HUMAN FACTORS IN THE DESIGN OF SPACECRAFT

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MONOGRAPH SERIES
OF THE
NEW LIBERAL ARTS PROGRAM

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Preface

Reading is more effective and pleasant when the reader knows what to anticipate. That anticipation is what I want to accomplish in this preface. Let me begin by telling you what this monograph is not. It is not a history of the U.S. space program, nor a human factors textbook nor a science and technology textbook. However, when you have finished reading it you will have had a thumbnail sketch of the history of the space program. You will also have a pretty good idea of what human factors is all about and especially its applications in aviation and space. Finally, if I have been successful, you will have had your fancy tickled by some of the issues of science and technology that I have shared with you.

The first chapter tells the meaning of the terms *human factors* and *ergonomics*, and goes on to tell a bit about the early developments in the fields. Each of the following chapters is an essay dealing with a bit of the history of spaceflight as it was manifested in the design of a specific vehicle or group of vehicles. I have selected an assortment of human factors issues to illustrate both the breadth and depth of the discipline, but this does not come close to being an exhaustive characterization. I hope that some of my enthusiasm for human factors work rubs off because you too are intrigued by the non-intuitive, and delight in finding elegant solutions to unexpected problems.

H.W.

Acknowledgements

I am indebted to a number of persons and agencies who assisted me. The curators at the National Air and Space Museum were gracious and helpful. Special thanks go to Lillian Kozlowski, for the photographs of the Skylab restraint shoes. NASA made available most of the photographs in this work. Support of the Sloan Foundation made possible this monograph, and the series of which it is a part. Mike Visich and John Truxal at SUNY, Stony Brook were the expert, patient, and supportive kind of editors one usually only hopes for. Thanks to Orbis Publishing, Ltd., of London, for allowing me to reproduce cockpit renderings.

Closer to home I want to thank Pamela Hawkes and Terri Van Eaton of Claremont McKenna College for their care and expertise in the preparation of the manuscript. Detlef Ott did all the photographic work. My Research Assistant, William Fulton, was a splendid facilitator. Several students and colleagues commented on drafts of chapters. Their comments improved the accuracy and clarity of the manuscript, and are much appreciated.

Closest to home, I want to thank my wife Ann, of the University of La Verne. Having commented on every draft of every chapter, she has made signal editorial contributions. Her steadfast support, inspiration, and comradeship helped to make this my happiest writing task.

Chapter One

What is Human Factors?

The term *human factors* refers to the kind of things that should be given special consideration when designing something to be used by a human being. For instance, prehistoric people, without knowing anything about the discipline of human factors, chose triangularly wedge shaped stones with which to chip flint because that shape could be held quite well in a human hand. A much more sophisticated chopping device was the tomahawk of the Native Americans which had a more easily grasped handle which also added leverage to the swing of the head. Here a round stick was used for the handle and selected so that the stick's diameter was appropriate to the size of the user's hand.

There is another term which is essentially synonymous with human factors and that is the term *ergonomics*. In Great Britain and much of the rest of the world, human factors is referred to as ergonomics (from the Greek meaning *the science of work*). The latter term had its origin in the early studies of the fatiguing effects of operating machinery which were conducted following the dawn of the industrial revolution. The amount of force required to move a lever with a finger or a hand was seen as important if an operator were to be effective throughout a long workday. An *erg* is a measure of work. Before defining an erg, I have to complicate matters a bit by first defining a *dyne* which is a force used in specifying the meaning of an erg. A dyne is the force required to impart an acceleration of one centimeter per second per second to a mass of one gram. An erg then, is the work done by a force of one dyne acting over a distance of one centimeter. Hence, the study of the effort required to operate some apparatus and the amount of that effort which produced fatigue became known as ergonomics. From there the meaning of the term spread to the study of how people interact in any way with apparatus. In this monograph I shall treat the terms ***human factors*** and ***ergonomics*** as synonymous unless otherwise specified.

Even without a formal discipline of human factors, people have been delightfully ingenious over the years in designing various utensils and machines that are well adapted for use by humans. Consider the following illustrations: The handgrip of the pistol; the metal tea kettle with a wooden grasp on the handle; wall mounted light switches; the screwdriver; the crescent wrench; the broom; the steering wheel; the pedal and sprocket crank on a bicycle; the horse saddle with stirrups; the eggbeater; and the coffee cup with a handle. All of these are very functional and often beautiful devices.

However, even these highly evolved everyday devices can have poor design features. I recently attended a dinner at a prestigious hotel in Washington, D.C.. A colleague sitting next to me picked up his coffee cup and before reaching his lips with it, quickly set it down, pulled his finger from the handle and shook his hand in pain. It turns out that, apparently in an effort to be stylish, the designer had created a circular handle through which only one finger could be placed. A crockery cup filled with liquid is too heavy to be comfortably held with only the force of the thumb and forefinger. Thus, inevitably, the cup tilted downward until the middle finger came into contact with the wall of the cup and provided the leverage to serve as a brace to hold the cup level. Unfortunately the wall of the cup was hot--that, after all, is why there was a handle in the first place. As I looked about our table and at other tables in the room I saw people holding their cups in a variety of awkward postures as they tried to position them so that they could be held with only the thumb and forefinger. Here was a cup handle design that may have looked attractive but from a human factors point of view it was a bad design. Well-designed cup handles are both attractive and allow the middle finger to serve as a brace so that the cup may be handled with comfort. The human factors discipline has developed precisely to avoid the kind of design errors just described.

Some patience on the part of the reader will be required as I attempt to define human factors (and of course, ergonomics) because the definition is not simple. Persons engaged in human factors work perform different types of functions which may be regarded as being either scientific or professional. The scientific functions revolve around efforts to establish just what the capabilities of a human being are. The professional functions are associated with the application of the scientific facts to specific design situations. Professional human factors persons work closely with design and engineering teams and most frequently in industrial settings such as in the design of office furniture or aircraft cockpits. On the other hand, those human factors workers who are primarily involved in the science aspects of the field are typically associated with research and educational institutions and study such things as the range of physical and mental capabilities of human beings, how learning takes place, the nature of complex systems, techniques of measurement, and safety principles.

The picture is further complicated by the fact that both the scientific and professional functions are multi-disciplinary in nature. The most relevant sciences to human factors are biology and physiology, psychology, sociology, anthropology, and mathematics and statistics. The most relevant professions to human factors are industrial design, engineering, and architecture. In practice the lines between all of these distinctions are often blurred. This is in part what makes the discipline difficult to define but it is also, in part, what gives the discipline a certain element of charm and vitality. It is fascinating to have to take into consideration cultural expectations, social norms, individual needs, physical capabilities, as well as esthetics, economic factors, and the physics of the machinery, when designing something for use by humans. However this is not an easy task, and a brief look at the history of human factors will help clarify how and why this discipline came about.

The beginning of a formal discipline of human factors occurred in the United Kingdom in the late 1940s when a group of scientists from different disciplines who had been working with human problems associated with World War II formed a society "concerned with the human aspects of the working environment" (Edwards, 1988, pp.4-5). Edwards relates that one of their members (K.F.H. Murrell) coined the term ergonomics. Thus the Ergonomics Society was formed in 1949. Similar developments were under way in other countries including the U.S. where, in 1957, the Human Factors Society was formed. This organization which now has more than 4,000 members publishes a bimonthly journal, ***Human Factors***, and monthly, the ***Human Factors Society Bulletin***. Finally, the national organizations that began springing up in countries around the world were united with the forming of the International Ergonomics Association which held its first congress in 1961.

> The International Ergonomics Association brings together organizations and persons concerned with ergonomics or human factors; i.e., the relations between man and his occupation, equipment, and environment in the widest sense, including work, play, leisure, home, and travel situations (Hendrick and Brown, 1984, p.viii).

It is probably safe to say that the two primary events that gave rise to the field of human factors were World Wars I and II. It was at these times that very large numbers of young men were recruited to serve in the military services. In that capacity they would have to be trained to operate trucks, tanks, rifles, machine guns, cannons, various types of boats, ships, and submarines, and airplanes. Suddenly there was an acute need to know which persons to select to be able to competently operate these tools of war. In this phase of the development of human factors the emphasis was on personnel selection--given that we have this machinery to be operated, what human characteristics are needed to do that? Selection issues became primary again in Britain in 1942 when bomber crews, subjected to terrible stress (e.g., 10% survival rates over a thirty-mission tour of duty), were developing neurotic symptoms at an alarming rate. There was a great need to select people for the complex, expensive, and time consuming training who were least likely to be disabled by the stress of warfare in the air.

However, not all of the development of human factors came under the guise of selection. With the development of military aircraft in World War I came the need to provide the aviator with instruments that presented him with information about his direction, speed, and altitude, and the status of his aircraft systems such as fuel, oil, and engine speed. Since there would often be only brief moments in which the instruments could be looked at, it became important to determine which location on the panel was best for each instrument and how that information should be portrayed. Also, as pilots moved from one type of aircraft to another, the issue of standardization began to show up. A pilot who was accustomed to finding information in a certain location in one type of aircraft could experience a fatal delay in trying to find it in a different airplane! Likewise, a pilot accustomed to having a control in one location, could, during the heat of battle or during an emergency, operate the wrong control with catastrophic results.

These kinds of issues were greatly amplified during World War II as a result of the dramatic increase in the complexity of aircraft and the amount of information and the number of controls being made available to aircrew members. For example, the World War I Sopwith Camel had a combined total of 16 controls and instruments (See Figure 1.1 on page 7). However, the Supermarine

Spitfire of World War II had 57 combined controls and instruments (See Figure 1.2 on page 8). In the twenty years that separated these two famous fighter planes, aircraft speeds had increased by 300% and the number of combined controls and instruments had increased by 350%! Terrible accidents were occurring with equally terrible frequency, and they were being attributed to *pilot error*. Pilots cried "foul--these accidents were caused by ***design error***"!

It wasn't long before designers, engineers, and psychologists were teaming up to study how pilots might be able to distinguish one control from another by feel, and how controls might be arranged so that they would be employed in some sequence that matched the circumstances. The readability of the ubiquitous round dial with one or more hands was challenged and studied. The usefulness of color coded bands on dials--green for normal range, yellow for caution, and red for danger was explored. Reaction times were studied, information processing models were developed, and terms from electronics such as channel capacity were employed to help understand what pilots were referring to as information overload.

During this phase of the development of human factors we see a shift in emphasis from selection--choose the person with the capability of performing this task, to one of design--how can this task be arranged so it can be accomplished with ease and grace. During both of these phases there was a heightened demand for more information about human capabilities and methods for measuring them. Thus theoretical and applied human factors evolved in unison.

It would be a mistake to imply that the war efforts represented all of the impetus for the newly developing discipline of human factors. Others, often in very different domains were beginning to address these issues. For instance, in 1947, Laszlow Moholy-Nagy, Director of the Institute of Design in Chicago, wrote the following in reference to the young field of industrial design.

