Multidisciplinary Spacesuit Modeling and Optimization: Requirement Changes and Recommendations for the Next-Generation Spacesuit Design

by

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and the Engineering Systems Division
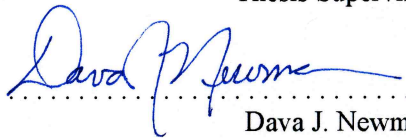in Partial Fulfillment of the Requirements for the Degrees of

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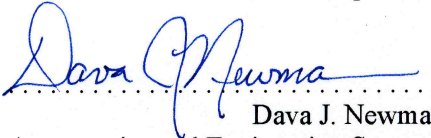and Master of Science in Technology and Policy**
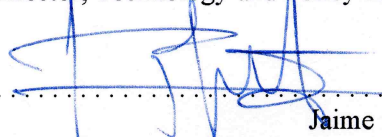
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ABSTRACT

The ability for crewmembers to perform spacewalks is an essential component of human spaceflight. Spacewalks are absolutely crucial for planetary exploration because they enable astronauts to explore their environment, conduct scientific experiments on the planetary surface, construct space-based infrastructure, and perform maintenance activities. The spacesuit is the primary piece of enabling hardware for spacewalks. Given that the United States is embarking on an ambitious mission to return to the Moon and eventually travel to Mars (as mandated by the U.S. Vision for Space Exploration), a new spacesuit will be built. The objective of this thesis is to aid the designers of the next-generation spacesuit through critical analysis of existing spacesuits and quantitative optimization of future spacesuit architectures.

Spacesuits change substantially over their design lifetimes; for example, the American spacesuit, the Extravehicular Mobility Unit (EMU) has undergone over five hundred changes in its twenty-five year operational life. These design changes have been triggered by requirement changes, which in turn were mandated by political and technological changes in the system's environment. This observation points to the fact that the next-generation spacesuit must be designed with the ability to cope with the likelihood of changing requirements after it has been fielded. This goal, as I show in this thesis, can be accomplished in two steps: first, the system designer must have an understanding of what requirement changes are likely to occur; second, quantitative analysis can be used to determine how requirement changes affect the design and subsequently what designs can more readily accommodate change.

This thesis is divided into two parts that map into the two steps. Part I is comprised of a comparative analysis of the EMU and Russian Orlan spacesuits. In order to understand how the spacesuits have changed, I propose a change framework that links changes in a system's environment to changes in its requirements, which in turn necessitate design changes. In Part I, I trace a single environment change, the use of the Shuttle EMU aboard the International Space Station (ISS), to ten requirements changes that resulted in a multitude of EMU design changes. This section finds that the divergence of the

American and Soviet spaceflight programs in the late 1970s, with the Americans concentrating on the Shuttle and the Soviets on station-based flight, is essential to understanding differences in American and Soviet/Russian spacesuit design. Because of the Soviet/Russian space program's experience with long-duration, station-based spaceflight, the Orlan spacesuit was able to more readily adapt to the ISS environment. Whereas Part I looks back at the evolution of spacesuit architectures, Part II looks ahead toward the future of spacesuit design. The second part of the thesis discusses the development of a multidisciplinary spacesuit model and uses an N-Branch Tournament Genetic Algorithm to optimize the spacesuit design vector for mass, mobility, and pre-breathe time. Because the model used for this optimization is multidisciplinary, fundamental tensions in spacesuit design are captured that have not before been explored with existing single-discipline models. Part II finds that the optimal spacesuit garment is different in microgravity than on the planetary surface because the desired mobility is different. Taken as a whole, this thesis offers a comprehensive evaluation of spacesuit design and evolution, and should prove useful in the design of the next-generation spacesuit.

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Nomenclature

ε = radiator emissivity

μ = mean value

σ = Stefan-Boltzmann constant

C = battery capacity

Cp_{Water} = specific heat of water

g = gravity

m_{batt} = battery mass

m_{PMAD} = power management and distribution hardware mass

$\dot{m}_{In}$ = mass flow rate at inlet

$\dot{m}_{rad}$ = mass flow rate through radiator

$\dot{m}_{rad,bypass}$ = mass flow rate around radiator

$\dot{m}_{sub}$ = mass flow rate through sublimator

$\dot{m}_{sub,bypass}$ = mass flow rate around sublimator

n = transmission efficiency

$P_{battery}$ = power generated by battery

P_{CM} = power generated by crewmember

P_{demand} = power needed by suit

$P_{SuitLeak}$ = power lost to environment through suit

q_{rad} = actual heat rejected by radiator

$q_{rad,max}$ = maximum heat rejected by radiator

q_{sub} = actual heat rejected by sublimator

q_{tot} = total heat inputted to spacesuit

ROM_x = range of motion for arms, legs, or torso

SA_{rad} = radiator surface area

T_{amb} = ambient temperature

$T_{rad,Out}$ = temperature at the radiator outlet

$T_{sub,In}$ = temperature at the sublimator inlet

$T_{sub,Out}$ = temperature at the sublimator outlet

$T_{Water,Out}$ = temperature at the thermal subsystem exit

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$T_{Water,In}$ = temperature at the thermal subsystem entrance

$Torque_x$ = joint torque of arms, legs, or torso

V_{batt} = battery volume

$w_{x\,t}$ = weighting factor for the arms or legs

CCC = Contamination Control Cartridge

DCM = Display and Control Module

DCS = Decompression Sickness

EMU = Extravehicular Mobility Unit

EVA = Extravehicular Activity

GA = Genetic Algorithm

GCR = Galactic Cosmic Radiation

HUT = Hard Upper Torso

HX = Heat Exchanger

IVA = Intravehicular Activity

ISS = International Space Station

LCG = Liquid Cooling Garment

LCVG = Liquid Cooling and Ventilation Garment

LiOH = Lithium Hydroxide

Metox = Metal Oxide

MR = Metabolic Rate

PBT = Pre-Breathe Time

PLSS = Portable Life Support System

SAA = South Atlantic Anomaly

SAFER = Simplified Aid for EVA Rescue

SOP = Secondary Oxygen Pack

When working outside the environment, i.e., outside the habitation in the ether, nakedness would be inadvisable. In the ether, in the void, workers would put on special protective clothing resembling a diving suit. Such suits, like the enclosed habitations, would provide oxygen and absorb human exhalation. They would constitute a form of miniature habitation, tightly fitting the inhabitant's body.

K.E. Tsiolkovsky, *Exploration of the Universe with Reaction Machines*, 1926

1 Introduction

It is impossible to know when the need for spacesuits in outer space first became apparent. Fictionalized accounts of space travel from 165 A.D. through the early nineteenth century envisioned other-worldly adventures undertaken in unpressurized sailing vessels, balloons, and even by bird.[1] The first mention of spacesuits in fiction is found in Jules Verne's *From the Earth to the Moon*, where Verne describes spacesuits similar to those developed during Project Apollo.[2] K.E. Tsiolkovsky, the father of cosmonautics, first wrote of spacesuits as an engineering possibility in his 1926 work *Exploration of the Universe with Reaction Machines*. In this prescient work, Tsiolkovsky describes the basic functions of modern spacesuits: pressure production, oxygen delivery, contaminant removal, thermal control, mobility, and protection from the sun's rays.[3] Working independently, German visionary Hermann Oberth described the basic design of a spacesuit in 1929 (Figure 1):[4]

I would make them of thin polished tin and, in principle, similar to the deep-sea divers' equipment already in use today. For hands, I would attach claws. The feet could have hooks with which the diver can hold on to the cables or rings especially attached for this purpose to the projections of the rocket. . . . I would embed the joints in a balloon of canvas lined with a thin layer of rubber on the inside The whole diver's equipment could be tested before the ascent by sticking it into a somewhat large deep-sea diver's suit and using the air hose of the deep-sea equipment to evacuate the space between the two suits.
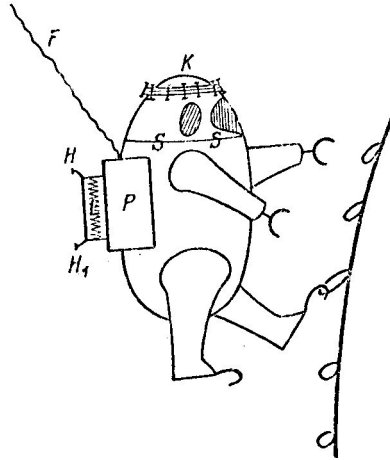
Figure 1. First Known Spacesuit Sketch

Since the early conceptions of spacesuits in the 1920s, spacesuits have become an integral part of humankind's exploration of space. Spacewalks, or Extravehicular Activities (EVAs), have been a reality since Alexi Leonov's 12 minute EVA from the Voskhod spacecraft in March of 1965.[5] During the past forty years, spacesuits have enabled astronauts to walk on the Moon, service satellites, and assemble the International Space Station (ISS). The current goals of the U.S. space program, announced in January of 2004, call for a return to the Moon and eventual human exploration of Mars.[6] In this next era of planetary exploration, spacesuits will play an even more important role, enabling astronauts to interact with their surroundings and helping them to accomplish the scientific and engineering goals of the mission. For this reason, the development of EVA systems was defined as a key enabling technology in the Report of the President's Commission on Implementation of United States Space Exploration Policy.[7] The main purpose of this thesis is to aid the designers of the next-generation spacesuit through rigorous analysis of existing spacesuits and quantitative optimization of future spacesuit architectures.

1.1 Thesis Objectives and Contributions

As the U.S. prepares to design its first new spacesuit in three decades, it is important to understand the spacesuit in the context of EVA systems, learn from previous American and Russian spacesuit designs, and bring to bear quantitative modeling and optimization methods. As stated above, the main purpose of this thesis is to aid in the design of the

next-generation spacesuit by recognizing lessons learned in past spacesuit design and identifying best practices for future designs. The approach this thesis takes toward spacesuit design is multifaceted; policy considerations are deliberated alongside technical requirements, past challenges with present realities, single-mission optimums with multi-mission designs.

The first contribution of this thesis is its broad, integrated perspective. This work builds on the existing spacesuit literature by reflecting upon the spacesuit as one part of a complex, system-of-systems and advocates that the design of the next-generation spacesuit be in full cooperation with the other systems that enable EVA. Additionally, the thesis provides detailed case studies of the change histories of both the American Extra-Vehicular Mobility Unit (EMU) spacesuit and the Russian Orlan spacesuit. The comparative analysis of these two suits is a second contribution to the existing spacesuit literature. A firm understanding of how each system came to be along with the knowledge of how and why each system changed is essential to designing future spacesuits capable of adapting to change.

The final contribution of this thesis is the use of multidisciplinary optimization techniques in spacesuit design. Because the model used for this optimization is multidisciplinary, fundamental tensions in spacesuit design are captured that have not before been explored with existing single-discipline models. Optimal design vectors for multiple operational environments are discussed. Taken as a whole, this thesis offers a comprehensive evaluation of spacesuit design and evolution, from both a qualitative and analytic perspective. The specifics of each chapter are outlined below.

1.2 Thesis Outline

This thesis is divided into two parts. The first part is qualitative in nature and presents a snapshot of spacesuits in time (synchronic view) as well as their evolution in time (diachronic view). Part I consists of Chapter 2, An Integrated Systems Approach to Spacesuit Design, Chapter 3, Understanding Change and Requirements Evolution in the Design of the EMU, and Chapter 4, Comparative Analysis of the U.S. EMU and Russian Orlan Spacesuits.

The objective of Chapter 2 is to understand the spacesuit in the context of EVA and study what the technical community has written about spacesuit design. The traditional

approach to EVA has customarily focused on, and sought to optimize, individual pieces of hardware in isolation of the rest of the system. By having a component focus, the traditional approach has often introduced inefficiencies into the system, generated logistics and supply management problems, and created hardware legacies that are hard to change and upgrade. In its stead, Chapter 2 presents an integrated systems approach for EVA system design that seeks to optimize the overall system, rather than the individual pieces of hardware.

Chapter 3 is a diachronic view of the American EMU spacesuit. It explores one fundamental environmental change, using the Space Shuttle EMU aboard the ISS, and the resulting EMU requirement and design changes. The EMU, like other complex systems, faces considerable uncertainty during its service life. Changes in the technical, political, or economic environment cause changes in requirements, which in turn necessitate design modifications or upgrades. Chapter 3 makes the case that flexibility is a key attribute that needs to be embedded in the design of long-lived, complex systems to enable them to efficiently meet the inevitability of changing requirements after they have been fielded.

Chapter 4, the final chapter in Part I, discusses the design of the Russian Orlan spacesuits and compares their current design to the design of the EMU. This chapter finds that differences in the design of the EMU and Orlan are attributable to the varied foci of the two programs. Because the Soviet/Russian program centered upon long-duration, station-based spaceflight, the Orlan was designed to be maintainable on orbit, at the cost of volume and crew time. On the other hand, the American Shuttle program of short, highly intensive missions mandated that the suits require little on-orbit maintenance and stowage volume as possible, leading to the design of a highly compact and complex spacesuit. Chapter 4 provides a contrast of these two designs and illuminates dimensions not seen by examining a single system.

Whereas Part I represents the qualitative core of the thesis, the analytic substance is found in Part II. Chapter 5, Development of a Multidisciplinary Spacesuit Model, and Chapter 6, Multi-Objective Spacesuit Design Optimization, bring to bear design optimization techniques used for complex, multidisciplinary systems.

Chapter 5 describes the development of a multidisciplinary spacesuit model. Although a partial understanding of the operation and performance of a spacesuit at the subsystem

level can be attained using existing, single-discipline models, the spacesuit is a highly-interdependent, human-sized spacecraft, and an integrated model is needed to aid in the understanding, design, and operation of the spacesuit as a complex engineering system. The model developed in this chapter includes thermal, power, mobility, and oxygen subsystems and captures the interaction effects between these modules.

Chapter 6 uses the spacesuit model to explore the design space with respect to the objective functions of mass, mobility, and pre-breathe time. First, a sensitivity analysis is performed to gauge the effect of the design vector and parameters on the objective functions. Secondly, a single point optimization is performed in a Mars environment using an N-Branch Tournament Genetic algorithm. Finally, this optimization is repeated in the microgravity environment and differences in the optimal design vector are discussed.

Chapter 0 contains conclusions and recommendations for future work.

2 An Integrated Systems Approach to Spacesuit Design

The purpose of this chapter is two-fold: (1) to advocate for an integrated systems approach to EVA systems design, and (2) to give an overview of what the technical community has written about spacesuit design. Section 2.1 introduces the traditional approach to EVA system design and presents an integrated systems approach that seeks to optimize the overall system, rather than the individual pieces of hardware. Section 2.2 is a literature review of spacesuit design and outlines key work in the history of the American and Soviet/Russian space programs.

2.1 Contrasting Traditional and Integrated Approaches to EVA Systems Design

Even though EVA is an activity, it is often thought of in terms of its enabling hardware. The most common public image of a spacewalk is the spacesuit, the current U.S. version of which is called the EMU. The spacesuit is itself a complex engineering system, providing a variety of functions including protection from radiation and particle impacts, a breathable atmosphere, temperature control, and mobility. Table 1 shows a detailed breakdown of the EMU's functions, categorized by the two main parts of the spacesuit, the life support system and the spacesuit garment. Although the spacesuit is the primary piece of hardware used during an EVA, spacewalks would not be possible without a litany of other hardware including an airlock, tools, restraint devices and handholds, cameras, communication devices, and many other smaller pieces of hardware.

Table 1. Principal Functions of the EMU

Primary Life Support System	Spacesuit Garment
primary oxygen supply	atmosphere containment
suit pressure and ventilation	high mobility joints
communications	thermal isolation
breathing gas purification	cooling distribution
temperature control	drinking water
power	waste collection
emergency oxygen supply	radiation protection
biomedical and suit data	micrometeoroid debris protection

In the context of exploration-class EVA, this list grows to include rovers, dust mitigation devices, and scientific equipment (Figure 2). The EVA system is in fact a complex, system-of-systems.

The traditional approach to EVA systems can be characterized as spacesuit-centric. Although the EVA system includes all of the hardware mentioned above, the capability to perform an EVA is sometimes used as a synonym for the spacesuit itself. In other words, the function of performing a spacewalk is treated as interchangeable with the primary piece of hardware that enables it. The main drawback of the traditional approach is the danger of making design decisions at the individual component or subsystem level without the keeping entire system in mind and without anticipating change. This approach can introduce inefficiencies into the system, generate logistics and supply management problems, and create hardware legacies that are difficult to change and upgrade.

The electrical subsystem of the EMU is a good example of the legacy problems resulting from the lack of a systems approach to EVA, and illustrates some of the disadvantages of the traditional (component-focused) approach. The EMU contains five different types of batteries, one each to support the function of the EMU electrical subsystem, helmet lights, camera, Simplified Aid For EVA Rescue (SAFER), and the Pistol Grip Tool. The battery for each of these subsystems was designed and uniquely optimized for that subsystem. The helmet light batteries, for example, were sized according to the duration, illumination, and redundancy requirements of the lights only. When the mandate for a new capability that required power arose, new, individually optimized batteries were designed for it as well. Because each new battery is uniquely

Rover	Informatics	Tools
propulsion	medical monitoring	surface excavation
power	wireless communication	assembly
communications	electronic field notebook	repair
navigation	systems monitoring	mobility aids
scientific instrumentation	voice/video data	navigation
		scientific instruments
Airlock	**Suit**	**Other**
suit don/doff	primary life support system	software
depress/repress	spacesuit garment	procedures
recharge suit consumables		training
decontamination		personnel

Figure 2. Primary Components of the EVA System-of-Systems

designed, the EMU is replete with one-of-a-kind subsystems. Rather than reusing proven designs, each new battery system introduces a set of hardware idiosyncrasies, increases the chance of technology infant mortality, and adds to system mass, volume, and complexity. Battery supply management difficulties intensify with the number of batteries by increasing the number of spares that must be stored on the Shuttle or ISS. Optimizing a system for a single, specific purpose creates a legacy that is often hard to change and upgrade. In contrast to the traditional approach, the integrated systems approach views the capability to perform an extravehicular activity as the goal, then aims to design the overall system to achieve that capability.

From an integrated systems point of view, the ability for crewmembers to safely perform useful work outside the primary spaceship is the end goal. Although the distinction is subtle, the difference is that the integrated systems approach focuses on the end goal (EVA), whereas the traditional approach focuses on the means to that end (spacesuit design). This focus establishes the overall system architecture and guides all decisions made within the system. The integrated systems approach improves system interfaces because of the need to design hardware in concert. Designing with the overall system in view allows engineers to take advantage of system redundancies, increasing reliability and easing logistics problems. To extend the example of the EMU batteries, it is the capability to provide power that designers should consider first, not the battery itself. In addition, rather than focusing solely on the specific power requirements for a certain subsystem, system-wide needs should be anticipated and assessed. Even though

specific power needs are known upfront, engineers would be well-advised to design for a broad range of power requirements, in anticipation of potential changes / increases in the EMU's power requirement in the future. This approach is already used in the design of some portions of the EMU: for example, when NASA upgraded the EMU glove heaters to a new 12V design, engineers designed the electrical harness with extra connectors for 12V devices, easing the implementation of future suit upgrades and adding flexibility to the system.

Continuing to focus on the power subsystem, a second recommendation following from the integrated systems approach is the standardization and adoption of a modular design for the power supply. This recommendation could be implemented by a design similar to the AAA/AA/C standard batteries in everyday use. A discrete number of standardized batteries can be used not only in the EVA system, but also in any system throughout the spacecraft requiring power. In this way, engineers could focus on providing a few reliable products, battery chargers could be common, and fewer batteries would have to be certified. For example, if a particular subsystem required two 'AA' type batteries, the system could be designed with space for three or four batteries. Initially, only two batteries would be used, but more could be added as the power needs increased. Logistically, a small number of each battery type would be adequate to back up the entire system, saving space and mass. Any improvement in battery technology would affect all systems in the same manner, so only one upgrade method would have to be designed. The benefits of commonality extend beyond hardware into procedures, human interfaces, and ground support equipment.

The traditional approach to EVA has customarily focused on, and sought to optimize, individual pieces of hardware in isolation of the rest of the system. By having a component focus, the traditional approach has often introduced inefficiencies into the system, generated logistics and supply management problems, and created hardware legacies that are hard to change and upgrade. The systems approach advocated here can aid the development of an exploration-class EVA system by optimizing the system as a whole and designing for uncertainty. Because we have limited a priori knowledge of what explorers might encounter on the surface of the Moon or Mars, it is necessary to design a system capable of adapting to changes in requirements based upon what we discover and

how the environmental uncertainty unfolds. Flexibility can be added to the system via hardware design (e.g., modularity), software implementation, crewmember training, and procedure development. Although it is not possible to anticipate each uncertainty, a flexible system will meet changing requirements and be capable of incorporating advances in technology with minimal performance and resource (e.g., mass, volume, and cost) penalties.

2.2 Literature Review

The previous section highlighted the importance of spacesuit systems design. The purpose of this section is to give the reader an overview of the literature in the field of spacesuit design, which can be placed into two general groups. The first group focuses on operational spacesuits, such as the EMU or the Soviet/Russian Orlan spacesuit, while the second group documents research on future spacesuit designs and technologies. Although most papers in the area of spacesuit design come from American, European, or Soviet/Russian authors, a few spacesuit-related papers have been published from engineers involved in China's human space program.[8-10]

The existing literature on the EMU is thin and focuses on the early and middle history of the spacesuit. A few publications describe Shuttle[11,12] and ISS EVA requirements and general spacesuit concepts.[13-18] The references that concentrate on the EMU as a whole do so primarily in the context of modifying the system for future programs.[19-24] Other papers document the development or analysis of particular EMU subsystems including carbon dioxide removal,[25,26] thermal protection,[27] power,[28] micrometeoroid protection,[29,30] radiation protection,[31-34] and mobility.[35] Balinskas and Tepper, spacesuit engineers, describe in detail the early development of the EMU.[36] The most current information on the specifications of the EMU is the EMU Data Book, published by Hamilton Sundstrand.[37] A more general book, authored by Harris, outlines the history of pressure suits and spacesuits and gives insight into their operation.[38] Although access to information on the Soviet/Russian space program was limited during the Cold War, the literature published since 1990 is surprisingly rich and equal in detail, if not more detailed, than the EMU literature.

