FSTS
Future Space Transportation Study

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Andrews Space & Technology developed the Future Space Transportation Study for the National Aeronautics and Space Administration. Andrews Space & Technology markets its research capabilities through SPACEandTECH.COM.

ABSTRACT

Andrews Space & Technology's NASA NRA 8-27 activity, termed the Future Space Transportation Study (FSTS), uses a multiphase analysis process to identify future commercial markets and flow down requirements to the vehicle level. The current study focused on three potential markets: space-based semiconductor fabrication, biomedical industry applications, and LEO passenger travel. AS&T foresees a demand for in-space semiconductor laboratory facilities in the 2007 time frame as the semiconductor industry attempts to reinvent the methods it uses to manufacture their products. The pharmaceuticals industry is well suited to space migration. Through trend analysis, specific products have been identified that will benefit from space unique resources. The LEO passenger travel market has also been thoroughly investigated. Preliminary analysis shows very attractive business opportunities and interviews have confirmed this projection. Market analysis and interview data was utilized to derive top-level Reusable Launch Vehicle system requirements to serve the investigated markets.

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EXECUTIVE SUMMARY

Introduction

Business opportunities for space based activities of non-aerospace companies do exist and will be the driving factors in the development of next generation launch vehicles.

Business opportunities for space based activities of non-aerospace companies do exist and will be the driving factors in the development of next generation launch vehicles.

S-commerce, or S-business, is the use of space by a company to provide products and services, both terrestrial and extraterrestrial. Space commerce is presently made up of companies that manufacture and operate launch vehicles, satellites and related ground infrastructure, including spaceports, teleports and ground terminal/receiver equipment. These products and services serve commercial, civil and military customers. Total revenues of the world space industry (excluding the countries of the former Soviet Union and China) currently totals approximately US$100 billion annually. In the future, space commerce will continue to see revenue growth while expanding to include many companies and industries that are not traditionally thought of as users of space. The terrestrial companies will begin to incorporate the use of space resources into the development and use of their services and products. The markets focused on during this phase of the study were selected based on an assessment that they might offer near term products or services and be sufficiently large and competitive to tackle the risks and invest in space.

Conclusions

Conclusion #1: This Future Space Transportation Study was a limited scope effort that analyzed approximately 20% of the potential future markets, as outlined by the Commercial Space Transportation Study (CSTS) published in 1994. The results of the limited market analyses conducted here supported the general conclusions put forth by the CSTS: that the space launch market is in-elastic above a certain launch price point (approximately $600 per pound) and elastic for prices below. At this time, AS&T has conducted insufficient analysis to make further recommendations on the size, shape and slope of the elasticity curve. We maintain that conducting further market analysis to define elasticity is critical to the continued growth and evolution of the space launch industry.

Conclusion #1: The results of the limited market analyses conducted here supported the general conclusions put forth by the CSTS: that the space launch market is in-elastic above a certain launch price point (approximately $600 per pound) and elastic for prices below.

Conclusion #2: Many of the future markets will be enabled once the frequency and cost of space access achieves thresholds that allow established terrestrial industries to make money in space. This fact, that new revenues will come from multiple established industries, reduces the investment risk of fielding a 2nd Generation Launch System. As an example, many emerging launch vehicle companies (i.e. Kistler Aerospace Corporation, Kelly Space & Technology, Pioneer Rocketplane, Rotary Rocket, etc.) relied almost solely on the emergence of LEO communication satellite constellations, a new and unproven industry itself, to attract investment and achieve commercial viability. This created a situation where business risk was piled on top of business risk. In contrast, this market study indicated that future market revenues will come from many different business sectors and consist of capturing very small fractions of large established industries. Figure A highlights an example based on the markets studied as part of this report.

Conclusion #2: Many of the future markets will be enabled once the frequency and cost of space access achieves thresholds that allow established terrestrial industries to make money in space.

Future Commercial Space Markets	
Space Business Park •Materials (new alloys, composites, hi-temp superconductor, etc.) **•Pharmaceuticals / Biotech / Medical** •Optics **•Semiconductors**	**Tourism / Passenger Travel** •Suborbital Tourism **•LEO Passenger Travel** (hotels) •Romantic Excursions •Extra-LEO Tourism (Lunar C cycles) •Adventure Travel (Moon, Mars, etc.) •Tourism Based Services (clothing, fashion, spacesuits, food)
Space Services / Logistics •Supply / Cargo Transport (up/down) •Space Tug •Spacecraft Service Platform •Maintenance Depot •Warehousing (un/pressurized) •Gas and Propellant Storage •Space Burial	**Entertainment** •Gambling •On-orbit Sound Stage •Sporting Events •Personal Spacecraft **Commercial Science / Exploration / Exploitation** •Astronomy •Mining / Resource Prospecting •Waste Management and Disposal •Medical / Nuclear / Toxin Disposal

Figure A: List of Future Space Markets with studied markets highlighted.

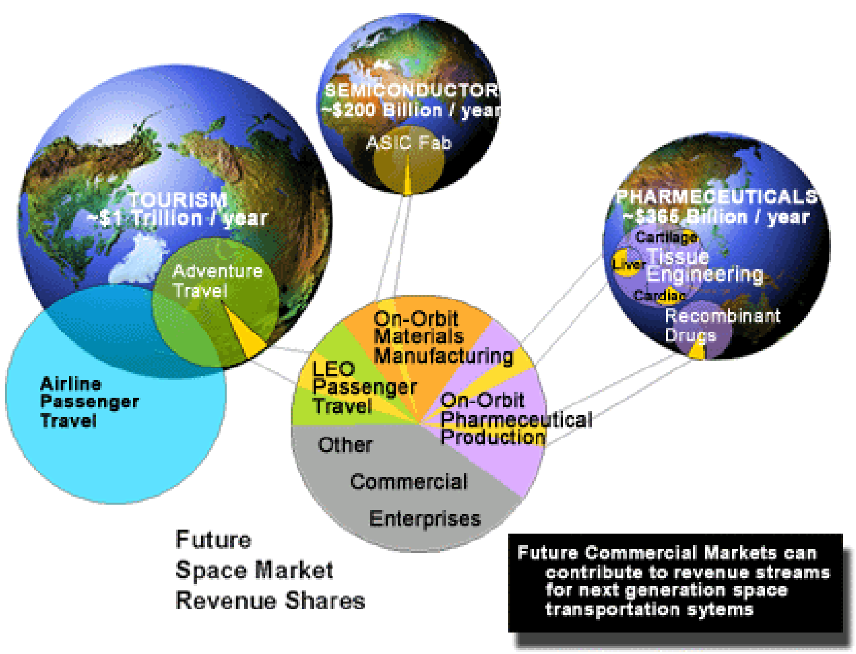


Figure B: Analysis indicates that future market revenues will come from large and established industries that can improve their bottom line by doing business in space.

Conclusion #3: A 2nd Generation Launch Vehicle, designed to address future markets, must be designed to work around the business cycles demanded by the future user community.

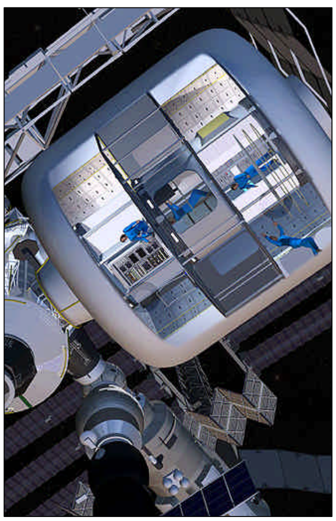
The tourism industry has annual revenues of US$1 trillion. Adventure Travel comprises approximately US$200 billion of those. Assuming that safety can be improved and costs significantly reduced, it is not unfathomable that a 2nd Generation Launch System can capture (or add) 1% or US$2 billion in annual revenues from commercial passenger travel and tourism.

The semiconductor and pharmaceutical industries, which have approximately US$550 billion in combined annual revenues, spend between 10% and 15% on

Research & Development. High technology industries are typified by a fierce competitive landscape, which has everyone looking for a competitive advantage and causes companies to take high risks. If a 2nd Generation Launch System could provide the companies with frequent low-cost access to orbiting research facilities, it is well within the grasp of reality that these companies could spend at least 1% of their annual R&D budgets on space based research, which could easily total another US $500 million. These revenues, US$2.5 billion for R&D and passenger travel, are nearly equal to current commercial GEO satellite launch revenues, and can significantly impact the business case of a commercial 2nd Generation LV.

Conclusion #4: Future markets must be developed in concert with a 2nd Generation Launch Vehicle.

Conclusion #3: Based on this path finding study, which represents the first comprehensive system study to derive transportation design requirements for the future markets, the study team concluded that a 2nd Generation Launch Vehicle, designed to address future markets, must be designed to work around the business cycles demanded by the future user community. As an example, both airline companies interviewed outlined the need to limit the time from when a passenger boards a vehicle to when they arrive at their destination. Specifically, the airlines would prefer to limit the time between when a passenger boards to when they are launched to two hours, and to limit the transit time from launch to arrival at the destination to six hours. For the Space Shuttle, this span averages approximately two to three days due to the relaxed launch window and extensive orbit phasing operations. To correct for this, a 2nd Generation vehicle must routinely meet a very narrow launch window (measured in seconds) in all-weather conditions. As another example, semiconductor companies develop a new generation of microchips, build multibillion-dollar factories, pay off their capital investments and generate huge profits (80% profit margins) all in the span of 18 to 24 months. For these companies, R&D campaigns are measured in hours, days and weeks. Currently, it takes years to plan, design, and implement orbital tests. Until these disparate business cycles are reconciled by improvements in space transportation and on-orbit infrastructure, many of the future markets will remain unaddressable.



Conclusion #4: Future markets must be developed in concert with a 2nd Generation Launch Vehicle. It was clear from the study team's interviews that very few people outside the space industry understand the benefits of space and how it could benefit their business. Furthermore, the space infrastructure required to address the needs of the future markets is very different than what is operating today. Many of these future markets require new facilities and processes, in addition to the Earth to Orbit transportation infrastructure, which require years to develop and deploy. As a result, any space transportation service provider who expects to address future markets can not, must not, rely on a "build it and they will come" philosophy. It is incumbent upon industry and NASA to devise a future market incubation plan that serves to: 1) promote space awareness to non-aerospace companies; 2) incubate near term future markets (e.g. space tourism); and 3) act as "stepping stones" that will lead to fully developed, robust commercial space commerce.

Methodology

The Future Space Transportation Study is the first comprehensive system study to derive transportation design requirements for the future markets.

AS&T interviewed potential future users to:

1. develop business concepts for the user's particular market;
2. identify market price pressure points; and
3. derive RLV design attribute requirements to address the particular market.

Andrews Space & Technology developed an approach for FSTS that was divided into four distinct phases, interleaved with two interview opportunities with each selected industry representative. In the initial market analysis step, the targeted market is gauged by applying the defined Measures of Effectiveness (MOE). The following MOE's were defined and used:

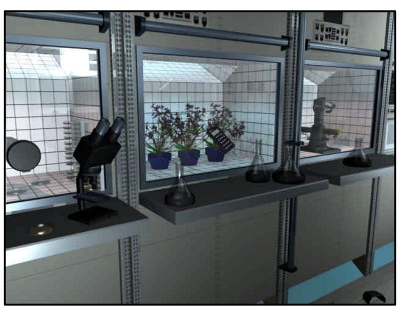
- Technology Readiness Level (TRL)
- Business Readiness Level (BRL)
- Utilization of Space Unique Resources
- Product Value per Unit Mass
- Value Chain Intersection with Space Unique Resources
- Market Size
- Market Trends
- Space-based Market Concept Maturity

The animation developed for the FSTS study was highly effective in introducing the concept of future markets and exciting the interviewees about their business opportunities.

If the market was found to be attractive as indicated by these metrics, it became a candidate for the next step in the process. Prior to soliciting interview opportunities with industry representatives, the identified market was analyzed for emerging customer opportunities. The following criteria were developed to determine the feasibility of each customer's business opportunity:

- Product Quality
- Product Quantity (Yield)
- Product Innovation (Uniqueness)
- Product Development (Roadmap)
- Time to Market
- Production Cycle Time
- Profitability

After these parameters had been quantified, a plausible business scenario was put forth to selected industry representatives. In the first of two interviews, initial reactions were solicited from select industry representatives. Interviews consisted of a brief presentation of the proposed scenario (including the video trailer), followed by a question and discussion session for a total duration of approximately 90 minutes. Andrews Space & Technology (AS&T), in conjunction with Digital Empire, created a brief (4.5 minute) video that characterizes the opportunity of Future Commercial Space Markets.



The video trailer, which presented a scenario of business activity in 2012, was highly effective in setting the mood of the meeting toward an out-of-the-box discussion of future market possibilities. The video trailer can be viewed at http://www.andrews-space.com/en/corporate/FSTS.html

The approach developed by AS&T has proven to be an effective tool to systematically explore the emerging markets of commercial space utilization. The process has resulted in a broad scope overview of the requirements of any future launch system that is to serve these emerging markets. Additional iteration of the process is expected to refine the fidelity of the obtained mission and operations model data.

There is an immediate market opportunity for commercial on-orbit laboratory facilities.

Market Conclusions:

Space Manufacture of Semiconductors

The potential of space-based semiconductor manufacturing for the foreseeable future (present to 2012) is low. Industry leaders are continuing to scale down geometry features via wet processes and limited vacuum application. The potentially cleaner environment of space may not reduce defects and increase yield of semiconductor production because 95% of the contamination in today's processes are believed to come from process tools and are thus inherently internal to those processes. Radical tool redesigns, aimed at eliminating those contaminants, are not anticipated in the future 10-year scope of this investigation. In two more generations microchips will have features less than 30 nm and semiconductors as we know them will not function due to quantum mechanical limits (electronic tunneling through CMOS gates). There are a number of alternate approaches in work and the availability of laboratories with microgravity and ultra hard vacuum were definitely of interest.

Tissue engineering is enabled by microgravity and may lead to treatments for many medical conditions.

A few small companies are pursuing the development of "dry resist" processes that are amenable to space-based semiconductor manufacturing. However, these conceptual-phase development efforts have yet to show a significant improvement over terrestrial processes.

Although it was not the focus of this effort, interviews with "traditional" semiconductor manufacturers did uncover a significant interest for an On-Orbit Research Facility. We highly recommend the investigation of an On-Orbit R&D facility as part of future studies. This stems from the fact that, within the next seven years, semiconductor companies will reach physical limits of material and present manufacturing processes, which they have refined over the last decade. Currently, they are searching for "revolutionary" methods of manufacturing follow-on generations of products. If an on-orbit research facility existed today, interviewees would be willing to pay up to US$20 million for a single flight to conduct tests and build certain production elements that could lead to breakthrough material and manufacturing advancements. However, this market is only addressable if the companies are offered routine access: no less than once a month. Demand would significantly increase if the price for a week's research could be reduced to less than US$1 million.

Small yield increases of recombinant drugs produced in microgravity may save millions in production costs.

The semiconductor market spends between US$20B and US$30B annually on R&D. This works out to between US$385M and US$577M per week! Based on the interview feedback, if a 2nd Generation Launch Vehicle could provide weekly access, semiconductor companies could spend up to US$20M per week (3% of the world semi-conductor R&D funds) for the use of an Orbital R&D Facility. At this time, AS&T has insufficient data to develop elasticity demand curves for On-Orbit R&D expenditures as a function of price per pound to LEO.

Biomedical Market

Current and on-going research demonstrates the significant advantages of on-orbit research and manufacturing which has attracted the interest of pharmaceutical market leaders.

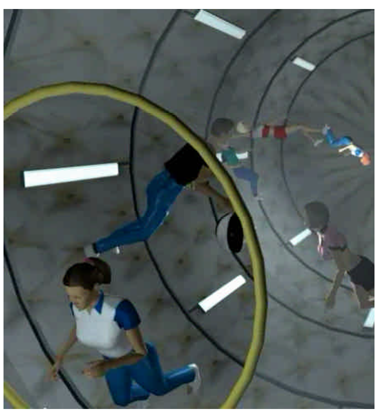
Access to microgravity laboratories is needed to drive market development.

Liver tissue is the most likely early candidate for commercially viable space-based tissue engineering. Tissue engineering technologies have the potential to address diseases and disorders that account for about half of the nation's total healthcare costs. Tissue culture experiments performed on the shuttle and Mir have demonstrated the positive effects of microgravity on three-dimensional tissue growth and differentiation, and thus the potential for improved products. Liver disease in the United States resulted in 25,175 deaths in 1997, while only 4,000 people received a liver transplant (in 1996). Based on 1985 data, liver and gall bladder disease cost the US health care industry US$17 billion (adjusted for inflation). Space based tissue engineering could possibly save tens of thousands of lives and has the potential of saving the US health care industry billions of dollars.

Space-based manufacture of recombinant drug could represent a substantial market. Recombinant protein drugs and diagnostic agents are one of the fastest growing segments of the pharmaceutical industry generating US$20 billion in annual revenues. Microgravity production of recombinant drugs offers the potential of improved quality and yield. An improvement in yield of only a few percent has the potential to save millions in production costs.

The LEO Passenger Travel market is exhibiting a growing demand for LEO passenger services. Unlike many other s-Business opportunities, this market is exerting a "pull" for products to supply LEO Passenger transportation and infrastructure services.

While biotechnology firms are aware of some of the advantages of microgravity, very few have performed microgravity experimentation for the manufacturing of biotechnology products. Like the semiconductor industry, biotechnology firms are in an extremely competitive and risky market space. Also like the semiconductor industry, biotechnology firms spend between 10% and 15% of their annual revenues on R&D. In addition to the actual products identified as part of this study, and their potential revenues, there is a significant demand for unique research and development facilities, which would likely include an orbital R&D laboratory. The biotechnology industry has US$365 billion in global annual revenues, which translates to between US$700 million and US$1.05 billion in weekly R&D expenditures. The benefits of an orbital R&D facility to this industry are significant. Although AS&T has insufficient data to develop an accurate elasticity curve, our research indicates that there would be significant interest if a space transportation infrastructure could support the biotech industry's business and research requirements. At this time, these are nebulous because so little applied research and product development has been done in this area. Increased access to laboratories on the International Space Station and from commercial services will be a necessary precursor to large-scale development of an on-orbit biotech research and production market.



LEO Passenger Market

The LEO Passenger Travel market is real and exhibiting a growing demand for LEO passenger services. Unlike many other s-business opportunities, this market is exerting a "pull" for products to supply LEO Passenger transportation and infrastructure services. During 2000, multiple companies; including MirCorp's "Citizen Explorer", BrainPool's "Space Commander", and NBC's "Destination Mir" television program; announced intentions to fly "citizen explorers" to orbital destinations, many as part of entertainment endeavors. The value of these commitments, publicly listed as US$20 million per flight, is estimated at US$140 million. World wide, the tourism industry has US$1 trillion in annual revenues, with US$200 billion of those coming from adventure travel related activities. Given that the current market can support demand at US$20 million a ticket (for Dennis Tito), market growth potential is significant. Kelly Space & Technology, as part of their NASA NRA8-27 effort, conducted a survey and placed the demand at 10,000 tourists a year at a ticket price of US$400,000, which would yield annual revenues of US$4 billion at that price point. This value is consistent given the adventure travel industry revenues (US$200B). As part of this study, Andrews Space & Technology did not have the resources to conduct a thorough demographic study. Our effort was focused on interviewing the airline industry, gauging their interest in the space travel market, and using the interviews to derive space transportation design requirements. However, we strongly recommend that a broader sampling (Kelly's survey, conducted by Harris Interactive, interviewed 2000 people in the United States) would benefit the business case development and aerospace industry acceptance of the market's credibility.

During 2000, multiple companies announced intentions to fly "citizen explorers" to orbital desinations, many as part of entertainment endeavors including MirCorp's "Citizen Explorer", BrainPool's "Space Commander", and NBC's "Destination Mir" television program. The value of these commitments, publicly listed as US$20 million per flight, is estimated at US$140 million.

2nd Gen RLV System Requirements Derivation

AS&T analyzed the data collected from the interview process and utilized a system engineering process to identify a broad requirements set of 50 requirement / attribute pairs. The various attribute/requirement pairs were chosen to reflect the needs of the markets that are to be served, while maintaining the minimum number of limitations imposed on the transportation system designer. All of the collected attributes were sorted in six major categories (Scheduling, Operations Performance, Interfaces, Business, and Provider Specific), including the important distinction between requirements imposed by the customer of a space transportation industry (Customer Specific), and those determined by the "space-line" and imposed on the vehicle manufacturer directly (Provider Specific).

Requirements values were derived for each individual market segment and the most limiting values distilled based on the investigated markets (see Table A as an example). Based on the three markets analyzed, the Space Travel market has the most limiting requirements (Figure C). The current uncertainty of these numbers is significant, but the accuracy of the model will further increase with the collection of additional data.

Table A: Comparison of Market Requirements Severity

4-2-10 Pressure Environment	
Range of pressure and maximum rate of change acceptable to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	0 – 2 atm
LEO Travel Market	FAR Part 25 Subpart D Sec 25.841
Limiting Values	**FAR Part 25 Subpart D Sec 25.841**

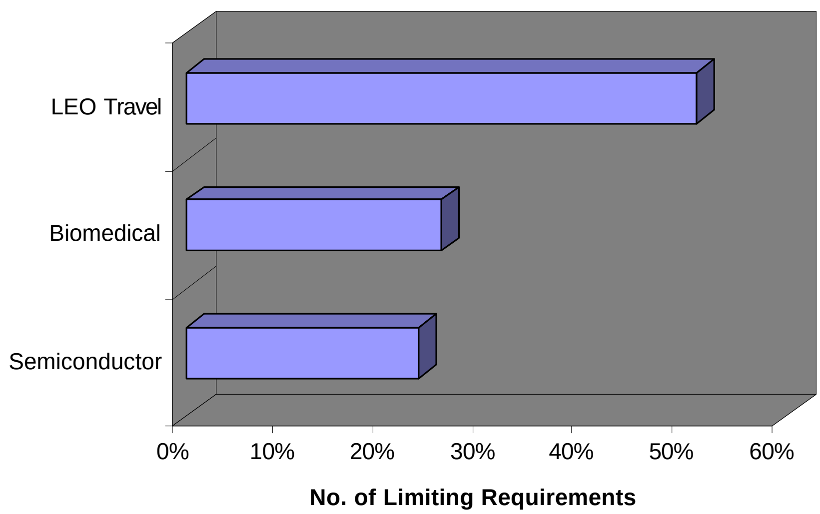


Figure C: Comparison of Market Requirements Severity

Summary

This study examined three future space markets. Of the three, one, microchip manufacture showed limited in application as a space market driver. The other two, biomedical processing and adventure travel showed high potential for near term mission applications and large revenue potentials

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LIST OF ABBREVIATIONS

AMD	Advanced Micro Devices
AS&T	Andrews Space & Technology
BRL	Business Readiness Level
CD	Compact Disk
CDR	Critical Design Review
CSTS	Commercial Space Transportation Study
DRM	Design Reference Mission
DSP	Digital Signal Processor
DVD	Digital Versatile Disk
FSTS	Future Space Transportation Study
GDP	Gross Domestic Product
GTO	Geostationary Transfer Orbit
HDTV	High Definition Television
IC	Integrate Circuit
ICA	Integrated Commercial Architecture
ISS	International Space Station
JSC	Johnson Space Center
L/V	Launch Vehicle
LBP	LEO Business Park
LEO	Low Earth Orbit
MOE	Measure of Effectiveness
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PC	Personal Computer
PDR	Preliminary Design Review
PHLC	Primary Human Liver Cells
QRL	Quick Reference Legend
RLV	Reusable Launch Vehicle
RWV	Rotating Wall Vessel

S/C	Spacecraft
SCG	Silicon Crystal Growth
SCP	Semiconductor Circuit Production
SELETE	Semiconductor Leading Edge Technologies
SEMI	Semiconductor and Equipment International
SEMI	Semiconductor Equipment and Materials International
SOW	Statement of Work
SSTO	Single Stage To Orbit
TI	Texas Instruments
TRL	Technology Readiness Level
TV	Television

1 Introduction

AS&T is convinced that near term business opportunities for space based activities of non-aerospace companies do exist; and will be the driving factors in the development of next generation launch vehicles.

This document is the final report for NASA NRA8-27 (Future Space Transportation Study, FSTS-1) provided by Andrews Space & Technology to NASA Marshall Space Flight Center.

Figure 1: Mission Model Forecasts Market Traffic

Figure 1 provides a sampling of some of the organizations and companies actively conducting or planning business in space. The space agencies and government organizations of the world have been actively developing technologies and proving operations of space systems. Companies have begun to employ those technologies to provide products and services which they are marketing commercially. Since most companies involved in space commerce have been doing business to supply and service government space activity for many years that market sector is fairly well characterized and understood. During the 1990s forecasts for the commercial GSO satellite market segment has steadily improved, with annual forecasts being produced by the Commercial Space Transportation Advisory Committee (COMSTAC) which advises the Federal Aviation Administration (FAA) Associate Administrator for Commercial Space Transportation. A companion forecast of the commercial NGSO satellite market segment is provided by the same office. However, forecasts for future commercial markets are only just now being undertaken.

1.1 Background

Considerable scientific research has been undertaken to explore the opportunities that low-Earth-orbit might present to utilize the space environment. Very little of that study effort has investigated how the research might be translated into business opportunities. There has also been very little effort dedicated to understanding what the transportation requirements to serve these new markets might be, until now. Andrews Space & Technology has developed and implemented the first phase of the Future Space Transportation Study (FSTS-1) as a part of NASA's 2nd Generation Reusable Launch Vehicle Risk Reduction Program. Currently, the space industry is working hard to significantly improve safety and reliability, and moving towards "airline type" operations for the next generation of space access. As part of these efforts, resources have been allocated to identify non-aerospace companiesthat could profit from doing business in space. AS&T is convinced that near term business opportunities for space based activities of non-aerospace companies do exist; and that they will be the driving factors in the development of next generation launch vehicles.

In Phase 1 of the FSTS effort, AS&T has endeavored to survey a diverse cross-section of potential future markets through sound analysis, direct interaction with the potential market users, and subsequent analysis of customer feedback. While this study does not claim to be comprehensive (only 20% of the identified future markets were analyzed), the resulting data provides a broad-spectrum insight into the emerging space business opportunities and their associated demands and expectations of the space launch service industry.

1.2 Intended Audience

This report is comprehensive and does not assume familiarity with any previous publications on the FSTS effort. It is intended as a guideline to long-term policy and decision makers, who wish to base their strategic planning on observable market trends for future space transportation demand. In addition, this report documents the FSTS study methodology, and analysis results; whose accuracy may be continually improved through repeated execution with a growing number of industries and their representatives.

1.3 Study Scope & Objectives

S-commerce, or S-business, is the use of space by a company to provide products and services. Space commerce is presently made up of companies that manufacture and operate launch vehicles, satellites and related ground infrastructure, including spaceports, teleports and ground terminal/receiver equipment. These products and services serve commercial, civil and military customers. Total revenues of the world space industry (excluding the countries of the former Soviet Union and China) currently totals approximately US$100 billion annually. In the future, space commerce will continue to see revenue growth while expanding to include many companies and industries, not traditionally thought of as users of space, which will begin to incorporate the use of space resources into the development and use of their services and products. The markets focused on during this phase of the study were selected based on an assessment that they might offer products or services which could "earlier" take advantage of space, as well as serving markets sufficiently large and competitive to warrant the risk and investment to use space. Phase 1 of FSTS focused on the following markets:

- Semiconductor Research and Fabrication
- Biomedical Research and Production
- LEO Adventure Travel & Space Tourism

The microchip fabrication market was selected based on prior work in this area. Wafers and chips are very high value/low mass products and the highly competitive semiconductor industry is among the largest industries in the world. The biotech/medical product opportunities were selected because they are high value/low mass products for which space might provide unique advantages and opportunities, and it is a highly competitive industry with high profits and risks. Adventure Travel/Space Tourism was selected because the tourism industry is very large with statements emanating from the industry actually asking for products that would permit their clientele to access space.

1.4 Study Process

The NRA8-27 activity, which AS&T termed the Future Space Transportation Study (FSTS), uses a multiphase analysis process to identify possible future commercial markets and flow down requirements to the space transportation system vehicle level. The complete roadmap of the FSTS effort, with its intermediate and final data products, is illustrated in Figure 2. Although the diagram flows from left to right, in actuality the process derivation started at the right side with 2nd Generation RLV Design Requirements and worked backwards through the business process.

