Chapter 2

MICROGRAVITY RESEARCH ABOARD THE ISS

This chapter expands on the first part of the hypothesis presented in Figure 1.1: the use of the International Space Station as a host creates the perfect low-cost environment for technology maturation. The chapter discusses the challenges of μ-g research identified from the literature search and through past experiences of the MIT SSL. Literature about the ISS, including a review of research up to date, helps identify the type of experiments conducted in the ISS; this chapter specifies what the thesis regards as a technology maturation experiment, as related to current research conducted aboard the ISS. Lastly, the chapter presents the special resources offered by the ISS.

2.1 Issues and Challenges of Microgravity Research

The literature review of Chapter 1 provides insight into the issues and challenges faced by microgravity research. Achieving maturation of space technologies was tied by the Technology Readiness Levels to the ability to operate in representative environments. The TRLs and availability of these environments define the challenges of micro gravity research. TRLs were introduced in Chapter 1 as a proposed method to mature technology in a step-wise manner. As shown in Figure 1.2 on page 39, three primary drivers have impact on the ability of a technology to follow all TRLs: risk, complexity, and cost. The review of other facilities indicated that remote operations also pose a challenge to space technology maturation. Lastly, it is shown by the fact that previous space stations programs were driven in many ways by political and social needs, and that the high visibility of these programs is an issue which cannot be ignored.

Risk. Risk exists in every stage of space technology maturation, from the feasibility of the program itself to the actual operation of equipment. Risks are created by the environment, costs, and politics which surround microgravity research. The space environment creates risks not experienced inside the earth atmosphere, such as space radiation and collision with natural objects. The inability of humans (in most cases) to work directly with deployed spacecraft of the projects can result in the permanent reduction of capabilities unless full redundancy is implemented. When humans can access the spacecraft, the availability of resources (including time, equipment, and parts) to repair spacecraft is limited. Costs, while an important factor on their own, also contribute to the risk of a space mission; the costs drive the development time down and limit the ability to create fully redundant systems. Politics also adds to the risks of a mission, although in a different manner. Due to politics, space engineering tends to work in a conservative fashion, many times utilizing old-but-trusted technologies, rather than the latest technologies, for common parts of a space craft; these older technologies usually work behind highly advanced science items. Creating interfaces between the technologies puts a risk the feasibility of the mission and can potentially limit the usefulness of the new advanced technologies to be tested. When only advanced technologies exist, the risk of using them is too high for the political drivers behind the project. Politics can also reduce the time for development, creating new risks due to unforeseen problems. Reducing the risk of a mission by allowing humans to operate new technologies in a controlled environment is a goal for the use of the ISS.

Complexity. Space systems are some of the most complex systems created by human kind. Spacecraft interface dozens of sub-systems, contain up to miles of cable, which carry thousands of electronic signals, utilize advanced science items, and operate using a number of different robust real-time software implementations. While a specific tool for a spacecraft can be tested on its own in simple manners during preliminary tests, as that tool is integrated into the rest of the spacecraft, the complexity of its operations grow. That is, as a technology matures towards a high TRL, the complexity of using the tool grows. Increased complexity usually results in higher costs and the need for more personnel to work on the development of the technology. The increased complexity also adds to the risk, as the addition of interfaces creates new possible failure points. Therefore, it is desirable to lower the complexity of a mission and/or to mature individual sub-systems as far as possible prior to integration into the more complex spacecraft. Further, it is desirable to test the integration of sub-systems in an environment which does not necessarily add as much complexity as developing the space-qualified product.

Cost. For many space programs, cost becomes the deciding factor in the future of the mission. Space missions have costs higher than most other research on the ground due to the need for expensive specialized equipment, launch vehicles, and operational costs. The other issues presented also create an increase in cost, for example: reducing risk by redundancy increases cost; increased complexity increases cost; the drivers behind politics are mostly economic. The high cost of these missions creates inbalance in the funding of the science programs for ground-based research and space-based research; this forces space-based research to be highly beneficial to the funding sources, something adding extra burden to the researchers beyond the direct science goals of a mission. Therefore, to overcome the issue of cost for space research one must first, allow multiple researchers to benefit from the research, ensuring that the research benefits a large portion of the population; and second, that the other factors which affect the cost of a mission are reduced in such a way that the ultimate cost of the mission is also reduced.