Quite a few English language references have been published documenting the maturation of the Soviet/Russian space program in general and spacesuits in particular.[39]

These papers describe the history of Soviet/Russian spacesuit development, beginning with the design of high altitude pressure suits as in the U.S.[5,40,41] Russia's current Orlan spacesuit has been in operation since 1997 and has undergone four major revisions. Several papers describe the evolution of the Orlan and the challenges of using a spacesuit for long-term, station-based operations.[42-46] In addition, a few papers have been written to describe EVA medical challenges and compare the U.S. and Russian approaches to astronaut safety.[47-49] I.P. Abramov, a member of the original Zvzeda spacesuit development team, wrote a book detailing the technical and political history of Russian spacesuits and published many design details for the first time.[50] For a detailed history of EVA see "Walking to Olympus," which includes a description of each individual US and Soviet/Russian EVAs through 1997 including duration, tasks accomplished, and milestones.[51]

While the literature mentioned thus far has focused on the design and development of operational U.S. and Russian spacesuits, almost half of the overall spacesuit literature focuses on the design of next-generation spacesuits. Scientists and engineers have been anticipating interplanetary travel for decades and have been publishing design concepts for planetary spacesuits since the mid-1960s.[52] These papers range from descriptions of general suit architectures[53-58] to ideas for spacesuit garment design[59-63] and life support system design.[64,65] The most developed designs are described in papers documenting planned operational spacesuits, such as the joint European-Russian EVA Suit 2000.[66-68] Quite a few papers discuss EVA requirements for planetary missions.[69-78] Some researchers work on the design of an advanced EVA subsystem such as bioinstrumentation,[79] thermal control,[80-82] cooling garment,[83] radiator,[84] electronic cuff checklist,[85] and materials.[86] The remaining papers discuss testing of EVA systems in Mars analog sites such as the Arctic circle.[87-89]

3 Understanding Change and Requirements Evolution in the Design of the EMU

Whereas Chapter 2 discussed an approach to designing the EVA system-of-systems, this chapter focuses on the design evolution of a single spacesuit, the EMU. This chapter explores one fundamental environmental change, the decision to use the Space Shuttle EMU aboard the ISS, and the resulting EMU requirement and design changes. The EMU, like most complex engineering systems, faces considerable uncertainty during its service life. Changes in the technical, political, and economic environments may cause changes in requirements, which in turn necessitate design changes.

Section 3.1, Introduction to Requirements Change, challenges the common presumption that requirements change should be avoided and proposes a new attitude toward change. Rather than artificially freezing requirements, system designers are beginning to acknowledge that change is inevitable in the design of any long lifetime system and design their systems to be able to adapt to this change. Section 3.2, History and Background of the EMU, examines the history of the EMU, describes its major components and functions, and discusses the baseline environment in which the spacesuit was initially designed to operate. Fundamentally, the EMU was conceived as a limited-capability spacesuit to be used in emergency situations. However, immediately after it was fielded, NASA began to make changes to the EMU for a variety of reasons. Section 3.3, EMU Environment Change, explores the implications of the decision to modify the

Shuttle EMU for use aboard the ISS, and the resulting requirements and design changes. The conclusion summarizes important findings: first, given the number of requirement and design changes that occurred in the EMU, the next generation spacesuit, which will likely be fielded for a decade or two, will have to be designed with the ability to cope with the inevitability of changing requirements after it has been fielded; second, more generally, flexibility will become an increasingly critical property that needs to be embedded in the design of complex engineering systems, and thus allow them to easily cope with uncertainty and changes in their environment and requirements. This chapter is a comprehensive review of the requirement and design changes of the EMU and aims to benefit the designers of the next generation spacesuit. A thorough understanding of the current spacesuit and the changes it has undergone could aid in achieving an even better design for future spacesuits, emulating the EMU in its strengths and learning from its weaknesses.

3.1 Introduction to Requirements Change

Traditional systems engineering wisdom, developed and supported by decades of experience in designing and operating complex engineering systems, holds that requirements should be frozen as early as possible during the system's development phase, one rationale being that requirement changes or instabilities have a negative impact on both system life-cycle cost and development schedule. Furthermore, it is believed that the later in the development phase a requirement change is requested, the higher the cost penalty is to implement this change, as shown in Figure 3 (adapted from Ref. 90).

In practice however, freezing requirements, whether during the development phases or after fielding a complex engineering system, is unrealistic. The IEEE Standard 1233 recognizes this fact and states that:[91]

> Although it is desirable to freeze a set of requirements permanently, it is rarely possible. Requirements that are likely to evolve should be identified and communicated to both the customers and the technical community. A core subset of requirements may be frozen early. The impact of proposed new requirements must be evaluated to ensure that the initial intent of the requirements baseline is maintained.
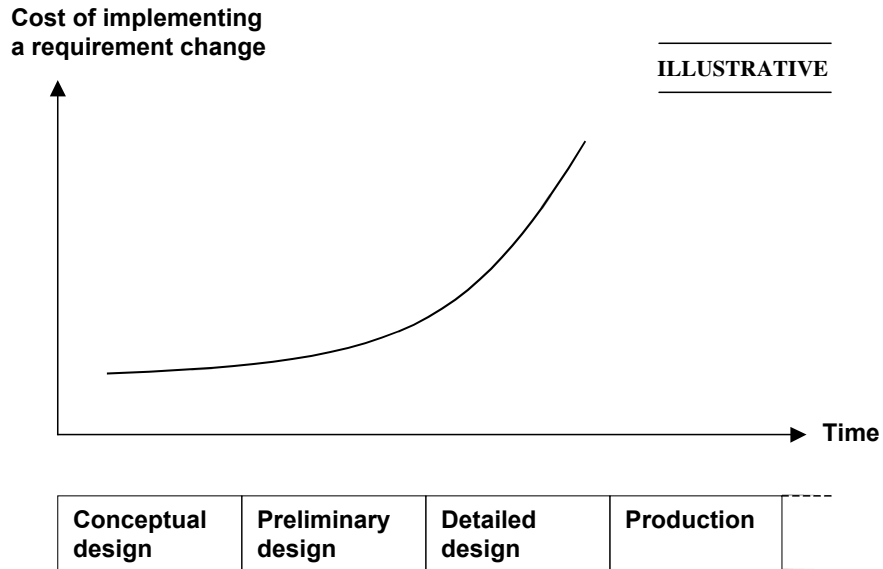
Figure 3. Rationale for an Early Freeze of System Requirements

In short, requirement changes in the traditional systems engineering approach are undesirable, but are cautiously tolerated when they are inevitable.

The last two decades have witnessed a trend in increasing system design lifetime. For example, communication satellites have seen their design lifetime increase from seven to fifteen years over this time period.[92] This trend – also observed in the design of other aerospace and numerous defense systems – is the result on the one hand of budgetary constraints and financial pressure to maximize the return from such high-value assets, and on the other hand of increased reliability and technical advances that allow complex engineering systems to remain operational for such long periods of time. Why is this observation a complicating factor to the traditional attitude towards requirement changes?

Engineering systems often operate in complex and rapidly evolving environments. As their design lifetime increases, it becomes increasingly probable that the initial environment from which the original system requirements were derived changes during the system's operational life. This environment change, whether political, economic, physical or technological, will in turn cause requirement changes as a result of new customer or user needs, or new identified opportunities. However, the same budgetary constraints mentioned previously often mandate that the fielded system be modified or upgraded to satisfy the new requirements and provide enhanced capabilities, instead of developing a new, clean-sheet design. In this context, it is unrealistic to attempt to freeze

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requirements as early as possible, and the traditional attitude of the systems engineering community towards *change* needs to be revisited: requirement changes will occur, especially in long-lived systems, and instead of resisting them or passively accepting them, it is preferable that system engineers "design for change," or embed flexibility in the design of complex engineering systems. Design flexibility is the property of a system that allows it to respond to changes in its initial objectives and requirements that occur after the system has been fielded, in a timely and cost-effective way.[93]

Increasingly, system designers recognize that their systems operate in a dynamic environment, and that the systems are likely to change. Managers are beginning to experiment with how to value uncertainty.[94] Several new tools have been developed, and old tools modified, to attempt to predict how changes in one part of an operating system will affect the whole.[95-97] Rather than passively reacting to change, some system architects are beginning to develop design methodologies that could make their systems resilient to change.[98,99] This chapter argues that requirements change is an inevitability in the life of any complex system and that embedding flexibility in the design enables it to react more efficiently to change.

3.2 History and Background of the EMU

The EMU, the U.S. spacesuit, is a miniature spacecraft in the sense that it provides all of the functions necessary to sustain life in a human-sized, mobile form. This section examines the history of the EMU, describes its major components and functions, and discusses the environment in which the EMU has operated in the Space Shuttle era. This constitutes the *baseline environment* of the spacesuit against which we contrast the usage of the EMU aboard the ISS, as well as the requirement and design changes that ensued from this environment change.

3.2.1 EMU History: a Hesitant Commitment to an Invaluable System

EVA has been a reality for the U.S. since the Gemini Program in 1965. Clean-sheet spacesuit designs were undertaken for the Gemini, Apollo, and Shuttle programs whereas modifications of existing designs were used for Skylab and ISS.[24] Throughout the Apollo and Skylab programs, NASA gained extensive experience with EVA and spacesuit design. The capability for humans to work outside the spacecraft proved invaluable time and again: for example, Skylab astronauts performed twelve contingency EVAs to fix

unanticipated problems, repeatedly saving the space station from abandonment.[13] However, despite the advantages of EVA capability, early Shuttle designs did not include the means to perform EVA. This function was added later, and then only to provide the ability to perform limited contingency operations.[38] Because of the delayed decision to develop a Shuttle spacesuit, EMU development lagged behind the Shuttle by approximately four years. The vast majority of the overall Shuttle program was conducted without a development phase, a reality especially true for the EMU. Initial hardware designs were tested to flight standards and certified in parallel with early Shuttle flights. The merging of the final testing and operational phases resulted in approximately 4,000 person-hours of EMU processing between flights, compared to less than 1,000 today.[21] As America's ability to perform complex operations in space increased, so too did the EVA time required to achieve those objectives. Table 2 shows the total person-hours of EVA time logged by American astronauts for each major human spaceflight program. The EMU has performed more than 75 percent, by duration, of all American EVAs. That the EMU was initially designed as a limited capability suit to satisfy minimal mobility and operational requirements is astounding in light of the fact that it has been subsequently used to repair satellites, construct a massive space structure, and maintain the ISS.

Table 2. Summary of EVA Duration by Program [as of 13 May 2006]

Program	Total EVA Duration	Suit Used
Gemini	12:40[100]	G-4C
Apollo	165:17[51]	A7L/A7LB
Skylab	82:52[51]	A7LB
Shuttle	993:35[51,101-134]	EMU
ISS	231:54[134-144]	EMU

3.2.2 Functionality and Configuration

In order to understand how changes propagated through the EMU design as a result of environmental changes, it is important to first understand how the system operates. This section provides an overview of the functionality of the EMU as well as a brief description of its major components. The EMU performs a variety of functions, including providing a breathable atmosphere, mobility, temperature control, and protection from

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radiation and particle impacts. The two main components of the EMU are the Primary Life Support System (PLSS), the spacesuit backpack, and the pressure garment. A detailed schematic of EMU components is shown in Figure 4 (adapted from Ref. 37).

Proceeding from the top to the bottom of the EMU, the helmet assembly is comprised of a clear, polycarbonate bubble and visors to protect from sun and impact. The helmet connects to the Hard Upper Torso (HUT), a fiberglass shell that is the main structural support for other elements of the suit including the PLSS. The Display and Control Module (DCM) is mounted to the front of the HUT and contains external fluids and electrical connections, thermal, pressure, and communication controls, and a display of suit parameters. The arm assembly is attached at both shoulders of the HUT and contains two mobility bearings, one each at the shoulder and wrist. The lower torso assembly is the bottom half of the EMU and consists of the waist, brief, leg, and boot assemblies. The PLSS has primary oxygen tanks and an emergency secondary oxygen pack. The Contaminant Control Cartridge (CCC) removes CO_2, odors, particulates, and other contaminants from the oxygen. The battery supplies power for most EMU functions and the sublimator, fan/pump/separator, and water tank work together to remove excess heat from the system. When the EMU is inside the Shuttle or ISS airlock, it connects to the vehicle via an umbilical, which attaches to the front of the DCM.

Comfort and mobility within the EMU are provided for through several pieces of hardware. Before donning the spacesuit, astronauts put on the Liquid Cooling and Ventilation Garment (LCVG), a tight-fitting, elastic body suit with flexible tubing woven into the fabric. Whenever the crewmember is wearing the EMU, cold water circulates through the tubing, removing excess body heat. The cooling garment also contains larger tubes, which transport oxygen back to the PLSS for scrubbing. As described above, mobility is provided through bearings located at the shoulder, upper arm, wrist, and waist. Finally, five different layers of material provide thermal, radiation, and puncture protection. The innermost layer is the pressure garment bladder, which contains the suit atmosphere. The pressure garment cover is outside of the bladder and works to keep the bladder in place. The final three layers are collectively called the Thermal Micrometeoroid Garment, which consists of a rip-resistant material, thermal layers, and
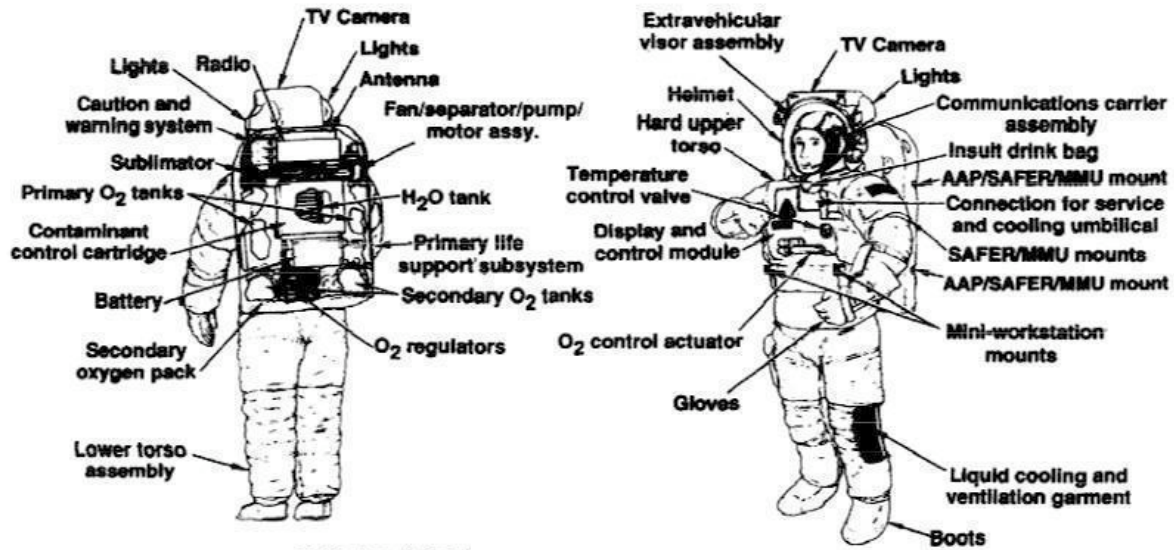
Figure 4. Extravehicular Mobility Unit Components

an outermost layer that resists contamination, puncture, and reflects radiation. The number of thermal layers varies widely and is the thickest in the HUT and PLSS and thinnest in the fingers, where the need for mobility is critical.

3.2.3 Definition of Environment

One goal of this chapter is to demonstrate how environmental changes trigger requirement changes, which in turn necessitate design changes. The meaning of *environment* is not restricted to the narrow sense of physical environment, such the temperature and pressure surrounding a system. Instead, it is expanded it to include political, economic, and technological conditions as well (Figure 5). As an illustration, the environment of the maple tree in a yard includes physical factors such as the soil conditions, rain patterns, and sunlight, political factors such as a rule against the tree shadowing the neighboring yard, and economic factors such as whether or not the owner received a subsidy to plant the tree. Similarly with the EMU, changes in its baseline design were caused by changes in its environment: physical, political, technological and economic environments or conditions as will be discussed in detail shortly.

3.2.4 Baseline Environment: Space Shuttle Mode

As noted above, the EMU was originally conceived as a limited-capability spacesuit to be used exclusively in emergency situations. This contingency-only environment quickly gave way to routine use of the EMU for satellite servicing, an operational mode termed

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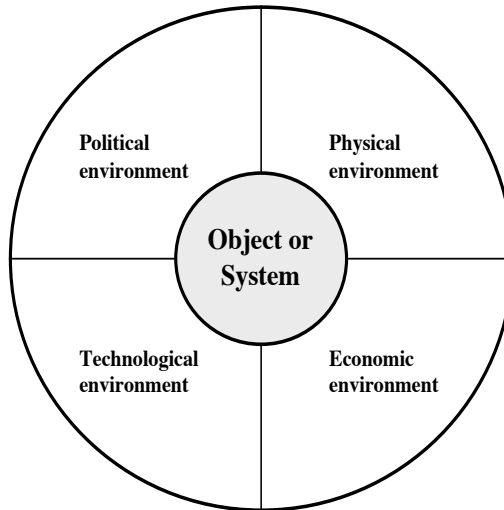
Figure 5. Different environments of an object or system

the Shuttle environment. This section outlines general reasons for EMU design changes and explores one specific change that occurred as a result of shifting the EMU to the Shuttle mode.

Immediately after the EMU was fielded, NASA began to make changes to it for one of four reasons:

1. Hardware Failure – if a part did not function properly or was found to be out of specification, it was flagged and changed.
2. Obsolescence – when a manufacturer ceased making a particular part.
3. Hardware Upgrade – when advances in technology lead to improvement in suit capability.
4. Goal Change – a programmatic decision to use the EMU in a way in which it was not originally intended.

Broadly speaking, the first three reasons for change occur because of an altering physical or technological environment, whereas the fourth is a consequence of the shifting political and economic environment. A number of the changes to the EMU are a consequence of the first and second reasons simply because they are not optional; when a part fails or a key material is no longer available, it must be fixed or replaced. The third reason is infrequent because, although engineers have an infinite supply of ideas for

upgrades to the EMU, there are rarely enough resources to implement them. Changes in a program's goals, the fourth reason for change, are often imposed from outside of the technical community; with the EMU these changes often come from Congress or the Executive Branch. One important goal change that came soon after the EMU was designed followed from the decision to use the Shuttle to release and service satellites. The primary purpose of the EMU for most of the 1980s was to assist in this process.

One design change that came as a result of the EMU transitioning from contingency-only to satellite servicing is an increase in its operating pressure. The EMU was initially designed for a 28.3 kPa (4.1 psia) operating pressure primarily because this pressure was close to NASA's operational experience with the Apollo suits, which operated at 26.9 kPa (3.9 psia). Operating at a low pressure is advantageous in that it increases mobility by decreasing the effort for an astronaut to move inside the suit because the astronaut does less work to compress the gas-filled suit. However, it also puts the astronaut at an increased risk of Decompression Sickness (DCS) and extends the time an astronaut must pre-breathe pure oxygen to avoid DCS. Humans living at the Earth's surface breathe an atmosphere comprised of about 79 percent nitrogen and 21 percent oxygen at 101.4 kPa (14.7 psia). As we breathe the nitrogen in and out, it becomes saturated in our blood and is at risk of coming out of solution at reduced pressures, similar to the effect of carbon dioxide bubbles being released when a soda can is opened. Nitrogen gas bubbles in our system can cause a host of medical problems including "the bends," mental impairment, and death. In order to avoid DCS, astronauts must either experience slow decompression over a period of days or pre-breathe pure oxygen for a period of hours prior to EVA. NASA realized in the early 1980s that the pre-breathe time necessary for a 28.3 kPa (4.1 psia) suit was unacceptably long and the Shuttle could not reduce its cabin pressure low enough for the crew to experience slow decompression. Because EVAs were becoming more commonplace, reducing the overhead of performing a spacewalk was a priority. Physiological experts eventually concluded that if the suit pressure were raised to 29.6 kPa (4.3 psia), a combination of reducing the Shuttle pressure and pure oxygen pre-breathe would be acceptable. This change required changes in the pressure regulator bands, changes in the crack pressures of the relief valves, and a recertification of the EMU.

Substantial requirements changes were again levied upon the EMU first in anticipation of using it to support Space Station Freedom and later as a result of the need to use the EMU aboard the ISS. The basic capabilities of the EMU, however, to support life in space and enable useful work, remained unaffected, and a number of EMU components such as the cooling garment, helmet, external visors, DCM housing, and the Communications Carrier Assembly headset have remained unaltered. The next section describes the changes that occurred as a result of using the EMU for the construction and operation of the ISS.

3.3 EMU Environment Change

This section examines how environmental changes for the EMU caused requirements changes, which lead to EMU design changes. The section begins with the political decision to use the Shuttle EMU aboard the ISS and explores the resulting requirements and design changes. Next, the change in the physical environment surrounding the EMU and changes in the technical environment are examined and the resulting requirements and design iterations are traced. Table 3 summarizes these changes.

3.3.1 Scrub '89

In 1989, the spaceflight community experienced a major setback and was forced to eliminate or considerably cutback many programs when funding was significantly reduced; Congress that year proposed to cut NASA's budget by more than $1 billion (about 8%), including reducing space station funding by $395 million. Plans for an international space station were substantially downsized and, more importantly, the plan to build a new, advanced space suit to service the space station and serve as a test bed for planetary exploration technologies was eliminated. This event became known in the space community as "Scrub '89" and was the watershed event that mandated a change in the EMU's goals from Shuttle spacesuit to space station suit. The decision NOT to build a space station-specific spacesuit, and instead to modify the EMU marked a shift in the *modus operandi* of that system. Because on-orbit time was limited during the Space Shuttle era, the EMU was designed to operate virtually maintenance-free during the mission. Now that the EMU was to serve aboard the ISS, two requirements changes occurred that are further discussed in the following: more on-orbit time between hardware processing, and extended EMU life.[22]

Table 3. Summary of Shuttle EMU Changes for ISS

Environment Change - Use Shuttle EMU Aboard ISS

Requirement Change	Design or Procedure Change
Make EMU sizable on-orbit	Adjustable cam sizing in softgoods
	Sizing rings in arms and legs
	Hard Upper Torso replaceable on-orbit
	Hard Upper Torso redesigned
Increased EMU life	Recertification of EMU components
	Change in static seal material
	Noise muffler redesign
	Flow filter redesign
	Coolant water bladder material change

Environment Change - Physical Environment of ISS

Requirement Change	Design or Procedure Change
Minimum metabolic rate lowered	Cooling garment bypass designed
	Heated gloves redesigned
Lower probability of penetration	Track orbital debris
	Define allowable penetrations
Different radiation exposure	Carefully plan all EVAs
Risk of propellant exposure	1-hr bake-out procedure
	Lengthen umbilical

Environment Change - Technical Environment Advances

Requirement Change	Design or Procedure Change
Advance in suit joint technology	Joint patterning and materials changed
	Bearing design and materials changed
Need for delicate assembly tasks	Glove design and materials changed
Increased EMU life	Battery redesign
	Carbon dioxide removal technology upgrade
	Carbon dioxide sensor upgraded
Secondary system in case of crewmember separation	Design SAFER rescue system

3.3.2 On-Orbit Sizing

In the Apollo era, spacesuits were manufactured for individual crewmembers. This philosophy shifted slightly during the Shuttle era due to a rapid increase in the membership of the astronaut corps and in the number of EVAs. The major components of the suit – HUT, lower torso assembly, arm assembly, LCVG – came in discrete sizes that were uniquely adjusted to fit an individual crewmember using cloth strips sewn into the

suit by technicians on the ground. Each Shuttle mission flew three EMUs, two primary and one backup, and the two EVA astronauts were often chosen to be of similar physical size so that they could fit in the same backup suit. In the ISS era, EMUs are on-orbit for a period of months and need to be reconfigurable to fit a range of body sizes. The change in requirement from "one suit-one person" to "one suit-many people" caused several design changes. Changes to the spacesuit garment included added sizing cams to the lower arms, Waist Brief Assembly, knees, and legs and sizing rings at the thigh and leg. In order to further aid on-orbit sizing and servicing, NASA also changed the design of the HUT and DCM to make them replaceable on-orbit.[23] In theory, a crewmember can disassemble the EMU and remove the DCM or HUT to make repairs or change size, although this has not been done to date.