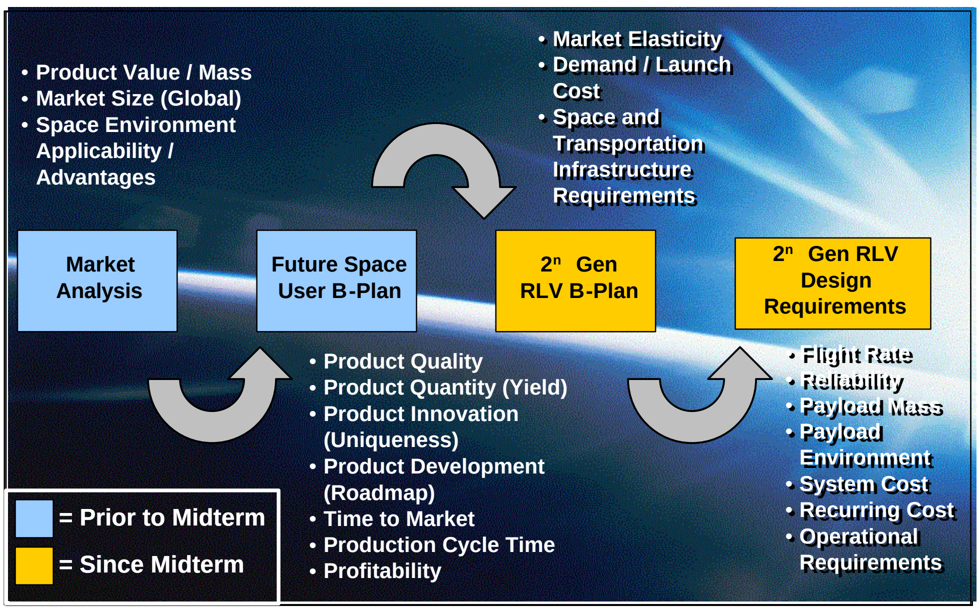


Figure 2: Future Space Transporation Study Process

1.4.1 2nd Generation RLV Business Case

The driving force for determining the 2nd Generation RLV Design Requirements is the 2nd Generation RLV Business Plan. From the business plan key design requirements, or attributes, can be determined. These include flight rate, system reliability, payload performance, launch environments, system cost, recurring cost and operational requirements. These attributes are essentially the system level Second-Gen RLV design requirements, from which the stage and subsystem requirements are derived.

1.4.2 Future Space User Business Case

Continuing to work backwards, the 2nd Generation RLV Business Plan is predicted on the business plans of its customers. The information derived from the customer's business plans; such as market elasticity, demand versus launch price, and infrastructure requirements; is used to develop the 2nd Generation RLV business case.

The 2nd Generation RLV Business Case and the Future Space User Business Case, as described above, can be performed either individually or in an integrated fashion. Regardless, these two activities are highly inter-dependent. Because of this, Andrews Space & Technology has placed particular emphasis on studying future markets in conjunction with their derived design requirements.

1.4.3 Market Analysis

The precursor to developing the Future Space User Business Case is identifying companies or industries that can benefit from doing business on-orbit. These companies must have one, if not several, compelling reasons to relocate portions of, or expand, their business to a space based facility. Specific reasons include improvements in product quality, product quantity, the product's uniqueness, the ability to enable a new product or market, reductions in time to market, and reductions in production cycle time. All of these lead to an improvement in the company's bottom line or ability to turn a profit.

1.5 Document Organization

The organization of this report follows the FSTS process roadmap illustrated in Figure 2 above. Following this introduction, the rationale of the study methodology is discussed in detail in Chapter 2. In Chapter 3, the markets chosen for this phase of the study are discussed in detail and the results of industry interviews are presented. Chapter 4 presents an example of the RLV system requirements, which can be expected to flow from the mission model.

2 Study Methodology

In this section, the study methodology used to implement the developed process is illustrated. A description of the methodology and each of its individual component steps is followed by the definition of Market Analysis Metrics. Lastly, the Transportation System Attributes used to define 2nd Generation RLV Design Requirements are also listed.

2.1 Task Flow and Definition

Andrews Space & Technology implemented the outlined process (Section 1.3) by developing an approach that is divided into four distinct phases, interleaved with two interviews with each selected industry representative. Figure 3 provides an illustration of the process.

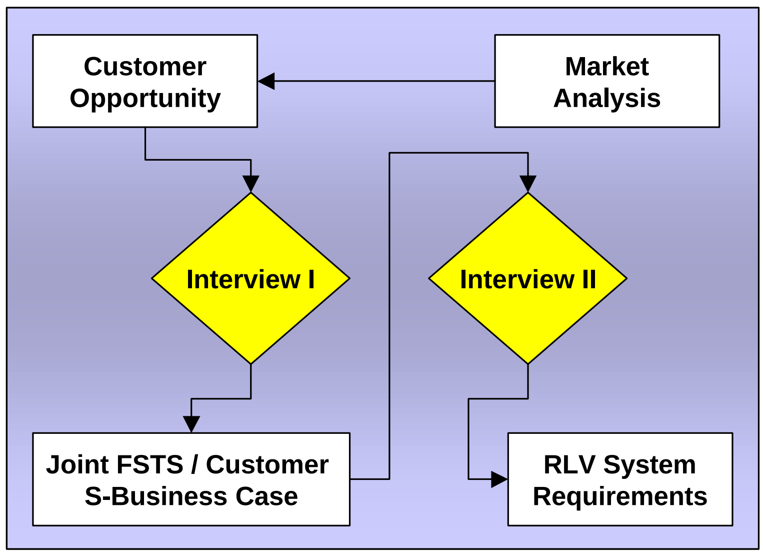


Figure 3: FSTS Analysis Process Overview Chart

2.1.1 Market Analysis

In the initial market analysis step, the targeted market is gauged by applying the defined Measures of Effectiveness (MOE). The following MOE's were defined:

- Business Readiness Level (BRL)
- Utilization of Space Unique Resources
- Product Value per Unit Mass
- Value Chain Intersection with Space Unique Resource
- Market Size
- Market Trends
- Space-based Market Concept Maturity

If the market was found to be attractive as indicated by these metrics, it became a candidate for the next step in the process.

2.1.2 Customer Opportunity

Prior to soliciting interview opportunities with industry representatives, the identified market was analyzed for emerging customer opportunities. The following criteria were particularly emphasized in this activity:

- Product Quality
- Product Quantity (Yield)
- Product Innovation (Uniqueness)
- Product Development (Roadmap)
- Time to Market
- Production Cycle Time
- Profitability

After these parameters had been investigated, a plausible business scenario/concept was put forth to selected industry representatives.

2.1.3 Interview 1

Andrews Space & Technology created a brief (4.5 minute) video that characterizes the opportunity of future commercial space and develop multimedia modules targeted toward the specific Future Commercial Markets to be analyzed as part of FSTS-1. In addition, AS&T interviewed selected future users to develop a business concept with adequate return on investment to interest the users' upper management.

In the first of two interviews, initial reactions were solicited from select industry representatives. Interview candidates were chosen based on the company's likelihood of mounting the investment effort needed to successfully execute the proposed scenario, and competitiveness in the chosen market.

Interviews consisted of a brief presentation of the proposed scenario, followed by a questioning and discussion session for a total duration of approximately 90 minutes.

2.1.4 Joint FSTS / Customer S-Business Concept

Once the initial interview activities had been completed, AS&T proceeded to develop joint space transportation / customer industry business concepts. These were based on the comments obtained from the initial interviews and AS&T's engineering feasibility analyses.

2.1.5 Interview II

In the follow-up interview, the industry representative was presented with the joint business concept to generate additional comments and identify those areas of the proposed
s-business scenario particular attractive to the commercial industry.

2.1.6 Transportation System Requirements

In this final analysis step, AS&T derived the system level launch vehicle requirements from the provided customer input using AS&T's RLV design experience.

2.2 Market Analysis Metrics

A number of measures of effectiveness have been identified and used in this study to permit assessment of the business readiness level of candidate products and services.

These metrics are based on repeatable data to permit independent and objective measure between different products and industries, and to allow comparison between terrestrial and space-based approaches. The use of a methodical approach allows for the rapid screening, ranking and assessment of candidate opportunities.

2.2.1 Technology Readiness Levels (TRL)

Technology Readiness does not necessarily coincide with Business Readiness. As a result, AS&T developed a Business Readiness Level system to track product development and business maturity.

Most commercial products are based on existing technology that has been previously demonstrated or is already in use. Products may use a technology in new ways, or combine several technologies to offer a new or different value to their customer, but rarely will a successful commercial product employ unproven or undeveloped technologies. The maturity and usability of a technology can be measured by using NASA's Technology Readiness Level (TRL) measure, which is shown in Table 1.

Table 1: Technology Readiness Level Definitions.

Basic Technology Research:	
TRL 1	Basic principles observed and reported, research to prove feasibility.
TRL 2:	Technology concept and/or application formulated.
TRL 3	Analytical and experimental critical function and/or characteristic proof of concept.
Technology Demonstration	
TRL 4:	Component and/or breadboard validation in laboratory environment.
TRL 5:	Component and/or breadboard validation in relevant environment.
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space).
TRL7:	System prototype demonstration in a space or operational environment.
System Test, Launch, and Operations:	
TRL 8:	Actual system completed and "flight qualified" through test demonstration (ground and space).
TRL 9:	Actual system "flight proven" through successful mission operations.

However, even though a technology may be mature enough to be incorporated into a commercial product, technology readiness is an insufficient condition in itself for a technology to be developed into a product.

2.2.2 Business Readiness Levels (BRL)

NASA has an established measurement of technical risk defined as the Technology Readiness Level. In order to provide an equivalent metric to categorize the business risks, AS&T has developed a Business Readiness Level (BRL) system. Table 2 outlines these BRL metrics.

Every product goes through a sequence of activities as it is developed for a market. These activities correspond to the Business Readiness Levels defined in Table 2.

Table 2: Business Readiness Level Definitions.

BRL Level	BRL Definition
BRL 1	Technology concept observed and reported. Initial finance spreadsheet developed.
BRL 2	Technology concept defined and initial financial model developed.
BRL 3	Program SRR and initial Business Plan developed.
BRL 4 (Authority to Offer)	Program PDR and Business Plan updated with new market projections and system costs. Initial meetings with potential customers and investors.
BRL 5	Subsystem testing completed and Business Plan refined with more accurate system costs. In negotiations with potential customers and investors. Finance team in place.
BRL 6 (Authority to Proceed)	Program CDR (90% drawing release). Final Business Plan with new market projections and system costs. Anchor tenant signed up. Investors lined up and ready to commit significant money.
BRL 7	First implementation ready for testing. Program 70% financed. First year customers signed up.
BRL 8	First industrial implementation tested. Second instance in final assembly. Program 90% financed. Two years of customer backlog.
BRL 9 (Initial Operating Capability)	Industry in commercial operations, fully financed, with operating customer backlog.

2.2.3 Utilization of Space Unique Resources

Space provides a number of resources that can individually or collectively add monetary or technical value to an enterprise. These same resources can also be detriments to space based enterprise. Some of these resources are unique to space, others, while not unique to space, can add value to the product. Table XXX, outlines the attributes of the space medium, and how they may benefit a product or business. Mapping these space resources against an industry's value chain can identify where space-based opportunities might exist.

For each product opportunity, space resources have been mapped against the industry value chain to determine which space resources provide positive and negative opportunities. As an example, Figure 4 shows the Quick Reference Legend (QRL) for the semiconductor industry.

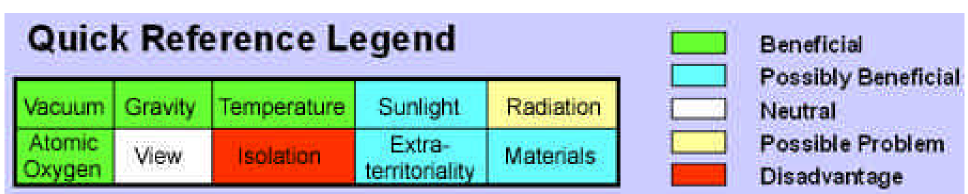


Figure 4: Semiconductor Market Quick Reference Color Legend

Table 3: Space Unique Resources and Associated Benefits (Source: CSTS Report, 1994).

Feature	Description	Explanation	Benefits to Users
Vacuum	10E-3 to 10E-13 Pa	Easy Access to vacuum several orders of magnitude harder than economical / feasible in Earth laboratories	Ultra-cleanliness; rapid outgassing; high-precision analysis & fabrication; vacuum-dependant processes (atomic / molecular deposition, sputtering, etc.).
Gravity	Variable: ?g to hyper-g	Tethered / rotating facilities decouple weight from mass, allowing variable control of fundamental physical "constant"	Buoyancy cancellation or emphasis, convection; container less processing; diffusion dominance or suppression, surface tension, film behavior; novel kinetics (micro & macro); macro-structures
Temperature	200 to 350 K (passive) Source (sun) 5780 K Sink (dark sky) 3 K	Wide range using passive techniques; hard vacuum facilitates achieving / using extreme temperatures (cryogenic, high-temp with solar or nuclear)	Uses benefiting exclusively radiative transfer; long-term thermal stability; superconductivity; IR observation; thermal processing
Sunlight	1470 W/m^2	Unattenuated solar spectrum; can be virtually constant	Non-depletable energy source for thermal use or reliable electrical power; UV source; export to space and Earth users
Radiation	MeV – GeV particles, weak-flux trans-UV photons	Geomagnetically trapped e^- and P, episodic solar proton events (high or polar orbits); cosmic rays; controllable with collimated shielding, filters	Irradiation-mediated chemical / biological sample processing;
Atomic Oxygen Ram Flux	v~8km/sec (@300km) ~10-19 $m^{-2}sec^{-1}$	Extremely erosive to oxidation-susceptible materials	Chemical milling, etching & sputtering processes
View	Optically unimpeded ever-changing Earth view	Orbit-dependant; map-like overview of geology, meteorology, ecology, sociology, technology; best astronomical clarity (full-spectrum).	Astronomy; long-range optical monitoring: Earth sciences; security; entertainment imagery; new, unique type of tourism
Isolation	Infinite room; proximity controllable, costly, detectable	No ecology-based environmental restrictions; extremely limited opportunities for information leaks, espionage, oversight, interference	Hazardous chemistry / bio processing; nuclear activities (orbit dependant); greater freedom for all activities
Extra-territoriality	Orbits inherently trans-national	Affiliation selectable; choice of regulatory regimes and legal precedents / statutes; opportunity for novel arrangements	Flexibility to design conducive business arrangements
Materials	Unlimited variety & quantity	Not immediately available; asteroidal / lunar sources; retrieval requires extensive, interplanetary operations infrastructure	Heavy manufacturing; material export (incl. Pt-group); space settlement; eventual autonomy from Earth

2.2.4 Product Value per Unit Mass

The start-up phase of commercial reusable space transportation will likely follow historical trends, where the focus is on products will likely have a high value/low mass characteristic. Shipwrights and aircraft manufacturers produced vehicles exhibiting a dependency on markets that were high value/low-mass/low-volume as they developed and introduced their earliest vehicles. During the early days of reusable space transportation, there is a greater likelihood that space manufacture of a pharmaceutical product or semiconductor chip in space will be much more profitable than producing ball bearings. It is also likely that early products will more likely address the higher end of their respective markets, requiring more challenging quality, but commanding higher prices, and being produced at lower volumes; volumes more readily achievable by startup systems. Products and markets were screened and ranked for high value/low mass “units” to identify candidate product opportunities.

2.2.5 Value Chain and Space Resource Intersection

Value chains are the key to understanding Space Business Opportunities.

Every industry, as well as each company within an industry, has a unique approach to doing business. The value chain of an industry includes customers, design/research labs, manufacturers (prime), suppliers, distributors, regulators, investors (investment banks, stock analysts, tracking stocks/funds, venture capitalists…), transportation providers, trade associations, trade/technical journals publishers, advertisers, and academia / universities that uniquely serve each industry. The way these entities interact with each other and exchange money for products define a value chain.

Each step in the value chain can be mapped against the resources that are unique to space. For many steps, space has a neutral, no-value added/lost effect, and for some steps, space may be marginal to severely detrimental. However, there will be steps that are identified where space can add value to the business activity.

An opportunity for space to add value to a business process exists, when the mapping of space resources with a step within the value chain, intersects. For example, a process that uses vacuum would intersect with the space resources list. An opportunity might exist for space based vacuum processing of the product. Further analysis of the opportunity would be required to determine if space offers value-added benefits.

2.2.6 Market Size

The market has to be large enough for the provider of a commercial product to obtain a profit on investment. Most of the numbers are non-existent or closely held; as a result, inference is required to assess a market’s potential. The numbers that characterize a market include:

- Revenues (annual profitability)
- Units (number, unit wholesale costs)
- Number of companies
- Cycle time (order to delivery)
- Number of factories (new factory starts per year, non-recurring/recurring factory costs, factory operational life)
- Research expenditures (total market)

In addition, market maturity is of interest. This parameter can be partially measured by the penetration of the product into its customer base, which includes penetration by geographic region and use. The applications towards which an industry is targeting its research expenditures can suggest areas of future growth and market size.

The processes, and sometimes equipment, for most markets have applicability in related or similar industries and products. Once research is undertaken, and processes/equipment developed for one industry, in many cases, it can be quickly adapted and adopted for related products. For example, on orbit production of wafers for semiconductors may not be competitive with terrestrial factories, but the process to produce solar power panels and flat-panel displays is closely related, using much of the same equipment. It thus faces similar production problems and challenges. Solar Power panels can be produced cheaply and readily on Earth, so it might not be a candidate at this time for on-orbit manufacture. However, yields for large flat panel displays have stayed very low, and shifting their production to space might dramatically improve yields.

2.2.7 Market Trends

Forecasts are always a suspect to assumptions, and process idiosyncrasies. However, used carefully and correctly they can suggest future trends, as well as opportunities. Year to year changes in revenues, number of units sold, companies entering/leaving the industry, factory investment, etc. can indicate possible market trends. The overall market trend can be reflected in revenue growth/decline, and growth/decline in the number of units produced. Characteristics of product evolution might be reflected in changes in mass, volume, power, reliability, feature sets, etc. For example, the trend in commercial satellites has been declining mass used for structure and propellant, with that now available mass used to provide more capable revenue producing feature sets. This is possible due to the continued miniaturization of electronics, a shift in structures from metals to composites, and advances and changes in propulsion systems. While permitting the product to serve a broader customer set, increasing (hopefully) overall revenues (for a variety of reasons costs often decline as improvements accrue), this has ramifications for other products, such as future space launch systems, which may need to provide more lift and volume capabilities.

2.2.8 Space-Based Market Concept Maturity

In order to develop a business case, a product concept baseline must be established so that the engineering complexity and costs can be evaluated. In addition, any space-based product/process must be compared against terrestrial equivalents. The concept needs to be of sufficient detail so that it is clear the process is complete enough to produce the product. This should drive out a facility lay-out for a selected production rate, which in turn should provide enough detail to measure the up and down traffic (mass, volume, frequency, etc.) required for the manufacture of the product to be profitable. As the concept matures, non-recurring activities and costs, as well as recurring activities and costs, may be estimated. Feedstock will be identified, as well as the form of the finished product, which can suggest requirements for the up/down elements of the space transportation system.

Industries will most likely take advantage of space incrementally. While possible, it is unlikely that an existing terrestrial enterprise will move all of its processes, or all of the steps of one process, off-planet all at once. A new enterprise, which has no terrestrial base or legacy, might initiate its manufacturing or service activity in space.

Questions such as the following can be asked, analyzed and possibly answered:

- Can the customer achieve profitability? Can the customer’s customer achieve profitability?
- Can “multiple” revenue streams sustain development and operation of a vehicle or a facility?
- Can a vehicle developer or operator achieve profitability? How about a facility developer or operator?

2.3 Transportation System Attribute Definitions

One of the goals of the Future Space Transportation Study (FSTS) is to derive transportation system and vehicle requirements. In order to provide a consistent methodology between individual market analyses, a list of 50 system attributes was compiled, and the associated requirements extracted from data for each market under consideration. Figure 5 illustrates the definition of the terms “Attribute” and “Requirement” in this context.

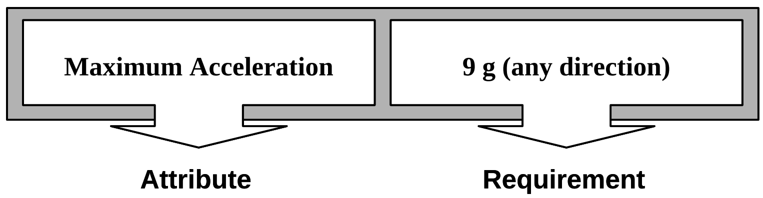


Figure 5: Definition of “Attribute” and “Requirement” Terms

The various attribute/requirement pairs considered in this study were chosen to represent the needs of the market that is to be served, while maintaining the minimum number of limitations imposed on the transportation system designer. All of the collected attributes are sorted in six major categories, each with a number of sub-categories:

1. **Scheduling**
   Payload Schedule
   Operations Schedule
2. **Operations**
   Reliability
   Safety
3. **Performance**
   Payload Mass
   Payload Manifest
4. **Interfaces**
   External Infrastructure
   Payload Accommodations
5. **Business**
   Economics
   Regulatory Agencies
6. **Provider Specific**
   Scheduling
   Operations
   Interfaces
   Business

Category 6 follows from the important distinction of “Customer Requirements” versus “Provider Requirements”. With the exception of the LEO Passenger Travel market, all emerging S-commerce industries investigated in this study are potential customers of a space transportation service provider. The analysis of these markets thus leads to the derivation of Customer Requirements. Requirements derived from the analysis of the LEO Passenger Travel market are Provider Requirements, and are thus listed in a separate category as “Provider Specific”. As an example, from an airplane manufacturer’s perspective, the airline is a provider, the person in first class is a customer. The service provider will impose a cost requirement on the transportation system in order to secure a certain return on investment, the customer only cares about the price he paid for his ticket. Also, note that Customer Requirements are imposed on the transportation system as a whole (including any ground facilities), whereas Provider Requirements tend to be imposed on the vehicle itself.

Note that any given market under investigation may lead to multiple mission scenarios, each associated with its own set of requirements. In particular, delivering something into orbit is viewed distinct from returning it from orbit. This enables the possibility of using a variety of vehicles to serve a single market, each with a specialized role if desirable. Thus, when a requirement refers to a “destination”, it also needs to specify whether this destination lies on orbit or Earth (and similarly for the point of departure).

Table 4 lists the headings of all 50 attributes identified for the purpose of this study. Below it, each attribute is described in detail. The corresponding requirements are listed in the discussion section of each market analysis and summarized in Chapter 4.

Table 4: Transportation System Attributes Listing.

Number	Attribute Heading
1-0-0	**Scheduling**
1-1-0	*Payload Schedule*
1-1-1	Payload Processing Time
1-1-2	Pre-Departure Idle Time
1-1-3	Transit Time
1-1-4	Post-Arrival Pad Time
1-2-0	*Operations Schedule*
1-2-1	Advance Booking Time
1-2-2	Departure Window
1-2-3	Access Notification
2-0-0	**Operations**
2-1-0	*Reliability*
2-1-1	Successful Delivery
2-1-2	Service Availability
2-1-3	On-Time Delivery
2-2-0	*Safety*
2-2-1	Emergency Egress
2-2-2	Abort Capabilities
2-2-3	Catastrophic Failure
3-0-0	**Performance**
3-1-0	*Payload Mass*
3-1-1	Payload Mass
3-1-2	Payload Rate
3-2-0	*Payload Manifest*
3-2-1	Multiple Destinations

Number	Attribute Heading
3-2-2	Multiple Payloads
4-0-0	**Interfaces**
4-1-0	*External Interfaces*
4-1-1	Facility Location
4-1-2	Infrastructure Attributes
4-1-3	Payload Processing
4-2-0	*Payload Accommodations*
4-2-1	Payload Volume
4-2-2	Acceleration Loads
4-2-3	Processing Orientation
4-2-4	Data Interface
4-2-5	Deployment Parameters
4-2-6	Shock Environment
4-2-7	Vibration Environment
4-2-8	Acoustic Environment
4-2-9	Temperature Environment
4-2-10	Pressure Environment
4-2-11	Payload Consumables
4-2-12	Structure Interface
4-2-13	Atmosphere Composition
4-2-14	Impact Prevention
4-2-15	Radiation Protection
4-2-16	Illumination
5-0-0	**Business**
5-1-0	*Economics*
5-1-1	Standardization
5-1-2	Price Stability
5-1-3	Specific Payload Price
5-1-4	Evolvability
5-2-0	*Regulatory Issues*
5-2-1	Regulation
5-2-2	Service Globalization
6-0-0	**Provider Specific**
6-1-0	*Scheduling*
6-1-1	Turn-Around Time
6-1-2	LRM Exchange Time
6-2-0	*Operations*
6-2-1	Ops Reliability
6-3-0	*Interfaces*
6-3-1	Support Equipment
6-4-0	*Business*
6-4-1	Specific Payload Cost
6-4-2	Technology Globalization

The following sections detail the definition of each attribute / requirement pair. Note that the heading numbers do not correspond to the requirement numbers, which have been included in parenthesis behind the heading for reference.

2.3.1 Scheduling (1-0-0)

Payload Schedule

1-1-1 Payload Processing Time: Time from payload delivery to the carrier to payload being fully integrated into the vehicle.

1-1-2 Pre-Departure Idle Time: Time from sealing the vehicle to departure.

1-1-3 Transit Time: Time from departure to arrival (min/max). This requirement may address the need for loiter times, shelf-live restrictions of components (e.g. batteries), or passenger comfort in addition to product cycle-times or other economical considerations.

1-1-4 Post Arrival Idle Time: Time from vehicle arrival until the payload is made available to the customer.

Operations Schedule

1-2-1 Advanced Booking Time: Maximum and minimum lead time acceptable to the customer when booking a payload manifest.

1-2-2 Launch Window: Maximum delay the system can absorb and still launch successfully.

2.3.2 Operations (2-0-0)

Reliability

2-1-1 Successful Delivery: Probability of the vehicle delivering the customer payload successfully and as scheduled.

2-1-2 Service Availability: Probability of a flight being available when requested by a customer (assuming minimum lead-time is observed).

2-1-3 On-Time Delivery: Probability of the customer payload departing and arriving on time. Note that this includes the activities of pre and post payload processing, and is thus the probability of the entire system.

Safety

2-2-1 Emergency Egress: Any required emergency Egress capabilities for crew, cargo or passengers.

2-2-2 Abort Capabilities: Any required vehicle, landing site, and operations capabilities for abort scenarios.

2-2-3 Catastrophic Failure: Maximum probability of catastrophic system fault (loss of payload) acceptable to the payload customer.

2.3.3 Performance (3-0-0)

Payload Mass

3-1-1 Payload Mass: Maximum and/or minimum mass for any single payload to be transported.

3-1-2 Payload Rate: Anticipated rate of payload mass transported per year of customer / provider relations.

Payload Manifest

3-2-1 Multiple Destinations: Minimum and maximum number of destinations for a single mission flight.

3-2-2 Multiple Payloads: Number of payloads and distinct payload types for a single flight.

2.3.4 Interfaces (4-0-0)

Requirements related to the interface of the transportation system to infrastructure type facilities as well as the payload itself.

External Interfaces

4-1-1 Facility Location: Desired locations of transit departure and arrival. This is not necessarily identical to the location of payload processing (see 4-1-3).

4-1-2 Infrastructure Attributes: Types of infrastructure the vehicle is required to be compatible with during nominal operations (commercial airport, spaceport, specific launch ranges, national or geographic locations, ISS, Mir, etc.).

4-1-3 Payload Processing: Limitations on facility type / location / capabilities (cleanroom specifications, security, passenger amenities, etc.) where the payload is handed to the service provider.

Payload Accommodations

4-2-1 Payload Volume: Range of three-dimensional volume the payload may occupy. Note that a maximum as well as a minimum is of interest, since very small, yet massive and/or fragile payloads are conceivable (high value small crystals, super dense exotic materials, etc) and may require specific accommodations.

4-2-2 Acceleration Loads: Level, direction and duration of maximum acceleration sustainable by the payload.

4-2-3 Processing Orientation: Any limitations on the orientation in which the payload can be loaded onto the vehicle (horizontal vs. vertical).

4-2-4 Data Interface: Requirements on the type, rate, direction, and interface of data transfers required by the payload while in the supervision of the carrier. Also, specifications for any particular mission segment during which the data transfer is required (if applicable).

4-2-5 Deployment Parameters: Attitude, rotation rates, and relative velocity requirements (with associated accuracy) imposed by the payload customer for the payload if deployed in flight. (This requirement has no value if the payload is loaded/unloaded at external infrastructures.)

4-2-6 Shock Environment: Level and direction of maximum shock loads the payload may be subjected to.

4-2-7 Vibration Environment: Level, mode and spectrum of maximum vibration loads acceptable to the payload. This includes the first fundamental resonant frequency for cargo items.

4-2-8 Acoustic Environment: Level and spectrum of maximum acoustic loads acceptable to the payload.