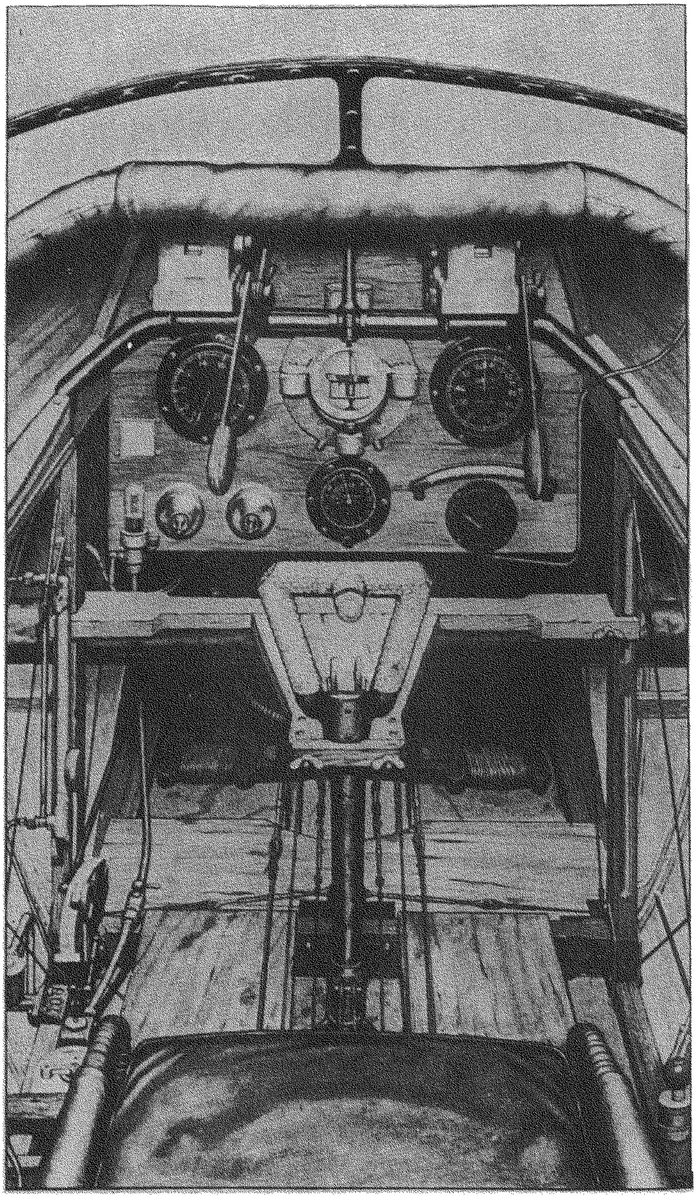


Figure 1.1
The Cockpit of a Sopwith Camel. (Photo courtesy of Orbis Publishing, Ltd., London).

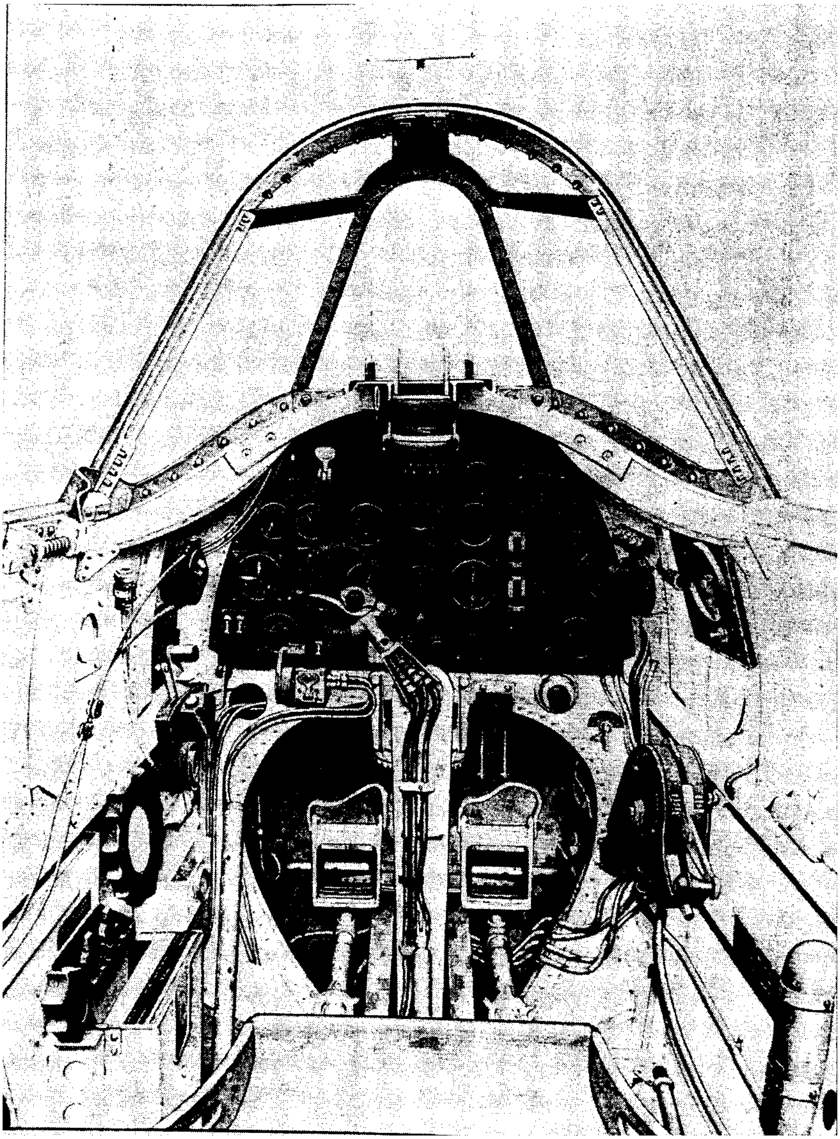


Figure 1.2
The Cockpit of a Supermarine Spitfire. (Photo courtesy Orbis Publishing, Ltd., London).

> Therefore a designer can work best if he is familiar with the art, science, social and economic requirements of his period plus the industrial processes and the basic mechanical principles involved in a certain problem. But it is not his task to compete with the engineer, nor should the engineer indulge in the idea that he can do a perfect design. It is their intimate collaboration which is needed, especially at the start, a mutual willingness to exchange ideas and yield to suggestions improving the productions, the function and the "looks" of the product, that is, its psycho-physical perfection (p.34).

Here we see the beginnings of the call for design teams that would meld the arcane knowledge of different specialists, each with overlapping capabilities so that they can communicate, but each also bringing different emphases and points of view to bear on the same problem. We see in Moholy-Nagy's statement too, the recognition that there are social and psychological aspects to any design challenge.

Moholy-Nagy spoke of an enduring problem that designers and engineers have in doing things the way they have always been done even after it isn't necessary and it might even be disadvantageous. For instance, he described a group of experiments by some of his students in developing superior designs for molded plastic screwdriver handles. These handles, with their complex curves, conformed to the shape of the area between the fingers and the massive muscle at the base of the thumb when in the grasp of a hand. They were attractive and more comfortable to hold and use than traditional screwdriver handles. Yet, "By a peculiar inertia, the commercial tool handles in plastics still imitate the old wood handles turned on the lathe" (Moholy-Nagy, 1947, p.35).

Psychologists have labeled this "peculiar inertia", *functional* *fixedness*--"the degree to which an object cannot be perceived as functioning in, or belonging to, a context different from that in which it has just been perceived or employed..." (English & English, 1958, p.218). An illustration of this phenomenon from aviation will clarify the point.

Once airplanes began going as fast as 100 MPH pilots could no longer sit out in the open on the wing as they had on the Wright Brother's planes. This gave rise to the enclosed fuselage to hold pilots and passengers. But in those days it was still deemed essential that the pilot's head be exposed to the wind stream so that he could better sense the forces acting upon the machine. So, for a designer, a cockpit was a drag-producing hole in an otherwise beautifully streamlined fuselage. Making that cockpit small so that the pilot's body filled it up as much as possible to keep out swirling winds was simply good design.

However, once an airplanes could fly at nearly 400 MPH and at altitudes in excess of 30,000 feet where temperatures were regularly colder than -50^0 F, it became obvious that pilots would have to be protected from the elements. Thus, a clear plastic canopy was added to the early model Spitfires that covered the cockpit by connecting between the windshield and the aft fuselage that sloped to the tail. Unfortunately, however, the cockpit was still a tiny open cockpit design that simply had a canopy added to it as an afterthought. Now the heads of taller pilots rested against that canopy. The problem was solved in later Spitfire models by molding a small dome into the top of the canopy to accommodate the top of the pilot's head. This bulge was to become one of the identifying features of the Spitfire (See Figure 1.3 on page 11).

It was the need to design things properly for the crew in the first place that gave a special impetus to the development of human factors. Some of that impetus came from workers in medicine and physiology.

The 150-200 HP engines of World War I had been replaced

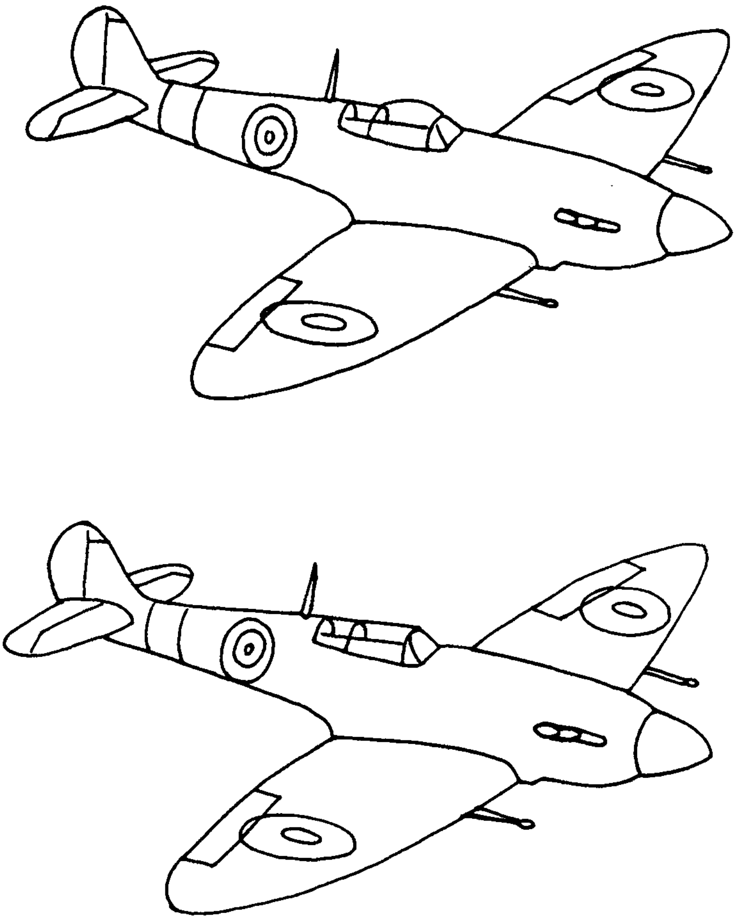


Figure 1.3.
Drawings of the prototype Spitfire (lower) with canopy that touched pilot's heads, and a drawing of the Spitfire V (upper) with the characteristic curved canopy to accommodate the pilot's head. (Drawings by Naomi Matsuo).

by engines of 1,500-2,000 HP in World War II. These turbo-supercharged engines allowed aviators to routinely fly to the edges of the stratosphere where life could not be maintained unassisted. Other members of a design team became necessary, bringing to bear the special skills and points of view that had not been needed before. Pilots now had to be kept warm at freezing high altitudes and cooled on sunny days at low altitude in their new "greenhouse" cockpits. They had to have supplemental oxygen in the rarified air near the stratosphere. To nearly everyone's surprise, pilots transitioning quickly between sea level and the low atmospheric pressures at high altitudes would need to be protected against "the bends"--the same disorder that plagued deep sea divers who surfaced too quickly.

