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Can The International Space Station Pay For Itself?

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CAN THE INTERNATIONAL SPACE STATION PAY FOR ITSELF?

An Interactive Qualifying Project Report

Submitted to the Faculty

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Degree of Bachelor of Science

by

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Abstract

The feasibility of obtaining a profit from the International Space Station is examined. Current and future transportation methods and the prospects of manufacturing, tourism, and research in space are discussed, showing that it is currently impractical to generate a profit from the ISS due to considerable initial and transportation costs, a restricted timeframe and limited benefits from such ventures.

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1 Introduction

The overall goal of this report is to determine whether or not it is economically and technologically feasible to make a profit in space by taking advantage of the current status and position of the International Space Station (ISS). However, before addressing this issue at its heart, we must first analyze the requirements of achieving this goal: efficient/inexpensive transportation, and a product or service that takes advantage of the inherent qualities present in a microgravity (i.e. “weightlessness” of space) environment provided by the ISS.

First of all, transportation between the ISS and the location where the majority of these products or services will be utilized (in most cases, the Earth’s surface) must be either extremely efficient or inexpensive in order to provide any real financial profit. As of today, the main method of transportation between the Earth’s surface and the ISS is realized by the Space Shuttle, which is capable of moving material from Earth to space for $4,729 per pound[1]. This cost will undoubtedly contribute to the massive startup cost inherent in any construction of facilities required to generate a product or service in space. This cost will have to be reduced through technological advances in order for us to feasibly present a plan for generating a profit in space.

Additionally, we must also identify a product or service whose demand on Earth justifies the production or presentation thereof in a microgravity environment. In the case of a product, we must identify the clear advantages provided by production in space. If this product is to be manufactured or processed somehow in a facility up in space, the microgravity environment must present a clear advantage over performing the processing or manufacturing on the Earth’s surface, where construction of a facility and periodic raw material costs would be significantly cheaper. Overall, whatever we may produce or process in space must be “better” than what is available on Earth. “Better” may be defined as lower production costs, higher quality standards, etc—this product must be able to provide some tangible advantage to the consumer, who eventually ends up paying for the product. In addition, there may be some products that can only be manufactured in a microgravity environment, creating a monopoly for that particular product. This also gives the end-user motivation to pay for the product.

In the case of a provided service, the overall requirements are the same: the consumer should be motivated to pay for such a service. Thus, such a provided service must also be “better” than what is attainable on Earth, or unique enough that such a service has never before been seen.

Now that our requirements for developing a profitable product or service within the realm of space have been established, we will examine previous space stations as well as the current International Space Station to determine how each incarnation does or does not meet those guidelines.

1.1 Previous Space Stations

Salyut[2]

Mankind has been able to keep passengers in orbit for extended periods of time for over 35 years. The first manned orbital space station was the Salyut 1 which was launched on April 19, 1971 by the Russians. Salyut 1 was part of the Soviet Salyut program, which launched a total of 8 space stations into orbit in a little over a decade (with the last one launching April 19, 1982).

Due to technical difficulties, some of the early stations were never manned. The earlier stations were only able to support a crew for a short while if at all. Problems such as flight control and pressure loss was a serious issue and even resulted in the death of several cosmonauts. However, as Figure 1 clearly shows, the Salyut program learned from early mistakes and later models were much more successful.

Space Station	Days in Orbit	Days Occupied
Salyut 1	175	24
Cosmos 557	54	0
Salyut 2	11	0
Salyut 3	213	15
Salyut 4	770	92
Salyut 5	412	67
Salyut 6	1,764	683
Salyut 7	3,216	816

Figure 1. Salyut Space Stations.

The two final stations were each able to house cosmonauts over the course of several years. The repeated attempts at the Salyut station allowed the designers to correct mistakes and learn from the failures of previous missions.

Skylab[3]

Skylab was the first American space station. It was launched on May 14, 1973 and stayed in orbit for over 6 years. Despite its relatively long time in operation, it was only occupied for 171 days. Compared to the later Salyut stations, that may seem like a relatively short period of operation. Still, many procedures were learned or expanded upon due to the Skylab program.

During the initial launch, Skylab was severely damaged by the loss of the station's micrometeoroid shield/sun shade and one of its main solar panels. Some of the debris pinned the other solar panel to the side of the station. This caused the station to operate with a huge power shortage. To fix it, the first crew had to do a space-walk and make the repairs in space. Even still, some of the parts were not designed to be repaired in space. This undoubtedly bore an impact on later space endeavors to make in-space repairs more feasible.

During that period in which Skylab has operational, the researchers onboard logged over 2,000 hours on experiments. The experiments included 8 solar tests during which the Sun's coronal holes were discovered. Many of the tests studied the long-term effects of microgravity on the astronauts, which would be important information of future missions.

Skylab reentered Earth’s atmosphere on July 11, 1979. While the station had its share of difficulties, those difficulties showed researchers some of the possible complications that could arise in space as well as how better to deal with them. Many of the experiments, especially the ones involving microgravity, would provide good research for future missions.

Mir[4]

Mir is known as the world's first long-term space research station and had its initial launch on February 19, 1986. It was in orbit for over 15 years and was occupied for approximately 80% of that time.[5] It holds the record for longest continuous human presence in space at just under 10 years.

In many ways, Mir is similar in concept to the International Space Station. Like the ISS, Mir was comprised of modules, each of which had to be brought into orbit separately and then joined in space. It was comprised of 7 main modules which were too big to be brought up feasibly on one payload. The ISS was assembled in a similar fashion.

Mir also generated some interest from tourists. While space tourism didn't quite have the foundation it needed to make tourism on Mir easily possible, it did help pave the way for tourism on the ISS. Companies like MirCorp, which were invested in tourism on Mir, jumped their focus to the ISS when Mir was removed from orbit in 2001.[6] This surely helped jump-start the space tourism market's investment in the ISS.

Mir also represented the first international efforts in regards to space stations. While Mir was built by the Soviet Union, In September 1993 U.S. Vice-President Al Gore and Russian prime minister Viktor Chernomyrdin announced that in preparation for the ISS, the U.S. would be involved in upcoming Mir projects, under the code name Phase One (the ISS being Phase Two). While working together on the Mir, the two nations were able to resolve some diplomatic issues regarding to communication, trust, obligations and mutual goals. This helped pave the way for better cooperation during the work on the ISS.

1.2 Current Space Station

The current International Space Station is a multinational manned space research facility currently still being assembled in low earth orbit (360 km). The ISS is under the control of five national space agencies: the National Aeronautics and Space Administration (USA), the Russian Federal Space Agency (Russia), the Japan Aerospace Exploration Agency (Japan), the Canadian Space Agency (Canada), and the

European Space Agency (Europe). It was planned to be a merger of the proposed space stations of NASA (Space Station Freedom), Russia (Mir-2), and Europe (Columbus)[7]. Currently, the main function of the ISS is to perform advanced scientific research in a microgravity environment. These experiments range from biomedical applications such as ALTEA (Anomalous Long Term Effects in Astronauts' Central Nervous System) to measurement systems such as MAMS (Microgravity Acceleration Measurement System), to name a few examples[8].

Construction

Construction began in 1998 with the Russian launch of the first Zarya functional module. Since then, construction of the ISS has continued in sequences of small launches of individual functional modules, and the ISS now contains four main pressurized modules: the two Russian modules (Zarya, Zvezda) and two US modules, Destiny and Unity (Node 1). The Zarya provides electrical power, storage, and propulsion; the Zvezda provides living quarters and life support systems; the Unity module facilitates connections to the other modules, while the Destiny Laboratory Module is the primary research laboratory for the ISS. As of December 2006, the ISS consists of the following modules and elements, shown in Figure 2[9]:

Element	Flight	Launch Vehicle	Launch date	Length (m)	Diameter (m)	Mass (kg)
Zarya FGB	1A/R	Proton rocket	20 November 1998	12.6	4.1	19,323
Unity Node 1	2A - STS-88	*Endeavour*	4 December 1998	5.49	4.57	11,612
Zvezda Service Module	1R	Proton rocket	12 July 2000	13.1	4.15	19,050
Z1 Truss	3A - STS-92	*Discovery*	11 October 2000	4.9	4.2	8,755
P6 Truss - Solar Array*	4A - STS-97	*Endeavour*	30 November 2000	73.2	10.7	15,824
Destiny	5A - STS-98	*Atlantis*	7 February 2001	8.53	4.27	14,515
Canadarm2	6A - STS-100	*Endeavour*	19 April 2001	17.6	0.35	4,899
Joint Airlock - Quest Airlock	7A - STS-104	*Atlantis*	12 July 2001	5.5	4.0	6,064
Docking Compartment - Pirs Airlock	4R	Soyuz rocket	14 September 2001	4.1	2.6	3,900
S0 Truss	8A - STS-110	*Atlantis*	8 April 2002	13.4	4.6	13,971
Mobile Base System for Canadarm2	UF-2 - STS-111	*Endeavour*	5 June 2002	5.7	2.9	1,450
S1 Truss	9A - STS-112	*Atlantis*	7 October 2002	13.7	4.6	14,124
P1 Truss	11A - STS-113	*Endeavour*	24 November 2002	13.7	4.6	14,003
External Stowage Platform (ESP-2)	LF1 - STS-114	*Discovery*	26 July 2005	4.9	3.65	2,676
P3/P4 Truss - Solar Array	12A - STS-115	*Atlantis*	9 September 2006	73.2	10.7	15,824
P5 Truss	12A.1 - STS-116	*Discovery*	10 December 2006	13.7	3.9	12,598

Figure 2. Current ISS Components, December 2006.

The completed ISS will consist of several of these pressurized modules and pertinent elements connected to a truss. This truss is connected to four pairs of large photovoltaic modules, the station's power supply. Yet to be launched in the future are additional laboratory and experiment modules, as well as two more interconnecting modules, Node 2 and Node 3.

Construction of the ISS began in 1998 and was expected to end in 2004 or 2005, but the schedule experienced numerous setbacks, namely the Columbia shuttle disaster in 2003 and various delays in the 1990s. The Columbia incident halted Space Shuttle flights until July 2005 (Discovery). As of today, construction is projected to end in 2010, with the end of the ISS project in 2017[10].

Cost

In addition, the original cost of the ISS was estimated in 1994 to be around $8 billion. Today, construction alone is projected to reach $53 billion by the end of the ISS's service life in 2017. This figure does not include the projected $38 billion spent on the Space Shuttle program, which has almost exclusively been used for construction and supply of the ISS (construction of the ISS requires more than 40 spaceflights, 33 of which are expected to be carried out by the Space Shuttle). The $1.8B 2005 ISS annual budget allocation was as follows:

- Development of new hardware: $70M
- Spacecraft operations (software, logistics, maintenance): $800M
- Launch and Mission operations (mission integration, medical support, Shuttle launch site processing): $450M
- Operations Program Integration (maintenance of flight and ground hardware and software): $350M
- ISS Cargo/crew (supplies, cargo, crew): $140M

In addition, Figure 3 outlines NASA's current plan for continuing operations on the ISS until the end of its service life in 2017:

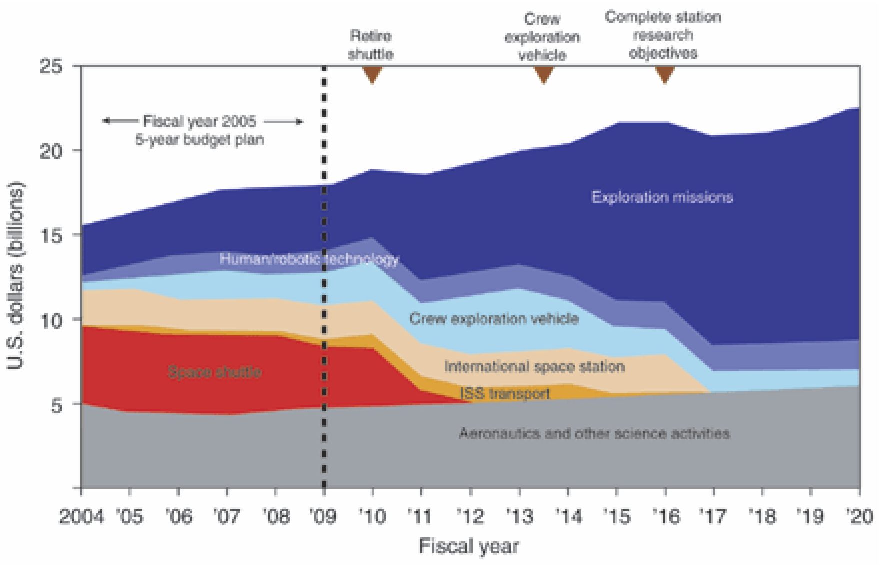

Figure 3. NASA Budget, 2004-2020.

As one can see, the Space Shuttle should be phased out by 2012, and the ISS should retire from service in 2017 if NASA progresses according to plan.

Due to the fact that construction of the ISS is far behind its original schedule and well over budget (currently estimated at approximate total of $100 billion), we are interested to see whether or not the full potential of the station can ever be actualized. We intend to explore several avenues by which the ISS can "pay" for itself; either financially, or bring about some worthwhile development that could potentially improve the general quality of human life (i.e. non-financial gain).

We will operate under several basic assumptions. First of all, we will assume that our timeline will extend only until the Space Station is expected to shut down (currently 2017). Any research not performed under this assumption will invalidate itself, as the station will no longer have resources dedicated to its operation. Finally, we will assume that any potential methods of realizing the full potential of the ISS directly involve the ISS itself, or take advantage of some aspect of the ISS's current status. For example, we would not investigate any aspects of space tourism that do not explicitly include the ISS as a potential tourist destination, or any orbital manufacturing facility that operates separate from the ISS. We are seeking to utilize the ISS directly in hope of some tangible gain.

2 Propulsion

In this section, we will examine the evolution of propulsion systems for launching cargo and personnel into space, discussing past, present, and future implementations. In addition, we will also discuss evidence for and studies regarding launch costs for future vehicles within our timeline. It follows that if we are to make a profit in space, we most likely will need a regular means of transportation to and from the International Space Station. To enable us to determine the most likely means of transportation that will be available in the future, we will analyze the advances made in the field of launch vehicles, starting in the past and working to the present, and extrapolate from there to likely future means of transportation.