4-2-9 Temperature Environment: Range of temperature and maximum rate of change acceptable to the payload customer. Note that this does not include heat rejection and absorption requirements, which are covered under 4-2-11 “Payload Consumables”.

4-2-10 Pressure Environment: Range of pressure and maximum rate of change acceptable to the payload customer.

4-2-11 Payload Consumables: Type, amount and rate of consumables required/rejected by the payload. Including heat, electrical power, fluids (N_2, O_2, water, etc.) and solids (e.g. food, refuse, etc.).

4-2-12 Structure Interface: Type and restrictions of the structure interface required by the payload (e.g. Marmon Clamp, Passenger Seat, etc.).

4-2-13 Atmosphere Composition: Composition of the atmosphere (if any) that the payload is exposed to during transit.

4-2-14 Impact Prevention: Maximum probability of penetrating debris impact acceptable to the payload customer.

4-2-15 Radiation Protection: Type and intensity of radiation levels acceptable to the payload customer.

4-2-16 Illumination: Level and spectrum of illumination(s) required inside the payload compartment during all mission phases. May include specifications such as "window seats".

2.3.5 Business (5-0-0)

Requirements related to the business and political concerns of the payload customer.

Economics

5-1-1 Standardization: Any customer imposed requirement with the goal of encouraging open standardization as to avoid captive-customer scenarios

5-1-2 Price Stability: The maximum percent fluctuation the specific payload price may exhibit over time without disabling the customer business case or product market.

5-1-3 Specific Payload Price: The price per unit mass of payload delivered to its destination charged by the service provider to the payload customer.

5-1-4 Evolvability: Requirements on the systems ability to adapt to changing requirements.

Regulatory Issues

5-2-1 Regulation: Required regulatory standards for customer payload accommodation.

5-2-2 Service Globalization: Any requirements on the international availability of services required by the payload customer.

2.3.6 Provider Specific (6-0-0)

Provider specific requirements are of interest to the industry providing the transportation service to the payload customers, but not to the payload customer itself.

Scheduling

6-1-1 Turn-Around Time: The total time from the vehicle's arrival to the next scheduled departure. Note that this is not identical with vehicle turn around time, since the requirement states only the limitations on the time-interval between flights, and not how many vehicles are utilized in the entire fleet to accomplish compliance.

6-1-2 LRU Replacement: The time needed to replace any Line Replaceable Unit (LRU) of the system.

Operations

6-2-1 Operations Reliability: The percentage of the transportation systems intended lifetime during which it is required to operate fault free and with nominal performance within the design envelope.

Interfaces

6-3-1 Support Equipment: Possible limitations on support equipment interfaces to accommodate legacy infrastructure or COTS availability of system components.

Business

6-4-1 Specific Payload Cost: Cost to the service provider per unit mass of payload delivered to the designated destination.

6-4-2 Technology Globalization: Requirements on international accessibility of LRUs and other support equipment (e.g. ITAR or national security restrictions).

3 Market Analysis

3.1 On Orbit Semiconductor Fabrication

This section shall discuss the market opportunities for On-orbit Semiconductor Fabrication. Two aspects of fabrication were investigated on this report. First, the process of growing silicon crystal ingots and slicing them into wafers shall be investigated. Second, the process of manufacturing the conductive paths of the semiconductor circuit is looked at.

The worldwide semiconductor industry will experience double-digit growth through 2001. The semiconductor market is projected to grow from US$153 billion in 1999 to US$244 billion by 2003.

Strictly speaking a semiconductor is any type of crystalline solid intermediate in electrical conductivity between a conductor and an insulator. This type of material can be treated chemically to transmit and control an electric current. Tiny devices are made using this material and have the ability to control and amplify electronic signals. A number of elements are classified as semiconductors including silicon, zinc, and germanium. These elements have the ability to conduct electrical current, and they can be regulated in the amount of their conductivity. Silicon is the most widely used semiconductor material because it is easily obtained. Silicon is extracted from sand; in ultra-pure form, the controlled addition of minute amounts of certain impurities (called dopants) alters the atomic structure of the silicon. The silicon can then be made to act as a conductor or a nonconductor, depending upon the polarity of an electrical charge applied to it. By extension, devices made with silicon are called semiconductors, and sometimes microchips or "chips."

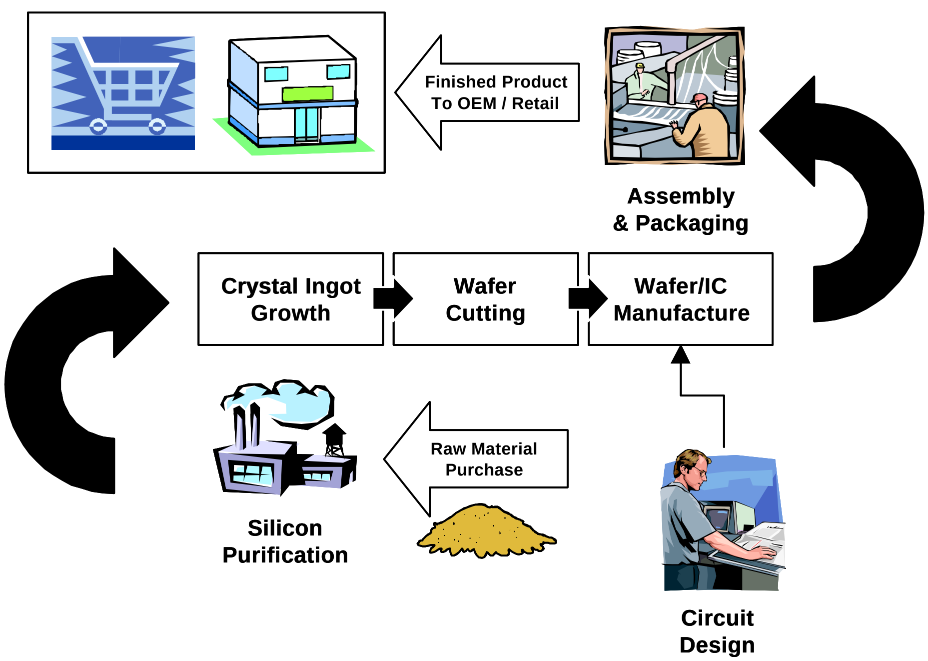


Figure 6: Semiconductor Product Value Chain

Semiconductors fall into two broad categories: discrete devices and integrated circuits (ICs). Discrete semiconductors are single-function electronic components such as diodes, transistors, and optoelectronics. Discrete devices contribute nearly US$12 billion, or 10%, to the semiconductor industry's worldwide sales. ICs are small pieces of silicon into which multiple devices (diodes, capacitors, resistors, and/or transistors) have been microscopically engineered. Digital, analog, or mixed-signal (performing digital and analog functions) ICs perform a variety of functions. The digital IC, made of gates representing on-off switches, is at the heart of the computer and telecommunications revolution and makes up the largest segment of the chip industry, with 70 percent of sales worldwide.

The microprocessor digital IC, comprising millions of transistors, is the "brain" inside a computer. Intel Corporation has an 80% share of the microprocessor market, while rival Advanced Micro Devices has acquired half of the market for sub-US$1,000 PCs. The microcontroller digital IC combines microprocessor and logic and memory functions and is used in everything from home stereos to the security alarms that protect them. Motorola is the top maker of these ubiquitous chips, of which Americans typically encounter 300 each day. The digital signal processor (DSP), which converts sound and light signals into digital information, is used in CD players, digital cameras, and cell phones. Veteran IC maker Texas Instruments is the leading producer of DSPs, which are driving the market demand for improved digital communications. Analog (non-digital) chips process real-world phenomena such as sound, pressure, and temperature. Claiming the remaining 20% of semiconductor sales worldwide, analog ICs are used in thermostats and medical instruments. Figure 6 shows the typical product value chain of the semiconductor industry, for a typical product, all the way from basic natural resources to the finished integrated circuit.

There are a number of areas where the semiconductor value chain intersects with the unique resources that space has to offer. Figure 7 shows the Quick Reference Legend (QRL) for the semiconductor market.

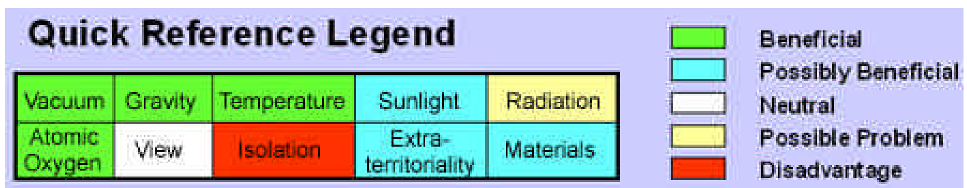


Figure 7: Semiconductor Market Quick Reference Legend

3.1.1 Semiconductor Market Overview

The following three section provide a brief overview of the global semiconductor market; as well as broken down into the three distinct geographical regions of interest.

3.1.1.1 Global Semiconductor Market Size

The semiconductor industry is a relatively new industry, having come into existence within the last 40 years, and having greatly expanded in the last 20 years. The U.S. semiconductor industry is a US$76.6 billion industry and a leading contributor to the nation's economy. Semiconductor manufacturing is the United States fourth-largest industry (after motor vehicle manufacturing, petroleum refining, and vehicle parts and accessories). In terms of value-added the semiconductor industry is now America's largest manufacturing industry -- contributing 20 percent more to the U.S. economy than the next leading industry.

The average wage in the semiconductor industry is approximately US$55,000, nearly twice the average of private industry overall. The industry employs an estimated 260,000 people nationwide, and semiconductor products are the enabling technology behind the U.S. electronics industry, which provides employment for 4.2 million Americans, in all 50 states. The U.S. controls more than 50 percent of the global chip market, while Japan controls about 25 percent, and other Asian countries and Europe control about 20 percent. Top manufacturers include Intel (whose microprocessors are found in 80 percent of all PCs), NEC (Japan's top PC maker), Toshiba, Motorola, and Texas Instruments.

Globally, semiconductor sales add up to more than US$125 billion (expected to hit US$215 billion in 2002). Trends in the next five years promise to bring even more competition to the semiconductor materials field. The industry appears to be moving toward a competitive phase similar to the last half of the 1980s, even while retaining the large annual growth rates of the first half of the 1990s.

Driven by the use of personal computers, consumer electronics, and communications equipment, the worldwide semiconductor industry will experience double-digit growth through 2001. The semiconductor market is projected to grow from US$153 billion in 1999 to US$244 billion by 2003. The Americas will continue to be the leading region of semiconductor revenue through 2003.

3.1.1.2 Regional Semiconductor Market Sizes

Semiconductor revenue in the Americas will grow from US$51 billion in 1999 to US$83 billion by 2003. Asia/Pacific revenue will increase from US$35 billion in 1999 to US$58 billion in 2003. Semiconductor revenue in Europe will jump from US$33 billion in 1999 to US$52 billion in 2003. Revenue in Japan will reach US$35 billion in 1999 and grow to US$51 billion in 2003.

3.1.2 Silicon Crystal Growth & Wafer Production

While one focus of AS&T's study of future space transportation markets focuses on the production of semiconductor integrated circuitry products (microchips, CPU, memory, etc), another possible area of opportunity for space based manufacturing is the production of the silicon wafers used as the raw material for microchip fabrication. This brief overview introduces the approach and the anticipated resulting data from an investigation of that possible future market.

3.1.2.1 SCG & Wafer Production Market Analysis

The manufacturing of silicon wafers ready to be etched with circuitry is a two-step process: the first step is to grow a single crystal silicon ingot of roughly cylindrical shape. In the second step the cylinder is sliced into individual wafers, which are then prepared for circuit deposition.

For the first step of ingot crystal growth, there are significant advantages the space environment has to offer, a more detailed discussion follows below. However, current data indicates that the second step of wafer slicing and preparation, while possible to implement in space, derives no advantages from space unique resources. On the other hand, since ingot growth and circuit manufacturing both appear to derive benefits from an on-orbit location, the intermediate step of wafer slicing should be performed at the same locale. Additionally, no significant disadvantages have been identified for migrating this process to space.

The following sections discuss the possible market opportunities for both the growth of silicon ingots and the subsequent preparation of individual wafers in an on-orbit industrial facility.

3.1.2.1.1 Market Size

Due to the strong increase in the demand for semiconductor circuitry over the past decade, the need for high quality silicon wafers has grown similarly. Figure 8 below shows the world production of silicon wafers during the last year.

While regional fluctuations are apparent, the total world production has steadily increased to a 5.4 billion dollar market, with no indication of slowing down in the foreseeable future.

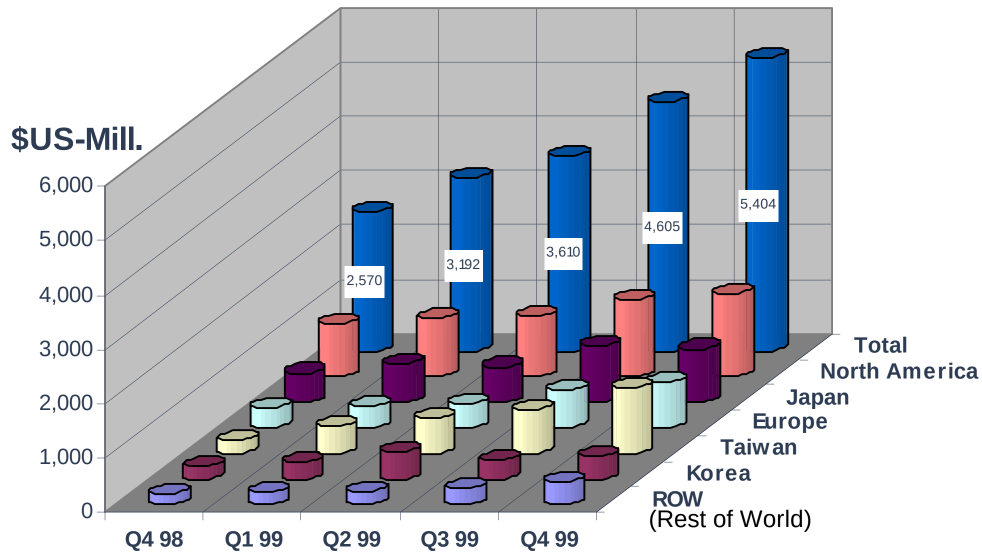


Figure 8: World Production of Silicon Wafers during 1999

3.1.2.1.2 Value Chain Intersection with Space Unique Resources

As shown previously in Figure 6 (page **Error! Bookmark not defined.**), manufacturing a silicon wafer ready for circuit etching is a two-step process, first a single crystal Ingot is grown, and then the ingot is sliced into wafers.

For use in electronic devices, single crystals silicon cylinders are grown by slowly withdrawing seed crystals from molten silicon. Silicon, in the form of cylinders or "ingots", is the primary crystalline material used in the production of 99 % of all semiconductors. Most semiconductor manufacturers obtain single crystal silicon ingots from other firms.

Several techniques are available to grow silicon crystal ingots from seed crystals. The most common terrestrial technique for silicon crystal growth is the Czochralski Process. In order to assess the transferability of this manufacturing technique towards a space-based facility, its terrestrial counterpart will now be briefly discussed.

The Czochralski Process involves bringing into contact a dislocation-free seed crystal and a melt. Single-crystal silicon is obtained by precise and strict control of the rotating rate and pulling rate of a rotational mechanism that suspends the seed crystal over the melt. Since silicon expands about 10% in volume after it solidified from its melt to its solid state, it cannot be grown in some kind of crucible. Even if the crucible can withstand the expansion, excess stresses exerted on the Silicon will cause undesirable dislocation effects on the crystal.

The Czochralski Process, as shown in Figure 9, is included in a cooled silica enclosure. It is the most common process used in terrestrial crystal growth of industrial scale. The crucible is made of graphite or quartz. The silicon is kept in molten condition. As mentioned before, a seed crystal is suspended over the melt. Once it is inserted into the melt, the tip of the seed crystal will begin to melt. After it reaches a molten state, the rotational mechanism is slowly pulling away from the melt at a rate of about 10 um/sec (0.0004 in/sec). The resulting crystal is a single-crystal grew by the progressive freezing at the liquid-solid interface. It can measure up to 2 m (6.6 ft) in length with a diameter of 12cm (4.7 in).

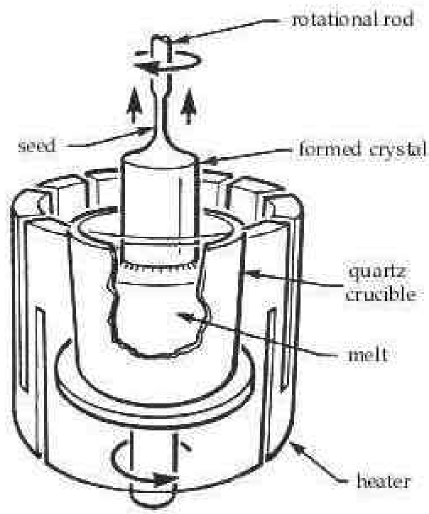


Figure 9: The Terrestrial Czochralski Process

For growing doped crystal, impurities can be added to the melt. Some of the most common impurities are P, As, Sb, B, and Al. One problem encountered in growing doped crystal is the difference in impurity concentration of dopant in the solid and the liquid state. The pulling rate of the seed crystal is limited to the concentration gradient of the growing crystal. Care must be taken that the dopant concentration does not fluctuate too much along the direction of crystal growth.

The presence of oxygen in silicon poses another problem. The oxygen usually comes from the erosion of the quartz crucible. The concentration of oxygen found in silicon depends on the rotating rate. Fast rotations tend to produce higher concentration of oxygen atoms. Although fast growth rate (faster rotation of the seed crystal out of melt) helps dislocations propagate out of crystal, it also introduces large amount of unwanted oxygen atoms. Most of the oxygen ends up as SiO_2. They tend to segregate along dislocations. Circuits built on that part of the crystal are therefore defective. Hence controlling the rotational rate and keeping oxygen concentration level low are crucial to crystal growth.

There are two distinct advantages that the space environment may offer in the growing of silicon ingots: the microgravity environment increases the crystal growth rate, and the high quality vacuum helps to reduce crystal impurities.

In the following step of preparing circuit ready wafers from the ingot, the wafers are typically made by slicing 75 to 300 mm (3 to 12 in) diameter slices, .05 to .1 millimeters (.002 to .004 in) thick, from the purified silicon cylinder. Wafers may be produced in the same location as the final ICs (starting with single crystal silicon cylinders as the raw material), or purchased by the IC manufacturer from an outside supplier; a company that provides silicon wafers as the end product usually also grows the silicon ingots in house. The following steps are required in the process of manufacturing a wafer from a single crystal silicon cylinder:

1. Wafer Shaping:
   In the first step of wafer preparation, the ingots are shaped into wafer-form through a series of cutting and grinding steps, usually performed using diamond-tipped tools. The ends of the silicon ingots are removed and individual wafers are cut from the ingot.

2. Wafer Polishing (Lapping):
   The wafers may then be polished using an aluminum oxide/glycerin solution to provide uniform flatness in a process called lapping.
3. Wafer Etching:
   This initial shaping of the wafers leaves imperfections in the surface and edge of the wafers that are removed in an etching step. Chemical etching involves the use of hydrofluoric, nitric, or acetic acids as well as alkaline solutions of potassium or sodium hydroxide.
4. Wafer Finishing:
   A final polishing step is performed to provide a smooth surface for subsequent processing. In this step, wafers are mounted on a fixture, pressed against a polishing pad under high pressure, and rotated relative to the pad. A polishing slurry, typically containing silicon dioxide particles in sodium hydroxide, is used. This step is both a chemical and mechanical process; the slurry reacts chemically with the wafer surface to form silicon dioxide, and the silica particles in the slurry abrade the oxidized silicon away.
5. Wafer Cleaning:
   In some cases, silicon wafers are ultrasonically cleaned in potassium chromate or other mild alkaline solutions, and finally the wafers are rinsed in deionized water and dried with compressed air or nitrogen.

The only direct advantage of implementing this procedure in a space-based environment is that of simplified handling (due to microgravity), and thus the ability to decrease wafer slice thickness. However, since there are significant advantages to the locating the growth process as well as the IC etching processes into space, it becomes advantageous to perform the slicing step in space as well.

When performing crystal growth in the space environment, the following advantages are anticipated:

- Increased crystal growth rate (reduced cycle-time)
- Increase of crystal size (increase yield)
- Improved crystal purity “Low Defect Density” (increase yield)

3.1.2.1.3 Product Value per Unit Mass

The market value of silicon wafers various between US$150-US$100 per 200mm (7.9 in) wafer. This is equivalent to approximately US$26,000-40,000/kg (US$12,000-18,000/lb).

3.1.2.1.4 Market Trends

Semiconductor wafers and substrates form the basis of the US$800 billion worldwide electronics industry. Semiconductors have given rise to a proliferation of new products for information-based economies. This key technological driver accounts for 30% of economic growth in the US alone.

The semiconductor industry has a long-term growth rate of 17% and exceeded US$150 billion in 1998. The recent semiconductor industry slump and the international financial crises that inspired it are showing signs of recession.

Silicon technology is gearing up for the move from 200 to 300 mm (8 to 12 in) wafers but a host of issues is causing delays. The slump in revenues, the lack of available processing equipment, the enormous costs of constructing a new 300 mm (12 in) fab, and uncertainty about how financially beneficial the new technology will be have conspired to create a climate of doubt about just when the transition will take place.

While most observers are agreed on the overall trend to larger wafers (up to 450 mm by 2010), the market for wafers of less than 120mm (5 in) is lively and stable. Appealing to those customers who either cannot afford more sophisticated processing equipment or have no need for large die counts, small wafers are holding onto their 5% wafer market share.

The customer set for silicon wafers is changing. Fabless semiconductor houses are an increasing presence with 30% annual growth. Foundries that do only part of their business with fabless firms are now facing uncertainties in terms of wafer supplies. The turnaround in the semiconductor market could see manufacturers outsourcing 10% of their IC production to foundries as they try to rush dormant lines into production. The result could be a shortage of wafers by 2001 followed by a steep increase in wafer prices.

New markets and shifting demand will fuel the growth of semiconductor wafers and substrates. The incredible growth in wireless and fiber optic communications, along with the advent of sub-US$1000 PCs, cable boxes and satellite TV, and HDTV and DVD, will provide rapidly growing, long-term demand for semiconductor wafers and substrates in their many manifestations.

The push for greater performance at lower prices has brought new wafer technologies into the market including epitaxial wafers and silicon-on-insulator structures, both of which are extending into high-end niches and fostering new opportunities. While Silicon will remain the dominant material for substrates and wafers for the foreseeable future with demand exceeding US$7 billion in 1999, the emerging trend of silicon-on-insulator technology indicates an eventual departure of the industry from silicon crystal growth for the formation of single crystal ingots. This unfortunately bodes ill for the long-term market of silicon growth in space facilities.

3.1.2.1.5 Space Based Market Concept Maturity Level

While only very limited research has been conducted on the processes of producing wafers in space-based fabs, a wealth of information exists in the area of crystal growth in the microgravity environment of space.

Soviet materials science experiments began with experiments on Soyuz-6, Apollo-Soyuz and Salyut-5 (the latter being the first Soviet fluid physics experiments conducted). These early investigations revealed that microgravity had a complex and often contradictory effect on processes such as mass transfer, crystallization of melts, crystal growing from solution and the spreading of melts in capillaries. This necessitated further theoretical and experimental studies. From 1976-1982 about 130 experiments were carried out on suborbital rockets. This confirmed the possibility of improving the quality of various materials and, most notably, of growing pure ingots of germanium and silicon by fast crystallization.[1,2]

The US government is also actively pursuing this area, since refining methods that produce ultra-pure materials are important for a number of commercial and national defense applications. As feature sizes of integrated circuits get progressively smaller, the purity of the semiconductor materials from which they are fabricated has historically been increasingly important. In general, ultra-pure refining methods include micro-gravity and high- pressure fabrication methods that suppress convection currents in the material and allow even distribution of impurities or their elimination.[3]

3.1.2.1.6 Business Readiness Level

The concept of manufacturing silicon wafers in space has been identified, and some testing at the component level in the relevant environment has been conducted. The industry supporting this effort is mature and operating at a global scale. This warrants a

Business Readiness Level rating of BRL 2: "Technology concept defined and initial financial model developed".

3.1.2.2 Customer Opportunity

This section summarizes the opportunities presented to the target industries by a migration of the product manufacturing process into a space-based facility.

3.1.2.2.1 Product Quality

Growing silicon crystal ingots in the space environment is expected to decrease the amount of defects in the final ingot, both due to irregularities in the growth process and contamination. With semiconductor design moving to increasingly dense circuitry, the demand for high purity wafer substrates will also increase.

3.1.2.2.2 Product Quantity (Yield)

The migration of the growth process to a space-based facility allows for significantly increased crystal growth rates, and possibly thinner slicing of the final wafer; thus reducing the time to produce an ingot, and increase the yield in numbers of wafers obtained from each ingot.

3.1.2.2.3 Product Innovation (Uniqueness)

No unique product properties are currently foreseeable with a shift of wafer production to space based facilities.

3.1.2.2.4 Product Development (Roadmap)

Since no unique properties are associated with the space-based manufacture of silicon wafers, a given manufacturer will not limit its future technology development roadmap by opting not to pursue this particular road. However, due to the significant improvements in yield and quality that the space-based process may have to offer, pursuing this opportunity may grant a decisive competitive advantage to any company willing to do so.

3.1.2.2.5 Time to Market

No change in the time to market parameter is anticipated for the case of space-based wafer fabrication.

3.1.2.2.6 Production Cycle Time

The faster growth rate of crystal ingots in the microgravity environment may lead to improved time to product cycle times, for a given number of manufacturing installations.

3.1.2.2.7 Profitability

While some data has been gathered on the economic profitability of migrating wafer fabrication processes into space, a direct comparison between profits in the terrestrial and space-based manufacturing processes remains to be developed by the conclusion of this study.

3.1.2.3 Industry Interview Status

Out of a large group of potential interviewees, a total of 8 companies were selected and key individual contacted for the possibility of arranging an interview. Several interviews were conducted with the information collected ranging from neutral to negative. This suggests a more incremental approach is required to develop interest in using on-orbit manufacturing processes for this market.

3.1.3 Semiconductor Circuit Production

Andrews Space & Technology has investigated semiconductor circuit production including both analog, digital, and mixed signal devices. Initially, this market appeared to be promising due to the product's high value per mass. After data was collected via interviews, this potential market has been classified as a non-near-term commercial space market.

3.1.3.1 SCP Market Analysis

The following sections provide a quantitative overview of the SCP market within the framework of the previously established market metrics.

3.1.3.1.1 Market Size

In 1996 and 1997 the semiconductor industry was feeling the international economic recession and the market size decreased from US$125 billion to US$115 billion. However, the market rebounded when the Internet revolution was in full swing. Market sizes have increased since 1999 and will continue to accelerate through 2001. Figure 10 shows what the global market sizes were and also breaks down the market into specific sectors. Memory and microprocessors have recently been and are forecasted to be over the next few years, the dominant semiconductor sector. Double-digit annual growth rates are expected over the next 27 months for all world markets, peaking in 2001 at nearly 20% in America and Asia.

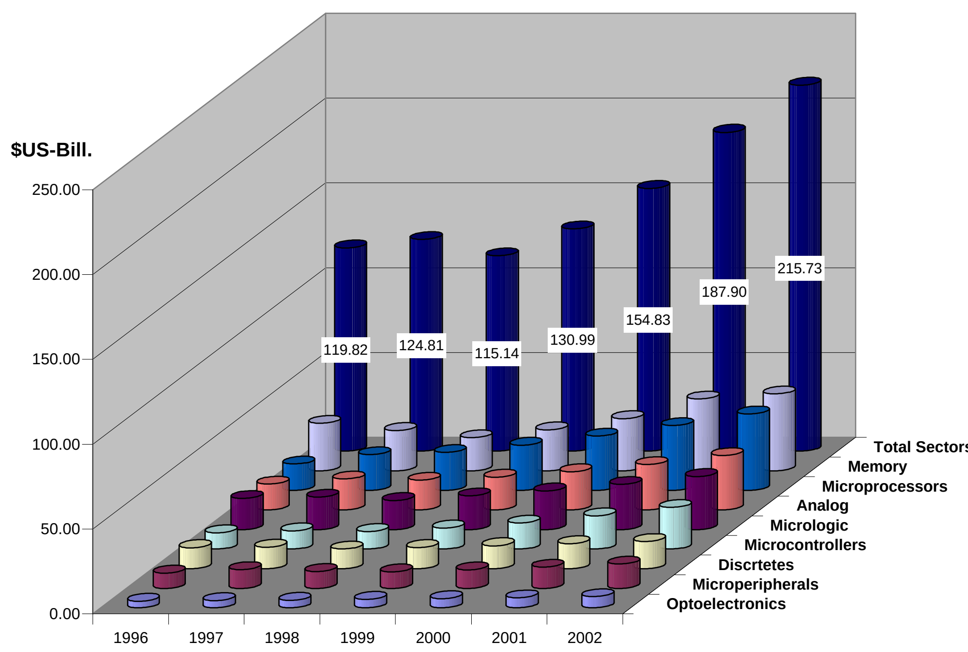


Figure 10: Semiconductor Market Sector Size 1996-2002 (Forecast)

3.1.3.1.2 Value Chain Intersection with Space Unique Resources

State-of-the-art semiconductor fabrication facilities, known as foundries or "fabs" are a capital-intensive investment. The non-recurring costs for constructing a modern fab can exceed three billion U.S. dollars and these facilities are expected to be in use for as little as three to five years. In contrast, due to the high value of these products and the current demand of semiconductors, these facilities have the ability to pay for themselves in as little as one year. However, like the aerospace industry, this is a high-risk market.