World War I pilots in their tiny planes seldom flew missions that lasted longer than about an hour. However in World War II, bomber pilots, and even their fighter escorts, found themselves flying missions that lasted 5 to 8 hours. New problems of fatigue and the errors that accompanied it manifested themselves, and physiologists and psychologists set about measuring these factors.

For instance, in a study of propeller driven aircraft, Wichman, McIntyre, and Accamazzo (1979) showed that pilots in flight breathe about 75% more rapidly than they do at rest before the flight. This physiological arousal is due in part to the demands of operating a complex machine and in part to the high levels of noise generated by reciprocating engines, propellers, and wind. When pilots wore expandable foam ear plugs which reduced the noise level by about 24 decibels (db), the increased rate of breathing was reduced by 30%.

The point had been reached where simply selecting hardier and hardier air crews was no longer a reasonable solution. It was time for someone to pay special attention to the needs and capabilities of the humans who would fly these magnificent machines, and to make this information available at the time the machines were first being designed. The discipline to which those people belong is human factors.

We have had a brief glimpse back at the genesis of human factors to discover what the discipline was like in its early days. The next chapters will explore some of the human factors issues that have arisen in the design of vehicles that would leave the atmosphere entirely and venture into space.

The following chapters will take you on a very brief tour of some of the major projects in the U.S. space program. During that journey you will see a continuing evolution of the field of human factors and ergonomics. By the time you have completed this monograph you will have a more complete picture of the current state of this discipline. What you have learned in this chapter is enough to get you started. But, as you will see in the final chapter, modern human factors has broadened its scope considerably, partly as a consequence of the development of other new concepts such as systems theory.

Chapter Two

The Mercury Capsules

From a human factors point of view the very beginning of the space program took a step backward before taking a big step forward. The launching of the first orbiting satellite, ***Sputnik I,*** in 1957 by the Soviet Union, set off an intense space race between the U.S. and Russia. During the next few years other satellites were launched, each adding more excitement and intensity to the race. The Russians then put a dog in orbit, and the race made one of its quantum leaps in intensity--now living creatures from earth had made it into space and survived. Altogether seven Soviet dogs made space flights; the U.S. answered with monkey and then ape flights. But finally, what everyone following this great adventure knew was going to have to happen sooner or later took place. On April 12, 1961, Yuri Alekseyevich Gagarin upped the ante once more by going into space and orbiting the earth in the Soviet Union's *Vostok I* spacecraft.

Only four years had elapsed between the launch of Sputnik I and Yuri Gagarin's flight in Vostok I. Sputnik I was a simple 23 inch, 184 pound sphere that sent out a beeping radio signal, but Vostok I carried a living human being into the vacuum of space. Gagarin's vehicle kept him comfortable in the incredible cold of the earth's shadow and in the direct rays of the sun, unfiltered by

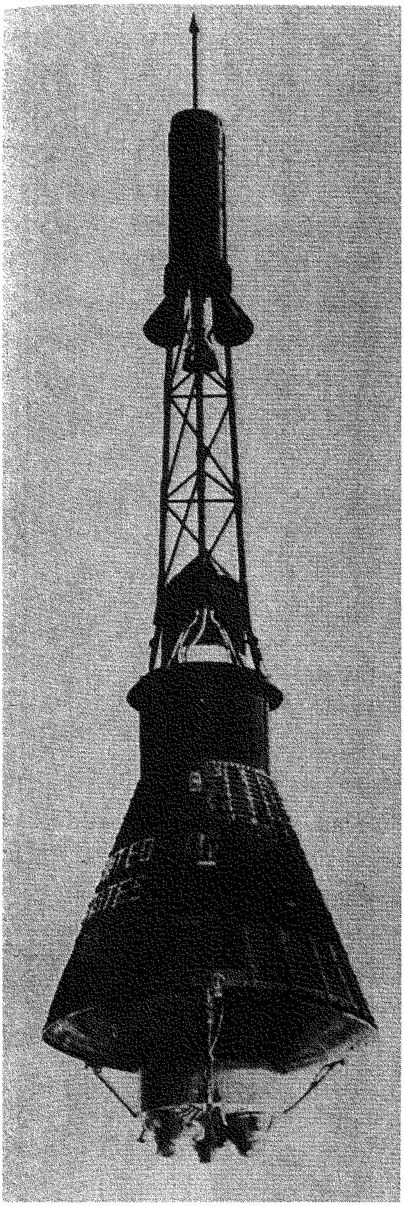


Figure 2.1
A Mercury capsule with its escape rocket on the tower. (NASA photo).

an atmosphere. He communicated with colleagues on earth, ate, drank, wrote on paper, and maneuvered his craft. He re-entered the earth's atmosphere at some 17,000 miles per hour and completed the safe return of him and his remarkable machine by parachute. Never in the history of the world had so much technical progress taken place in so short a time. Engineers were striding through the history of technology wearing seven-league boots.

In April of 1961, Gagarin became the first human in space. In May, Alan Shepard became the first American in space in a suborbital flight of 15 minutes duration. In July, Virgil (Gus) Grissom became the second U.S. Astronaut to enter space with another suborbital flight that lasted a minute longer than Shepard's. The pace was quickening once again. Then, less than a month later, on August sixth, Gehrman Titov, in a Soviet Vostok II, blew the lid off the race when he orbited the earth for 25 hours and 18 minutes. It was now the turn of the United States to up the ante once again. NASA'S history of the Mercury Program put it this way:

> With American technological prestige damaged in the court of world opinion, the United States responded after Shepard's suborbital ride, when President John F. Kennedy proposed and an eager Congress agreed to make Mercury the first phase of an epochal national venture in the manned exploration of the Earth-Moon system (Swenson, Grimwood, and Alexander, 1966).

This was truly an exciting time in the history of technology. But there are some things we need to remember in order to understand the mind sets of the people involved. The rockets that the seven Mercury astronauts planned to ride into space had been designed to carry aloft ballistic missile warheads. Modifying the rockets to carry large bulky spacecraft was going to be no small undertaking, and some things, such as their rate of acceleration, could not be changed in the short amount of time available. Thus, the forces to which the astronauts would be subjected required special crew selection procedures. Here again we see human factors stepping back to find the people capable of meeting the demands of the equipment rather than stepping forward to show how to make the equipment fit the needs of the users.

But this was a heady time for engineers, and if a man in space is what people wanted, they knew they could *put one there*. Everything went along pretty well until the men who would be *put there* were selected. They would have little to say about the rockets upon which they would ride, but they would have much to say about the capsules in which they would ride. Before it was all over, there would be serious conflicts with the engineers upon whom they were so dependent; and the psychologists, whom they loathed, would come to be their allies.

This brings us to the title of this chapter--The Mercury Capsules. "Capsule" was a term hated by the astronauts, and Herculean efforts were made by NASA to get the vehicles referred to as spacecraft and not capsules. Once again we are reminded; if one is going to design for an animal, one had better understand the nature of that beast. These astronauts were all recruited from the ranks of military test pilots. As Tom Wolfe would so aptly show in his book of the same title, these men had ***The Right Stuff*** (1979)!

Figure 2.2
The chimpanzee "Ham" who flew in a Mercury capsule. (NASA photo).

The first astronauts were mercilessly teased by their colleagues at Edwards Air Force Base who were then flying exotic rocket powered aircraft such as the Bell X-1, and the North American (now Rockwell) X-15. The aircraft test pilots referred to the Mercury capsules as "Spam cans" and the astronauts as the "meat" inside the can. After all, what did it take to fly one of these "capsules"? Not much obviously, if dogs were doing it in the Soviet Union, and monkeys and apes were doing it in the U.S.. Until the astronauts came along, the engineers filled the Spam cans with chimps--now they filled them with chumps.

Let's see how an astronaut described the situation back then. Following is an excerpt from a talk given by astronaut Donald K. Slayton at the annual symposium of the Society of Experimental Test Pilots in Los Angeles on October 9, 1959.

> First I would like to establish the requirement for the pilot...Objections to the pilot range from the engineer, who semi-seriously notes that all problems of Mercury would be tremendously simplified if we didn't have to worry about the bloody astronaut, to the military man who wonders whether a college-trained chimpanzee or the village idiot might not do as well in space as an experienced test pilot. The latter is associating Mercury with the Air Force MISS or Army Adam programs which were essentially man in a barrel approaches. The answer to the engineer is obvious and simple. If you eliminate the astronaut you can see that man has no place in space. This answer doesn't satisfy the military skeptic, however, since he is not questioning the concept of a man in space but what type man. I hate to hear anyone contend that present day pilots have no place in the space age and that non-pilots can perform the space mission effectively. If this were true the airplane driver could count himself among the dinosaurs not too many years hence.
>
> * * *
>
> Not only a pilot, but a highly trained experimental test pilot is desirable...as in any scientific endeavor

> the individual who can collect maximum valid data in minimum time under adverse circumstances is highly desirable. The one group of men highly trained and experienced in operating, observing, and analyzing airborne vehicles is the body of experimental test pilots represented here today (Quoted in, Swenson, Grimwood, and Alexander, 1966).

Clearly engineers had developed space craft that did not need pilots. They had also created automated space craft that were sophisticated enough to keep high order biological organisms alive and comfortable enough to perform simple tasks. If passengers were to be transported to the moon as President Kennedy had charged, that would be fine. Engineers could build a craft that would take them there automatically. In fact, it was even once suggested that the astronauts be anesthetized during flight so that they couldn't cause any problems!

What was it besides the doggedness of these macho aviators who insisted on being able to control things that justified having a (conscious) pilot on board who would have the capability of over riding automated systems? It turns out that it was a phenomenon that has become very important in human factors and that is reliability. Given that a spacecraft has a variety of different subsystems, any one (or more) of which might fail, a single pilot can be trained to be a backup for any of them. Even if there is a single mechanical backup for a system, a pilot on board can be yet a third level of redundancy. What is more, a pilot can sometimes improvise, when all else fails, and either make do without a system or repair it enough to be adequate.

The following quotation from the speech, "Quality and Reliability Control", given by S.E. Skinner, Executive Vice President of General Motors Corporation in 1959, clarifies the relationship between complexity, quality, and reliability in automobiles.

> If the parts going into the 1959 car were of the same quality level as those that went into the 1927 car, chances would be even that the current model would not run.
>
> This does not mean that the 1927 car was no good. On the contrary, its quality was excellent for that time. But it was a relatively simple product, containing only 262 critical parts. The 1959 car has 688 such parts. The more the critical parts, the higher the quality level of each individual part must be if the end product is to be reliable (Quoted in Swenson, Grimwood, and Alexander, 1966).

It was estimated that the Mercury space craft had in excess of 40,000 critical parts. The scale and scope of the problem of reliability in such a complex system was so awe inspiring that it was hard to know where to begin in addressing it. The end result was that the decision was made to put a pilot "in the loop"--meaning the decision and operating loop. To do this the crew member would have to be able to override the automated systems that already existed and had served the monkeys and mice so well. Doing this was an extremely costly, time consuming and ground breaking job. The reason for this was that, while we had decades of information about the responses of aircraft control systems, there was no information about how a human's control inputs could be translated into the proper outputs of such devices as tiny rocket engines, called reaction thrusters, that would maneuver a space vehicle traveling in excess of 17,000 MPH in a vacuum.