Remote Operations. The need for remote operation means that the scientists will not be present in the actual tests; rather an astronaut is trained to operate the facility. While astronauts are highly-educated members of the space community, they are rarely experts on all the experiment fields to which they are assigned. Yet, in some cases astronauts will have to make decisions based on real time results; these decision potentially affect the success of the research. In these cases astronauts will require substantial training to be able to make the best decisions; at the same time the experimental facility will need to provide astronauts real-time feedback information for them to make the necessary decisions. In other cases astronauts may not need to do any decision making, but in that case a researcher must create an automated experiment and/or create the necessary data links to make the decisions on the ground and command the space-based experiment remotely. A researcher needs to balance the need of astronauts to make real-time decisions as compared to the complexity needed to automate the equipment.

Visibility. The visibility of space missions is usually on the extremes: the major missions are highly visible and subject to substantial public review while smaller missions go unnoticed, very few are in the middle ground. This presents a challenge to the researcher. Highly visible missions will face extreme safety and public relations pressure. This tends to increase the cost of the mission as the safety requirements increase. Public relations pressure tends to affect the timeline of the mission, sometimes forcing steps to be skipped; at the same time, public relations tend to criticize high costs, forcing the mission to balance the cost to achieve the necessary safety with the cost to achieve the scientific goals (sometimes causing cuts in the goals of the mission). In a similar fashion, a high-visibility mission calls for the use of advanced technologies to attract the attention of the public; but the safety concerns drive towards the use of conservative technologies in other parts of the project. On the other hand, a low-visibility mission will face hard times to obtain the necessary funding and attention to be successful. Even if the necessary funding is obtained, low visibility of a mission may cause its facilities and results to not be used effectively, making the mission short-lived.

The use of the International Space Station should address these issues and challenges. Ultimately we wish to answer:

- Can the use of the ISS reduce the risk of space technology maturation?
- Is the complexity of a project that goes through the ISS reduced?
- Can the cost of a project be reduced by using the ISS?
- Are the remote operations of the ISS effective?

- Can the use of the ISS remove the visibility factor from the feasibility of a mission?

2.2 Research Areas of the International Space Station

To answer whether the ISS can address the issues and challenges of space research one must first understand what the ISS is. Appendix D presents a detail review of the resources available aboard the ISS and the current challenges and future upgrades of the program. This section concentrates on the objectives of the ISS program, creating a direct relationship with the success of past space stations, and helping identify the research conducted aboard the ISS which directly relates to the results of this thesis.

The objectives of the ISS as stated in the ISS Familiarization Manual developed by NASA are:

> "The purpose of the ISS is to provide an “Earth orbiting facility that houses experiment payloads, distributes resource utilities, and supports permanent human habitation for conducting research and science experiments in a microgravity environment.” (ISSA IDR no. 1, Reference Guide, March 29, 1995)
>
> "This overall purpose leads directly into the following specific objectives of the ISS program:
> - Develop a world-class orbiting laboratory for conducting high-value scientific research
> - Provide access to microgravity resources as early as possible in the assembly sequence
> - Develop ability to live and work in space for extended periods
> - Develop effective international cooperation
> - Provide a testbed for developing 21st Century technology."
>
> [NASA, 1998]

After creating these objectives, NASA worked to further detail the research objectives of the ISS. To this purpose, NASA has created an ongoing program to determine the "research directions" of the ISS. During the development of these directions, NASA first defined the ISS as a special type of laboratory, one which has three special purposes:

- "an *advanced testbed* for technology and human exploration;

- a *world-class research facility*; and
- a *commercial platform* for space research and development." [NASA, 2000]

As of January 2000 the NASA Office of Life and Microgravity Science Applications had identified a number of research fields which can directly use the resources provided by the ISS to advanced human knowledge and provide benefits to the people in the ground; these are presented in Appendix D.

The objectives and research directions of the ISS address some of the challenges identified in the first section of this chapter by creating a facility which will benefit a large number of scientists; ultimately the science obtained will benefit a large portion of Earths population once NASA's science objectives are met.

2.2.1 Thesis Research Area Identification

The ISS creates a special environment in space for conducting a wide range of microgravity experiments. This section studies the types of experiments conducted aboard the ISS and defines the type of experiments that this thesis concentrates on.

NASA conducts multiple research experiments in the ISS simultaneously. Each “expedition” of the ISS – each crew rotation – is given a delimited set of tasks, which are published by NASA. Table 2.1 shows the experiments that Expedition 6 conducted through their six month rotation. This expedition was chosen as a sample since it constituted a six month period when the ISS operated normally with three crew members and standard supply missions.