The following steps are a condensed summary of the extensive number of process steps required in the process of manufacturing a semiconductor layer on a single sliced silicon wafer:

1. Oxidation Layering:
   A thin layer of silicon dioxide is produced on the wafer by mixing highly pure oxygen with hydrogen at temperatures above 1,000^{o}C (1,800^{o}F).

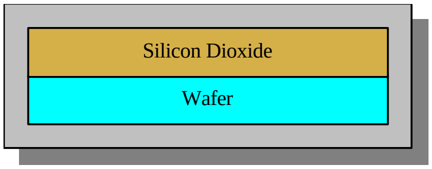


Figure 11: Semiconductor Process Oxidation Layering

2. Photoresist Application:
   A small amount of typically liquid photoresist is applied to the layer of silicon dioxide by rapidly spinning (>3,000 rpm) the wafer to apply a uniform layer.

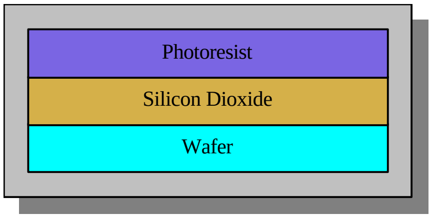


Figure 12: Semiconductor Process Photoresist Application

3. Photolithography:
   A computer-generated pattern is used to create a mask, which is placed over an ultraviolet light. This light is applied to the photoresist-covered wafer. The pattern on the mask is transferred to the photoresist since areas of the resist have been exposed to UV and the mask prevents exposure to the rest of the wafer.

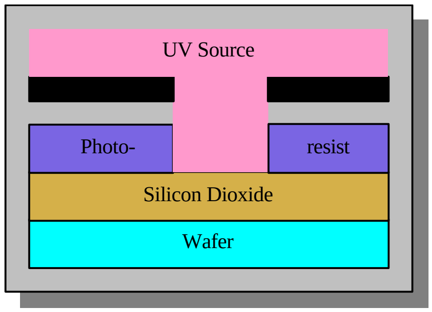


Figure 13: Semiconductor Process Photolithography

4. <u>Photoresist Development:</u>
   Much like a photograph, the photoresist is developed and those areas exposed to UV light are removed.

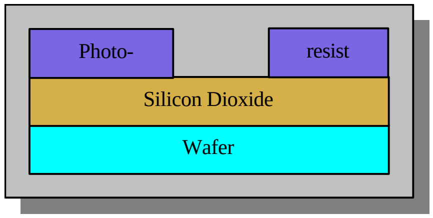


Figure 14: Semiconductor Process Photoresist Development

5. <u>Etching:</u>
   Acidic or basic solutions are used to remove the silicon dioxide that is unprotected where the previously developed photoresist has been removed. The remaining photoresist is also removed, leaving only a pattern of silicon dioxide where the unexposed photoresist was.

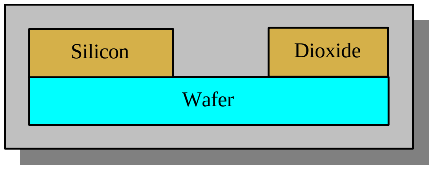


Figure 15: Semiconductor Process Etching

6. <u>Metal Deposition:</u>
   Conductive metals such as aluminum, copper, or gold are deposited on the exposed wafer where the silicon dioxide has been removed by the etch. There are two methods to do this, evaporation and sputtering. Sputtering applied the metal by bombarding a metal source with a plasma, causing tiny particles of metal to form to the wafer. Evaporation introduces gaseous metal (via high temperature and high vacuum) that condenses to the cooler wafer surface. The finished layer now has conductive metal and resistive silicon dioxide in the pattern defined by the lithographic mask.

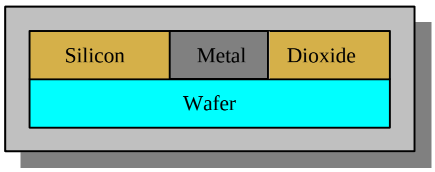


Figure 16: Semiconductor Process Metal Deposition

7. <u>Cleaning:</u>
   Not only at the end of a layer process but also several times between the 1-6 the wafer surface is cleaned and polished using large amounts of heavily de-ionized water.

AS&T has identified the renewable hard vacuum and naturally clean environment of space for application in this process. Vacuum is used in several steps (more detailed steps than listed here) in the semiconductor manufacturing process. There are members of industry and academia who believe that significant recurring cost reductions can be eliminated if establishment and maintenance of vacuums are no longer necessary via space manufacturing.

Significant costs also occur in modern foundries to establish and maintain a clean-room environment. These clean-rooms help eliminate defects due to the contaminants of the surrounding environment. Currently, most foundries operate manufacturing processes occur in level 10 or level 1 (cleaner than level 10) facilities. Some research indicates that migration to a space environment may decrease defects due to the surrounding environment, and eliminate the costs associated with terrestrial fabrication clean-room establishment and maintenance.

3.1.3.1.3 Product Value per Unit Mass

Microchips vary in value from US$20,000 to US$1,000,000 per kg (US$10,000 to US$500,000 per lb) depending on type, making them highly capable of absorbing relatively high transportation cost per unit mass.

3.1.3.1.4 Market Trends

One of the most prevalent trends that the semiconductor market deals with is scalability. In most cases, performance is directly related to geometry feature size. This is due to the time it takes current to traverse the distance between transistor gates. As the space between the gates decrease, the circuits are able to function faster. However, there is a fundamental limit to this scale. The industry anticipates a migration to changing the ways different semiconductor component materials interface to improve performance after the geometric scale limit has been reached. This trend has been estimated to develop during the next ten years. Currently, the technology in this market has a turnover rate of about 3 years, which is an acceptable rate by consumers. Each generation of semiconductors has scaled down by approximately 30%. Increased automation is another market trend that has been identified.

3.1.3.1.5 Space Based Market Concept Maturity Level

A major area of research necessary to facilitate on-orbit semiconductor manufacturing that has been explored is the wakeshield facility. The University of Houston and NASA have teamed several times in the past and have flown multiple missions aboard shuttle demonstrating this technology. NASA is also investigating plans for a long-term wakeshield facility aboard the International Space Station. These facilities are capable of creating the ultra-vacuum environment, which may be of benefit to the semiconductor manufacturing process.

3.1.3.1.6 Business Readiness Level

The concept of manufacturing semiconductors in space has been identified, and wake shield testing has been conducted in the past, as has general vacuum and microgravity research. The industry supporting this effort is mature and operating at a global scale. This warrants a Business Readiness Level rating of BRL 2: “Technology concept defined and initial financial model developed”.

3.1.3.2 Customer Opportunity

3.1.3.2.1 Product Quality

Four space attributes were identified as having the potential of affecting SCP product quality. A natural LEO vacuum environment of 10^{-6} torr (~10^{-7} psi) as well as a wake shield environment of 10^{-15} torr (~10^{-16} psi) could be utilized to decrease product contamination due to the natural production. Micro-gravity has been identified as a benefit to the handling of large diameter wafers, as plate bending may be a problem in terrestrial fabs. Atomic oxygen ram flux in LEO could be utilized as a cleaning agent in the SCP process. Extraterritoriality would apply to this market as tax laws, export/import laws, and environmental regulation are not defined for LEO and may be a benefit to this industry. Conversely, extraterritoriality may be a hindrance to this industry as currently anything transported to/from space from the United States is considered an export/import and is subject to taxes, tariffs, inspection, etc.

3.1.3.2.2 Product Quantity (Yield)

According to data obtained during meetings with Professor Glenn Chapman of Simon Fraser University and the Boeing Company, AS&T concluded that yields of small geometry feature ICs (approx. 50 nanometer) may significantly be increased due to the natural clean environment of space.

3.1.3.2.3 Product Innovation (Uniqueness)

Academic circles have indicated that space manufacturing may enable the semiconductor industry to migrate to smaller geometry features, particularly to 50 nanometer (2e-6 in) size geometry features. Academic papers and interviews extrapolate that a class 0.01 clean room is required for 50-nanometer (2e-6 in) geometry feature production. In a wake shield environment, a clean room class of 0.001 has been suggested possible.

3.1.3.2.4 Time to Market

No significant time to market implications have been identified by the migration of on-orbit SCP.

3.1.3.2.5 Production Cycle Time

The initial data collected suggests that if all-dry SCP processes were available, the time eliminated from the creation and maintenance of vacuum and clean room would decrease production cycle time by as much as from 90 days to just over 10 days.

3.1.3.2.6 Profitability

A profitability analysis has not yet been conducted due to the elimination of SCP as a near-term commercial space opportunity.

3.1.3.3 Industry Interview Status

3.1.3.3.1 Target Industry Identification

Initially, 292 semiconductor companies around the globe were identified. From that list, geography and the ability to identify and locate appropriate employees to interview were taken into consideration to a total of 7 select interview candidates.

3.1.3.3.2 Initial Contact Response

Initial response was mixed regarding AS&T's requests to meet with the candidates in as Interview I situation (defined in Section 2.1). Here is a brief synopsis of those responses: Specific names of the participating companies have been withheld at the interviewees' requests.

Candidate 1 was left multiple voice messages and did not return calls.

Candidate 2 granted the request for an interview.

Candidate 3 informed AS&T during a telephone conversation that his company is "fab-less" (i.e. this company subcontracts production of the semiconductors for a fraction (1/400) of the capital investment). This type of company who designs semiconductor layouts and does not produce semiconductors was found to be a significant section of the semiconductor market.

Candidate 4 was unresponsive.

Candidate 5 granted AS&T's request for an interview.

Candidate 6 was left multiple voice mails and did not return calls.

Candidate 7 granted request for an interview.

3.1.3.3.3 Meeting Minutes

Critical data was collected regarding on-orbit SCP during the target industry interviews. This section summarizes what was discussed during the interviews and what data was obtained regarding this industry.

Interview 1

AS&T met with the Vice President and Director of Candidate 1. This company is a "fab-less" semiconductor designer. While their level of knowledge was not to the level of what was desired as far as fabrication information, important information about this sector of the market was collected. Primarily, it became apparent that the suggestion of 100% dry processing might be very difficult to implement. Especially in the polishing processes, water is a key ingredient to SCP and they were reluctant to believe that total dry processes could be implemented.

Another important response AS&T gathered from this interview regards the tools used to the SCP processes. The interviewees felt their industry would resist the embrace of space manufacturing due to all the machines and tools used in a fab which are designed for use in gravity and would need to be redesigned for use in LEO, assuming no gravity control system was implemented. Furthermore, it was postulated that a large fraction of the contamination responsible for chip defects are due to the tools themselves, and are internal to the process and not as much a function of the environment as anticipated. Both interviewees could think of no benefit micro-gravity would provide to SCP.

The question of extraterritoriality raised some eyebrows in this interview. The notion that tax benefits and environmental legislation variability from producing in space may make the development costs of on-orbit SCP tolerable to the industry. They were also interested in U.S. protection as a U.S. territory.

Interview 2

This company was an invaluable source of information to AS&T during the interview. The interviewee confirmed the data received from the first interview involving contamination. 95% of SCP contamination is believed to be due to process equipment. Since the current model for migrating SCP to space does not inherently change the process equipment, he saw no advantage in contamination reduction by initiating that migration. In fact, the highest class clean-room Interviewee 2 operates is a class 1. Moving production to a class .01 clean-room or better would not significantly increase yields, since the reduction in contamination from the environment is negligible compared to the contamination from process equipment.

The hypothesis that <130 nm (5e-6 in) geometry features are only possible by a combination of lithographic dry photoresist and wake shield strength vacuum was negated by the fact that Interviewee 2 has developed in the lab geometry features much less than 130 nm (5e-6 in) today on Earth with current wet processes.

Continued investigation needs to be undertaken to demonstrate that there are compelling reasons for the SCP market to migrate to space. Terrestrial research is driven by highly competitive forces leading to the continual introduction of terrestrial based solutions; processes for which space-based solutions might have been competitive or leading-edge if they had received earlier attention and implementation.

Interview 3

Interviewee 3 was generally more enthusiastic about space manufacturing, however he could not identify any attributes of on-orbit manufacturing which would greatly benefit the semiconductor processing market. He identified short cycle time and time to market as a key attribute of the current manufacturing market and identified a time of 18-24 months as the upper limit for receiving initial samples from the development of a new process.

One phase of space manufacturing development that the interviewee suggested that would be paramount to the feasibility of migration of manufacturing in space is a ground-based laboratory phase. Specifically, the price points of creating a space-like environment on earth as compared to actually migrating to space should be investigated.

Analog integrated circuits do not require the same order of magnitude of geometry feature size as RF and digital circuits. As AS&T has identified 130 nm geometry features as a necessity in the future of semiconductor manufacturing, the interviewee informed us this is not true in the case of analog type circuits such as CMOS and power management circuits. The geometry feature size of these circuits is roughly 10 times the size as the digital circuits.

Finally this source was able to quantify an approximate cost requirement for a fully manufactured wafer to be commercially viable. Currently costs for a finished wafer (processing costs) are approximately $1,000. The subject interviewed felt <$500 per finished wafer would be an appropriate competitive price for this market.

3.1.4 Semiconductor Manufacturing Market Derived RLV System Requirements

A broad requirements set of 50 requirement / attribute pairs were identified in Section 2.3. In the current section, the specific requirements values for the Semiconductor Manufacturing Market are listed, as derived from the interviews AS&T conducted with selected industry representatives and supporting documentation. While the uncertainty of these numbers in estimated to be significant, the accuracy of the model will increase with the collection of additional data.

The processing steps discussed here are a sequential part of the entire Semiconductor Industry Value Chain. Therefore, the manufacturing processes require regular and "just-in-time" delivery of payloads to and from orbit. Failures of these deliveries significantly hamper delivery of the product to the buyer.

The data that is presented assumes an on-orbit fabrication facility producing up to 12,000 processed wafers per year. This data is also scalable, dependant upon the production of the facility. Most of the data presented here applies to materials manufacturing in space, in general.

Only the requirements number and heading are listed for each requirement value (for the complete definition of the requirement / attribute see Section 2.3). Where no numerical value is given, a qualitative discussion is provided if it was available. Note that the requirements numbering does not follow the heading numbers of this report and is provided in parenthesis behind the section heading for the readers reference. A summary of all collected requirements is presented in Section 5 of this report.

Scheduling (1-0-0)

<u>Payload Schedule</u>

1-1-1 Payload Processing Time: No data.

1-1-2 Pre-Departure Idle Time: No data.

1-1-3 Transit Time: Out-gassing is an anticipated problem for wafers being delivered to the fabrication facility. The out-gassing contaminates the surrounding area and compromises the clean environment necessary for space processing. A solution may utilize loitering of the vehicle until the out-gassing subsides to an acceptable level. What that level is or how long a vehicle may need to loiter are values not known at this time.

1-1-4 Post Arrival Idle Time: No data.

1-1-3 Operations Schedule: No data.

1-2-1 Advanced Booking Time: No data.

1-2-2 Launch Window: No data.

Operations (2-0-0)

Reliability

2-1-1 Successful Delivery: TBD. Space-based semiconductor processing is only a part of the entire semiconductor manufacturing sequence (including wafer production, wafer slicing, packaging, terrestrial distribution, etc.), successful delivery reliability will impact the entire semiconductor market and customer product cost. The successful delivery reliability is dependent upon the number of payloads, their frequency, and the just-in-time manufacturing requirements.

2-1-2 Service Availability: TBD. The market identifies and anticipates tele-presence to be a factor in semiconductor manufacturing by the year 2010. This may reduce the customer's need for service flights. Without tele-presence, the service availability acceptable to the semiconductor manufacturers is not known at this time.

2-1-3 On-Time Delivery: To reiterate question 2-1-1, the supply chain of the semiconductor industry shall depend on transportation of payload, especially down mass. On-time delivery of down mass is important for continuing terrestrial delivery of payload. Required probability of on-time delivery is not known at this time.

Safety

2-2-1 Emergency Egress: No data.

2-2-2 Abort Capabilities: No data.

2-2-3 Catastrophic Failure: No data.

Performance (3-0-0)

Payload Mass

3-1-1 Payload Mass: Present data indicated that the material mass required to produce a single wafer is about 0.25 kg per wafer. This includes wafer, consumables (processing materials) and container. Assuming an on-orbit fabrication facility producing up to 12,000 processed wafers per year, this equates to approximately 3,000 kg (6,600 lb) of payload to orbit per year per facility. The number of facilities in orbit (and the total annual payload) is not known at this time.

3-1-2 Payload Rate: A minimum frequency of regular weekly down mass is required for the industry to maintain distribution. This translates to approximately 60 kg (130 kg) of down-mass per week. A maximum frequency for up-mass, or the longest amount of time acceptable between re-stocking, is one flight every 3 months or 750 kg (1,650 lb).

Payload Manifest

3-2-1 Multiple Destinations: There is no requirement to visit multiple destinations for a single payload being delivered to a single fabrication facility.

3-2-2 Multiple Payloads: Up mass shall be less likely to include multiple payloads than down mass as up mass is expected to be relatively infrequent as compared to down mass (refer to question 3-1-2). Multiple payloads may be utilized with standardized ship-and-shoot packages for convinience of payload integration and delivery.

Interfaces (4-0-0)

External Interfaces

4-1-1 Facility Location: No specific locations required at this time, however proximity to terrestrial transportation systems (air, rail, truck, etc.) shall be required.

4-1-2 Infrastructure Attributes: Capability of docking and transferring cargo to an on-orbit facility. Extensive spaced-based (assumedly International Space Station) development and testing is required for these processes. Therefore, compatibility with the ISS is desired.

4-1-3 Payload Processing: Currently, some manufacturing processes have a Class 10 clean-room requirement. It is not known if this environment would be necessary for payload processing. Unless the wafers are in a delicate stage of processing when being launched to orbit, this is not anticipated to be a requirement.

Payload Accommodations

4-2-1 Payload Volume: Up mass payload volume is aniticpated to be much greater than down mass volume. Assuming 250 wafers down mass with a thickness of 1 mm and 2 mm protective layering between each delicate wafer, a cylindrical payload of 0.75 m in length and 0.30 m in diameter is formed. There would be some kind of standardized cargo container around this cylinder. A weekly down mass payload measuring approximately 1 m x 0.5 m x 0.5 m shall be assumed. The up mass volume can’t be computed at this time as materials and processes for space-based processing is not known.

4-2-2 Acceleration Loads: Maximum of 1.0 g in all directions downmass. Maximum 3.0g upmass.

4-2-3 Processing Orientation: The length of a wafer (~1 mm) is relatively small compared to its diameter (300 mm). Therefore its crystalline structure is susceptible to fracture due to plate bending. A specific processing orientation may be necessary as to reduce loads in certain directions. Those orientations have not been computed at this time.

4-2-4 Data Interface: No data.

4-2-5 Deployment Parameters: No data.

4-2-6 Shock Environment: No Data.

4-2-7 Vibration Environment: No Data.

4-2-8 Acoustic Environment: No data.

4-2-9 Temperature Environment: No data.

4-2-10 Pressure Environment: The requirement to obtain a vacuum environment as soon as possible may be desirable for later space processing.

4-2-11 Payload Consumables: No data.

4-2-12 Structure Interface: No data.

4-2-13 Atmosphere Composition: The requirement to obtain a vacuum environment as soon as possible may be desirable for later space processing. Purified N2 or vacuum are possible choices.

4-2-14 Impact Prevention: No data.

4-2-15 Radiation Protection: Payload is extremely sensitive to radiation and will most likely need to be shielded. Shipping container may be designed to shield radiation. Acceptable levels of radiation are not known at this time, but shall translate as a significant design factor for payload container, and transit time to on-orbit facility.

4-2-16 Illumination: The only illumination required may be for video telemetry of transfer of payload from vehicle to on-orbit facility or vice-versa.

Business (5-0-0)

Economics

5-1-1 Standardization: A standardized payload container with minimal processing shall be required due to frequency of down mass flights.

5-1-2 Price Stability: No data.

5-1-3 Specific Payload Price: Currently, processed wafers are valued as high as US$1,000,000 per kg. This means a weekly down mass payload of 60 kg could be valued as high as 60 million U.S. dollars. The specific payload price acceptable to the manufacturers would be determined by the business case, which is not presented here and has not been developed.

5-1-4 Evolvability: Wafers diameter total production increases as a function of time. Payload sizes and frequencies shall be scalable to adapt to the semiconductor market.

Regulatory Issues

5-2-1 Regulation: Debris mitigation may be beneficial as debris compromises cleanliness attributes of the manufacturing environment. The lack of current environmental regulation in space currently allows manufacturers uncontrolled operating scenarios.

5-2-2 Service Globalization: If a vehicle and on-orbit facility has protection as a United States Territory, this may increase the likelihood of investment and development of space-based manufacturing.

Provider Specific (6-0-0)

Scheduling

6-1-1 Turn-Around Time: Turn-around time shall be no less than one week to meet the down mass frequency requirement for a facility.

6-1-2 LRU Replacement: TBD. Significant redundancy is required in these processes. Due to the high value of the product, LRU replacement time may be relatively short.

Operations

6-2-1 Operations Reliability: No data.

Interfaces

6-3-1 Support Equipment: No data.

Business

6-4-1 Specific Payload Cost: No data.

6-4-2 Technology Globalization: No data.

3.1.5 Market Development Scenario

A possible Orbital Semiconductor Manufacturing Roadmap is shown in Figure 17 below.

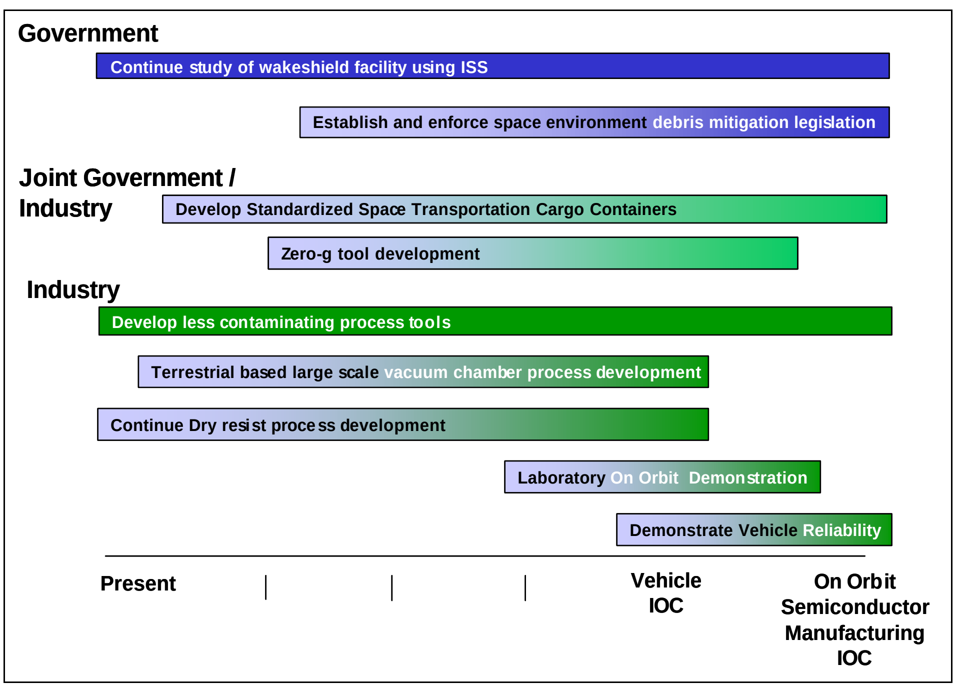


Figure 17: On Orbit Semiconductor Manufacturing Roadmap

NASA should continue with development of a wakeshield facility aboard the International Space Station. This will demonstrate feasibilities and identify problems with working in this environment early on. The lack of zero-g tools make on orbit semiconductor manufacturing less attractive. Government needs to team with industry to develop zero-g tool programs to identify future needs. Semiconductor manufacturing may benefit significantly from debris mitigation legislation. An unregulated space environment may prove to be unattractive to potential manufacturers.

Dry resist and other less water intensive processes must continue to be developed in order to eliminate the massive consumables currently necessary to manufacture semiconductors. Industry must continue to develop less contaminating process equipment. The benefits of on orbit fabrication are negated by current state of the art in process equipment.

Large-scale vacuum testing on Earth is a step which may further accelerate the development of on orbit compatible manufacturing processes.

Once vehicle IOC is achieved, reliability must be demonstrated to insure safe transportation of high-value semiconductor payloads.

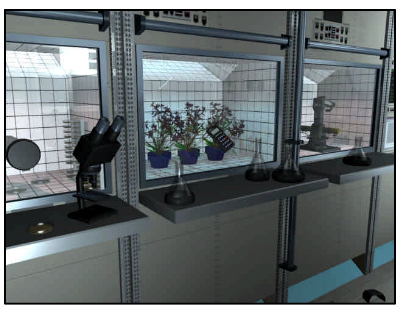
When space-manufacturing products are common, standardized shipping containers will undoubtedly be used. Industry and space agencies should endeavor to design and implement compatible systems and interfaces whenever possible.

3.2 On Orbit Biomedical Manufacturing

The second market focus of the current study phase is the production of pharmaceuticals and medical products in space-based facilities.

3.2.1 Biomedical Market Overview

A history of manned space flight and increasing complex experimentation in space and on earth has yielded a large amount of data on the effect of microgravity on living organisms. While much of the impact of space travel on the human body has been detrimental, the underlying cellular and sub-cellular alterations that are understood to be largely responsible for these effects is the result of a novel microenvironment that has potential advantage in the fields of tissue culture and engineering, tissue physiology and pathophysiology, and recombinant protein production.



A space-based operation permits the decoupling of mass and gravity. Beyond the direct effects of microgravity on cells, such an environment fundamentally changes certain physical properties, especially pertaining to fluid dynamics, in a manner that is impossible to obtain in a gravity environment. This has potential benefits by permitting certain manufacturing processes in pharmaceutical production, and often more significantly, permits new methods of separating product from waste. This has the potential of ultimately permitting the manufacture of new drugs and bioactive compounds, and in the nearer term, enhancing the processes involved in the production of current drugs. For some drugs, even minor enhancements in separation and purity translate into a major cost savings.

A bioreactor is a system designed to be a vessel in which to perform biological reactions, and is usually used to culture cells in suspension or attached to a surface, often micro-carrier beads, by providing the environmental and nutritional requirements of the cells or aggregates of cells. Bioreactors are used to generate tissue constructs, and in the manufacturing of recombinant products.

3.2.1.1 Space environment Benefits

Figure 18 shows the Quick Reference Legend (QRL) for the biomedical market.

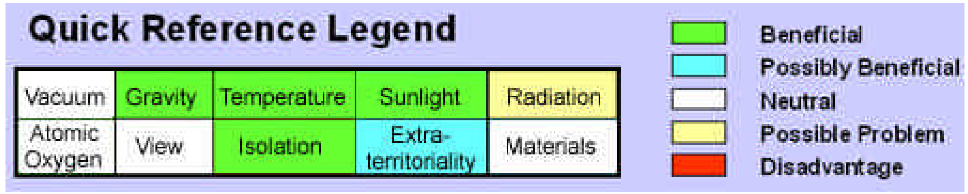


Figure 18: Quick Reference Legend for the Biomedical Market

The following properties of space are significant in the consideration of orbital cell and tissue culture and product separation:

- Isolation: space provides an environment that is unique in the ease of bioisolation
- Environment: variations in temperature, pressure, light, and other environmental factors are available
- Microgravity: variable gravity from microgravity to hyper gravity can be obtained and sustained

3.2.1.2 Effects of Microgravity

Gravity imparts certain properties to molecules and solutions. The absence of gravity decouples the mass, thus altering the physical and chemical states. Specifically microgravity imparts alterations in surface electrochemistry, decreased rates of sedimentation, alteration of hydrostatic pressure, and decrease in buoyancy-driven flows. Such changes increase the significance of other physical phenomenon, whose effect is masked in a terrestrial environment. All of these alterations have the potential to increase the efficacy of separation of different types of molecules and macromolecular structures, thus permitting enhancement of product separation.