Both logistics issues and safety concerns motivated the redesign of the HUT. The original HUT design, known as the pivoted HUT, was available in five sizes from small to extra large and had four different sizes of Body Seal Closure, the connection between the upper and lower torso. The term "pivoted HUT" comes from the type of shoulder joint in the unit, which was mobile, but only single-fault tolerant and the point of lowest safety in the entire EMU. The new design, known as the planar HUT, has a smaller number of sizes, but a lower risk of failure.

3.3.3 Increased Life

The other requirement changes that occurred as a result of the decision to use the Shuttle EMU aboard the ISS were the following: 1) extension of EMU life, 2) increase in the number of EVAs a particular EMU could perform, 3) increase in the shelf life of the EMU, and 4) increase in the number of days between ground servicing. Given the significantly extended stay of astronauts aboard the ISS compared to the duration of flight of the Space Shuttle (several months for the ISS compared with a couple of weeks for the Shuttle), the EMU was required, following the decision to use it aboard the ISS, to be capable of performing twenty-five EVAs in 180 days instead of the original requirement of three EVAs in ten days. In addition, the EMU was required to be capable of undergoing 180 days in space without being serviced. Rather than undertake an extensive redesign of the EMU in order to meet these new requirements, NASA engineers decided to upgrade the shortest life items so that they would last at least 180

days.[38] For example, some of the changes included replacing seal materials, a redesign of the PLSS vent loop noise muffler, changes in the flow filters, and a change in the coolant water bladder material.

3.3.4 Physical Environment of ISS

The ISS operates in a different physical environment than the Space Shuttle. Changes to the thermal profile, radiation environment, micrometeoroid hazard, and contaminant exposure risks all drove physical and operational changes to the EMU.

The EMU is designed to accommodate four specified levels of metabolic loading: minimum rate, maximum rate, average rate, and a short-duration spike value. Because of anticipated rest periods during space station construction, the requirement for minimum metabolic rate changed from 117 W (400 BTU/hr) to 103 W (350 BTU/hr).[37,38,145] Space Shuttle astronauts have two countermeasures to mitigate periods of low thermal loading during EVA. First, mission planners can schedule rest periods while the astronauts are in the sunlight. Second, astronauts can rest within the Shuttle payload bay, thereby increasing the thermal loading on the EMU due to the high emissivity of the materials in the payload bay and the increased thermal radiation from the Shuttle itself.[36] Because neither of these countermeasures is available to ISS crew, the design of the EMU was modified to accommodate the requirement change.

Lowering the minimum metabolic rate requirement resulted in three design changes: the development of a cooling garment bypass, the design of glove heaters, and the addition of thermal mittens to the suite of EMU support equipment. The crewmember is able to control the water flow rate through their cooling garment via a temperature control valve, located on the front of the DCM. In the original EMU design, the lowest setting of the temperature control valve still allowed a minimal amount of water flow through the cooling garment. The cooling garment bypass modifies the function of the temperature control valve such that when a crewmember is cold, they are able to block flow completely from the cooling garment, while water continues to run to the PLSS and to the DCM to cool the electronics. In this setting, the astronaut is warmed entirely through body heat. This new setting is necessary to keep the crewmembers warm during periods of rest on ISS EVAs.

EMU glove design also changed to incorporate both active and passive thermal control. The design and implementation of glove heaters was due in part to the anticipated needs of space station EVAs, but primarily driven by cold temperatures experienced during training prior to the first Hubble Space Telescope servicing and repair mission, STS-61 in 1993. During a thermal vacuum test chamber run, astronaut Story Musgrave developed a mild case of frostbite in the fingers of his right hand.[146] In response to this event, NASA developed the first generation glove heater, using 3V resistance heaters incorporated into the glove thermal micrometeoroid garment on the back of each fingernail.

Penetration and subsequent loss of pressure by micrometeoroids and orbital debris is a longstanding vehicle and spacesuit concern. Although the baseline requirement of a probability of no penetration of 0.995 over ten years has not changed, the amount of orbital debris increased significantly between early Shuttle flights and ISS operation. By 1994, the chance of penetration for particles larger than 0.1 cm diameter was greater for orbital debris than for micrometeoroids and the overall probability of no penetration continues to decrease. Although no design changes were adopted to mitigate this problem, two procedural and organizational changes occurred. First, NASA introduced the concept of allowable penetrations, under the assumption that the EMU's emergency oxygen supply would be able to keep up with small leaks. Second, NASA tracks orbital debris and plans EVAs accordingly.[36]

The ISS inclined orbit and mission duration changes the radiation environment crewmembers experience. During a mission, astronauts are exposed to three principal types of space radiation: Van Allen Belt radiation, Galactic Cosmic Radiation, and radiation from solar proton events. Although the orbit of the ISS does have an effect on the radiation levels experienced by the astronauts, the overriding factor in radiation dosage is the lengthened duration of the crew outside the Earth's protective atmosphere. Analysis of the new environment concluded that, with proper monitoring and planning, NASA could maintain its current standards on radiation exposure without additional EVA-specific shielding.[147]

The ISS has small jets that provide it with altitude control. The propellants used by the jets pose an exposure risk to EVA astronauts. Although the Shuttle has similar jets, they

are located around the Space Shuttle Main Engines, in an area inaccessible to EVA astronauts, whereas on the space station it is possible for EVA crewmembers to traverse into hazardous zones around the jets. Because of this physical environment change, engineers modified EMU supporting hardware. In the event an EVA crewmember becomes contaminated with one of the propellants, they must wait outside the airlock for about an hour, in a "bake out" period, to allow the propellant to evaporate. The umbilical that attaches to the airlock and refills the EMU's consumables was lengthened to allow the astronaut to use ISS consumables during this period.

3.3.5   Technical Environment Advances

Advances in technology enable hardware upgrades not necessarily because the old part ceased to perform its function, but because newer parts are available to perform the function better. Because these kinds of changes are not mandatory, they are sometimes rejected due to lack of resources. As a result, EMU engineers often get to upgrade antiquated technology only when it happens to be in line with a funded program, such as the ISS. This section examines hardware upgrades made to the EMU as a result of the decision to use it aboard the ISS. These upgrades include increased mobility joints; an upgraded glove design; upgrades to the EMU batteries, CCC, and a new carbon dioxide (CO_2) sensor; and the design of the SAFER.

Advances in materials and joint design increased the mobility of the EMU. Working inside of a spacesuit is akin to working inside a balloon. Each time you move an arm or leg, you must do work to compress the gas inside the balloon as it shrinks in volume while bending. The amount of torque necessary to move increases as the pressure inside the balloon rises. The EMU pressure garment has two mechanisms that facilitate spacesuit movement. Joints are formed by special patterning of the spacesuit fabric to minimize the change in volume. At the knee, for example, the patterning allows the fabric to expand across the kneecap and collapse behind the knee, reducing the amount of gas that must be compressed. Bearings allow isovolumetric rotation of joints, and are manufactured by placing small spheres in a track around the circumference of a joint. Bearing torque is directly related to the contact area between the spheres and the tracks. Engineers decreased joint torque by improving in the way that joints are patterned and using stronger materials. Using a spacer between each sphere decreased bearing torque,

cutting in half the number of spheres in the tracks and the surface contact area between the spheres and races.

There is a basic tradeoff in glove design between durability and tactility. For most of the shuttle years, a lower tactility glove was sufficient to perform EVA tasks, and desirable because of its increased life. However, transitioning from Shuttle operations to delicate ISS assembly procedures caused a change in glove design. The EMU gloves are currently on their sixth iteration and are distinguished by their series number. Series 1000 and 3000 were used throughout the 1980s and were custom manufactured for individual crewmembers. The 3000 series gloves offered individual finger adjustment capability, but patterning caused excessive hand fatigue over an 8-hour EVA. 4000 series gloves were very robust, had a very long life, and were used until the mid-1990s. To achieve this durability, engineers traded off tactility and feedback, causing higher hand fatigue. Around 1995, NASA introduced the 6000 series glove, which incorporates a lower-torque wrist bearing and increases tactility and feedback. Although this glove helps the crewmember to grasp small objects, its life is shorter compared to the 4000 series.

The design changes for PLSS batteries, CCC, and CO_2 sensor were motivated by the increased design life of the EMU. By adding more plates into the cells of the silver-zinc batteries, the wet life was increased from 170 to 425 days. The old style of the CCC used charcoal and lithium hydroxide to remove trace contaminants and carbon dioxide. One CCC could only be used for one EVA before needing ground servicing. The new design of CCC uses metal-oxide to absorb CO_2 and is regenerable on-orbit a minimum of 55 times. The EMU CO_2 sensor was upgraded from an electrochemical sensor to an infrared transducer for safety and maintenance reasons. The electrochemical sensor had a delayed response time to the level of CO_2 in the spacesuit atmosphere and also required recalibration before each Shuttle flight. The infrared transducer has an almost immediate response time and requires little maintenance.

Flight rules dictate that EVA crewmembers must be tethered to the host vehicle at all times. In the event of a separation, the Space Shuttle is able to reposition itself and rendezvous with the astronaut. The ISS is incapable of such a maneuver. In order to add a second layer of safety in the event of crewmember separation, engineers designed the SAFER system.[16] SAFER is a cold-gas propulsion system that provides adequate

propellant for a crewmember to maneuver back to the ISS via a hand controller. The SAFER system fits below the PLSS and does not interfere with suit mobility.

This chapter examined the baseline environment in which the spacesuit was initially designed to operate during the early Space Shuttle era, and then contrasted it with the ISS environment. The chapter demonstrates how changes in the physical, technical, and political environment of the spacesuit resulted in requirement changes, which in turn necessitated design changes to the EMU. The final section traced ten requirement changes that resulted from the decision to use the Shuttle spacesuit aboard the ISS, and discussed the twenty-four design changes that ensued. The next chapter is a comparative analysis of the Russian Orlan and American EMU spacesuits and identifies the underlying environmental causes behind differences in the two suits.

4 Comparative Analysis of the U.S. EMU and Russian Orlan Spacesuits

Chapters 2 and 3 focused on how spacesuits fit into the broader category of EVA systems and how the current American spacesuit has evolved to meet changing requirements. However, spacesuit development is not unique to the U.S. The world's first EVA was performed by Alexi Leonov on March 18, 1965 in a spacesuit designed in the U.S.S.R.[5] When designing the next-generation spacesuit, it will be important to carefully examine the past experience of both the U.S. and the U.S.S.R./Russia in order to understand what requirements changes are likely to occur in the future. Figure 6 shows the cumulative EVA time (in person-hours) for both the U.S. and the U.S.S.R./Russia from the first EVA in the mid-sixties through April 2006. Whereas the U.S. EVA program is characterized by times of intense activity punctuated by long periods of inactivity, the Soviet/Russian EVA program from the mid-1980s reflects a more continuous pace. This difference is reflected in the design of the spacesuits themselves. Soviet/Russian spacesuit engineers favor evolving their systems over time, developing a relatively large number of design iterations, while the U.S. tends to have a smaller number of substantially different spacesuits.

This chapter explores the design differences of the U.S. and Soviet/Russian spacesuits and identifies the underlying causes behind these differences and their implications for the evolvability of the design. The divergence of the American and Soviet human
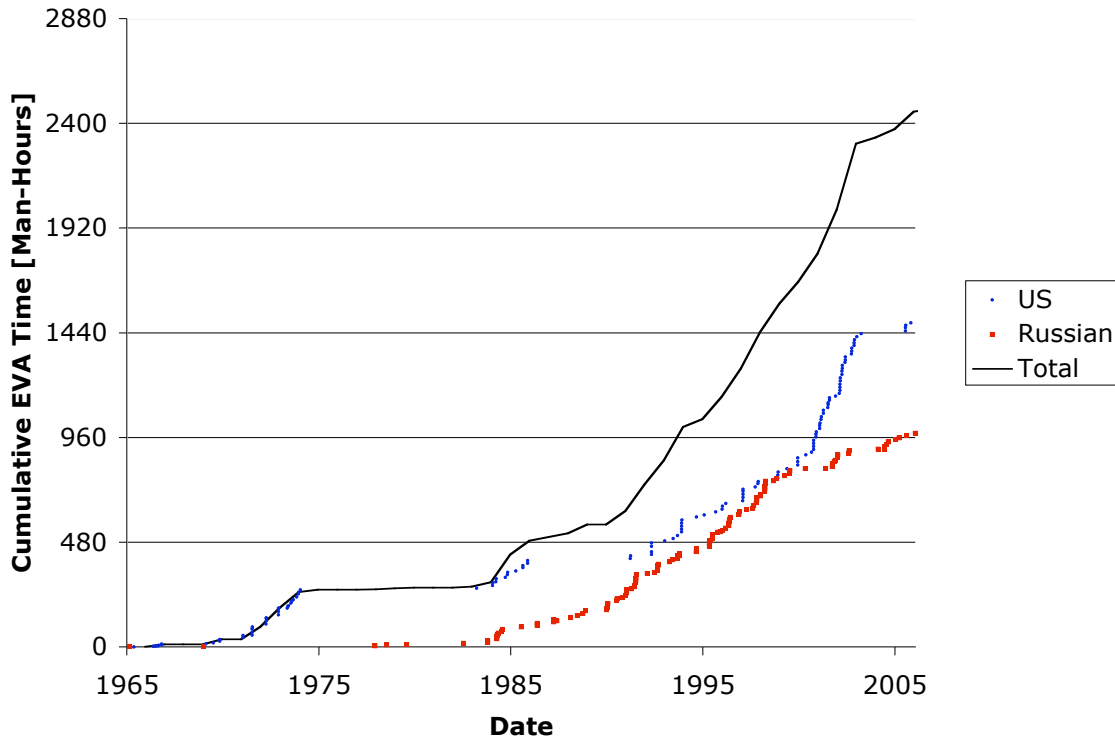
Figure 6. US and Russian Cumulative EVA Time [as of 13 May 2006]

spaceflight programs in the late 1970s, with the Americans concentrating on the Shuttle and the Soviets on station-based flight, is one key to understanding differences in American and Soviet/Russian spacesuit design. The purpose of this chapter is to apply the framework introduced in Chapter 3 to the U.S. and Soviet/Russian spacesuit designs. However, rather than examining design differences across time (as was the case with the EMU), this chapter examines design differences across space. The chapter first gives a brief summary of Soviet/Russian spacesuit design, then explores the design differences of the American EMU and Russian Orlan-M spacesuits in detail, and concludes with an analysis of the differences in the U.S. and Soviet/Russian spacesuit environments.

4.1 Brief History of Soviet/Russian Spacesuit Design

Despite being designed in near-complete isolation from each other, early Soviet and American spacesuit development is remarkable in its similarity. As in the U.S., early Soviet spacesuits were derived from high-altitude pressure suits used by pilots. The first cosmonauts wore an emergency-only rescue suit designed to operate for five hours in the event of a cabin depressurization. Cosmonauts wore these 23 kg suits continually

throughout the mission. The SK-1, used during Vostok missions 1 to 5, was designed, tested, and operated in only six months.[5] The SK-2 suit used on Vostok-6 was modified to fit Valentina Tereshkova, who became the first woman in space in 1963. The spacesuit garment was changed to have a smaller shoulder breadth, larger hip breadth, smaller waist, and a smaller neck.[5] Like the spacesuits worn during the Mercury missions, the SK suits were made from completely soft materials and did not have any life support capability other than what was provided by the vehicle.

Following the success of Vostok, the Soviet program planned an EVA to determine if humans could perform useful work outside the spacecraft. The Berkut spacesuit, like the SK-1, was a completely soft suit and was not removed during the mission (with the exception of the helmet). "Berkut" means "golden eagle," a name that began the Soviet/Russian tradition of naming their spacesuits after birds. The Berkut was the first Soviet spacesuit to incorporate a dual bladder design, such that if one pressure bladder were punctured during operation, the second bladder would automatically inflate. This feature has been included on each subsequent Soviet/Russian spacesuit design. The Berkut had a basic open-loop life support system designed for 45 minutes of operation and was connected to the vehicle via an umbilical that provided oxygen in case of an emergency. The spacesuit garment was developed in only nine months and used by Alexi Leonov on Voskhod-2 on March 18, 1965 to perform the world's first EVA.[5]

With the knowledge that EVA was indeed possible, the Soyuz-4 and 5 missions sought to demonstrate docking and EVA transfer of crew from one spacecraft to another. To accomplish this task, engineers developed the first spacesuit dedicated solely to EVA, the Yastreb (meaning "hawk"). The Yastreb spacesuit had a closed-loop life support system in a pack worn strapped to the legs, which provided oxygen and carbon dioxide removal for 2.5 hours and was used successfully in January 1969.[5]

Following these initial missions, the Soviets embarked on the L-3 Lunar Project, a human mission to the Moon. During the mid to late sixties, engineers designed two spacesuits to support a Moon mission. One suit (the Krechet, which means "golden falcon") was to be worn by the crewmembers on the lunar surface and the other suit (the Orlan, meaning "bald eagle") was for the crewmember orbiting the Moon. Although the L-3 project was canceled in 1973 and neither suit ever flew, some features developed for

them became standard in subsequent spacesuit designs. The Krechet was the first Soviet suit to incorporate a HUT into the otherwise soft spacesuit garment. The life support system was attached to the HUT via a large hatch through which the cosmonaut entered and exited. The Krechet was also the first Soviet suit to use a liquid cooling garment (LCG) that circulated water cooled by a sublimator around the crewmember for thermal comfort.[5] The Orlan was similar in design, but lacked a self-contained life support system in order to save weight.[40] These features, rear entry, HUT, sublimator cooling, and an LCG became customary on all future Soviet/Russian suit designs.

Between the initial design of the lunar Orlan suit in 1977 and the present, there have been five major Orlan revisions including the current Orlan-M, all of which have been designed for long-duration spaceflight. The five major Orlan revisions represent a gradual improvement in mobility and self-contained life support capability. With each revision, the Orlan became less dependent upon an umbilical to provide it with capability, eventually eliminating the need for an umbilical in 1990. Orlan revisions have also included more mobility elements, such as joint bearings, and focused on fitting a larger range of crewmember sizes.[40] The most recent version of the Orlan-M spacesuit, used aboard the ISS, focused primarily on enabling interoperability between the EMU and the Orlan and included substantial changes to the Orlan's on-board systems.[148]

The remainder of this chapter focuses on operational spacesuits, designs that were flown aboard Soviet/Russian vehicles. However, as in the U.S., there have been a number of experimental Soviet/Russian spacesuit design efforts aimed at creating future spacesuits.[149] One effort, the EVA Suit 2000, was a joint endeavor between Russia and Germany and attempted to unite Russian experience with Western design principles. This suit was to be used on the proposed Buran space shuttle, European Hermes vehicle, and the ISS. The EVA Suit 2000 would have accommodated both male and female crewmembers and was planned to be operated for 5-7 years without ground servicing. This design effort is interesting because it provides insight into how the Russians might design a new suit if they could start from scratch.[67] The EVA Suit 2000 met a similar fate as the proposed U.S. ISS-specific spacesuit; it was canceled due to funding constraints.

To gain insight into current Russian spacesuit design, it is helpful to draw some parallels between Russian and American spacesuit design evolution. Figure 7 shows the

chronological development of spacesuits in both programs and illustrates similarities in the trajectory of each. As mentioned previously, both countries evolved their early spacesuits from high-altitude pressure suits. Both nations also began their human spaceflight programs with suits that would become active in emergency situations only, termed intravehicular activity (IVA) rescue suits. Next, both the U.S.S.R. and the U.S. designed suits to serve the dual purpose of rescue and EVA, with the U.S.S.R. subsequently designing its first EVA-only spacesuit, the Yastreb. Next, the U.S.S.R. and America focused on landing on the Moon and designed planetary spacesuits that were completely self-contained. It is here in history that the two programs diverged. After the lunar effort, the Soviet space program focused instead on long-duration spaceflight based on a series of space stations. America, meanwhile, briefly experimented with space station Skylab, but went on to design a suit for multiple short-term Shuttle missions and more recently began to modify the EMU for long-duration missions. Table 4 and Table 5 give a detailed account of each country's operational spacesuits and track changes in parameters such as suit pressure, mobility elements, and power usage. These tables provide insight into why the EMU and Orlan-M spacesuits exist as they do today.