2.1 The Past: Saturn V

On May 25, 1960, in response to the Soviet Union's launch of the world's first artificial satellite (Sputnik 1) and Soviet cosmonaut Yuri Gagarin becoming the first human to travel in space, then-US President John F. Kennedy deemed it necessary for America to go to the moon. At the time, however the US possessed no means by which to accomplish such a feat. A rocket far more large and powerful than the Mercury rockets used at the time would be required.[11]

What would ultimately become the Saturn V rocket was announced on January 10, 1962. It would be the most massive space vehicle ever built; a three stage rocket that stood 363 feet tall and weighed 6,699,000 pounds. It would be capable of delivering a payload of 47,000 kg, (103,400 lb) to lunar orbit, or 118,000 kg (259,600 lb) to low earth orbit. The first stage, fueled with RP-1 rocket fuel and liquid oxygen oxidizer was 138 feet tall, which was designed to burn for 2.5 minutes, taking the rocket up to 61km in altitude. The second stage, fueled with liquid hydrogen and liquid oxygen, burned for 6 minutes, providing the required thrust to propel the vehicle to an altitude of 185km and 24,600 km/h, close to the required orbital velocity. The third stage burned for 2.5 minutes, and remained attached to the Command Service Module while in orbit around the earth. This was so that, after the spacecraft's systems had been checked, the third stage burned for 6 minutes to bring the spacecraft up to the 10 km/s required escape velocity. After this velocity had been reached, and the vehicle was on its way to the moon, the Command Service Module separated from the third stage, rotated 180 degrees and docked with the Lunar Module, which until this point had been stored further below in the third stage. The remaining fuel and oxidizer In the tanks of the third stage was then vented, changing its trajectory and, from Apollo 13 onwards, directed it to impact the moon, the impact of which was measured by seismometers to help map the moon.[12]

At the time of its operation, NASA needed a large rocket to send men to the moon. The Saturn V was just the large and powerful vehicle needed. However, a Saturn V rocket cost an impressive 431 million 1967 US dollars[13]. For comparison, this corresponds to approximately 1.804 billion 2000 US dollars, or 2.11 billion 2007 US dollars[14]. As a result, one of the main reasons for the cancellation of the Apollo program, and as such the ultimate demise of the Saturn V rocket was its cost of operation.[15] Once the Soviets had been beaten to the moon, and the public interest in sending astronauts to the moon began to wane, the 'necessity' of such a large rocket also began to fade. As such, after the launch of Skylab on May 14, 1973, the rocket was never launched again.[16]

2.2 The Present: The Shuttle

The successor to the Saturn V as NASA's workhorse launch vehicle is the Space Transportation System (STS), more commonly referred to as the Space Shuttle. First launched on April 12, 1981, the Shuttle is a manned re-useable space plane. That is, instead of being a single rocket with a capsule or other cargo stashed at the top, it is a plane-like vehicle with assorted booster elements attached. A shuttle launch requires four primary components. The first is the orbiter itself, a plane-shaped vehicle. The orbiter houses the crew of up to seven in addition to up to 24,400 kg (53,700 lb) of cargo to low earth orbit or 3,810 kg (8,390 lb) to geostationary transfer orbit in its 60-by-15 ft (18 m by 4.6 m) payload bay. The orbiter contains three main engines, known as the Space Shuttle Main Engines (SSME), which are provided the necessary liquid oxygen and liquid hydrogen fuel via the second major component, the 153.8 ft (46.9 m) long external tank. The tank in its current form contains the 1,387,457 lb (629,340 kg) of liquid oxygen (LOX) and the 234,265 lb (106,261 kg) of liquid hydrogen (LH2) required to power the shuttle into space.[17] Attached to the external tank is a pair of 149.16 feet (45.5 m) long re-useable solid rocket boosters. These solid rocket boosters are the largest solid-propellant motors ever flown. The boosters provide approximately 83% of the thrust at lift-off, to lift the shuttle off the pad and up to an altitude of about 150,000 feet (45.7 km). After the solid fuel has been burned off, the boosters detach from the main tank and fall, guided by parachute, into the ocean, where they are recovered and refurbished for reuse.[18]

The shuttle has been used to deploy 66 satellites to date, with 16 planned missions remaining. Notable cargo includes the Hubble Space Telescope, Galileo, Magellan Probe, the Chandra X-ray Observatory and many components of the International Space Station. A fundamental advantage of the shuttle is its ability not only to deploy hardware, but also to re-acquire orbiting satellites, something other spacecraft have limited ability to do.[19]

However, there have been several notable failures of the Space Shuttle launch vehicle since its inception. Most recently, the Space Shuttle Columbia disaster, in which the Space Shuttle Columbia disintegrated upon re-entry into Earth's atmosphere, temporarily suspended the space shuttle program and construction of the ISS. The disintegration of the shuttle upon re-entry was caused by a small piece of foam insulation breaking off the main propellant tank and striking the leading edge of the left wing, damaging the Shuttle's thermal protection system (TPS). This eventually led to the demise of the Columbia. This tragedy set the Space Shuttle program back over two years[20].

There also remains the 1986 Challenger incident, in which the Space Shuttle challenger disintegrated 73 seconds into its flight after an O-ring seal in the solid rocket booster failed. This eventually led to the disintegration of the orbiter, destruction of the Shuttle, and the deaths of all 7 crew on board. The Challenger disaster set the Shuttle program back 32 months[21].

Even in the face of these disasters, in an age of construction in space, exemplified best by the International Space Station, the Space Shuttle has proved a valuable asset. Its ability to be used as a work platform has made it an indispensable part of launch industry as a whole. The Ares launch vehicle will replace the Shuttle after its retirement in 2010.

2.3 The Future: Ares launch vehicle

The Ares family of rockets is NASA's next generation of orbital launch vehicle. Consisting primarily of the Ares I[22], the crew launch vehicle, and the Ares V, the cargo launch vehicle[23], the Ares program is under development to take over launch duties from the aging shuttle around 2010.

Ares I: Crew launch vehicle

The Ares I is an inline, multistage rocket designed as a crew launch vehicle to replace the shuttle in future space operations. Its primary objective is to "carry a new generation of space explorers into orbit".[24] Overall it is 309 feet long, and weighs 2 millions pounds ready to launch. It is anticipated to have a launch capacity of approximately 25 tons. The rocket is comprised of two stages; the first stage is a reusable solid rocket motor/booster. This booster is derived from the current shuttle solid rocket booster, with a new forward adaptor. This adaptor has been developed to accommodate the second stage of the Ares rocket, which is not present in the shuttle launch. The second stage is powered through the use of the J-2X rocket engine. This engine is a derivation of the Saturn J-2 engine used when America first sought the moon. The J-2 rocket engine powered the Saturn IB and Saturn V rockets during the Apollo program. The upper stage will also contain the 280 thousand pounds of fuel required to power the vehicle into orbit[25].

Ares V: Cargo launch vehicle

The Ares V rocket is under development to assist NASA in the task of delivering resources into space safely and reliably. The Ares V is also a multistage rocket. The primary stage is comprised of two reusable solid rocket boosters, similar to the ones used in the Ares I vehicle, also derived from the current solid rocket boosters used on the shuttle. Additionally, the first stage contains a liquid fueled rocket booster, referred to as the core propulsion stage. This booster is also a derivative of the Saturn V rockets. The booster tank, again containing liquid oxygen and liquid hydrogen (LOX/LH_2) fuel, powers five RS-68 rocket engines, upgraded versions of those used in the Delta IV rocket, developed by the U.S. Air Force in the 1990s[26]. The upper stage is again powered by the J-2X rocket engine, the same derivative of the Saturn V J-2 rockets used in the Ares I. The final stage of the Ares V rocket is the Earth Departure Stage. This stage is also powered with a J-2X liquid oxygen and liquid hydrogen (LOX/LH_2) fueled engine. The earth departure stage is designed to power the Orion crew capsule out of earth orbit and on to the moon.[27]

Orion Crew Vehicle[28]

The Orion Crew Vehicle is NASA’s next-generation manned spacecraft with a four to six man capacity, and will be launched with the Ares I launch vehicle described above. It consists of a crew module and a service module, which hold the crew and the spacecraft’s propulsion system and onboard supplies. Its modular design was partially a reaction to the Space Shuttle Columbia disaster in 2003, where a piece of foam insulation broke off during liftoff and caused the eventual vaporizing of the shuttle upon re-entry[29]. Director of the Integration Office in the Exploration Systems Mission Directorate Neil Woodward stated, “Going with known technology and known solutions lowers the risk,” [30] referring to fact that the Orion module is reminiscent of the older Apollo Command/Service Modules. The design of this module, as well as the overall new Ares spacecraft program shows that NASA is indeed falling back on older, more familiar, and more reliable technology.

This could only be seen as an attempt on NASA's part to focus primarily on safety and less on sheer efficiency of transport, which is what we would desire in terms of minimizing launch costs.

2.4 Evolution of Launch Vehicles

As can be seen in Table 1, a major revision of NASA's primary launch vehicle has occurred every 20 to 25 years. The Saturn V was NASA's first substantial orbital launch vehicle in 1962, and was followed by its replacement, the Space Shuttle in 1981, to be followed by its anticipated replacement, the Ares family in 2010. This would suggest that with the retirement of the Space Shuttle, the Ares family of rockets can be anticipated to be the mainstay of NASA's launch fleet for some years to come. For this reason, we do not anticipate that any major changes will take place in the foreseeable future, with regard to launch vehicles.

Launch Vehicle	Saturn V	Space Shuttle	Ares I/V
Inaugural Flight	1962	1981	2010

Table 1. NASA Main Launch System and Inaugural Flight.

It would seem safe to extrapolate the next major revolution in NASA launch vehicle to occur sometime around the year 2035; a date beyond the target deadline for this investigation. As such, it would be imprudent to examine any launch vehicle or other technology that is not in some form of advanced development at this time. Cost analysis of launch systems will therefore be based primarily on data derived from current and near future vehicles, primarily those systems developed by NASA: the Space Shuttle and Ares.

2.5 Launch Dynamics: Cost

There are two major areas of interest when discussing launch costs. Specifically, the areas relate to the demand of launch services relative to launch cost. There are two types of goods, those whose demand is launch cost-dependent, and those which are not (cost-independent). With cost-independent services, it is said that the demand is inelastic with cost. The demand for cost dependent services, on the other hand, is said to be elastically related to its cost. That is, if the cost for the good or service increased, the demand for it would decrease, and vice versa.

2.5.1 Current Atmosphere: Cost-Independent Payload

year	launch	manuf	total	% L	% M		
2000	5.3	11.5	64.1	8.27	17.94	31.55	
2001	3	9.5	64.4	4.66	14.75	24.00	
2002	3.7	11	71.3	5.19	15.43	25.17	
2003	3.2	9.8	74.3	4.31	13.19	24.62	
2004	2.8	10.2	82.7	3.39	12.33	21.54	
2005	3	7.8	88.8	3.38	8.78	27.78	
ave	3.50	9.97	74.27			25.77	
sum	21	59.8	445.6				

Table 2. World Satellite Revenues by Sector, 2000-2005.[31]

Cost independent goods are those for which the cost of preparing the cargo for launch significantly outweighs the launch cost itself. The demand for launch services for such goods will not change significantly to a large change in payload to orbit costs. This area is not one for which large growth is anticipated, and as such, a large financial gain is not anticipated. Products that typically fall into this category are typically large individual items, such as communication satellites. The reason for this is because the cost of design and manufacture of satellites is substantial even relative to the cost of launch. As detailed in a June 2006 report on the state of the satellite industry[32], presented by the Futron Corporation[33], the total manufacturing costs for all satellites launched privately from 2000 to 2005 totaled 59.8 billion dollars, whereas the total launch costs for the same satellites totaled 21 billion dollars. The launch cost totals a mere 25% of the total cost-to-orbit of any particular satellite. Given that the development and construction costs for future satellites remain relatively stable, any reduction in launch costs will not have a dramatic impact on the future demand for satellite launch vehicles, as even a 50% saving in payload to orbit costs will only reduce the total drawing board to orbit costs of a satellite program by approximately 12%. These modest savings will not likely be an enabling factor for the increase in satellite to orbit opportunities. As such, the launch of satellites is not anticipated to reap the gains required to fund any sort of space endeavor such as the ISS.

The only significant gains anticipated in this area would be realized in the launch of facilities required for the processing of cost dependent payload. That is when launch costs decrease to a point at which it is no longer a disabling factor in other industries, there will be an increased need for the launch of those industries processing facilities. For example, if the cost of launching raw materials to an orbiting widget factory dropped to a point such that the manufacture of widgets in space became feasible, there would be a demand for a service to launch widget factories. The demand for the launch of widget factories is not directly related to the cost of launching said factories, but instead coupled to the cost of launching the dependent payload; the raw materials necessary for the manufacture of a widget.

2.5.2 Future Interest: Cost-Dependent Payload

Cost-dependent payload is such that the demand for payload launch is heavily dependent on the cost to get said payload into orbit. That is to say, that the demand for services is directly and inversely related to the cost for such a service. As the cost for the service decreases, the demand for it will increase. It is expected that this sector will reap true benefits, should the cost to orbit become low enough to enable it. We expect that the manufacture of goods in earth orbit—a low gravity environment—is a bright hope in the search for financial reward in space.

Raw materials for use in space manufacturing are indicative of the types of payloads that fall into a cost-dependent category. The profit for space manufacturing can be easily calculated as the difference of the value of goods sold and the value of the materials to create such goods. In this case, payload to orbit is a fundamental cost that must be factored in to the value of the goods. Until the cost to orbit is reduced as to swing that fundamental equation towards a profit, shipping materials into orbit will be a major disabling factor for the manufacture of goods in orbit. As seen previously, the raw materials required for the manufacture of widgets is a cost dependent payload. Until it is financially feasible, that is, until there is sufficient value added to a product by its manufacture in space, it simply won't be done to any large scale.

According to a Futron study, the reduction of launch costs would not have a dramatic impact on the demand for launch services from the existing government and commercial markets. The gains in launch cost reduction would be realized in what Futron refers to as 'evolving commercial markets'. These markets are such that current launch costs may be prohibitive to their operation. The Futron study suggests that launch cost reductions could have a significant impact on demand, given such markets degree of price elasticity.

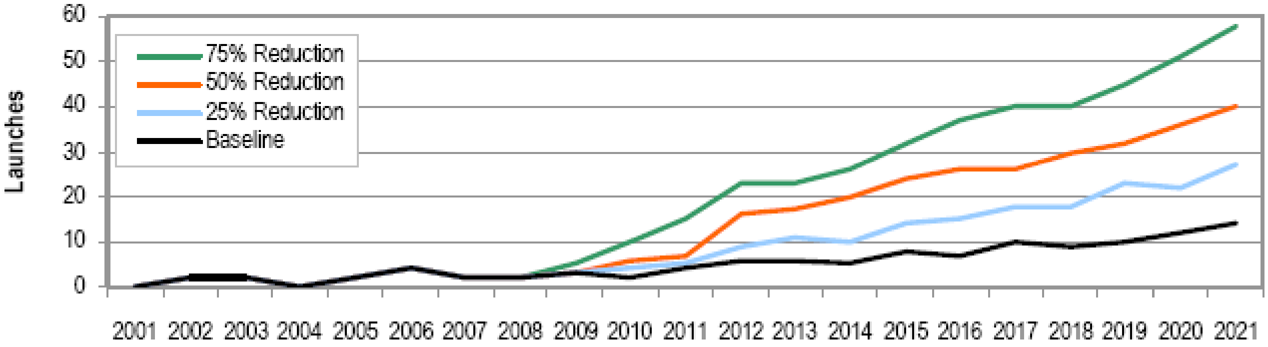

Figure 4: Impact of Decreasing Launch Prices on Evolving Commercial Market Forecasts[34].

Such markets include hazardous waste disposal, non-terrestrial mining, orbiting billboards, space crystal growth, space debris management, and space agriculture. These markets are characterized as emerging beyond a 20 year timeframe, as shown in Figure 4. This puts the emergence of these markets beyond the ISS's anticipated useful lifespan and as such not of much use in the financial recoup of the ISS.

In conclusion, there are several reasons to suggest that the future of propulsion and transportation between the Earth's surface and Earth orbit is not promising for our desires. First of all, a simple glance at the timetable of the evolution of launch vehicles places the next major paradigm shift in the world of propulsion at around 2035, which is far beyond our time limit of 2017 (the end of the ISS's service life). Secondly, due to the Columbia (and to a lesser extent, the Challenger) disasters, NASA's future propulsion endeavor, the Ares launch vehicles and the Orion Crew Vehicle, are slated to be based more on previous designs, emphasizing solid design principles and safety over radical propulsion changes and transportation efficiency. Finally, the Futron analytical study above suggests that cost-dependent payload, the type of cargo that we are interested in (in terms of making a profit), is characterized as emerging beyond a 20 year timeframe, again exceeding our time limit of 2017. Therefore, we find that it is very unlikely that the cost of transportation will decrease substantially in aiding us to make a significant profit.

3 Potential Methods

In this section, we will examine several potential methods of utilizing the current status of the International Space Station in hopes of generating revenue, in order to begin to recover some of the $100B investment already placed in the ISS. This is of course, in spite of the above propulsion analysis that suggests that the cost of transportation will not decrease substantially by 2017, the end of the ISS's service life. However, we will carry on with the analysis, citing current figures for transportation cost if necessary, to see whether or not they truly makes a difference.

For each scenario, we will look at the potential financial and non-financial (i.e. safety, security, procedural knowledge, etc.) gains, as well as the initial and ongoing costs required for each method. By doing this, we will be able to determine the overall feasibility of each potential method. Specifically, we will examine the topics of mass production and manufacturing, commercial tourism, and research in the microgravity environment that the ISS's current status provides.

3.1 Manufacturing

The process of manufacturing in space lends itself to mean that we would be identifying/developing a product to be mass-produced in orbit and to make said production financially feasible. Primarily, the reasons for pursuing manufacturing in a microgravity environment revolve around the advantages of doing so. One of these advantages is the lack of convection currents and sedimentation that are typically present in heating/cooling manufacturing processes on Earth. When a material is being cooled, say, from the liquid to the solid state, particles that solidify first tend to drift toward the bottom of the liquefied material, resulting in a skewed density distribution of the final cooled piece. In microgravity, this detriment can be eliminated, as there will be very little gravitational pull on a mixture of cooling material. As a result, the materials created in space have a much higher potential purity than materials created on Earth.