In addition to direct physical and chemical effects of microgravity, several decades of human space exploration has demonstrated the deleterious effects of microgravity on human health. While the specific cause of these effects are better explained on a cellular basis, the consequences of microgravity to an organism or organ are the primary concern of space medicine. In the longer term, the immunosuppression due to microgravity may hold promise for the treatment of certain chronic diseases and conditions, including burn victims. In the shorter term, such experimentation is impractical until a human presence in space is routine, and at this point the deleterious effects of microgravity, such as bone mineral loss, clearly out ways any short-term therapeutic possibilities.

It is currently understood that the cellular affects of microgravity are largely due to subcellular alterations that affect the morphophysiological and structural organization of cells.[4] Many studies have described cytoskeletal alterations caused by gravity. A current model of the mechanism by which cells sense and respond to microgravity is partly based on the discovery that cells use a tension-dependent architecture to organize and stabilize their cytoskeleton, and thus cellular forces can alter intracellular biochemistry and gene expression.[5]

In a gravity environment, most cultured cells are observed to grow in a two-dimensional manner. Complex organisms require three-dimensional growth for embyogenesis and organogenisis, and accomplish this by specifically activating cellular division along multiple planes according to a coordinated plan directed by cascades of gene expression. The precise mechanism by which cells are activated to grow and die via apoptosis, and the embryo and organs are formed, is a field of active research. While it is sometimes possible to artificially stimulate cellular division, three-dimensional growth is not usually observed *in vitro* (with some exceptions in the case of malignantly transformed cells). Three-dimensional growth of cultured cells is observed in microgravity and simulated microgravity. Microgravity is also observed to alter protein expression, with some cell lines exhibiting increased protein expression, and other cell lines (especially *in vivo*) exhibiting inhibited protein expression and DNA transcription. Additionally, some cell lines exhibit an increased tendency to transport proteins extracellularly in microgravity, presenting the opportunity to harvest recombinant proteins from the extracellular matrix or solution, rather than a cell extract.

3.2.2 Tissue Culture

Tissue is cultured for a variety of reasons. While most tissue culture is performed for research, such as pharmokinetic studies, future biomedicine is likely to implement tissue culture for a variety of applications such as autografting of genetically modified tissue. Most tissue cultures use commercially available cell lines that are often immortalized and are genetically well characterized. There are currently systems that utilize propriety cell lines to perform biochemical functions ordinarily performed by the body. An example of this is a system from Algenix Inc. that utilizes a liver cell line to perform some of the filtration functions of the liver.

The ultimate promise of tissue culture is to provide a source of transplantable organs grown from a seed culture of an individual's cells, thus providing a functioning organ of the same genome (and thus identical Major Histocompatibility Complex), eliminating tissue rejection. While the biomedical technology does not currently exist to create such a complex system of tissue differentiation from a seed culture, when it does exist, it will require the ability to grow cells in three dimensions. Additionally, there is substantial medical benefit from the ability to culture transplantable functional tissue, even without complete organ differentiation.

3.2.2.1 Tissue culture and engineering methods

There is a variety of tissue methods available each with advantages and limitations. The simplest system involves a petri dish that provides a plastic surface for cell adhesion, and results in a two-dimensional monolayer. Other systems include stirred fermentors, and Rotating Wall Vessels (RWVs), developed by NASA.

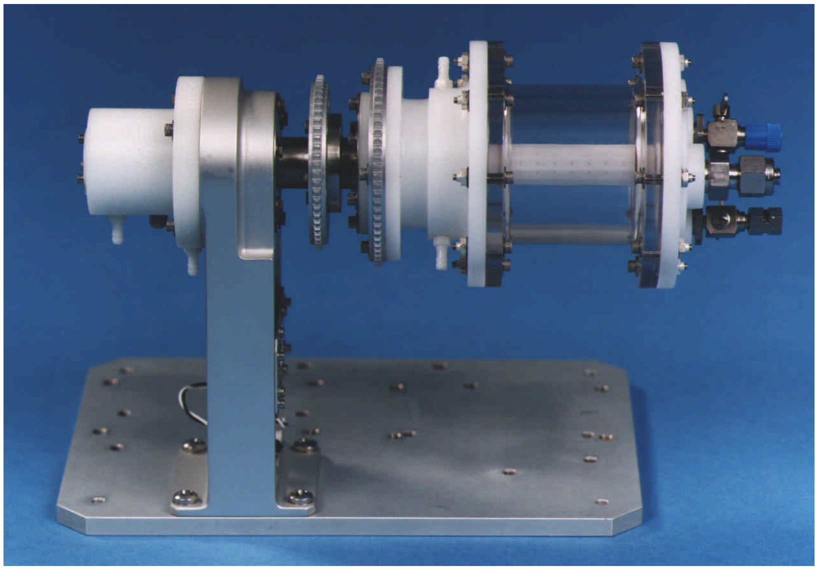


Figure 19: Rotating Wall Vessel Bioreactor (courtesy of NASA)

RWVs function by randomly rotating the vessel such that the cells remain in continual free fall, simulating microgravity, and can be used to culture cells in suspension or attached to microbead carriers. There are several variations of RWVs including a High Aspect Ratio Vessel (HARV) bioreactor, which produces extremely low shear forces.

The research potential for RWVs is great, and in the case of recombinant protein production the commercial application of increased recombinant protein yield is already being realized. The system is limited in how large the tissue growth can be, before shear forces become unacceptable.[6]

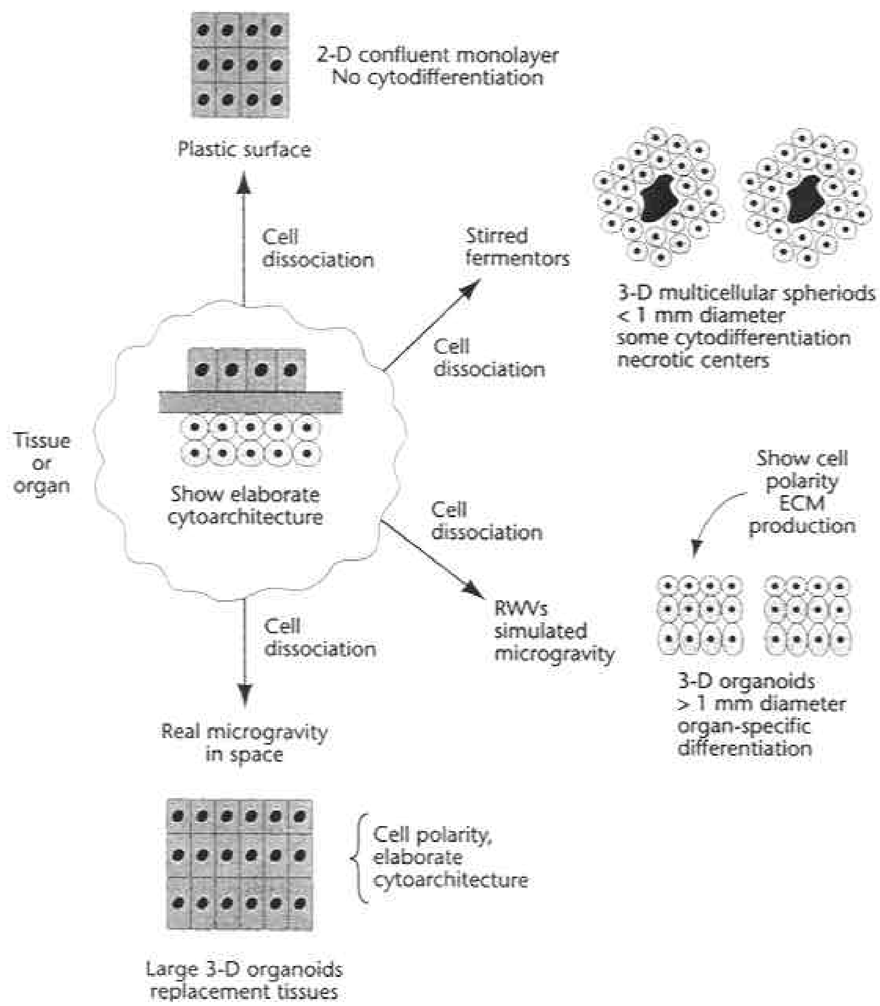


Figure T: Advantages of growing Tissue in Microgravity.[7]

3.2.2.2 Chondrocyte (Cartilage) Culture in Microgravity

Cartilage tissue is the first tissue to be artificially engineered and available for autologous transplantation. The major advantage of cartilage tissue that renders it more susceptible to tissue engineering is the lack of vascularization.

While terrestrial-based tissue-engineered cartilage is available, its quality is poor relative to normal cartilage, and the clinical conditions for which appropriate types and structures of cartilage can be engineered are limited. Microgravity offers an environment under which improved cartilage can be engineered. In one experiment, cartilage was cultured on earth and on Mir and then compared. While the Earth-grown cultures were larger (demonstrating the cell type-dependent macroscopic effects of microgravity), the Mir-grown constructs had greater differentiation.[8]

Since, in the case of cartilage, microgravity offers attributes that lead to an improved product, rather than enabling a new product, the increase in quality must be sufficient to justify the additional costs associated with orbital manufacturing. This requires more work on tissue engineering in microgravity (enabled by the ISS), and decreased launch costs.

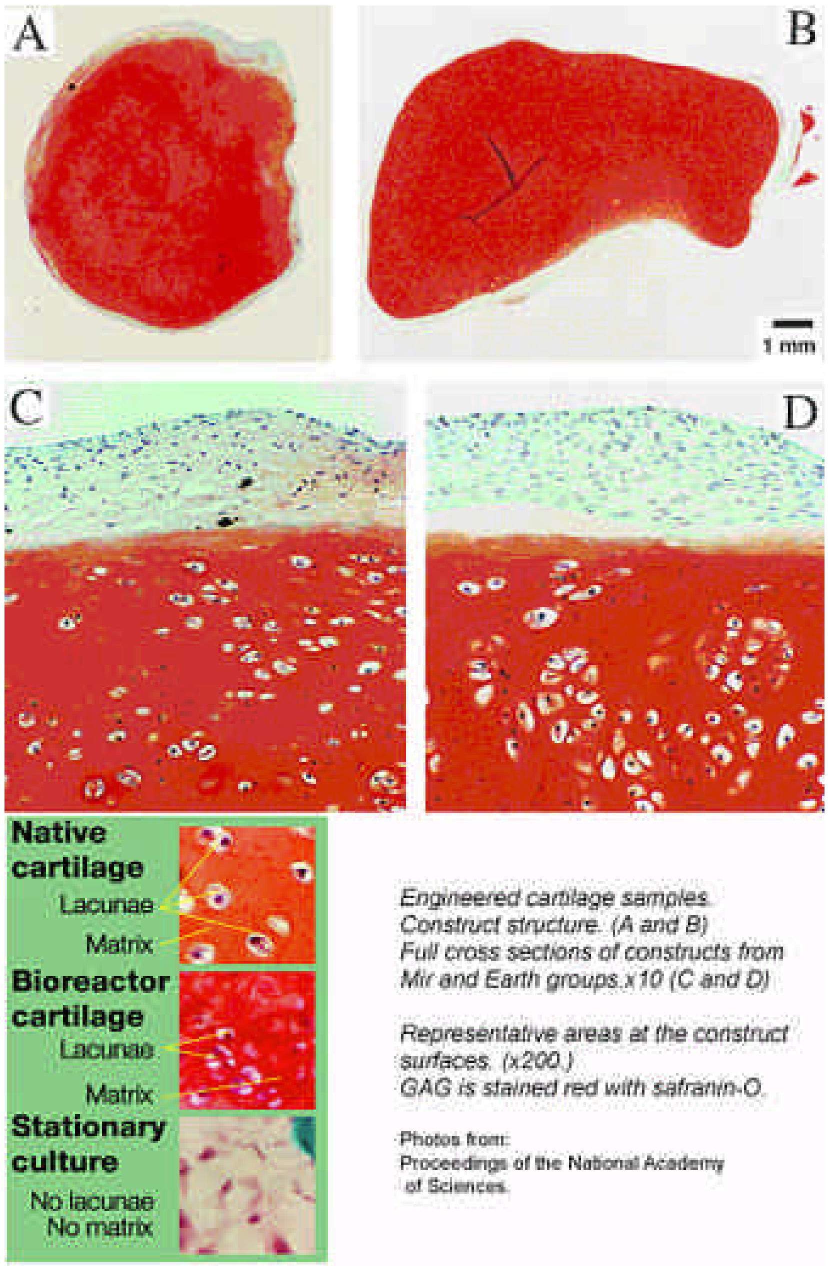


Figure 21: Engineered Cartilage Samples[8]

3.2.2.3 Hepatocyte (Liver) Culture in Microgravity

Liver tissue is the most likely early candidate for commercially viable space-based tissue engineering

Liver tissue is the most likely early candidate for commercially viable space-based tissue engineering for a number of reasons. These include the fact that microgravity is an enabling attribute; a great deal of work has already been done on liver cultures;

transplantable liver tissue can be therapeutic even without complete organ differentiation; and liver disease is a major public health problem in the United States. The waiting period for patients requiring cadaveric donor organs often exceeds a year, and short-time therapies exist to bridge the gap between liver damage and donor availability. One of the major limitations for performing partial resective or ablative therapies on patients with hepatocellular carcinoma is the inability to achieve adequate surgical margins while leaving sufficient functional reserve in the remaining liver. The ability to add to the functional reserve would effectively increase the number of patients who could receive curative surgery. Due to the scarcity of cadaveric donor organs, many patients are deemed ineligible for transplantation, often because of the extensiveness of the disease or current chronic hepatic infection. The availability of alternate sources of functional hepatic tissue would substantially increase the pool of patients who could receive life-saving tissue transplantation.

Specific applications for liver culture grown terrestrial or in space-based facilities are:

- Replacement liver tissue
- Filtration devices for temporary hepatic function
- Transplantable tissue after genetic modification of seed cells
- Pharmokinetic studies

3.2.2.4 Current Technology

Tissue culture experiments performed on the shuttle and Mir have demonstrated the positive effects of microgravity on three-dimensional tissue growth and differentiation, and thus the potential for an improved product.

Several studies have described culturing functional differentiated hepatic cells.[9,10,11] The common method is to use Primary Human Liver Cells (PHLC) harvested using collagenase perfusion, and then cultured in simulated microgravity with biodegradable scaffolds. While this method demonstrates the feasibility of the technique, the constructs are limited to a few centimeters due to the limitations of using simulated microgravity, as shown in Figure 22. While the issue of providing a blood supply and various supportive structures remains, advances in tissue engineering such as tubular scaffolds lined with endothelium would provide a mechanism to provide a vascular supply to the center of growing tissue, thus preventing a necrotic core.[12]

Figure 22[13]

Clinical application for tissue-engineered cartilage is already commercially available. However, tissue culture experiments performed on Mir have demonstrated the effects of microgravity on tissue differentiation, and thus the potential for an improved product. Figure 23 describes the clinical method used for the extraction and manipulation of cartilage cells. A space-based process would be similar, except that the cells would be cultured in space, and returned to earth for implantation.

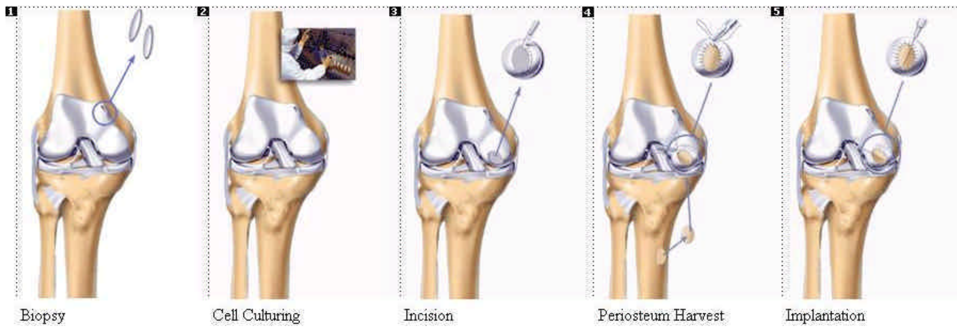


Figure 23: Clinical Application of Engineered Cartilage[14]

3.2.2.5 Market Dynamics

The following section summarizes a number of key metrics for this market.

Tissue engineering technologies have the potential to address diseases and disorders that account for about half of the nation's total healthcare costs.

3.2.2.5.1 Tissue Engineering

- Tissue engineering technologies have the potential to address diseases and disorders that account for about half of the nation's total healthcare costs

Source: National Institute of Standards and Technology, Advanced Technology Program, 1997.

3.2.2.5.2 Engineered Cartilage Market

- Nearly one million American undergo surgical treatment for cartilage injury
- Additional markets exist for surgical reconstruction

Note: The first ear reconstruction using tissue engineered cartilage was perform at the end of 2000.

- Carticel, a tissue engineered cartilage autologously reinjected into patients and made by Genzyme Inc, has been on the market for a few years with 1999 sales of nearly 1500.

Source: Genzyme Inc, Annual Report, 1999.

3.2.2.5.3 Chronic Liver Disease/Cirrhosis

- Deaths Annually: 25,175 (1997)
- Death Rate: 9.4 deaths per 100,000 population (1997)
- Cause of Death Rank: 10 (1997)
- Hospital Discharges: 356,000 (1996)

Source: Vital and Health Statistics Series 13, No. 138

3.2.2.5.4 Viral Hepatitis

- Deaths Annually: 3,780 (1997)
- Age-Adjusted Death Rate: 1. death per 100,000 population (1997)

Source: National Vital Statistics Reports, Vol. 47, No.19

- Cases of Hepatitis A Reported Annually: 31,582 (1995)
- Cases of Hepatitis A per 100,000 Population: 11.22 (1997)
- Cases of Hepatitis B Reported Annually: 10,416 (1997)
- Cases of Hepatitis B per 100,000 Population: 3.90 (1997)

Source: Health, United States: 1999

3.2.2.5.5 Liver Transplants

In 1996, approximately 4,000 persons underwent liver transplantation in the US for acute and chronic liver diseases.

3.2.2.5.6 Healthcare costs

The costs of liver transplantation and the medical costs of treating and managing patients with gall bladder and liver disease are considerable. Current conservative estimates are that liver and gall bladder disease account for at least US$17 billion dollars in health care costs yearly.

From NIH Publication No. 94-1447. "Digestive Diseases in the United States: Epidemiology and Impact" National Digestive Diseases Data Working Group, James E. Everhart, Editor. Value derived from total costs of hepatitis, hepatic cancer, liver disease, & gallbladder disease in 1985 and estimated for inflation.

3.2.2.5.7 Replacement Liver Tissue Market Analysis

The pharmaceutical industry, where patents exist on a product or method, is a market in which prices are largely set by what the market will bear, rather than by the actual costs associated with the development and production of a product. When determining the maximum constraints of a market, several factors are involved, with the most significant being an analysis by the medical insurance industry of what the cheapest treatment is that achieves satisfactory results. The greatest market for transplantable hepatic tissue will be, at least initially, comprised of patients for whom no acceptable alternative exists, thus eliminating competitive price factors. Price will be largely determined by the maximum each individual patient can afford. Since, in the absence of government intervention, the vast majority of US healthcare consumers are reliant on Medical Insurance for healthcare costs, this is limited by the maximum expenditure of the insurance package, often with a lifetime cap of US$1 million. It is extremely unlikely that greater than half of that amount would be available for the acquisition of transplantable tissue, and thus the absolute maximum amount that could be charged is US$0.5 million. A conservative estimate of the number of patients who would benefit from this therapy, especially considering the mortality associated with chronic liver conditions and neoplasm (see Table 5), is to assume that it is equal to the number of liver transplants that are performed annually in the US (greater than 4000). As with most markets, it is reasonable to presume that this number would increase as such therapy becomes more accepted and prevalent, and that accordingly, price would fall. Thus, the US market size is estimated to be approximately US$2 billion annually.

Table 5: Leading causes and numbers of deaths: United States, 1980 and 1998

Rank	1980			1998	
	All causes	1,989,841		All causes	2,337,256
1	Diseases of heart	761,085		Diseases of heart	724,859
2	Malignant neoplasms	416,509		Malignant neoplasms	541,532
3	Cerebrovascular diseases	170,225		Cerebrovascular diseases	158,448
4	Unintentional injuries	105,718		Chronic obstructive pulmonary disease	112,584
5	Chronic obstructive pulmonary diseases	56,050		Unintentional injuries	97,835
6	Pneumonia and influenza	54,619		Pneumonia and influenza	91,871
7	Diabetes mellitus	34,851		Diabetes mellitus	64,751
8	Chronic liver disease and cirrhosis	30,583		Suicide	30,575
9	Atherosclerosis	29,449		Nephritis, nephrotic syndrome, and ne	26,182
10	Suicide	26,869		Chronic liver disease and cirrhosis	25,192

[Data are based on the National Vital Statistics System]

The division of resources amongst the launch services, orbital manufacturing, and terrestrial processing for tissue culture products is less obvious than for other products. The automated and individualized nature of the manufacturing process suggests that essentially the entire infrastructure required for manufacture must be launched and recovered for each unit. Without the weight benefit of being able to leave infrastructure on an orbital platform for reuse, the cost advantage of unloading the payload from a vehicle into the platform, is not obvious. While an orbiting platform offers the advantage of power production and possibly radiation production, as well as not tying up the launch vehicle for protracted periods, the lack of the requirement for an orbital platform has the potential to reduce initial production costs, and reduce the construction time necessary to initiate a tissue production capability. Further study is required to establish the most efficient approach.

3.2.2.6 Cultures of Other Cell types

Three-dimensional growth using microgravity is likely to be an extremely useful research tool. Ultimately, as researchers encounter problem scaling up the cell aggregate culture, there will be more demand for experimentation in true microgravity.

The ability to culture various types of secreting and regulatory tissue (eg. Pancreatic tissue) provides a method gene therapy that avoids many of the risks of most current genetic transfer vectors (commonly modified viruses). Tissue samples could be manipulated in vitro using standard DNA transduction techniques, and the modified tissue cultured into functional organ or organoid form, and then used to surgically replace portions of the original tissue to restore function.

While the scientific advances required are greater, another cell type whose culture would be of great commercial and public health interest are cardiomyocytes (heart cells).

Table 6: Cells / Tissue Cultivated in Microgravity in Space and on the Ground.[15]

Cell/tissue	Environment	Observation	Reference
Lymphocytes	Several shuttle missions, Maser sounding rockets	Inhibited locomotion, impaired immunocompetence, impaired mitogenicity, changes in cytokine production, altered cellular signaling	16,17
Chondrocytes	RWV in space (MIR STS-79) for 4 months	In space culturing of pre-assembled 3-D aggregates, results in construct which are mechanically inferior to similar aggregates grown in RWV on the ground. Effect might mimic microgravity-induced loss of cartilage	18
PC12 cells	Six weeks serial passaging of cells in culture bags	Establishes feasibility of long term, serial passaging of cells in space, formation of large aggregates with epithelial morphology	19
MIP 101 leukemia cells	EDU-1 on STS-70	Increased proliferation, enhanced CEA production	20
Osteoblasts	Four days on STS-56 in Materials Dispersion Apparatus minilabs (MDA)	Inhibition of growth, reduction in serum growth activation, changes in microfilament structure	21
Myoblasts	Ten days on STS-45 in space Tissue Loss Flight Module “A” (TLMA)	Several permanent phenotypic alterations, including failure to fuse into myotubes	22
Neonatal rat heart cells	HARV	3-D organization, synchronous beating	23, 24

Cell/tissue	Environment	Observation	Reference
Rodent skeletal muscle satellite cells	HARV, STLV	Enhance proliferation, 3-D organization, attenuation differentiation	25, 26
MIP 101 leukemia cells	STLV	Increased proliferation, enhanced CEA production	27
Human Ovarian Tumor cells	STLV	Capability of growth out of the body, organization into differentiated tissue-like constructs, enhanced oncogene expression	28
Diverse human tumor cell	HARV	Organization of tissue-specific epitheloid structures, enhanced production of cell adhesion molecules	29
Human prostatic cancer cells	STLV, HARV	Enhanced differentiation, reduced proliferation in 3-D aggregates. Upregulation of growth factors and basement membrane proteins in co-cultures mimic physiological growth conditions of prostate epithelial cells with stromal cells, altered responses to sex hormones and growth factors	30, 31
PC12 cells	STLV, HARV	Formation of large aggregates exhibiting neuroendocrine differentiation, altered cellular signaling mechanisms	32
Normal human kidney cells	STLV	Re-expression of tissue-specific morphology (microvilli) and differentiation markers	33
Bovine cartilage	STLV	Macroscopic large 3-D constructs with enhanced tissue specific differentiation (ECM proteins e.g., chondroitin sulfate, and cytoskeletal proteins e.g., vimentin)	34, 35, 36
Murine osteoblasts	Clinostat	Decrease of differentiated phenotype (reduction of alkaline phosphotase and osteocalcin)	37
Lymphoid tissue HIV	HARV	Repopulation of human tonsil fragments with exogenously added T and B lymphocytes; capable of infection by HIV	38
Liver	HARV	Expansion of tissue from microscopic fragments, angiogenesis	39

3.2.3 Recombinant Protein and Small Molecule Drug Production

The effect of microgravity on cells in suspension is likely due to the cytoskeletal changes described previously. Recombinant proteins are proteins whose DNA code has been inserted (cloned) into a carrier organism (usually bacteria or yeast). The carrier organism then produces that protein, and the protein is harvested. Not all drugs produced by biotechnology are proteins, however. Some drugs are small molecules produced by the enzymatic action of cells, and are extracted and purified from cells. Sometimes recombinant proteins (usually with enzymatic functions) are inserted into cells to enable or enhance the production of small molecule drugs. The cells used for recombinant drug production are usually yeast or bacteria (often Escherichia Coli), and grown under controlled conditions in a bioreactor.

In many regards, space provides an ideal environment for the production of biotechnology drugs: quality control depends on a constant environment and no contamination; it is extremely difficult to obtain good expression of some proteins, making even small increases in production significant; and most of the processes that would take place in space are largely automated.

Experiments in microgravity have yielded mixed results, with some protein yields increasing, and some decreasing. The actual effect that microgravity will have appears hard to predict and seems to depend on the specific protein and system being used, although bacteria appear to be far more likely to have a decreased doubling-time, and grow to higher concentrations. More experimentation is required to determine the scope of the benefit of microgravity, and much of this will be done on the ISS. Similarly, there remains to be done a great deal of work developing microgravity-based separation procedures, that could increase the product yield. However, some initial work has been done that shows promise, and forms the basis of this evaluation.

3.2.3.1 Advantages of Microgravity for Recombinant Drug Production

Insofar as the harvesting of pharmaceutically useful recombinant proteins is concerned, the following are the advantages of microgravity:

- Increased protein yield
- Extracellular protein transport (likely due to low shear forces rather than microgravity)
- Novel environment may yield novel protein structure
- Variable gravity changes environmental constants significant for product separation (as described previously)
- The space environment is free from contaminants

Since some of the direct increased protein yield can be achieved with simulated microgravity, the cost benefit of producing recombinant protein in space would be in cases where:

- There is an increase in yield in true microgravity above that in simulated microgravity
- True microgravity yields a product unobtainable in a terrestrial environment
- Enhanced protein separation in microgravity increases yield
- Space provides an environment more suited for culture (an example would be isolation)

3.2.3.2 Antibiotic Production

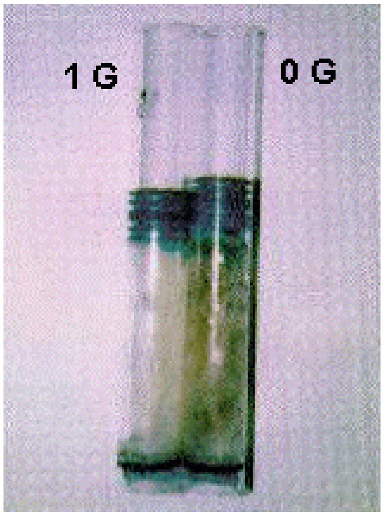
Actinomycin D is an antibiotic that is used as a chemotherapeutic in the treatment of some malignancies after the failure of first-line chemotherapeutics and other treatment modalities. Its mode of action is to intercalate into DNA effectively blocking transcription, thus being toxic to a dividing cell. Since malignantly transformed cells have lost control of their cell-cycle and are rapidly dividing, actinomycin D has a slightly selectively toxic effect to cancer cells, giving it its therapeutic index. Originally identified, and ordinarily cultured, as a product of strains of Streptomyces bacterium, the cellular production of actinomycin D is catalyzed in a series of steps involving critical enzymes that modify the peptide chain to give the protein its function. The chromophore of actinomycin D, a phenoxazinone ring, is derived from the catabolism of tryptophan.[40] The gene cluster for actinomycin D production has been cloned, allowing for the recombinant production of the drug in different species of bacterium.[41]

Monorden is a metabolic product of *Humicola fuscoatra* with antifungal properties.