Nevertheless, man was at last part of the system, and it became necessary to design the subsystems so that they were in harmony with the capabilities and desires of human pilots. And even though those pilots had been carefully recruited from a highly select portion of the population (the ranks of military experimental test pilots) to be able to perform well under severely adverse conditions, it made sense to make the working conditions as good as possible under the circumstances.

When one actually sees a Mercury capsule (one is on display in the National Air and Space Museum in Washington, D.C.), the appellation, Spam can, seems not such a bad one after all. The whole space ship was only about the size of the box a household refrigerator would come in. Figure 2.3 gives some indication of the size of the capsule relative to a person.

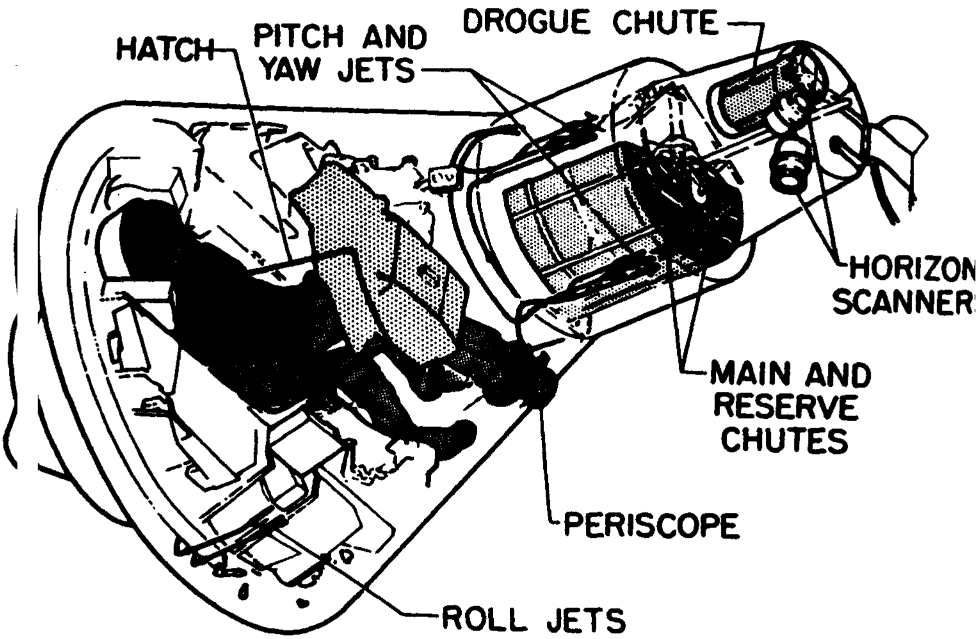


Figure 2.3
A drawing of the Mercury capsule that demonstrates its size relative to a person. (NASA drawing).

I will conclude this chapter by briefly examining three human factors concerns which were brought forth by the astronauts and which were changed to accommodate them. These three concessions to the future space pilots altered their circumstances drastically from those of the mice, monkeys and apes who flew before them. The three factors which humanized the modules and transformed them from capsules to spacecraft were the side egress hatch, the trapezoidal window, and the side-arm controller.

Clearly the men who rode these Mercury spacecraft into the many unknowns of space atop Redstone ballistic missile rockets were very brave. They were also capable of remarkable self control and had to have no tendency towards claustrophobia--the fear of closed places. They wore pressure suits which were very confining, they were placed into a tiny capsule with their backs only a few inches from the heat shield and their feet against the forward bulkhead of their tiny compartment. Their heads were encased in full face helmets, and they were strapped into their form fitting couches. The outer hatch was then closed and locked from the outside with 70 bolts. Their only way out, after unstrapping and disconnecting all of their hoses and wires, was to remove a forward pressure bulkhead panel and wriggle out of the top of the capsule through the parachute canister. Until the parachute was deployed there was no way out once an astronaut was locked inside.

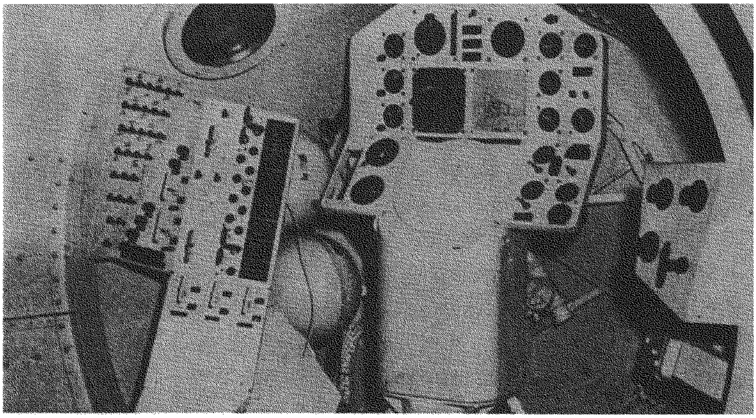


Figure 2.4
The interior of an early Mercury capsule showing the control panel and one of the port holes. The first Mercury flight did not have the window. (NASA photo).

This was simply too much for the astronauts to tolerate and they insisted on having the hatch on the side designed so that they could open or remove it at will. The problem was that the hatch with a latching mechanism weighed 69 pounds and, with the marginal power available in those early days of rocketry, that was too much weight for the capsules that were to go into orbit. In the end, the hatch was made removable by detonating small charges that sheared the 70 bolts and blew the hatch 25 feet away. This arrangement weighed only 23 pounds and was acceptable. Now, at least, once the spacecraft was in the water following a flight, its crewman had an easy way out quickly if that were necessary. An important element of control had been transferred to the pilot.

The engineers had placed two 10-inch port holes on either side of the instrument panel. It was very difficult for a helmeted astronaut, tightly strapped to his couch, to be able to see out of those port holes. The pilots not only wanted a proper window--they wanted a windshield out of which they could really see something. Humans don't take a ride into space and not want to look around and see the sights. In humans, vision is the dominant sense, and to inhibit free vision is to place a severe burden on a person as a biological organism. Windows give access to stimulation, provide important feedback about what is happening (e.g., one could see the deployed parachute out the window), and thus allow better prediction and control over the situation. This sense of perceived control is critical for reducing stress in humans.

A trapezoidal window was placed forward and above the pilot's head. By looking upward slightly he could see outside with a visual field of 30^0 horizontally and 33^0 vertically. The outer pane was made of Vycor glass a little over a third of an inch in thickness and could withstand temperatures in excess of 1500^0 F. Three inner panels, two of which were tempered glass, were bonded together to make the inner pane. According to Swenson, et al; "This fenestration was as strong as any part of the capsule pressure vessel" (1966, p.367). The astronaut was no longer like the chimp pressing buttons on what was essentially a video game.

He was now an active observer who could meaningfully report his findings to his earthbound colleagues and this made a big difference in what it meant to be an astronaut.

Finally we come to the single feature that most transformed the Spam can into a space ship--the control system that allowed the passenger to become a pilot by overriding the automatic controls and maneuver the craft by hand. When I say, "by hand", I mean that literally. The pilot was provided with a hand grip that could be tilted forward and back to affect pitch (up/down), left and right to affect roll, and could be twisted like a motorcycle hand grip to affect yaw (sluing left and right).

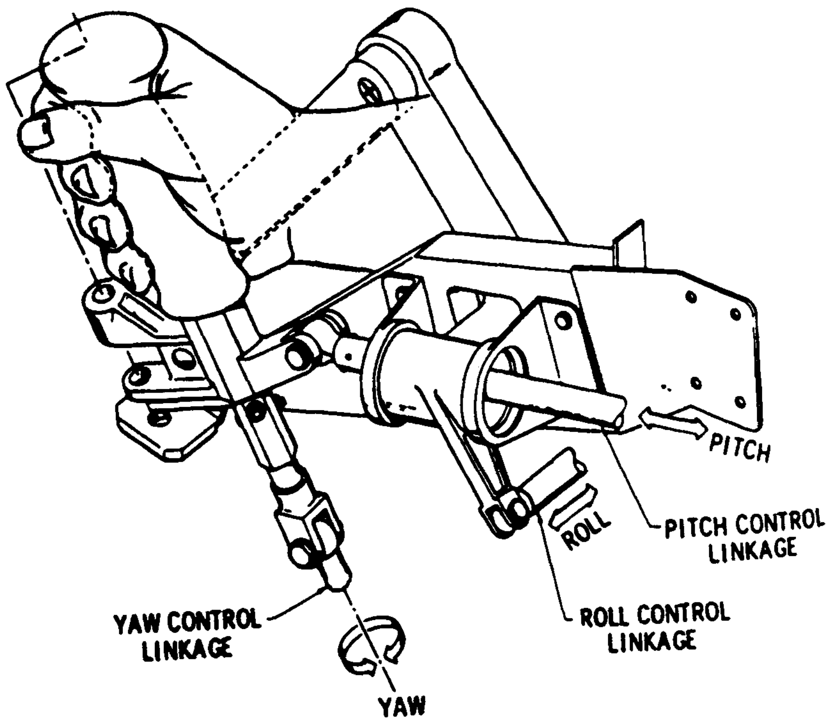


Figure 2.5
The side-arm controller showing some of its linkage. (NASA drawing).

In high performance military aircraft of the time, pitch and roll were controlled by a control stick held between the pilot's knees and yaw was controlled with the feet by a pair of rudder pedals. Numerous friendly arguments took place about the wisdom of adopting the new side arm controller as opposed to staying with the old stick and rudder pedals system because prior training would then transfer better, and after all, there were enough new things for the astronauts to learn and adapt to.

The fact is, however, that the old "joy stick" as it was affectionately called by pilots, had some serious shortcomings. It had worked well in providing a long lever arm to give early pilots the power necessary to easily move unboosted control surfaces against the force of the wind. The disadvantage this produced was that the stick had to move through quite a wide arc to accommodate large inputs. This required an extensive wide-open area which was clearly lacking in the Mercury spacecraft. Another disadvantage of the joy stick was that when flying in turbulence the bouncing of the pilot's arm often inadvertently moved the control stick, exacerbating the bouncing around. When the Navy's Blue Angels were flying their Douglas A-4 aircraft in air shows, some pilots put blocks of wood on the right rudder pedals. This pushed their right knees up high and allowed them to rest their right arms on the knees, thus stabilizing their hands so that they could reliably make the small control inputs necessary when flying at very high speeds only inches from each other. Now that the joy stick was no longer needed for leverage, its days were numbered.

Following some excellent human factors research, much of it conducted with humans in a centrifuge to provide tests with different g-loads, it was decided that a single side-arm controller could be counted on to work best through the regimes of normal g-loads, high g-loads, zero-g and heavy vibration. This controller was grasped with the hand while the pilot's arm was supported and stabilized by an arm rest. The controller worked very well in the Mercury spacecraft and has become the standard method for controlling pitch and roll in modern high performance fighters, although yaw is still controlled by rudder pedals in airplanes.