Additionally, there are readily available temperature extremes in space that can be used for manufacturing purposes. Heat and energy can be captured or absorbed from the Sun, while if a piece of material requires cooling, it can be directed away from the Sun's energy. Other notable advantages of manufacturing in space include access to the ultra-clean vacuum environment of space, the fact that raw materials can be harvested from the solar system (i.e. lunar regolith), and finally, that hazardous processes can be performed in space at little risk of contamination of the Earth. [35]

What we are looking to do, is to determine whether mass-production in space of a certain product can be financially viable in hopes of recovering some of the cost of the International Space Station. There are two major obstacles in our path: the initial cost of launching and construction of a manufacturing facility in orbit, and the ongoing cost of raw materials required for the manufacture of a product. However, to be able to draw conclusions about mass-production in microgravity as a whole, we will specifically examine the feasibility of constructing a semiconductor manufacturing and processing facility in orbit.

The main motivation behind the construction of a semiconductor processing facility in microgravity is primarily the monetary aspect: the worldwide semiconductor industry has been estimated to be worth $213B per year (by Philips CEO Frans van Houten)[36]. If somehow, we could produce substantially higher revenues, profit, or even simply a drastically higher volume of semiconductor chips in a microgravity environment, the financial implications would be enormous. Semiconductor chips could potentially be made much more cheaply and in a much greater volume, reducing cost to fabrication companies and ultimately to consumers as well.

3.1.1 Semiconductor Manufacturing

To understand the limitations of, as well as take advantage of the inherent capabilities presented to us with a microgravity environment, we must first investigate a typical semiconductor manufacturing process. The specific process for creating CMOS (complementary metal oxide semiconductor) silicon integrated circuits is detailed below. Although there are many different types of semiconductors used for production of semiconductor chips, silicon is the most widely used (95% of the current market)[37] and would be a typical scenario to be investigated.

Wafer Manufacturing[38]

Semiconductor chips are manufactured in a very standardized process. All semiconductor chips take the form of integrated circuits, which is essentially the fabrication of a microcircuit on a small (~10mm^2) piece of semiconductor material (in this case, silicon), also called a die. A silicon die is realized in multiple steps. First, one must create a much larger silicon wafer (10-20cm diameter) on which the integrated circuit is to be fabricated. To create these silicon wafers, metallurgical-grade (at least 98% pure) polycrystalline silicon is transformed into a silicon-containing gas, precipitated, and melted in a furnace in order to form the single-crystalline silicon required. Impurities, or dopants, added to the molten silicon at this stage allow control of the silicon's "type" and electrical characteristics. There are two types of silicon, N-type, typically formed by doping with phosphorus, and P-type, typically formed by doping with boron. After melting, a single crystal is slowly pulled from the molten silicon using the Czochralski method, which allows control of the diameter of the formed silicon ingot by altering rotation speed and pull rate. After the silicon ingot is pulled from the solution, it is allowed to cool. Using a diamond saw, the ingot (about 10-20cm in diameter) is cut into wafers with a typical thickness of ~1mm. These wafers will be subdivided into multiple identical dies later in the manufacturing process.

Photolithography; Well Definition[39]

Photolithography is the process by which certain areas of a silicon wafer can be masked off, so particular processing steps can be applied only to certain areas. After the wafer is prepared as stated above, whether it is N-type or P-type, certain regions of the wafer must be doped with impurities to create areas that are opposite in type to the type of the wafer. These regions are called wells. For instance, multiple P-type wells must be implanted into an N-type wafer. By creating these wells, circuit designers can connect these well regions to create transistors that serve an almost limitless number of functions in an integrated circuit design.

First of all, a layer of silicon dioxide is produced by oxidizing the surface of the silicon wafer. This is for protection of the microcircuit. Subsequently, photoresist is applied on top of the formed silicon dioxide. Photoresist, also known as PR, is a light-sensitive polymer that polymerizes when exposed to ultraviolet light. A glass mask is placed over this layer of photoresist, and the unmasked regions are exposed to ultraviolet light. This exposure makes the exposed regions insoluble to an organic solvent. The glass mask is removed, and the excess photoresist is removed with said organic solvent. The photoresist is baked in a furnace to harden, and the uncovered SiO_2 is removed with by etching with an acid or via a gas. This process can be repeated several times to cover and uncover multiple areas of the silicon wafer so as to expose them to other chemicals to alter the electrical characteristics of those uncovered regions.

Ion Implantation[40]

After each photoresist layer is hardened, and the uncovered SiO_2 is etched away, the intrinsic silicon of the wafer will be exposed. These uncovered areas can be exposed dopants that will cause the uncovered silicon wells to be converted to the opposite type. For instance, in a P-type wafer (also called P-type substrate), N-type wells can be created by exposing the uncovered areas to a gas containing phosphorus, and vice versa. However, this method of diffusion implantation has been largely replaced by the more precise method of ion implantation. In this alternate technique, an ion source is focused and accelerated to strike certain areas of the wafer, introducing dopants in that particular region. After ion implantation, the silicon wafers are annealed, where the wafer is heated to around 1000°C to thermally vibrate the introduced ions and allows bonds to reform. The resulting wells are shown in Figure 5.

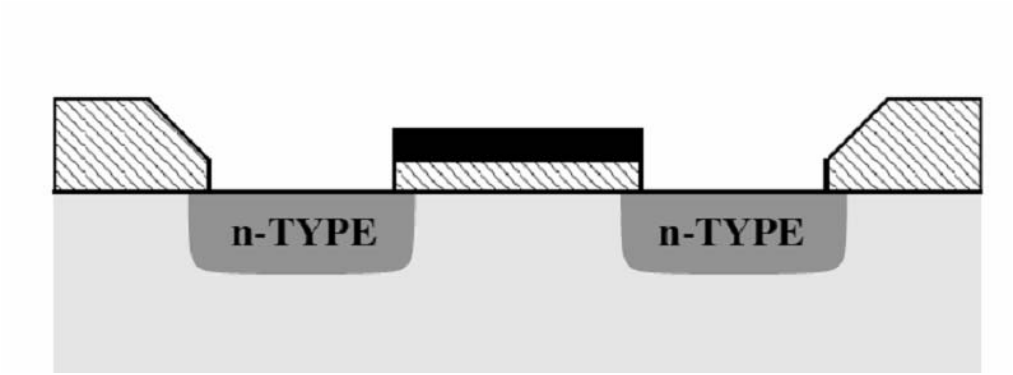

Figure 5. Well Implantation[41].

Oxidation[42]

After the wells are defined, a thick layer of silicon dioxide must be grown over the non-well regions as an insulator. As previously mentioned, areas of the silicon wafer can be oxidized to grow silicon dioxide, which is an ideal insulator in a silicon semiconductor. After masking the undesired regions with silicon nitride, oxygen gas is passed over unmasked areas of the silicon wafer, producing a thick layer of silicon dioxide. This reaction occurs at a high temperature, usually around 800°C to 1200°C. This thick layer is called the field oxide, and can be seen in the figure below as the shaded, thick, tapered regions on either side of the implanted wells, covering the surface of the wafer.

Additionally, the gate oxide must be grown. The gate is defined as the region separating two implanted well regions. In a general sense, the gate serves as the "switch" that turns the transistor on. There is no physical electrical connection from the gate to the region between the wells; it is purely capacitive in nature:

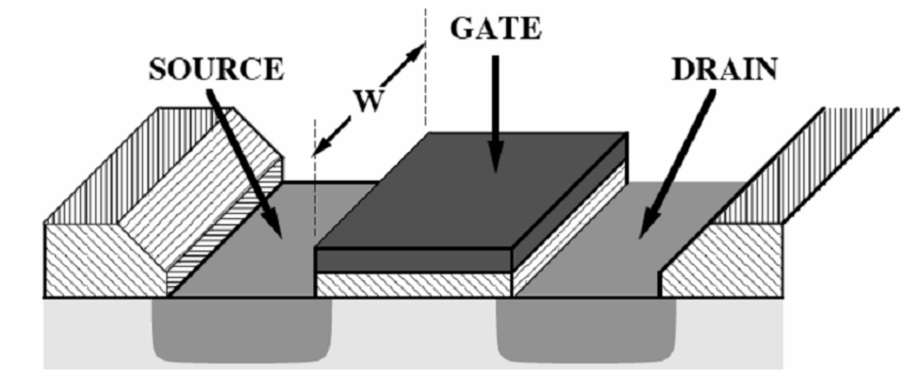

Figure 6. Gate Oxide[43].

In Figure 6, the wells are labeled Source and Drain, while the gate is physically separated by a layer of silicon dioxide from the silicon wafer.

Metal and Passivation Deposition[44]

The metal contacting the source, gate, and drain regions must be deposited. This metal is typically aluminum, and is deposited in a layer. The excess aluminum is etched away to leave a pattern shown in Figure 7:

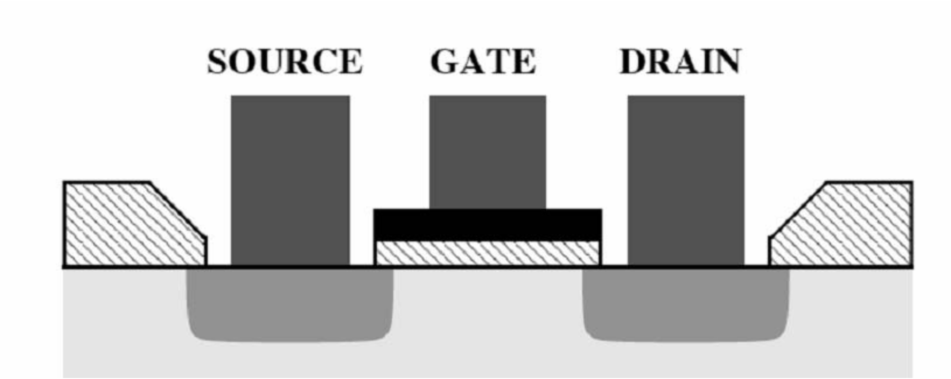

Figure 7. Aluminum Metallization[45].

Many layers of aluminum may be deposited per silicon wafer. After the last layer is deposited, a passivation layer of glass is deposited over the entire surface of the wafer for protection. Finally, the areas of the passivation that cover the areas used for bonding wires to the deposited must be etched away via acid or gas, allowing external electrical connection to the microcircuit.

Inspection/Test

After fabrication is complete, each die is cut away from the silicon wafer with a diamond saw, is packaged, and extensive testing and quality control commences. The quality control equipment usually consists of several types, including:

- CV Plotter, plots voltage-current characteristic between two pins on the die
- Inspection Microscope
- Scanning Electron Microscope
- Probers, used for injecting input signals and detecting output signals directly to and from the bonding pads on the die

Passing semiconductor devices are sold directly to the consumer, while failing devices are usually sent to a failure analysis department, who in turn try to detect systematic defects in the assembly line procedure.

3.1.2 Semiconductor Manufacturing in Space

In the following section, we will address some of the issues concerning semiconductor manufacturing specifically regarding the feasibility of doing so in space. The issues concerning equipment and manufacturing procedures specified in the previous section remain, but the following will pertain to adapting that general manufacturing procedure for a microgravity application.

Gallium Arsenide vs. Silicon[46]

Before we discuss the particular circumstances and challenges that a semiconductor facility in microgravity presents, we must first determine the semiconductor material we are interested in fabricating in space. There are two major candidates for the semiconductor of choice; the first is silicon, comprising about 95% of the current semiconductor market, and the second, gallium arsenide (GaAs), with a market share of the remaining 5%. Gallium arsenide is a very specialized semiconductor material boasting several major advantages over silicon: GaAs components in integrated circuits are faster than equivalent components fabricated in silicon; reduced parasitic (stray) capacitance in GaAs chips, again contributing to GaAs's speed advantage; the ability to make equivalent devices' die sizes smaller with GaAs, and finally, the ability to emit light, useful for making lasers, diodes, and other light-sensitive components. However, gallium arsenide semiconductor components have been unable to overtake silicon components in the market due to several disadvantages, namely: Gallium arsenide is rarer and more difficult to obtain than silicon (which is plentiful in the Earth's crust); Arsenic is very toxic, hindering widespread use of GaAs components; oxidation of GaAs does not result in an ideal insulator as with silicon (silicon dioxide, used in the manufacturing process as a mask), substantially complicating the manufacturing process, and finally, the conducting metal deposited on a GaAs microcircuit must be gold, which is much rarer and harder to obtain than aluminum, the conducting metal used in silicon integrated circuits.

Due to the complications inherent in gallium arsenide circuits, we will perform our semiconductor manufacturing analysis based on silicon integrated circuits. Although gallium arsenide integrated circuits have the potential for a higher rate of return on investment, they also require more complicated infrastructure and facilities. As such, we decided to stay with silicon, whose manufacturing process is (relatively) much simpler. If we perform our analysis with silicon, we will be able to determine the feasibility of a lower-risk, lower-reward orbital silicon semiconductor facility. If this analysis proves exceptionally beneficial in terms of rate of return, we will then further extrapolate our analysis for a higher-risk, higher-return gallium arsenide manufacturing process.

Equipment

Based on the processing steps outlined in the previous semiconductor manufacturing section as well as the analysis performed by the ENSC 100 group at the School of Engineering Science at Simon Fraser University[47], we have concluded that our semiconductor manufacturing facility will require the following equipment:

Lithography
- Wafer Stepper System
- Photoresist Coater
- Developer
- Bake Oven
- Photoresist Stripper
- Linewidth Measurement Equipment

Oxidation
- Solar Furnace

Ion Implantation
- Ion Implanter
- Thermal Annealer

Metal Deposition
- Sputtering System
- Residual Gas Analyzer

Etching
- Polysilicon/Nitride Dry Etcher
- Oxide Dry Etcher
- Metal Dry Etcher

Inspection Equipment
- CV Plotter
- Ellipsometer
- Spreading Resistance Probe
- Four-Point Probe
- Junction Sectioner
- Surface Profiler
- Inspection Microscope
- Scanning Electron Microscope
- Probers

During the lithography stage, the photoresist coater is used to coat the surface of a wafer with photoresist (PR). This PR is hardened in the bake oven, masked, and is exposed to light with the Wafer

Stepper System to polymerize the unmasked areas of the PR. The wafer is then passed through the Developer, which removes the exposed PR, preparing the wafer for plasma etching. After etching, the PR is completely removed with the photoresist stripper, and the linewidth measurement equipment is used to analyze the accuracy of the masked pattern.

Oxidation, which requires temperatures exceeding 1100°C, would have to take place in a solar furnace. This furnace could be powered by electricity generated from a large solar array, the details of which are discussed later.

The ion implantation stage involves two pieces of equipment; the ion implanter, used for introducing the N and P type dopants into the silicon wafer, and the annealer, which repairs damage done by the ion implanter by subjecting the wafer to temperatures of above 1000°C to allow chemical bonds in the silicon wafer to reform with the dopants.

A chemical vapor deposition process known as sputtering is used to deposit metal. The sputtering system uses a vacuum to deposit metal layers on the surface of a silicon wafer by "sputtering" charged metal particles in a reactive gas mixture at the wafer. The metal particles are accumulated on the surface of the wafer. The residual gas analyzer is a small mass spectrometer is used for process control and contamination monitoring in the sputtering system[48].

The etching process, or the removal of layers from the surface of a wafer, is performed on uncovered areas of a silicon wafer after it has been masked out by photolithography. In space, plasma etchers will be used rather than ordinary acid etching equipment (used in semiconductor facilities on Earth) due to the decreased weight of the etching chemicals (gases in plasma etchers vs. acids—liquids—in acid etching). The three types of etchers will be used for the various surfaces that will need etching—polysilicon & silicon nitride, silicon dioxide, and metal.

Finally, the inspection and test equipment is used for quality control of the processed wafers. This equipment is responsible for analysis of certain aspects of the wafers, including capacitance-voltage curves, thickness of deposited films, resistivity of certain regions, inspecting the surfaces of wafers for defects, etc. This ensures control of systematic defects that would otherwise wreak havoc on mass-production of processed silicon wafers in our facility.

The analysis done by the ENSC 100 group operates under the assumption that one device is required per facility. We are operating under a different assumption—that more than one of each piece of equipment will be in our facility. A detailed table of sample equipment costs is outlined in Appendix A: Semiconductor Facility Costs. With the exception of extremely specialized/hard-to-obtain equipment like the scanning electron microscope, etching equipment, and the solar furnace, we are assuming that we will want to have five of each equipment unit. The SEM will probably only be used for very specific device failure analysis and quality control, so we limit our factory to only two SEMs. We will also limit the plasma etchers to two of each, as each type of etcher is designed to remove only one type of material from the wafer. In the case of the solar furnace, the construction cost was estimated at around $1.5M by the ENSC 100 group, discouraging the implementation of more than one, and the furnace chamber would be spacious enough to accommodate many more wafers than the standard chamber sizes of the other equipment units. The cost analysis shows total equipment cost at around $20M, while the launch cost (at $4729 per pound)[49] is much higher, at about $1B. Additionally, the energy costs for constructing a large orbiting semiconductor manufacturing facility are staggering. Based on Appendix A, and a very enthusiastic citation of future solar cell installation efficiency at $3 per watt[50], the cost for installing these solar cells would be about $1.6M. Hence, the total startup cost of a relatively small orbital semiconductor manufacturing facility is around $1.055B, including equipment, launch, and energy costs.