Soviet/Russian Spacesuits	U.S. Spacesuits
0. High-Altitude Pressure Suits	0. High-Altitude Pressure Suits
1. SK-1/SK-2	1. Mercury
2. Berkut	2. Gemini G3C/G5C
3. Yastreb	3. Gemini G4C
4. Krechet	4. Apollo A7L
5. Orlan	5. Apollo A7LB
6. Orlan-D	6. Skylab A7LB
7. Orlan-DM	7. Shuttle EMU
8. Orlan-DMA	8. ISS EMU
9. Orlan-M	

IVA, IVA/EVA, Lunar, Umbilical EVA, Station-Based EVA
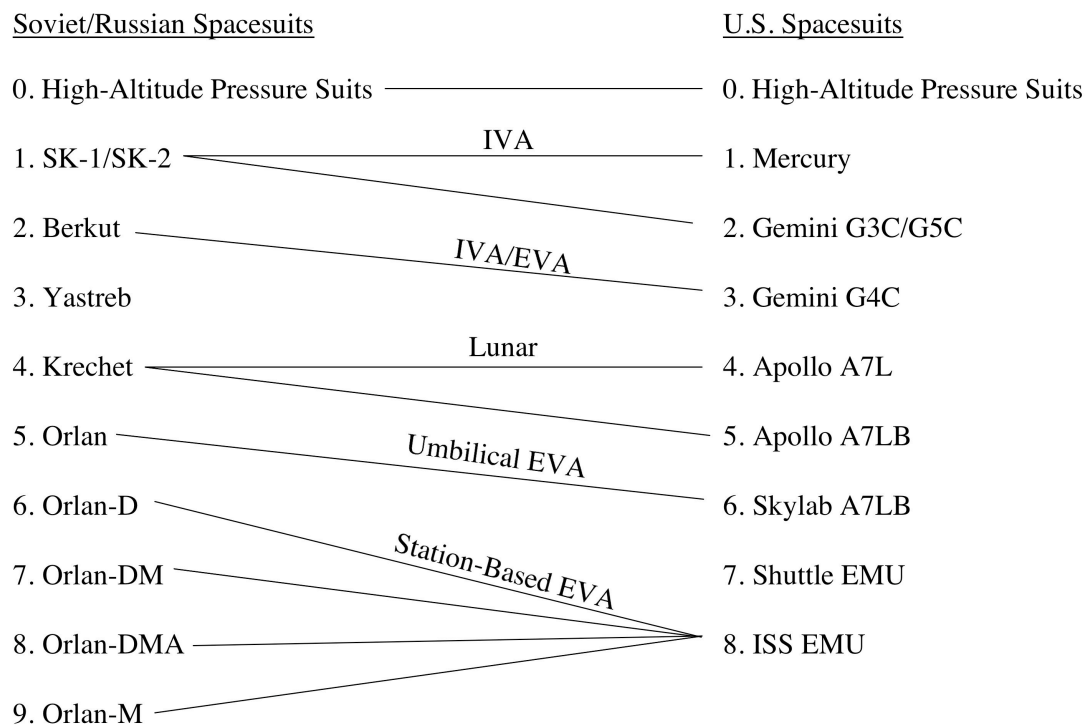
Figure 7. Soviet/Russian and American Spacesuit Design Comparison

Table 4. Russian Spacesuit Evolution

	Berkut	Yastreb	Orlan-D	Orlan-DM	Orlan-DMA	Orlan-M Mir	Orlan-M ISS
Year first operated	1965[5]	1969[5]	1977[40]	1985[40]	1988[40]	1997[40]	2001[150]
Purpose	IVA/EVA[5]	EVA[5]	EVA[40]	EVA[40]	EVA[40]	EVA[40]	EVA[150]
EVA Duration [hr]	0.75[5]	2.5[5]	5[40]	6[40]	6[40]	6[40]	6[40]
On-Orbit Life [yrs.]	1 mission (used once)[50]	1 mission (used once)[50]	3.5[40]	4[40]	4[40]	4[40]	4[40]
Nominal Pressure [kPa]	40[5]	40[5]	40[40]	40[40]	40[40]	40[40]	40[40]
Wet mass [kg]	42[5]	41[5]	73.5[40]	88[40]	105[40]	112[40]	112[40]
Power [W]	not published	not published	32[40]	32[40]	42[40]	54[40]	54[40]
MR [W] -avg. -max	n/a[50]	not published	300[40] 600[40]	300[40] 600[40]	300[40] 600[40]	300[40] 600[40]	300[40] 600[40]
Redundancy	dual bladder[5], emergency O$_2$[151] (same for all future suits)	all crit. components[50], double visor[50] (same for all future suits)	back-up oxygen bottle redesigned to be same as primary[42]	-	wrist pressure cuff added[40]	pressure regulators backed up[150] redundant water pump[150], wrist pressure cuff eliminated[38], dual glove bladder added[38]	-
Umbilical	for medical/ technical data, emergency O$_2$ and supported comm.[50]	for medical/ technical data, power, and supported comm.[50]	for medical/ technical data, power, and supported comm.[40]	for power[40]	none since 1990[40]	none[50]	none[50]
LSS	backpack (primary 0$_2$ only)[50]	strapped to legs, pressurized[50]	backpack parts rearranged to make replaceable parts easy to access	-	-	-	-

	Berkut	Yastreb	Orlan-D	Orlan-DM	Orlan-DMA	Orlan-M Mir	Orlan-M ISS
Mobility Elements	soft[5]	soft[5]	shoulder bearings, wrist bearings[38]	-	improved gloves[40]	elbow and ankle bearings[150], lengthening of legs[148], improved gloves,[40] improved fabric joints[38]	gloves include extra thermal flap[45]
Cooling	none[50]	fan[50]	LCG[50]	cooling areas on LCG decreased[40]	-	improved LCG,[150] vent tubing moved from bladder to LCG[38]	-
Heat Exchanger (HX)	none	evaporating HX (cooled air)[50]	sublimator[40]	-	-	-	-
Visors	internal light filter[50]	external light filter[50]	sun visor and light filter[41]	-	-	protective visor to reduce fogging[150]	-
Helmet	removable[5]	removable[50]	-	helmet lights added[40]	-	additional window for upward vision[150]	-
Sizing	individual[50]	individual[50]	limbs adjusted on-orbit, gloves unique[5]	-	-	increase in glove size range[38]	-
Don/Doff	front zipper[50]	front zipper[50]	back hatch[50]	-	-	hatch raised to facilitate don/doff[46]	-
Misc	open-loop LSS: oxygen circulated through suit once and was dumped into space[50]	-	added removable filters at the sublimator entrance[42], started cleaning cooling water with silver ions[42]	-	-	many LSS changes related to allowing Orlan to interface with ISS joint airlock[38], duplex comm. mode[38]	allowed crew to use some EMU elements (drink bag, tools e.g.)[150], duplex on radio,[150] improved fan[148]

Table 5. American Spacesuit Evolution

	Gemini G4C	Apollo A7L	Apollo A7L-B	Shuttle EMU	ISS EMU
Year first operated	1965[2]	1969[2]	1971[2]	1983[51]	2001[51]
Purpose	IVA/EVA[38]	IVA/EVA[38]	IVA/EVA[38]	EVA[152]	EVA[37]
EVA Duration [hr]	2.5[153]	4[154]	7[154]	7[145]	7[37]
On-Orbit Life [yrs.]	1 mission[153]	1 mission[36]	1 mission[155]	7 days[19]	180 days[38]
Nominal Pressure [kPa]	25.5[24]	27[19]	27[19]	29.6[37]	29.6[37]
Wet mass [kg]	16[156]	81.6[157]	96[2]	117[145]	145.5[37]
Power [W]	not published	56[155]	56[155]	97[28,37]	105[37]
MR [W]					
-avg.	410[153]	469[158]	469[158]	293[38]	293[37]
-max	586	586	586	586	586
Redundancy	dual zippers[159], emergency O_2[160]	emergency oxygen[157]	-	fail safe design, SOP[19]	-
Umbilical	for medical data, power, O_2, and comm.[153]	none[24]	none[24]	none[24]	none[37]
LSS	chest pack[2]	backpack strapped to suit[155]	backpack strapped to suit[155]	backpack mounted to HUT[38]	-
Mobility Elements	soft suit[38], neck bearing[38], wrist bearing[159]	soft suit[38], upper arm and wrist bearings[24,36]	-	HUT[38], added waist and shoulder bearings[36]	-
Cooling	air[38]	LCG[24]	LCG[155]	LCVG[24]	LCVG with bypass[20]
Heat Exchanger (HX)	evaporating HX (cooled air)[2]	sublimator[24]	-	-	-
Visors	attachable assy. with impact visor and light filter[38]	impact visor, light filter, and opaque sun visor[155]	-	-	-
Helmet	tight-fitting, removable[2]	bubble helmet[155]	-	-	-
Sizing	custom[38]	custom[38]	custom[155]	modular components, sized on ground[38], mostly custom gloves[38]	modular components, sized on-orbit[38], mostly custom gloves[38]
Don/Doff	through back zipper[159]	rear zipper[157]	front zipper[161]	detachable brief and upper torso[37]	-
Misc	glove fingertip lights, open-loop LSS[2]	external layer of Teflon attached to joints[156]	-	designed for male and female use[152]	-

The divergence of the American and Soviet human spaceflight programs in the late 1970s, with the Americans concentrating on the Shuttle and the Soviets on station-based flight, is one key to understanding the difficulties the U.S. has had operating the EMU aboard the ISS (see section 4.2.1). Table 6 and Table 7 show total Soviet/Russian EVA duration in person-hours by program and by spacesuit.[1] With the exception of the Voskhod and Soyuz programs, all Soviet/Russian EVA experience is station-based. The Soviet/Russians have a total of nearly 1,000 person-hours of station EVA experience, compared to about 230 hours for the U.S. Furthermore, Soviet/Russian engineers have completed four major upgrades to their station-based Orlan suit while the U.S. modified an existing Shuttle design. For all of the apparent similarities between the EMU and Orlan-M spacesuits, fundamental design differences exist primarily because the two suits were originally intended to operate in dissimilar operational regimes. Section 4.2 focuses on the design differences between the EMU and Orlan-M and describes each in detail.

Table 6. Soviet/Russian EVA Duration by Program

Program	Total EVA Duration
Voskhod	0:24[51]
Soyuz	1:14[5]
Salyut	106:20[51]
Mir	709:52[50,51]
ISS	162:06[50,162-170]

Table 7. Soviet/Russian EVA Duration by Spacesuit

Spacesuit	Total EVA Duration
Berkut	0:24[51]
Yastreb	1:14[5]
Orlan-D	79:20[51]
Orlan-DM	63:36[51]
Orlan-DMA	494:30[50,51]
Orlan-M	340:52[50,162-170]

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[1] This table counts one, 4-hour EVA with two crewmembers as 8 person-hours.

4.2 Design Differences between Orlan-M and EMU

This section gives a detailed description of the differences between the Orlan-M and EMU and includes operational as well as hardware distinctions. The design differences arise from distinct sets of requirements mandated by the two separate environments from and for which the suits were designed. The Russian environment is characterized by long-duration spaceflight, which leads to the use of a small number of cosmonauts, the need to maintain suits on-orbit, and the training of cosmonauts to operate somewhat autonomously. The American environment of short-term Shuttle missions, however, enabled a relatively large number of astronauts to perform EVAs and mandated that each minute of each Shuttle flight be used for productive work. This need for time efficiency meant that the suits were to require no maintenance on-orbit and each EVA must be meticulously planned and repeatedly rehearsed.

Although the two programs did face separate challenges, the basic requirement for a spacesuit to enable useful work outside the main vehicle was the same. Thus, the two suits also have similarities. First, both the Orlan-M and EMU are solely designed for EVA and are not used as rescue suits. Second, both suits use a HUT with soft arms and legs and include some mobility elements such as patterned joints and bearings. With regard to the life support system, both suits now operate without an umbilical and package the life support equipment in a backpack. Both suits use a liquid cooling garment with water cooled by a sublimator.[40] The EMU and Orlan-M use lithium hydroxide canisters (LiOH) for carbon dioxide gas removal, although the EMU can also use metal oxide (Metox).[24,37,38,50] Finally, both suits have a sophisticated caution and warning system that displays warning messages to the crew and keeps track of around 25 suit parameters.[19,43,149]

4.2.1   On-Orbit Life

Beginning with the original lunar Orlan suit, Russian engineers have designed their spacesuits to remain in orbit for its operational life of three to four years then to be burned upon reentry. Six Orlan suits were aboard Mir for more than two years and two suits were aboard for more than three years.[44] The Orlan's long on-orbit life is in sharp contrast with the EMU's original on-orbit life of one week. Russian designers have been

able to achieve their goal of extended Orlan operation through a combination of hardware design and operational measures, discussed in this section.

Russian reliance on crewmember servicing throughout the life of the spacesuit resulted in a number of hardware changes from the original lunar Orlan suit to the operational Orlan-D spacesuit. The primary and emergency oxygen tanks were redesigned to be interchangeable and easily accessible as were many components that needed regular servicing such as pumps and filters.[40] On the other hand, the major components of the EMU including the HUT, DCM, PLSS, and Secondary Oxygen Pack (SOP) were not originally designed to be changed on-orbit, but were redesigned in the 1990s out of necessity.[19] One inhibitor to this EMU redesign was the requirement that the EMU be able to withstand 100 Shuttle launches, resulting in the use of significant packaging to hold the EMU components in place during launch vibrations and accelerations.[171] The Russian suits, however, only needed to survive a single launch and could therefore make use of straps, rather than screws, to hold components in place.[172] This simplified suit casing facilitated on-orbit modification.

One major inhibitor to the extended use of spacesuits in orbit is water. Water is used in the cooling loop of both the Orlan-M and EMU, but is also an excellent solvent and medium for life that tends to produce filter-clogging precipitate. Both programs use biocides in the water and filters, but experience has led Russian engineers to design Orlan suits to be able to operate even with significant water contamination.[44] Orlan-DMA suit N18 was aboard Mir for 3 years and 10 months before it was brought back to Earth on STS-79 in September 1996. Because Orlan suits usually burn up on re-entry, evaluation of this Orlan suit represented a unique opportunity to perform a complete systems check. The only significant aberration from expected performance was a 22% increase in the hydraulic resistance of the cooling water loop and an increase in impurities in the hydraulic system water.[44] The American program encountered a related problem in 2003 when two of three EMUs aboard the ISS were determined to be "no go" for EVA due to water contamination.[19] During this period, the suits were repaired by careful replacement of pumps and filters, never intended to be handled on-orbit. Although the successful repair of the EMUs on-orbit is certainly a testimony to the hard work and ingenuity of the

crew, mission controllers, and engineers, replacement of similar components certainly would have been easier on an Orlan spacesuit.

In order to avoid water problems as much as possible, the Orlan suits are protected by both procedure and design. While the Orlan sublimator life is extended to three years with the use of an expendable filter, the EMU sublimator has a limited 177-hour operational life before needing replacement.[19,44] The Russians have discovered that thorough drying of Orlan suits after each EVA is key for long-term use. Mold has been observed if the suit is not sufficiently dried.[44] Because the Orlan ventilation is integrated into the suit (rather than incorporated into the cooling garment as in the EMU), the cosmonauts can activate the Orlan ventilation system while the suit is in storage through a ventilation connector, which helps to prevent bacteria and mold growth.[38]

4.2.2   Redundancy

A second major difference between the EMU and Orlan spacesuits is their safety requirements, which translates into different levels of redundancy in each suit. The EMU was designed with a "fail safe" philosophy, meaning that the suit can withstand any single failure and still get the crewmember back inside the vehicle or station safely.[19] The Orlan, on the other hand, was designed with a "fail operational" philosophy where the suit can still function after any one failure and be used to complete the EVA.[40] The fail operational philosophy resulted in the Orlan being designed with a dual bladder, visor, pump, and fan, whereas the EMU has only one of each of these elements.[19,40,173] This is not to say that the EMU is not safe; the EMU only uses redundant hardware where a single failure would put the astronaut's life in danger.[38] This philosophy allows the EMU to be a leaner design and avoid bulk through duplication. In general, a fail safe philosophy leads to a heavier design because more components are critical to the ability of the spacesuit to perform an EVA than are critical to the suit's ability to support an astronaut's life. By paying the price in mass, however, a fail operational spacesuit is more reliable because it is able to sustain a larger number of failures before an EVA must be aborted.

4.2.3   Mobility

From the point of view of a crewmember, mobility is one of the most important features of a spacesuit because it dictates how much work can be done. Joint torque and

range of motion are the prime determinants of spacesuit mobility. A difference in mobility between any two spacesuits arises from differences in the operating pressure of the suits and use of mobility elements such as joint bearings. The rule is that a low operating pressure and use of many bearings results in greater mobility. The Orlan operates at 40 kPa (5.8 psi) while the EMU operates at 29.6 kPa (4.3 psi).[40] The EMU has more mobility bearings than the Orlan, although the number of bearings in Orlan suits continues to rise in part due to American success with them.[46] According to crewmembers who have used both suits, the Orlan is stiffer and more fatiguing than the EMU.[173] A comparison of static torque and range of motion for the EMU and Orlan show that the EMU is substantially more mobile than the Orlan, with the exception of the wrist joint, which had comparable torque and range of motion values.[38] Here, as in the discussion of redundancy, reduced mobility should not imply that the Orlan is inferior to the EMU. A higher operating pressure results in a reduced pre-breathe time, giving the Russian suit added operational flexibility (discussed in section 4.2.8). This tradeoff between mobility and pre-breathe time is further explored in Chapter 5.

4.2.4 Life Support System

The primary difference in the life support systems of the EMU and Orlan is in their packaging. The EMU PLSS can be compared to a racecar, compact and efficient, whereas the Orlan is more like an old Ford, a bit bulky but easy to work on. As explained in 4.2.2, part of this difference comes from the Russian space program's design for long-duration flight and the subsequent need for their spacesuits to be maintained on-orbit. A second origin of this difference is a requirement levied on the EMU by the Shuttle and inherited by the ISS version of the EMU: when the EMU was originally designed, it had to be able to pass through the inter-deck hatch in case of an emergency, a requirement that imposes a front-to-back maximum dimension of 50 cm (19.75"). Conventional packaging methods were simply too bulky and ease of maintenance was scarified for compactness.[152] The Orlan, on the other hand, was free of this requirement and has an overall diameter of 80 cm (31.5").[45] A second difference in the life support systems of the suits is the use of an umbilical. Although neither suit now uses an umbilical, the Orlan umbilical was eliminated relatively recently in 1990, while the last time an American spacesuit used an umbilical was during the Skylab program in 1973-74.[40]

4.2.5 Sizing

Although the stated design philosophy of both programs is to be able to fit the widest range of crewmembers possible, the reality is that U.S. astronauts have a wider range of body sizes (and genders) than do Russian cosmonauts.[174] The Orlan-M garment is one-size-fits-all with a choice of two glove sizes. To adjust the suit size more finely, the cosmonaut tightens or loosens straps in the arm and leg. Orlan mobility is inhibited by the resultant bunching of material in the limbs.[173] In contrast, the EMU is required to fit a 5th percentile woman to a 95th percentile man and more than 9,000 combinations of suit sizes are possible, not including gloves which are often custom-made.[19] The EMU garment is essentially a modular design, with various sizes of arms, legs, and torsos available. To don the EMU, a crewmember first puts on the pants, then slides into the upper torso, and attaches the gloves and helmet. This donning process cannot be completed without the help of another crewmember. Although the Orlan cannot accommodate the same range of sizes as can the EMU, its garment is essentially integrated: the helmet, upper torso, and lower torso are permanently attached. To don the Orlan, a crewmember slides through a hatch at the back and is able to put on the spacesuit unassisted. The origin of this self-donning philosophy can be traced to the original Orlan suit, which was designed for use by the lone crewmember orbiting the Moon when the other two cosmonauts were on the lunar surface. The suit therefore had to be self-donning.[38]

4.2.6 Operations

As with differences in on-orbit life, redundancy, and life support system design, the differences in EVA operations between the U.S. and Russia stem primarily from Russia's considerable experience with long-duration spaceflight. Space Shuttle missions can be characterized as a ballet, where every move is choreographed and rehearsed in advance whereas long-duration spaceflight is more akin to a hiking expedition, training is needed, but the participants have more autonomy to determine the best course of action. As an example of how these divergent philosophies result in operational differences, although both programs use similar methods of training such as in neutral buoyancy pools or parabolic flight, Americans receive an average of 5-6 day-long pool training sessions per EVA compared to 2-3 days for Russians.[38,175] The Russian training is more general and aimed at providing a foundation of basic skills, whereas the U.S. training is more task-

specific.[51] Russians tend to let the need for an EVA arise naturally rather than schedule them in advance. On average, about 40% of Russian EVAs are unscheduled and needed for repair tasks.[41] Concentrating on skill-based training is one key to increasing the autonomy of the crewmembers, but will also likely require on-orbit refresher training for specific tasks.[176] Research into how to provide this just-in-time refresher training is ongoing.[177]

A second operational difference between the U.S. and Russia lies in the execution of the EVA itself. Americans almost always use foot restraints during EVA in order to establish a stable worksite whereas Russians tend to free float and use fewer handholds, footholds, and tether points (Figure 8, images courtesy of NASA).[51] Russians intentionally design their hardware not to need large forces or precise movements, eliminating the need for foot restraints.[175] The two programs also differ in their use of tools. In order to save space inside the pressurized station, Americans stow their tools in a box outside the ISS. During an EVA, they exit the airlock, traverse to the tool chest, retrieve the tools, attach them to their suits, then traverse to the worksite. Russians prefer to store their tools inside the station and load them into a toolbox before depressurizing because this method is more time efficient and does not involve attaching as many tools to the suit.[175] Lastly, the operational differences between American and Russian EVA were documented by astronaut Jerry Linenger, the first American to perform an EVA from a foreign space station in a foreign spacesuit. Linenger noted that the EVA timeline is of reduced importance for the Russians, and he observed no interaction between the crewmember left inside Mir and the EVA crew, in contrast to American EVA in which an intravehicular crewmember usually stays in contact with the spacewalkers.[51]

4.2.7 Radiation

Radiation is one of the most serious threats to human health in long duration spaceflight and protection has continually been identified as one of the key technologies that must be developed to enable sustained human presence on the Moon and exploration to Mars. As one example of the seriousness of radiation protection, a solar storm occurred on August 4, 1972, between Apollo 16 and 17. Had this storm occurred during one of the landings, it would have caused acute radiation sickness and possibly death.[178] Radiation is of particular concern during EVA because the crewmembers are outside the protective shielding of the spacecraft. Normally crewmembers wear a single dosimeter throughout a
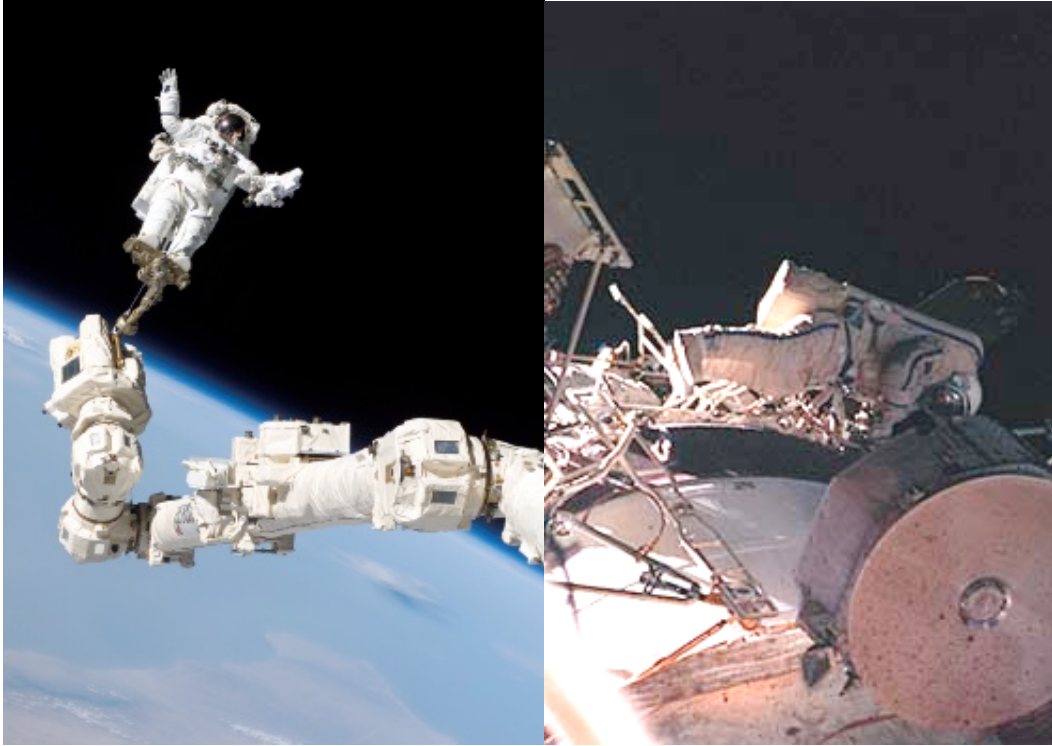
Figure 8. EVA Using Foot Restraints (Left) and Free-Floating (Right)

mission, yielding only a single data point for the entire mission. Furthermore, this dosimeter is worn underneath the HUT during an EVA, which is one of the most heavily shielded parts of the spacesuit and does not reflect radiation dosage in the head or limbs. Only one set of data exists that quantifies radiation dosage a single. During a spacewalk on April 29, 1997, crewmembers wore special dosimeters on the outside of their spacesuits that measured absorbed dose rates between 60 and 80 µGy per hour, 3 to 4 times higher than doses measured inside the station.[179] Despite this increased risk, radiation protection is usually accomplished by planning EVAs during periods of low solar activity.

