Chapter 5

MICROGRAVITY LABORATORY DESIGN PRINCIPLES

Through more than two decades the MIT Space Systems Laboratory has developed a number of successful microgravity experiments for the maturation of space technologies. Throughout the design and operation of these experiments researchers at the MIT SSL have learned a number of important lessons; initially those lessons were expressed as the MIT SSL Laboratory Design Philosophy, presented in Chapter 3. The development of the SPHERES laboratory for distributed satellite systems, presented in Chapter 4, implemented all the lessons learned from the past experiments, and led to the creation of a new philosophy which combines the original MIT SSL Laboratory Design Philosophy and the use of the International Space Station (Chapter 2). This new design philosophy condenses the lessons learned from all the previous chapters.

The intent of the principles presented in this chapter is to give both designers and evaluators of microgravity experiments for technology maturation a clear idea of what qualities a specific project must meet, rather than a long list of individual specific items. By generalizing the concepts, the principles encompass a wider range of technology maturation experiments, beyond the dynamics and control scope of the MIT SSL. The principles capture the most important concepts of the MIT SSL Laboratory Design Philosophy. The features of the philosophy lie within the principles as lower level methods to implement the principles. The principles also capture the lessons learned from the literature review about the ISS and the operations of MACE-II aboard the ISS. As presented in Chapter 2, the principles deal directly with iterative experiments for space technology maturation; while other types of iterative research (such as pure science) could benefit from the principles, the principles do not account for all aspects involved in the other types of research.

In order to define a set of principles, the concept of a principle must be clearly understood and defined first. The following definitions of *principle* guided the development of the ones presented in this thesis:

> *[Merriam-Webster, URL]*
>
> Main Entry: prin·ci·ple
>
> 1 a: a comprehensive and fundamental law, doctrine, or assumption b (1): a rule or code of conduct (2): habitual devotion to right principles <a man of principle> c: the laws or facts of nature underlying the working of an artificial device
>
> *[Crawley, 2003]*
>
> Principles are the underlying and long enduring fundamentals that are always (or almost always) valid.

Therefore, the objective of the principles is to address those *fundamental design issues that should hold true for all well-designed microgravity laboratories for space technology maturation operated aboard the ISS*.

The first three chapters provide the basis to understand the concepts that comprise the objective of the principles. These concepts are: *microgravity research, laboratory, space technology maturation,* and *ISS*. The concept of space technology maturation is explained in Chapter 1, which introduces the Technology Readiness Levels as an example of current evaluation methods to demonstrate space technology maturation. The chapter also discusses several microgravity and remote research facilities; Chapter 2 uses the literature research of the introduction and further research on the International Space Station to better identify the special resources of the ISS and the research conducted within. Chapter 3 introduces the dictionary (Merriam-Webster) definition of a laboratory, and specifies that this thesis concentrates on the need for a laboratory to support experimentation in a field of study. Chapter 3 also introduces the definition of a facility, stating that a facility must make a course of conduct easier and is established for a specific purpose. Therefore, it is possible to expand further on the objective of these principles: they guide towards the *development of a laboratory environment, supported by facilities,* to allow *multiple scientists* the conduct of research under *microgravity conditions, correctly utilizing the resources provided by the ISS,* such that they *cover a field of study* to *accomplish technology maturation.*

The following are the Microgravity Laboratory Design Principles presented in this chapter:

- Principle of Iterative Research
- Principle of Enabling a Field of Study
- Principle of Optimized Utilization
- Principle of Focused Modularity
- Principle of Remote Operation & Usability
- Principle of Incremental Technology Maturation
- Principle of Requirements Balance

The principles were derived by David Miller, Javier deLuis, and Alvar Saenz-Otero following guidelines presented in formal systems courses at MIT [Crawley, 2003]. Using these professional guidelines, the principles are presented using the following structure:

1. Principle name
2. Descriptive version of the principle - presents the principle in a way that its characteristics are understood for observation of a design to determine if said design includes the principle
3. Prescriptive version of the principle - presents the principle so that it can be used as a guideline in the creation of design goal or requirements
4. Basis of the principle - relates the principle to previous chapters to explain the basis upon which the principle was derived
5. Explanation - describes the principle in full

5.1 Principle of Iterative Research

Descriptive:

A laboratory allows investigators to conduct multiple cycles of the iterative research process in a timely fashion.

Prescriptive:

Design a laboratory so that complete research iterations can be performed at a pace appropriate for technology maturation.

Basis:

Facilitating the iterative research process was found to be a primary high-level feature of the MIT SSL Laboratory Design Philosophy (Chapter 3). The scientific process, the most common procedure used for scientific research, is iterative in nature. Therefore, conducting microgravity research must be an iterative process and a laboratory to conduct research must facilitate iterations.

Explanation:

It is essential for the scientific process that a hypothesis can be tested and modified as experiments are performed. As compared to the iterative research process originally explained in the development of the SPHERES laboratory (Figure 4.8 on page 118), the principle of iterative research dives further into the full process of technology maturation. This principle covers all the areas of the process: the conception of the problem, development of high-level hypothesis and designs, and test and evaluation of specific implementations.

For completeness, we define the different steps of the iterative process as utilized by this principle and the different feedback loops in the process:

- Conceive the need for a new technology and define its required capabilities.

  - Specify the intended benefits of the technology for the intended audience.
  - Develop the science requirements of the technology.
- Hypothesize about the goals and performance that can be achieved using a particular instantiation of a technology.
  - Develop the initial functional requirements needed in a facility to test the hypothesis.
  - Define the operational environment necessary to mature the technology.
- Design the facilities that allows this performance to be tested and confirms or refutes this hypothesis.
- Develop specific experiments to test the technology.
- Conduct the experiments to obtain data that is sufficient to support (or refute) the hypothesis.
- Analyze the data obtained, compare it with the goals and performance requirements developed during the hypothesis formulation, and determine whether to run further tests, change the experiment, update the hypothesis, or finish the tests reaching successful technology maturation.

Figure 5.1 illustrates the iterative research process used under this principle. The figure illustrates three possible decisions after data analysis:

1. Repeat the test to obtain further data. This feedback loop requires the experiment to run multiple times with repeatable and reliable results while maintaining a low risk of failure in case an unreliable experiment is run.
2. Modify the experiment design to allow for comparison of different designs conceived after the hypothesis to find the best design possible. To enable different designs the experiment facility must allow reconfiguration of its hardware and/or software.
3. Modify the hypothesis about the goals and performance requirements for the technology. This option results in changes to the science requirements for the facility, and therefore the ability to respond to these changes requires a facility to support substantial reconfiguration. Therefore, it is possible that a single facility cannot support this feedback loop, but rather that in these cases a new facility will have to be designed. The scientist must be aware of the existence of this loop not necessarily to design a facility which allows these types of modifications, but rather to be aware that a single facility may not be sufficient to mature a technology.

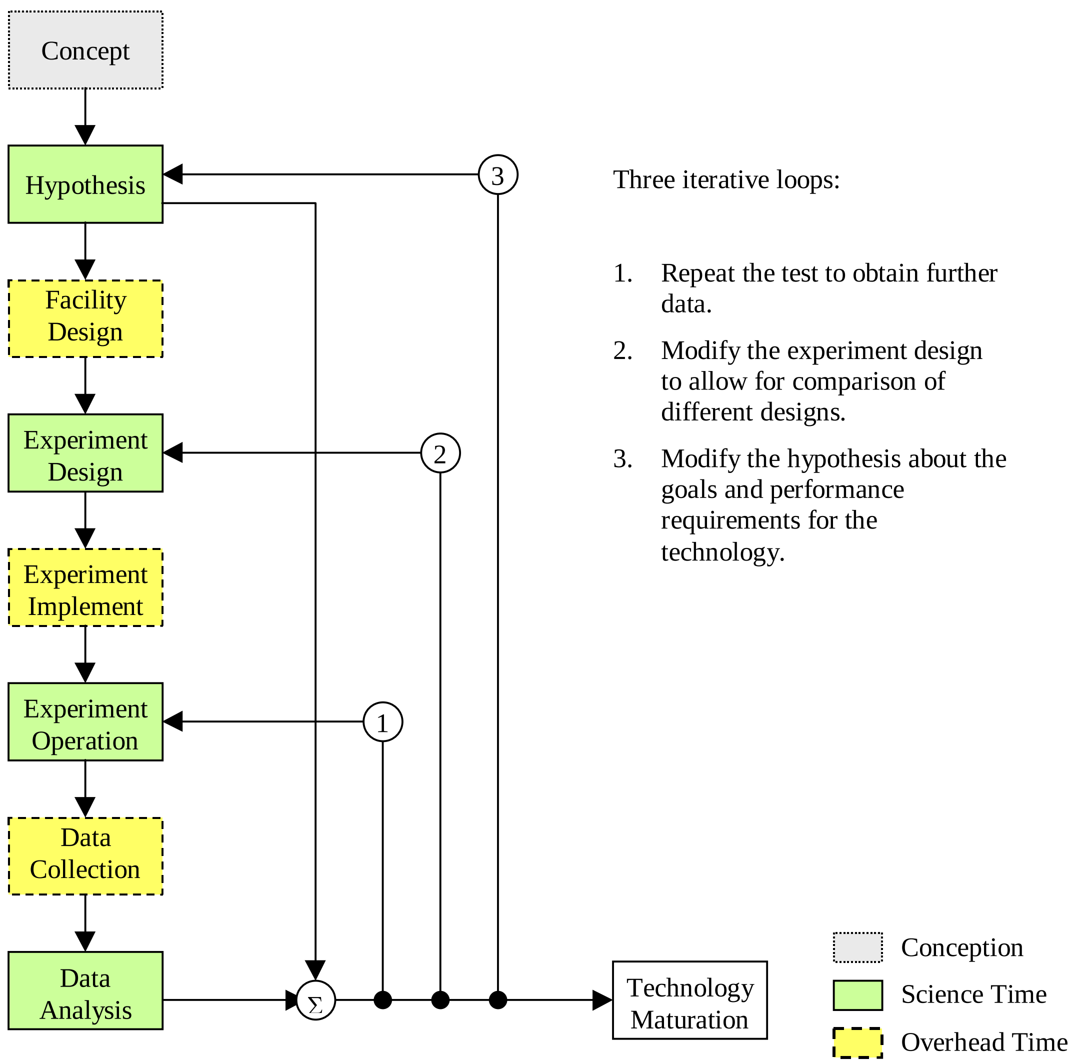


Figure 5.1 The iterative research process

Figure 5.1 shows the steps of the process (problem conception, hypothesis formulation, facility design, experiment design, experiment operations, data analysis, and technology maturation) and the main three feedback loops (repeat experiments, modify experiments, or modify the hypothesis). The figure categorizes the steps into three groups: the conception stage, science time, and overhead time. The definitions these times follow those presented in Section 4.3.1 on page 117: conception time is spent in the initial development of the problem; science time is spent by researchers developing new hypothesis or experiments and analyzing the data; overhead time is spent in enabling science time to occur. To actually *facilitate* the iterative research process, a laboratory must ensure that science time is maximized and flexible, while overhead time is minimized.

The principle of iterative research defines as science time the time spent formulating and modifying a hypothesis, developing specific experiments to test the hypothesis, operating the facility to obtain sufficient data, and analyzing the data (similar to what is presented in Chapter 4). Science time should be maximized and it should be flexible. That is, a researcher needs to have ample time to analyze data and determine new experiments and hypothesis without the pressure that the ability to conduct new experiments may expire. But the time must also be flexible, so that if a scientist is ready to conduct a new experiment, they can do so quickly, without a wait that would cause the loss of interest and/or relevance in the investigation or depletion of the resources available. Therefore, the operational plans of a laboratory should not prescribe strictly fixed research intervals, but rather provide scientists with a flexible schedule to conduct experiments. By minimizing the overhead time, a laboratory allows scientists to conduct experiments within short periods of time if they so desire. By ensuring the laboratory operates over an extended period of time, a laboratory provides researchers with enough science time.