Raw Materials

The raw material required for a semiconductor manufacturing facility is primarily comprised of intrinsic polycrystalline silicon. To take full advantage of the benefits that a microgravity environment has to offer, the single-crystalline silicon ingot must be grown while in space. Doing so allows a much better overall crystalline structure which will be of higher quality than an equivalent silicon crystal grown on Earth.[51]

Therefore, to do this, the silicon could be transported from Earth, and could then be molten and grown on the orbiting facility to then be processed into silicon wafers. However, the earth-to-orbit launch cost per pound is still very high, cited as $4,729 per pound on the Space Shuttle, by Futron Corporation[52]. Alternatively, silicon could be harvested from the lunar regolith, the soil that covers the surface of Earth's moon. The lunar regolith has been determined to be about 20% Si[53]. Figure 8 details the potential elements and compounds that can be extracted from lunar regolith.

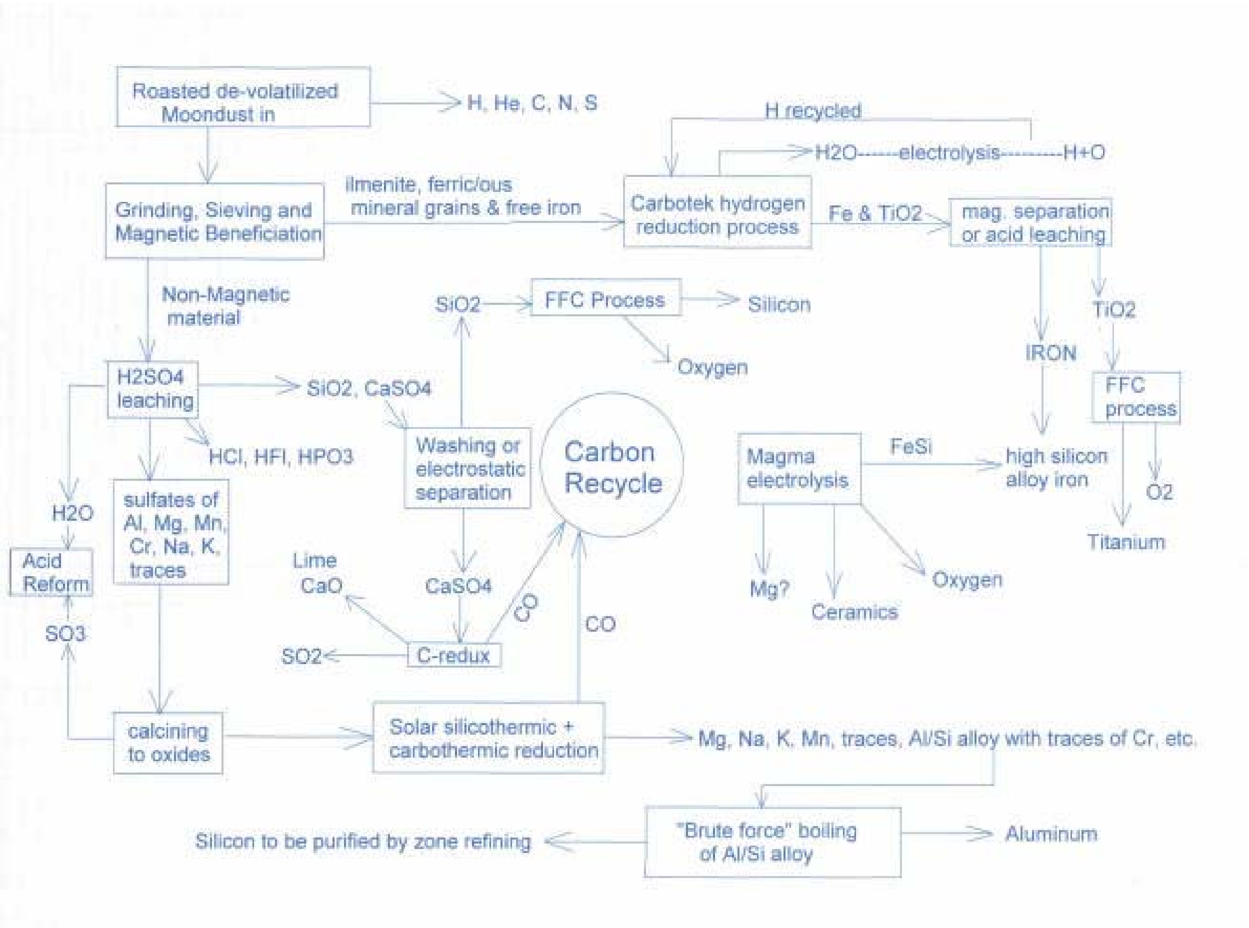

Figure 8. Lunar Regolith Processing Chart[54].

Starting in the top left hand corner of the chart, it is conceivable that via H_2SO_4 leaching, and through washing or electrostatic separation, silicon dioxide can be extracted from lunar regolith. With this silicon dioxide, pure silicon can be obtained through the FFC Cambridge process, a process for the extraction of a multitude of metals, semimetals, and nonmetals from their solid oxides with molten salt electrolysis[55]. These steps are fairly simple and can conceivably be done on a fairly large scale without an exceptionally high cost. However, extraction of silicon and other elements from lunar regolith has never before been attempted on a large scale. In addition, it is unlikely that the transportation infrastructure between an Earth-orbiting facility and Earth's moon will be in place, allowing for rapid transport of silicon-containing lunar regolith, within the next 20 years. Therefore, it is more probable that silicon will be more easily transported in elemental form or in its oxide (silicon dioxide; sand) from the Earth, than via extraction of lunar regolith and transportation from the moon.

Besides silicon used for the production of silicon wafers in space, the production of these wafers into semiconductor devices in space is dependent on the additional materials needed for processing. These include the deposited metal (in a silicon process, usually aluminum); a source of oxygen (used for oxidation of silicon to SiO_2, for gate and field oxide construction, and for passivation); various gases, used for diffusion implantation or plasma etching; and various chemicals, including photoresist, the light-sensitive chemical used for masking away certain areas of the silicon wafer. These materials will most likely need to be transported from Earth, as with the polycrystalline silicon wafers.

In general, most of the raw materials needed for semiconductor manufacturing, and for microgravity-based mass-production in general, will have to be transported from the Earth's surface. There simply is not enough of a transportation infrastructure in place for heavy transport to and from the lunar surface, and it is unforeseeable that such a system will be in place within the next 20 years.

Facility Construction

The average cost of a semiconductor manufacturing facility on Earth, such as the new Texas Instruments plant in Richardson, Texas, has been cited at about \$300M[56] without equipment costs. However, an equivalent facility in orbit will likely cost much more; the ISS Columbus cylindrical laboratory module was cited at €880M, or about \$1.15B[57]. The Columbus module was designed by the European Space Agency to carry out an array of experiments in space by implementing several laboratories within the module, including the Fluid Science Laboratory, the Biolab, and the European Physiology Modules.

Our semiconductor manufacturing facility will likely cost at least 10 times more, as much more space will be required for the equipment. The Columbus experimental module has a surface area of 112.7m^2 with a length of 6.871m and a diameter of 4.487m[58]. As a rough estimate, we can expect that, if our facility were constructed as a large module capable of docking to the ISS, that the length would be at least 5 times that of the Columbus module, due to the number of pieces of equipment. The diameter of the module would have to be the same to ensure compatibility with the ISS dock. By doing so, the surface area (and therefore the construction cost) increases by about 387.4m^2, or a factor of about 3.44. By this simple calculation, the cost of the facility sans equipment would be approximately 3.44*1.15B = 3.95B. This of course assumes comparable technological systems present in the module, enabling us to extrapolate information about the Columbus module to our semiconductor facility.

3.1.3 Numerical Analysis

To enable us to accurately grasp the financial feasibility of an endeavor such as building an orbital semiconductor processing facility, we must examine the initial and ongoing costs of construction and raw materials. In addition, we must compare the orbital semiconductor facility with an average semiconductor process here on Earth to determine if one has a distinct systematic advantage over the other.

Our initial investment would consist primarily of the module construction, module launch, equipment, equipment launch, and energy. The module construction cost was discussed in the previous section, and was determined to be approximately $3.95B for a module for our needs. Using the $4,729/lb. figure for price per pound into low-earth orbit Shuttle launches provided by Futron Corporation[59] and extrapolating the mass of the Columbus module (12,800kg), our module would have a mass of 12,800kg*3.44 = 44,032kg, whose launch cost would be $458.1M. The equipment (see Appendix A) would have a total cost of $19.646M, whose launch cost would come out to be $1.034B.

The energy cost has not yet been addressed. The most abundant and by far the easiest source of energy to capture is presented by the Sun. Ideally, a vast array of solar cells and storage batteries will satisfy all of the energy requirements of the module, estimated to be upwards of 550kW (see Appendix A). If we analyze the total power requirements of the equipment and ignore the other power requirements of the module (including life support, lighting, etc.), we can determine a one-time cost for solar cells. The Department of Energy recently released a publication[60] about a next-generation solar cell boasting 40.7% efficiency, enabling future systems to potentially have an installation cost of $3/watt. Using this figure, we can estimate that the energy requirements of the equipment alone will be about $1.6B (see Appendix A). Totaling these amounts, we see that our initial costs have an absolute minimum of $5.464B.

Our ongoing costs will consist of raw materials, equipment maintenance costs, and worker salaries. Our raw material cost is further broken down into chemicals and raw silicon. The chemicals consist of processing chemicals, such as photoresist, acetone, acids, dopants, etching gases, etc. The silicon cost consists of the solid or molten polycrystalline silicon that is launched into space to grow the single-crystalline silicon required in wafer production.

While the initial costs of constructing this facility may be high, we must determine whether the benefits realized by manufacturing in microgravity outweigh the risks of such a large initial investment. To do this, we will compare a typical semiconductor fabrication plant on Earth to our facility in orbit, in terms of efficiency, volume, and final cost per good device.

Production Yield

First of all, it is a fact of the semiconductor manufacturing process that Earth-grown silicon wafers exhibit a number of point defects[61] that affects the overall yield of the wafer. For instance, a given 20mm wafer may contain a certain number of these defects, as seen in Figure 9:

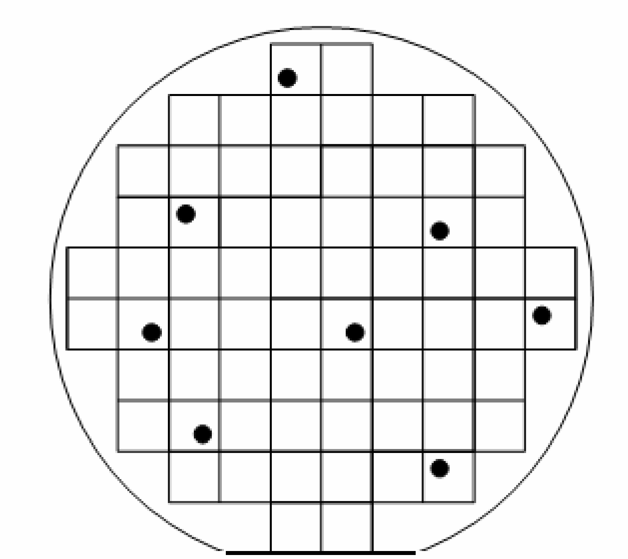

Figure 9. Point Defects Randomly Distributed Over Wafer; N = 68[62].

In the above figure, eight localized point defects are randomly located on the wafer. Continuing with the example, after dividing up the wafer into a total of 68 die regions, eight of the resulting dies will be defective, resulting in a decreased yield. We will deem the proportion of good dies per wafer due to lack of localized point defects as **Y1**. (For instance, in the above example, Y1 = 60/68 = 0.88.)

In general, Y1 is determined by the overall die area. If the die area is larger, there will be fewer die per wafer while keeping the total number of defective die the same. For example, in Figure 10:

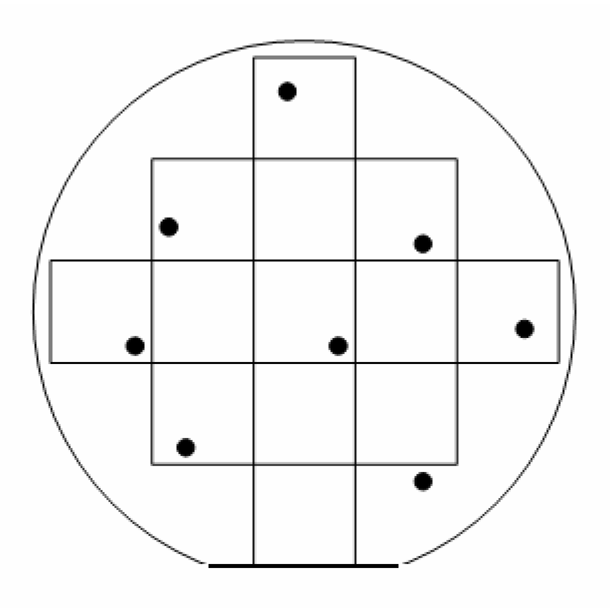

Figure 10. Point Defects Randomly Distributed Over Wafer; N = 13[63].

Here, there are a total of 13 die per wafer due to increased die area. However, 7 of these 13 die will end up being defective due to the presence of the same localized silicon defects.

The relationship between die size and yield Y1 on Earth-grown silicon can be summarized in Figure 11:

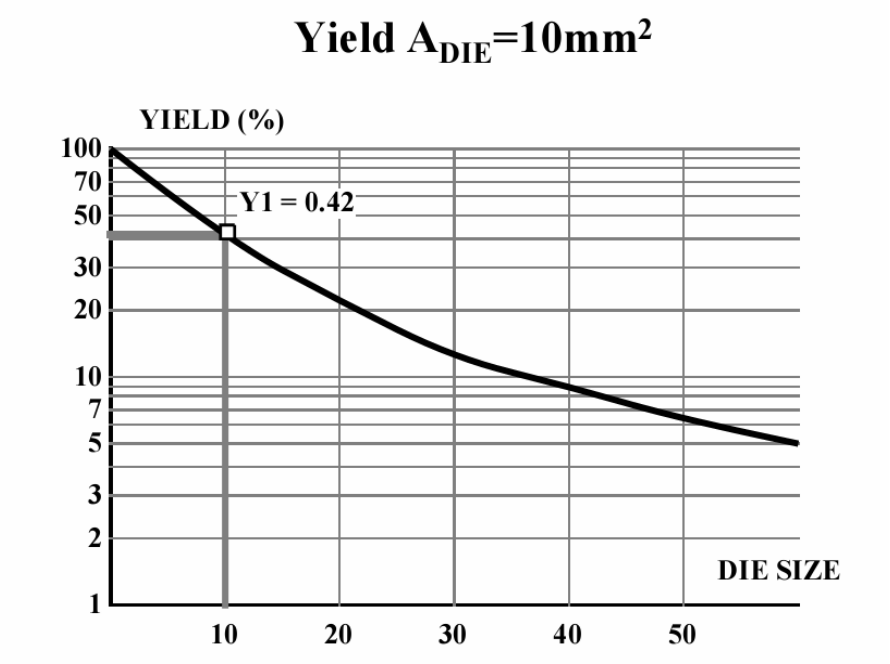

Figure 11. Y1 vs. Die Size[64].

For the purposes of this numerical analysis, we will assume that we are working with a typical die size of about A_{DIE} = 10mm^2, for which **$Y1_E$ = 0.42**.

For our microgravity facility, we will assume for simplicity that single-crystalline silicon ingots grown in space are of such high quality that they exhibit zero point defects per wafer. That is, that **$Y1_S$ = 1.00**. This is of course a very optimistic and highly unrealistic assumption, but it will serve to simplify the analysis. As a result, it follows from our assumption that efficiency of the utilized silicon increases by a factor of 1.00/0.42 = **2.38** in a microgravity environment.