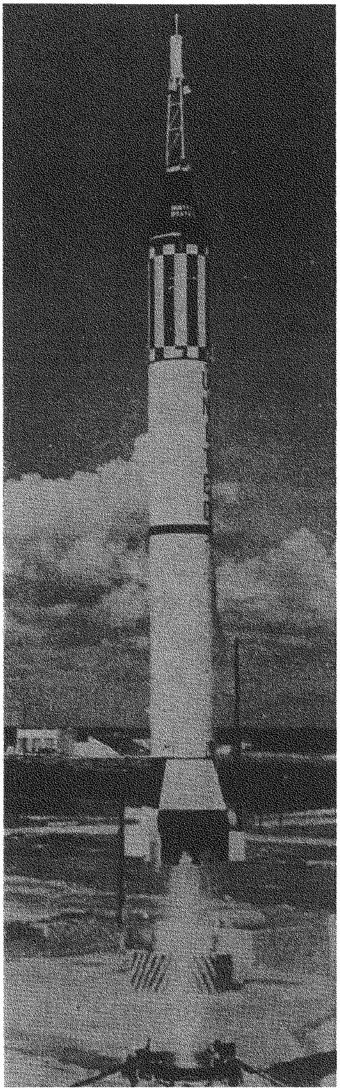


Figure 2.6
A Redstone rocket lifting off with a Mercury capsule and its escape tower. (NASA photo).

On May 5th, 1961, Alan Shepard successfully flew a Mercury spacecraft in suborbital flight with the Redstone missile as his rocket. On July 21st, Gus Grissom repeated the process to show that Shepard's success wasn't just luck. Then on February 20, 1962, John Glenn, using the more powerful Atlas rocket (also from a ballistic missile) orbited the earth in a Mercury spacecraft for nearly five hours. The U.S. had finally put an astronaut safely into orbit. Three more Mercury flights were flown by Wally Shirra, Gordon Cooper, and finally Scott Carpenter, whose time aloft exceeded 34 hours. It was time to move on to larger, two-man vehicles and the challenges they posed. We take those up in the next chapter on the Gemini spacecraft.

Chapter Three

The Gemini Spacecraft

Gemini was a program of twos. Gemini, meaning twins in Latin, was the name selected in 1962 for the program that would bridge the gap between the solo flights of Mercury and the three-man Apollo flights to the moon. The name came from the constellation in the northern hemisphere that contains the twin stars Castor and Pollux. Gemini was the second of the U.S. space efforts on the way to the moon. The Gemini spacecraft were large enough to carry two astronauts, and one of the primary goals of the program was to rendezvous and then dock with a second spacecraft.

Following Gordon Cooper's final Mercury flight in May of 1963, there was a twenty-two month hiatus in U.S. manned space flights until the first flight of a Gemini Spacecraft on an Atlas rocket in March of 1965. Meanwhile the Soviet Union flew seven astronauts (one, the first woman in space) in four different spacecraft. One of those spacecraft stayed aloft for over 119 hours (Vostok 5) and another carried three cosmonauts (Voskhod 1). This was an uncomfortable time for the U.S. Space Program. The decade in which President Kennedy had challenged the U.S. to reach the moon was already half over and the President was dead. Nevertheless, the program he had sparked was gaining momentum and the next, only somewhat less tenuous forays, were about to be made in space. The Gemini program had three very important moon-trip related goals. One, as mentioned earlier, was to rendezvous and dock, another was to demonstrate that people could work effectively in space for at least two weeks--the time needed for moon trips, and the last was to perfect re-entry procedures so that spacecraft would land reliably near their recovery ships.

The Gemini spacecraft looked like a somewhat larger version of its Mercury predecessor because it retained the same basic frustum-of-a-cone shape. And while it was only 20% larger than Mercury it had twice the cabin space and weighed in at 8,400 pounds--two and a half times heavier. It had two hatches and, of course, couches for two astronauts. See Figure 3.1 for a line-drawing of an entire Gemini spacecraft.

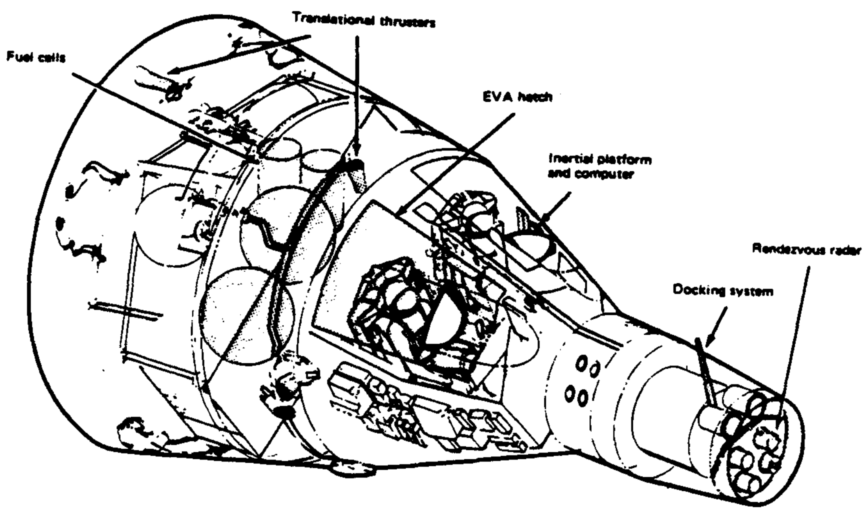


Figure 3.1
A Gemini spacecraft. (NASA drawing).

Instead of batteries which stored electrical energy for use during flight, the later Gemini spacecraft had fuel cells that created electrical energy during a flight (see Box 3.1).

Box 3.1

Fuel Cells

A fuel cell is a device in which energy in the form of electricity is released when a fuel is oxidized. While there are a number of different types of fuel cells employing different fuels, many have serious drawbacks such as operating at very high temperatures or pressures. The cells currently used in space vehicles mix two gasses, hydrogen as the fuel and of course oxygen, in an electrolyte. The two gasses are passed through porous catalytic electrodes that facilitate the uniting of the hydrogen and oxygen to produce water. As a water molecule is formed, liberated electrons move to the hydrogen electrode and away from the oxygen electrode thus producing an electric current (dc).

A spacecraft goes aloft with a tank of hydrogen, another of oxygen, and some fuel cells. When the hydrogen is catalytically oxidized in a fuel cell an electric current is generated supplying power. The resulting by-product of generating this electricity is pure water which is then available for drinking and other useful purposes.

But most different of all, the Gemini craft could truly be maneuvered in space. The cab in which the astronauts rode was the part that resembled the Mercury capsule, but attached to the rear of that, behind the heat shield, was an adapter section that could be jettisoned when it was time to return to earth. The adapter contained maneuvering engines, fuel tanks, electricity producing fuel cells, and other hardware that would not be required after re-entry began.

Human factors lessons learned in Mercury were continued in Gemini. Both Gemini astronauts had hatches and windows which were located as if they were small individual windshields in front of the astronauts. This was necessary because they would have to see well to be able to dock their Gemini spacecraft with an orbiting unmanned Agena docking target that also was launched by an Atlas rocket. The side-arm controller was retained as was the couch upon which the astronauts reclined during takeoff and to which they were secured in the weightlessness of orbit.

But Gemini introduced some new design problems. Now there would be two astronauts who would have to work together in very cramped quarters. But even more of a problem was the fact that one of Gemini's tasks was to demonstrate that humans could live and work well in space for a period of at least two weeks. This meant that the two pilots would not only work together in much the same way that airliner pilots and copilots work together, but they would have to perform all of their life activities for two weeks while seated virtually shoulder to shoulder. There could be no showers, toilets, nor wash basins. There would be no kitchen, dining room, nor bedrooms. In addition, Gemini astronauts would hand operate and maneuver the spacecraft much more extensively than was done in Mercury, and they would have to coordinate their activities so as to work in harmony as a team. Finally, new issues of safety arose. These astronauts would open their hatches while in space and one would go outside the vehicle. They also would have to fly up close to another object in space and then dock their craft to it.

All of the Gemini design problems involve safety so I will deal with that issue first. Improving safety is an important aspect of human factors research and the applied work of field professionals. However, safety cannot be discussed without first discussing the notion of the *system*, which I shall do next.

A system is some entity or whole that is made up of interrelated elements. For instance, an apartment house can be conceived of as a system made up of elements called apartments and perhaps some sort of parking structure and connecting walkways. Each apartment, however, can be thought of as a system made up of such elements as, rooms, hallways, ventilation ducts, wires, pipes, etc.. Likewise, a room can be conceptualized as a system made up of elements such as walls, ceiling, floor, windows, electrical outlets, and so forth.

Space vehicles are also systems made up of elements which in themselves are subsystems. Some elements of a space vehicle conceived of as a system are the airframe, the propulsion system, the communication system, the maneuvering system, the environmental system, and the electrical system. What human factors adds to this list of subsystems is the crew. Safety researchers think of the people in a system which is operated by humans, as one of the elements in that system.

Human factors safety professionals often operate as systems analysts when they serve as members of a design team. Having someone on a design team who thinks of the system as a whole is very important. For instance, suppose that three persons in a house each outfitted his or her own room. If each one put in a window air conditioner, a microwave oven, a television set, and a stereo system, they might have highly desirable rooms. But they might also have overtaxed the electric wiring for the house and be constantly blowing fuses so that now no one is happy. Clearly, someone should have been thinking of the whole system and how the sub-systems interact. Since human factors safety professionals are usually the only members of a design team knowledgeable about the human subsystem, it is incumbent upon them to think about the interrelations between all of the systems including the humans. Trollip and Jensen (1991), addressing human factors in general aviation, made a similar point with the following quotation from Circular 227 of the International Civil Aviation Organization (ICAO).

> Human factors is about people: it is about people in their working and living environments, and it is about their relationship with equipment procedures and the environment. Just as importantly, it is about their relationships with other people. Human factors involves the overall performance of human beings within the aviation system; it seeks to optimize people's performance through the systematic application of the human sciences, often integrated within the framework of system engineering. Its twin objectives can be seen as safety and efficiency (p. 1).

An example from aviation safety illustrates this well. Before an airplane lands the landing gear and the wing flaps are lowered. After an airplane has landed the wing flaps are retracted, but not the landing gear! The switches that operate these two subsystems are managed by yet another subsystem--the pilot. The two switches must not be confused. But, the human factors engineer knows that people very easily mistake one switch for another, especially when excited or distracted. Sanders and McCormick (1987) point out that, "...confusion between landing gear and flap controls was reported to be the cause of over 400 Air Force accidents in a 22-month period during World War II" (pp. 260-261). Making these switches distinctive was an important human factors contribution to air safety. Switches were made to look and feel quite different and even shaped so as to suggest their purpose. For instance, the landing gear switch was shaped like a small wheel and was soft like a rubber tire. The flap switch was hard to the touch and shaped like a miniature flap. Furthermore, the switches were situated away from each other to minimize errors caused by similarity of location. In this example, we see that elements of two of the subsystems were redesigned to make them more compatible with characteristics of the human subsystem which could not be redesigned. The human subsystem can be modified by training, of course, but in this case the training effect was too frequently being overridden by the effects of distraction and excitement.

Thinking of the Mercury spacecraft as a system, it had as one of its elements, an astronaut. The astronaut was of course a subsystem, but a system of its own nevertheless, and a complex system at that. Now in Gemini there would be two astronauts, each a physiological and psychological subsystem. But now the two of them would become the two elements comprising yet another subsystem--the crew. Their smoothly coordinated performance would be a prerequisite for a successful flight.