While actinomycin D is a relatively old chemotherapeutic, with limited therapeutic application due to its high toxicity, it is of particular interest since its recombinant production has been studied in microgravity with promising results. A joint effort by Bioserve and Brystol-Meyers Squibb has been undertaken to examine this production, and several microgravity experiments in the shuttle and on Mir have been undertaken, with several more planned.

Space-based production of the drugs Monorden and Actinomycin D have demonstrated a 75% increase in yield over ground based controls.

Initial experiments in 1996 using a test-tube apparatus demonstrated a 200% increased yield of Monorden in space compared to the terrestrial control. A change to a gas exchange fermenting system which increased the yield 20 times in the lab over the test-tube apparatus also demonstrated a yield in space of 75% over the matched ground control.



Monorden production in space (right) compared to a matched ground control (left); from STS-77. Image credit: BioServe.

Figure 24

In 1998, additional experimentation was done with the production of recombinant actinomycin D using E. Coli as a vector into which the gene cluster whose protein products are necessary for production was cloned. The results demonstrate an improvement of 75%.

It should be noted that if both cases the space-based manufacture yielded less than would be expected in a modern bioreactor optimized for terrestrial production. This indicates that a bioreactor intended for microgravity production would need to be optimized for production in that environment. Notwithstanding such considerations, a 75% increase in yield is a substantial increase, and if reproduced for recombinant drug that are difficult to manufacture and with high market value, this represents a substantial market.

3.2.3.3 Market Dynamics

The following section summarizes a number of key metrics for this market.

3.2.3.3.1 Examples of Recombinant Protein Drugs

The following table shows the sales and key information for some significant protein drugs.

Table 7: Commercial Recombinant Protein Production and Sales[42]

Company (s)	Product	Developer; Marketer	Product Category	FDA approval	First Approved Indications	1999 Sales (US$M)
Amgen	Epogen		Recombinant human erythopeiotin	Jun-89	Anemia associated with chronic renal failure including dialysis & non-dialysis patients; also anemia in Retrovir-treated patients	$1,760
	Infergen	Yamanouchi Pharm.	Consensus interferon; non-natural recombinant type 1 alpha interferon	Oct-97	HCV infection (chronic)	$26
	Neupogen	Kirin Brewery Co.	Recombinant granulocyte colony stimulating factor (G-CSF)	Feb-91	Chemotherapy-induced neutropenia	$1,260
Bayer	Kogenate	(licensed from Genentech)	Recombinant antihemophillic factor (factor VII)	Feb-93	Hemophilia A	$367
Biogen	Avonex		Recombinant interferon beta-1b	May-96	Relapsing multiple schlerosis	$621
Centocor (J&J)	Remicade	Schering-Plough	Chimeric monoclona antibody fragment to tumor necrosis factor-alpha	Aug-98	Moderate to severe Crohn's disease (including fistulizing Crohn's disease)	$88
	ReoPro	Lilly	Chimeric monoclona antibody fragment to GPIIb/IIIa platelet receptor	Dec-94	Anti-platelet; prevention of blood clots in the setting of high-risk percutaneous transluminal coronary angioplasty (PCTA)	$447
	Retavase	(acquired rights from Boehringer Mannheim & Dupont Merck)	Recombinant tissue plasminogen activator	Oct-96	Treamnet of acute myocardial infarction	$90
Chiron	Betaseron	Berlex Laboratories (Schering AG)	Recombinant interferon beta-1a	May-96	Relapsing multiple schlerosis	$430
	Proleukin	Ligand (Canada)	Recombinant human interleukin-2	May-92	Metastatic melanoma	$112
	Regranex Gel	Ortho-McNeil Pharmaceuticals (J&J)	Recombinant human platelet-derived growth factor	Dec-97	Lower extremety diabetic neuropathic ulcers	$72
Eli Lilly	Humulin	(licensed from Genentech)	Recombinant human insulin	Oct-82	Diabetes	$1,088
Genentech	Activase	Roche	Recombinant tissue plasminogen activator	Nov-87	Acute myocardial infarction	$236
	Herceptin	Roche	Humanized monoclonal antibody to HER2 growth factor receptor	Sep-98	Treatment of HER-2 overexpressing metastatic breast cancer	$188
	Protropin/ Neutropin/ Neutropin AQ	Roche	Recombinant human growth hormone	Oct-85	Growth failure in children due to chronic renal insufficiency, growth hormon inadequacy in children	$221
	Pulmozyme	Roche	Recombinant human DNase	Dec-93	Reduction of incidence of respiratory tract infections in patients with cystic fibrosis	$111
Genetics Institute	BeneFix	American Home Products (AHP)	Recombinant human factor IX	Feb-97	Treatment of hemophilia	$135
	Neumega	Wyeth-Ayerst (AHP)	Recombinant human interleukin-11 (platelet growth factor)	Nov-97	Chemotherapy-induced thrombocytopenia	$45
Genzyme	Ceredase/ Cerenzyme		Recombinant glucocerebrosidase	May-94	Glaucher's disease	$479
Hoffman-La Roche	Roferon-A	(licensed from Genentech)	Recombinant interferon alpha-2a	Jun-86	Hairy cell leukemia	$176
Idec Pharmaceut.	Rituxan	Genenteck; Hoffman- La Roche	Chimeric pan-B monoclonal antibody that targets CD20 on B cell surface	Nov-97	Treatment of refractory low-grade or follicular CD20-positive B-cell non-Hodgkin's lymphoma	$279
Immunex	Enbrel	Wyeth-Ayerst (AHP)	Dimeric fusion protein; recombinant soluble p75 tumor necrosis factor receptor linked to Fc portion of human IgG1	Nov-98	Moderate to severe active rheumatois arthritis (monotherapy in patients who have failed other therapies; also for use in combination with methotrexate	$367
	Leukine		Recombinant granulocyte macrophage colony stimulating factor (GM-CSF)	Mar-91	Autologous bone marrow transplant	$69

3.2.3.3.2 Recombinant Protein Drug Market Analysis

- Recombinant protein drugs and diagnostic agents are one of the fastest growing segments of the pharmaceutical industry generating US$20 billion in annual revenues.
- According to industry sources, for some products an improvement in yield of only a few percent can save millions in production costs.
- Industry sources state that more information about the increase in yield for a specific product and the launch costs are required to develop a business case.
- Biotechnology firms are aware of some of the advantages of microgravity, but very few have performed microgravity experimentation for the manufacturing of biotechnology products.
- Antibiotics have an annual global market in excess of US$20 billion.
- Nearly 86% of the 77 biotechnology medicines approved by the FDA are recombinant human proteins.

3.2.4 On Orbit crystallization facility

Proteins, under the appropriate physical and chemical conditions, can be induced to form a regular crystalline array. The primary use of such crystal structures is the ability to derive the proteins structure by x-ray diffraction studies of the crystallized protein. While the amino acid sequence of a protein can be determined either directly by amino-acid sequencing, or indirectly by DNA sequencing, for many proteins this information is insufficient to determine the exact final structure of the protein. Even though amino acid strings fold in largely predictable ways, other factors are involved in deriving the exact final three-dimensional structure, such as post-translational processing and chaperonins (other proteins whose function it is to assist proteins form their final shape). The significance of this is that the enzymatic and structural functions of many proteins are determined by their precise folded three-dimensional shape. Not only does this information yield invaluable insight into the specific bioactive properties and mechanisms of the proteins, but it allow drugs to be targeting to blocking those properties.

NASA has devoted substantial resources for evaluating and performing protein crystallization with scientifically and academically significant results. The improved facilities provided by the ISS will allow this research to continue.

3.2.4.1 Advantages of Microgravity for Protein Crystallization

Microgravity crystallization demonstrated increased size and quality

Experimental results from microgravity crystallization experiments indicate increased crystal size (as much as twice the volume), more uniform morphologies, and/or higher resolution diffraction data (0.1 to 0.8 A) than the best crystals possible in a terrestrial environment.[43]

3.2.4.2 Market Dynamics

The analysis performed by AS&T revealed no significant end-user product for protein crystallization. Protein crystal structure reveals valuable information for academic and scientific research, and advances development of certain drug development and fundamental understanding of certain cellular and biochemical processes.

Feedback from industry suggests that while there is market for crystallization facilities, the scope and size of the market is insufficient to substantially drive the development of future space transport.

NASA has devoted considerable resources to protein chemistry, often at the expense of cell biology. When launch facilities and orbital resources are available at a commercially acceptable price, it is likely that there will be an increase in industry utilization of microgravity for protein crystal growth.

3.2.5 Biomedical Market Derived RLV System Requirements

A broad requirements set of 50 requirement / attribute pairs were identified in Section 2.3. In the current section, the specific requirements values for the Biomedical Markets are listed, as derived from published papers, reports, reference data, and discussions with selected industry representatives and supporting documentation. While the current uncertainty of these numbers is estimated to be significant, the accuracy of the model will increase with the collection of additional data.

Only the requirements number and heading are listed for each requirement value (for the complete definition of the requirement / attribute see Section 2.3). Where no numerical value is given, a qualitative discussion is provided if it was available. Note that the requirements numbering does not follow the heading numbers of this report and is provided in parenthesis behind the section heading for the readers reference. A summary of all collected requirements is presented in Section 5 of this report.

Scheduling (1-0-0)

Payload Schedule

1-1-1 Payload Processing Time: For biomedical markets the payload processing time does not impose specific limitations provided that optimum conditions for the payload can be maintained.

1-1-2 Pre-Departure Idle Time: No specific requirement was determined, as long as payload conditions can be maintained.

1-1-3 Transit Time: Payload containing biomedical products does not have specific transit time specifications provided that payload conditions are maintained.

1-1-4 Post Arrival Idle Time: Arrival of biomedical payload into a microgravity environment does not have specific post arrival idle time specifications provided that payload conditions are maintained. Return to a normal gravity environment may have specific requirements depending on the specific payload. Since the doubling time of most mammalian cells is greater than several days, a daylong limitation should provide the outer limitation.

Operations Schedule

1-2-1 Advanced Booking Time: The time frame for booking a flight ranges from one month for custom tissue engineering payload, to flights scheduled over a year in advance for biochemical and recombinant pharmaceutical production. New products and test runs are likely to be added to existing scheduled flights.

1-2-2 Launch Window: No data.

Operations (2-0-0)

Reliability

2-1-1 Successful Delivery: There are no specific requirements for biomedical products. However, unsuccessful delivery attempts will impact the business case for each of the biomedical products.

2-1-2 Service Availability: Some biomedical products, especially custom tissue engineering will require year-round service.

2-1-3 On-Time Delivery: There are no specific requirements for on-time delivery, provided that the payload can be maintained at optimum conditions, and the degree of tardiness does not impact cell viability (expected to be a problem at approximately one week).

Safety

2-2-1 Emergency Egress: No data.

2-2-2 Abort Capabilities: No data.

2-2-3 Catastrophic Failure: No data.

Performance (3-0-0)

Payload Mass

3-1-1 Payload Mass: Variable. The greater the mass the better the business case since most products are scaleable in production. The minimum payload mass with a business case that closes depends on the specific product and whether orbital production is done in transit or on an orbiting platform. With an orbital manufacturing plant, the minimum weight would be greatly reduced.

3-1-2 Payload Rate: Variable. Depends on the specific products. Monthly Interval is likely to be minimal for many products.

Payload Manifest

3-2-1 Multiple Destinations: An unlikely requirement.

3-2-2 Multiple Payloads: An extremely likely requirement for some biomedical products. An ideal design would allow modular standard compartments.

Interfaces (4-0-0)

External Interfaces

4-1-1 Facility Location: No specific requirements. Locating near existing biomedical manufacturing plants would reduce initial costs. Location in the United States is likely to be required for regulatory approval of manufacturing plants.

4-1-2 Infrastructure Attributes: Requires access to some shipping routes for product distribution and material access.

4-1-3 Payload Processing: Payload processing must conform to pharmaceutical manufacturing standards regulated by the Food and Drug Administration (FDA). Payload processing must occur close to the arrival site for some biomedical products since transport adds time and stress limiting cellular viability.

Payload Accommodations

4-2-1 Payload Volume: Greatly determined by the specific product. For tissue engineering products, an individual compartment of approximately a cubic half-meter is likely to be required for each product, along with a central reservoir of nutrients, pumping, and filtration systems. The density of such a system will approach 1. For a recombinant product utilizing in-transit manufacturing, each bioreactor is likely to be several times larger, but again with a density approaching 1. For biochemical and chemical manufacturing of pharmaceutical, the volume will be greater since multiple reactions are likely, each requiring different apparatus. In the case of manufacture that occurs on an orbiting platform, the volume is dependent on the frequency of flights, and quantity of product. This will vary depending on the specific product.

4-2-2 Acceleration Loads: During nominal operation acceleration is not to exceed 1.0g in any direction for tissue-engineered products during re-entry. Products shall not exceed 3.0g for launch. Other biomedical product will have slightly higher tolerances.

4-2-3 Processing Orientation: No requirements for most products.

4-2-4 Data Interface: Most products will require extensive real time monitoring, and some will require remote manipulation.

4-2-5 Deployment Parameters: No deployment.

4-2-6 Shock Environment: No data. Many biomedical products are extremely sensitive to shock, but there is insufficient data to determine the exact constraints.

4-2-7 Vibration Environment: Cellular and crystal biomedical products are sensitive to vibration. Aqueous solutions and vibration absorption and minimization are required. The resonant frequencies vary by product, especially regarding crystalline products. Cells are sensitive to vibration in less frequency-dependent manner, but vibration is known to cause cellular dissociation.

4-2-8 Acoustic Environment: Cell lysis and crystalline fracture are both possible at higher sonic frequencies. Sonic insulation is necessary if acoustic loads are present in higher frequencies.

4-2-9 Temperature Environment: All biomedical products are extremely pressure sensitive. Temperature must be maintained within 0.1C of optimum. Some products, especially in-transit biochemical manufacturing will require temperature variation between 0C-100C. For many compartments, individual containers will require separate temperature and environmental controls.

4-2-10 Pressure Environment: Biomedical products are sensitive to pressure. Some product may require variable pressure between 0-2atm. No unplanned pressure change is acceptable in most cases.

4-2-11 Payload Consumables: Greatly varies by product. Recombinant and cellular products will require aqueous nutrients, O_2, N_2.

4-2-12 Structure Interface: No data.

4-2-13 Atmosphere Composition: Controlled and variable O_2 saturation within 0.1%, N_2 saturation within 0.1%, pH within 0.1. Each requires variation and individual control and monitoring within each compartment.

4-2-14 Impact Prevention: No data.

4-2-15 Radiation Protection: Susceptibility is likely to be similar to human limitations. Radiation barriers are necessary only if radiation levels are likely to 500mrad.

4-2-16 Illumination: Many biomedical products require no illumination. Some with photosensitive components or photoreactions will require constant or variable lighting. Some will require exposure to the spectrum at different levels with frequencies from the infrared range to ultraviolet.

Business (5-0-0)

Economics

5-1-1 Standardization: No data.

5-1-2 Price Stability: No data.

5-1-3 Specific Payload Price: No data. Depends on specific product.

5-1-4 Evolvability: No data.

<u>Regulatory Issues</u>

5-2-1 Regulation: Meet applicable FAA regulations. Meet applicable FDA regulations.

5-2-2 Service Globalization: Should remain in US jurisdiction at all times for regulatory purposes.

Provider Specific (6-0-0)

<u>Scheduling</u>

6-1-1 Turn-Around Time: No data.

6-1-2 LRU Replacement: No data.

<u>Operations</u>

6-2-1 Operations Reliability: An asset utilization rate of 50% or higher is required.

<u>Interfaces</u>

6-3-1 Support Equipment: Utilize existing manufacturing and processing infrastructure as much as possible.

<u>Business</u>

6-4-1 Specific Payload Cost: No data.

6-4-2 Technology Globalization: No data.

3.3 LEO Passenger Travel

3.3.1 Market Definition (via Market Metrics)

The LEO Passenger Travel market is exhibiting a growing demand for LEO passenger services. Unlike many other s-business opportunities, this market is exerting a "pull" for products to supply LEO Passenger transportation and infrastructure services.

Revenues of the worldwide passenger air travel market, which would be considered a close analog to the future LEO passenger travel market, totaled US$ 142.7 billion in 1998. The world wide fleet of vehicles consisted of 15,560 jetliners as of September 2000. In 1999, U.S. carriers enplaned 47,847,000 passengers. An entire infrastructure made up of airports, maintenance facilities, flight services, travel agents, air traffic management control systems, communication networks, etc. have grown up to support the movement of people by air and entire industries have developed which are dependent on the airline transportation market, such as hotels, resorts, cruises, rental cars, amusement parks, tour operators, etc.

The majority of revenues of the airline passenger market are derived from the business traveler, though the majority of passengers are leisure travelers. The airline operators depend on the business traveler being unable to take advantage of discounted advance ticket purchase.

The LEO Passenger Travel market sector can also be divided into two segments, business and leisure travelers. LEO passenger business travelers will be a byproduct of the respective market segments which they will be supporting. The LEO passenger traveler will be the customer of a broad infrastructure which includes transportation, lodging, food and entertainment services.

Due to funding and time constraints this study is narrowly focused on the needs of the LEO passenger traveler using the transportation (or vehicle) portion of the infrastructure. Future studies will be required to examine other portions of the LEO leisure and business travel experience.

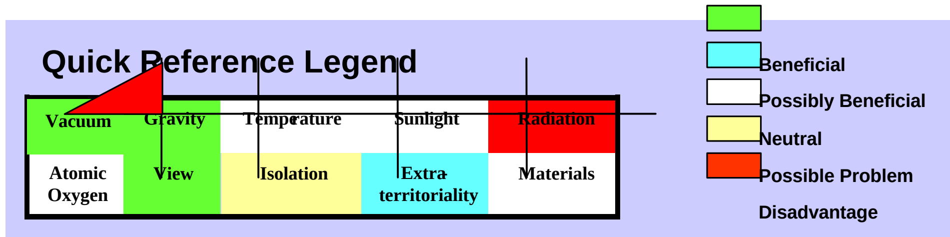


Figure 25: LEO Passenger Travel Space Benefits/Disadvantages

The LEO Passenger Travel market will be made up of both business and leisure travelers. The leisure traveler will be most attracted to the weightless experience and the view of Earth and space. Analogous to vacationing tourists who go scuba diving, some of the leisure travelers will want to experience a spacewalk. Some otherwise interested travelers will be repelled by their fear of radiation dangers, vacuum or isolation from Earth. As the experience matures the fears of some of those people will be mitigated and they will enter the pool of candidate travelers (there exists an analogous pool of individuals who have a strong fear of flying). Figure 25 illustrates the intersection of the benefits and disadvantages which attract and repel leisure LEO passenger travelers.

While the business traveler may personally enjoy some of the space experiences, the purpose of the travel will be focused on the benefits space brings to the business travelers products and not the experience of the trip. Business travelers will be traveling to space in support of their products, but will use the same lodging, food services and other traveler infrastructure elements during the trip, possibly demanding services which the leisure traveler may not require, such as secure communication with broadband capabilities.

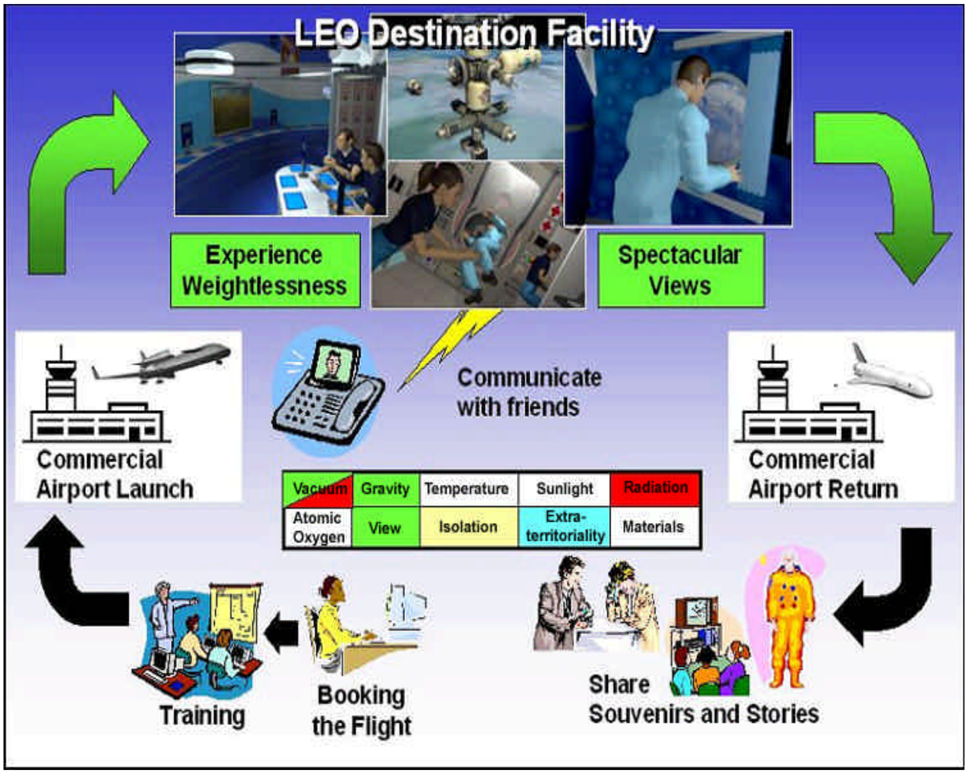
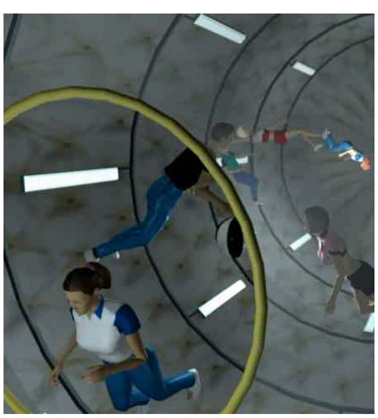


Figure 26: LEO Passenger Travel Value Analysis

Figure 26 illustrates that the actual spaceflight experience is part of the "value" attracting LEO passenger travelers, particularly the leisure traveler. The business will begin with advertising and booking prospective customers, some level of training, followed by the actual flight experience. Once on-orbit, the traveler will experience various weightless activities, as well as views of Earth and space. The experience ends with the return landing trip – though most travelers will gain significant pleasure, for some time afterward, in sharing their experiences with friends and family.

The Business Readiness Levels of most of the companies interested in offering LEO Passenger Travel are primarily no greater than 3, though there are a very few companies which are further along in their preparations and planning. Some of the companies exhibiting emerging interest and activity are mature operators in other aligned "passenger service" industries such as airline operations or tour services, while some are new startups with no alternate business activity. Only Energiya, manufacturer and operator of Mir space station and Soyuz spacecraft and associated launches has a BRL of 9. By 2010-2015 several companies could achieve BRLs of 9, and be actively offering LEO passenger travel products and services.



Overall this market sector is one which is exhibiting a growing demand for LEO passenger services, with announcements of plans or calls for the service occurring with increasing regularity. Unlike many other s-Business opportunities, this market sector is "pulling" for products to supply services, whereas in many of the other market sectors, most demand is being pushed by candidate product suppliers.

3.3.2 Commercial LEO Passenger Travel

There are no companies that have traditionally been involved in air passenger travel that are actively marketing LEO Passenger Travel, today. However, Hilton Hotels and brands. In April 1999, Virgin Group, owner of Virgin Airlines, incorporated a subsidiary named Virgin Galactic Airways, which is entertaining proposals to supply a transportation system. While Virgin has not yet made an investment in space transportation, the company has been "taking steps to ensure that it is positioned to get a piece of the action." Once Virgin chooses a vehicle the company says it may make an equity investment in the venture. Hilton has been using space for promotion since the 1960s. In the movie 2001, the PanAmSat "branded" spaceliner is shown docking with an orbiting Hilton hotel. Hilton periodically releases announcements regarding future plans to operate hotels orbiting in space and on the Moon. The airlines visited as part of this study were very aware of the advertising value associated with offering spaceflight services.

Energiya has begun offering Soyuz flights to Mir and ISS. Energiya is the manufacturer of the Russian Soyuz spacecraft, and operator of manned Soyuz launches, as well as the Mir space station. Two companies have negotiated contracts with Energiya for Soyuz launches. MirCorp has announced contracts to fly tourist Dennis Tito and a to-be-selected individual for an NBC television show, *Destination Mir*. MirCorp's original plans were to fly their "Citizen Explorer's" to the Russian Mir space station, but with Mir probably being deorbited in 2001 the company has been exploring gaining access to the International Space Station. Brainpool, a German television production company, has signed contracts with EADS for 7 Soyuz flights between 2002 and 2008 to launch their "Space Commander's".

Space Adventures has been incorporated as a joint venture of Omega World Travel and Quark Expeditions (Omega World Travel is a large U.S. tour operator), and Zegrahm Space Voyages was incorporated as a subsidiary of Zeghram Expeditions (a large tour operator in Europe). In late 1999 Space Adventures acquired Zeghram Space Voyages. Space Adventures is actively soliciting customers and has been booking deposits for sub-orbital flights, though the company has not yet selected a transportation provider. In the interim Space Adventures, and other companies, offers very short duration zero-G "tourist" opportunities on parabolic flights.

3.3.2.1 Industry Interviews

During this study eight airlines were contacted, of which five responded to a request for a meeting. Four of the five responding airlines agreed to meetings, and meetings were actually held with two airlines. The fifth company stated it was not interested in the space flight market at this time. For three of the four airlines this was an unresearched topic, but one of the airlines had already undertaken internal research on the subject. First interviews were actually held with two airlines, the other two airlines interested, but not sure with whom interviews should actually be conducted. Both of the interviewed airlines were of the opinion that demand for LEO passenger travel services are real. Both airlines strongly understood the publicity value that would accrue to an airline offering LEO passenger travel services. Meetings were with the Marketing organizations of the respective airlines, though they both indicated that meetings with their technical staffs would be required to assess the technology readiness, and hence their interest to invest and operate a LEO Passenger Travel service.

Issues of safety/reliability, publicity, price/cost, size of market, destination/activity, and product introduction were among the topics discussed during the meetings. All participants agreed that safety was a paramount, but achievable issue. Quantification of the risk however was deferred to future meetings with technical staffs, and would have to be architecture specific. It was agreed that price/cost are market and architecture driven, which are highly dependent on flight rate. While the airlines felt that a market exists for sub-orbital flight and orbital flight with no destination, the larger, more robust market of interest to them would be one which included a destination.

The lack of gravity was discussed in some depth. It will be both an attraction, as well as a difficulty which the traveler will have to deal with. The weightless experience will be part of almost every activity the traveler's encounter during their trip, including sleeping, eating, toilet activities, play, work, etc. The vehicle and destination system designs will need to accommodate the inexperience and unfamiliarity of the travelers. In some instances good design practices or issues affecting health and safety can be reinforced during a pre-flight training experience.

The suborbital market segment was briefly discussed. The general opinion was that the suborbital space tourism market would be almost instantly displaced when a product capable of reaching orbit was introduced. Without additional study an unanswered question remains – "Would a suborbital market last long enough for the manufacturers/operators be able to recoup their investments prior to the introduction of a transportation system capable of making orbit?"

NASA can assist the LEO passenger travel market by continuing investigation of spacesickness and devising mitigation measures.

Spacesickness (Space Adapt ion Syndrome) was discussed in some detail. The Cruise ship industry deals with seasickness on every voyage, so marketing around the problem can be successful. However, individuals who have experienced both events, indicate that spacesickness is by far a worse experience. Approximately half of spaceflight travelers experience the problem. The leisure experience and business traveler productivity will both be impacted by spacesickness. NASA can assist the LEO passenger travel market by continuing investigation of the phenomenon and devising mitigation measures.

3.3.3 LEO Passenger Market Derived RLV System Requirements

A broad requirements set of 50 requirement / attribute pairs were identified in Section 2.3. In the current section, the specific requirements values for the LEO Passenger Market are listed, as derived from the interviews AS&T conducted with selected industry representatives and supporting documentation. While the current uncertainty of these numbers is estimated to be significant, the accuracy of the model will increase with the collection of additional data.

Only the requirements number and heading are listed for each requirement value (for the complete definition of the requirement / attribute see Section 2.3). Where no numerical value is given, a qualitative discussion is provided if it was available. Note that the requirements numbering does not follow the heading numbers of this report and is provided in parenthesis behind the section heading for the readers reference. A summary of all collected requirements is presented in Section 5 of this report.

Scheduling (1-0-0)

Payload Schedule

1-1-1 Payload Processing Time: Due to existing standards in commercial airfreight, customer expectations are of a similar "ship & shoot" operations concept. Cargo (luggage) is delivered pre-packaged and minimal processing is required. Passengers will expect nominal terminal times of no more than 6 hours from arrival at the point of departure until the vehicle is completely loaded, sealed, and ready for take-off.