There are three basic types of radiation encountered by astronauts in LEO. The more predictable of these are the trapped particles in the Earth's radiation belts (known as the Van Allen belts). Because of the difference in location between the Earth's geographic axis and its magnetic axis, these radiation belts come closest to the Earth over the south Atlantic, a spot known as the South Atlantis Anomaly (SAA). Figure 9 is a projection of the SAA for STS-61, the first Hubble servicing mission, and shows regions of high-energy trapped protons (from Ref. 180). On Mir, cosmonauts got half of their total
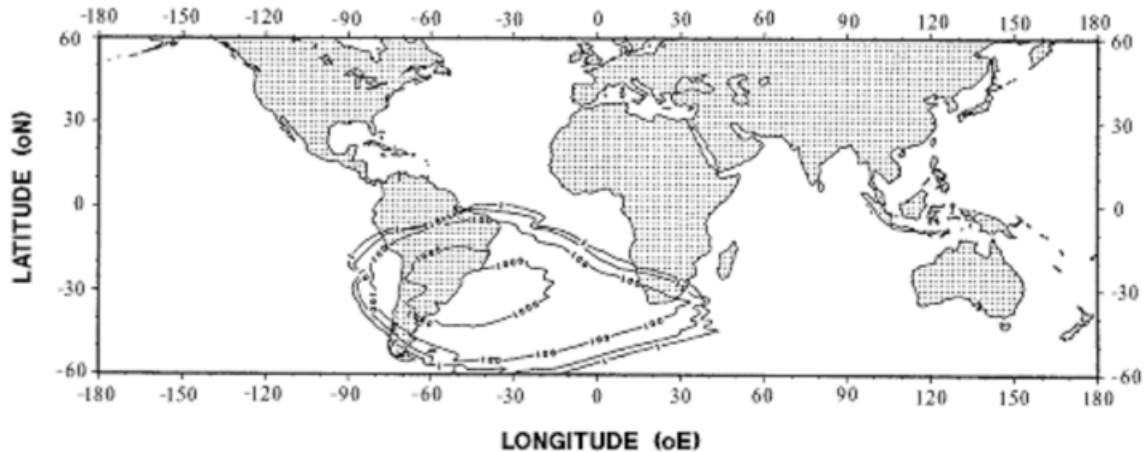
Figure 9. World Map Showing the South Atlantic Anomaly

radiation dose from the 2 to 5 percent of the time they spent passing through the SAA.
The second type of radiation is solar radiation, caused by particles generated by the Sun
during Solar Particle Events. This form of radiation is less predictable, but generally
follows the 11-year Sun cycle. The Earth's geomagnetic field protects from this kind of
radiation in low inclination orbits (orbits near the equator), but does not shield from solar
radiation above about 50 degrees latitude. The final form of radiation is Galactic Cosmic
Radiation (GCR), which is a source of penetrating radiation, mostly found in high
altitude orbits. Because of the energies of GCR particles, neither spacesuits nor space
stations block this type of radiation effectively.[179] Neither the EMU nor the Orlan-M
spacesuits have any special design features to help shield for radiation; rather, radiation
avoidance is accomplished by scheduling EVAs such that they do not occur during a
solar storm or when the station is passing through the SAA.

When Russia was added as a partner to the ISS, its planned orbit was changed to
accommodate launch from Russian sites. This new high-inclination orbit (51.6°)
increased the exposure of crewmembers to solar radiation. Even considering the worst
case, however, possible radiation exposure aboard the ISS is not life threatening. The
primary medical concern is increased risk of cancer.[178] In order to address this risk,
scientists performed a laboratory experiment to determine how the Orlan-M and EMU
spacesuits block radiation. A sophisticated measuring device was placed inside each
spacesuit, which was then exposed to various types of radiation. The study concluded that
each suit had advantages and disadvantages. For example, the Orlan helmet provided

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better eye protection while the EMU helmet provided superior brain protection. Overall each suit provided about the same level of radiation protection and the study concluded that there was no clear reason to prefer one suit over another.[179]

4.2.8   Medical Operations

The final difference in the American and Russian EVA programs is medical operations. Differences in medical operations arise from variation in the type and number of medical parameters measured during an EVA as well as a difference in the way each program manages the risk of decompression sickness. In general, Russians track more biometric parameters than do the Americans. During an EVA, Russian mission control monitors ECG, breathing frequency, heart rate, body temperature, and metabolic rate.[49] During the Gemini program, U.S. astronauts measured blood pressure, ECG, body temperature, and respiration rate, but the EMU currently tracks only ECG and metabolic rate. [79,160] As one indication of the physical stress caused by an EVA, increased protein and several erythrocytes can be found in the urine 1-2 days after a hard spacewalk, indicative of intense physical exertion.[49]

Comparison of biometric data across EVAs and between spacesuits can yield insights into the physical exertion required to do an EVA. Some evidence exists that suggests that experience can drastically lower the physical exertion required to perform an EVA. In one study of similar EVA tasks, heart rates in experienced EVA cosmonauts were 14-40 beats per minute lower than in novice crew.[49] One final interesting comparison can be made between American and Russian metabolic cost. Although metabolic cost is influenced by experience, the tasks required during an EVA, and the operating environment, it is also strongly influenced by suit mobility. As implied in section 4.2.3, EMU mobility appears to be greater than in the Orlan suits. This assertion is corroborated by metabolic data. The mean metabolic rate for Orlan-suited crewmembers on Mir was 3.7 kcal/min, while the mean rate during the STS-114 EVAs in the EMU at the ISS was 3.2 kcal/min.[49] Although this is an imperfect comparison, it does seem to indicate that the EMU requires less metabolic expenditure than Orlan.

A second major difference between the U.S. and Russian programs is in the risk management of decompression sickness. Because both spacesuits operate in a low-pressure environment, crewmembers are at risk of decompression sickness caused by the

gasification of nitrogen dissolved in their blood. Breathing pure oxygen before an EVA in order to purge the nitrogen from the blood mitigates this risk. Because the Orlan-M operates at a higher pressure than the EMU, the pre-breathe time for the Orlan is only 35 minutes, compared to 4 hours for the EMU.[173] This reduced pre-breathe time translates into a decreased footprint for a Russian EVA. On Mir, the total time required for an EVA – including pre- and post-EVA procedures – averaged 13 hours and this figure is even higher for U.S. EVA.[49] Risk of decompression sickness is measured by a metric called the R-value, a ratio of the tissue nitrogen partial pressure to the total pressure. Russia distinguishes between R-values for different tissues because each tissue releases nitrogen on a different timescale, with connective and fatty tissues releasing nitrogen the slowest.[48] An R-value of 1 represents no risk of decompression sickness and values above 1.4 are considered potentially dangerous.[180] For Russian EVAs from the beginning of the program through 1991, R-values ranged from 1-2.1 (μ = 1.83).[181] The U.S. defines a single R-value with a timescale on the same order as the connective and fatty tissues. For 15 EVAs from STS-6 to STS-37, R-values ranged from 1.3-1.8 (μ= 1.6).[47] Although differences in the calculation of the R-values account for some of the difference in pre-breathe time between the programs, the American program is more conservative with regard to decompression sickness. It is important to note, however, that neither program has ever documented decompression sickness in any of its active crew.

4.3 Analysis of change in Orlan and EMU design

The driving forces behind the variations between Orlan and EMU design are differences in the political, economic, physical, and technical environments of the two suits. These environment differences translated into two distinct sets of requirements, which led to many differences in design and operation. That the Russian system was able to more easily adapt to use aboard the ISS is understood in light of the fact that the environment adjustment was smaller for Russia than the U.S. Changing a spacesuit's requirement from operation aboard Mir to operation aboard the ISS does not result in as many design revisions as does changing the requirement from Shuttle to ISS operations. Indeed, almost all of the design differences identified in this chapter can be attributed to optimization of the Soviet/Russian spacesuits for station-based flight and optimization of the EMU for the Shuttle.

The U.S.S.R./Russia has focused on station-based spaceflight from the 1960s. Sergey Korolev, the Chief Designer of the Experimental Design Bureau that held primary responsibility for human space programs, believed that the early part of space development would involve the operation of spacesuits from space staions.[5] As discussed extensively in Chapter 3, the American space program did not focus on long-duration flight until the 1990s and chose to modify the existing EMU rather than build a new suit exclusively for the ISS. The space station mindset of the Soviet/Russian program imposed specific spacesuit requirements including: (1) a 3-4 year operational life without ground servicing, (2) on-orbit sizing, and (3) increased autonomy of crewmembers. These three requirements account for the design differences discussed in sections 4.2.1, On-Orbit Life; 4.2.2, Redundancy; 4.2.4, Life Support System; 4.2.5, Sizing; and 4.2.6, Operations. Each design or operational difference discussed in these sections is a result of optimization of the Orlan for station-based flight. However, not all design differences between the EMU and Orlan-M are attributable to station versus Shuttle use.

To this point, environment has been defined as political, economic, technical, or physical; the aggregate of these aspects can be termed the *cultural* environment. Differences in the cultural environment also account for design differences. For any complex design with multiple objectives, many solutions are possible that balance tradeoffs between the objectives differently. The final decision between competing designs often depends upon the relative importance a decision maker places on each objective. For example, the Soviet/Russian program chose to value a minimal pre-breathe time over increased mobility and designed interfacing hardware such that it could be operated with minimal tactility. As described in section 4.2.3, this decision led to design differences with the EMU because the U.S. program valued mobility over pre-breathe time. A second example of cultural differences resulting in requirement and design differences is the choice of different R-values to measure the risk of decompression sickness (4.2.8). The use of dissimilar R-values resulted from a difference in the application of the R-value metric and a difference in the willingness to accept risk. Understanding the environmental differences from where the design differences arise will help in the design of the next-generation spacesuit.

The future of human spaceflight is planetary exploration. Because the mission timescale of planetary exploration is on the order of months, the future regime of spaceflight more closely simulates current station-based flight. In other words, the EVA requirements for planetary exploration will be similar to those of long-duration, station-based flight. Because this is the environment the Soviet/Russian program has been operating in for almost thirty years, future EVA systems should incorporate many of the design and procedural strategies used by the Russians. Those strategies that resulted from Russia's focus on station-based spaceflight should be emulated because these changes will help the performance of the next-generation American spacesuit. The distinctions resulting from cultural differences should be discussed, but not necessarily followed, because each nation's strategy offers very effective performance, with different tradeoffs.

In conclusion, the different political, economic, technical, and physical environments of the Orlan and EMU led to stark differences in requirements, which translated into design differences. This section described those differences, both operational and hardware, and sought to understand the underlying causes of the distinctions. This chapter concludes Part I. Chapter 5 looks ahead toward the design of the next-generation spacesuit and describes the development of a multidisciplinary spacesuit model.

5 Development of a Multidisciplinary Spacesuit Model

This chapter describes the development of a multidisciplinary spacesuit model. Several spacesuit models currently exist in the literature for spacesuit thermal,[80,182,183] mobility,[35] and power subsystems; however, none of these models incorporates all of these disciplines simultaneously. Although a partial understanding of the operation and performance of a spacesuit at the subsystem level can be attained using existing models, the spacesuit is a highly-interdependent, human-sized spacecraft, and an integrated model is needed to aid in the understanding, design, and operation of the spacesuit as a complex engineering system. This chapter begins with an overall description of the model, describing the choice of the design vector, objective functions, and model parameters. Next, the interactions between the subsystems and objective functions are discussed. Finally, the details of the four subsystems – thermal, structures, oxygen, and power – are explained. Chapter 6 uses the spacesuit model to conduct multi-objective optimization. This model was initially developed as a class project and I gratefully acknowledge the help of my project partner, Cristin Smith.

5.1 Objective Functions

This section discusses the organization of the model a high level and elaborates on the choice of objective functions. The inputs and outputs of each subsystem are listed in Figure 10. One basic assumption of this model is that the spacesuit will be a gas pressure suit using a liquid cooling garment and life support backpack. The purpose of the model

Suit pressure
EVA duration
CO_2 removal technology
Oxygen properties

Oxygen Flow Module

Subsystem mass
Life support system volume

Suit heat leak
Crew metabolic rate
Mass flow rate
Radiator ε
Radiator surface area
Ambient temperature
EVA duration
Water T into cooling garment
Water properties

Thermal System Module

Subsystem mass
Power needed

Gravity environment
Suit pressure
Percent hardness of suit

Structures Module

Subsystem mass
Subsystem volume
Mobility metric
Pre-breathe time

EVA duration
Power needed
Battery technology

Power System Module

Subsystem mass
Subsystem volume

Figure 10. Model Inputs and Outputs

is to gain insight into multidisciplinary interaction in the next-generation spacesuit, the design of which will likely occur within the next ten years. The architecture of the spacesuit was therefore assumed to be an evolution of existing operational spacesuits and excluded promising, but low readiness level technologies such as mechanical counter-pressure. This assumption has the effect of freezing basic design features of current spacesuits and allows us to explore designs within our present operational knowledge. The first step in the model development was the selection of the spacesuit objective functions and the subsystems that were necessary to evaluate these objectives. Mass, volume, pre-breathe time (PBT), and mobility were selected as the four initial objective functions. Spacesuit mass is of prime concern for two reasons: first, launch costs dictate that the spacesuit be as light as possible; second, the crewmember must carry the spacesuit, and high mass limits mobility and spacewalk duration. Spacesuit volume directly affects the design of other vehicle subsystems, such as the airlock, due to

stowage and don/doff requirements. For mobility reasons, spacesuits often operate at reduced pressures requiring astronauts to pre-breathe pure oxygen for a given amount of time prior to the EVA in order to reduce the risk of decompression sickness. The PBT is currently a major operational constraint to the speed and frequency of EVAs. The final objective function is mobility. The quantity and quality of work an astronaut can do inside a spacesuit is strongly influenced by the amount of work exerted to move and the range of motion of the spacesuit joints.

The four objectives represent the primary measures of utility for a spacesuit design. The ideal spacesuit has low mass, stowage volume, and pre-breathe time, and high mobility. Even though each of these objectives is highly desirable, they compete with each other and the spacesuit designer must trade between them. For example, a spacesuit with high mobility can either be manufactured with hard components that have isovolumetric joints, or it can be a soft suit that necessitates a lower operating pressure. Use of hard components, while enhancing mobility, will drive up suit mass and stowage volume, and a low pressure suit will have a high pre-breathe time.

5.2 Model Subsystems and Parameters

The four subsystems, oxygen flow, thermal, structures, and power, predominantly determine the objective functions. The subsystems include oxygen flow, thermal, structures, and power. The oxygen subsystem models the flow of oxygen from the primary oxygen tanks located in the suit backpack, into the spacesuit garment, and back into the life support system where it is scrubbed for carbon dioxide. The thermal subsystem models water flowing from the cooling garment worn by the crewmember and into the backpack where it is cooled and returned to the cooling garment. The third subsystem, structures, models the spacesuit garment as hard, soft, or a combination of the two. As an example, the EMU has a hard, fiberglass upper torso and soft arms and legs. The final subsystem, power, is a technology switch that includes known data on a variety of power storage methods. Other possible modules could include data, communications, radiation, and tool interface. However, the four modules chosen are the primary drivers for the hardware design of the spacesuit and chiefly establish its representative parameters such as mass and volume.

The next phase of the modeling process was the selection of a design vector, the elements of which represent the key aspects of a spacesuit design. These elements are operating suit pressure, suit garment hardness, power technology, and carbon dioxide removal technology. Because of pre-breathe constraints, it is assumed that the spacesuit operates at 100% pure oxygen. The operating pressure is a continuous variable bounded between 25 kPa (the human physiological limit) and 101 kPa (pressure at sea level).[184] The suit garment hardness variable is a discrete scalar value and determines the hardness of the arms, legs, and upper torso. The carbon dioxide removal and power variables are both technology switches and select among given technology options. Although there are dozens of possible design variables, the four chosen have the most influence on the objective functions and consequently are among the first decisions made when designing a spacesuit.

Because the ultimate goal of the model is to explore possible spacesuit designs across a variety of environmental and operational conditions, model parameters allow the simulation of diverse conditions. The model includes eight operating environments, corresponding to the Moon (hot, average, and cold), Mars (hot, warm, average, and cold), and microgravity that determine the values of the ambient temperature, ambient pressure, gravity, and suit heat leak (Table 8). The heat leak parameter is the amount of power escaping from the suit and is related to wind conditions, solar flux, and ambient temperature. The model also includes three EVA profiles to specify how the crewmember's metabolic rate changes during the EVA (Table 9). For example, during a moderate EVA, the crewmember generates 150W for one quarter of the total EVA duration, 260W for 45 percent of the EVA, 300W for 27 percent of the EVA, and has a peak power generation of 400W for three percent of the EVA. These metabolic profiles are based upon known metabolic rate ranges as well as metabolic rate data from the three STS-114 EVAs. Finally, a parameter that specified the duration of the EVA was included. Current durations are approximately seven hours, but future EVAs could be substantially shorter or longer. The model parameters enable the simulation of a variety of EVA and mission profiles.

Table 8. Environment Parameters

Environment	T_{amb} [°C]	P_{amb} [Pa]	$P_{SuitLeak}$ [W]
Mars Warm	-23	850	5
Mars Cold	-123	850	168
Mars Average	-58	850	47.5
Mars Hot	20	850	-50
Moon Hot	150	0	-90
Moon Cold	-170	0	100
Moon Average	0	0	10
Microgravity	0	0	10

Data from Refs. 38,158,182

Table 9. Metabolic Rate Parameter

	Easy EVA	Moderate EVA	Hard EVA
Rest (150 W)	50%	25%	5%
Light Work (260 W)	45%	45%	25%
Moderate (300 W)	5%	27%	40%
Hard Work (400 W)	0%	3%	30%
Max Exertion (590 W)	0%	0%	10%

Data from Ref. 37, page 1-1 and STS-114 EVA Data

5.3 Model Interactions

With an understanding of the basic construction of the model, this section looks at the interaction between the model subsystems and objective functions. As indicated in Table 10, the mass of the suit is determined primarily by the structures subsystem, with small contributions from each of the other subsystems. In reality, the mass of the spacesuit has significant contributions from both the life support backpack and the spacesuit garment; however, because the materials and support structure of the backpack was assumed to be common to all designs, the weight of the life support backpack is largely fixed. The small variations in backpack weight are due to changing amounts of cooling water, oxygen, and battery power needed for each mission. Similar to spacesuit mass, the suit volume is also dominated by the structures subsystem in our model. This is again due to the fact that large changes in volume occur when switching between an all-hard and all-soft suit that overwhelm the smaller changes caused by selecting a different carbon dioxide removal device, reducing the size of the suit water tanks, or using a different battery. The remaining objectives, PBT and mobility, are determined by the structures subsystem and represent a significant tradeoff that must be made when designing a spacesuit. In a

Table 10. Subsystem/Objective Function Interaction

S/O	Mass	Volume	PBT	Mobility
Oxygen	+	+	-	-
Thermal	+	-	-	-
Structures	++	++	++	++
Power	+	+	-	-

++	strong correlation
+	slight correlation
-	no correlation

predominantly soft suit, such as the EMU, PBT and mobility are competing objectives. As spacesuit pressure increases, PBT decreases and mobility likewise decreases.

5.4 Spacesuit Model Development

This section presents the development and validation of each model subsystem. Each of the four subsystems is described in detail, including assumptions, and validation against known values of operational spacesuits.

5.4.1 Oxygen Flow Model

The oxygen flow subsystem models the flow of oxygen from its inlet into the suit, around the crewmember where it is contaminated with carbon dioxide, and returned to the life support system where the contaminants are removed. This subsystem model helps to determine the mass and stowage volume of the spacesuit. The model's user is offered a choice of technologies for carbon dioxide removal, lithium hydroxide or metal oxide. Given the spacewalk duration and suit pressure, this module also calculates the volume of the life support backpack. The model assumes that the suit helmet is similar in design to other spacesuits[37,38] and that the requirements for maximum inspired amount of CO_2 are the same as the current requirements for the EMU.[36] The model also assumes that the suit atmosphere is pure oxygen and assume values for oxygen use[36], suit oxygen leak[36], and tank storage pressure are similar to EMU values.[37]

The oxygen flow model was validated against three parameters: amount of oxygen needed, volume of primary oxygen tanks, and size of life support backpack. The model predicts that the crewmember will need 0.59 kg of oxygen for an eight-hour EVA, about seven percent less than the amount of oxygen the EMU carries.[37] The EMU has two primary oxygen bottles, with a total volume of 0.0079 m^3.[37] The model predicts a volume of .0073 m^3, 7.5% less than the actual volume. The length of the backpack is determined

primarily by the length of the primary oxygen bottles and the secondary oxygen bottles plus a fixed amount of space for the battery. The width and height are determined by rules of thumb. The dimensions of the PLSS are highly correlated to the actual values of the EMU (Table 11).

Table 11. Backpack Measurement Verification

	EMU [m]	Model [m]	% Error
Height	0.762	0.7000	8.1
Depth	0.129	0.1201	7.4
Width	0.350	0.3505	0.1

The EMU backpack measurements are from Ref. 37

5.4.2   Thermal Model

The thermal module combines physics-based modeling and known, empirical relationships to model heat transfer throughout the suit. This subsystem model helps to determine the mass of the spacesuit by calculating the weight of the life support backpack and amount of water consumed during the EVA. The primary purpose of a spacesuit thermal system is to reject waste heat from the crewmember and electronics and keep the crewmember at a comfortable temperature. The thermal model assumes that the crewmember is wearing a liquid cooling garment, consisting of a bodysuit with interwoven tubing, as is currently used on the EMU and Russian Orlan spacesuits. Waste body heat is collected via water running though the tubes. The model uses an empirical relationship between the metabolic rate of the crewmember and water temperature to determine the proper water temperature at the inlet of the garment ($T_{water,Out}$).[36] The model also assumes a mass flow rate ($\dot{m}_{In}$) and models the flow of water as it exits the spacesuit, goes through each of two heat rejection devices and flows back into the liquid cooling garment (Figure 11). The remainder of this section describes the relationships between the variables in the thermal subsystem.