The overhead periods are the time spent in designing the facility, implementing a specific experiment, and collecting data. The implementation of an experiment and data collection are described in Section 4.3.1 on page 117. Of special importance is the fact that the design of a facility is considered overhead time. A facility is built to support technology maturation, but it is not the technology itself. Therefore, if a scientist changes a hypothesis and must modify a facility, the time spent in implementing those modifications represent an overhead. A successful laboratory utilizes facilities which minimize the time needed to modify them, so that scientists can modify their hypothesis freely, without the worry that a change in a hypothesis will result in changes that would drive the project beyond its constraints. The principles presented in this thesis guide directly towards this goal: minimizing the time to design a facility by providing design guidelines and minimizing the time to modify a facility by considering the use of resources available in the ISS and modularity.

This principle considers the "depth" of the research: how deep an understanding of a specific area of research the laboratory allows a scientist to obtain. The more iterations, the better results for that specific experiment can be, and the deeper the understanding of the technology. This allows that specific area of the technology to mature utilizing the laboratory facilities designed under this principle.

5.2 Principle of Enabling a Field of Study

Descriptive:

A laboratory provides the facilities to study a substantial number of research areas that comprise a field of study.

Prescriptive:

The development of a facility that is to be part of a laboratory must allow investigation of multiple research areas within the field of study, supporting the necessary number of scientists to cover the field.

Basis:

The definition of a laboratory calls for it to allow research of a *field of study*. The MIT SSL Laboratory Design Philosophy (Chapter 3) calls to *support multiple investigators*. This principle originates from the two concepts. Past experience has demonstrated that to achieve technology maturation a filed of study must be researched by several scientists. The combination of their knowledge achieves technology maturation. While a successful experiment could conceivably allow research on a field of study without supporting multiple scientists, it is *almost always valid* to claim that multiple scientists will need to research the technology to achieve its maturation. In the rare case that a laboratory may allow a field of study to be researched by a single scientist, that is sufficient to satisfy this principle, as it would meet the definition of a laboratory.

Explanation:

In order to provide experimentation in a field-of-study, a laboratory must allow for experiments within the different research areas of the field. In order to conduct research on a field of study, all aspects of that field of study must be researched. Because researching a field of study is a large endeavor, it usually involves multiple scientists to work together to understand the field. Individual scientists concentrate on specific areas of the field, so that together the field is understood.

Therefore, this principle prescribes that:

- The study of multiple topics requires multiple experiments to be performed.
- Multiple investigators must work on individual topics to cover the whole field of study.
  - *Therefore* multiple investigators, whom perform experiments in their specific area of expertise within the field, must be supported.
- The laboratory must facilitate bringing together the knowledge from the specific areas to mature understanding of the field of study.

This principle considers the "breath" of the research, how much of a research area can be learned from the experiment. The larger the number of specific areas that a laboratory enables, the more technology matures.

5.3 Principle of Optimized Utilization

Descriptive:

A well-designed laboratory considers all the resources available and optimizes their use with respect to the research needs.

Prescriptive:

Consider all resources available to support the facility and optimize their use to benefit the research goals.

Basis:

Chapter 2 identifies the many special resources provided by the ISS, presenting the different facilities and tools available for research. Past MIT SSL experiments, presented in Chapter 3, demonstrate the need to use those resources correctly. The development of the SPHERES testbed (Chapter 4) concentrated heavily on the use of the ISS resources to reduce the challenges of microgravity research and fulfill the MIT SSL Laboratory Design Philosophy. But SPHERES does not utilize every one of the facilities and tools available aboard the ISS; rather, it makes the *optimal* use of those resources available to help it achieve its mission. Therefore, this principle originates not only from the fact that special resources exist on the ISS, but also from the need to customize the use of those resources to best fit the research objectives.

Explanation:

As presented in Chapter 2, the International Space Station offers a wide range of unique resources that make it ideal for the maturation of space technologies. While available to scientists, these resources are highly valuable, and they should be used in the best possible ways. Rather than thinking about using the least resources possible, this principle guides the researchers to use the resources in the best manner possible; i.e., the goal is not to minimize the use of resources, but to optimize its use with respect to the research goals.

The special resources of the ISS were identified in Chapter 2; these are the resources that we wish to utilize to fulfill the science goals:

- **Crew** - Human presence is one of the most important characteristics that separate ISS operations from standalone spacecraft. The crew can help reduce the risk of an experiment, intervening in the case of unsuccessful tests to allow continuos operation of the facility even after failures in the theory. The correct use of the crew also reduces the complexity of facilities as less automation is needed. Most importantly, the crew can provide feedback to the researcher based on observations during the conduction of the experiment. The presence of the crew allows a human to interpret the operations of the facility and success of experiments, rather than depending solely on machine-captured data.

- **Power sources** - The ISS was designed to provide substantial amounts of electrical power research experiments, as well as several pressurized gas and liquid resources. Each experiment location is provided with kilowatts of electrical power. Many locations also provide cooling elements, nitrogen, and carbon monoxide. The use of these resources can greatly reduce the cost of a mission by directly reducing the required mass; alternatively, it can increase the value of the mission by allowing more mass and volume to be used for research activities.
- **Data telemetry** - The ISS communications system, in constant expansion, is clearly a special resource which benefits all users of the ISS. The availability of continuous high-bandwidth communications to ground reduces the cost and complexity of missions which would otherwise need their own communications equipment. Existent resources allow scientists to obtain their data, if saved within the ISS data handling systems, within hours of the experiments; scientist can use the system to upload new software. The bi-directional nature of the existing communications enables an ISS laboratory to close iterative research loops, allow software reconfiguration, and support multiple scientists in the use of one facility. Further, the availability of ever-increasing communications features will enable real-time video and other teleconferencing options as part of daily research operations to better create a virtual presence of scientists aboard the ISS.
- **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 allows a laboratory to enable the iterative research process by creating flexible operations schedules. Further, the long-term nature of the ISS allows technology to mature over incremental, controlled steps, without the need to constantly test high-risk equipment.
- **Benign Environment / Atmosphere** - All projects, whether they reside inside or outside of the ISS pressurized environment can benefit from the benign environment. A facility operated aboard the ISS can concentrate on the science rather than on survival of the project, since the ISS provides substantial infrastructure to protect the projects and their operations. The presence of humans, even if they don't interact with the experiment, protects the facility. Continuos monitoring of all ISS operations further safeguards the experiments. The controlled and measured environment protects the facili-

> ties through the availability of structural elements designed specifically to support research.
>
> 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.

This principle considers the resources of the ISS as elements which provide *value* to a laboratory. Rather than thinking about the use of the resources as a cost to the project or the ISS, the principle states that the correct use of each resource can provide positive value to a laboratory, and that the correct use of its resources has a positive effect on the ISS itself.

5.4 Principle of Focused Modularity

Descriptive:

A modular facility identifies those aspects of specific experiments that are generic in nature and allows the use of these generic components to facilitate as yet unforeseen experiments. Such a facility is not designed to support an unlimited range of research, but is designed to meet the needs of a specific research area.

Prescriptive:

During development of a facility identify the generic components while ensuring the initial research goals are met.

Basis:

The MIT SSL Laboratory Design Philosophy (Chapter 3) calls for the creation of *generic vs. specific equipment* while allowing both *hardware* and *software reconfiguration*. Further, it calls for the creation of a *physical end-to-end simulation* of the technology. The SPHERES laboratory, even without having reached the ISS, has allowed multiple scientists to perform experiments over several years due to its generalized hardware and support of reconfiguration. Therefore, it is concluded that any successful laboratory that is to operate aboard the ISS can benefit from a clear distinction between general purpose equipment and science-specific features while remaining focused on its initial science goals.

Explanation:

Since experiments *almost always* contain basic elements that can support other similar experiments, the design phase of a facility should identify these common elements. These generic parts should be made available for future experiments as long as it does not compromise the mission of the original experiment. In this fashion, a laboratory is created by accepting facilities that provide some form of generic equipment which can be later used by new experiments.

The call for *focused* modularity is to prevent a "do-everything" system which may deviate the facility from meeting its original goals. The generic equipment should be identified after the design of the original experiment; the original design should not be to create generic equipment.

If a system does not have any components that meet any of this criteria, then there is a high probability that the scientist chose a narrow field of study for the experiment, such that the design of the facility does not share any common components with other possible experiments in the same field. Note that while this possibility reflects back to the Principle of Enabling a Field of Study, the Principle of Modularity remains separate. An experiment that enables a field of study does not necessarily have to be modular; or vice versa, a fully modular facility may not enable a whole field of study, but it may allow deep understanding of a small area of study.

5.5 Principle of Remote Operation & Usability

Descriptive:

A remotely operated laboratory, such as those in the ISS, must consider the fact that remote operators perform the everyday operation of the facility while research scientists, who do not have direct access to the hardware, are examining data and creating hypothesis and experiments for use on the facility.

Prescriptive:

An ISS experiment must accommodate the needs for a remote operator and a research scientist not in direct contact with the experiment.

Basis:

These principles are specifically intended to support the development of laboratories for operations aboard the International Space Station. As Chapter 1 explains, the development of all ground based laboratories, even those in remote locations, stresses the need to allow scientists to be present in the laboratory. The use of the ISS not only precludes the idea that the scientist be present at the laboratory, but Chapter 2 even presents several challenges to the effective use of the ISS crew time. Therefore, as opposed to the development of ground-based laboratories, ISS-based laboratories must provide the necessary facilities to account for remote operations and provide the correct usability for both the operator and the scientists in the ground.

Explanation:

Remote laboratories are based on remote locations because they offer a limited resource that researchers cannot obtain in their home locations. The design of remotely operated laboratories must account for the following facts about the operation:

- Operators

  - Are usually not experts in the specific field.
  - Are a limited resource.
- Research Scientists
  - Have little or no experience in the operational environment.
  - Are unable to modify the experiment in real-time.
  - Are usually an expert in the field but not in the development of facilities and testing environments.
  - May not have full knowledge of the facility design, especially when multiple scientists are invited to participate as part of a larger project.

The goal of a remote facility is to allow for a virtual presence of the research scientist in the operational environment. This includes the need for continuous communications between the operator and the research scientist, preferably in real-time. The availability of real-time two-way video is an important resource that benefits remote operations. In all cases, the use of high bandwidth communication systems, even if not real-time, should maximize the transfer of knowledge between the operator and researcher, especially when that is required to operate the facility successfully. In general the operator should have some idea of the expected results of each experiment in order to quickly transmit to the researcher information. In other words, the researcher should not solely depend on the communication of data, but also use the operator for feedback on the experiment.

Ultimately, the remote environment should allow a full virtual presence of the research scientist, where the operator becomes an extension of the scientist.

5.6 Principle of Incremental Technology Maturation

Descriptive:

A successful ISS laboratory for technology maturation allows technology maturation to transition smoothly between 1-g development and the microgravity operational environment in terms of cost, complexity, and risk.

Prescriptive:

Provide a representative μ-g environment that allows researchers to maturate technology in incremental steps between earth-based prototypes and flight equipment.

Basis:

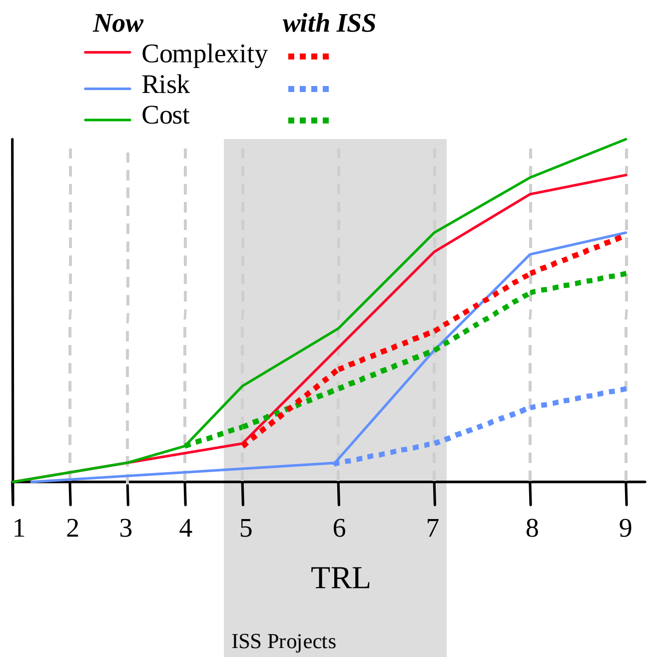
Chapter 2 identifies the primary challenges of microgravity research as risk, complexity, cost, remote operations, and visibility. Chapter 1 presents the concept of Technology Readiness Levels; Figure 1.2 on page 39 illustrates the general trend of three of these challenges (risk, complexity, and cost) to increase substantially as a project progresses through the TRLs. This principle emerges from the need to mature technology with limited and smooth increments of risk, complexity, and cost as the technology matures. The steepest increases originate from the need to provide a *relevant environment*; this principle calls for the correct use of the ISS environment, presented in Chapter 2, to create said environment without the current steep jumps pictured in Figure 1.2.