1-1-2 Pre-Departure Idle Time: No specific requirement was determined, as long as requirement 1-1-3 is met.

1-1-3 Transit Time: For the delivery of cargo associated with passenger travel as well as passenger transport itself, a transit time of 6 hours or less is desirable, 2-3 hours would be ideal. However, transit times of up to 1 week may be acceptable (with sacrifices in passenger comfort) in emergency situations. Durations in excess of 1 week are unacceptable due to safety concerns.

1-1-4 Post Arrival Idle Time: Again, the commercial airline industry did establish a standard for this value, and future space travel customers will expect similar service. Passengers will want to disembark within 30 minutes of arrival, and need to have access to their belongings within 1-2 hours of arrival at locations on orbit or on the surface.

Operations Schedule

1-2-1 Advanced Booking Time: The time frame for booking a flight (making a reservation) ranges from 1 week for business travel to as much as 3 months for tourism. Less than 1 week is desirable for business ravel, but not required.

1-2-2 Launch Window: No data.

Operations (2-0-0)

Reliability

2-1-1 Successful Delivery: No data.

2-1-2 Service Availability: No data.

2-1-3 On-Time Delivery: The current airline service on-time performance as of August 2000, ranges from 83% (NW Airlines) to 60% (America West Airlines).[44] On time performance is defined as ?15 minutes of the scheduled departure and arrival time. Since, even the lowest ranked company still draws in a substantial market share, the requirement is set at 50%.

Safety

2-2-1 Emergency Egress: No data.

2-2-2 Abort Capabilities: No data.

2-2-3 Catastrophic Failure: While no definitive data has been gathered at this point, the current commercial airline safety record is 1:100,000 (fatalities per departures). It is uncertain, what rate would be acceptable to the paying transportation customer / general public.

Performance (3-0-0)

Payload Mass

3-1-1 Payload Mass: Up to 50,000 lbs.

3-1-2 Payload Rate: Up to 3000 flights over 16 years (see Section 4.X: Mission Model for more detailed information).

Payload Manifest

3-2-1 Multiple Destinations: At least one destination, possibly two, but specialized Orbit to Orbit transport is more likely than multi-destination flight plans.

3-2-2 Multiple Payloads: Assortment of non-standardized cargo (luggage) and multiple passengers. However, a standardized form factor is conceivable.

Interfaces (4-0-0)

External Interfaces

4-1-1 Facility Location: Centralized passenger and cargo processing is required (commercial airport type operations).

4-1-2 Infrastructure Attributes: Needs to be able to depart and land at commercially accessible infrastructures (spaceports), and be capable of pressurized docking with on orbit infrastructure.

4-1-3 Payload Processing: Standards in compliance with commercial airport operations are required. Passengers will expect luxurious accommodations during pre- and post-flight processing.

Payload Accommodations

4-2-1 Payload Volume: As required for the accommodation of human passengers. Estimated at up to 3,200 cubic feet. In addition, all passenger cabins must comply with FAR Part 25 Subpart D Sec. 25.785, “Personnel and Cargo Accommodations”.

4-2-2 Acceleration Loads: During nominal operation acceleration is not to exceed 1.5g in any direction except axial forward, not to exceed 3.0g. In emergency situations FAR Part 25 Subpart D Sec. 25.561 (3) (i)-(v) applies.

4-2-3 Processing Orientation: Horizontal loading and unloading is highly desirable for passenger services.

4-2-4 Data Interface: No data.

4-2-5 Deployment Parameters: No data.

4-2-6 Shock Environment: No data.

4-2-7 Vibration Environment: No data.

4-2-8 Acoustic Environment: TBD decibels.

4-2-9 Temperature Environment: Must comply with FAR Part 25 Subpart D Sec 25.831.

4-2-10 Pressure Environment: Must comply with FAR Part 25 Subpart D Section 25.841.

4-2-11 Payload Consumables: No data.

4-2-12 Structure Interface: All doors and exits must meet FAR 23.783 and FAR 23.807 (a)(3), (b), and (c). Adequate seating for passengers must be provided.

4-2-13 Atmosphere Composition: Need to comply with FAR Part 25 Sub-part D Sec. 25.831.

4-2-14 Impact Prevention: No data.

4-2-15 Radiation Protection: No data.

4-2-16 Illumination: Adequate illumination for passenger travel must be provided. Synthetic outside vision ("window" seats) are highly desirable.

Business (5-0-0)

Economics

5-1-1 Standardization: No data.

5-1-2 Price Stability: No data.

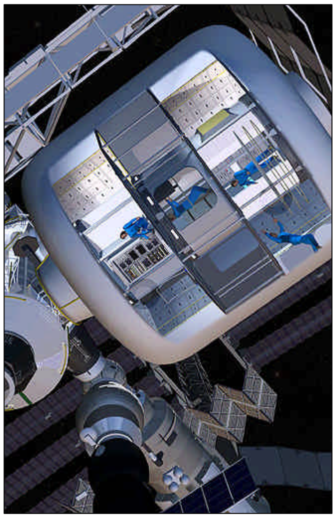
5-1-3 Specific Payload Price: The price range identified in the current economical model isUS$500-US$1,000 per pound to LEO/ISS .for passenger travel, andUS$1,750-US$3,000 per pound to LEO/ISS for cargo (see Section 4.X: Mission Model for more detailed information).

5-1-4 Evolvability: Highly desirable that vehicle meet evolving requirements over 20 year life span.

Regulatory Issues

5-2-1 Regulation: Meet applicable FAA regulations.

5-2-2 Service Globalization: Be suitable for operation from and to international destinations, and be capable of servicing international customers regardless of citizenship.



Provider Specific (6-0-0)

Scheduling

6-1-1 Turn-Around Time: Initially no more than 10 days (at IOC). Needs to progress to no more than 56 hours by IOC+15 years.

6-1-2 LRU Replacement: No data.

Operations

6-2-1 Operations Reliability: An asset utilization rate of 50% or higher is required.

Interfaces

6-3-1 Support Equipment: Utilize existing airport infrastructure as much as possible.

Business

6-4-1 Specific Payload Cost: Payload cost is to be 40% (or more) below specific payload price.

6-4-2 Technology Globalization: No data.

3.3.4 Market Development Scenario

> Once the International Space Station is operational the facility should begin welcoming travelers to utilize the on-orbit infrastructure….. This class of business traveler should be opened to include winners of commercial promotions such as MirCorp's "Citizen Explorer", BrainPool's "Space Commander", and NBC's "Destination Mir" television program.

Today, the only LEO passenger travel services which exist are operated by NASA, using the space shuttle, and by Energiya, using Soyuz rockets and Soyuz spacecraft. In the future it is expected that a commercial LEO passenger travel market will develop. Figure 27 identifies some steps which can be undertaken between now and the introduction of a new system, which can develop and encourage commercial use.

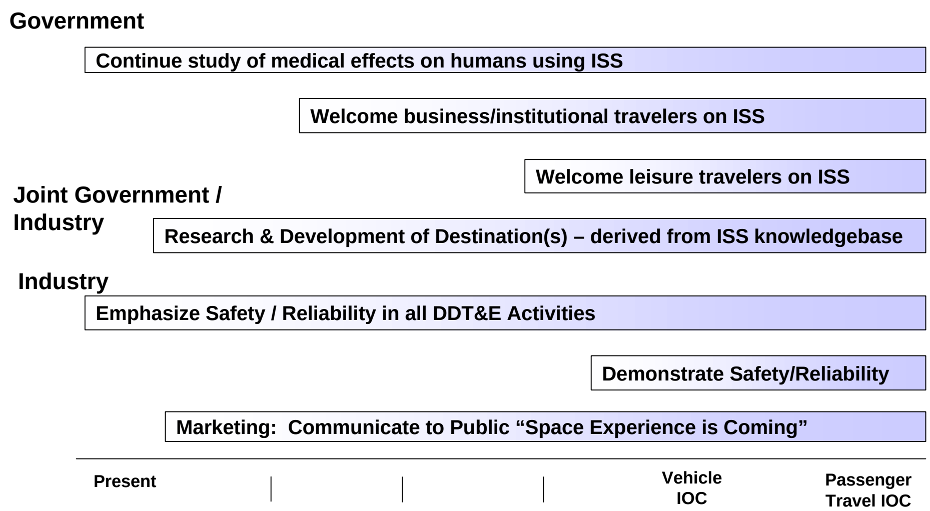


Figure 27: LEO Passenger Travel Market Development Roadmap

> As ISS operational experience matures, facility should be opened up to leisure travel.

The government should continue to study and monitor the effects of the space experience on human beings. As necessary, steps to mitigate negative effects should be researched, tested and implemented. Once the International Space Station is operational the facility should begin welcoming industry and institutional travelers to conduct research and utilize the on-orbit infrastructure. Such travelers could be mandated to undertake rigorous training prior to their travel experience. This class of business traveler should be opened to include winners of commercial promotions such as MirCorp's "Citizen Explorer", BrainPool's "Space Commander", and NBC's "Destination Mir" television program – provided that the participants complete the appropriate training programs.

As experience operating the International Space Station matures, the facility should be opened to leisure travelers. These travelers would contract directly with commercial services for training, transportation (using the shuttle system or Soyuz), and lodging/food services, etc.. The corporate service provider would become responsible for fulfillment of all necessary operations to supply the requested services.

A space tourism study conducted with the appropriate demographic population would benefit the business case development and aerospace industry acceptance of the market credibility.

Industry must take a leadership position, during the DDT&E phase of creating a next-generation space transportation system, on safety/reliability requirements. All phases of the business enterprise should have safety/reliability as a fundamental backdrop when decisions and actions are taken. Industry should work with the government to define, articulate and demonstrate the fulfillment of the safety/reliability requirements.

In addition industry needs to actively promote and market the forthcoming LEO Passenger Travel experience. Repeated communication to the public that commercial space travel is coming soon will accelerate its acceptance when it becomes available.

4 2nd Generation RLV Design Requirements

A broad requirements set of 50 requirement / attribute pairs was identified in Section 2.3. Requirements values were derived from each market segment and are documented at the end of each market analysis section. The current section summarizes the requirements derived from all of the market segments, and identifies the most limiting values for a system that is to serve all of the investigated markets. While the current uncertainty of these numbers is estimated to be significant, the accuracy of the model will increase with the collection of additional data.

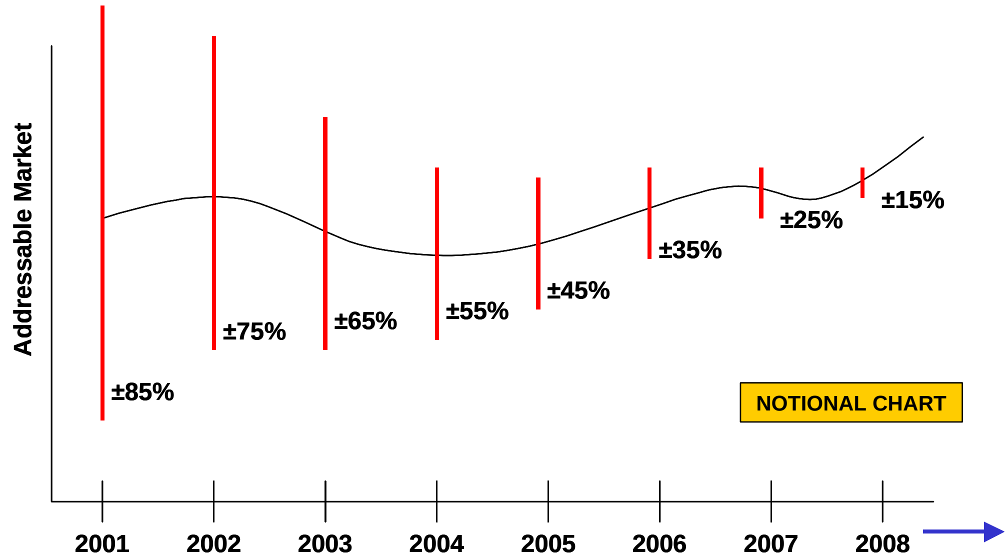


Figure 28: Future Commercial Market Fidelity Increases over Time

Selected future commercial market segments have been identified and reviewed to determine their requirements, such as orbital destination, mission mass, flight rate, payload parameters, etc. Requirements of each market segment were then reviewed against other market segments to determine where the requirements might intersect and differ. Instances in which multiple markets have the same requirements, strengthens the need to implement a particular requirement. Where they differ, the cost of designing to the extra requirements must be weighed against risk and potential return. In the market segments reviewed for this study many of the requirements have been found to be partially or wholly within the domain of NASA's access to space station technical requirements, though often business and operational requirements may conflict.

In the market segments reviewed for this study many of the requirements have been found to be partially or wholly within the domain of NASA's access to space station technical requirements, though often business and operational requirements may conflict.

4.1 Requirements Derivation Process

Figure 29 illustrates the requirements derivation process. Where no quantitative data was collected for a given market segment, a qualitative comparison was attempted. However, in all cases, quantities data supersedes qualitative data as the limiting factor in the requirements summary.

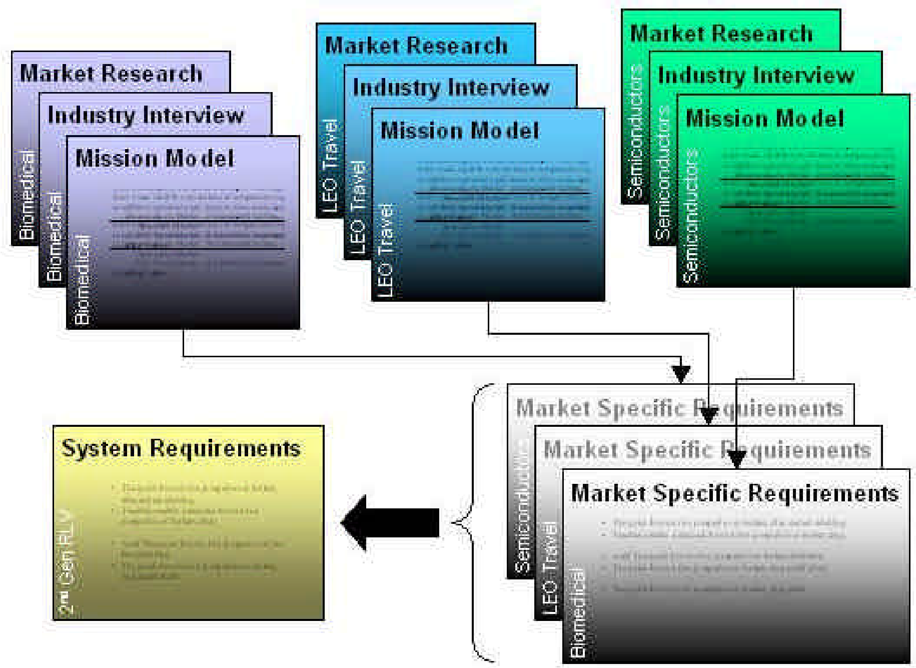


Figure 29: RLV System Requirements are derived from Market Needs

The various attribute/requirement pairs considered in this study were chosen to reflect all the needs of the market that is to be served, while maintaining the minimum number of limitations imposed on the transportation system designer. All of the collected attributes are sorted in six major categories, each with a number of sub-categories:

Interfaces

- ***External Interfaces***
  - **Facility Location**
  - **Infrastructure Attributes**
  - **Payload Processing**
- ***Payload Accommodations***
  - **Payload Volume**
  - **Acceleration Loads**
  - **Processing Orientation**
  - **Data Interface**
  - **Deployment Parameters**
  - **Shock Environment**
  - **Pressure Environment**
  - **Payload Consumables**
  - **Structure Interface**
  - **Atmosphere Composition**
  - **Impact Prevention**
  - **Illumination**

Provider Specific

- ***Scheduling***
  - **Turn-Around Time**
  - **LRM Exchange Time**
- ***Operations***
  - **Ops Reliability**
- ***Interfaces***
  - **Support Equipment**
- ***Business***
  - **Specific Payload Cost**
  - **Technology Globalization**

Scheduling

- ***Payload Schedule***
  - **Payload Processing Time**
  - **Pre-Departure Idle Time**
  - **Transit Time**
  - **Post-Arrival Pad Time**
- ***Operations Schedule***
  - **Advance Booking Time**
  - **Departure Window**
  - **Access Notification**

Performance

- ***Payload Mass***
  - **Payload Mass**
  - **Payload Rate**
- ***Payload Manifest***
  - **Multiple Destinations**
  - **Multiple Payloads**

Operations

- ***Reliability***
  - **Successful Delivery**
  - **Service Availability**
  - **On-Time Delivery**
- ***Safety***
  - **Emergency Egress**
  - **Abort Capabilities**
  - **Catastrophic Failure**

Business

- ***Economics***
  - **Standardization**
  - **Price Stability**
  - **Specific Payload Price**
  - **Evolvability**
- ***Regulatory Issues***
  - **Regulation**
  - **Service Globalization**

4.2 Requirements Listing

In the following, each requirement is restated, together with summarized data from each market segment (where available). Each requirements group is then distilled into the limiting case.

1-1-1 Payload Processing Time	
Time from payload delivery to the carrier to payload being fully integrated into the vehicle**.**	
Semiconductor Market	No Data
Biomedical Market	No limitations.
LEO Travel Market	6 hours maximum
Limiting Values	**6 hours maximum**

1-1-2 Pre-Departure Idle Time	
Time from sealing the vehicle to departure	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	**No Data**

1-1-3 Transit Time	
Time from departure to arrival (min/max). This requirement may address the need for loiter times, shelf-live restrictions of components (e.g. batteries), or passenger comfort in addition to product cycle-times or other economical considerations.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	2 h desired, 6 h maximum, 1 week emergency
Limiting Values	**2 h desired, 6 h maximum, 1 week emergency**

1-1-4 Post Arrival Idle Time	
Time from vehicle arrival until the payload is made available to the customer.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	0.5 h desired, 2 h maximum
Limiting Values	**0.5 h desired, 2 h maximum**

1-2-1 Advanced Booking Time	
Maximum and minimum lead time acceptable to the customer when booking a payload manifest.	
Semiconductor Market	No Data
Biomedical Market	1 month to 1 year.
LEO Travel Market	Less than 1 week desired, 3 months maximum
Limiting Values	**1 week to 1 year**

1-2-2 Launch Window	
Maximum delay the system can absorb and still launch successfully.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	2 hours (Next orbit)
Limiting Values	**2 hours (Next orbit)**

2-1-1 Successful Delivery	
Probability of the vehicle delivering the customer payload successfully and as scheduled.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	98%
Limiting Values	**98%**

2-1-2 Service Availability	
Probability of a flight being available when requested by a customer (assuming minimum lead-time is observed).	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	95% availability
Limiting Values	**95% availability**

2-1-3 On-Time Delivery	
Probability of the customer payload departing and arriving on time. Note that this includes the activities of pre and post payload processing, and is thus the probability of the entire system.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	50%, same day delivery
Limiting Values	**50%, same day delivery**

2-2-1 Emergency Egress	
Any required emergency Egress capabilities for crew, cargo or passengers.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	Demonstrated egress after takeoff failure
Limiting Values	**Demonstrated egress after takeoff failure**

2-2-2 Abort Capabilities	
Any required vehicle, landing site, and operations capabilities for abort scenarios.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	1/10,000 chance of abort failure
Limiting Values	**1/10,000 chance of abort failure**

2-2-3 Catastrophic Failure	
Maximum probability of catastrophic system fault (loss of payload) acceptable to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	< 1/10,000
Limiting Values	**< 1/10,000**

3-1-1 Payload Mass	
Maximum and/or minimum mass for any single payload to be transported.	
Semiconductor Market	1,600 lb minimum up, 135 lb minimum down
Biomedical Market	No Data
LEO Travel Market	Up to 50,000 lbs to LEO/ISS (up/down)
Limiting Values	**1,600-50,000 lbs up / 135-50,000 lbs down**

3-1-2 Payload Rate	
Anticipated rate of payload mass transported per year of customer / provider relations.	
Semiconductor Market	77,000 lb per year minimum
Biomedical Market	No Data
LEO Travel Market	Up to 9.3 million pounds per year (up/down)
Limiting Values	**77,000 lb/year min, 9.3 million lb/year max**

3-2-1 Multiple Destinations	
Minimum and maximum number of destinations for a single mission flight.	
Semiconductor Market	1
Biomedical Market	No Data
LEO Travel Market	1 minimum, possibly 2.
Limiting Values	**1-2 Destinations per flight**

3-2-2 Multiple Payloads	
Number of payloads and distinct payload types for a single flight.	
Semiconductor Market	Assortment of standardized containers
Biomedical Market	Assortment of standardized containers
LEO Travel Market	Assortment of non-standardized luggage / passengers
Limiting Values	**Passengers, standardized containers, non-standard luggage**

4-1-1 Facility Location	
Desired locations of transit departure and arrival. This is not necessarily identical to the location of payload processing (see 4-1-3).	
Semiconductor Market	Access to ground transport infrastructure
Biomedical Market	Domestic location for any given customer
LEO Travel Market	Commercial airport type operations
Limiting Values	**commercial airports, multiple countries**

4-1-2 Infrastructure Attributes	
Types of infrastructure the vehicle is required to be compatible with during nominal operations (commercial airport, spaceport, specific launch ranges, national or geographic locations, ISS, Mir, etc.).	
Semiconductor Market	On orbit infrastructure compatibility is required.
Biomedical Market	No Data
LEO Travel Market	Airport / on-orbit infrastructure compatibility
Limiting Values	**Airport & Orbit Infrastructure compatibility**

4-1-3 Payload Processing	
Limitations on facility type / location / capabilities (cleanroom specifications, security, passenger amenities, etc.) where the payload is handed to the service provider.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	Luxurious airport accommodations
Limiting Values	**Luxurious passenger accommodations**

4-2-1 Payload Volume	
Range of three-dimensional volume the payload may occupy. Note that a maximum as well as a minimum is of interest, since very small, yet massive and/or fragile payloads are conceivable (high value small crystals, super dense exotic materials, etc) and may require specific accommodations.	
Semiconductor Market	Minimum of 8 cubic feet
Biomedical Market	No Data
LEO Travel Market	Up to 3,200 cubic feet
Limiting Values	**8-3,200 cubic feet minimum**

4-2-2 Acceleration Loads	
Level, direction and duration of maximum acceleration sustainable by the payload.	
Semiconductor Market	Max 1.0g downmass; Max 3.0g Upmass
Biomedical Market	Max 1.0g (nominal) downmanss; Max 3.0g upmass
LEO Travel Market	Max 1.5g (nominal) downmass; Max 3.0g upmass FAR 25.561(3) emergency
Limiting Values	**Max 3.0g at launch then Max 1g in all directions (nominal)**

4-2-3 Processing Orientation	
Any limitations on the orientation in which the payload can be loaded onto the vehicle (horizontal vs. vertical).	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	Horizontal loading / unloading highly desirable
Limiting Values	**Horizontal Loading / Unloading**

4-2-4 Data Interface	
Requirements on the type, rate, direction, and interface of data transfers required by the payload while in the supervision of the carrier. Also, specifications for any particular mission segment during which the data transfer is required (if applicable).	
Semiconductor Market	No Data
Biomedical Market	Real Time telemetry
LEO Travel Market	No Data
Limiting Values	**Real-time Telemetry**

4-2-5 Deployment Parameters	
Attitude, rotation rates, and relative velocity requirements (with associated accuracy) imposed by the payload customer for the payload if deployed in flight. (This requirement has no value if the payload is loaded/unloaded at external infrastructures.)	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

4-2-6 Shock Environment	
Level and direction of maximum shock loads the payload may be subjected to.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

4-2-7 Vibration Environment	
Level, mode and spectrum of maximum vibration loads acceptable to the payload. This includes the first fundamental resonant frequency for cargo items.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

4-2-8 Acoustic Environment	
Level and spectrum of maximum acoustic loads acceptable to the payload.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	TBD decibels
Limiting Values	No Data

4-2-9 Temperature Environment	
Range of temperature and maximum rate of change acceptable to the payload customer. Note that this does not include heat rejection and absorption requirements, which are covered under 4-2-11 "Payload Consumables".	
Semiconductor Market	No Data
Biomedical Market	Stabilized 0-100 C, with 0.1 C accuracy
LEO Travel Market	FAR Part 25 Subpart D Sec 25.831
Limiting Values	**Stabilized 0-100 C, with 0.1 C accuracy**

4-2-10 Pressure Environment	
Range of pressure and maximum rate of change acceptable to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	0 – 2 atm
LEO Travel Market	FAR Part 25 Subpart D Sec 25.841
Limiting Values	**FAR Part 25 Subpart D Sec 25.841**

4-2-11 Payload Consumables	
Type, amount and rate of consumables required/rejected by the payload. Including heat, electrical power, fluids (N_2, O_2, water, etc.) and solids (e.g. food, refuse, etc.).	
Semiconductor Market	No Data
Biomedical Market	O2, N2
LEO Travel Market	H2O, Food & Refreshments
Limiting Values	**Varies with Payload**

4-2-12 Structure Interface	
Type and restrictions of the structure interface required by the payload (e.g. Marmon Clamp, Passenger Seat, etc.).	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	FAR Part 25 Subpart D Sec 23.783, 23.807
Limiting Values	**FAR Part 25 Subpart D Sec 23.783, 23.807**

4-2-13 Atmosphere Composition	
Composition of the atmosphere (if any) that the payload is exposed to during transit.	
Semiconductor Market	Pure N2 or Vacuum
Biomedical Market	No Data
LEO Travel Market	FAR Part 25 Subpart D Sec 25.831
Limiting Values	**Varies with Payload**

4-2-14 Impact Prevention	
Maximum probability of penetrating debris impact acceptable to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	1/10,000 probability of penetration
Limiting Values	**1/10,000 probability of penetration**

4-2-15 Radiation Protection	
Type and intensity of radiation levels acceptable to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	AEC requirements; NASA requirements
Limiting Values	**AEC requirements; NASA requirements**

4-2-16 Illumination	
Level and spectrum of illumination(s) required inside the payload compartment during all mission phases. May include specifications such as “window seats”.	
Semiconductor Market	Visible light for video monitoring
Biomedical Market	No Data
LEO Travel Market	Passenger illumination required, “windows” desirable
Limiting Values	**Visible light illumination, “windows” desired.**

5-1-1 Standardization	
Any customer imposed requirement with the goal of encouraging open standardization as to avoid captive-customer scenarios	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

5-1-2 Price Stability	
The maximum percent fluctuation the specific payload price may exhibit over time without disabling the customer business case or product market.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

5-1-3 Specific Payload Price	
The price per unit mass of payload delivered to its destination charged by the service provider to the payload customer.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	$500-US$1000 / lb passengers,US$1,750-US$3,000 / lb cargo
Limiting Values	**$500-US$1000 / lb passengers,US$1,750-US$3,000 / lb cargo**

5-1-4 Evolvability	
Requirements on the systems ability to adapt to changing requirements.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	Must be able to meet projected traffic growth
Limiting Values	No Data

5-2-1 Regulation	
Required regulatory standards for customer payload accommodation.	
Semiconductor Market	No Data
Biomedical Market	Meet applicable FAA and FDA regulations
LEO Travel Market	Meet applicable FAA regulations
Limiting Values	**Meet applicable FAA and FDA regulations**

5-2-2 Service Globalization	
Any requirements on the international availability of services required by the payload customer.	
Semiconductor Market	No Data
Biomedical Market	Remain in customer jurisdiction at all times
LEO Travel Market	International destinations and customers
Limiting Values	**Conflicting requirements**

6-1-1 Turn Around Time	
The total time from the vehicle's arrival to the next scheduled departure. Note that this is not identical with vehicle turn around time, since the requirement states only the limitations on the time-interval between flights, and not how many vehicles are utilized in the entire fleet to accomplish compliance.	
Semiconductor Market	One week maximum
Biomedical Market	No Data
LEO Travel Market	10 days minimum, 56 hours desired
Limiting Values	**56 hours – 1 week**

6-1-2 LRU Replacement	
The time needed to replace any Line Replaceable Unit (LRU) of the system.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	LL turnaround time.
Limiting Values	**LL turnaround time**

6-2-1 Operations Reliability	
The percentage of the transportation systems intended lifetime during which it is required to operate fault free and with nominal performance within the design envelope.	
Semiconductor Market	No Data
Biomedical Market	Asset utilization 50% or higher
LEO Travel Market	Asset utilization 50% or higher
Limiting Values	**Asset utilization 50% or higher**

6-3-1 Support Equipment	
Possible limitations on support equipment interfaces to accommodate legacy infrastructure or COTS availability of system components.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	Maximum utilization of existing infrastructure
Limiting Values	**Maximum utilization of existing infrastructure**

6-4-1 Specific Payload Cost	
Cost to the service provider per unit mass of payload delivered to the designated destination.	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	40% below price or less
Limiting Values	**40% below price or less**

6-4-2 Technology Globalization	
Requirements on international accessibility of LRU's and other support equipment (e.g. ITAR or national security restrictions).	
Semiconductor Market	No Data
Biomedical Market	No Data
LEO Travel Market	No Data
Limiting Values	No Data

Figure 30 shows how many requirements are driven by each of the markets examined in this study.