First, the total amount of heat added to the suit is calculated (q_{tot}):

$$q_{tot} = P_{CM} + P_{Battery} - P_{SuitLeak} \qquad (1)$$

where P_{CM} is the power added to the suit by the crewmember, which changes during the
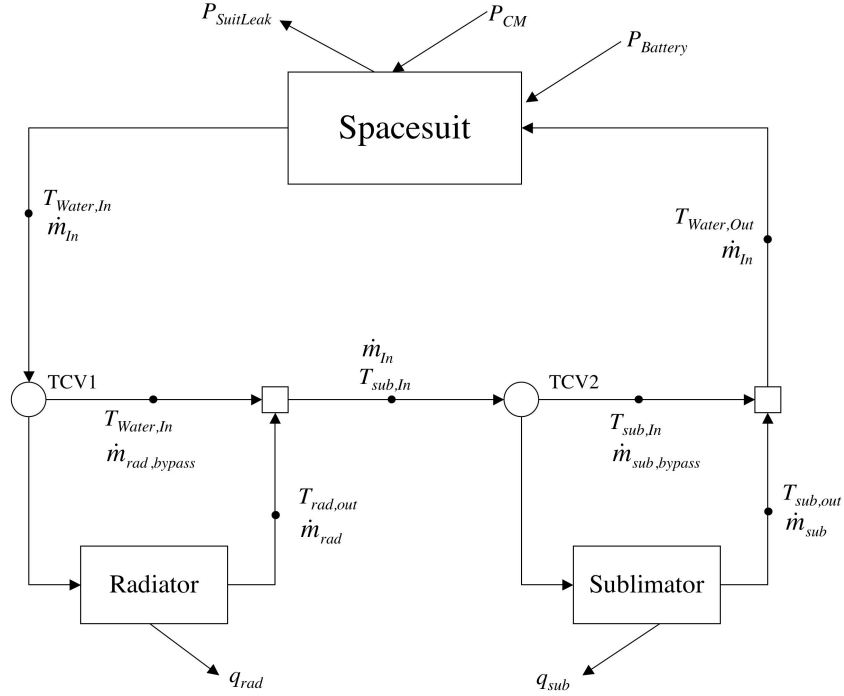
Figure 11. Thermal Subsystem Schematic

EVA, $P_{battery}$ is the waste heat given off by the battery and other electronics, and $P_{SuitLeak}$ is the heat leaking from the suit. The model then calculates the temperature of the water into the thermal subsystem ($T_{Water,In}$):

$$T_{Water,In} = \frac{q_{tot}}{\dot{m}_{In} Cp_{Water}} + T_{Water,Out} \tag{2}$$

where $\dot{m}_{In}$ is the mass flow rate of the water, Cp_{Water} is the specific heat of water, and $T_{Water,Out}$ is the temperature of the water going out of the thermal subsystem (and into the cooling garment). Next, the model determines the maximum heat that the radiator could possibly reject ($q_{rad,Max}$):

$$q_{rad,Max} = SA_{rad} \sigma \varepsilon \left(\frac{T_{water,In} + T_{water,Out}}{2} + 273.15 \right)^4 - \left(T_{amb} + 273.15 \right)^4 \tag{3}$$

where SA_{rad} is the surface area of the radiator, determined by the dimensions of the life support backpack, σ is the Stefan-Boltzmann constant, ε is the radiator emissivity, and T_{amb} is the ambient temperature.

The model assumes that the radiator is the preferred method of rejecting heat because the radiator does not consume water and is not dependent upon a pre-determined environmental pressure to function. The model then compares the heat that the radiator needs to reject (q_{tot}) to the maximum amount that the radiator could possibly reject ($q_{rad,Max}$) and determines whether or not the radiator alone can handle the heat rejection. If the radiator can handle it ($q_{tot} < q_{rad,Max}$), then the thermal control valve for the sublimator (TCV2) is turned off and the model iterates to find how much water should go through the radiator in order to reject q_{tot}. The iteration process varies the setting of TCV1 from fully closed to fully open and at each step calculates the amount of water going through the radiator ($\dot{m}_{rad}$), the amount of water bypassing the radiator ($\dot{m}_{rad,bypass}$), and the temperature at the outlet of the radiator ($T_{rad,out}$). The setting for TCV1 is determined when the temperature at the outlet of the radiator ($T_{rad,out}$) equals the desired temperature at the outlet of the thermal subsystem ($T_{Water,Out}$).

In the case where the radiator cannot handle the heat load ($q_{tot} > q_{rad,Max}$), then all of the water first goes through the radiator and the model iterates to see how much additional water must go through the sublimator in order to reject a total of q_{tot}. The model then iterates the settings of TCV2 from fully closed to fully open and finds the flow rate of the water going through the sublimator ($\dot{m}_{sub}$), the rate of the water bypassing the sublimator ($\dot{m}_{sub,bypass}$) and the temperature at the outlet of the sublimator ($T_{sub,out}$). As with TCV1, the setting for TCV2 is determined when the temperature at the outlet of the sublimator ($T_{sub,out}$) equals the desired temperature at the outlet of the thermal subsystem ($T_{Water,Out}$). If the sublimator is activated, model then uses the duration of the EVA stage to calculate how much water the sublimator consumed during the current phase (rest, light work, etc.). This process is then repeated for each of the five values of metabolic rate and a total amount of water consumed is added to the system mass.

The thermal model assumes that the system is in steady state, that all components are adiabatic except the radiator and sublimator, and that the specific heat of water is constant over the temperature range. The thermal subsystem also assumes that the

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radiator is a grey body radiating to a black body enclosure and that the temperature of the water in the radiator is the average of the radiator inlet and outlet temperatures.

In order to validate the model, published results from a similar spacesuit thermal model were used.[36] The thermal subsystem model outputs were compared to the Campbell, et al. model outputs for the Mars nominal environmental case (Table 12 and Table 13). The Campbell model calculates the temperature of the water into the thermal unit ($T_{water,In}$) whereas the model presented in this chapter uses an empirical relationship based upon the crewmember metabolic rate to find this value. Because of the slight difference in assumptions between the two models, the total amount of heat that the thermal model must reject is slightly different. The large difference in TCV2 settings can be explained by the fact that the heat rejected by the sublimator is not very sensitive to the TCV setting. Conversely, the TCV setting is very sensitive to the amount of heat that is rejected. Other than this one discrepancy, the values for the model match well with the published, validated Campbell data. The amount of water consumed by the sublimator was also validated. For a strenuous, 8-hour EVA in micro-gravity, the model predicts the crewmember will consume 3.4 kg of water, very close to the EMU's value of 3.6 kg.[37]

Table 12. Thermal Model Validation, P_{CM} = 275 W

	Campbell[8]	Model	% Error
q_{rad}	157	164	4
q_{sub}	84	64	24
TCV1	0.97	1	3
TCV2	0.07	0.03	57
$T_{water,In}$	23.6	24.15	2

Table 13. Thermal Model Validation, P_{CM} = 400 W

	Campbell[8]	Model	% Error
q_{rad}	141	147	4
q_{sub}	230	206	10
TCV1	1	1	0
TCV2	0.35	0.12	66
$T_{water,In}$	18.39	18.9	3

5.4.3 Structural Model

Of the four spacesuit model subsystems, the structures subsystem most influences each model objective. This subsystem is primarily responsible for determining the mass and stowage volume of the spacesuit and solely determines the suit's operating pressure and PBT. The structures subsystem models the spacesuit garment and uses published data with physics-based modeling to determine the mass, volume, mobility, and pre-breathe time for the spacesuit garment. As explained in 3.3.5, the amount of work a crewmember must do to move any joint increases with the pressure inside the suit. In a hard suit, the joints are isovolumetric, so the crewmember does not have to do any work to compress the gas inside the suit. Consequently, joint torques are not a function of pressure in a hard suit and their magnitudes are reduced. In order to model PBT as a function of pressure, the model assumes that the vehicle pressure will be 101 kPa and uses an empirical relationship.[180]

Of approximately twenty spacesuit joints, the model focuses on the mobility of the seven outlined in Table 14. These seven joints provide mobility for most movements and cover the three major sections of the suit, the arms, legs, and torso. Based upon the division of the spacesuit into these three segments, five possible spacesuit hardness fractions are defined, detailed in Table 15. Even though it might seem reasonable to model percent hardness as a continuous variable, this does not make physical sense. No spacesuit design would have just one hard arm or leg, for example. Discretizing the hardness fraction in this manner allows the model to capture the designs of all existing or past spacesuit designs (about ten in all).

Table 14. Suit Mobility Body Section Breakdown

Arms	Elbow flexion/extension
	Shoulder flexion/extension
	Shoulder abduction/adduction
Legs	Hip flexion/extension
	Hip abduction/adduction
	Knee flexion/extension
Torso	Torso rotation

Table 15. Suit Hardness Description

% Hardness	Description
0	completely soft suit, I-Suit concept
0.3	hard upper torso (HUT), soft limbs
0.5	hard arms, HUT, soft legs
0.8	soft arms, HUT, hard legs
1	completely hard suit, AX-5 concept

Because the values for range of motion and joint torque depend upon detailed factors such as friction between fabric layers, patterning of the soft joints, and the specific design and materials used in the bearings, the model uses empirical data for joint torque and range of motion. The I-Suit concept, A7LB, EMU, and D-Suit concept all had soft arms and legs and had published data on range of motion and torque.[185,186] The AX-5 concept was a completely hard suit and also had published range of motion and torque data.[187] Finally, hard upper torso data was available for the EMU only. Ranges of motion and torque values were averaged for joints that had multiple data points. The stowage volume and mass data also came from these sources.

As mentioned, torque is a function of pressure for soft spacesuit joints. In order to model the relationship between joint torque and pressure, the subsystem implements a physical model of soft spacesuit joints, using the membrane model developed by Fay and Steele[188] and validated by Schmidt, et al.[35] The membrane model models the joint as a cylindrical tube and treats the spacesuit fabric wall as an inextensible layer that wrinkles when bent. Using this physical model, a relationship between the joint torque and suit pressure was derived. Even though joint torque is a function of flexion angle, the model assumes a single value for the torque of each joint.

In order to define the mobility metric, the structures subsystem uses normalized range of motion and torque values for each joint as well as weighting factors determined by the environment. For all environments, mobility in the upper body and torso is important to be able to accomplish most tasks. In microgravity, stiff spacesuit legs are beneficial because the astronaut is often locked into a foot restraint and can use the stiff lower torso to counteract the forces imposed on the suit by the EVA activities. Conversely, on the Moon and Mars lower body mobility is important for locomotion and tasks where the

crewmember must bend their legs (accessing the planetary surface, sitting in a rover, e.g.). First, the range of motion values for the arms, legs, and torso were linearly normalized between 0 and 1, with 0 representing the lowest range of motion and 1 representing the highest. Next, the torque values were normalized, but this time 0 represented the highest torque and 1 represented the lowest. Assuming that range of motion and torque are equally weighted and each individual joint is equally important, the mobility objective is as follows:

$$mobility = w_{arms}(ROM_{arms} + Torque_{arms}) + w_{legs}(ROM_{legs} + Torque_{legs}) + w_{torso}(ROM_{torso} + Torque_{torso}) \qquad (4)$$

Each of the range of motion and torque variables can take on a maximum value of 1, which represents the best possible range of motion and lowest torque. For example, in the Moon or Mars environment, mobility is desired in the entire suit so w_{arms}, w_{legs}, and w_{torso} are all equal to 1. In this case, a mobility metric of 6 represents the best possible suit mobility. In the microgravity environment, $w_{legs}= 0$ because leg stiffness is desirable so a mobility metric of 4 represents the most mobile suit. By this metric, the mobility of the EMU in microgravity is 2.9 whereas the mobility of an all-hard suit scores a perfect 4.

Because the mobility metric output was based on empirical data, with the exception of the relationship between joint torque and pressure, validation was unnecessary. The empirical model used to determine the PBT is slightly different than that used by the EMU community and predicts a PBT of 4.67 hours for a spacesuit at the same pressure of the EMU, a 14% error from the actual EMU pre-breathe time of 4 hours.

5.4.4   Power Module

The power module outputs the mass, volume, and thermal output of the power subsystem for a space suit. The module is also capable of modeling reserve power for contingency purposes. The module is capable of modeling all of the energy storage options in Table 16.[189-191]

In order to determine the necessary capacity of the spacesuit batteries, one must consider the power requirement, the time during which power is required, the depth of discharge of the battery (DOD), as well as a transmission efficiency (*n*). The following

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Table 16. Power Options for Spacesuit

Energy Storage	Energy Density [W-hr/kg]	Volumetric Density [W-hr/L]
Batteries (NiCd)	35	80
Batteries (NiH$_2$)	60	60
Regenerative Fuel Cells	~1000	~35
Batteries (NiMH)	60	100
Batteries (Lithium-Ion)	170	400
Batteries (AgZn)	130	240
Li-Solid Polymer Electrolyte	200	375
Li-Solid Polymer Inorganic Electrolyte	200	300

equation outlines this calculation:[192]

$$C = \frac{(P_{demand} * t_{EVA})}{DOD * n} \tag{5}$$

where C is the battery capacity, P_{demand} is the power needed from the other suit subsystems, and t_{EVA} is the EVA duration. To determine the mass and volume of the battery, the following two equations are used:

$$m_{batt} = \frac{C}{energy\_density} \tag{6}$$

$$V_{batt} = \frac{C}{volumetric\_density} \tag{7}$$

where m_{batt} is the mass of the battery and V_{batt} is the volume of the battery. In addition to determining the mass of the batteries themselves, one must also take into consideration the power management and distribution hardware which is approximated using the following rule of thumb:[192]

$$m_{PMAD} = 0.02 * P_{demand} + 0.025 * P_{demand} \tag{8}$$

The power subsystem assumes that the power for the spacesuit will be provided by batteries (i.e. energy storage) rather than primary power generation methods such as solar arrays or fuel cells. The model also assumes that the transmission efficiency between the battery and the load is 0.9 and that the power management and distribution mass includes all of the necessary wires and electronics to distribute the power. In order to validate the power module, known data for the EMU 2000 Series AgZn Batteries was used. The average power used by the EMU primary battery was inputted (63.8 W) and an EVA duration of 8 hours and the model predicted the mass and volume of the battery within five percent.

5.5 Utility and Limitations of the Spacesuit Model

This thesis views the spacesuit as an integrated multidisciplinary system that should be designed using optimization approaches similar to those used for primary space systems such as the habitat or vehicle. In order to accomplish this task, the EVA community should begin by building an integrated, multidisciplinary model of the spacesuit. The model presented in this chapter has many limitations and is not intended to be the ultimate spacesuit model, but represents a starting point for future development.

One limitation of this model is the overwhelming effect the spacesuit hardness variable has on the mass and stowage volume objectives. A more advanced model could demonstrate the effect choices like backpack packaging and oxygen tank pressure have on the suit and could generate more accurate values for mass and stowage volume. However, none of these design variables have competing objectives and subsequent optimization would merely select the lightest materials, most compact geometry, and highest possible tank pressure. The current model does capture the tradeoff between a hard, mobile garment with high mass and volume and a soft, light, and compact garment with low mobility. It is this area of uncertainty that subsequent optimization routines explore.

In this chapter, a multidisciplinary spacesuit model was developed and validated against the EMU. The next chapter will use this model to conduct a series of multi-objective optimization studies across a variety of environments in order to help determine how to best design the next-generation spacesuit.

6 Multi-Objective Spacesuit Design Optimization

The previous chapter described the development of a multidisciplinary spacesuit model that evaluated spacesuits on the basis of mass, stowage volume, pre-breathe time, and mobility. This chapter uses that model to explore spacesuit architectures. First, a sensitivity analysis is performed to gauge the effect of the design vector and parameters on the objective functions. Second, a single point optimization is performed in the Mars normal environment using an *N*-Branch Tournament Genetic algorithm. Finally, this optimization is performed in a variety of environments and differences in the optimal design vector are discussed.

6.1 Sensitivity Analysis

Sensitivity analysis is an important precursor to optimization because it helps to capture the effect of the model assumptions and inputs to the objective functions. The effect of the design vector was measured for an 8-hour, moderate EVA in the normal Mars conditions. The initial design vector had a suit pressure of 56.4 kPa, hard legs and upper torso (corresponding to a hardness of 0.8), power technology of AgZn, and CO_2 removal technology of LiOH.

The sensitivity analysis shows that a 10% decrease in spacesuit pressure causes the PBT to increase from less than five minutes to almost an hour and the mobility to improve by 2%. The sharp increase in PBT reflects the extra time needed for the body's tissues to release nitrogen. The sensitivity of the objective functions to the remaining

discrete design variables was determined in comparison to the next most similar option. For example, increasing suit hardness from hard legs and upper torso (hardness of 0.8) to hard arms, legs, and upper torso (hardness of 1), increases volume by 20% and mass by 16%. Changing the power option only has an effect on volume and mass of about 5%. Finally, changing the CO2 removal technology increases mass by 8%. Overall, the sensitivity analysis indicated that the objective functions are substantially affected by the choice of suit pressure and suit hardness and less affected by CO2 removal technology and battery technology choice. The results of the sensitivity analysis are shown in Table 17.

Table 17. Sensitivity Analysis

Pressure (kPa)	Power	Hardness	CO_2 Removal	Mobility	Volume (m^3)	Mass (kg)	PBT (hr)
56.489	AgZn	0.8	LiOH	4.55	0.71	150	0.02
50.84	AgZn	0.8	LiOH	4.62	0.71	150	1.01
56.489	RFC	0.8	LiOH	4.55	0.72	143	0.02
56.489	AgZn	1.0	LiOH	6.0	0.85	172	0.02
56.489	AgZn	0.8	Metox	4.55	0.71	162	0.02

A second analysis was performed to gauge the sensitivity of the objective functions to the parameters of EVA duration, planet, temperature, and crew workload. Cutting the EVA duration in half only causes an decrease in volume and mass on the order of 1%. This is due to the fact that the major determinants of mass such as suit hardness and backpack structure are fixed and overwhelm the slight increase in water and oxygen mass needed for a longer EVA. Increasing the ambient temperature or metabolic rate increases the mass less than 1% because the astronaut must carry more cooling water. Finally, changing the planet from Mars to the Moon has little effect on the mobility metric. However, a change from Moon or Mars to micro-gravity changes the mobility metric substantially because lower-body mobility is desirable on planetary surfaces but not in microgravity where a stiff lower body is advantageous in establishing a stable work platform. In summary, the design variables have a greater effect on the objective functions than the parameters. The spacesuit hardness design variable has an overwhelming effect on mass and volume.

6.2 Single Point Optimization

This section describes the optimization methods used on the model and gives results for an optimization performed for an 8-hour, moderate EVA on an average Mars day. First, the model set-up for optimization is given, and then the genetic algorithm method is described. Finally, the results are discussed.

6.2.1 Model Configuration for Optimization

As described in sections 5.3 and 5.4.3, the spacesuit hardness design variable has an overwhelming effect on mass and volume. Although mass and volume are normally competing objectives (a smaller volume usually indicates a high density and therefore high mass), because the spacesuit garment is a hollow, hard shell, mass and volume are directly related. Initial four-objective optimization using the *N*-Branch Tournament Genetic Algorithm (described in section 6.2.2), revealed this trend. Figure 12 is a two-dimensional slice of the four-dimensional Pareto front showing the relationship between mass and stowage volume. Each design falls near the y = x line indicating that the mass and stowage volume objectives are not competing with each other.
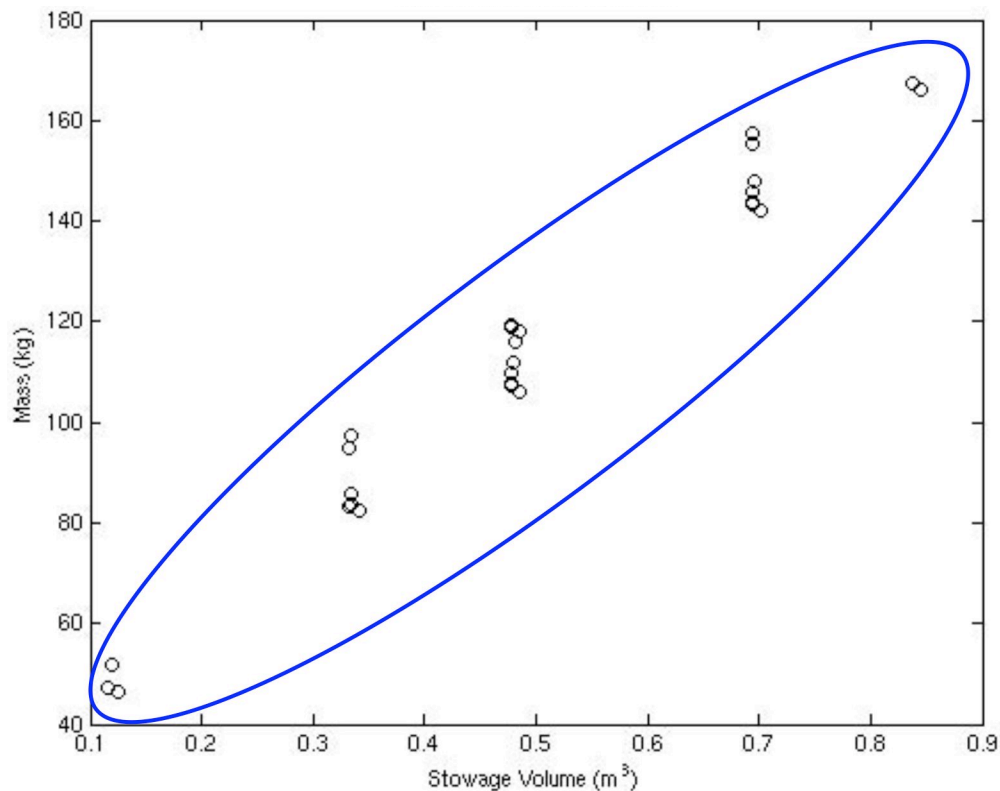

Figure 12. Pareto Front for Mass and Stowage Volume

Because the mass and stowage volume objectives are not competing with each other, the stowage volume objective is eliminated from the objective function:

$$J(\mathbf{x}) = \begin{bmatrix} mass \; [\text{kg}] \\ -mobility \; [0-6] \\ PBT \; [\text{hr}] \end{bmatrix} \tag{9}$$

where $\mathbf{x}$ is the design variable vector

$$\mathbf{x} = \begin{bmatrix} P_{suit} \\ PowerTechnology \\ CO_2RemovalTechnology \\ HardnessFraction \end{bmatrix} \tag{10}$$

Therefore, the problem formulation becomes:

min $\quad J(\mathbf{x}, \mathbf{p})$

such that $\quad 25 \text{ kPa} \le x_1 \le 101 \text{ kPa}$

$$x_2 = 1, 2, 3, 4, 5, 6, 7, 8 \tag{11}$$

$$x_3 = 1, 2$$

$$x_4 = 0, 0.3, 0.5, 0.8, 1$$

where $\mathbf{p}$ are the model parameters

$$\mathbf{p} = \begin{bmatrix} Environment \; [1\text{-}8] \\ EVA_{duration} \; [\text{hr}] \\ MR \; [1\text{-}3] \end{bmatrix} \tag{12}$$

Here, the environment parameter includes information on the planet and temperature conditions and the metabolic rate (MR) profile as described in section 5.2, Table 8 and Table 9. This problem formulation was used for all of the optimization and analysis presented in the rest of this chapter.