Explanation:

Technology maturation is an essential step for space programs. Current Technology Readiness Levels are used as a baseline to evaluate when a new technology is ready for flight. Due to the large jumps in cost, complexity, and risk between TRLs, they are not always followed systematically. Higher TRLs call for operations in a *relevant* environment to demonstrate maturation. A *relevant* environment is representative of the final operational environment in space; creating such an operational environment usually causes the steep jumps in cost, complexity, and risk. The lack of access to a representative space environment hinders the ability of scientists to demonstrate technologies at all TRLs. Therefore, there is a need to better support the maturation of technologies by enabling access to a relevant environment without steep jumps in complexity, risk, and cost, allowing incremental technology maturation.

The goal of incremental technology maturation is to make the complexity, risk, and cost increase smoothly as one moves across TRL levels, while being realistic of the changes in the environment required. With current test environments, excluding the ISS, there is an important steep jump when moving from the component level (TRL 4) to the system level (TRL 5) in a relevant environment, and a similar, if not steeper, jump when moving from a relevant (TRL 6) to a space environment (TRL 7). Further, the definition of relevant environment is not exact, sometimes leading to a relevant environment being a high-fidelity simulation and analytical model, rather than physical exposure to the system. Therefore, in many cases, the jump from TRL 6 to TRL 7 is very steep. The ISS provides an environment that can closely, if not fully, satisfy the requirements for a space environment; yet the presence of humans in the ISS can greatly reduce the risks involved, and the existence of the ISS itself can reduce the costs. Further, successful tests in the ISS may lead to less complexity when moving to higher TRL levels by providing scientists with a better understanding of the system.

Figure 5.2 builds on Figure 1.2 to present a pictorial representation of the increase in challenges as technology matures through the TRLs both with and without the use of the ISS as a host. The goal of incremental technology maturation is presented in the dotted lines: as one enters TRLs 5, 6, and 7, the ISS provides an environment where cost, risk, and complexity do not go through substantial jumps. The major increases should only be seen as the project leaves the benign environment of the ISS and enters the space environment. These increases should not be as pronounced as before, since the technology has been demonstrated in full microgravity conditions; the increases should be due to technical requirements, the need for new hardware, and the inherent challenges of launching a spacecraft into orbit; but the increases should no longer be due to any remaining need for further scientific knowledge of the problem.



TRL 1-2	Basic principles & concept
TRL 3-4	Proof-of-concept & laboratory breadboard
TRL 5	Component validation in relevant environment
TRL 6	System prototype demonstration in relevant environment
TRL 7	System prototype demonstration in space environment (usually skipped due to cost)
TRL 8	Flight system demonstration in relevant environment
TLR 9	Mission Operations

Figure 5.2 Smoothing TRL transitions

5.7 Principle of Requirements Balance

Descriptive:

The requirements of a laboratory are balanced such that one requirement does not drive the design in a way that it hinders the ability to succeed on other requirements; further, the hard requirements drive the majority of the design, while soft requirements enhance the design only when possible.

Prescriptive:

Maximize the hard requirements of a design and balance their effect on the design; minimize the soft "decirements" and ensure they don't drive substantial portions of the design.

Basis:

Chapter 2 presents the use of the ISS; Chapter 3 calls for the implementation of multiple features to satisfy the MIT SSL Laboratory Design Philosophy. The two chapters do not necessarily call for the same design to be created. Further, neither chapter accounts for the viability or cost to create a laboratory which implements the features called for. This principle arises from the lessons learned in the development of the SPHERES laboratory, which fulfills the majority of the ideas of Chapters 2 and 3. The design of SPHERES required several iterative design cycles to implement the features called for in Chapters 2 and 3 while remaining within the necessary cost and implementation constraints. The development necessitated that the different requirements which arise from the use of the ISS and the MIT SSL Laboratory Design Philosophy to be continuously reviewed so that no single requirement drove the project outside of its constraints.

Explanation:

Hard requirements are usually set at the start of a project to determine the goals that must be met; they are mostly quantitative. Soft 'decirements' are features desired by the scientists but which do not necessarily have a specific value or which are not essential for the success of the mission. A successful design creates a realistic set of requirements, maximizing the number of hard requirements, while taking into account the other principles presented herein:

- Balance the need for depth and breadth of a laboratory.
- Determine the correct amount of modularity needed.
- Prevent use of resources that are not needed; utilize the useful resources to their maximum.

Developing requirements is an iterative process just like any other system design problem, therefore to meet this principle the scientist is expected to iterate on the requirements of the other principles and then balance them. The other principles should be evaluated first, so as to develop a set of basic requirements for the facility. Using the requirements created from the other principles, this principle calls for the balance of effort into each of the other principles.

This principle does not call for all the requirements to be perfectly balanced or to necessarily eliminate the soft requirements; rather, this principle calls for the scientist to proactively pursue a realistic justification for each requirement and to ensure that a substantial part of the effort into the development of the facility goes towards clearly defined needs.

5.8 The Design Principles, the Design Philosophy, and the ISS

These chapter incorporates all the features of the MIT SSL Laboratory Design Philosophy (Chapter 3) for use in experiments which operate aboard the International Space Station (Chapter 2) into a set of concise design principles which broaden the scope of their applicability into a wide range of space technology maturation missions. Table 5.1 relates the design philosophy and use of the ISS to the design principles, demonstrating the ability of the principles to not only incorporate all of the features presented in Chapters 2 and 3, but also to account for critical design issues which were not directly present in the previous chapters.

All the features of the MIT SSL Laboratory Design Philosophy are accounted for in the Microgravity Laboratory Design Principles. The high-level feature of *facilitating the iterative design process* translates directly into the *Principle of Iterative Research*, with the majority of the features within the group *support of experiments* also being part of the iterative research principle. The high level feature of *supporting multiple investigators* joins several reconfiguration features to form the *Principle of Enabling a Field of Study*. The larger group to *support reconfiguration and modularity* is part of both the *Principle of Enabling a Field of Study* and the *Principle of Focused Modularity*. The principle of focused modularity describes why these features form part of both principles, since a laboratory could potentially support a field of study without being modular. The *Principle of Operations and Usability* is based on features of the MIT SSL Laboratory Design Philoso-

TABLE 5.1 Design Principles, the Laboratory Design Philosophy, and the ISS

	SSL Design Philosophy											
		Support of Experiments						Reconfiguration and Modularity				
Principle	**Facilitating Iterative Research Process**	**Data Collection and Validation**	**Repeatability and Reliability**	**Human Observability and Manipulation**	**Supporting Extended Investigations**	**Risk Tolerant Environment**	**Supporting Multiple Investigators**	**Generic versus Specific Equipment**	**Physical End-to-End Simulation**	**Hardware Reconfiguration**	**Software Reconfiguration**	**ISS**
Iterative Research	✓	✓	✓		✓	✓						
Enabling a Field of Study					✓		✓		✓	✓	✓	
Optimized Utilization												✓
Focused Modularity								✓		✓	✓	
Remote Operations & Usability	✓	✓		✓								✓
Incremental Technology Maturation						✓						✓
Requirements Balance												

phy as well as the operations of the ISS to ensure that a remotely operated facility utilizes the ISS correctly and enhances research at the same time. The use of resources available in the ISS is captured within the *Principle of Optimized Utilization*. The challenges of microgravity research, presented in Chapter 2, are addressed together with the need to create a *risk-tolerant environment* within the *Principle of Incremental Technology Maturation.* Lastly, the *Principle of Requirements Balance* glues together all the other principles beyond what the MIT SSL Laboratory Design Philosophy and the literature research on the ISS call for. The principle of requirements balance is an oversight of the other principles to ensure that a mission is successful.

5.9 Science in the ISS to Date: Applicability of the Principles

This section reviews the science conducted aboard the ISS so far to identify common designs and operations implementations to identify if the principles presented in this thesis are exhibited in past experiments, even if not specifically designed to do so. The existence of the traits of the principles in past experiments provide insight into how the principles should be applied to future experiments.

The ISS is currently hosting the crew of Expedition 10. Expeditions 1-7 consisted of three crew members; expeditions 8-10 have two crew members. The smaller crew on the later expeditions has limited the ability to conduct science aboard the ISS, therefore it is more relevant to study the science conducting during a 'full' expedition. Expedition 6, which was the last expedition to operate with a standard crew of three and performed the expected number of experiments that will take place in the long-term, has been fully researched. Table 5.2 shows all the experiments in Expedition 6. The NASA White Papers [NASA, URL1] about each experiment were reviewed to understand the design and operations of each project. The white papers provide sufficient information to identify the general characteristics of the experiments and determine whether the design follows a specific principle. These reviews do not evaluate the experiments, the reviews identify if past experiments exhibit the characteristics of a principle to determine the applicability of the principles.[1]

The Expedition 6 results demonstrate some important trends related to the principles. As Chapter 2 explains, the thesis concentrates on iterative space technology maturation experiments. Expedition 6 conducted 21 different experiments: ten in the bioastronautics area, six in the physical sciences, two in space product development, and three in space flight technologies. Out of the ten bioastronautics experiments, six are *exposure* experi-

1. The Principle of Requirements Balance is **not** used in this review since the deployment of the project aboard the ISS implies the mission successfully met its principal requirements. Further, the basic information presented in the white papers does not provide enough insight to determine specific requirements of a mission.

TABLE 5.2 Experiments in Expedition 6

Id	Field	Experiment	*Repeat*	*Size*	Iterative	Field	Utilization	Modularity	Usability	Maturation
1	Bioastronautics Research	The Effects of EVA on Long-term Exposure to Microgravity on Pulmonary Function (PuFF)	✓	*M*			✓	✓	✓	
2		Renal Stone Risk During Space Flight: Assessment and Countermeasure Validation (Renal Stone)	✓	*M*			✓		✓	
3		Study of Radiation Doses Experienced by Astronauts in EVA (EVARM)	✓	*M*			✓		✓	
4		Subregional Assessment of Bone Loss in the Axial Skeleton in Long-term Space Flight (Subregional Bone)	✓	*S*	Only Pre/Post flight					
5		Effect of Prolonged Spaceflight on Human Skeletal Muscle (Biopsy)	✓	*S*	Only Pre/Post flight					
6		Promoting Sensorimotor Response Generalizability: A Countermeasure to Mitigate Locomotor Dysfunction After Long-duration Space Flight (Mobility)	✓	*S*	Only Pre/Post flight					
7		Spaceflight-induced Reactivation of Latent Epstein-Barr Virus (Epstein-Barr)	✓	*S*	Only Pre/Post flight					
8		*Entry Monitoring*			*DELAYED*					
9		Chromosomal Aberrations in Blood Lymphocytes of Astronauts (Chromosome)		*S*	Only Pre/Post flight					
10		Foot/Ground Reaction Forces During Space Flight (Foot)		*L*			✓		✓	
11	Physical Sciences	Protein Crystal Growth-Single-locker Thermal Enclosure System (PCG-STES)	✓	*L*	✓	✓	✓	✓	✓	✓
12		Microgravity Acceleration Measurement System (MAMS)	✓	*M*						
13		Space Acceleration Measurement System II (SAMS-II)	✓	*M*						
14		Investigating the Structure of Paramagnetic Aggregates from Colloidal Emulsions for the Microgravity Sciences Glovebox (MSG-InSPACE)	✓	*L*	✓		✓		✓	
15		Vibration Isolation System for the Microgravity Sciences Glovebox (MSG-g-LIMIT)	✓	*M*	*No data*					
16		Coarsening in Solid-Liquid Mixtures for the Microgravity Science Glovebox (MSG-CSLM)		*M*			✓		✓	
17	Space Product Development	Zeolite Crystal Growth Furnace (ZCG)	✓	*L*		✓		✓	✓	✓
18		Microencapsulation Electrostatic Processing System (MEPS)	✓	*L*		✓		✓	✓	
19	Space Flight	Crew Earth Observations (CEO)	✓	*S*			✓			
20		Earth Knowledge Acquired by Middle-School Students (EarthKAM)	✓	*S*						
21		Materials International Space Station Experiment (MISSE)	✓	*L*		✓	✓	✓	✓	✓

ments (one was delayed), and the principles do not apply to them, as they do not create the facilities to implement a laboratory, but rather only use the fact that humans are exposed to the microgravity environment. Of the remaining four experiments, three exhibit the characteristics of the *optimal utilization* and *operations and usability* principle. The last experiment (PuFF) makes use of *modularity.*