Packaging

The cost of packaging is usually a fixed cost per die. For our example, which is detailed in IC Economics by McNeill, we will say that the fixed cost to package one die, or **C_P**, is **$1.70**. Additionally, there is a second yield loss due to imperfections in the packaging process, known as **Y2**, which is about **0.95** on Earth. We will assume that both these values (C_P and Y2) remain the same between Earth and microgravity environments, since the major benefit from a microgravity environment is in the growth of the silicon ingot.

Other Terms

The other terms that will be used in this analysis are described below:

- **C_W = $4000** (semi-arbitrary wafer cost). Here, we will assume we are using **20cm** diameter wafers. For simplicity, we will assume that wafers grown in space are identical in cost to wafers grown on Earth.
- **N = 3141.5** (gross die per wafer) = $\pi(10\text{cm})^2/A_{DIE}$ = $31415\text{mm}^2/10\text{mm}^2$. The total number of die that can be produced from a single wafer.

A review of terms already covered:

- **$Y1_E$ = 0.42** (Terrestrial yield loss due to silicon point defects)
- **$Y1_S$ = 1.00** (space-bound yield loss due to silicon point defects, i.e. 0% loss)
- **C_P = $1.70** (universal semi-arbitrary fixed packaging cost per die)
- **Y2 = 0.95** (universal semi-arbitrary yield loss due to packaging imperfections)

Process

For simplicity, we will assume that the manufacturing and packaging process proceeds as follows:

- Wafer costing **$$C_W$** is divided up into **N** dies
- **N** dies suffer a yield loss of **Y1** due to silicon point defects
- **N * Y1** dies are packaged at a packaging cost of **C_P** per die
- **N * Y1 * Y2** dies pass through the packaging stage and pass quality control

Therefore, the cost per good packaged chip is defined as

$$C = \frac{C_W + N \cdot Y1 \cdot C_P}{N \cdot Y1 \cdot Y2}$$

Where C_W + N*Y1*C_P is the cost of the wafer and cost of packaging N*Y1 dies, and N*Y1*Y2 is the overall number of packaged chips that pass quality control.

Cost Analysis: Earth vs. Space

On Earth, the cost per good packaged chip:

$$C_E = \frac{4000 + 3141.5 \cdot 0.42 \cdot 1.70}{3141.5 \cdot 0.42 \cdot 0.95} = \$4.98 \text{ per good packaged chip.}$$

In space, the cost per good packaged chip:

$$C_S = \frac{4000 + 3141.5 \cdot 1.00 \cdot 1.70}{3141.5 \cdot 1.00 \cdot 0.95} = \$3.11 \text{ per good packaged chip.}$$

It certainly appears that it is *cheaper* to manufacture semiconductor chips in a microgravity environment, as the increase in Y1 from 0.42 to 1.00 decreases the cost of the chip considerably.

Volume Analysis

The above cost per chip analysis does not take into account the volume of devices produced on Earth vs. in microgravity. The weekly volume analysis performed by the ENSC 100 group at Simon Fraser University[65] on their semiconductor facility in space yielded a rough estimate of 15 cassettes of 25 wafers each, per week. This figure was obtained by examining the bottlenecking stages of the semiconductor process, which were determined to be the Developer/Photoresist stages, for which the time to process one cassette through these stages was approximately 11 hours. Therefore, the theoretical maximum yield per week was determined to be 7*24/11, or about 15 cassettes per week, if processing continued 24 hours per day, 7 days per week. Our orbital semiconductor fab has five of these Developer/Photoresist equipment sets, allowing a theoretical limit of 75 cassettes of 25 wafers per week (**V_S = 1,875** wafers per week). Additionally, the group found that the average throughput of a semiconductor fab in 1996 was 40 cassettes of 25 wafers per week. Today, ten years later, a medium-sized silicon fab is capable of processing about **V_E = 4,750** wafers per week[66]. It is obvious that while a space-bound silicon fab is capable of making each chip for less, that terrestrial facilities definitely have a much higher weekly volume of processed wafers. So, which one is preferable over the other?

We took the cost per good chip analysis as well as the volume analysis of the terrestrial and orbital silicon fabs and performed a weekly profit analysis with respect to sale price. The weekly profit is given by: (Wafers per week)(Gross die per wafer)(Yield loss 1)(Yield loss 2)(Sale price – Cost per good die), or:

Terrestrial profit per week = $V_E N Y_{1E} Y_2(P - C_E)$

Orbital profit per week = $V_S N Y_{1S} Y_2(P - C_S)$

Plotting the profit versus sale price in Figure 12, we have:

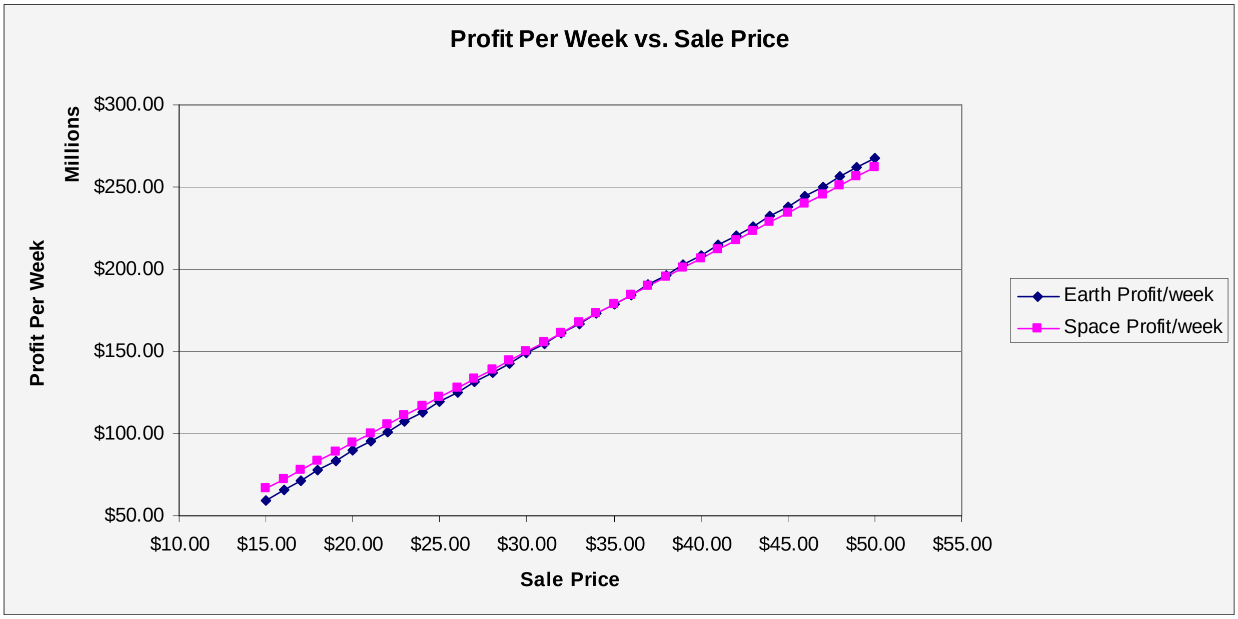

Figure 12. Weekly Profit Analysis, Earth vs. Space.

While it does seem that at a lower sale price, a space-bound semiconductor fab will make a higher weekly profit, and that at a higher sale price, a terrestrial semiconductor fab will make a higher weekly profit, the difference is more or less negligible. The fact is that, in space, the benefit of the high yield counteracts the relatively low production volume; whereas on Earth, an overall increased production volume counteracts the yield losses inherent in the process. Ideally, we would like to have both a high yield (low losses) and a high production volume, which would result in substantially higher profits.

However, in pursuit of such a solution, we would have to take into account the immense startup costs. In fact, there are a slew of uninvestigated costs associated with any space manufacturing application. For instance, this analysis does not take into account the transit cost of the raw materials and finished products to and from the orbital module, manpower and associated requirements, including food, housing, life support, etc., and equipment and module maintenance costs, etc.

Concluding Thoughts

In conclusion, it seems from the profit analysis that an orbital fab does not produce a substantially larger return than a terrestrial approach, and as such, a comparison of startup costs for both situations immediately reveals that the time required to reach the break-even point is much farther away in the orbital case.

Thus, it appears that the extra time and effort invested in an orbital manufacturing facility does not provide any substantial reward above and beyond that presented in a terrestrial fab. Given the above financial analysis, we find it highly unlikely that any endeavor in the area of orbital manufacturing would be undertaken in the foreseeable future.

3.2 Tourism

The concept of space travel being available to the public has been a popular fantasy since the first successful launches into space. In fact, pop culture seems to regard space tourism as an all-but-inevitable step in successful space exploration. Nearly every popular piece of popular science fiction, from *2001* to *Star Trek*, is built upon the foundation that space travel is both open to the public and fairly commonplace. There is clearly a market desire for a space tourism industry.

With that said, many factors need to be taken into account to determine whether or not there is any profit in space tourism in the near future. Current costs for a two-week stay in space run approximately $20 million. Even then, trips are booked years in advance and customers spend months in preparation.[67] Even at such high costs, it does not necessarily mean that any net profit is made by the space program for such endeavors, as the entire effort could be intended simply to invest public interest in space projects. After establishing that there is in fact profit in space tourism in the near-future market economy, the International Space Station’s role in this market would still need to be established. After all, the ISS is only intended for 6 passengers, so what part, if any, would it play in any viable, long-term space tourism market?

During the era of the space race, both Russia and America developed a great national interest in the issue of space tourism. Famous authors, such as Arthur C Clarke and Joanna Russ, fueled public interest with a flood of new science fiction novels that almost unilaterally involved some form of notable human presence in space. The Soviet space program was particularly determined to broaden its pool of cosmonauts and adamantly sought out a wide range of people for their cosmonaut program. It was during this effort that the first female cosmonaut, Valentina Tereshkova, was brought into the Soviet space program. It is still the opinion of many people that Tereshkova was not as qualified as other cosmonauts but was given the position to increase public interest in the space program. In some circles, she is even consider the first actual “space tourist.”[68] The Soviet space program also adamantly sought out potential cosmonauts from the Warsaw pact, the USSR, and eventually non-aligned countries. Unfortunately, as the space race dwindled and moon landings were achieved, the need for space exploration decreased dramatically.[69]

It wasn’t until about a decade later that space tourism began to take a real public interest. NASA began to allow payload specialist positions on shuttle flights, which allowed corporate representative and political supporters a chance at space travel. Payload specialists are typically members of a space mission that have special knowledge pertaining to something onboard the shuttle or station, such as a particular experiment or piece of technology. The significance of the inclusion of payload specialists on missions was that these specialists were not selected by NASA. Instead, corporations with a vested interest in a particular mission would choose a representative to handle the project while it was in space. While these representatives still needed to meet strict physical requirements, they were not part of the Astronaut Candidate Program.[70] As a result of the inclusion of payload specialists, passengers not directly affiliated with any space program began to routinely assist with in-space missions.[71]

More recently, the space program has begun to take its first private financiers into space. At the current time, only the Russian space program actively takes tourists into space. Russian officials select candidates from a list of applicants and a tourist is required to pay $20 million and train for months before being allowed to go up into space and stay on the ISS.[72] NASA initially objected to the Russians’ use of the ISS for tourism. They argued that bringing a relatively inexperienced person aboard a shuttle and the station could put the mission and its members at unnecessary risk. However, after reassurances of proper levels of training and safety by the Russians, NASA gave up its argument.

In April of 2001, Dennis Tito becomes the first ever space traveler to pay completely by his own means. His flight was made possible by the company Space Adventures, which acted as a go-between and coordinated with the Russian space program. After he went through the proper training and testing, Tito went aboard a Soyuz spacecraft and stayed in space for the duration of 10 days.[73] One year later, in April 2002, Mark Shuttleworth, a 27 year-old internet millionaire from South Africa also traveled to the ISS with the help of Space Adventure’s collaboration with the Russian space program.[74]

In 2003, officials of the Russian space program again expressed their interest in bringing tourists into space, stating that they intended to bring two individuals into space in the 2004-2005 timeframe. The company Space Adventures was hired to find people who were willing to pay the $20 million as Tito had to take a 10-day trip into space. The planning took longer than expected, but eventually Gregory Olsen, traveled into space in 2005 followed by Anousheh Ansari in 2006. Anousheh Ansari officially became the first ever female traveler to purchase a trip into space.[75]

More tourists are expected to make their way into space in the coming years. The most recent candidate was software engineer Charles Simonyi, who was slated to launch into space in April of 2007. Clearly, there is a public interest in space tourism. However, factors such as cost and time need to be examined to determine if larger-scale space tourism is a feasible step in the near future.

There have been several overly-optimistic predictions over the last two decades in regards to when private-sector space tourism would occur. Such predictions have often been made by pro-space parties such as NASA which suggests an inherent bias. Recent studies by third parties such as Zogby and Futron offer a more neutral analysis of the current situation of the space tourism market. Also, with the emergence of several corporations, such as Virgin Galactic and Space Adventures, with a vested interest in space tourism, it seems logical that an attempt at a more commercialized approach at space tourism might soon be underway.

Perhaps one of the more promising endeavors is the upcoming launch of Virgin Galactic's SpaceShipTwo. The shuttle is designed by aerospace designer Burt Rutan. Rutan and his team have prior experience in the field, having already designed and piloted SpaceShipOne for three suborbital flights in 2004 and as a result winning the $10 million Ansari prize. Parts of several SpaceShipTwos are already in production in Scaled Composites in Mojave, California.[76] Current estimates say that the SpaceShipTwo's maiden voyage will likely occur in 2008 or 2009.[77]

While it seems as though commercial space tourism will occur sooner rather or later, it has not yet been determined whether or not the market is a sustainable one at this time. While public interest exists, the cost of such voyages into space will severely restrict the number of clientele. Also, long-term space voyages require some sort of station in orbit, and previous station construction has been both costly and time-consuming.

Thus far, there has currently been only one remotely viable method for space tourism pioneers to get into space. Wealthy individuals could pay a sum of $20 million to the Russian Space Agency be brought to the ISS for a 10-14 days stay via the Russian Soyuz shuttle.[78] Even at such a high price, transportation through the RSA was completely booked through 2009. This would imply that the current supply in the market outweighs consumer demand for the cost of $20 million a voyage. Even still, for such a stay in space the cost is likely to be higher for a strictly commercial venture in space tourism. RSA officials have admitted that even $20 million per tourist still did not cover all the costs associated with such missions. Government funds were therefore needed to pay for the rocket booster and other expenses.[79]

Even so, initial endeavors in the private sector of space tourism show some promise. Virgin Galactic is likely to become one of the first companies to launch their first passenger-carrying spacecraft in 2008 for $200,000 a seat. They have already booked enough passengers to fill several flights' worth of seats aboard their suboribital flier, the SpaceShipTwo. Other companies such as Space Adventures Ltd. and Bigelow Aerospace are the forerunners in circumlunar trips and commercial space launches, respectively.

Still, with costs running from $200,000 (per flight on Virgin Galactic's SpaceShipTwo) to an estimated $100,000,000 (Space Adventures Ltd. circumlunar missions), the consumer pool for such space endeavors will be quite limited.[80] The Zogby/Futron 2002 Report determined that, according to the financial status of previous space tourists and the data collected during their survey regarding current spending patterns for vacations, ticket prices should be no more than 10 percent of a person's net worth. Therefore, the potential consumer base for space-related endeavors varies between people with a net worth of $2 million and $1 billion. The survey put other limiting factors on the client base, such as health, interest and the fact that the novelty of space travel will wear off as it becomes more mainstream.

It would also appear that the Virgin Galactic's cost-per-ticket of $200,000 would unlikely cover the cost of the launch. According to a study by Futron, *Space Transportation Costs: Trends in Price per Pound to Orbit*, the average costs of price-per-pound of getting an object into low earth orbit varies approximately from $2,000 to $8,500.[81] Assuming conservatively that the SpaceShuttleTwo operates near $2,000 per pound to launch into LEO and that the average passenger is 200 lbs, the actual cost per passenger would be around $400,000. Granted, SpaceShipTwo may use a more efficient means of transportation. Even so, the difference in cost necessary to turn a profit on such launches would be a near 1:2 ratio.

Despite the incredible cost barrier to overcome, recent projections seem optimistic. The Zogby/Futron 2002 Report anticipates that the current cost of $20 million for a 2-week trip into space should be cut in half by the year 2012. Assuming that the private sector continues to grow, and that the government-run facilities continue to maintain their current level of operation, the report suggests that there is potential for over 60 passengers and 26 flights for long-stay orbital missions annually. The projected estimates in revenue within the US market alone could be as high as $300 million by 2012. The market for suborbital flights will be even larger.[82] While this is clearly promising news, it does imply that space tourism is a very sound long-term investment. Compared to the billions invested in space each year, an optimistic estimate of return of $300 million might not be the most profitable market for many corporations to invest in.