Research of the goals behind each of the twenty experiments that took place on Expedition Six allows division of the experiments into the following main areas:

- Experiment Operation Types
    - Observation
    - Exposure
    - Iterative Experiments

TABLE 2.1 Research experiments of Expedition 6

Id	NASA Field	Experiment	Area	Type
1	Bioastronautics Research	The Effects of EVA on Long-term Exposure to Microgravity on Pulmonary Function (PuFF)	Science	Iterative
2		Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (Renal Stone)	Science	Exposure
3		Study of Radiation Doses Experienced by Astronauts in EVA (EVARM)	Science	Exposure
4		Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (Subregional Bone)	Science	Exposure
5		Effect of Prolonged Spaceflight on Human Skeletal Muscle (Biopsy)	Science	Exposure
6		Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-duration Space Flight (Mobility)	Science	Exposure
7		Spaceflight-induced Reactivation of Latent Epstein-Barr Virus (Epstein-Barr)	Science	Exposure
8		"Monitoring of Heart Rate and Blood Pressure During Entry, Landing, and Egress: An Index of Countermeasure Efficacy (Entry Monitoring)"	Science	Exposure
9		Chromosomal Aberrations in Blood Lymphocytes of Astronauts (Chromosome)	Science	Exposure
10		Foot/Ground Reaction Forces During Space Flight (Foot)	Science	Iterative?
11	Physical Sciences	Protein Crystal Growth—Single-locker Thermal Enclosure System (PCG-STES)	Science	Iterative
12		Microgravity Acceleration Measurement System (MAMS)	Technology	Exposure
13		Space Acceleration Measurement System II (SAMS-II)	Technology	Exposure
14		Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions for the Microgravity Sciences Glovebox (MSG-InSPACE)	Science	Iterative
15		Vibration Isolation System for the Microgravity Sciences Glovebox (MSG-g-LIMIT)	n/a	n/a
16		Coarsening in Solid-Liquid Mixtures for the Microgravity Science Glovebox (MSG-CSLM)	Science/Tech	Iterative
17	Space Product Development	Zeolite Crystal Growth Furnace (ZCG)	Science/Tech	Iterative
18		Microencapsulation Electrostatic Processing System (MEPS)	Science	Iterative
19	Space Flight	Crew Earth Observations (CEO)	Education	Observation
20		Earth Knowledge Acquired by Middle-School Students (EarthKAM)	Education	Observation
21		Materials International Space Station Experiment (MISSE)	Science	Exposure

- Major areas of study
  - Educational
  - Pure Science
  - Technology

Experiment Operation Types

Observation. Experiments that consist solely of the observation of celestial bodies (either the Earth or others), are considered observation experiments. For example, when astronauts are asked to take pictures of Earth, without conducting any further research on the results.

Exposure Experiments. Exposure experiments are those that utilize the μ-gravity environment of the ISS solely to expose material to the reduced gravity and/or space environment, without actively conducting experiments in the ISS with the materials or subject being tested. These experiments include, for example, medical experiments where astronaut biological data are measured before and after the flight, but no science is performed during the expedition – possibly the astronauts may conduct special exercises during the expedition, but since no measurements or other science is conducted during the expedition itself, these are considered exposure times, not research times.

Iterative Experiments. The other main type of operations for ISS experiments are those that require multiple iterations of test runs while the experiments are aboard the space station. This definition does not preclude the type or location of the experiments, but rather identifies their operational nature. An experiment may be performed either inside our outside the station, and it may be for pure science or tests of new technologies. The most important concept for this type of operation is that the facilities must be able to present results and perform new experiments during their time in the ISS.

Experiment Areas

Educational. The ISS is often used to conduct activities with an educational goal. The ISS crew continuously communicates with students on Earth, via both audio and video; they take pictures to be used in educational exercises, and even sometimes conduct simple experiments developed by children. This research time is outside the scope of this thesis, since the goal is not directed towards the development or understanding of new technologies.

Pure Science Experiments. A large portion of experiments aboard the ISS are conducted to learn more about the pure sciences. These experiments use μ-g to understand how things behave differently between gravity and micro- gravity conditions. They also help create materials in new ways that are not possible on Earth. Ultimately these experiments provide results for use in ground products. In some cases, the experiments utilize many of the ISS resources to conduct iterations of the full research cycle, where results are obtained aboard the ISS and new experiments started with knowledge obtained from those initial results. In other cases pure science experiments consist solely of observation or exposure.

Space Technology Experiments. These experiments are those that test new technologies for use in future space missions. These technologies allow better understanding of the μ-g environment to facilitate the access and use of space. While pure science experiments study the effects of the space environment on biological or physical items, space technology experiments demonstrate the ability of human created items to operate correctly in a microgravity environment. The experiments aboard the ISS allow the necessary technology demonstration in a relevant space environment to advance the technology through several TRLs (the definition of a relevant environment is presented in Appendix A).