The six physical science experiments are more evenly divided in the use of the principles. Two experiments (PCG-STES and MSG-InSPACE) exhibit many characteristics of the principles. It is interesting to see that these two experiments are the only ones that clearly exhibit the ability to perform iterations aboard the ISS. The experiments provide the necessary facilities for astronauts to repeat experiments in a manner that advances the iterative research process. While MSG-InSPACE appears limited in scope, PCG-STES provides research facilities for a large number of scientists to conduct a wide range of protein crystal growth experiments. Further, PCG-STES exhibits modularity. Both experiments utilize the resources available on the ISS to simplify the design of their facilities and enhance their capabilities by utilizing the astronaut time efficiently.

On the other hand, several physical sciences experiments on this expedition were effectively exposure experiments. The MAMS and SAMS-II experiments simply collect data for analysis later on. They do not exhibit any of the characteristics of the principles.

Space product development shows a growing trend toward exhibiting the characteristics of the design principles. One experiment, ZCG, exhibits a large number of the principles, only lacking enabling iterative research (while the utilization does not appear optimized, since it appears that the experiment could benefit from further crew time utilization and better interfaces, it correctly uses the standard ISS experiment rack supplies). The MEPS experiment also lacks the ability to enable the iterative research process, and it seems it would benefit strongly from better use of the ISS resources. But, the experiment does provide modular facilities for multiple researchers and has been designed to operate remotely with ease.

The space flight experiments of Expedition 6 consisted of an observation experiment (CEO), an educational experiment (EarthKAM), and an space technology research experiment (MISSE). The first two experiments do not exhibit a substantial number of characteristics from the principles. MISSE, on the other hand, exhibits several characteristics of the principles. MISSE is an exposure experiment, in that its samples are located outside the ISS and left unattended for an extended period of time; therefore, MISSE does not enable iterative research. But the facilities of MISSE do provide a modular setup where a large number of scientists can study a substantial amount of materials science. Further, the design directly accounts for several of the resources of the ISS: power, benign environment (exposed), and long-term experimentation. MISSE even accounts for the use of crew time since the exposed facility is designed to be accessed by EVA in case changes are needed. Lastly, MISSE was designed to allow cheap access to the space environment to better understand material science, effectively creating a facility to enable incremental technology maturation for space materials.

A trend identified in the operational description of a majority of these projects is that many researchers are proud that their facilities practically do not use crew time. In many cases the crew simply turns the experiment on and does not interact with it again until samples or data must be returned to the scientists. The extremely limited crew time has clearly pushed experiments to operate autonomously, and the fact that a human is present in the operational environment has not been utilized correctly. As a consequence of requiring autonomous experiments due to limited crew time, all these autonomous experiments do not enable iterative research aboard the station. Rather, the experiment provides data for one iteration; subsequent operations require delivery of further hardware to or from ground and direct interaction of the scientist.

The experiments of Expedition 6 confirm the stated intent of the principles: to guide in the development of iterative space technology maturation experiments. The review of the experiments clearly indicates that the principles do not apply to observation or education. On the other hand, the experiments of Expedition 6 which required multiple samples, a wide range of scientists, or interfaces with the crew exhibited the characteristics of a large number of the principles. Further, it is interesting to note that these experiments are physically and operationally *large* compared to the other experiments; the need to provide the necessary facilities requires the experiment to utilize more space.

Past experiments of the ISS show that the principles presented in this chapter are applicable to space technology maturation experiments conducted aboard the ISS. While not all of the experiments conducted aboard the ISS will benefit directly from these principles, it is clear that a substantial portion of the larger experiments conducted aboard the ISS will. Therefore, a researcher who identifies a new technology need requires clear and concise guidelines on how to apply these principles to achieve technology maturation. The next section presents a design framework to aid scientists in following these design principles.

5.10 Design Framework

The design framework concentrates on allowing a research scientist to design a laboratory, with its necessary ISS and ground based facilities, that meets the principles. The framework consists of several design steps which sequentially detail the requirements of the facilities that comprise the laboratory. The framework also provides general guidelines to evaluate if a specific design principle is being satisfied by the laboratory and determine whether there are benefits towards the maturation of the space technology by operating aboard the International Space Station. Through this framework the scientists can introduce their perspective of the science goals as well as the constraints of the project.

The application of the principles onto a new design does not occur in parallel for all the principles. As explained in the *Principle of Requirements Balance*, the design process is itself iterative, and therefore composed of several steps. With this in mind, the strategy presented in Figure 5.3 was developed. The figure groups the principles into the following main actions: determination of mission objective, identification of a field of study, initial design of a facility, identification of modular elements and design of operational elements, and balancing of the requirements. The application of each principle has been ordered so at to create an incremental set of requirements for the design of the facility. The order should help refine the requirements at every step. These actions are iterated until a final design is achieved.

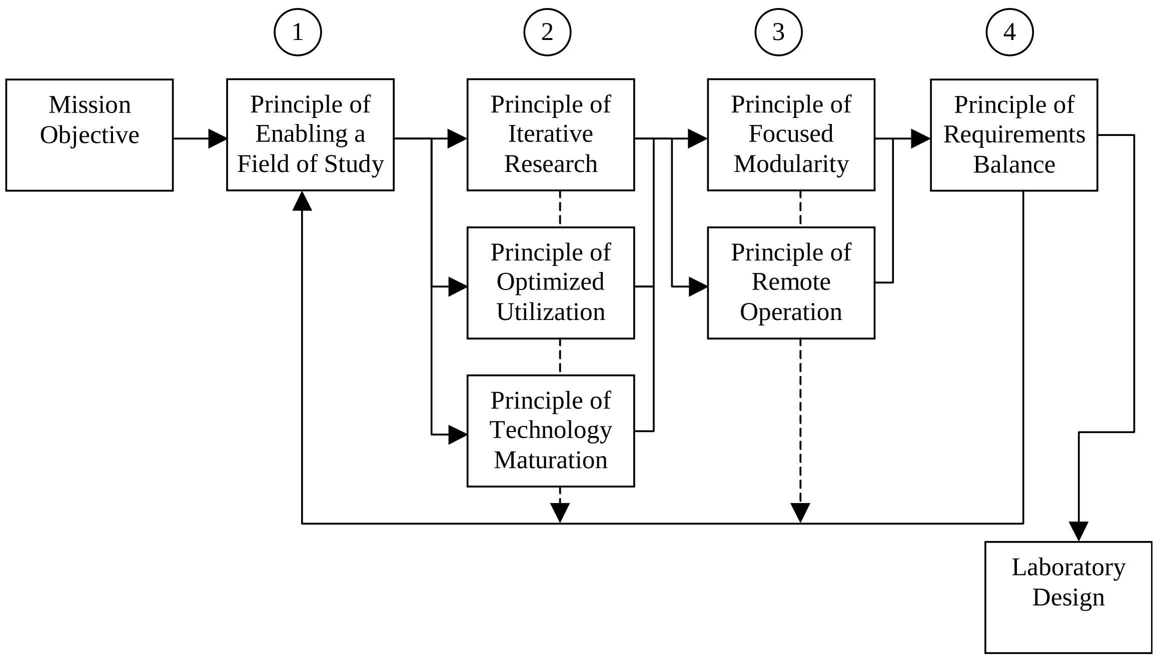


Figure 5.3 Design principles application strategy

The mission objective is determined by the customer. These objectives determine the science requirements of the mission. To satisfy these requirements, a laboratory must usually demonstrate results which cover a large area of study and which compare several designs to identify the best solution. The design principles of this thesis provide benefits when the research scientist charged with the mission determines that technology maturation is necessary and believes that the mission may benefit from operating in the ISS. In that case, the following steps should be taken to create a facility which will benefit from being in the ISS and which will facilitate the maturation of the space technology:

Step 1 - Identify a Field of Study

• Principle of Enabling a Field of Study

The first step is to identify the field of study the facility will support. The initial attempt is to select a large enough area in the field of study that the experiment can support technology maturation, but not so large that it is impossible to identify a clear set of science requirements.

Step 2 - Identify Main Functional Requirements

• Principle of Iterative Research
• Principle of Optimized Utilization
• Principle of Technology Maturation

The next step combines three principles that allow identification of the main functional requirements for the facility.

The principle of iterative research sets several requirements for the facility. Through this principle the scientist can determine the need for inputs and outputs, data capture and transfer rates, and requirements on the repeatability and reliability of the system. The principle also calls for the scientist to set requirements on the scheduling of experiment sessions and needs for data analysis.

The principle of optimized utilization provides an essential piece of information: should this facility be part of the ISS program or not? The principle requires the scientist to study the reasons for operating in the ISS and how the resources made available by the ISS are being used by the facility. It also gives the scientist an idea of which resources affect the facility heavily and which do not. Once it is determined which ISS resources should be used, a clear set of interface requirements to the ISS can be created.

For a facility to achieve technology maturation it must provide a representative environment for assembled sub-systems and/or prototypes. The definition of that environment and those systems are cast into clear requirements for the facility.

After all these requirements have been created it should be possible to identify a limited set of design options for the facility. These designs will be further studied in step 3.

Step 3 - Refine Design

• Principle of Focused Modularity
• Principle of Remote Operations and Usability

Step 2 identified all the major requirements for the system to achieve the science goals and helps create a limited set of candidate designs. Step 3 identifies those designs that best meet the call for modularity and ensures that the designs meet the need for remote operations.

As described within the principle of modularity, its goal is not that the initial objectives are for a modular system, but rather to identify those parts of a design that can be modular. Therefore, the principle of modularity is applied once a set of designs has been selected to search for those elements of the facility that meet the principle.

The principle of remote operation and usability requires a minimum set of information to provide valuable feedback, specifically: knowing what type of data the operator needs and what processing tools the scientist needs.

Step 4 - Review Requirements and Design

• Principle of Requirements Balance

Once the set of requirements has been finalized and a preliminary design conceived, the principle of balanced requirements calls for a review of the requirements prior to going on. At this point the scientist must evaluate whether the proposed facility has any requirements that have too much effect on the cost of the mission, and if they should be changed.

If the scientist determines that the requirements should be reviewed, the process should restart at step one to maintain objectivity. If the scientists agrees with the weight of each requirement and determines that the mission objectives will be met, then the process is finalized.

These steps provide a general overview of the laboratory design process to implement the design principles. The following sections presents general guidelines to determine functional requirements which satisfy the design principles.

5.10.1 Step 1 - Identify a Field of Study

This step utilizes the *Principle of Enabling a Field of Study* to determine the breath of the research. The following section presents guidelines to determine the range of the research that should be possible to research in a space technology maturation laboratory.