6.2.2 Genetic Algorithm Overview

The genetic algorithm (GA) is a heuristic search technique that mimics Darwin's theory of Natural Selection and the principal of Survival of the Fittest.[193] It begins with an initial population of randomly generated design vectors for an engineering system, evaluates them on the basis of the objective and constraint function values, and selects

the designs that perform the best to mate and populate the next generation.[194] The GA incorporates parent selection, crossover or mating, and mutation operators to match the behavior of biological populations in their evolutionary processes (Table 18). The GA approach is most applicable to spacesuit optimization because of its ability to handle discrete and continuous design variables and nonlinear design space.[193] Discrete design variables such as power and CO2 removal technology switches prohibit the use of gradient-based techniques.

Table 18. Genetic Operators

Genetic Operator	Type
Selection	N-Branch Tournament
Crossover	Uniform
Mutation	Small rate ($< 1\%$)

Multi-objective optimization differs from single objective optimization in that there are numerous designs that satisfy the objectives equally well. With a single objective, the design that best fulfills this objective is the most favorable. However, with multiple objectives, it is possible to have a family of designs that fulfill the objectives in different ways and represent tradeoffs between the objectives. To take a simple example, imagine that you wanted to purchase a new car and your objectives were to maximize performance and minimize cost. You could choose to buy a new car with great performance at a high price or an old car with okay performance at a much lower price. Neither of these cars is clearly favored and which one you choose depends on how you value cost versus performance. In the nomenclature of optimization, these two cars are *non-dominated*. A solution to an optimization problem is non-dominated if no other solutions exist that rate better on all objectives simultaneously. In our car example, the new car has a higher cost than the old car, but it also has a better performance so the new car is not dominated by the old. The set of all non-dominated solutions to an optimization problem is called the Pareto set. At the completion of a genetic algorithm search, the designer has a family of non-dominated solutions, which allows the decision maker to choose the ultimate design based on how they value the objectives relative to each other.

The *N*-branch tournament selection approach was adopted to solve this three-objective spacesuit optimization problem because it does not evaluate the designs based upon a

single meta-objective that is a combination of each individual objective.[195] Rather, *N*-branch tournament selection establishes a competition during which a number of members of the population compete based on a fitness value associated with each objective. The optimization algorithm is described in Figure 13.
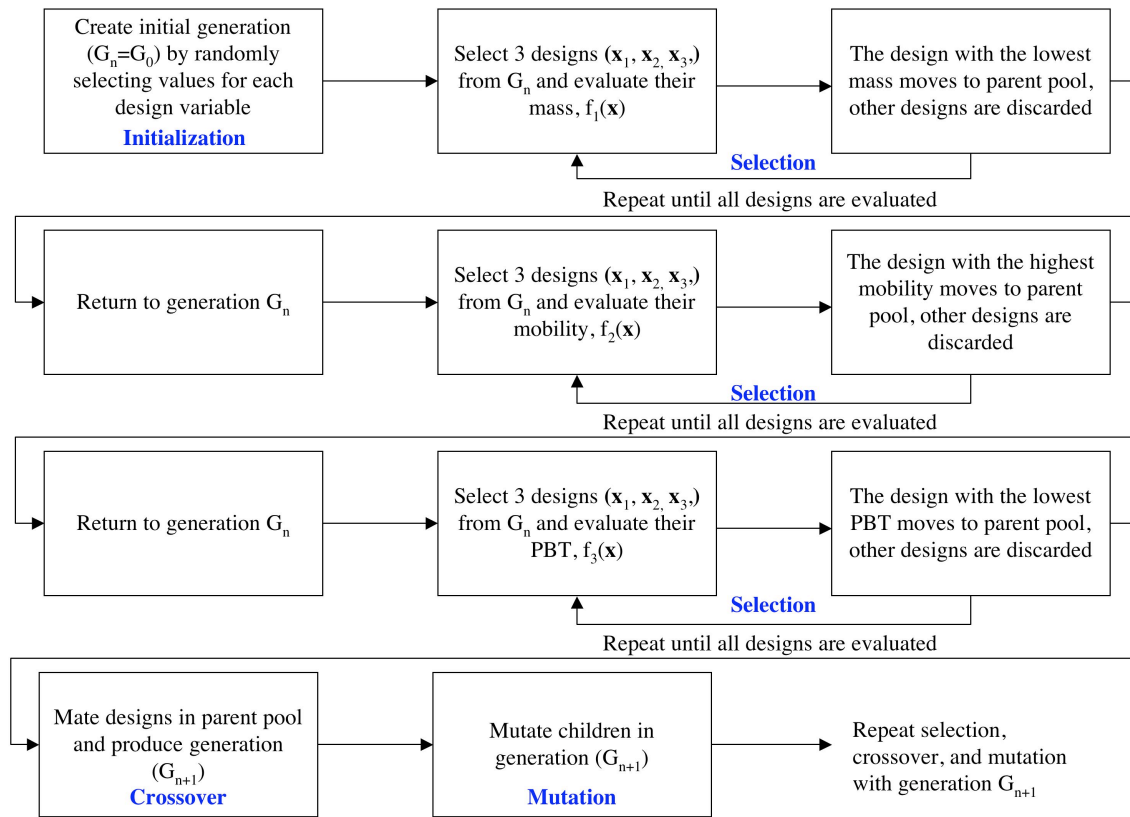

Figure 13. Genetic Algorithm Process Including *N*-Branch Tournament Selection

In the first step, an initial generation of designs are created by randomly choosing values for each design vector variable within the specified bounds. Next, three of these initial designs are selected and compete based upon mass. The design with the lowest mass is placed into the parent pool and this process is repeated until all the original designs have competed. At the end of this round, one third of the designs will be in the parent pool. Then, all the initial designs are restored and compete three-at-a-time based on mobility. This process is repeated once more for PBT. At the end of this process, the parent pool is the same size as the initial population; however, the parent pool now contains up to three copies of each initial design vector. The final two steps are crossover and mutation. In crossover, designs from the parent pool are selected two-at-a-time and

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their design vectors swapped to produce the next generation. Each child then has the possibility of having its design vector randomly mutated. The mutation step helps to keep the algorithm from getting trapped in local optima. The selection, crossover, and mutation steps are then repeated for a pre-determined number of generations. The resulting solutions are then passed through a Pareto filter to eliminate the dominated solutions and determine the Pareto set.

6.3 Results for Single Point Optimization

For the first optimization, the model parameters were set to a moderate, 8-hour EVA in an average Mars climate. After running the GA for 400 generations and passing the solutions through a Pareto filter, the algorithm converged on 123 spacesuit deigns, any of which could be considered the "best" design depending on the relative importance of the objectives. Because there are three objectives, the family of non-dominated solutions creates a surface in three-dimensional space. The three-dimensional plot of the Pareto front as well as three, two-dimensional plots are shown in Figure 14. The utopia point represents the best possible design (high mobility, low mass, and low PBT). Five designs are highlighted in each plot and the corresponding objective function evaluations and design vectors are shown in Table 19.

This set of non-dominated designs helps the spacesuit engineer to better understand the tradeoffs in designing a spacesuit. There is no one design that is a clear winner and each design involves sacrificing to some extent one or more of the objectives. For example, the plots show general trends such as the direct relationship between mass and mobility and between pre-breathe time and mobility. This is because increasing the mobility generally involves adding bearings to the suit joints (increasing mass) or decreasing the suit pressure (increasing PBT). One of the most striking characteristics of the plots in Figure 14 is the striations in the data. The two-dimensional plots of PBT and mass and PBT and mobility show three long lines of points as well as an outlying point on the x-axis (point 1). These groups of points correspond to the different possible values of the spacesuit hardness variable. This design variable strongly influences mass and volume, creating the distinct sections in the Pareto front.

The points in Table 19 were selected to show designs across the spectrum of the Pareto front. Point 1 is an all-hard suit operated at a high pressure. Because of its
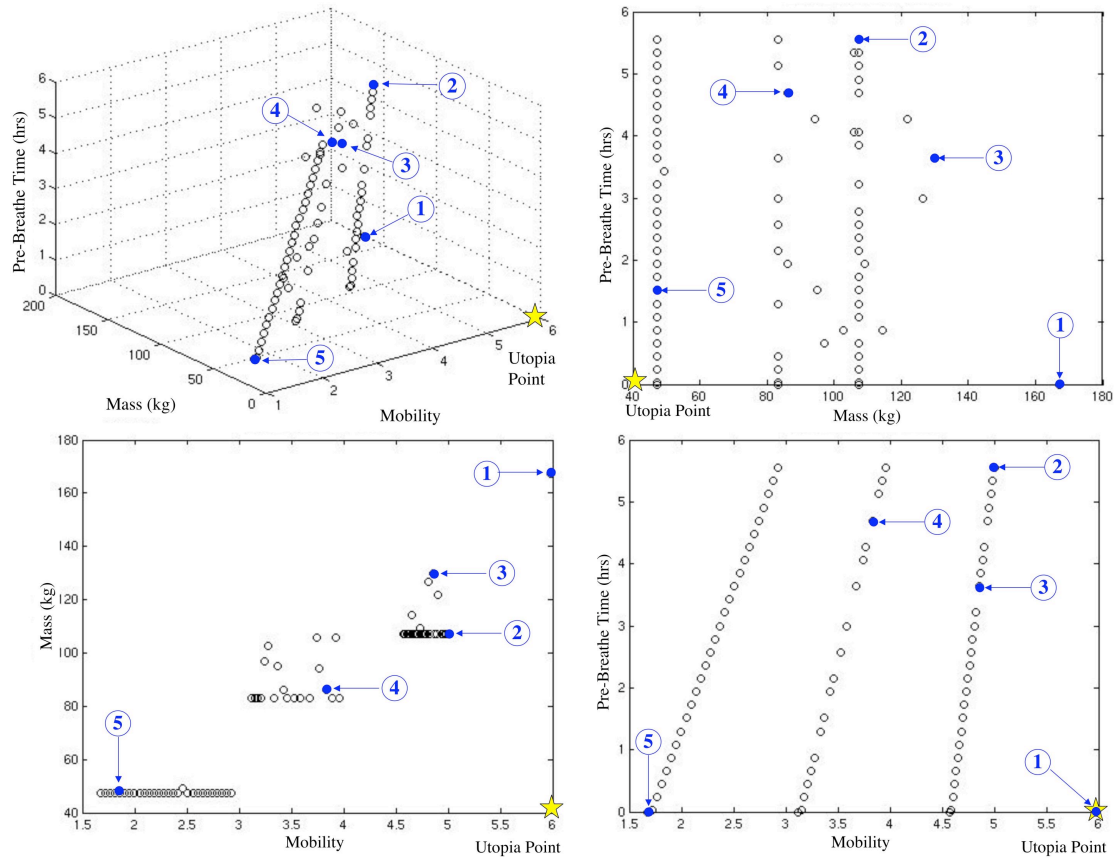
Figure 14. Spacesuit Optimization Pareto Frontiers for Mars Average

Table 19. Points on Pareto Front for Mars Average

Point	Mobility (0-6)	Mass (kg)	PBT (hr)	Pressure (kPa)	Power Technology	CO$_2$ Tech.	Hardness
1	6	167	0	101	Fuel Cell	LiOH	all hard
2	5	107	5.6	25	Fuel Cell	LiOH	hard arms, HUT, soft legs
3	4.9	130	3.6	35.9	NiMH Battery	Metox	hard arms, HUT, soft legs
4	3.8	86	4.7	29.8	Li-Solid Polymer Inorganic Electrolyte	LiOH	HUT, soft arms and legs
5	1.7	47	0	57.7	Fuel Cell	LiOH	all soft

configuration, it scores a perfect 6 on mobility and has no PBT, but has the highest possible mass. Point 2, a low-pressure suit with hard arms and a HUT, is excellent on mobility and mass, but sacrifices PBT. Suit 3 is similar to Suit 2, but has a slightly higher operating pressure, which increases its PBT. Suit 5 is an all soft suit, operated at a relatively high pressure. This suit sacrifices mobility for PBT and mass. All of these suits (points 1, 2, 3, and 5) score well on two objectives, but poorly on the third. Suit 4, a low-pressure suit with a HUT, strikes a compromise between the three objectives, scoring medium on mass, mobility, and PBT. Most of the suit designs use LiOH for CO_2 removal and fuel cells for their power. This is because LiOH offers a weight savings over Metox and the fuel cell technology is the most energy dense of all the technologies. It is interesting to note, however, that not all designs along the Pareto front have these options. This is due to the mutation aspect of the GA and emphasizes the point that the GA cannot guarantee that it will find the global optima. It is not immediately clear which of the suits in the Pareto frontier is the "best." Indeed, the final selection will depend upon how the decision maker chooses to trade the objectives.

It is interesting to note that no spacesuit designs with a hardness of 0.8 (HUT, hard legs, soft arms) are in the Pareto front for the Mars environment. This is due to the fact that for Mars, mobility for the arms and legs are weighted equally. Therefore, a spacesuit with poor arm mobility, but good leg mobility is equivalent to a spacesuit with good arm mobility and poor leg mobility. At any given pressure, the mobility metric of a suit with hard arms and soft legs (hardness fraction of 0.5) is the same as the mobility metric of a suit with soft arms and hard legs (hardness fraction of 0.8). However, the suit with hard arms and soft legs (0.5) weighs less than the suit with soft arms and soft legs (0.8) and the two suits have the same mobility and pre-breathe time so the lighter suit always dominates the heavier suit, eliminating it from the Pareto front. This result would not be the same if upper and lower body mobility were valued differently.

This initial investigation suggests that the power and CO2 removal technologies have little impact on the spacesuit architecture, whereas suit hardness and suit pressure have a far greater impact. Often suit pressure and hardness are determined at the beginning of the design effort and these early choices greatly influence the overall characteristics of

the spacesuit. These results should be useful in the design of the next generation of spacesuits.

6.4 Multi-Environment Optimization

Until this point in the analysis, only spacesuits designed to operate in the Mars environment have been considered. However, spacesuits are used in multiple environments and for multiple purposes including microgravity missions (both short and long-term), planetary exploration, EVA, and launch and entry. As described in chapters 3 and 4, system requirements emanating from different environments are distinct and lead to the design of substantially different spacesuits. The purpose of this section is to explore different spacesuit environments, analyze how a spacesuit's optimal design might change for each environment, and determine if certain suit designs might be better suited to operate in multiple environments.

In order to investigate how a spacesuit design might change in a different environment, an optimization analysis similar to that described in section 6.2.2 was performed, but in the microgravity environment. The algorithm converged on 113 designs in the Pareto front and the results of this analysis are presented in Figure 15 and Table 20. One of the major differences between the two Pareto fronts is the mobility metric. In a planetary environment, the mobility metric ranges from 0 to 6 (the arms, torso, and legs can each contribute up to 2 points to the overall metric, see section 5.4.3.) For the microgravity environment, however, the metric only ranges from 0 to 4 because leg mobility is not considered desirable in microgravity. A second difference is in the number of striations seen in the data. The two-dimensional plots show only two majors striations, corresponding to hardness fractions of 0.3 (HUT, soft arms and legs) and 0.5 (HUT, hard arms, soft legs). In fact, no suits with hardness fractions of 0.8 (HUT, soft arms, hard legs) or 1.0 (all hard) are in the Pareto front. The reasons for this choice will be explained next.

The points in Table 20 (and identified in Figure 15) were selected to highlight the similarities and differences in the Pareto fronts for Mars and microgravity. The CO_2 removal technology and power technology variables did not change between the two environments. This is a realistic result as the choice of those technologies depends upon the EVA duration, mission duration, required number of cycles, and desire to reduce
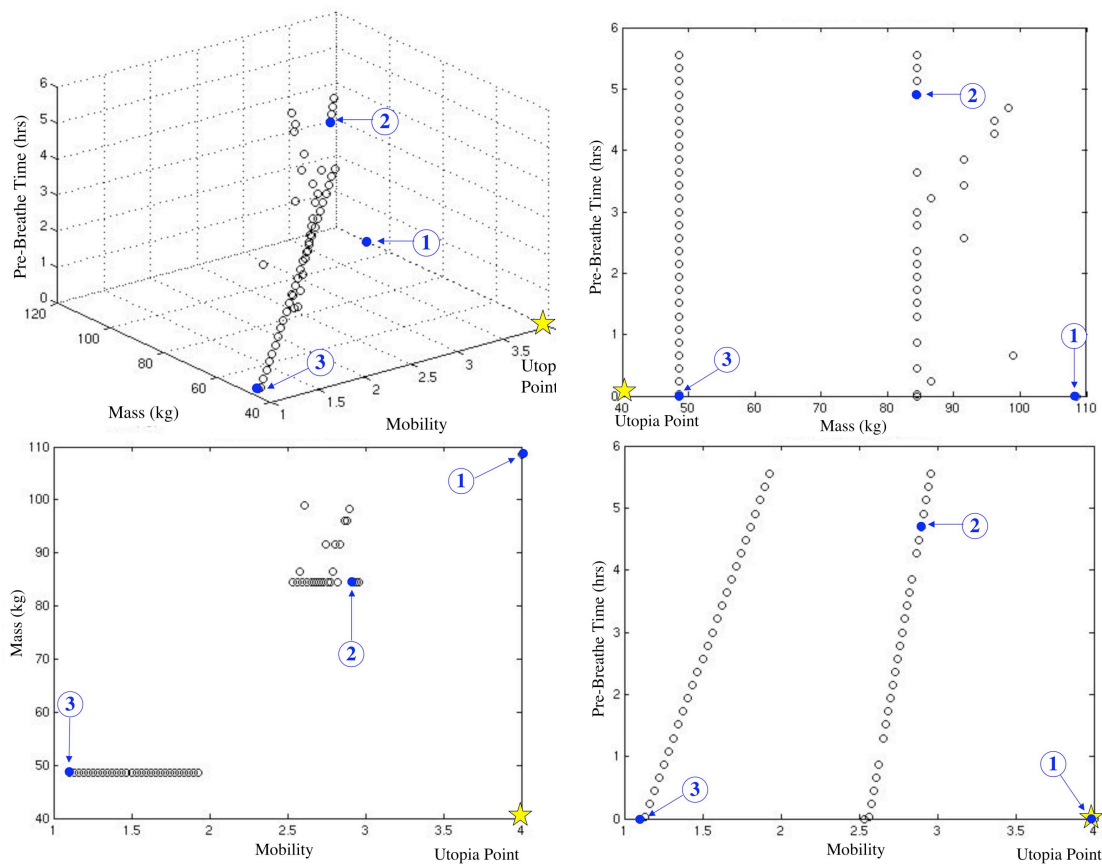
Figure 15. Spacesuit Optimization Pareto Frontiers for Microgravity

Table 20. Points on Pareto Front for Microgravity

Point	Mobility (0-4)	Mass (kg)	PBT (hr)	Pressure (kPa)	Power Technology	CO$_2$ Tech.	Hardness
1	4	108	0	101	Fuel Cell	LiOH	HUT, hard arms, soft legs
2	2.9	84	4.9	28.6	Fuel Cell	LiOH	HUT, soft arms and legs
3	1.1	49	0	57.7	Fuel Cell	LiOH	all soft

mass, none of which varies with location. The interesting changes in the design vector occurred in the hardness variable and spacesuit pressure. As mentioned, no suits with a hardness of 0.8 or 1.0 were in the Pareto front. Both of these types of suits have hard legs, which increases mass by adding mobility in the legs. Since lower body mobility is not optimized in microgravity, designs with hard legs are dominated by designs with soft legs because the soft leg designs have lower mass, equivalent PBT, and equivalent mobility. Also, no suits with a hardness fraction of 0.5 (HUT, hard arms, soft legs) and a pressure lower than 58 kPa are in the Pareto front. For suits with hard arms and soft legs, designs with low pressure have a higher PBT than suits with higher pressure. Because the suits have hard arms and a HUT, mobility is not a function of pressure; therefore, suits with a hardness fraction of 0.5 and low pressure are dominated by suits with a hardness fraction of 0.5 and a higher pressure.

Point 1 in Table 20 has approximately the same objective function evaluations as point 1 in Table 19, but has a different design vector. For both environments, point 1 represents a suit that sacrifices mass for mobility and PBT. In the Mars environment, perfect mobility can only be found in an all-hard suit and low PBT corresponds to a high pressure. For microgravity, perfect mobility can be found in a suit with hard arms and a HUT, of which the lightest is a 0.5 suit (HUT, hard arms, soft legs). Point 2 in Table 20 has a similar design vector and objective function evaluations as Point 4 in Table 19. This point is a design vector similar to that of the EMU. It is quite interesting that the EMU lies on the Pareto front for both the Mars and microgravity environments. In both environments, the EMU has a moderate mass, mobility, and relatively high PBT. Point 3 in Table 20 also has a similar design vector and objective function evaluations as point 5 in Table 19. This point represents a spacesuit that sacrifices mobility for mass and PBT. For both environments, this corresponds to an all-soft spacesuit with a low pressure. Table 21 compares the mobility, mass, PBT, pressure, and hardness fractions of the two points discussed that are included in both Pareto fronts.

Table 21. Comparison of Pareto Points for Mars and Microgravity

Point	% Mobility Mars[a]	% Mobility µg[b]	Mass Mars (kg)	Mass µg (kg)	PBT (hr)	Pressure (kPa)	Hardness
4/2	63	73	86	84	4.7	29.8	HUT, soft arms and legs
5/3	28	28	47	49	0	57.7	all soft

[a] defined by dividing the mobility metric of this design by the maximum possible mobility for Mars (e.g. 3.8/6 = 0.63)
[b] defined by dividing the mobility metric of this design by the maximum possible mobility for microgravity (e.g. 1.1/4 = 0.28)

From this analysis, one can conclude that the optimal spacesuit garment design might or might not be different for different environments, depending upon how the decision maker weighs the objective functions relative to each other. For example, we have seen that optimizing mobility and PBT while allowing mass to be unconstrained, leads to different garment designs in the microgravity and planetary environments. However, valuing mass and PBT over mobility or valuing all three objectives the same can lead to similar garment designs.

7 Conclusion and Recommendations for Future Work

7.1 Summary and Contributions

The ability for crewmembers to perform spacewalks is an essential component of human spaceflight. The current goals of the U.S. space program call for a return to the Moon and eventual human exploration of Mars. In this next era of planetary exploration, spacesuits will play an important role, enabling astronauts to interact with their surroundings and helping them to accomplish the scientific and engineering goals of the mission. The main purpose of this thesis is to aid the designers of the next-generation spacesuit through rigorous analysis of existing spacesuits and quantitative optimization of future spacesuit architectures.