There are basically three different times when systems integration takes place. First is when an object, such as a space vehicle, is being designed. Engineers often count on human factors specialists to tell them how fast people can react to various kinds of stimuli, what kinds of reach capability for feet and hands has to be planned for, and what amounts of force can be required to manipulate something without producing undue fatigue. When several different instruments have to be scanned to accumulate the information with which to make a decision, human factors specialists will work out the positioning of those instruments so that the crew's scan moves efficiently in a logically systematic order.

The second opportunity for systems integration usually occurs after a prototype has been built and one can try out the operation of various systems in a simulation of actual flight. Nowadays it is common to build mockups and even high fidelity simulators concurrently with the building of the prototype vehicle so that some of these issues can be dealt with before the actual vehicle is completed. For example, when the Lockheed Corporation was developing the L-1011 wide-body airliner, they built a mockup of the cockpit with its window configuration, an instrument panel, and the planned lighting. Then they mounted the mockup on a truck bed and drove it around to get the sun at every angle under all kinds of lighting conditions from dawn to dark to make sure that the instrument panel was shielded from outside glare that might prevent a pilot from reading an instrument at some critical moment, and to establish that none of the internal lighting produced reflections off of the windows which might be distracting or even disorienting when flying in clouds.

The third opportunity for systems integration is after a system has become operational. Human factors specialists participate in accident reviews, but more proactively, they respond to complaints from crew members and debrief crew members after flights to determine whether the operation might be improved.

Dealing with systems integration, whether human, mechanical, or electrical, requires that the specialists involved have empirical data about the performance of the subsystems under various conditions. Unfortunately, in the early stages of the space program those data simply didn't exist, or were incomplete, because many situations were being faced for the first time. As a consequence, much of the human factors work involved getting the needed data by carefully observing and measuring performance during flights. Meanwhile, human factors involvement in designing the early spacecraft often followed the tried and true tradition of whenever you don't know, select people who can do the job under almost any circumstances, and then train, train, train them until they can do it adequately no matter how difficult or inefficient the procedure.

When it came to designing the early spacecraft as both a cockpit and a habitat in which to live for two weeks, the same principle held because the booster rockets were not yet powerful enough to loft any but the most minimal spacecraft. The design had to be almost entirely cockpit and only minimally habitat. The astronauts had to be selected so that they were persons who could tolerate sitting side by side, shoulder to shoulder, for two weeks while they worked, ate, slept, and performed such bodily functions as scratching, yawning, eating, tooth brushing (with toothpaste that can be swallowed), shaving, urinating, and defecating. Of course, because there were no data on the physiological effects of space flight, urine and feces had to be collected separately, saved, and stored in marked containers for later analysis. However, one could not simply defecate in a bag, seal it and tag it. This had been tried in earthbound simulations, but bacteria naturally found in the feces created chemical reactions that produced gases which inflated the bags until they burst with dreadful olfactory consequences. Therefore, bacterial action had to be stopped immediately after defecation. To that end, each fecal bag contained a capsule filled with an agent to kill the bacteria. With the filled and sealed bag in hand an astronaut had to press and break the capsule and then knead the agent through the feces for proper distribution before stowing the bag. The later biological analyses were facilitated by knowing precisely what and when the astronauts ate and drank, and what activities they were involved in between ingesting and eliminating.

The kind of habitat design problems faced with these tiny spacecraft and the ways in which they were solved, is illustrated by the following anecdote from NASA's history of the Gemini program. This dealt with the flight of Gemini VII which was to last 14 days.

> Stowage of food and gear was a special problem on a two-week flight. Unfinished meals and food wrappers could quickly clutter up the spacecraft, as Cooper and Conrad had learned in the eight-day mission. Extra storage space in the small cabin had to be found before the 14-day trip. GPO [Gemini Project Office] Deputy Manager Kenneth Kleinknecht went with Borman and Lovell to St.

> Louis, where Spacecraft 7 was going through its test phases, to help them hunt for more space. The search for an extra garbage dump was successful: waste paper from their meals could go behind Borman's seat for the first seven days and behind Lovell's for the next seven. After working out procedures, the crew practiced stowing for launch, orbit, and reentry, until they were sure they knew where to put every scrap of paper (Hacker & Grimwood, 1977, p.277).

An element of safety that should be considered here has to do with the spirited nature of human beings. While the scientists referred to above were gathering their physiological, social, and psychological data about the performance of the astronauts in space flight, the astronauts were demonstrating the enormous adaptability of the human being. Not only were the astronauts courageous in the face of terrible dangers both known and unknown, but they were able to tolerate stiflingly claustrophobic enclosures, little control over what was happening, total lack of privacy, unusual foods, cumbersome clothing, and the indignity of the violation of strongly ingrained social norms, all in the context of knowing that if something went wrong and they couldn't get out of orbit, they would simply circle the earth until their meager supplies gave out and then they would die.

The very spirit that allowed these early astronauts to function effectively under such onerous conditions is the same spirit that can cause a variety of safety problems. During WW II many neophyte pilots were killed during training when, while ***playing*** with their airplanes, they crashed during such activities as buzzing a girlfriend's house. Too large a number of combat pilots were killed when they crashed while doing low altitude victory rolls over their airfields when returning from a mission in which they shot down an enemy plane. Playfulness is not limited to aviators. It is a cause for much on-the-job safety concern in industry where, for instance, something playfully thrown may inadvertently injure someone who, not expecting things to be flying through the air, unintentionally gets in the way; or the nozzle of an air hose teasingly shoved against the seat of someone's pants causes internal injury when the air blast bursts through the victim's anus.

The astronauts were no less high spirited than most young American men. Some of their playfulness turned out not only to be harmless but was probably useful, and perhaps essential, in managing anxiety. However, space travel was clearly a dangerous and very expensive business and, as such, was considered serious business and playfulness was seldom tolerated or applauded. For example, astronaut Walter M. Shirra, Jr., purchased a corned beef sandwich from "Wolfie's" on North Atlantic avenue in Cocoa Beach and gave it to John W. Young, who along with Virgil (Gus) I. Grissom were the pilots on Gemini III. Young smuggled the sandwich aboard the spacecraft. When the time came, while in orbit, to eat the space food with which they had been supplied, Young brought out the sandwich and handed it to Grissom. As it turned out, Grissom only took a couple bites of the sandwich because he didn't want to get any loose crumbs floating about. The primitive state-of-the-art of space food that could be reconstituted with injected water was the brunt of many jokes by dissatisfied astronauts at that time. However, joke or not, the astronauts had committed an unauthorized behavior and NASA authorities were deeply distressed. When the press got wind of this the storm spread to the floor of Congress where the lawmakers expressed their anger and dismay at this behavior.

At times the astronauts felt that they were working for a humorless agency. "Gus" Grissom had flown a Mercury flight in a spaceship named *Liberty Bell 7* on which the hatch blew off unexpectedly after the spacecraft had landed in the ocean following its flight. Before help from the recovery ships could arrive the craft began filling with water and, while Grissom was saved, the craft sank and was lost. It had been a tradition in the Mercury program for astronauts to select a name for their spaceships.

Gordon Cooper however had trouble selling NASA on the name *Faith 7* for the last craft in the Mercury program. Now, following the sinking of his first spaceship, Grissom wanted to name his Gemini spacecraft *Molly Brown* after the heroine in the stage hit *The unsinkable Molly Brown.* NASA leaders thought the name lacked the dignity called for. "...but since Grissom's second choice was 'Titanic', they grudgingly consented, and the name remained 'Molly Brown', though only quasi-officially. Later spacecraft were officially referred to by a Roman numeral, although a few had nicknames as well" (Hacker & Grimwood, 1977, p. 233).

Not all unauthorized actions or attempts at humor ended on such sour notes. After a nerve wracking series of setbacks Gemini VII and Gemini VI-A had been launched (in that order) and demonstrated that they could rendezvous and fly together safely only a few feet apart. This paved the way for a later docking of two craft in space and again proved the utility of the side-arm controller for sensitive maneuvering. It was late December and both of the crews and the ground personnel were jubilant over their hard won success. Astronauts Shirra and Thomas P. Stafford were the crew on Gemini VI-A. Hacker and Grimwood (1977) tell the following story.

> But Stafford caught everybody's attention for a few minutes. In an excited tone he reported:
>
> > Gemini VII, this is Gemini VI. We have an object, looks like a satellite going from north to south, probably in polar orbit....Looks like he may be going to reenter soon. Stand by one....You just might let me try to pick up that thing.
>
> [Unbeknown to anyone else, Shirra and Stafford had smuggled a small harmonica and some bells on board Gemini VI]]

> Over...the communications circuit came the strains of the pilots playing "Jingle Bells." The spirit of Christmas glowed--Gemini VII was about to begin its 12th day and VI-A, having demonstrated rendezvous in fine fashion, was going home (p.289).

Shirra, who played "Jingle Bells" on the harmonica had been given the small four hole instrument by a music producer. Stafford, who served as the rhythm section, brought along some bells that had been tied to his boots as a joke by a staff member during a simulation exercise. Hacker and Grimwood report the following rationale for the happy outcome of this deviant behavior.

> It had been Shirra who furnished the corned beef sandwich that had created such a furor for the Gemini III crew. Asked, some time after his flight why he "didn't get too much static for the harmonica," Shirra replied, "I think the timing was pretty good on that."

Human factors specialists have not developed any sure-fire rules for governing high spirited behavior. However they do know, and remind everyone, that it will occur and that it can have a salutary effect but that frequently it backfires with tragic results. Thus playfulness awareness becomes part of safety training. Deciding when humor is appropriate is a judgment call (as Shirra implied) but that doesn't mean there are no relevant principles that can be applied. For example, humor and other high spirited behavior is appropriate only when it is not likely to have any deleterious effect on activities. Sandwiches are not appropriate in space because of problems with crumbs. Furthermore, medical personnel wanted to know exactly what went into each astronaut and what came out, so eating unauthorized food could have been a problem. However, playing "Jingle Bells" put no other system at risk and so the astronauts got away with it.

Gemini program was a success. Twelve flights were made and a wealth of new information was gathered that would assist in the design of future equipment and the planning for systems integration. In addition, the couch restraint system continued to prove itself and the side-arm controller came through with flying colors. It had been demonstrated that spaceships could rendezvous and maneuver close together, then dock and disconnect with relative ease. Although it was not much fun in such close quarters, it was clear that crews could live and work effectively in space for periods long enough to go to the moon, and that they fully recovered from the effects of their extended periods of weightlessness. Reentry procedures improved and now space vehicles were landing so close to their recovery ships that they were being photographed on their way down beneath their brightly colored parachutes. On now, to Apollo and the moon.

Chapter Four

The Apollo Spacecraft

> *I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth....*
>
> President John F. Kennedy
> May 25, 1961

We now come to the time in the early U.S. Space program when it began to seem as though the above challenge from President Kennedy might realistically come to fruition. Astronauts had flown six Mercury space craft, four of them in orbit. Ten pairs of astronauts had orbited in Gemini space craft. Among them, they had rendezvoused, docked, worked outside the space craft, had orbited as far as 853 miles above the earth, and had stayed aloft as long as two weeks. All of this had been accomplished without a single spaceflight fatality. The year was 1968. The U.S. had a new and larger space ship, called *Apollo* that carried a crew of three. As with its predecessors, it retained the shape of a truncated cone, and had a service module attached to the flat end behind the reentry heat shield. However, attached to the rear of this service module was yet another cylindrical vessel called the lunar module.