Principle of Enabling a Field of Study

Identifying the field of study and the areas which comprise it is a subjective process conducted by the research scientist to ensure the mission science objectives are fulfilled. The science objectives sometimes immediately identify the field of study; for example, when the mission objective is to mature the technology of a specific spacecraft subsystem as defined by [Larson, 1992]. In this case, the field of study may be propulsion, avionics, or structures. The research scientist can then identify the areas of study which comprise this sub-system, and select those areas which the laboratory allows to be studied. Other times, the mission objectives may not immediately identify the field of study; the mission objectives may be too broad to clearly identify a field of study or too narrow to be considered a complete field. For example, the mission may call for the observation of stellar objects, in which case the scientist must determine what part of a spacecraft for space observation requires technology maturation, and select that part as the field of study. On the other hand, a mission objective may simply call for the optimization of a specific control algorithm; in those cases the scientist needs to determine if its possible to study a substantial part of the controls field, rather than concentrate on the single algorithm. If the objective of the research scientist is to develop a laboratory for space technology maturation, rather than a single facility to test a specific concept, the research scientist must identify the field of study for the laboratory, even if that differs slightly from the science mission.

Once a field of study has been clearly defined, the subject areas which comprise the field of study must be identified. Each area must be complimentary to another, rather than replicate efforts on gaining the same type of knowledge. A laboratory allows the study of a meaningful number of the areas such that, when the knowledge gained from tests in all areas covered by the laboratory is brought together significant steps are taken to mature the technology.

The identification of specific areas of study allows the designer to determine if multiple scientists will need to conduct research in the laboratory in order to cover all the areas. Determining the need to support multiple scientist is necessary at this point, since the facilities will have different requirements depending on the number of scientists involved. Guidelines for these requirements are presented below. If at this point the determination is made that one scientist can perform all required research, there is a high probability that the initial field selection was too narrow; specific area of a field of study was selected, rather than a field of study. The designer should return to the first step and ensure that a field of study is being covered.

The facilities to support a field of study, researched by multiple scientists, must provide the following functionalities:

- Allow all scientists to create models of their work in their home locations.
- Create simple interfaces for the scientists to utilize the testing facilities.
- Ensure efficient data transfer between the scientists and the testing facilities.
- Provide flexible operations plans for scientists to conduct experiments.
- Enable software and/or hardware reconfiguration to cover all subject areas.

At this point it is useful to calculate an initial cost of creating the laboratory environment by using existing guidelines such as those presented in [Larson, 1992] or existing design tools such as those developed by [Matossian, 1996], [Shaw, 1998], [Mosher, 2000], and

[Jilla, 2002]. These initial costs can be used to determine the number of areas of study which should be covered by the laboratory to obtain a benefit by studying a substantial part of a field, rather than developing individual test facilities for each area of study. The following equation, based on the methods proposed in [Meyer, 1997] to measure the efficiency of product platforms, provides a general idea of the efficiency of using a laboratory rather than multiple facilities:

$$J = \frac{m}{n} \cdot \frac{K_{lab} + \sum_{i=1}^{n} k_i}{\sum_{i=1}^{n} K_i} \tag{5.1}$$

where:

m = total number of areas in the field of study

n = number of areas covered by the laboratory

K_{lab} = cost of the common laboratory facilities

k_i = cost of enabling each area of study

K_i = cost of developing an independent facility for each area of study

The numerator considers the costs of implementing derivative products; the numerator represents the cost of implementing new products every time. The factor m/n relates the total number of areas of study with the ability of the laboratory to support multiple areas; as more areas are supported, the factor decreases. The goal is to ensure that the cost J is less than 1.

Using the guidelines presented in [Larson, 1992] and the experience of the MIT SSL microgravity projects, it is possible to make the following assumptions:

- The costs K_i will always be larger than the costs k_i, since developing complete facilities requires substantial launch cost and development of common equipment.
- The costs k_i will not be constant for all ares of study.

- The cost K_{lab} will be larger than the costs K_i, since it requires the addition of resources to support multiple scientists.

Under these assumptions, the general trends of cost J can be represented graphically, as shown in Figure 5.4. While the figure shows only a pictorial representation of cost J, it provides the designer with important information:

- Utilizing this measure, a laboratory must cover multiple areas of study; even if the cost of a facility is small, not covering multiple areas of study results in a high cost.
- As the cost of supporting areas of study increases, a facility will need to support more areas to result in a cost factor less than 1.
- It is possible that supporting certain areas of study results too high and drives the cost beyond the threshold as it is added.

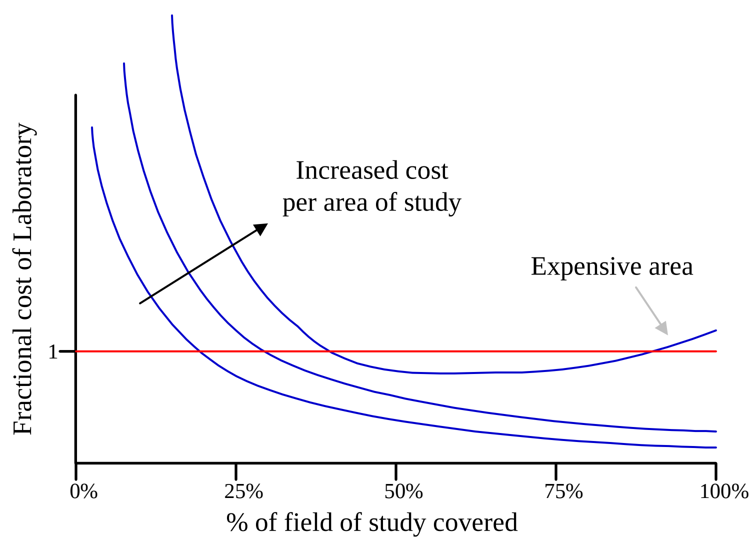


Figure 5.4 General trend of cost J using cost function *5.1*

5.10.2 Step 2 - Identify Main Functional Requirements

This step calls for scientists to determine the main functional requirements of the laboratory once the field of study has been defined. Three principles are used to determine these requirements: *Principle of Iterative Research*, *Principle of Optimized Utilization*, and

Principle of Technology Maturation. The guidelines to determine the functional requirements using these principles are presented next.

Principle of Iterative Research

Designing a laboratory to satisfy the Principle of Iterative Research requires that the facilities of the laboratory permit to close at least one of the iterative loops presented in Figure 5.1 on page 204; preferably, a laboratory which operates aboard the ISS not only allows repetitions of experiments (loop 1), but also modifications of experiments (loop 2) and the hypothesis (loop 3). For this to occur, a facility design must exhibit efficient and sufficient *data collection and analysis tools,* as well as the *ability to reconfigure* the facilities with new experiments that reflects the knowledge obtained during previous iterations. Further, the laboratory needs to develop a *flexible operations plan* which provides scientists with sufficient and flexible science time.

Data Collection and Analysis Tools

Data collection is part of the overhead time; data analysis is part of science time. The design of a laboratory should minimize the work to collect data, and ensure that the collected data are of the appropriate quality. At the same time, the laboratory must provide the correct tools for efficient data analysis to support or refute experiments and hypothesis.

Data collection consists of four main parts: capture bandwidth, precision, accuracy, and data transfer. For successful data collection, the following guidelines should be met:

- **Bandwidth -** The data sampling rate indicates the maximum bandwidth of the collected data. The facilities must be designed with the maximum bandwidth possible, so that they can be used for as yet unforeseen research. In no case should the Nyquist criterion (sample at twice the frequency of the highest mode of the system which should be observed) not be met for known system bandwidths; further, as per [Larson, 1992], the sampling factor should be 2.2 to account for model uncertainties.
- **Precision -** Data precision tells the scientist how small a change in the physical system can be measured. A high precision system can measure small

changes; a low precision system can only measure big changes. As a general guideline, the precision should be a fraction of the "impulse bit" (the smallest actuation possible) of a system, such that the sensors can successfully measure the effects of one impulse bit.

- **Accuracy -** Data accuracy accounts for how close a measurement is to the actual physical event. The higher the accuracy, the closer the measurement is to reality. Because accuracy greatly benefits from in-flight calibration [Larson, 1992], the scientist must design a laboratory so that its measurement systems can be calibrated once operational aboard the ISS. If in-flight calibration is not possible, the scientist must account for the physical effects of launch and deployment on the ultimate accuracy of the system and ensure it is of good enough quality for successful research.
- **Transfer -** Once captured, that data must reach the scientist. Data transfer does not necessarily need to be in real-time in order to meet this criteria, although real-time data could benefit experiments. But the transfer times must not substantially affect the available science time; data transfer times should never be a substantial fraction of data analysis time. Therefore, a facility must interface correctly to available communications resources to minimize the data transfer time.

Once the data reaches the scientist they must be analyzed. A complete laboratory provides scientists with data analysis tools which minimize the time between receiving the data and the start of analysis. It is not sufficient to make the data available to the scientist, they must be able to use it efficiently. For this, the laboratory must clearly define the type of data transferred to the scientist and the format in which the data is transferred. Further, tools to convert the data into those formats which best suit the needs of the scientist must be created before experiments are conducted, so that data analysis time is spent in examining the data, rather than in making the data available and presentable in the correct format.

Enable reconfiguration

In designing a laboratory which facilitates the iterative design process, it is necessary to determine the level of reconfiguration necessary to close each of the three iterative loops presented in Figure 5.1. The design process should include the identification of what is needed to close each of the three loops, and subsequently, based on the resources available for the project, determine which loop is to be closed. The following points serve as guidelines to determine what is required to close each of the loops:

- Repeat Experiments
  - Ensure the operator's interfaces permit starting tests with minimal overhead from repetitive tasks.
  - Facilitate the repetition and/or measurement of initial conditions.
  - Enable resupply of consumables.
  - Provide sufficient space for data storage.
- Modify Experiments
  - Enable initial conditions to change sufficiently for the difference between experiments to be relevant.
  - Allow scientists to specify a different set of variables for the system, be it via hardware or software changes, consistent with DOE techniques ([Fisher, 1935],[Mead, 1988],[Antony, 2003]).
  - Allow changes in the response of the system to the same actuation by the addition or removal of hardware or software
- Modify the Hypothesis
  - Allow for the modification of both sensors and actuators so that different types of data are available as research progresses.
  - Ensure that new models of the problem are supported by the facilities that support the operator and the researcher.
    - The facilities aboard the ISS must allow any software or hardware which utilizes models of the problem to be fully reconfigured.
    - The data analysis tools of the researcher must allow its models to be updated.
  - Provide for the ability to modify the operational plans of the laboratory to accommodate for the need to develop new facilities; allow these new facilities to operate under new plans.

The capability of a laboratory to allow modifications must be bound by the limit of the available resources. For example, if a program only calls for one launch to the ISS, then it is not possible to claim that the system can be fully reconfigured by a second launch; reconfiguration must be enabled in the original facility. On the other hand, if a program has secured several flights to the ISS, it can utilize those to modify the facilities sufficiently to enable modification of the hypothesis without having to implement more complex features in the original hardware.

Flexible Operations Plan

Enabling data collection and reconfiguration features in a laboratory does not guarantee successful iterative research. The iterative research process greatly depends on the availability of time for the scientist to conduct the necessary research. Therefore, a flexible operations plan which provides this science time is essential. Figure 5.5 illustrates this concept. The experience from MODE, DLS, and MACE has shown that too short or too long a time between iterations has a negative effect on the iterative research process. This concept is captured in the bottom plot. On the other hand, an experiment quickly benefits as iterations start; but the benefits from each iteration decreases each time; ultimately, the benefit asymptotes as the number of iterations increases. This concept is illustrated in the left side plot. The center plot shows that there exists a middle area where both the time between iterations and the number of iterations provide substantial benefits to the science. The goal is to design all laboratories to allow iterations in this area.

