist in nature. Using a small tissue sample of cow cells, a steak can be grown in three to four weeks. (Patel, 2019) This process would potentially allow a completely self-sustaining environment with very little waste. As long as there remain cells to start a culture, meat can be made in a self-sustaining cycle. Take a sample, grow into edible tissue, rinse, and repeat.

While this may not merit the use of a large-scale facility, the potential use in future manned missions, such as to Mars, a six month journey. Having a reliable, sustainable food source would effectively decrease the cost of such a mission, as that decreases payload weight, which directly correlates to launch cost. Less weight spent on consumables increases fuel efficiency, as well as increasing the portion of the payload that can be used for other essential items. Rather than bring months-worth of dehydrated rations, fresh food can be grown for consumption during transit

4.C. Microgravity Smelting

There are several inorganic products that would make sense to manufacture in space, including metallic alloys, and fiber optic cables. In microgravity, materials can blend together without gravity causing impurities, as well as separation on the top and bottom, forming a stronger, more uniform alloy. One particular alloy that bears more consideration is a patented Magnesium alloy developed by Dr. Prashant Kumta, the chair of the Bioengineering Department at the University of Pittsburgh. Dr. Kumta has done extensive research on magnesium alloys, which are not only lighter than the standard aluminum alloys, but stronger and more versatile as well. According to Kumta, “The alloy’s improved mechanical properties, ability to store charge, and lightweight structure will make it an attractive material for aerospace, energy storage, and automotive applications.” (Kumta, 2019) In addition, magnesium alloys can be used as a replacement for stainless steel, titanium, or cobalt-chrome alloys in the medical field.

With a density similar to bone, and the ability to safely biodegrade within the human body, AZ31B magnesium makes an excellent choice for medical implants or other devices. Currently, stainless steel and titanium are largely used for implants because of their strength and limited reactivity inside the human body. However, both metals are heavy; 316L stainless steel, the most commonly used steel alloy, has a density of 8 grams per cubic centimeter, almost ¼ pound per cubic inch. Titanium alloys are lighter than steel, with a density of about 4.54 grams per cubic centimeter, which equates to 0.164 pounds per cubic inch. Both metals could be replaced by magnesium alloy, which has similar strength, but a density of 1.77 grams per cubic centimeter, 0.0639 pounds per cubic inch.

Due to lower density and weight, the AZ31b magnesium alloy also makes sense to manufacture in orbit. As stated above, smelting in microgravity increases the distribution of constituent metals. Doing so removes impurities as well as improves strength. Dental implants, one of the primary metallic implants, are made out of titanium, and costs approximately $50 to manufacture. A typical dental implant is shown in Figure 3, compared to a normal tooth. Titanium itself costs close to $25 per pound, whereas commercially pure magnesium is a fraction of the cost, $2.45 per pound.

Figure 3: A Dental Implant and Crown vs. Healthy Tooth

Magnesium alloys are not limited to applications in the medical field. According to Kumta, “fixtures or accessories in the aerospace industry - such as seats and lighting…” can be made from magnesium alloy, and “...will be lighter which will consequently reduce fuel consumption.” (Kumta, 2019) An increase in fuel efficiency would not be limited to the aerospace sector alone, as automobiles would also benefit from reduced weight. This would directly correlate to decreasing global carbon emissions, as cars would achieve more miles per gallon of fuel, reducing the amount of gasoline being consumed.

Magnesium alloy can be produced on board the ISS through the use of high temperature furnaces. The ISS National Lab currently possesses one such furnace, a Solidification Using a Baffle in Sealed Ampoules (SUBSA) unit.The SUBSA furnace is capable of reaching temperatures over 1,450 degrees Fahrenheit, and maintain a completely sterile environment during the smelting process. It has previously been used onboard the ISS to melt semiconductor crystals. Despite the limited volume of the SUBSA furnace, it should be viable to begin smelting on board. Expansion through additional furnaces is always an option.

A potential issue is the somewhat volatile nature of magnesium, and its propensity to burn very intensely. In air, magnesium will combust readily, provided an initial source of energy to trigger the reaction. The energy given off by burning magnesium is sufficient to split water molecules into oxygen and hydrogen gas, another extremely combustible element. This makes a magnesium-fueled fire rather difficult to extinguish by traditional means. However, like most fires, magnesium requires oxygen to burn. If exposed to the vacuum of space, the fire will be extinguished. While venting the atmosphere of the ISS is far from ideal, it is much preferable to the entire station being reduced to a burned-out hulk.

4.D Fiber Optics

Fiber optics are glass cables capable of transmitting large amounts of data at very high speeds, with very low signal loss. Most fiber optic cables today are made either from silica glass or plastic, however they can also be made from other glasses. The type of glass that would benefit most from microgravity is called ZBLAN. This is a fluoride-based glass, rather than silica. It has the molecular formula of ZrF_4-BaF_2-LaF_3-AlF_3-NaF. Ideally, ZBLAN fibers can transmit data with 10x-100x the efficiency of traditional silica fiber optics. However, it cannot be produced effectively on earth. This is because gravity causes impurities to form as a result of imperfect component distribution. In an article published by the ISS National Lab, “these defects that occur during the process of solidification result in the formation of microcrystals…" which effectively negates any usefulness for the majority of applications.

Microgravity is necessary because it suppresses the formation of these microcrystals during the process of drawing the glass out into a fiber. To create fibers, glass is superheated, which causes a bead to form. The bead falls, drawing out a fiber behind it. The process is similar to pulling taffy: grab one end, pull, repeat. The end result is a clear fiber free of impurities, shown in Figure 4 on the left. Made In Space is a company currently researching ZBLAN onboard the ISS. According to cofounder and Chief Engineer Michael Snyder, "…if you could suppress most or all of the crystallization in ZBLAN, the advantages…are huge compared to silica fiber." (Kasap, 2018)

Figure 4: Pure and Imperfect ZBLAN Samples

Using theoretical loss limits, the signal loss of a 10 km-long silica glass fiber optic cable would be equivalent to the signal loss of a 2000 km-long ZBLAN cable. If the theoretical loss is at all close to the actual signal loss, it would be possible to run a single cable across the floor of the Atlantic Ocean without the need for a repeater.

5. Conclusion

What do we do with the International Space Station once it has been defunded by the governments of the world? There are many, many potential uses, however, the most likely impactful and beneficial use of the ISS include usage as an orbital organ farm or as manufacturing facility. The framework and technology largely exist today. The potential for positive change is high. A transplant organ farm would save thousands of lives per year, as the waiting list for an organ transplant gets churned through. Technological marvels could drastically improve quality of life, from lower gasoline prices to higher, more reliable internet speeds. The end of the International Space Station's intended lifespan is inevitable, likely within the next decade. When it does, we will know how to best make use of the unique environment and opportunities it provides.

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Biography

Casey Allman was born in Texas on October 12, 1997, and spent most of his life in Dallas, Texas. In 2016, he enrolled in the Aerospace Engineering and Plan II Honors programs at the University of Texas at Austin, with a focus on Space Flight. In college, he was a member of the Longhorn Rocketry Association, as well as the Broccoli Project. He plans to graduate in 2020, and work in the aerospace industry.