This module contained, folded up so as to fit inside, a smaller, spindly- legged space craft in which two of the Apollo astronauts could descend to the moon's surface and return again to Apollo as it orbited the moon. The moon lander was called the *LEM*--an acronym for Lunar Excursion Module.

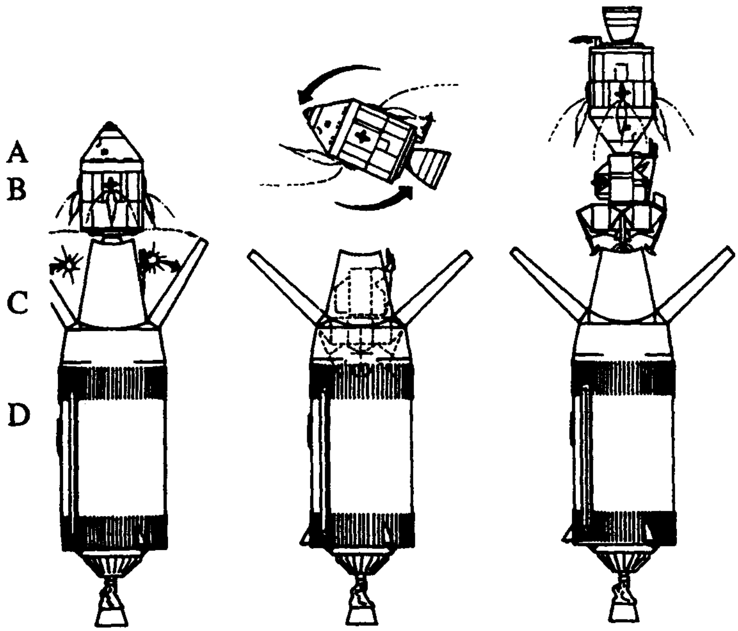


Figure 4.1
Line drawing of an Apollo space craft (A through C) still attached to the third stage of the Saturn rocket (D). A = The command module. B = The service module. C = The lunar module, shown with its panels opened and the LEM inside. Once on a trajectory towards the moon, the lunar module panels are discarded, the command and service module pulls forward and turns around as shown, the tip of the command module's cone is jettisoned and the command module docks with the LEM. The trio of LEM, command, and service modules, then pull away from stage three of the Saturn and go on to the moon. (NASA drawing).

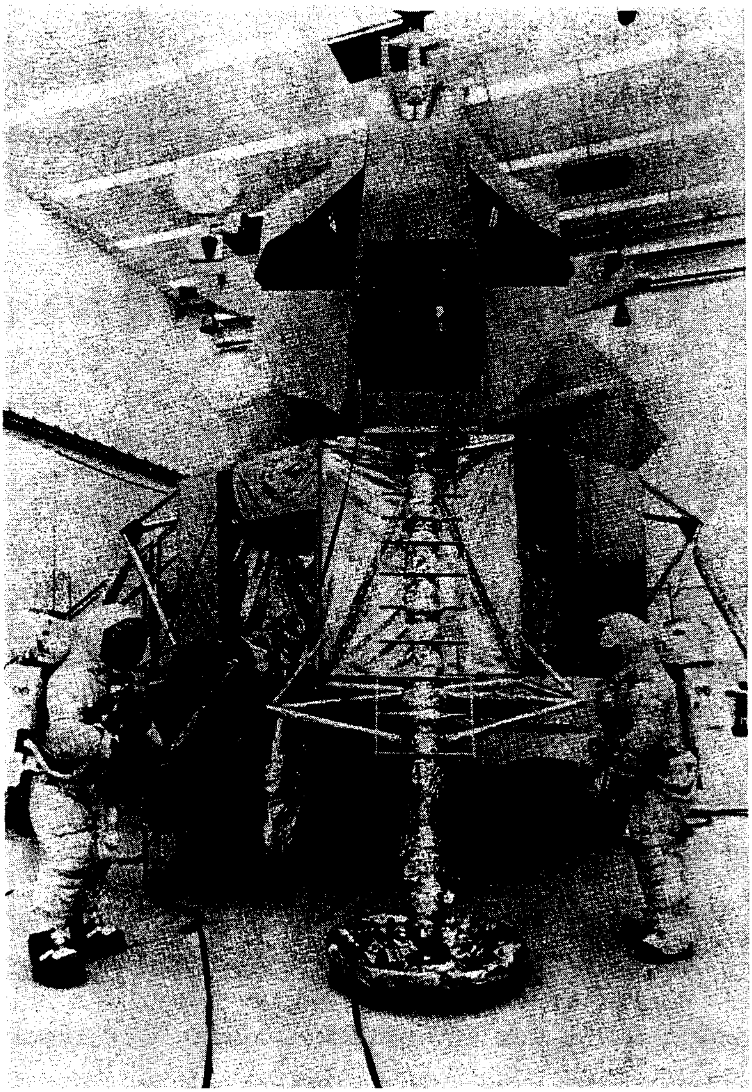


Figure 4.2
The Lunar Excursion Module (LEM). Apollo 13 astronauts James Lovell (left) and James Haise are shown in training. The hatch is the dark square opening located above the ladder. The triangular windows are above to the left and right. (NASA photo).

Perhaps even more incredibly, the U.S. had a little four-wheeled electric car, called the ***Lunar Rover,*** for driving around on the moon once they got there.

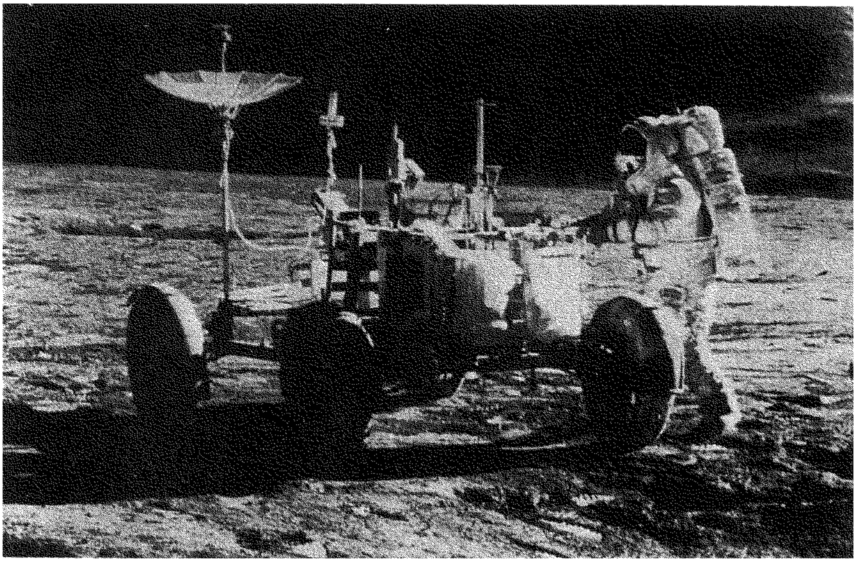


Figure 4.3
Apollo 15 astronaut James Irwin and the lunar rover in the Hadley-Appenines region of the moon. (NASA photo).

The U.S. also had developed an extremely powerful three-stage rocket, called the ***Saturn*** *5*. Its first stage could develop 7.75 million pounds of thrust (equivalent to about 180 million horsepower), and it was a hundred times more powerful than the Redstone rocket that boosted Alan Shepard into suborbital flight in his Mercury capsule. The Saturn 5's first stage consumed its 4.6 million pounds of propellant in 3 minutes and 40 seconds. In addition to being the most powerful machine ever devised, it was among the most complex, and yet its many thousands of parts had an amazing 99% reliability. In the end, without a single failure, this 363-foot behemoth would propel 27 U.S. astronauts to orbits around the moon.

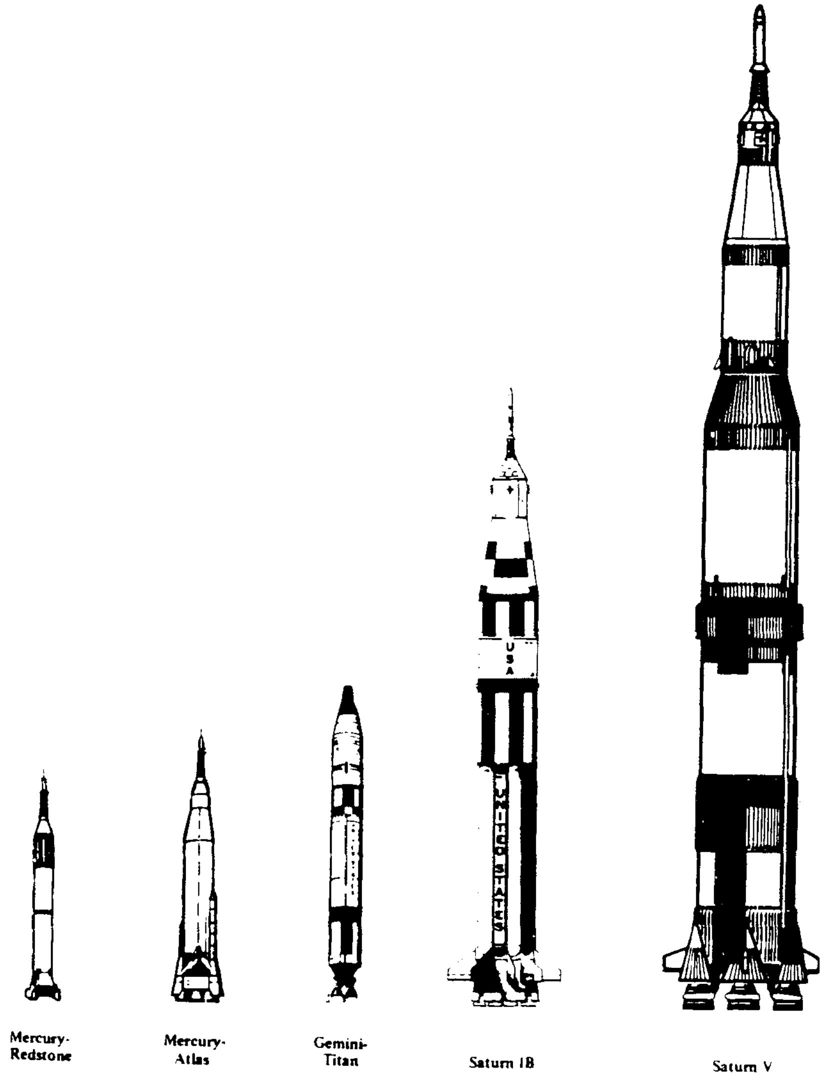


Figure 4.4
The relative sizes of the manned launch vehicles. (NASA drawing).

Before addressing some of the human factors issues associated with the Apollo space craft and other related equipment, I will turn our attention briefly to human factors and the garments that are worn in space flight, and then to a nasty physiological surprise that first occurred in the U.S. space program during Apollo.

The clothing and space suits worn by astronauts have important human factors implications for comfort, safety, and the basic ability to conduct required activities. In the open cockpit days of flying, helmets and goggles, and fur lined coveralls became two of the symbols of aviators. But they were more than simply decorative accouterments to make the wearer look more dramatic. They made it possible to do the job of flying. The goggles protected pilots' eyes from constantly blurring due to tears elicited by wind blast. The heavy clothing protected against the colder temperatures at altitude. For instance, at sea level, when the temperature is a pleasant 72^0 F, the temperature at 12,000 feet is in the mid-30's.