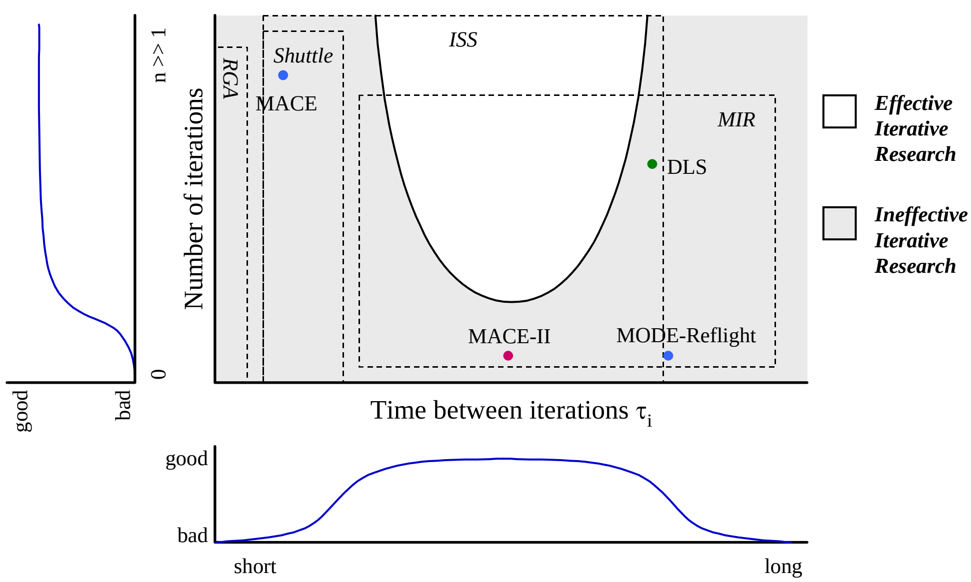


Figure 5.5 Achieving effective iterations though flexible scheduling.

Reduced gravity airplanes (RGA) provide very short time periods between iterations, only allowing the capture of data. MACE, MODE, and MODE-Reflight all operated aboard the Space Shuttle, which provides only short periods to analyze data and iterate. MODE-Reflight is shown twice, since the second flight was effectively a single iteration of the first flight, since lessons were learned, but the time between the two flights was exceedingly long. MACE-II operated aboard the ISS for an extended period of time, but the lack of communications at the time prevented a significant number of iterations to take place. DLS, which operated aboard MIR, was close to operating in an effective region of the iterative research process, but the long delays in communications between the researchers, NASA, and their Russian counterparts proved to have some negative effect on the research.

Figure 5.5 does not indicate quantitative figures for the actual time between iterations or the number of iterations that must be accomplished. Each scientist must determine the quantitative values for their specific research projects, since they can vary widely. The following guidelines should be followed in determining these values:

- An iteration consists of all the actions between conducting an experiment, collecting the data, achieving scientific knowledge, and applying that knowledge to mature a technology. An iteration is *not* the time it takes an operator to repeat an experiment; it includes all the steps to conduct the experiment, analyze the data, and determine the next step to take.
- Do *not* force the time between iterations, τ_i, to be fixed; find a minimum and maximum time between iterations which provides enough flexibility to the research scientist.
    - The minimum time between iterations must account for the need to analyze data and upload, at least, new experiments.
    - The maximum time between iterations must account for the resources available to the program. Also, it must account for other research which could reduce the value or replace the research of the laboratory.
    - Increasing the number of scientists using the laboratory enables the creation of a fixed time between iterations, as it increases the possibility that any one scientist will make use of the facilities when available, even if the others need further analysis time.

- It is beneficial to maximize the number of iterations which can be executed in the laboratory, especially if multiple scientists are involved in the research.

Principle of Optimized Utilization

A primary goal of the principle of Optimized Utilization is to change the way in which people think of the resources available in the International Space Station. The review of ISS experiments presented in Section 5.9 indicates that the majority of projects currently consider the cost of utilizing a resources; the design of existing facilities attempts to minimize the cost by reducing the use of resources. While in general this is a common goal of space missions, the use of the ISS should not follow those standards. ISS resources provide *value* to missions, and the correct use of these resources should maximize the value obtained by the project from using the correct resources for the specific science goals. Therefore, the development of a laboratory must consider all the resources available and optimize their use with respect to the research needs.

The first step in designing a laboratory which correctly utilizes the resources available aboard the ISS is to understand the resources and select those that are useful to the research:

- *Understand the resources and limitations of the ISS.* [NASA, 1998] and [NASA, 2000b] provide substantial information on the resources available for research aboard the ISS; the finding from these references are summarized in Chapter 2.
- *Determine the needs of the research.* Based on the mission objectives and the other principles, the designer can determine the general operational processes of the facilities which will operate aboard the ISS and at Mission Control. The general operations provide insight into which resources benefit the mission.
- *Realize which resources do not provide a benefit to the research.* While the goal is to maximize the value obtained from the resources aboard the ISS, there may be cases in which utilizing a resource presents more challenges than benefits to the science. If a resource cannot provide positive value to the mission, the scientist must realize this early in the design process, and decide not to use that resource.

A set of guidelines based on value models presented in [Cook, 1997] was developed to help better understand the availability of resources aboard the ISS. The value curves presented in [Cook, 1997] utilize Taguchi functions which consist of Nominal is Better (NIB), Larger is Best (LIB), and Smaller is Best (SIB) models. The original Taguchi NIB functions are centered around a central value (the curves are symmetrical about the best value), which is not necessarily the case for the ISS resources. Therefore, these functions have been adapted to generate value curves which better represent the availability of resources aboard the station.

The Taguchi method normalizes the value obtained from a resource between 0 (least value) and 1 (most value). The parameters which define the shape of the value curves represent the availability of the ISS resources identified in Chapter 2 based on the information provided in [Hagopian, 1998], [NASA, 1998], [NASA, 2000b], [NRC, 2000] and [Durham, 2004]. The curves represent the ability of the ISS to provide that resource; if the resource can benefit the laboratory, then the amount of resource to utilize should be consistent with the value curve.

Table 5.3 summarizes the findings of the availability of the special ISS resources and Figure 5.6 presents the resulting value curves. The table indicates the type of modified Taguchi value curve used for each resource (NIB, LIB, or SIB); in one case a value curve is not appropriate, and Yes/No (Y/N) values are recommended. The *base* value indicates a starting value for the design. The *critical* value represents the point at which the ISS can no longer provide that resource, and further usage would negatively affect other research operations aboard the station; therefore, experiments should not use these amounts of resources. The *ideal* column indicates the point at which the ISS resources can be best shared among research facilities. The determination of these values was based on the following information about each resource:

- **Crew -** Human presence is one of the most important characteristics that separate ISS operations from standalone spacecraft. Therefore, the value of this resource is based on a nominal is better (NIB) curve - the astronauts

TABLE 5.3 Summary of ISS special resources

Resource	Type	Unit	Base	Critical	Ideal
Crew	NIB	hours/month	10	144	18
Power Sources - usage	SIB	kW	4	20	2
- percentage	LIB	%	50	0	100
Telemetry	NIB	Kbps	7	1000	100
Duration	NIB	months	6	120	6
Benign Env't / Atmosphere	Y/N	-	[1 0]	-	-

should perform tasks for the experiment, but only for a limited time. The parameters were obtained as follows:

- The review of Expedition 6, with three astronauts aboard the ISS, provided a total of 2160 hours per month of astronaut time. According to NASA approximately 10% of astronaut time can be used for science experiments Therefore there are a total of 216 hours per month available for science. Review of ISS science up to date reveals that there are approximately a dozen experiments in the ISS at any one time, leaving approximately 18 hours per experiment per month as an ideal value

The recommended NIB value curve drops sharply as less than eight hours per month of astronaut time are used, since it results in a waste of an important resource of the ISS. If more than 50 hours per month are used, the facility starts to reduce the available resources to other projects, also reducing its value.

- **Power sources -** The value of the ISS with respect to power is presented using two measures:
  - *Minimize total power.* The curve for absolute power utilization is a smaller-is-better (SIB) curve since the total power consumed should be minimized. The ISS will provide up to 46kW of electrical power; each locker provides an average of 2kW of power, making that the ideal value. The base value of 4kW is based on an average of 12 experiments present in the station at any one point. The critical value of 20kW is based on the maximum available power using special resources.
  - *Maximize power fraction used from ISS.* This is a larger-is-better (LIB) measure - a facility should maximize the percentage of power used from the ISS with respect to the total facility power.
- **Telemetry upload/download -** The ISS communications system value is based on the NIB value curve. The available data bandwidth is 1.5Mbps, with expected upgrades to 15Mbps in the next couple of years. Given that

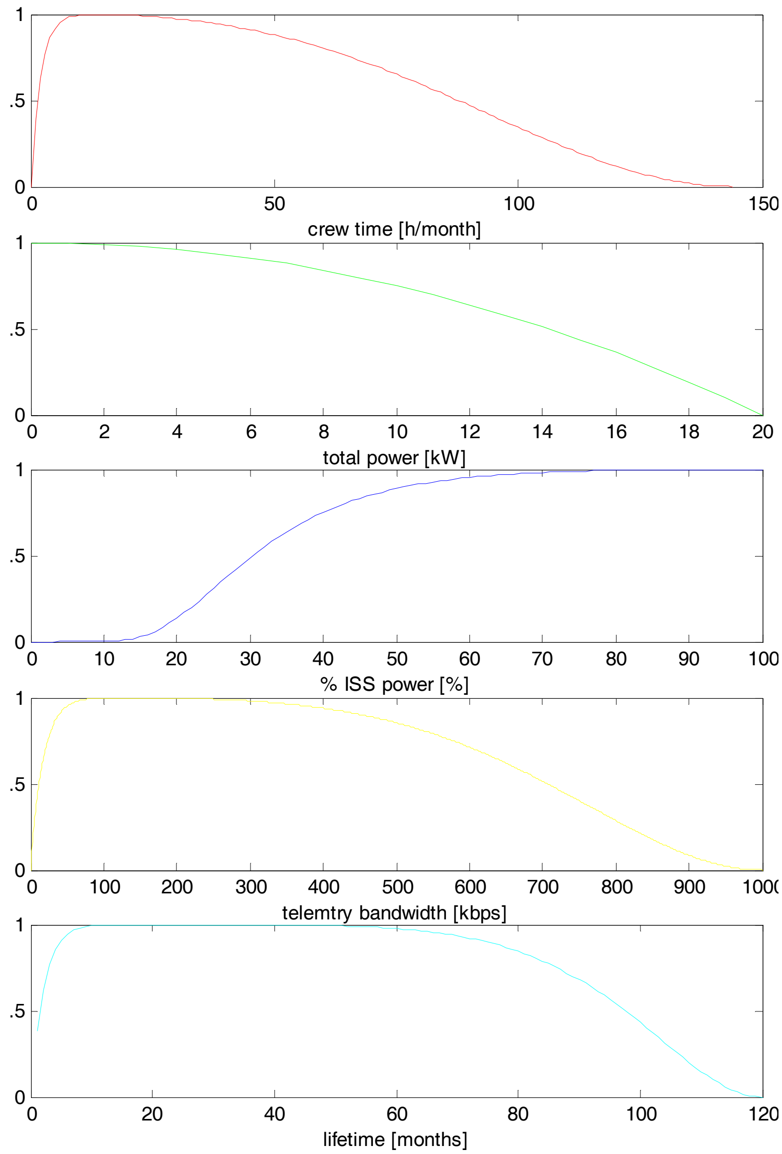


Figure 5.6 Value curves for ISS unique resources

there are approximately a dozen experiments in the ISS, the current ideal value is for each project to use approximately 100Kbps of bandwidth on average.

- **Long-term experimentation -** The parameters for long term experimentation take into account the presence of astronauts in a schedule of every six months and an ISS life expectancy of 15 years. An NIB curve is recommended for long-term experimentation. The ideal value for the longevity of an experiment is one expedition (six months), due to training and other operational constraints. The other limit is the station's life expectancy of approximately 10 years from now. The value between six months and several years of operation is almost the same, since the limitations from the ISS perspective lie solely on astronaut training and availability. The value drops for shorter periods, since the expenses in the deployment of a project to the ISS should be amortized over longer operations. The value curve is not an LIB because experiments that reside too long in the ISS restrict the availability of resources, preventing other facilities from operating and limiting the science conducted aboard the station.