Because spacesuits change substantially over their design lifetimes, the next-generation spacesuit must be designed with the ability to cope with the likelihood of changing requirements after it has been fielded. This goal, as I have shown in this thesis, can be accomplished in two steps: first, the system designer must have an understanding of what requirement changes are likely to occur; second, quantitative analysis can be used to determine how requirement changes affect the design and subsequently what designs can more readily accommodate change. My thesis was divided into two parts to address these two steps. Part I was qualitative in nature and presented a snapshot of spacesuits in time as well as their evolution in time. Part I consisted of Chapter 2, An Integrated Systems Approach to Spacesuit Design, Chapter 3, Understanding Change and

Requirements Evolution in the Design of the EMU, and Chapter 4, Comparative Analysis of the U.S. EMU and Russian Orlan Spacesuits.

The objective of Chapter 2 was to understand the spacesuit in the context of EVA and study what the technical community has written about spacesuit design. The traditional approach to EVA has customarily focused on, and sought to optimize, individual pieces of hardware in isolation of the rest of the system. By having a component focus, the traditional approach has often introduced inefficiencies into the system, generated logistics and supply management problems, and created hardware legacies that are hard to change and upgrade. In its stead, Chapter 2 presented an integrated systems approach for EVA system design that can aid the development of an exploration-class EVA system by optimizing the system as a whole and designing for uncertainty. Because designers have limited a priori knowledge of what explorers might encounter on the surface of the Moon or Mars, it is necessary to design a system capable of adapting to changes in requirements based upon what we discover and how the environmental uncertainty unfolds. Flexibility can be added to the system via hardware design (e.g., modularity), software implementation, crewmember training, and procedure development. Although it is not possible to anticipate each uncertainty, a flexible system will meet changing requirements and be capable of incorporating advances in technology with minimal performance and resource (e.g., mass, volume, and cost) penalties.

Chapter 3 looked at the evolution of the American EMU spacesuit over time. The chapter began by challenging the common presumption that requirements change should be avoided and proposed a new attitude toward change. Rather than artificially freezing requirements, system designers should acknowledge that change is inevitable in the design of any long lifetime system and design their systems to be able to adapt to this change. Chapter 3 then examined the history of the EMU, described its major components and functions, and discussed the baseline environment in which the spacesuit was initially designed to operate. Fundamentally, the EMU was conceived as a limited-capability spacesuit to be used in emergency situations. However, immediately after it was fielded, NASA began to make changes to the EMU for a variety of reasons. The final section in Chapter 3 explored the implications of the decision to modify the Shuttle EMU for use aboard the ISS, and the resulting requirements and design changes. Chapter 3

concluded by observing that, given the number of requirement and design changes that occurred in the EMU, the next generation spacesuit, which will likely be fielded for a decade or two, will have to be designed with the ability to cope with the inevitability of changing requirements after it has been fielded.

Chapter 4, the final chapter in Part I, discussed the design of the Russian Orlan spacesuits and compares their current design and evolution to the design of the EMU. The driving forces behind the variations between Orlan and EMU design are differences in the political, economic, physical, and technical environments of the two suits. These environment differences translated into two distinct sets of requirements, which led to many differences in design and operation. Because the Soviet/Russian program has historically centered upon long-duration, station-based spaceflight, the Orlan was designed to be maintainable on orbit, at the cost of volume and crew time. On the other hand, the American Shuttle program of short, highly intensive missions mandated that the suits require as little on-orbit maintenance and stowage volume as possible, leading to the design of a highly compact and complex spacesuit. Indeed, almost all of the design differences identified in this chapter can be attributed to optimization of the Soviet/Russian spacesuits for station-based flight and optimization of the EMU for the Shuttle. Since the mission timescale of future planetary exploration is on the order of months, the future regime of spaceflight more closely simulates current station-based flight. Because this is the environment the Soviet/Russian program has been operating in for almost thirty years, future EVA systems should incorporate many of the design and procedural strategies used by the Russians. Those strategies that resulted from Russia's focus on station-based spaceflight should be emulated because these changes will help the performance of the next-generation American spacesuit.

Whereas Part I represents the qualitative core of the thesis, the analytic substance is found in Part II. Chapter 5, Development of a Multidisciplinary Spacesuit Model, and Chapter 6, Multi-Objective Spacesuit Design Optimization, bring to bear design optimization techniques used for complex, multidisciplinary systems.

Chapter 5 described the development of a multidisciplinary spacesuit model. Several models currently exist in the literature to describe individual spacesuit subsystems; however, none of these models incorporates all of these disciplines simultaneously.

Although a partial understanding of the operation and performance of a spacesuit at the subsystem level can be attained using existing, single-discipline models, the spacesuit is a highly-interdependent, human-sized spacecraft, and an integrated model is needed to aid in the understanding, design, and operation of the spacesuit as a complex engineering system. This chapter began with an overall description of the model, describing the choice of the design vector, objective functions, and model parameters. The spacesuit design vector consists of a continuous spacesuit pressure variable, and discrete variables that determine the power technology, carbon dioxide removal technology, and spacesuit hardness. The objective functions of the model are suit mass, stowage volume, PBT, and mobility. The model user can set an environment parameter that determines the location (Moon, Mars, or microgravity) and ambient environmental conditions. The user can also set the duration of the EVA and specify a metabolic profile for the spacewalk. Chapter 5 described the interactions between the subsystems and objective functions and noted that the hardness of the spacesuit garment primarily determined the spacesuit mass and volume and solely determined the suit PBT and mobility. The chapter described the development and validation of each model subsystem in detail and discussed the limitations of the model.

Chapter 6 used the spacesuit model to explore optimal spacesuit architectures with respect to the objective functions of mass, mobility, and pre-breathe time. First, a sensitivity analysis was performed and determined that the PBT is very sensitive to the spacesuit pressure, mobility is sensitive to both the suit pressure and hardness, and the mass is sensitive to garment hardness. Secondly, a single point optimization was performed in the Mars normal environment using an *N*-Branch Tournament Genetic algorithm. There is no one design that was a clear winner and each design involved sacrificing to some extent one or more of the objectives. Most optimal designs have a fuel cell and LiOH carbon dioxide removal technology. The designs ranged from an all-hard suit with great mobility and PBT, but poor mass to an all-soft suit with low mass, but poor mobility and PBT. Finally, this optimization was performed in the microgravity environment and differences in the optimal design vector were discussed. This second optimization run chose similar power and carbon dioxide removal technologies, but different spacesuit garment designs. The garments on the microgravity Pareto front were

softer because lower body mobility was not desired. It is quite interesting that the EMU was on the Pareto front for both the Mars and microgravity environments. In both environments, the EMU has a moderate mass, mobility, and relatively high PBT. From this analysis, one can conclude that the optimal spacesuit garment design might or might not be different for different environments, depending upon how the decision maker weighs the objective functions relative to each other. Chapter 6 showed that optimizing mobility and PBT while allowing mass to be unconstrained, leads to different garment designs in the microgravity and planetary environments, while valuing mass and PBT over mobility or valuing all three objectives the same can lead to similar garment designs.

This work builds on the existing spacesuit literature by reflecting upon the spacesuit as one part of a complex, system-of-systems and advocates that the design of the next-generation spacesuit be in full cooperation with the other systems that enable EVA. Additionally, the thesis provided detailed case studies of the change histories of both the American EMU and the Russian Orlan spacesuit. A firm understanding of how each system came to be along with the knowledge of how and why each system changed is essential to designing future spacesuits capable of adapting to change. The final contribution of this thesis is the use of multidisciplinary optimization techniques in spacesuit design. Because the model used for this optimization is multidisciplinary, fundamental tensions in spacesuit design are captured that have not before been explored with existing single-discipline models. Taken as a whole, this thesis offers a comprehensive evaluation of spacesuit design and evolution, from both a qualitative and analytic perspective.

7.2 Recommendations for Future Work

Future work on this topic could expand in two dimensions: (1) deepening the analysis into best practices for the design of the next-generation spacesuit, and (2) extending this work to other complex engineering systems. This section discusses each of these two dimensions and raises questions that could be addressed in future work.

7.2.1   Further Spacesuit Analysis

One clear suggestion for future work would be to add fidelity to the spacesuit model to increase the accuracy of the current subsystems, include more variables in the design

vector, and incorporate more objective functions. The existing subsystems assume that the basic design of the next-generation spacesuit will be similar to that of existing operational spacesuits. However, removing this assumption would allow alternative concepts such as mechanical counter pressure, foam packaging for the life support backpack, and variable stiffness spacesuit limbs to be explored. Adding subsystems could involve the development of a communications module to model the spacesuit radio and telemetry hardware. As an example of an additional objective function, the mass objective could be divided into two parts, single-EVA spacesuit mass and multiple EVA spacesuit mass, both of which would be minimized. The model currently outputs single-EVA mass and so selects lighter technologies (such as LiOH) even though they might only last for a single EVA and be inefficient in the long-term.

A second interesting study would be to interview the spacesuit stakeholders and try to evaluate their preferences for the various objective functions. With multi-objective optimization, it is possible to have a family of designs that fulfill the objectives in different ways and represent tradeoffs between the objectives. Interviewing stakeholders such as crewmembers, mission control personnel, spacesuit engineers, and policymakers could help to eliminate portions of the design space and allow designers to focus on a few promising design vectors. These designs could then be developed in detail to further refine the model's initial estimations of mass, PBT, and mobility.

7.2.2 Extension to Other Systems

Another interesting area for future work would be the extension of the framework presented in this paper to other complex engineering systems. The inefficiencies created by optimizing a single piece of hardware (rather than the entire system) occur repeatedly in design problems. Although this thesis focused on the contribution of the spacesuit to the EVA system, the EVA system is itself one part of an even larger system called Life Support and Habitability. Applying the integrated systems approach to the Life Support and Habitability system could further ease logistics problems and produce mass savings. Because the spacesuit and the vehicle or planetary habitat provide similar functions, one could imagine many commonalities in hardware. Collective design of like components would benefit the system as a whole.

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9 Appendix A – Image Gallery

Astronaut John Glenn with Flight Surgeon Dr. William Douglas and equipment specialist Joe Schmitt prior to the Mercury-Atlas 6 mission. Glenn is wearing his pressure suit, a modified version of the U.S. Navy Mark IV high-altitude suit and carrying a portable ventilation unit. (Image courtesy of NASA S62-00330.

Soviet SK-1 pressure suit worn by Yuri Gagarin during training. Note that this suit, like the Mercury suit, is completely soft. Both suits are worn depressurized during the duration of the mission and only activated in the case of an emergency. (Image courtesy of the Smithsonian Institution 97-15263.)
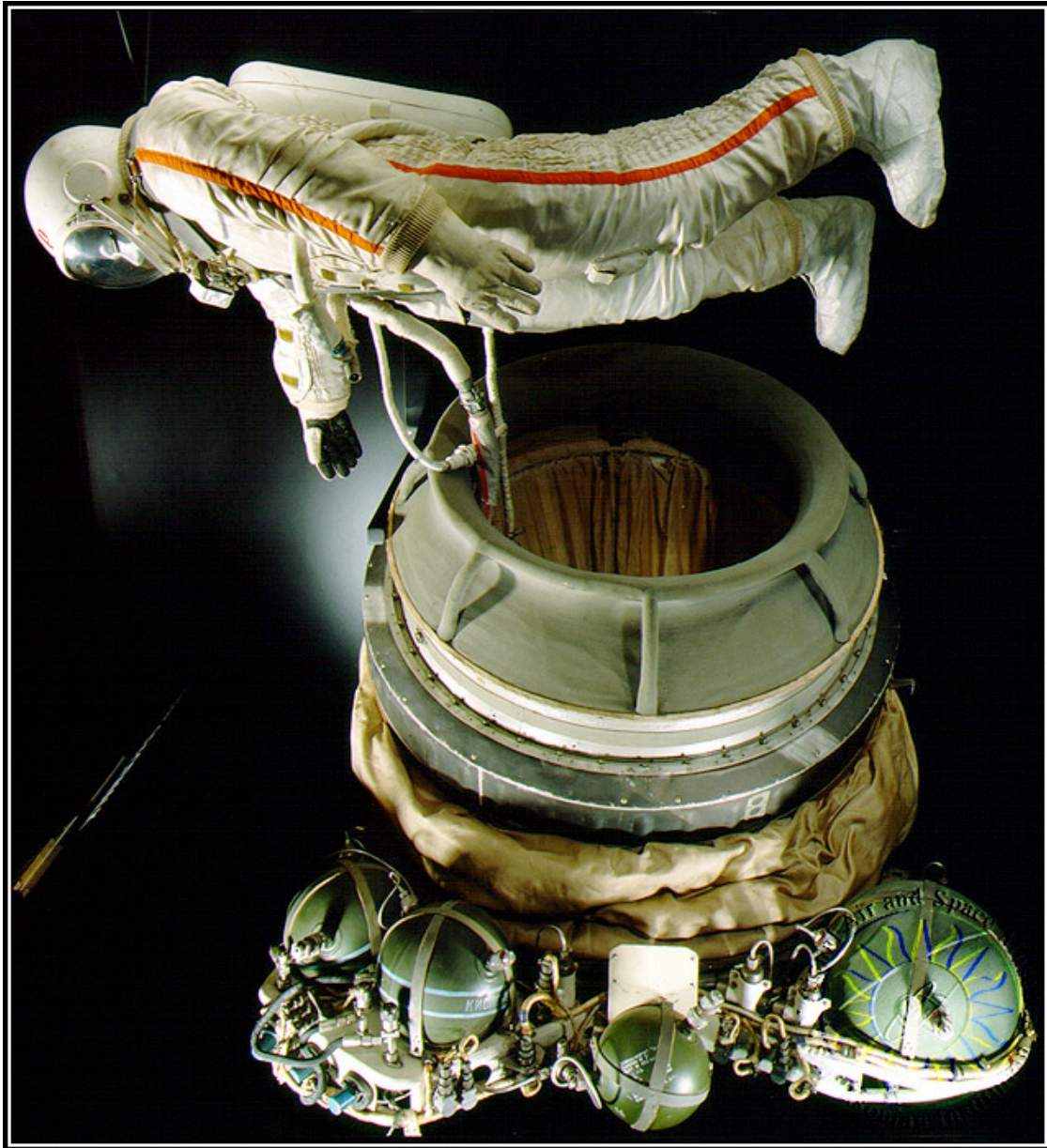
Berkut spacesuit worn by Alexi Leonov in preparation for the world's first EVA on March 18, 1965. The umbilical supplies emergency oxygen, supports communications, and transmits medical and technical data. The suit also has a backpack that supplies primary oxygen. Also pictured is the inflatable airlock used during training for the Voskhod 2 mission. This airlock allowed the vehicle to remain pressurized. (Image courtesy of the Smithsonian Institution 97-16249-12.)
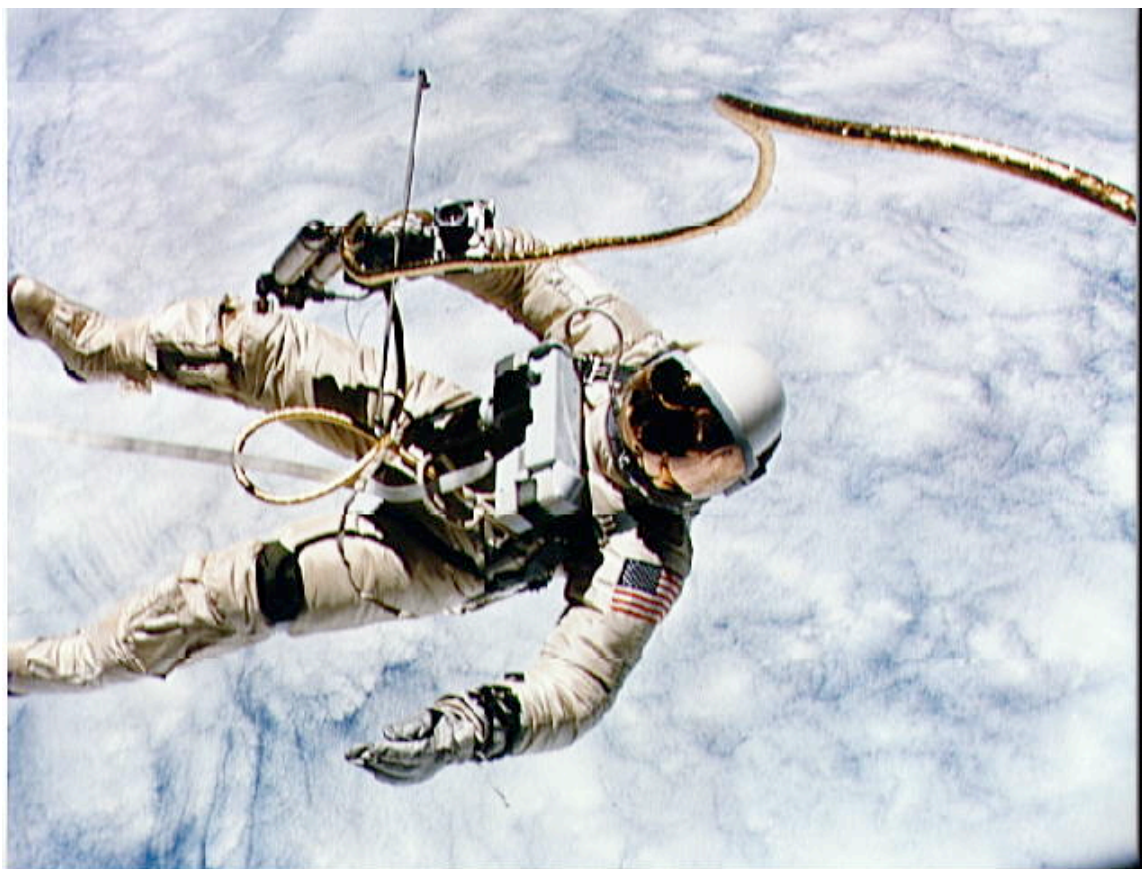
Ed White during the first U.S. EVA on June 3, 1965 wearing his G4C EVA spacesuit. The gold umbilical carries power, oxygen, communications, and medical data and attaches White to the spacecraft. White is carrying a cold gas, hand-held maneuvering unit. Like the Mercury suit, this spacesuit is completely soft and has a close-fitting helmet. White has an emergency oxygen pack strapped to his chest. Because the Gemini spacecraft lacked an air lock, the entire cabin was depressurized, exposing both White and James McDivitt to vacuum. (Image courtesy of NASA S65-30427.)

Soviet Yastreb spacesuit used on the January 1969 Soyuz 4/5 mission in which two cosmonauts transferred from Soyuz 5 to Soyuz 4 using this type of spacesuit. This spacesuit used an umbilical for power, communications, and to transfer medical and technical data. The life support system was worn strapped to the legs so that the crewmembers could fit through the capsule hatch. The life support system included an evaporating heat exchanger that cooled the oxygen circulating around the cosmonauts. (Image courtesy of Andy Salmon.)

Astronaut Buzz Aldrin wearing the A7L spacesuit during Apollo 11. The spacesuit garment is completely soft with the exception of upper arm and wrist bearings. The life support system is worn strapped to the back and includes an oxygen and emergency oxygen supply, CO_2 removal capability, battery, sublimator, and radio. Underneath the spacesuit, the astronaut is wearing a liquid cooling garment, which circulates cool water around the crewmember. (Image courtesy of NASA AS11-40-5903.)
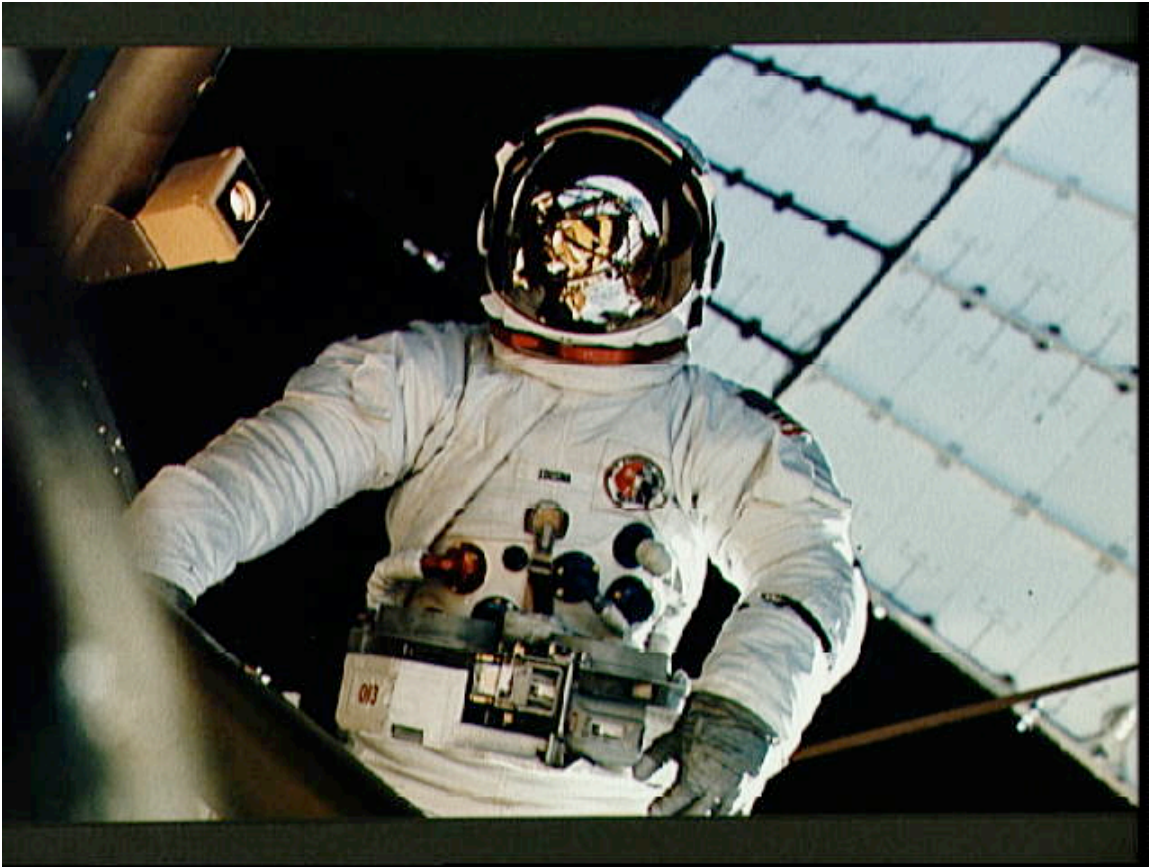
Astronaut Jack Lousma during a Skylab EVA on August 6, 1973. This spacesuit is a version of the Apollo A7L-B suit, modified to use an umbilical rather than a Portable Life Support System (PLSS). (Image courtesy of NASA SL3-117-2099.)

Two images of the Russian Orlan-M spacesuit aboard the ISS. This spacesuit has soft arms and legs, but a hard upper torso. The helmet lights pictured in these images were developed by NASA and adapted for use on the Orlan. (Images courtesy of NASA, top: ISS010-E-21175, bottom: ISS011-E-11958.)

Astronaut Don Pettit during a training exercise wearing an EMU. The spacesuit is connected to the airlock with an umbilical, but would be disconnected prior to an EVA. Pettit is wearing a paper checklist on his left arm. (Image courtesy of NASA, JSC2002E36205.)