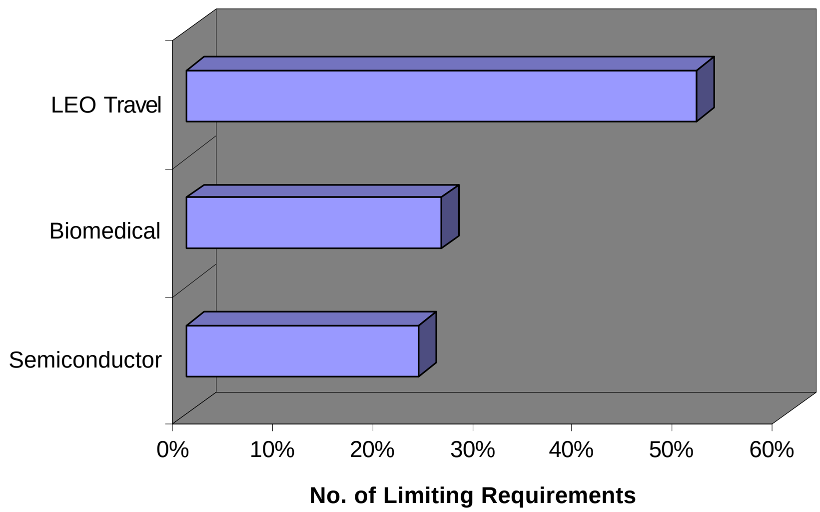


Figure 30: Comparison of Market Requirements Severity

It is apparent that the LEO Travel market with its associated transport of passengers and life-support issues imposes the most restrictive requirements on the design of the launch vehicle. However, the larger number of requirements may also indicate that this particular market is better characterized than the others at this point. Additional data must be gathered to further differentiate between these two possible interpretations.

5 Conclusions and Recommendations

Conclusion #1: This Future Space Transportation Study was a limited scope effort that analyzed approximately 20% of the potential future markets, as outlined by the Commercial Space Transportation Study (CSTS) published in 1994. The results of the limited market analyses conducted here supported the general conclusions put forth by the CSTS: that the space launch market is in-elastic above a certain launch price point (approximately $600 per pound) and elastic for prices below. At this time, AS&T has conducted insufficient analysis to make further recommendations on the size, shape and slope of the elasticity curve. We maintain that conducting further market analysis to define elasticity is critical to the continued growth and evolution of the space launch industry.

Future Commercial Space Markets	
Space Business Park •Materials (new alloys, composites, hi-temp superconductor, etc.) **•Pharmaceuticals / Biotech / Medical** •Optics **•Semiconductors**	**Tourism / Passenger Travel** •Suborbital Tourism **•LEO Passenger Travel** (hotels) •Romantic Excursions •Extra-LEO Tourism (Lunar C cycles) •Adventure Travel (Moon, Mars, etc.) •Tourism Based Services (clothing, fashion, spacesuits, food)
Space Services / Logistics •Supply / Cargo Transport (up/down) •Space Tug •Spacecraft Service Platform •Maintenance Depot •Warehousing (un/pressurized) •Gas and Propellant Storage •Space Burial	**Entertainment** •Gambling •On-orbit Sound Stage •Sporting Events •Personal Spacecraft **Commercial Science / Exploration / Exploitation** •Astronomy •Mining / Resource Prospecting •Waste Management and Disposal •Medical / Nuclear / Toxin Disposal

Figure 31: List of Future Space Markets with studied markets highlighted.

Conclusion #2: Many of the future markets will be enabled once the frequency and cost of space access achieves thresholds that allow established terrestrial industries to make money in space. This fact, that new revenues will come from multiple established industries, reduces the investment risk of fielding a 2nd Generation Launch System. As an example, many emerging launch vehicle companies (i.e. Kistler Aerospace Corporation, Kelly Space & Technology, Pioneer Rocketplane, Rotary Rocket, etc.) relied almost solely on the emergence of LEO communication satellite constellations, a new and unproven industry itself, to attract investment and achieve commercial viability. This created a situation where business risk was piled on top of business risk. In contrast, this market study indicated that future market revenues will come from many different business sectors and consist of capturing very small fractions of large established industries. Figure 32 highlights an example based on the markets studied as part of this report.

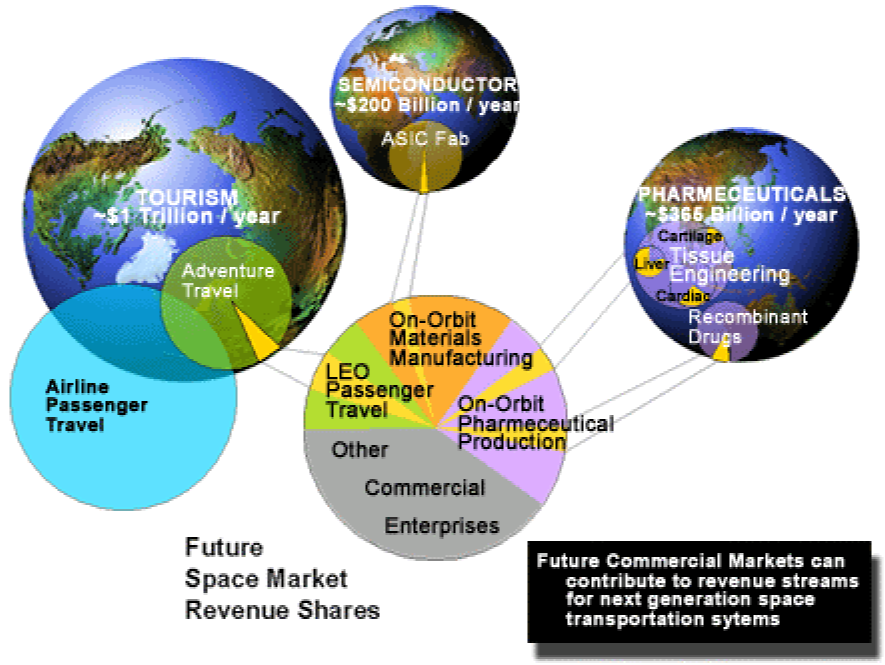


Figure 32: Analysis indicates that future market revenues will come large and established industries that can improve their bottom line by doing business in space.

The tourism industry has annual revenues of US$1 trillion. Adventure Travel comprises approximately US$200 billion of those. Assuming that safety can be improved and costs significantly reduced, it is not unfathomable that a 2nd Generation Launch System can capture (or add) 1% or US$2 billion in annual revenues from commercial passenger travel and tourism.

The semiconductor and pharmaceutical industries, which have approximately US$550 billion in combined annual revenues, spend between 10% and 15% on Research & Development. High technology industries are typified by a fierce competitive landscape, which has everyone looking for a competitive advantage and causes companies to take high risks. If a 2nd Generation Launch System could provide companies with frequent low-cost access to orbiting research facilities, it is well within the grasp of reality that these companies could spend at least 1% of their annual R&D budgets on space based research, which could easily total another US $500 million. These revenues, US$2.5 billion for R&D and passenger travel, are nearly equal to current commercial GEO satellite launch revenues, and can significantly impact the business case of a commercial 2nd Generation LV.

Conclusion #3: Based on this path finding study, which represents the first comprehensive system study to derive transportation design requirements for the future markets, the study team concluded that a 2nd Generation Launch Vehicle, designed to address future markets, must be designed to work around the business cycles demanded by the future user community. As an example, both airline companies interviewed outlined the need to limit the time from when a passenger boards a vehicle to when they arrive at their destination. Specifically, the airlines would prefer to limit the time between when a passenger boards to when they are launched to two hours, and to limit the transit time from launch to arrival at the destination to six hours. For the Space Shuttle, this span averages approximately two to three days due to the relaxed launch window and extensive orbit phasing operations. To correct for this, a 2nd Generation vehicle must routinely meet a very narrow launch window (measured in seconds) in all-weather conditions. As another example, semiconductor companies develop a new generation of microchips, build multibillion dollar factories, pay off their capital investments and generate huge profits (80% profit margins) all in the span of 18 to 24 months. For these companies, R&D campaigns are measured in hours, days and weeks. Currently, it takes years to plan, design, and implement orbital tests. Until these disparate business cycles are reconciled by improvements in space transportation and on-orbit infrastructure, many of the future markets will remain unaddressable.

Conclusion #4: Future markets must be developed in concert with a 2nd Generation Launch Vehicle. It was clear from the study team's interviews that very few people outside the space industry understand the benefits of space and how it could benefit their business. Furthermore, the space infrastructure required to address the needs of the future markets is very different than what is operating today. Many of these future markets require new facilities and processes, in addition to the Earth to Orbit transportation infrastructure, which require years to develop and deploy. As a result, any space transportation service provider who expects to address future markets can not, must not, rely on a "build it and they will come" philosophy. It is incumbent upon industry and NASA to devise a future market incubation plan that serves to: 1) promote space awareness to non-aerospace companies; 2) incubate near term future markets (e.g. space tourism); and 3) act as "stepping stones" that will lead to fully developed, robust commercial space commerce.

5.1 Study Methodology

Andrews Space & Technology was contracted to develop Market Metrics and Measurements of Effectiveness to maximize the utility of the Future Space Transportation Study. To that end, AS&T (in conjunction with Digital Empire) has created a brief 4.5 minute) video that characterizes the opportunity of future commercial space and develop multimedia modules targeted toward the specific Future Commercial Markets to be analyzed as part of Task 1.1. In addition, AS&T interviewed selected future users to develop a mission model with adequate return on investment to interest the users' upper management.

The FSTS approach taken by Andrews Space & Technology was divided into four distinct phases, interleaved with two interview opportunities with each selected industry representative. In the initial market analysis step, the targeted market is gauged by applying the defined Measures of Effectiveness (MOE). The following MOE's were defined:

- Technology Readiness Level (TRL)
- Business Readiness Level (BRL)
- Utilization of Space Unique Resources
- Product Value per Unit Mass
- Value Chain Intersection with Space Unique Resource
- Market Size
- Market Trends
- Space-based Market Concept Maturity

If the market was found to be attractive as indicated by these metrics, it became a candidate for the next step in the process. Prior to soliciting interview opportunities with industry representatives, the identified market was analyzed for emerging customer opportunities. The following criteria were developed to determine the feasibility of each customer's business opportunity:

- Product Quality
- Product Quantity (Yield)

- Product Innovation (Uniqueness)
- Product Development (Roadmap)
- Time to Market
- Production Cycle Time
- Profitability

Andrews Space & Technology devised Business Readiness Levels to parallel Technology Readiness Levels, to assist in systematically assessing product readiness for market.

After these parameters had been investigated, a plausible scenario was put forth to selected industry representatives. In the first of two interviews, initial reactions are solicited from select industry representatives. Interview candidates were chosen based on the company's likelihood of mounting the investment effort needed to successfully execute the proposed scenario, and competitiveness in the chosen market.

Interviews consisted of a brief presentation of the proposed scenario (including the video trailer), followed by a questioning and discussion session for a total duration of approximately 90 minutes.

The animation developed for the FSTS study was highly effective in meeting introduction to lead discussion toward future market possibilities.

The study also developed and used an animation as part of the introductory interview meetings. This animation, which presented a scenario of business activity in 2012 was highly effective in setting the mood of the meeting toward an out-of-the-box discussion of future market possibilities.

The approach developed by AS&T has proven to be an effective tool to systematically explore the emerging markets of commercial space utilization. The process has resulted in a broad scope overview of the requirements of any future launch system that is to serve these emerging markets. Additional iteration of the process is expected to refine the fidelity of the obtained mission and operations model data.

5.2 Semiconductor Market Conclusions

There is an immediate market opportunity for commercial on-orbit laboratory facilities.

The potential of space-based semiconductor manufacturing for the foreseeable future (present to 2012) is low. Industry leaders are continuing to scale down geometry features via wet processes and limited vacuum application. The potentially cleaner environment of space may not reduce defects and increase yield of semiconductor production because 95% of the contamination in today's processes are believed to come from process tools and are thus inherently internal to those processes. Radical tool redesigns, aimed at eliminating those contaminants, are not anticipated in the future 10-year scope of this investigation. In two more generations microchips will have features less than 30 nm and semiconductors as we know them will not function due to quantum mechanical limits (electronic tunneling through CMOS gates). There are a number of alternate approaches in work and the availability of laboratories with microgravity and ultra hard vacuum were definitely of interest.

A few small companies are pursuing the development of "dry resist" processes that are amenable to space-based semiconductor manufacturing. However, these conceptual-phase development efforts have yet to show a significant improvement over terrestrial processes.

Although it was not the focus of this effort, interviews with "traditional" semiconductor manufacturers did uncover a significant interest for an On-Orbit Research Facility. We highly recommend the investigation of an On-Orbit R&D facility as part of future studies. This stems from the fact that, within the next seven years, semiconductor companies will reach physical limits of material and present manufacturing processes, which they have refined over the last decade. Currently, they are searching for "revolutionary" methods of manufacturing follow-on generations of products. If an on-orbit research facility existed today, interviewees would be willing to pay up to US$20 million for a single flight to conduct tests and build certain production elements that could lead to breakthrough material and manufacturing advancements. However, this market is only addressable if the companies are offered routine access: no less than once a month. Demand would significantly increase if the price for a week's research could be reduced to less than US$1 million.

The semiconductor market spends between US$20B and US$30B annually on R&D. This works out to between US$385M and US$577M per week! Based on the interview feedback, if a 2nd Generation Launch Vehicle could provide weekly access, semiconductor companies could spend up to US$20M per week (3% of the world semi-conductor R&D funds) for the use of an Orbital R&D Facility. At this time, AS&T has insufficient data to develop elasticity demand curves for On-Orbit R&D expenditures as a function of price per pound to LEO.

5.3 Biomedical Market

Current and on-going research demonstrates the significant advantages of on-orbit research and manufacturing which has attracted the interest of pharmaceutical market leaders.

Tissue engineering is enabled by microgravity and may lead to treatments for many medical conditions.

Liver tissue is the most likely early candidate for commercially viable space-based tissue engineering. Tissue engineering technologies have the potential to address diseases and disorders that account for about half of the nation's total healthcare costs. Tissue culture experiments performed on the shuttle and Mir have demonstrated the positive effects of microgravity on three-dimensional tissue growth and differentiation, and thus the potential for improved products. Liver disease in the United States resulted in 25,175 deaths in 1997, while only 4,000 people received a liver transplant (in 1996). Based on 1985 data, liver and gall bladder disease cost the US health care industry XXXX US$17 billion (adjusted for inflation). Space based tissue engineering could possibly save tens of thousands of lives and has the potential of saving the US health care industry billions of dollars.

Small yield increases of recombinant drugs produced in microgravity may save millions in production costs.

Space-based manufacture of recombinant drug could represent a substantial market. Recombinant protein drugs and diagnostic agents are one of the fastest growing segments of the pharmaceutical industry generating US$20 billion in annual revenues. Microgravity production of recombinant drugs offers the potential of improved quality and yield. An improvement in yield of only a few percent has the potential to save millions in production costs.

Routine access to microgravity laboratories is needed to drive market

While biotechnology firms are aware of some of the advantages of microgravity, very few have performed microgravity experimentation for the manufacturing of biotechnology products. Like the semiconductor industry, biotechnology firms are in an extremely competitive and risky market space. Historically, biotechnology firms spend slightly more on R&D, approximately 15% of their annual revenues. In addition to the actual products identified as part of this study, and their potential revenues, there is a significant demand for unique research and development facilities, which would likely include an orbital R&D laboratory. The biotechnology industry has US$365 billion in global annual revenues, which translates to approximately US$1.05 billion in weekly R&D expenditures. The potential benefits of an orbital R&D facility to this industry are significant. Although AS&T has insufficient data to develop an accurate elasticity curve, our research indicates that there would be significant interest if a space transportation infrastructure could support the biotech industry's business and research requirements. At this time, these are nebulous because so little applied research and product development has been done in this area. Increased access to laboratories on the International Space Station and from commercial services will be a necessary precursor to large-scale development of an on-orbit biotech research and production market.

5.4 LEO Passenger Market

The LEO Passenger Travel market is exhibiting a growing demand for LEO passenger services. Unlike many other s-Business opportunities, this market is exerting a "pull" for products to supply LEO Passenger transportation and infrastructure services.

The LEO Passenger Travel market is real and exhibiting a growing demand for LEO passenger services. Unlike many other s-business opportunities, this market is exerting a "pull" for products to supply LEO passenger transportation and infrastructure services. During 2000, multiple companies; including MirCorp's "Citizen Explorer", BrainPool's "Space Commander", and NBC's "Destination Mir" television program; announced intentions to fly "citizen explorers" to orbital destinations, many as part of entertainment endeavors. The value of these commitments, publicly listed as US$20 million per flight, is estimated at US$140 million. World wide, the tourism industry has US$1 trillion in annual revenues, with US$200 billion of those coming from adventure travel related activities. Given that the current market can support demand at US$20 million a ticket (for Dennis Tito), market growth potential is significant. Kelly Space & Technology, as part of their NASA NRA8-27 effort, conducted a survey and placed the demand at 10,000 tourists a year at a ticket price of US$400,000, which would yield annual revenues of US$4 billion at that price point. This value is consistent given the adventure travel industry revenues (US$200B). As part of this study, Andrews Space & Technology did not have the resources to conduct a thorough demographic study. Our effort was focused on interviewing the airline industry, gauging their interest in the space travel market, and using the interviews to derive space transportation design requirements. However, we strongly recommend that a broader sampling (Kelly's survey, conducted by Harris Interactive, interviewed 2000 people in the United States) would benefit the business case development and aerospace industry acceptance of the market's credibility.

5.5 2nd Gen RLV System Design Requirements

In the market segments reviewed for this study many of the requirements have been found to be partially or wholly within the domain of NASA's access to space station technical requirements, though often business and operational requirements may conflict.

AS&T analyzed the results from the interview process and utilized a system process to identify a broad requirements set of 50 requirement / attribute pairs. The various attribute/requirement pairs were chosen to reflect all the needs of the markets that are to be served, while maintaining the minimum number of limitations imposed on the transportation system designer. All of the collected attributes were sorted in six major categories (Scheduling, Operations Performance, Interfaces, Business, and Provider Specific), including the important distinction between requirements imposed by the customer of a space transportation industry (Customer Specific), and those determined by the "space-line" and imposed on the vehicle manufacturer directly (Provider Specific).

Requirements values were derived from each individual market segment and the most limiting values for a system that is to serve all of the investigated markets were distilled from the individual limiters. The current uncertainty of these numbers is estimated to be significant, but the accuracy of the model will further increase with the collection of additional data.

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Appendix A: Market Trend Forecasting

In order to obtain a general understanding of occurrence of events in the future, a look into the past is crucial. Future market growth rates can be time trended by looking at diverse technologies that have been introduced since the late 1800's and reached twenty-five percent of the potential market. Given the introduction year of a product, the typical time to reach twenty five percent market can be extrapolated based on when the product will be introduced. Figure 33, Market Growth Trend Regression Analysis, indicates over time that there is a reduction in the time it takes a product to reach twenty-five percent market share. This general trend appears logical based on general improvements in methods, processes and communications over time.

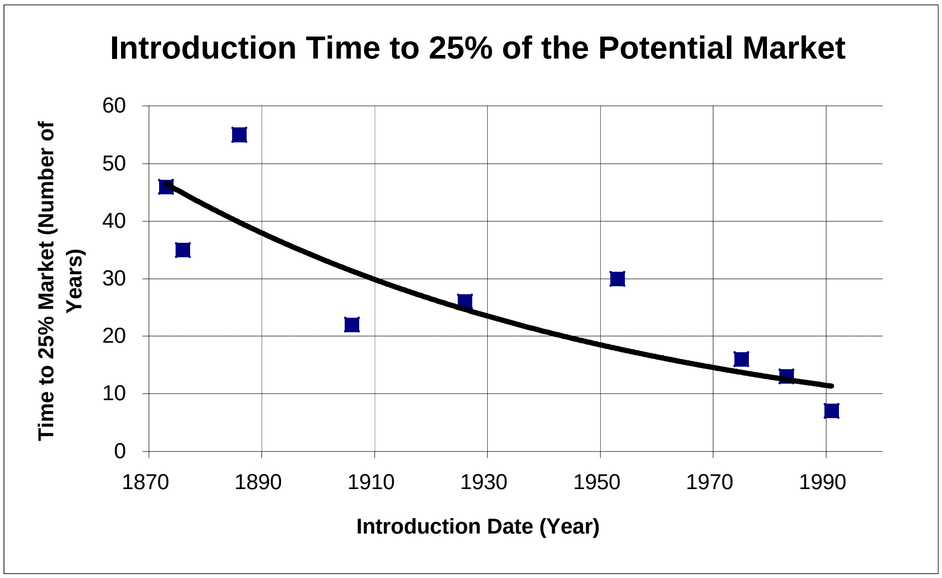

Figure 33: Market Growth Trend Regression Analysis

The outliers from the historical trend provide useful information on market growth rates. The data points above the trend line indicate that the market growth rate is slower than average historical growth. The data points below the indicate products with growth rates faster than the historical average. Various factors can cause an acceleration or deceleration of market growth rate. These factors include but are not limited to the following:

1. Infrastructure availability - The amount of investment in infrastructure cost necessary to support the product has an impact on market growth rate.
2. Patent/proprietary issues - A product that is patented or proprietary but not being applied can decelerate market growth.
3. Price – The price consumers are willing to pay for a product affects the market growth rate
4. Product specification - Product specification is defined as what the customer's needs are and whether the product meets the purpose. This could be in terms of quality, capability or any other characteristics that can be defined by the customer.
5. Packaging – The design and production of a product that is practical in size, shape, and easy to use in application.

6. Market approach – The business development strategy for approaching the consumer market.

In Figure 33, the two outliers above the trend line are automobiles and microwave ovens. It took the automobile industry fifty-five years instead of forty years to reach twenty-five percent of the potential market. Reasons causing this are possibly price, infrastructure cost and market approach. Upon introduction, automobiles were not affordable to the public. Consumers did not see it cost effective to transition from carriages/trains to automobiles. When, in 1908 Henry Ford made cars affordable to the people working in his factories, he opened the market to the general public. The decelerated market growth rate could also be caused by a lack of infrastructure in the early years for automobiles. It took a large investment in infrastructure to support automobiles. Packaging issues caused the microwave oven twelve years longer to reach twenty-five percent of the potential market. Invented in 1947, the microwave oven weighed 750 pounds and was not a practical size for consumers. Before market introduction in 1953 the product was repackaged to be acceptable in the wide consumer application.

The outliers below the trend line are the telephone, radio and the World Wide Web. These points all fall in the communications industry. It appears that all data points within the communications industry have an accelerated market growth rate with the exception of the television. The market growth rate of television industry follows a typical market growth trend line, but relative to the communications industry, television market growth rate is slow. Television industry did not do as well relative to the communications industry due to low capability. The number of channels available for viewers was very limited. Because consumers desired more variety, television did not meet consumer requirements.

The market growth rate trend can be modeled based on the above analysis. The output of the model is the number of years required to reach twenty-five percent of the potential market. The approach is to use the general market growth trend to predict a typical time to reach twenty-five percent potential market. Adjustments to typical time span can be made based on factors discussed in the above section that can cause market growth to accelerate or decelerate. The weighted impact of the individual factors upon market growth rate then needs to be determined. The default value is equal weighting amongst the factors unless otherwise specified. Each product being analyzed will be ranked relative to each other. An empirically derived value, the product score, will determine how much adjustment will be made to the typical time span to reach twenty-five percent potential market. The inputs required for this model are:

1) Year of product introduction to market
2) Weighted impact on market growth rate factors (Default value is 100% / 6 = 16.7%)
3) Ranking of factors (F_R) affecting market growth rate
    a. Infrastructure availability
    b. Patent/proprietary issues
    c. Price
    d. Product specification
    e. Packaging
    f. Market approach

Each product is ranked according to the following ranking score (P_S):

1 = Very poor relative to other products

2 = Poor relative to other products

3 = Normal relative to other products

4 = Good relative to other products

5 = Very good relative to other products

The product score = ? F_{Ri}* P_{Sj} where I = 1 to 5 and J = growth rate factors “a” to “f”.

A normal product score that falls in the market growth trend rate is 3. A product score of 5 would indicate (5-3)/3 = 66% faster than normal growth. A product score of 1 would indicate (1-3)/3 = -66% or 66% slower than normal growth.

Historical market growth time trending analysis is useful for two different reasons. It allows the market analyst to predict how long it should typically take to reach twenty-five percent of the potential market provided the product introduction year. In addition, the market analyst can see how well they are doing relative to the trend. Various factors affecting the trend could be analyzed to accelerate the market growth.

The time to reach 25% potential market is one discrete number within a product life cycle. The capability to predict the time to reach various levels of the potential market can add great value to market analysis. A methodology will be discussed to predict the time to reach various levels of the potential market.

The time to reach various levels of the potential market in a product life cycle follows an “S” curve. This is depicted in Figure 34. The concept of the “S” curve is that at the initial stage of the product life cycle starts at a slow market growth rate, reaches its highest level between point A to point B and decelerates at the end of the life cycle.

The “S” curve equation needs refinement. The product life cycles of diverse technologies need to be analyzed in relation to the time to reach their potential market.

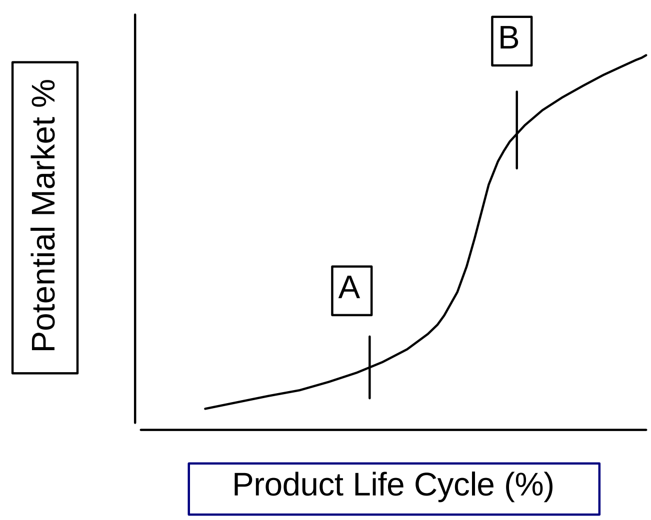

Figure 34: Product Life Cycle vs. Potential Market S-Curve

The flow chart in Figure 35 summarizes market growth trends. The first step allows the analyst to extrapolate a typical time span to reach twenty five percent of the market. The second step adjusted the typical trend based on peculiar situations that may affect the product being analyzed. The third step allows the analyst to view the potential market through at various stages of the product life cycle.

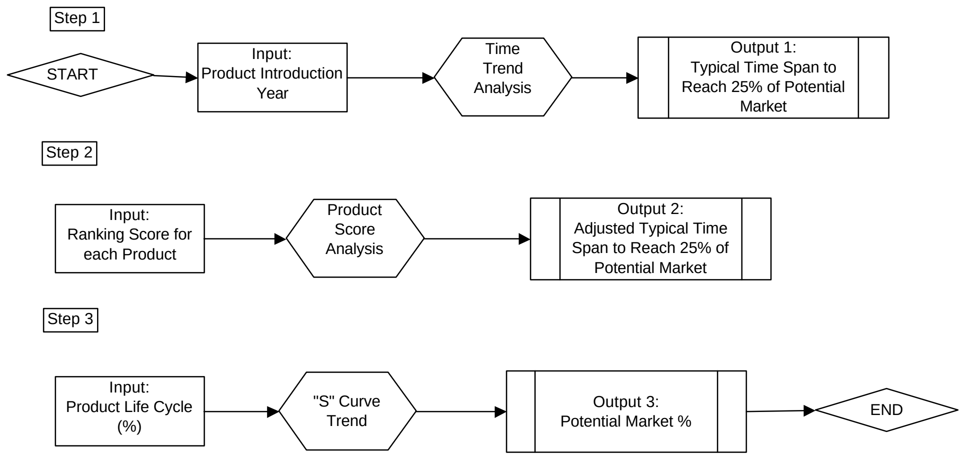

Figure 35: Market Growth Trend Flowchart

A methodology has been discussed for market growth trend analysis. This methodology is based on historical trends of diverse technologies as is applicable to space environment market growth trends. The time to market growth rates for products developed in space have the same constraints and accelerating parameters as can be seen from the historical examples provided in this section. This market introduction model will be validated by calibration to known innovative products over the past century.