- **Benign Environment / Atmosphere -** The value of utilizing the benign environment of the ISS does not follow a Continuos curve; rather, it is a binary yes/no determination. A scientist should consider the following points to ensure the laboratory's facilities benefit from this resource:
  - The monitoring capabilities of the ISS should be utilized to safeguard the facilities aboard the station.
  - Astronauts should be able to prevent and/or repair damage to a facility to ensure long-term operations.
  - Facilities aboard the ISS should utilize the standard interfaces of the ISS available for research, including the availability of structural mounting points, supply lines, and data connections.
  - Facilities which operate inside the ISS should reduce their cost by utilizing standard components without special treatments to account for the space environment.

Principle of Incremental Technology Maturation

The achievement of technology maturation in an experimental setup suggests that the operational environment of the experiment resembles the final application enough so that the technology is considered reliable for operations in the next level of technology readiness. Therefore, in order to determine how well a design meets this principle, one must examine how far into the TRLs we can go using this facility and how much the cost and risk can be reduced by developing technologies in the ISS.

To measure how far into the TRLs a technology can be advanced, we use the tests for each TRLs that apply to operations in the ISS: TRL 5, TRL 6, and TRL 7. An ISS experiment should provide advancement at least to TRL 5, preferably TRL 6. Some facilities may even provide TRL 7 advancements if the final technology is compatible with the ISS environment. To measure how far into the TRL's a technology can be advanced, we use the established tests for each TRL [Lindensmith, 2003]:

TRL 5:

1. The "relevant environment" is fully defined.
2. The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.
3. Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment"
4. Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.

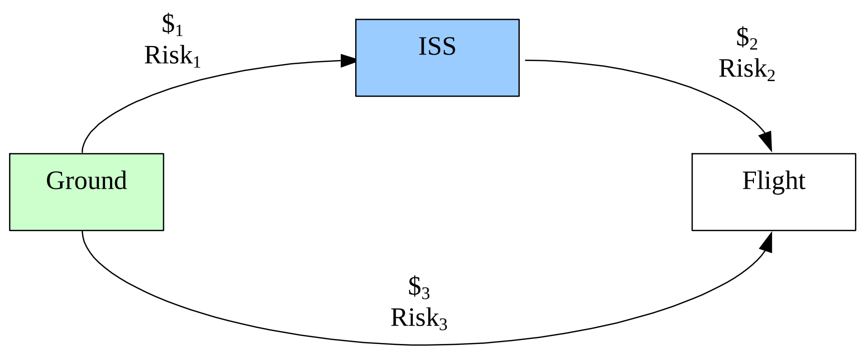
TRL 6:

1. The technology advance is incorporated in an operational model or prototype similar to the packaging and design needed for use on an operational spacecraft.
2. The system/subsystem model or prototype has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission.
3. Analytical models of the function and performance of the system/subsystem model or prototype, throughout its operating region, in its most stressful environment, have been validated empirically.
4. The focus of testing and modeling has shifted from understanding the function and performance of the technology advance to examining the effect of packaging and design for flight and the effect of interfaces on that function and performance in its most stressful environment.

TRL 7:

TRL 7 requires both an actual system prototype and its demonstration in a space environment. The prototype should be at the same scale as the planned operational system and its operation must take place in space.

The use of the ISS should allow the challenges of microgravity research to be reduced by by providing a representative environment to mature technology. The researcher must determine whether obtaining this advance in technology by using the ISS provides an advantage, especially in terms of the risk and cost involved in a space mission. This concept is illustrated in Figure 5.7. The figure shows that there is a certain risk and cost for each step towards developing new missions. The cost/risk can be that incurred in the deployment of a technology in ground-based facilities followed by one or more flight programs; this cost is represented by $\$_3$ and $Risk_3$ in the figure. The risk/cost can also be split by using the ISS as an intermediate step, with one or more steps taken aboard the ISS ($\$_1$, $Risk_1$) before deployment of the space mission ($\$_2$, $Risk_2$). Incremental technology maturation should allow the total cost and risk of a mission to be lower by using the ISS as an intermediate laboratory to develop technologies incrementally.



Goal:

$$\$_1 + \$_2 < \$_3$$
$$Risk_1 + Risk_2 < Risk_3$$

Figure 5.7 Two paths to flight operations

Reducing risk and cost are not independent of each other, but they are not necessarily proportional to each other. To reduce risk the cost may need to go up, but the reduced risk may result in a lower program cost if problems are prevented. Therefore, the following cost function accounts for the fact that lowering risk can reduce total program costs even at a higher individual cost, while at the same time penalizing extreme cost increments. It quantifies the risk of a mission in terms of the cost of mission failure, the probability of failure, and weigh it by the possible advances from the mission in terms of TRL levels:

$$R = \frac{\$_{TRL} \cdot \rho}{w(TRL_{\#})} \tag{5.2}$$

where

$\$_{TRL}$ = cost of the facility to allow a specific TRL advance

ρ = probability of failure of the mission such that a TRL advance could no longer take place (if a facility allows multiple TRL advances, each of them should be considered independently)

$w(TRL_{\#})$ = the weight assigned to the TRL numbers 5, 6, or 7. Achieving each TRL brings the technology closer to maturation at different levels, therefore the weight accounts for the level of technology advancement:

$w(5) = 1$

$w(6) = 1.5$

$w(7) = 3$

The resulting "risk" is presented in units of cost, such that it can be combined easily with the total cost of the mission to determine the cost/risk value for a step:

$$J(\$, R) = \$ \cdot \left(\frac{\$ + R}{\$ - R}\right) \tag{5.3}$$

where

$\$$= total cost of the facility

R = total risk/cost of the facility

If a laboratory allows maturation of a technology for multiple TRL's, the cost of achieving each level should be accounted independently, and then the total cost added together. For example, if a laboratory allows a technology to mature through both TRL 5 and 6, then its total cost should have two parts: first, the cost to deploy the laboratory for operations aboard the ISS and costs related to achieving TRL 5; second, the operational costs (without deployment costs, such as launch, if none are incurred) for achieving TRL 6.

5.10.3 Step 3 - Refine Design

Once the primary functional requirements of the system are defined in Step 2, Step 3 identifies possibilities to get added value from the laboratory's facilities by providing guidelines to decide on the level of modularity in the design and ensure that remote operations take place efficiently. The principles of *Focused Modularity* and *Remote Operations & Usability* apply in this step.

Principle of Focused Modularity

The Principle of Focused Modularity calls for the identification of parts of a facility which are generic equipment that could be utilized by other facilities with similar needs. Of outmost importance in the application of this principle is to remember that the creation of a modular system must not deviate the project from its original mission objective. Modular systems must be identified after the initial design of the facility has been created to meet the science goals of the mission, not designed a-priori as part of the mission objectives.

In some sense it is obvious whether a system is modular or not; a modular system has multiple components that can be interchanged to create different configurations. The following criteria, helps to further identify the applicability of modularity to parts of the system; it also helps in the design process, to ensure that modularity is thought off as an integral part of the system while ensuring that the science goals are met:

- **Inter-disciplinary use** - if the component can be used in different disciplines within the field it should be generic equipment
- **Reconfiguration** - if the component easily allows the experiment to change the general area of study of the experiment, while supporting all other functions, it should be generic equipment
- **Obsolescence** - only those components that are not expected to be obsolete by the time of re-use should be made generic

- **Life-time** - only those components whose life-time is over the anticipated time to re-use should be made generic
- **Cost amortization** - if the component cost is likely to be amortized by future use in different experiments it should be generic equipment
- **Maintain original goals** - the immediate research should not be compromised by making a specific equipment generic

The goal of the criteria helps to ensure that the component will not change the original goals, not be obsolete, and will be fully functional at the time of re-use. Further, it guides towards the ability of generic equipment to add value to the facility by ensuring the component will expand the functionality of the system. Table 5.4 presents a truth table that indicates whether equipment should be generic or not: based on this criteria.

TABLE 5.4 Modularity criteria truth table

Inter-discipline	Reconfigure	Obsolete	Life-limited	Cost Amortize	Original Goals	Make Modular
x	x	x	x	x	0	0
x	x	0	x	x	x	0
x	x	x	0	x	x	0
1	x	1	1	x	1	1
x	1	1	1	x	1	1
x	x	1	1	1	1	1

Key: 0 = no, the criteria is not met
1 = yes, the criteria is met
x = irrelevant

Principle of Remote Operation and Usability

A successful laboratory exhibits the following characteristics to support both operators and research scientists by creating the necessary facilities both at the ISS and the ground-based location of the scientists:

- **Operators**
  - Provides the operator with the necessary controls to conduct research efficiently
    - Available controls must ensure the operator can actuate or command the facility in every way necessary to perform the experiments
    - Extraneous controls should not be present to minimize the distractions of the operator.
    - Repetitive tasks not directly related to conducting experiments and obtaining relevant data should be minimized.
    - The controls must meet the requirements for interfaces as defined by the ISS boards and to account for human abilities. The controls must consider the user of tools such as quickening, predictors, and virtual displays in the case where the operator must perform real-time maneuvers or commands.
    - The operator must always feel safe to stop an experiment.
  - Ensures that the data is safely transferred to the scientists regardless of operator actions.
    - A clear data-path must be defined prior to operations so that data is not lost or delayed inadvertently
  - Presents relevant information to the operator for successful run of experiments.
    - Allows operators to conduct full cycles of the inner-most iterative research process loop presented in Figure 5.1: they can repeat experiments to obtain substantial data without the intervention of the scientists.
    - Provides the operator with enough information to make decisions about the course of the experiment while minimizing the risk to the research.
    - Reduces the dependency of real-time audio/video contact between the scientist and the operator.
    - Presents only the necessary information for the successful run of experiments, but does not burden the operator with data not essential to the conduction of experiments.
  - Enables operators to provide feedback to the research scientists from their observations in the operational environment.
  - Provides methods to conduct real-time communications with the research scientists under pre-specified circumstances.

            - Does not require real-time communications under standard operating conditions.

- **Research Scientists**
    - Minimizes the efforts and time to collect the data obtained in the remote environment.
        - The scientist(s) must know in advance the expected delays to obtain the data
        - The structure of the data must be fully documented to allow for quick data parsing when the data is received
        - Data can be separated into two levels of importance; this fact must be especially considered if the experiment requires a high amount of data
            - Critical data needed to continue experiments after one set of operations must reach the scientist efficiently and in a short period as compared to the iteration period
            - Support data that is not essential for continued operations can be transferred in a slower fashion
        - Provides data management tools to extract the data relevant to the scientist with minimal overhead.
    - Allows scientists to upload information and data to the operator
        - The scientists must be able to contact the operator to ensure correct operations of the facilities aboard the ISS.
        - After reviewing the data and modifying their hypothesis, the scientists must have efficient interfaces to upload new experiments to the ISS.
    - Provides real-time communications under pre-specific circumstances but does not require real-time communications for the scientist to evaluate the progress of the research.
    - Allows scientists to predict results and compare them with the collected data.
        - Ground based facilities should be made readily available to scientists so that they can predict the results of experiments conducted aboard the ISS.
            - These facilities can include simulations, 2D testing environments, and the use of the microgravity testing facilities presented in Chapter 1.
        - The facilities should provide methods to compare predicted results and results from the data obtained aboard the ISS.

Because the interfaces for the operator and the scientist serve a different purpose, there is no need for both interfaces to be the same; rather, the facility design should consider each interface separately to meet their specific needs. Further, a laboratory may utilize several facilities to help the scientist, each with its own interface. (The operator aboard the ISS should only be required to use on interface.)

5.10.4 Step 4 - Review Requirements and Design

The final step before starting a new iteration (or concluding the functional requirement identification process) is to ensure that none of the previous steps creates requirements which drive the system outside of its constraints and/or create conflicts between the principles. The *Principle of Requirements Balance* is utilized in this step.

Principle of Requirements Balance

This principle exists to incorporate two important concepts into the design of a facility beyond those presented in the previous principles: the need to maintain a missions within its constraints; and to ensure that no single requirement is driving the design of a laboratory, but rather there is a balance in the design. Therefore, this principle necessitates that the design requirements for the laboratory be specified before it can be applied.