At the current moment, the ISS meets the demand for space tourism because other issues such as limited transportation and high costs restrict the number of space tourists. In fact, they are so great an issue that as of 2006, only 4 tourists have been aboard ISS for a prolonged stay. However, with the private sector beginning to take shape and the projected decrease in costs, it is likely that the number of tourists in space will grow relatively quickly. At most, the ISS is designed to handle 6 passengers. Even if one were to assume that the ISS served primarily as a tourist attraction, it could only hold 4 tourists and 2 crew members on board at any given time. It should also be noted that with 4 tourists onboard, the tourists would essentially be paying $80 million every two weeks for the trip, or in other words about $40 million weekly. That'd gross about $2.1 billion annually. In perspective, ISS-related costs will be approximately $19 billion for Shuttle flights from 2006 until 201, which is well over $2.1 billion a year. Add to that the actually budget allocated to the ISS itself (which also runs into the billions annually), and it is clear that tourism alone cannot support the ISS. Therefore, while it may be a viable stopgap to house tourists, it is by no means a viable long-term solution to the issue of space tourism. Eventually, if the space tourism market bears fruit, corporations will create "space hotels" to house tourists during their space voyages. At this point, the ISS will no longer be a necessary part of space tourism.

That said, the ISS has clearly contributed to the progression of space tourism. It provided the space tourism market with a decent launch point from which commercialized space tourism companies can begin to work with a relatively low risk. Rather than needing to build a station in orbit, they have been able to use the ISS to begin putting tourists into space by working with the Russian space agency. This has and will continue to help businesses determine if a larger space tourism market is worthwhile while only investing a marginal amount of the money and effort they would have needed to build their own station. In that regard, the ISS is perhaps a vital part of the short-term plan for space tourism, but it is unlikely that it will serve a purpose in the long-term for commercial space tourism and just as unlikely that it will ever turn a profit from tourism endeavors.

3.3 Research

By definition, research is not as immediately profitable an option as is the prospect of mass-production in a microgravity environment, or space tourism. However, the ability to cultivate knowledge in a low gravity environment is likely to yield future dividends, the scope of which is difficult to predict at this time. To gain some insight as to the profitability present in space research, we will examine the issue of protein crystallography in a microgravity environment.

The crystallization of organic protein macromolecules is a very important area of research in medicine and science today. The information that the growth of these crystals reveals about the inherent 3-dimensional structure of the protein can lead to major scientific breakthroughs with regard to manipulating these proteins to our benefit. This information is obtained by X-ray diffraction, an analysis technique used to determine the crystalline structure of a protein.

However, successful growth of these protein crystals is limited on Earth, primarily by the presence of gravity and its adverse effects on crystallization. Primarily, these protein crystals are grown by creating a supersaturated liquid solution of the protein, and slowly evaporating away the water. One of the main problems plaguing the growth of these crystals is the presence of sedimentation. Sedimentation is the process by which crystallized material forming at the top of the solution cannot be supported in suspension by the uncrystallized liquid, and sinks to the bottom. This motion causes partially formed crystals to grow into each other, disturbing the crystal structure, making X-ray diffraction analysis futile. The other major problem concerning protein crystallization in Earth's gravitational environment is the presence of convection currents in a crystallizing solution. These currents form as a result of the increasing density of a crystallizing lattice in solution. As the crystal grows in size, the liquid surrounding the crystal becomes less concentrated than the crystal itself. This liquid tends to rise to the top, creating convection currents of moving solution that travel upwards, next to the crystal. These currents have an adverse effect on the resulting crystal, as they can affect the position and orientation of the individual proteins in the crystal. This causes imperfections in the crystal lattice, and reduces the detail level in a resulting X-ray diffraction analysis.

Thus, interest began for growing crystals in a microgravity environment, where crystals are subject to reduced sedimentation and convection currents. On the ISS, which orbits 360km above the Earth's surface, the acceleration due to gravity is about 4μg, [83] where 1g is equivalent to the gravitational acceleration on Earth—9.8m/s^2. In microgravity, crystallization would happen primarily by diffusion. By growing higher-quality crystals, there is hope that scientists will be able to better understand the functionality of certain protein crystals and take advantage of them by modifying their environments in order to produce specific outcomes.

Thus far, there have been many protein crystals that have been grown in a microgravity environment in an attempt to enhance the properties and uses of each, and as such, examining each in great detail would be fairly repetitive, and it would be unlikely to result in different conclusions. Therefore, it makes logical sense to take the seemingly most promising protein crystal, investigate a "best-case" scenario, and draw conclusions about other, less promising protein crystal research in microgravity. The following list of protein crystals which have already been synthesized in microgravity and studied is available from the Committee on Science and Technology, from the U.S. House of Representatives website[84]:

- **Gamma-interferon**, which is important in anti-viral research and for treatment of certain types of cancer
- **Alpha-interferon**, used against chronic hepatitis B and C, hairy cell leukemia, Karposi's sarcoma, multiple myeloma, and melanoma
- **Factor D**, a protein important in heart disease, stroke and complications associated with cardiovascular surgery
- **Insulin**, a protein important in, and used as, a drug for diabetes mellitus
- **Elastase**, a key protein known to cause the destruction of lung tissue in patients suffering from emphysema

- **Malic enzyme**, a protein important in the development of antiparasitic drugs
- **Isocitrate lyase**, a protein important for the development of anti-fungal agents
- **Human serum albumin**, the most abundant protein in our blood, responsible for the distribution of many different drugs (even aspirin) to various tissues in our body
- **Canavalin**, a protein isolated from edible plants -- its structure is of interest because the information can be used to genetically engineer more nutritious plants.
- **Proline isomerase**, a protein important in tissue rejection

Examining the list, many of the protein crystals listed above deal with very specific conditions that affect only a small proportion of the population, and the population aware of these conditions is an even smaller proportion. Insulin, however, represents the very protein responsible and also the very drug for an increasingly common condition in the United States. An article published on CNN[85] states that there has been a sudden spike in cases of type 2 diabetes stemming from a combination of lack of physical exercise and unhealthy eating habits, and hence, public awareness of this condition is very high. Thus, it can be conjectured that research to find a "cure" or at least a more effective treatment of diabetes would have the most public and private attention and support, and therefore, insulin research would be the most promising. Hence, we will investigate only this most promising avenue of protein crystallography research in a microgravity environment: that of growing a longer-lasting insulin formulation for use in diabetic patients, reducing the need to produce as much insulin on Earth. But first, we will examine the disease behind the need for insulin research: diabetes mellitus.

Diabetes mellitus is a disease involving the inability of the human body to process glucose from food intake. In a healthy human being, this process is controlled by a polypeptide hormone, insulin, which regulates carbohydrate metabolism. In a person suffering from diabetes, this metabolism is blocked or limited in some fashion, and the non-metabolized glucose thus remains in the bloodstream, causing hyperglycemia (excess sugar in the blood). Hyperglycemia in turn causes the symptoms used to diagnose diabetes, including glycosuria and polyuria—the excretion of glucose in the urine, leading to excretion of large amounts of urine and dehydration. In addition, glucose cannot enter the hypothalamus (which controls appetite and hunger), causing the diabetic patient to eat incessantly, even though this hunger will never subside due to the body's inability to process glucose. Further complications can include several life-threatening ailments, including eye damage, kidney damage, and atherosclerosis (hardening of the arteries).[86]

There are two types of diabetes mellitus, commonly referred to as Type I (juvenile-onset) and Type II (adult-onset) diabetes. Type I diabetes is the less common, and more serious disease, involving the body's own inability to produce enough insulin in the pancreas. Type I diabetes must be treated with regular insulin injections for survival. Type II diabetes is the more common disease, where the body produces insulin normally, but the body's tissues do not respond to insulin, and very little glucose is metabolized. This may be due to the presence of fewer insulin reception sites on cell membranes. Unlike Type I diabetes, Type II diabetes does not require regular insulin injections for survival, and is usually avoided in favor of managing diet and exercise to control the disease. In most cases, Type II diabetes occurs in the obese, as the number of insulin reception sites is inversely proportional to body fat. Weight loss by diet and exercise control is effective in about 90% of Type II diabetes patients, but the remainder must receive regular insulin injections. [87]

Diabetes mellitus is a widespread disease in the United States. As of June 2006, 7.8% of all Americans aged 18 and older suffer from diabetes mellitus.[88] The population of the United States as of July 2006 is 298,444,215[89]; thus, from the above statistic, it can be said that approximately 23 million Americans suffer from diabetes mellitus. Additionally, NASA has found that $1 out of every $7 spent on healthcare is spent on diabetes research and insulin manufacturing[90], in an effort to promote their early research on producing insulin crystals in space. With a fiscal year healthcare budget exceeding $6.5 billion[91], this certainly seems like an area to which further research and resources should be devoted. From a glance, the problem of diabetes mellitus and insulin research and production seems to be promising in terms of generating profits with regard to the United States. The target audience is a large proportion of the American population, and a large percentage of the annual healthcare budget is already devoted to diabetes and insulin research. If a breakthrough were to occur with regard to treating diabetes patients, there is certainly a potential for substantial revenues and profits.

Prior to 1982, the only insulin available for treatment of diabetes mellitus was derived the pancreases of cows, horses, pigs, or fish. The insulin harvested from these sources was effective for human treatment, as the differences between insulin from these animals and human insulin are a few amino acids at most (bovine insulin has three amino acid differences, whereas porcine insulin has only one). However, there were issues regarding this source of insulin when allergic reactions began to surface in the target audience. Since 1982, human insulin has been genetically engineered, beginning with Eli Lilly (founder of Lilly Pharmaceuticals)'s development of Humulin, produced by injecting human DNA into e.coli such that the bacteria will produce human insulin. This process can be performed on a large scale, enabling genetically engineered insulin to dominate the market. [92]

There are several different types of insulin required for diabetic patients, distinguished by the time frame and the intensity of insulin that enters the human body via the injection. There are many different products of each type. One example of the fastest-acting insulin injection is insulin lispro, first marketed by Lilly as Humalog. This family of insulin begins to work within 5 to 15 minutes of injection and is active for 3 to 4 hours.[93] This fast-acting insulin is typically injected before or after a large meal to supplement the body's ability to process the ingested food. However, the type of insulin that holds the most promise for benefiting from microgravity research and development is basal insulin—the insulin that is injected regularly into the bloodstream to maintain a relatively constant level of the hormone, and thus also a manageable level of glucose in the blood.

Current pharmaceutical companies, including Novo Nordisk and Sanofi Aventis, are marketing their own brand of genetically engineered basal insulin, named Levemir, and Lantus, respectively. Both are delivered through subcutaneous injection, and are marketed to the consumer in an insulin "pen", a complete system for diabetics to inject insulin. Levemir is the common name for insulin detemir, marketed by Novo Nordisk.[94] Lantus is the common name for insulin glargine, marketed by Sanofi Aventis. Both start working within 1 to 2 hours, and remain active for up to 24 hours. Thus, a diabetic patient would need to inject him/herself with Levemir/Lantus every 24 hours to maintain a safe basal level of insulin in their bloodstream.

Although current research has allowed the development of longer-lasting insulin, requiring fewer and fewer daily injections, the injection process is still relatively painful and causes moderate discomfort. More critically, injecting insulin is by no means a replacement for the natural pancreas's precise feedback control over the level of insulin in the bloodstream. An injection is simply a large influx of the hormone into the bloodstream, and in a best-case scenario, these sudden spikes of insulin would average out to a smooth, normal level in the bloodstream. However, this rarely happens; excess unmetabolized glucose damages vital organs and arteries, eventually leading to kidney and eye damage, and atherosclerosis. To remedy this, it would be ideal to have an insulin formulation that releases itself into the bloodstream more slowly and gradually than current treatments allow for. This would also reduce patient discomfort by reducing the required frequency of injections. To quote Dr. Marianna

Long, associate director of the NASA Center for Macromolecular Crystallography, "What we're looking for, long-term, is a time release formulation of insulin… And what this means for the patients is fewer shots per day, and maybe fewer shots per week, and their lifestyle would be a lot easier."[95]

Chemically, insulin is a polypeptide hormone that consists of two chains, the A-chain (21 amino acids) and the B-chain (30 amino acids). Individual insulin monomers combine to form hexamer structures. This hexamer structure is the actual substance that is injected into the bloodstream.[96] These hexamer structures undergo allosteric transitions between two states, R and T. The transition between these two states is regulated by the presence of certain ions and molecules. There is a desire to identify these additive ions and molecules that would favor the R state over the T state, as this would result in a more stable insulin preparation, and thusly a potentially longer-lasting insulin formulation. [97] Currently, normal injected insulin is of the form T6 (indicating that each monomer within the hexamer structure is of the T form), which is the least possible stable formulation. Under the presence of certain additives and particular conditions, this T6 form can allosterically transform to a more stable T3R3 or R6 state (the number after the letter indicates the number of monomers exhibiting a particular allosteric state). With regard to the T3R3 state, Dr. G. David Smith, a scientist at Hauptman-Woodward Medical Research Institute stated, "With T3R3 insulin, a diabetic could have a longer basal level of insulin."[98]

In the past, the microgravity environment of the Space Shuttle STS-95 was used to grow insulin with a much better crystal structure than could ever be achieved on Earth. Microgravity improves crystallization, as there are no sedimentation and convection currents in a low-g environment to disrupt the distribution of the material. These crystal growth experiments were performed in 1998 on STS-95[99], and the crystals were brought back to Earth for microscopic analysis. In particular, one crystal of the T3R3 state of insulin was brought back for analysis and details were resolved down to 1.4Å. Previously, an insulin T3R3 crystal grown on earth had details resolved down to 1.9Å. Scientists were hopeful that from this new, clearer image of T3R3 insulin, that they could develop chemicals based on this new information to design a formulation of injected insulin that would dissolve at a slower rate than allowed by current medical technology. [100]

In spite of the hope that scientists had for designing a longer-lasting insulin formulation, a decade has passed without much progress in this field. In 2000, the Commission on Physical Sciences, Mathematics, and Applications Space Studies Board published a report entitled "Future Biotechnology Research on the

International Space Station”, in which they addressed the issue of protein crystallization in microgravity as a whole. The report states that NASA’s macromolecular crystallography program has garnered inconclusive results, and that “the impact of microgravity crystallization on structural biology as a whole has been extremely limited.” The report goes on to specify that “at this time, one cannot point to a single case where a space-based crystallization effort was the crucial step in achieving a landmark scientific results.” [101] This includes the growth of T3R3 insulin on STS-95. The report also states that no biotechnology or pharmaceutical companies have contributed financial resources to the microgravity protein crystallization program, and it is likely to remain that way, until microgravity’s benefits can be realistically demonstrated.[102]

However, for a moment, assume that NASA was indeed able to identify the chemical and organic additives that resulted in growth, development, and marketing of a new T3R3 insulin consumer product. Without taking into account the costs of research and development, financial analysis can be performed to see how much revenue could be made, and thus, how much could be saved if this new insulin treatment could be marketed. First, let’s assume that currently, patients are using Levemir, a current insulin injection system that maintains a basal level of insulin for 24 hours. Levemir is available in 3 mL pen devices, costing $0.1008 per unit (10 units per injection).[103] Assuming injection takes place once daily, the annual cost to each patient is 365.25 * $1.008 = $368.17. To find the total annual budget spent on insulin injections, we take the current US population, 298,444,215 (as of July 2006), and identify the proportion of the population that requires regular insulin injections to survive; that is, all Type I diabetes patients, and approximately 10% of all Type II diabetes patients. The incidence of Type I diabetes mellitus in the United States is 15 in 100,000. [104] This corresponds to a total of 44,767 Type I diabetics. The incidence of Type II diabetes in the United States is 1 in 17 Americans,[105] yielding a figure of 17,548,520 Type II diabetics. 10% of these patients are insulin-requiring, or 1,754,852 patients. Thusly, we can approximate the total number of patients in the United States with either Type I diabetes or insulin-dependent Type II diabetes to be 1,799,619. Assuming that each of these individuals is taking Levemir on a daily basis with the dosage described above, the total annual budget for insulin injections in the United States totals to approximately $66,256,932. If we could reduce injections to once every 3 days via microgravity research/development and marketing of a new T3R3 insulin formulation, the annual cost would be reduced to 1/3rd of the original cost, or $22,085,644, or 1/3rd of the original cost. This results in an annual savings of approximately $44,171,288. This is still a very small amount, when compared to the expected $100 billion cumulative budget of the ISS. With a generous estimate of the lifetime of the ISS to be 20 years from now, the reduced costs of insulin treatment would save $883,425,760, still less than 1% of the projected cost of the ISS.