Thesis Concentration

This thesis concentrates on iterative experiments that serve science and technology goals. Emphasis will be on those experiments related to space technology, but some science experiments can serve as an important example of how the ISS enables research in space to advance an area by allowing iterations. The thesis does not dive into experiments that are solely for observation or exposure, other than to identify the division of time spent in the ISS between these types of experiments and to evaluate the subsequent effectiveness of the use of the ISS.

2.3 Special Resources of the ISS

This chapter begins with the introduction of the major challenges and issues of microgravity research identified through literature research: risk, complexity, cost, remote operations, and visibility. The goal of the chapter is to identify whether the ISS can help reduce the negative effect of these issues on space technology maturation. The chapter presents an overview of the ISS objectives and identifies the challenges of the ISS itself. This study of the ISS leads to the identification of several special resources of the station which do in fact help it reduce the effects of the identified challenges, and which contribute to the correct utilization of the ISS as a laboratory for space technology maturation. The following resources have been identified as most important:

Crew. The fact that humans are present in the space station to interact with and control different facilities is the most obvious and yet many times overlooked resource available in the ISS. While all reviewed reports identified crew availability as a major challenge for the ISS, clearly indicating the need to maximize their time dedicated to research, many times scientists put heavy emphasis on automation and independence from the crew. Yet, the crew can help reduce the effects of many challenges: risk is reduced since humans can stop an experiment which is operating incorrectly; complexity and cost can be reduced by the need to remove automation tools. Therefore, any project that uses the ISS should actively use the humans to help the science and reduce risk, complexity, and cost. The ultimate goal is to determine the correct balance between astronaut availability and need.

Communications. The issue of communications and data download resonated through all the reviews of the ISS. Correct use of the ISS communications system, and its constant expansion, is clearly a priority for NASA and a special resource which benefits all users of the ISS. The availability of continuous high-bandwidth communication to ground reduces the cost and complexity of missions which would otherwise need their own communications equipment. The availability of ever-increasing communications features will help with the issue of remote operation as real-time video and other teleconferencing options become increasingly available. Therefore, scientists should utilize the ISS as a direct communications link between them and their experiments.

Long-term experimentation. A unique features of the ISS is that it allows long-term microgravity experimentation in a laboratory environment. The long-term nature of the ISS helps to reduce the effects of high visibility as space research becomes part of daily life at NASA and the scientific community. The ISS allows space technology advances to come over longer periods of time, where specific one-time events (such as a landing or a docking) no longer need to mark the success or failure of a mission. Instead, the long-term nature of the ISS allows technology to mature over small steps in a low-visibility environment, allowing scientists to better concentrate on their research rather than outside factors. At the same time experiments which reach the space station will always have high visibility among the scientific community. Further, once they demonstrate revolutionary advances, new technologies will gain high-visibility among the public in general.

Power sources. The ISS can provide several kilowatts of power to each experiment. Because power is usually a trade-off between mass (i.e., larger batteries provide more power but have larger mass), utilizing the existing power sources of the ISS can help to substantially reduce the mass of an experiment, and in turn its cost. Because power sources are a constant safety concern, removal of power sources from an experiment also reduces the risk of the mission. Therefore, ISS supplied power should be utilized by the experiments, otherwise experiments that send their own power sources are duplicating an existing resource and wasting up-mass to the ISS.

Atmosphere. While some times an experiment intends to demonstrate the ability of its hardware to operate in a space environment, the development of ‘rad-hard’ techniques has been understood for several decades. Instead, many experiments wish to demonstrate the ability of their hardware and software to perform correctly in a microgravity environment without the need to worry about hardware failures. In these cases the pressurized environment of the ISS not only provides safety for humans, but also for electronics and structures. Experiments that can be performed inside the station can have a substantial reduction in cost, complexity, and risk, as compared to free-flyers in space, since they no longer need to worry about being exposed to the space environment radiation and vacuum. Cost is reduced directly by the use of standard components; complexity is reduced since protection equipment is no longer necessary; risk is reduced since the experiment is no longer exposed to the harsh conditions of space and therefore the probability of failure is lowered.

Table 2.2 summarizes the special resources of the ISS and their effects on the challenges of microgravity research. The next chapter will present the MIT SSL Laboratory Design Philosophy, which also addresses those challenges, but from the perspective of creating a new experiment which not only uses existing resources but also creates new features to build upon the existing resources.

TABLE 2.2 Special resources of the ISS that facilitate microgravity research

Resource	Risk	Complexity	Cost	Remote Operations	Visibility
Crew	↓	↓	↓		
Communications			↓	↓	
Long-term experimentation					↓
Power Sources	↓	↓	↓		
Atmosphere	↓	↓	↓		

↓ = reduces challenge