Developing requirements is an iterative process just like any other system design problem, therefore to meet this principle the scientist is expected to iterate on the requirements of the other principles and then balance them. The other principles should be evaluated first, so as to develop a set of basic requirements for the facility. Using the requirements created from the other principles, this principle calls for the balance of effort into each of the other principles.

Once the first iteration of a design achieves a clear set of requirements, the first step is to determine which are hard requirements and which are soft *decirements*:

- *Hard requirements* are usually set at the start of a project to ensure that the science objectives are met. Hard requirements are essential for the success of a mission. These requirements are mostly quantitative, and their values seldom change after the mission has been defined. When these requirements are qualitative, they clearly define a feature or characteristic that must be present in the mission for its success.

- *Soft 'decirements'* are features desired by the scientists but which are not essential to the success of the mission. These requirements can add value to the mission, but usually due to secondary objectives. Their realization usually occurs after the hard requirements have been set and a scientists sees other possibilities beyond the primary mission objectives. Soft requirements are not usually quantitative, but rather describe another feature desired in the mission. These soft requirements should be treated carefully, as they are the usual source of *requirements creep*.

Once the requirements have been identified as hard and soft, this principle calls to ensure that the majority are hard requirements. If the majority of the requirements are soft, then the scientist must review the design by restarting the design process described in Figure 5.3 on page 225.

Once a clear set of hard requirements drives the design, one can improve on the measure of requirements balance by taking into consideration the effort put into meeting each of the other principles. This effort should be a combination of quantitative facts of the facility (e.g. cost, personnel, design time, etc.) as well as a subjective evaluation of the scientist (e.g. expected research value, expected time to maturation, etc.). The scientist should collect as much data as possible on the proposed designs to obtain reasonable expected effort to satisfy each requirement and assign each requirement a value representative of the effort.

This principle does not call for all the requirements to be perfectly balanced or to necessarily minimize the soft requirements. A project with balanced requirements will exhibit limited variations between the efforts to meet each requirement. This principle calls for the scientist to proactively pursue a realistic justification for each requirement and to ensure that a substantial part of the effort into the development of the facility goes towards clearly defined needs.

5.11 ISS NGO Evaluation Framework

The call for the creation of a Non-Governmental Organization (NGO) to institutionalize research aboard the ISS creates a unique scenario in the evaluation of programs that are to be operated aboard the station. Among the driving principles in the recommendation of the NRC is that:

> "Basic and applied scientific and engineering users should be selected on the basis of their scientific and technical merit, as determined by peer review." [NRC, 1999]

Current procedures at NASA separate the safety, training, and funding/selection processes; rarely do these processes take into account their effects on the other. The NGO scientists who select projects for the space station are challenged with the need to consider all parts of a project in its ability to successfully operate aboard the ISS. In order to concentrate on the scientific and technical merit of a mission, NGO scientists will need to fully understand the safety and operational limitations of the ISS. When reviewing a mission proposal, the technical limitations of the ISS should not immediately be considered something to prevent a program with high scientific value from taking place. The NGO scientists must care about the success of a mission as something that benefits the ISS.

The design principles provide important guidelines to allow and NGO scientist to determine the ability of a mission to successfully mature space technologies aboard the ISS. In arriving to this determination, the NGO scientist will concentrate on the following points:

- Correct utilization of the ISS
- Technology advancement
- Mission probability of success
- Mission scope

The following sections present a framework for the ISS evaluator to use in determining the correct application of the design principles in a mission design, taking into account that the evaluator is likely to only have high-level knowledge of the project.[1]

Principle of Iterative Research

The evaluation of iterative research must first consider the need for the experiment to allow iterations aboard the ISS in order for the technology to mature. In some cases a single experiment may be all that is needed, and in those case the evaluation should not penalize the experiment. In the cases where the ISS reviewer determines iterations would benefit the research, then they must also review the proposed facility to ensure it can conduct successful iterations. The ISS evaluator must be able to determine from the proposal that a facility will allow enough iterations to achieve technology maturation.

The following questions provide the insight necessary to determine if a facility supports the iterative research process:

1. Does the experiment collect the data necessary to support or refute the hypothesis?
2. Do the operational plans of the facility provide sufficient flexibility for efficient iterations?

3a. Can the facility perform multiple experiment runs with repeatability and reliability?

3b. Can the facility be reconfigured while in the ISS in such a way to provide new meaningful results and/or reflect changes in the hypothesis?

A positive answer to the first question is essential since the iterative research process requires the ability to collect sufficient data to validate or refute the hypothesis. The second question requires that the facility operations allow enough time for scientists to examine the data and present meaningful results. Note that the question does not set a timeframe for the data analysis, but the requirement that the time exists. The third question

1. The *Principle of Requirements Balance* is not used by the NGO evaluators. The balance of requirements is directly related to the design of the laboratory; it does not directly affect the effective use of the ISS nor a project's suitability to operate aboard the station. When a design change occurs due to this process, the research scientist should communicate that to the ISS evaluators when addressing the specific principle where the change occurred.

addresses the ability of a laboratory to close at least one of the iterative research loops. Part 3a is the ability to close the first loop of figure Figure 5.1 on page 204; part 3b addresses the possibility to close the second and third loops.

Principle of Enabling a Field of Study

The ISS evaluator should be able to readily identify the space technology to be matured and the selected field of study that the laboratory will cover. It should be clear how research on that field will directly allow maturation of the space technology. The evaluator must also be able to identify the specific areas of study which the laboratory enables to be researched. The areas of study must be complementary to other science already conducted aboard the space station.

Upon identifying the areas, the evaluator should make their own determination on the need to support multiple scientists in order for the laboratory to be successful. The determination of the ISS evaluator should be the same as that proposed by the research scientist, otherwise the proposal should be returned for review.

If multiple scientists are to be supported, then the ISS evaluator must determine the ability of the laboratory to successfully host them. The proposal should include the development of facilities both aboard the ISS and ground-based to support the scientists. Specifically, the ISS evaluator should look for:

- The existence of efficient data paths for the transfer of data to/from the ISS and multiple scientists.
- The ability of scientist to analyze the data in their home facilities.
- Flexible operations plans for scientists to conduct experiments within the limits of the ISS.
- The need to reconfigure hardware and/or software in the ISS based facility and the existence of support mechanism to allow said reconfiguration.

The ISS evaluator is concerned with the success of the mission, but must also ensure that a mission does not create undue burden upon the ISS program by not having the necessary facilities to support multiple scientists. The research scientist who proposes a mission must always provide the means to distribute the data to and from the multiple scientists, while the ISS staff must ensure the data is readily available to the scientist in charge of the laboratory. Similarly, the need to change operational plans and reconfigure the facilities aboard the ISS should be determined by the scientist, and only that scientists should communicate the changes to the ISS staff.

Principle of Optimized Utilization

The ISS reviewer should give priority to the use of the special resources of the ISS over the needs of the project. The research scientists should present their model of the cost/benefit of the resources, allowing the ISS staff to better understand why resources are used (or not). As the principle prescribes, the goal is to optimize the use of resources, not maximize them; therefore, a good proposal will clearly define when the use of a unique ISS resource has a negative effect on the proposal. If a valuable resource is not used at all, but the ISS evaluator determines the project could make use of that resource, the project should be sent back for review by the researcher. In the case where very few or none of the special ISS resources are used by a project, the ISS reviewer may recommend that the project is better suited for operation as an independent satellite.

Principle of Focused Modularity

The evaluation of modularity from the ISS perspective consists solely on what the project provides. It should be expected that the scientist already made the trade-off between what should be modular or not. The ISS staff may identify further modular systems and recommend that the project be re-designed if needed. A modular project should receive higher priority, especially if its modular items can benefit a large number of scientists in the future.

Principle of Remote Operation & Usability

The ISS evaluator will concentrate on the operators' point of view. The mission’s ability to succeed, given the requested data transfer capacities and real-time interaction with the crew, must also be considered, since the ISS evaluator must care about the success of the project as well. Therefore, the ISS evaluator must see the following characteristics in the laboratory:

- The operator has the necessary interfaces to control the facilities aboard the ISS in an efficient and safe manner.
- The operator is presented the information necessary to successfully evaluate experiments.
- The operator can provide feedback to the research scientists from their observations in the operational environment.
- A clear data path has been established for the download and upload of data.
- The need for real-time communications has been clearly defined.

Principle of Incremental Technology Maturation

Using the guidelines for the TRL levels, the ISS staff must evaluate the level of the technology maturation the project provides. Balancing the need for maturation with the other principles (such as a wide field of study), the ISS reviewer should give priority to those projects that provide the most technology maturation. The evaluation must take into account the project's ability to succeed in achieving that level of maturation.

5.12 Summary

The lessons learned in the development of the SPHERES Laboratory for Distributed Satellite Systems (Chapter 4) following the guidelines of the MIT SSL Laboratory Design Philosophy (Chapter 3) for use aboard the International Space Station (Chapter 2) resulted in the development of seven design principles for microgravity laboratories for space technology maturation. These seven principles are:

- *Principle of Iterative Research* - enable scientists to conduct iterative research through repetition of experiments to obtain the necessary data to support or refute a hypothesis; provide the capability for scientists to analyze that data and modify their theories on a flexible schedule, and allow reconfiguration of the facilities to allow for changes in experiments and hypothesis.
- *Principle of Enabling a Field of Study* - a laboratory allows research in a field of study, which consists of multiple research areas. To enable the study

of a field, it is almost always true that multiple scientists will participate in the mission. Therefore, to enable a field of study a laboratory must provide the tools necessary to support multiple scientists: the ability for scientists to create models and analyze data in their home location; simple operational interfaces; and efficient data transfer mechanisms.

- *Principle of Optimized Utilization* - the ISS provides several special resources not available in any other space research environment: crew, power, long-term experimentation, and a benign environment/atmosphere. Successful laboratories must use these resources effectively, with the idea tat the use of the resources adds value to the mission, rather than being a cost.
- *Principle of Focused Modularity* - the facilities of a laboratory almost always include common parts that can be used by a wide range of applications within the field of study of the laboratory. Those parts, the generic equipment, should be identified and designed in a modular fashion so that they can be utilized by as yet unforeseen research.
- *Principle of Remote Operation & Usability* - operations aboard the ISS occur in a remote environment where it is practically impossible for the research scientist to be present in the operational environment. Therefore, it is essential that the operators have the necessary tools and information to conduct effective runs of experiments, while the scientists have efficient access to data obtained from the experiments for analysis. Ultimately, the operator should become a virtual extension of the scientists aboard the ISS.
- *Principle of Incremental Technology Maturation* - the ISS provides a representative space environment for a large number of missions, capable of pushing the TRL of a technology between levels TRL 5 and TRL 7. Utilizing the ISS should achieve this technology levels with the risk and cost increasing incrementally, without steep jumps as the technology level increases. Successful use of the ISS should allow technology maturation with a lower cost and risk than deployment of the mission directly from ground-based tests to the space environment.
- *Principle of Requirements Balance* - the previous principles create a wide range of functional requirements. For a laboratory to succeed, these requirements must be balanced, ensuring that the hard requirements, which directly affect the ability to succeed in the mission, drive the mission efforts. Soft requirements, desired features not directly affecting the success of the mission, should only be implemented when they do not cause the mission to break its constraints and do not contradict any hard requirements.

Two frameworks are presented for the use of these principles: a design framework for research scientists who will develop new space technology laboratories, and an evaluation framework for members of a proposed NGO that will manage research activities aboard the ISS. The design framework provides scientists with guidelines to determine the functional requirements of the laboratory's facilities (both ground-based and aboard the ISS). The evaluation framework presents guidelines for an NGO scientist to determine the effective use of the ISS while taking into account the success of the mission and the achievement of technology maturation.

The next chapter presents the results obtained so far with the SPHERES testbed and uses the design framework presented in this chapter. The chapter evaluates the success of SPHERES in fulfilling the design principles, even if it was designed prior to their development.