Also, this does not take into account for launch and construction costs of an insulin manufacturing plant in orbit. Lilly Pharmaceuticals has recently begun construction of a $435 million insulin manufacturing plant[106]. Bear in mind, however, that this cost is for a structure on Earth, and that a similar (albeit on a much smaller scale) structure in orbit, or on the ISS, would cost on the order of $100 million, including launch costs. A similar ISS laboratory module, the Enterprise, is cited as having a cost on this order[107]. Although the one-time fixed cost of constructing an insulin manufacturing facility in orbit certainly seems less than the approximate $883 million profit cited above, it is still another $100 million that needs to be paid upfront. Additionally, even if this facility was built, there is no guarantee that an improved insulin formulation will be developed to even generate the aforementioned revenue. This also does not take into account the raw material costs for production in space, nor the means by which to propel them into orbit.

Thus far, the research and development of an improved insulin injection product in microgravity has been extremely limited. The only progress that a new insulin formulation has seen has been the crystallization of a T3R3 crystal in a microgravity environment, after which x-ray diffraction image analysis was performed. Since 2000, there has been no evidence to suggest that any further work has been done, or will ever be done, specifically regarding the development of T3R3 insulin for commercial distribution. In addition, even if NASA funds research and development of a T3R3 insulin formulation, the return-on-investment analysis for the ISS shows revenues of $880 million, which is still a miniscule proportion of the total expected cost of the ISS. Finally, this figure does not take into account the one-time fixed cost of facility construction, raw material costs, and the means by which this facility is to be propelled into low earth orbit. Thus, it is safe to say that even though the prospect of manufacturing insulin in space could perhaps produce a better product, the immense upfront and material costs, the relatively low profits generated, as well as the uncertainty of ever finding this formulation of insulin, makes even the best-case scenario a waste of time and money.

3.4 Other Methods

There are, of course, other methods to making a profit besides the three previously discussed topics. However, we did not feel that it was important to address these issues in the same scope and as exhaustively as we did with the topics of research, manufacturing, and tourism. This is because we were able to immediately dismiss some of these topics as being unviable in the light of making the ISS profitable.

Decentralization of Launch Services

The first method that we decided could be easily and immediately dismissed was the commercialization of transportation, or decentralization of launch services, in terms of Earth-to-orbit propulsion. Our initial impulse was that if NASA openly contracted their main means of transportation out to several other companies, that at least one of them would find a method of propulsion that would be more efficient than the current Space Shuttle. NASA would then reward them with a contract for that company to manufacture the means of transportation for NASA's future endeavors into space. However, there was one vital flaw with this: What happens in case of another tragic accident, like the Columbia or the Challenger? Perhaps NASA could not trust another external entity to manage their transportation infrastructure, in fear of the flak that it might receive should a catastrophe occur. NASA would be publicly criticized for sacrificing human safety in the interest of more efficient transportation for cargo. In addition, the company performing these services for NASA would surely be in danger of severely damaging their reputation should one of their transport vehicles be lost due to some equipment malfunction. Finally, the public would inevitably be more concerned with astronaut safety over transportation efficiency.

Orbital Launch Platform

Secondly, the ISS could potentially be used as a "jumping-off" point for more regular, manned expeditions into deeper reaches of space. The ISS could be eventually developed into some sort of space platform in which spaceships could land and refuel, serving to lengthen the range of those spaceships. This idea was still viable until NASA announced their intent to develop a permanent lunar base. NASA themselves have stated that establishing this outpost on the moon would be used to prepare for a manned trip to Mars, serving the very purpose of extending the range of manned flight[108]. NASA's hope is that the lunar base will begin construction in 2020 and that there is a continual presence on the moon's surface by 2024. Since NASA has already announced that their goal is a lunar outpost with a timeline beyond that of the service life of the ISS, it seems extremely unlikely that the ISS would be used in a similar fashion.

Defensive Purposes

One use for the International Space Station that has been examined in fair detail is the concept that the station could be used as a military asset. The uses could range from a defense against terrorism to a means of deploying attacks from orbit. For the sake of this paper, all of these studies are relatively inconsequential. From the standpoint of generating an economic analysis, there isn't enough information to go on other than speculation. As of March 2007, there are currently no defense contracts in development for the ISS, so it is therefore impractical to assess the cost and return of such an investment when at the moment no course has been chosen.[109] Furthermore, and perhaps the greater issue, the current international presence in the ISS project makes the use of the station for the defense of any one nation inconceivable. The current agreement for international cooperation dictates that the ISS can only be used for "peaceful purposes".[110] The difference between remote observation and reconnaissance is a fine line and the odds of all involved nations agreeing to a single militaristic endeavor are slim.

Orbital Atmospheric Harvesting

The predominant problem with orbital atmospheric harvesting, as with many other in-orbit industrial applications, remains the dramatically increased cost associated with startup and operation, coupled with the minimal increase in value associated with such operations. The primary value added to the product when discussing in-orbit gaseous harvesting is the location of the resulting product. That is, the benefit of harvesting gasses from the upper atmosphere in orbit is that the gas is at the site of potential usage. The market for gasses in orbit is currently very minimal, and the projected growth of that market over the time span in question remains dubious at best. There appears to be no need at this time, nor in the foreseeable future, for the volume of distilled gasses in orbit that such a venture would produce. Thus the return on such a project would be minimal at best. As such we do not foresee the orbital atmospheric harvesting market to be substantial enough within the lifespan of the ISS to be worth examining further.

4 Conclusion

Could the International Space Station ever manage to pay for itself? From a financial perspective, the answer is a resounding “no”. We have seen that the necessary technological advances and infrastructure required to achieve such a goal is far beyond the scope of developments in the foreseeable future. As such, the initial startup costs for any large-scale endeavor in orbit are prohibitively large relative to the time-dependent return. That is to say, that the time required recovering the initial startup costs is far beyond the expected lifespan of the International Space Station.

Every endeavor into orbit requires a method of transportation. The current means of achieving this is through the use of a chemical rocket. At this time (and for the foreseeable future), the efficiency of these chemical rockets is not likely to change by the order of magnitude that we deem necessary. As such, we predict that the launch costs of any major venture into space will be the most significant inhibiting factor. Specifically, with regard to NASA, the future of space travel involves human exploration of the Moon and Mars. NASA is primarily developing manned spacecraft whose main purpose is to successfully deliver human payloads into orbit. Consequently, these vehicles contain multiple-redundant systems, and will thusly be too expensive for profitability. NASA’s focus is on safety, rather than overall efficiency; principles that do not facilitate the cost-consciousness required by modern industry.

The prospect of large-scale manufacturing is an unviable option as a means for generating profits within our given timeframe. Though the presence of a microgravity environment has definite benefits specifically to a semiconductor manufacturing process, the high startup costs and the relatively low overall increase in yield do not justify the increased complexity of operating in orbit. These same observations can be extended to other manufacturables. The truth is that if a product can be manufactured on Earth, it is not very likely that its manufacture in orbit can be performed more cheaply. The real necessity for a viable manufactured product in orbit is that its production in a microgravity environment adds substantial value to the product, overcoming the increased cost and complexity required to perform said manufacturing in orbit. We have not been successful in finding any particular product that has a substantial financial benefit from its manufacture in space. As such, we find that manufacturing in space is substantially limited by the financial feasibility thereof.

We also looked into the possibility of utilizing the International Space Station for commercial tourism purposes. While currently there have been concessions to make the ISS a tourist destination, there is little financial feasibility in doing so. The combination of the current capacity of the ISS and the costs associated with transporting tourists from Earth to the station renders this action nonviable for a long-term monetary return. In addition, the tourism target audience is becoming large enough to support an independent market in space tourism. This independent market, aimed at space tourism, is anticipated to dominate the market for tourists. As such, it is likely that the number of space tourists hitching a ride on the Space Shuttle will dwindle as this independent market for space travel blossoms.

Since the ISS was designed primarily as a research platform, the question or whether or not it can pay for itself in a financial sense is dubious at best. While the idea of research does not sound like it is immediately profitable, there is no doubt that performing research is fruitful. The quantification of perceived future gains through research is difficult to assess in the light of generating a profit. Although by definition, research is figuratively pouring resources into a black hole, the knowledge gained is often worthwhile.

It is the belief of the authors of this report that humanity belongs amongst the stars. The construction and operation of the International Space Station is a step towards this goal. The construction of the ISS was humanity's first international extraterrestrial large-scale construction project. The procedural knowledge gained from actually carrying out the construction and the operation of the ISS will have laid the groundwork for future space ventures. Indeed, the research-oriented vision of the ISS never lent itself to be potentially profitable; the first step of an extended expedition rarely is.

Appendix A – Semiconductor Facility Initial Costs

Equipment: Lithography								
Equipment	**Company/model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**	**Quantity**	**Equipment Price**	**Total Mass (kg)**	**Total Power (W)**
Wafer Stepper System	Fusion Systems	$177,000.00	3636	6600	5	$885,000.00	18180	33000
Photoresist Coater	SVG Series 90	$297,000.00	1926	6240	5	$1,485,000.00	9630	31200
Developer	STI ST-4062	$37,000.00	1926	1650	5	$185,000.00	9630	8250
Bake Oven/Vapor Prime	Thermolyne 9000	$4,500.00	642	2208	5	$22,500.00	3210	11040
Photoresist stripper	Matrix System 1	$58,000.00	156	3600	5	$290,000.00	780	18000
Linewidth Measurement	Nonometrics CD-50	$58,500.00	40	1800	5	$292,500.00	200	9000
Equipment: Oxidization								
Equipment	**Company /Model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**				
Solar Furnace	n/a	$1,500,000.00	7488	0	1	$1,500,000.00	7488	0
Equipment: Ion Implantation								
Equipment	**Company/Model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**				
Ion Implanter	n/a	$750,000.00	20	10000	5	$3,750,000.00	100	50000
Rapid thermal Annealer	A.G. Associates Heatpulse 2101	$500,000.00	181	10000	5	$2,500,000.00	905	50000
Equipment: Metal Deposition								
Equipment	**Company/Model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**				
Sputtering System	Perkin Elmer 4450/8850	$387,000.00	20	20800	5	$1,935,000.00	100	104000
Residual Gas analyzer	INFiCON Quadrex 100	$250,000.00	20	12000	5	$1,250,000.00	100	60000
Equipment: Etching								
Equipment	**Company/Model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**				
Polysilicon/Nitride Dry Etch	Tegal 1511-ES	$177,000.00	5616	6240	2	$354,000.00	11232	12480
Oxide Dry Etch	YEECO LL-250	$486,000.00	5616	6240	2	$972,000.00	11232	12480
Metal Dry Etch	TEGAL 1512E	$297,000.00	5616	6240	2	$594,000.00	11232	12480
Equipment: Inspection and Test								
Equipment	**Company/Model**	**Unit Price**	**Unit Mass (kg)**	**Unit Power (W)**				
CV Plotter	n/a	$50,000.00	10	3450	5	$250,000.00	50	17250
Ellipsometer	Rudolph Auto-EIIII	$81,000.00	10	3450	5	$405,000.00	50	17250
Spreading Resistance Probe	n/a	$50,000.00	80	3600	5	$250,000.00	400	18000
Automatic Four-point Probe	Magnetron M-800	$10,500.00	80	3450	5	$52,500.00	400	17250
Junction Sectioner	n/a	$50,000.00	80	3450	5	$250,000.00	400	17250
Surface Profiler	Sloan Detak IIA	$58,500.00	10	3450	5	$292,500.00	50	17250
Inspection Microscope	Leitz Ergolux AMC	$58,500.00	10	1320	5	$292,500.00	50	6600
Scanning Electron Microscope	AMRAY 1845FE	$477,000.00	3900	3600	2	$954,000.00	7800	7200
Probers	Electroglas 2001X Automatic	$177,000.00	1248	660	5	$885,000.00	6240	3300
						Equipment Price	**Total Mass (kg)**	**Total Power (W)**
Equipment Cost	**$19,646,500.00**					**$19,646,500.00**	99459	533280
Launch cost ($/lb)							$4,729.00	
Equipment Launch Cost	**$1,034,751,544.20**						**$1,034,751,544.20**	
Solar Cell Installation Cost ($/W)								$3.00
Energy Cost	**$1,599,840.00**							**$1,599,840.00**
Module Construction Cost	**$3,950,000,000.00**							
Module Mass (kg)	44032							
Module Launch Cost	**$458,100,121.60**							
Total Initial Cost	**$5,464,098,005.80**							

References

von Braun, Wernher, and Frederick I. Ordway III. "Space Exploration." Encyclopedia Americana. Grolier Online http://ea.grolier.com/cgi-bin/article?assetid=0364530-05 (accessed April 24, 2007).

Clark, John. "Space shuttle", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.639500, last modified: July 15, 2002.

Iannotta, Ben. “Turning space travel into tourism,” Aerospace America, November 2006, FEATURES; Pg. 36.

Rachmiel Levine, et al., "Insulin", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.347200, last modified: May 17, 2001.

Morris, Jefferson. “First crewed Ares I launch targeted for 2013 - NASA,” Aerospace Daily & Defense Report, January 8, 2007 Monday, News; Pg. 3.

James J. Pelosi, "Space station", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.639600, last modified: April 24, 2003.

Jesco von Puttkamer, "Space flight", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.639000, last modified: November 8, 2004.

"Columbia Disaster: Why did the space shuttle burn up?", From Science News, Vol. 163, No. 6, Feb. 9, 2003, p. 83. Copyright © 2003 Science Service, as published under license in AccessScience@McGraw-Hill, © The McGraw-Hill Companies 2000-2003.

"Space Woes: NASA programs reel from shuttle problems", From Science News, Vol. 168, No. 6, August 6, 2005, p. 94 as published under license in AccessScience@McGraw-Hill, © The McGraw-Hill Companies 2000-2005

Building A New Rocket: It IS Rocket Science, Space Daily, December 1, 2006 Friday, 1284 words, Staff Writers, WASHINGTON, Dec. 1.

TUNNEL 9 COMBINES CUTTING-EDGE CAPABILITIES FOR ORION, US Fed News, January 26, 2007 Friday 1:31 AM EST, US Fed News, ARNOLD AFB, Tenn.

NEXT SHUTTLE MISSION TO READY SPACE STATION FOR LAB MODULES, States News Service, February 15, 2007 Thursday, States News Service, WASHINGTON.

Works Cited

[1] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002. http://www.futron.com/pdf/FutronLaunchCostWP.pdf, accessed Aug. 23, 2006.

[2] “Salyut,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Salyut&oldid=116459715, accessed April 12, 2007.

[3] “Skylab,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Skylab&oldid=119637818, accessed April 12, 2007.

[4] “Mir,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Mir&oldid=120003543, accessed April 12, 2007.

[5] Figures rounded by taking the number of days in orbit (5,511) compared to the number of days occupied (4,594)

[6] “Space Tourism,” in HobbySpace.com, http://www.hobbyspace.com/Tourism/tourism2.html, accessed April 12, 2007.

[7] “International Space Station”, in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=International_Space_Station&oldid=118010889, modified March 26, 2007, accessed March 28, 2007.

[8] “NASA – Exploration Systems – ISS Expedition Experiment List.” National Aeronautics and Space Administration, http://exploration.nasa.gov/programs/station/expedition.html, accessed March 28, 2007.

[9] “International Space Station”, in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=International_Space_Station&oldid=118010889, modified March 26, 2007, accessed March 28, 2007.

[10] “International Space Station”, in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=International_Space_Station&oldid=118010889, modified March 26, 2007, accessed March 28, 2007.

[11] “Saturn V,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Saturn_V&oldid=121657414, modified April 10, 2007, accessed April 12, 2007.

[12] “Saturn V,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Saturn_V&oldid=121657414, modified April 10, 2007, accessed April 12, 2007.

[13] Wade, Mark. “Saturn V,” in Astronautix, http://www.astronautix.com/lvs/saturnv.htm, accessed April 12, 2007.

[14] Samuel H. Williamson, "Five Ways to Compute the Relative Value of a U.S. Dollar Amount, 1790 - 2005," MeasuringWorth.Com, 2006, http://www.measuringworth.com/calculators/compare/, accessed April 12, 2007.

[15] “Saturn V,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Saturn_V&oldid=121657414, modified April 10, 2007, accessed April 12, 2007.

[16] “Saturn V,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Saturn_V&oldid=121657414, modified April 10, 2007, accessed April 12, 2007.

[17] “Space Shuttle External Tank,” in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_Shuttle_external_tank&oldid=117380469, modified March 23, 2007, accessed April 12, 2007.

---

[18] "Space Shuttle Solid Rocket Booster," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_Shuttle_Solid_Rocket_Booster&oldid=120195826, modified April 4, 2007, accessed April 12, 2007.

[19] "Space Shuttle Program," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/wiki/Space_Shuttle_program, modified April 9, 2007, accessed April 12, 2007.

[20] "Space Shuttle Columbia Disaster," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_Shuttle_Columbia_disaster&oldid=120347775, modified April 4, 2007, accessed April 7, 2007.

[21] "Space Shuttle Challenger Disaster," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_Shuttle_Challenger_disaster&oldid=120868663, modified April 7, 2007, accessed April 7, 2007.

[22] "Ares I," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Ares_I&oldid=117334905, modified March 23, 2007, accessed April 7, 2007.

[23] "Ares V," Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Ares_V&oldid=118595938, modified March 28, 2007, accessed April 7, 2007.

[24] "Constellation Program: America's Fleet of Next-Generation Launch Vehicles: The Ares I Crew Launch Vehicle," NASAfacts, http://www.nasa.gov/centers/marshall/pdf/151450main_8-40598-CLV.pdf, accessed April 12, 2007.

[25] "Ares I/V Launch Vehicles," NASA, http://www.nasa.gov/pdf/146764main_CLV_CaLV_Description.pdf, accessed April 12, 2007.

[26] Constellation Program: America's Fleet of Next-Generation Launch Vehicles: The Ares V Cargo Launch Vehicle," NASAfacts, http://www.nasa.gov/centers/marshall/pdf/151451main_8-40599-CaLV.pdf, accessed April 12, 2007.

[27] "NASA – Constellation Program: Ares V Cargo Launch Vehicle," NASA, http://www.nasa.gov/mission_pages/constellation/ares/aresV.html, accessed April 12, 2007.

[28] "Orion (spacecraft)," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Orion_%28spacecraft%29&oldid=119850142, modified April 3, 2007, accessed April 7, 2007.

[29] "Space Shuttle Columbia Disaster," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_Shuttle_Columbia_disaster&oldid=120347775, modified April 4, 2007, accessed April 7, 2007.

[30] "Orion (spacecraft)," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Orion_%28spacecraft%29&oldid=119850142, modified April 3, 2007, accessed April 7, 2007.

[31] "State of the Satellite Industry Report, June 2006," Futron Corporation, http://www.futron.com/pdf/resource_center/reports/SIA_2005_Indicators.pdf, page 7, accessed April 12, 2007.

[32] "State of the Satellite Industry Report, June 2006," Futron Corporation, http://www.futron.com/pdf/resource_center/reports/SIA_2005_Indicators.pdf, accessed April 12, 2007.

[33] "Futron Corporation – Decision Support," Futron Corporation, http://www.futron.com/, accessed April 12, 2007.

[34] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002. http://www.futron.com/pdf/FutronLaunchCostWP.pdf, accessed Aug. 23, 2006.

[35] "A NASA Recipe for Protein Crystallography", National Aeronautics and Space Administration, virtualastronaut.jsc.nasa.gov/teacherportal/pdfs/ProteinCrystallography.pdf, accessed January 24, 2007.

---

[36] "Semiconductor industry," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Semiconductor_industry&oldid=121713170, modified April 10, 2007, accessed April 12, 2007.

[37] "Gallium Arsenide vs. Silicon," http://www.ensc.sfu.ca/people/faculty/jones/ENSC100/Gamma/gallium.html, accessed February 14, 2007.

[38] Johns, David A., Martin, Ken. "Analog Integrated Circuit Design." pp. 82-83. John Wiley & Sons, Inc., 1997.

[39] Johns, David A., Martin, Ken. "Analog Integrated Circuit Design." pp. 83-84. John Wiley & Sons, Inc., 1997.

[40] Johns, David A., Martin, Ken. "Analog Integrated Circuit Design." pp. 85-87. John Wiley & Sons, Inc., 1997.

[41] McNeill, John A. "Studio 1 Review," http://ece.wpi.edu/~mcneill/4902/lectures/studio_01/Studio_1.pdf, accessed February 14, 2007.

[42] Johns, David A., Martin, Ken. "Analog Integrated Circuit Design." pp. 88-90. John Wiley & Sons, Inc., 1997.

[43] McNeill, John A. "Studio 1 Review," http://ece.wpi.edu/~mcneill/4902/lectures/studio_01/Studio_1.pdf, accessed February 14, 2007.

[44] Johns, David A., Martin, Ken. "Analog Integrated Circuit Design." p. 93. John Wiley & Sons, Inc., 1997.

[45] McNeill, John A. "Studio 1 Review," http://ece.wpi.edu/~mcneill/4902/lectures/studio_01/Studio_1.pdf, accessed February 14, 2007.

[46] "Gallium Arsenide vs. Silicon," http://www.ensc.sfu.ca/people/faculty/jones/ENSC100/Gamma/gallium.html, accessed February 17, 2007.

[47] "Manufacturing Machinery," http://www.ensc.sfu.ca/people/faculty/jones/ENSC100/Gamma/design2.html, accessed February 12, 2007.

[48] "Residual gas analyzer," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Residual_gas_analyzer&oldid=119073339, modified March 30, 2007, accessed April 12, 2007.

[49] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002. http://www.futron.com/pdf/FutronLaunchCostWP.pdf, accessed Aug. 23, 2006.

[50] "New World Record Achieved in Solar Cell Technology", Department of Energy, http://www.energy.gov/news/4503.htm, accessed February 13, 2007.

[51] "Protein Crystal Growth," NASA Marshall Space Flight Center, http://science.nasa.gov/msL1/pcg_why.htm, accessed February 16, 2007.

[52] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002. http://www.futron.com/pdf/FutronLaunchCostWP.pdf, accessed Aug. 23, 2006.

[53] "Lunar regolith," http://www.moonminer.com/Lunar_regolith.html, accessed February 12, 2007.

[54] "Lunar regolith," http://www.moonminer.com/Lunar_regolith.html, accessed February 12, 2007.

[55] Chen, Dr. George Z. "The FFC Cambridge Process," September 24, 2003, http://www.msm.cam.ac.uk/djf/FFC_Process.htm, accessed February 16, 2007.

[56] Angelo, William J. "Semiconductor Plant Aims for High Sustainability," http://construction.com/NewsCenter/Headlines/ENR/20060612j.asp, June 12, 2006, accessed February 20, 2007.

[57] Gründer, Matthias. "Columbus Module Handed Over," http://www.flug-revue.rotor.com/FRheft/FRHeft06/FRH0607/FR0607h.htm, June 8, 2006, accessed February 20, 2007.

---

[58] "Columbus (ISS module)," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Columbus_%28ISS_module%29&oldid=121745022, modified April 10, 2007, accessed April 12, 2007.

[59] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. September 6, 2002. http://www.futron.com/pdf/FutronLaunchCostWP.pdf, accessed Aug. 23, 2006.

[60] "New World Record Achieved in Solar Cell Technology", Department of Energy, http://www.energy.gov/news/4503.htm, accessed February 13, 2007.

[61] McNeill, John A. "IC Economics," http://ece.wpi.edu/~mcneill/handouts/iceconomics.pdf, accessed February 13, 2007.

[62] McNeill, John A. "IC Economics," http://ece.wpi.edu/~mcneill/handouts/iceconomics.pdf, accessed February 13, 2007.

[63] McNeill, John A. "IC Economics," http://ece.wpi.edu/~mcneill/handouts/iceconomics.pdf, accessed February 13, 2007.

[64] McNeill, John A. "IC Economics," http://ece.wpi.edu/~mcneill/handouts/iceconomics.pdf, accessed February 13, 2007.

[65] "Economics of Manufacturing in Space," http://www.ensc.sfu.ca/people/faculty/jones/ENSC100/Gamma/econo.html, accessed February 13, 2007.

[66] Leachman, Robert C.; Hodges, David A. Competitive Semiconductor Manufacturing Program, Engineering Systems Research Center, University of California at Berkeley. "Benchmarking Semiconductor Manufacturing," ieeexplore.ieee.org/iel5/10057/32251/01503302.pdf?arnumber=1503302, accessed February 21, 2007.

[67] "Tourists Visit the International Space Station," SpaceToday Online, http://www.spacetoday.org/Astronauts/SpaceTourists.html, modified 2004, accessed April 12, 2007.

[68] "Valentina Tereshkova," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Valentina_Tereshkova&oldid=117153584, modified March 22, 2007, accessed April 12, 2007.

[69] "Space Tourism," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_tourism&oldid=122074783, modified April 11, 2007, accessed April 12, 2007.

[70] "NASA – Astronaut Requirements," NASA, http://www.nasa.gov/audience/forstudents/postsecondary/features/F_Astronaut_Requirements.html, modified January 29, 2004, accessed April 12, 2007.

[71] "Space Tourism," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_tourism&oldid=122074783, modified April 11, 2007, accessed April 12, 2007.

[72] "Tourists Visit the International Space Station," SpaceToday Online, http://www.spacetoday.org/Astronauts/SpaceTourists.html, modified 2004, accessed April 12, 2007.

[73] "Space Adventures, Not MirCorp, Brokered Tito Trip to ISS," Space.com, http://www.space.com/news/spacestation/tito_space_adventures_010206.html, modified February 6, 2001, accessed April 12, 2007.

[74] "Space Adventures Coordinating New Space Tourist's Trip", Space.com, http://www.space.com/missionlaunches/missions/new_tourist_010720.html, modified July 20, 2001, accessed April 12, 2007.

---

[75] "Space Tourism," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_tourism&oldid=122074783, modified April 11, 2007, accessed April 12, 2007.

[76] "Virgin Galactic details its space travel plans," MSNBC, http://www.msnbc.msn.com/id/15654772, modified November 10, 2006, accessed April 12, 2007.

[77] "Space Tourism," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_tourism&oldid=122074783, modified April 11, 2007, accessed April 12, 2007.

[78] "Space Tourism Market Study: Orbital Space Travel & Destinations with Suborbital Space Travel," Futron Corporation, http://www.futron.com/pdf/resource_center/white_papers/SpaceTourismMarketStudy.pdf, October 2002, accessed April 12, 2007.

[79] "Space Tourists Lining Up; Russians Hope $20M Price Tag Will Help Pay For ISS," Space.com, http://www.space.com/news/russian_space_tourists_020118.html, modified January 18, 2002, accessed April 12, 2007.

[80] "Space Tourism," in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Space_tourism&oldid=122074783, modified April 11, 2007, accessed April 12, 2007.

[81] "Space Tourism Market Study: Orbital Space Travel & Destinations with Suborbital Space Travel," Futron Corporation, http://www.futron.com/pdf/resource_center/white_papers/SpaceTourismMarketStudy.pdf, October 2002, accessed April 12, 2007.

[82] "Space Tourism Market Study: Orbital Space Travel & Destinations with Suborbital Space Travel," Futron Corporation, http://www.futron.com/pdf/resource_center/white_papers/SpaceTourismMarketStudy.pdf, October 2002, accessed April 12, 2007.

[83] "Introductory Mechanics Problems Laboratory: Space Station," www.physics.niu.edu/~physlabs/labs/Plab4.pdf, accessed February 1, 2007.

[84] "Website for the Committee on Science and Technology, U.S. House of Representatives," http://www.house.gov/science/delucas_4-9.html, accessed April 12, 2007.

[85] "Spike in diabetes – especially among the young – charted by country," in CNN Health, http://archives.cnn.com/2000/HEALTH/11/06/diabetes.atlas/index.html, modified November 6, 2000, accessed February 4, 2007.

[86] Jaime Davidson, Peter E. Bressler, "Diabetes", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.190300, last modified: April 10, 2000, accessed April 12, 2007.

[87] Jaime Davidson, Peter E. Bressler, "Diabetes", in AccessScience@McGraw-Hill, http://www.accessscience.com, DOI 10.1036/1097-8542.190300, last modified: April 10, 2000, accessed April 12, 2007.

[88] "Early Release of Selected Estimates Based on Data From the January-June 2006 National Health Interview Survey", Center for Disease Control and Prevention, http://www.cdc.gov/nchs/data/nhis/earlyrelease/200612_14.pdf, released December 2006, accessed April 12, 2007.

[89] "CIA – The World Factbook – United States", in The CIA World Factbook, https://www.cia.gov/cia/publications/factbook/geos/us.html, last modified: December 19, 2006.

[90] Dooling, David, "Crystal-clear view of insulin", in NASA Science Headlines, http://science.nasa.gov/NEWHOME/headlines/notebook/msad22jul98_1.htm, released July 1998.

---

[91] "Government Performance Results Act Final FY 2005 Annual Performance Plan", in U.S. Department of Health and Human Services, Health Resources and Services Administration, http://www.hrsa.gov/about/perplan/default.htm, released February 2004.

[92] "Insulin", in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Insulin&oldid=122219783#Principles, modified April 12, 2007, accessed April 12, 2007.

[93] "Insulin", in Wikipedia, the free encyclopedia, http://en.wikipedia.org/w/index.php?title=Insulin&oldid=122219783#Types, modified April 12, 2007, accessed April 12, 2007.

[94] "Levemir: long-acting basal insulin for diabetes", http://www.levemir-us.com/, accessed January 16, 2007.

[95] Dooling, David, "Crystal-clear view of insulin", in NASA Science Headlines, http://science.nasa.gov/NEWHOME/headlines/notebook/msad22jul98_1.htm, released July 1998.

[96] Dooling, David, "Crystal-clear view of insulin", in NASA Science Headlines, http://science.nasa.gov/NEWHOME/headlines/notebook/msad22jul98_1.htm, released July 1998.

[97] "Future Biotechnology Research on the International Space Station", Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board, http://newton.nap.edu/openbook.php?record_id=9785&page=14, released 2000.

[98] Dooling, David, "Crystal-clear view of insulin", in NASA Science Headlines, http://science.nasa.gov/NEWHOME/headlines/notebook/msad22jul98_1.htm, released July 1998.

[99] "STS-95 Experiment: Commercial Protein Crystal Growth". Shuttle Press Kit, http://www.shuttlepresskit.com/sts-95/experiment30.htm, last modified October 14, 1998.

[100] Dooling, David, "Crystal-clear view of insulin", in NASA Science Headlines, http://science.nasa.gov/NEWHOME/headlines/notebook/msad22jul98_1.htm, released July 1998.

[101] "Future Biotechnology Research on the International Space Station", Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board, http://newton.nap.edu/openbook.php?record_id=9785&page=1, released 2000.

[102] "Future Biotechnology Research on the International Space Station", Commission on Physical Sciences, Mathematics, and Applications, Space Studies Board, http://newton.nap.edu/openbook.php?record_id=9785&page=2, released 2000.

[103] Ennesser, Joseph. "Insulin Detemir," University of California, San Diego Medical Center, http://health.ucsd.edu/pharmacy/resources/Discourse%20Newsletters/Discourse%202006/v28_2.htm

[104] Lamb, William, M.D., "Diabetes Mellitus, Type 1," eMedicine@WebMD, http://www.emedicine.com/ped/topic581.htm, last modified June 27, 2006.

[105] Bloomgarden, Zachary, M.D. "Starting Insulin in Type 2 Diabetes," MedscapeToday@WebMD, http://www.medscape.com/viewarticle/412404, last modified August 30, 2001.

[106] "Lilly Picks Northern Virginia for $435M, 700-Job Insulin Plant" http://www.siteselection.com/ssinsider/bbdeal/bd020513.htm, accessed January 27, 2007.

[107] Lipman, Jonathan. "U.S., Russian Companies Team Up to Build ISS Module," http://www.space.com/news/spacestation/spacehab_991210.html, accessed January 27, 2007.

[108] Hawkins-Cox, Diane. "NASA wants permanent moon base," CNN.com, http://www.cnn.com/2006/TECH/space/12/04/moon.base/index.html, accessed April 7, 2007.

[109] "New ISS Duty: A Military Outpost?" Space.com, http://www.space.com/news/iss_military_010924-1.html, modified September 24, 2001, accessed April 12, 2007.

---

[110] Petras, Christopher M. “Military use of the International Space Station and the concept of ‘peaceful purposes’,” Air Force Law Review, http://findarticles.com/p/articles/mi_m6007/is_2002_Spring/ai_103223912, accessed April 12, 2007.