The following clothing anecdote from the history of aviation is another illustration of *functional fixedness* (doing things the old way even when inappropriate to new circumstances). During WWI an aviator was an officer and a gentleman and thus he dressed appropriately when he went to war. Of course it was not possible to wear a uniform dress cap or a metal helmet while flying in an open cockpit so an exception was made to allow the helmet and goggles. And of course the ubiquitous fur flight jacket was allowed over, the otherwise intact, uniform. The WWI uniform jackets had stiff standing collars much like the collars on modern U.S. Marine Corps dress blue uniforms. When on patrol, fighter pilots had to keep swiveling their heads about as they searched the skies for enemy aircraft and found their necks getting painfully chafed by these collars. Their solution to the problem was to insert a soft, almost lubricating, silk scarf between their necks and collars. Thus was born the other symbol of the aviator--the white silk scarf. Even during WWII fighter pilots left England for the skies of Germany wearing uniform dress shirts and neckties. Fortunately, the tradition of those garments has given way to the much more ergonomically sound flight coveralls of the modern aviator and astronaut. These coveralls have many adjustment tabs, and zippers that allow easy donning, removal, and ventilation. Pockets are available where they can be easily reached and none are located where they would be sat upon. Collars are loose, short so they won't rub against a crash helmet and the ends are curved so they won't flap in wind.

Before discussing space suits it is helpful to understand the functions they serve. In the early days of the space program, when rockets were not very powerful, space craft strength was limited by weight considerations. To make space craft lighter the pressure inside was reduced to about five pounds per square inch (psi). On earth, sea level pressure is 14.7 psi and in space the ambient pressure is zero. If a space craft were to have sea level pressure inside for its crew, and no pressure on the outside in space, then each square foot of the space craft's hull would have to contain a force of more than a ton (14.7 lb/ft^2 X 144 in^2/ft^2 = 2,117 lb), whereas, at 5 psi the force on the space craft hull is only 720 lb/ft^2. Humans can perform normally at 5 psi but only when breathing pure oxygen. Air contains about 78% nitrogen, 21% oxygen, and 1% traces of several other gasses.

To protect astronauts in the early space craft from the fatal consequences of an inadvertent decompression of the cabin, pressure suits were developed and worn during high risk times such as during launch, reentry, docking, and undocking. Later versions of such suits, then called space suits, allowed the cabin to be fully depressurized, the hatch opened, and an astronaut to venture out into the vacuum and intense solar radiation of space. Inside the suit was an oxygen atmosphere of about 3.7 psi which was still sufficient for normal human performance. However, if a cloth suit were inflated to 5 psi in the vacuum of space, an astronaut would have difficulty bending the arms or legs.

Two kinds of human factors issues were involved in space suit design. The first had to do with the nature of the suits themselves. The suits had to be comfortable enough to be tolerated (the early ones weighed 26 lbs), provide sufficient mobility to perform the required tasks, and maintain a proper working temperature. The second issue had to do with the ways in which the suits affected how the crew was able to operate equipment. For instance, since the astronauts wore inflated gloves they could not easily feel switches or other manipulanda. Also, when operating a switch, it was easy to bump and accidentally operate an adjacent one. To prevent inadvertent switch operation, switches located close to each other were provided with sheet metal barriers between them. Thus each toggle switch was mounted in a channel down which the gloved finger moved when activating the switch. Putting stronger springs in the switches caused them to compress the inflated glove sufficiently so that the switch could be felt by the finger inside and then when the switch was flipped the audible click was so loud it could be heard even when wearing a helmet and thus verified without having to look at it.

When astronauts began extra-vehicular activity (EVA), and ultimately, walking on the moon, the suits also had to protect them against ionizing radiation (e.g., gamma and x-rays), radiant heating in direct sunlight and radiant cooling in the shade (temperatures on the surface of the moon varied from 212^0 F down to -240^0 F), and injury from micro-meteoroids (about the size of a grain of sand). Lunar suits consisted of 26 layers and, including their portable life support systems, weighed about 750 lbs on earth (but only 1/6th of that, or 125 lbs, on the moon). Inadequate cooling was one of the most serious shortcomings of the first EVA suits. On an early Gemini flight an astronaut had to be pulled back into the spacecraft by his tether after his helmet's face plate fogged over from heat and humidity, and left him unable to see out to find his way back in.

Modern space suits are really miniature space craft themselves, and are marvels of human ingenuity. Long underwear with tiny coolant tubes like blood vessels removes heat from the astronaut's body. Gold plating on the helmet's face plate protects from too much light, as do plated sliding visors which are provided. Dual microphones provide redundancy for critical radio communications, and a helmet feature allows astronauts to ingest liquids while working in space. Gloved fingers are sewn into a curved position when relaxed, to give the astronaut's fingers the necessary leverage to be able to bend the inflated gloves. Bellows are sewn into the knee and elbow joints to allow for better flexibility. Incidentally, the engineer who designed this feature got the idea from watching a tomato worm turn a right-angle corner without changing its volume as a consequence of its bellows-like segments.

Kinesiology is "the science of the anatomy, physiology, and mechanics of purposeful muscle movement in man" (Blakiston's, 1979, p.725). Information from this field played an important role in the ergonomically effective design of the pressure suits used for launch and reentry, and in the design of the suits used by Apollo crews to explore the moon's surface, set out equipment, collect rocks, dig moon soil, take photographs, and even drive around in the lunar rover.

The nasty physiological surprise that occurred during Apollo was that astronauts began experiencing motion sickness.

> While adjusting to weightlessness, a number of astronauts had been afflicted by motion sickness. Although the 19 Americans who had flown in Mercury and Gemini had been immune to the poorly understood malady, almost half the Soviet cosmonauts, flying in the slightly larger Vostok and Voskhod spacecraft, had suffered from it. With the start of Apollo, the Americans lost their immunity; 9 of 29 astronauts had motion sickness in that program, with nausea and vomiting persisting in some cases for several days. Because the problem was occurring in the larger vehicles, some doctors believed the increased freedom of movement--particularly head movement--brought on the malady (Compton & Benson, 1983, p. 295).

While they seem to get over it within a day or two, many persons going into space find those first two days tainted by feelings of nausea. The amount of time spent in weightlessness does not seem to affect the onset. For instance, NASA uses a modified Boeing-707 type aircraft to fly parabolic arcs that produce about 40 seconds of weightlessness. After gaining speed in a dive the plane pulls up into a climb. The pilot then pushes forward on the controls and flies through a weightless arc that lasts less than a minute. Nevertheless, motion sickness is so common among researchers who have flown the short weightless flights in this plane that they have dubbed it, ***the vomit comet.***

You can imagine that vomiting in space, where nothing falls down, is very risky business. One clearly must not vomit inside a helmeted space suit, and if one vomits in a space ship the material must be contained in a waterproof bag. The nausea can fortunately be controlled with some drugs such as scopolamine. However, the drowsiness side effects are not consistent with the demands for high vigilance required of space flight. It seems that the nausea is caused when the brain gets information from the balance organs in the inner ear that conflicts with visual information. Research continues at a brisk pace among a variety of disciplines, including human factors, in an effort to better understand this phenomenon and to find alternatives to the use of drugs. Some preliminary success has recently been found using biofeedback techniques.

One of the classic areas of human factors effort and success has been in instrument design and arrangement. Persons operating complex machines must have information about how subsystems within the larger system are operating. Often they must have information from several sources that has to be integrated in order to make a proper decision. Early on, human factors workers realized that, most of the time, operators did not need precise information from each instrument. Rather, they needed general information such as whether a system was operating normally. By the early 1940s the workload in cockpits became too great because pilots often had many instruments (remember the cockpit of the Spitfire?) and little time to read each one carefully (see Figure 1.2).

A simple invention proved to be an effective device for reducing operator workload when reading instruments, and serves as a representative of a number of similar innovations. Instrument designers color coded different operational levels on the instrument face: for instance, normal range with a green arc beneath the numbers, caution range with a yellow arc, and danger range with a red arc. An illustration from aviation shows the value of color coding. On aircraft with normally aspirated (non-supercharged) reciprocating engines, the engines can usually be run at maximum power for some fixed period of time (often five minutes) which is long enough to complete a takeoff. In such cases, the controllable pitch propeller (prop) is set so that it can turn faster than usual for the same period of time. When starting the takeoff run, the pilot pushes the throttle and prop governor levers to the stops and releases the brakes. Then things really begin to happen fast! However, a quick glance at the engine and prop gauges to see that the needles are beyond the green arcs assures that full power and thrust are being developed. Shortly after liftoff, the pilot retards the throttle and prop levers until their gauge pointers are at the top of the green arcs. Again, only a couple of quick glances at the gauges are required at this critical time in the flight when most of a pilot's attention should be directed outside the cockpit. Later, when the aircraft arrives at cruising altitude and things have settled down some, the pilot can take the time to adjust the engine and prop cruise settings with precision by reading the instruments carefully.

Once the needles have been precisely set, only an occasional glance is required to determine if they are remaining steady or shifting position relative to the green arc. Normally all the pilot first needs is a rough approximation of needle position--the same or changed. If there is no change, no action is called for. Only if there is a change need the effort be taken to read the instrument carefully.

At first, this whole issue of color coding may seem trivial, but in fact, it is quite important. When only trend information is required and there are many instruments and there is little time, color coding is a powerful tool. Without such trivial-seeming features aviators would suffer from *information overload*--too much information and too little time to take it all in.

Another, less simple, innovation involves the shape of instruments. Notice that nearly every instrument in the Sopwith Camel and Spitfire cockpits (Figures 1.1 and 1.2) was round with a dial that moved in an arc across its face. There were sound mechanical reasons for building early instruments that way, and for most purposes they are easy to read with good accuracy. However, new technology makes it possible to design instruments in any shape we want. Round instruments are not very easy to read when they are changing rapidly. Important early human factors research, much of it carried out in new university aviation psychology laboratories, has shown that vertically oriented, straight line, or strip, instruments (such as a mercury thermometer) are often more quickly and accurately read.

Another example from aviation illustrates the way vertical strip instruments can be used to simplify information retrieval. Suppose that on the instrument panel of a four-engined airplane there are four vertical strip engine power instruments located adjacent to each other. The pilot can precisely set the first power lever by carefully reading the setting on its corresponding instrument. The other three levers then can be quickly moved so as to simply line up the three indicators with that on the first instrument. Then, during flight, a quick glance will tell whether all four indicators are still in a straight line. When used together with color coding, this combination effectively facilitates information transfer.

I have taken you back once again into the history of human factors and aviation in order to characterize some of the issues in instrument design. I will conclude this chapter with a brief discussion of the instruments and some other human factors aspects of the lunar rover (you may want to look back at Figure 4.3 to refresh your memory of that vehicle). I will then discuss an enduring dilemma involved with human factors innovation and illustrate it with an example from the development of the LEM.

Figure 4.5 shows the instrument panel of the lunar rover with its variety of instrument types. The instrument in the upper left corner is a simple pendulum which can be used on the moon because it has gravity. The instrument is organized so that it displays itself as a pendulum would, which for most adults is intuitively easy to understand. A quick glance and you know how much you are tilting. On the next instrument to the right, the pointer always keeps pointing back to the radio beacon on the LEM. By having an entire compass rose around the needle's mid-point, which represents the rover, it is easy to orient to structural features all around the horizon.

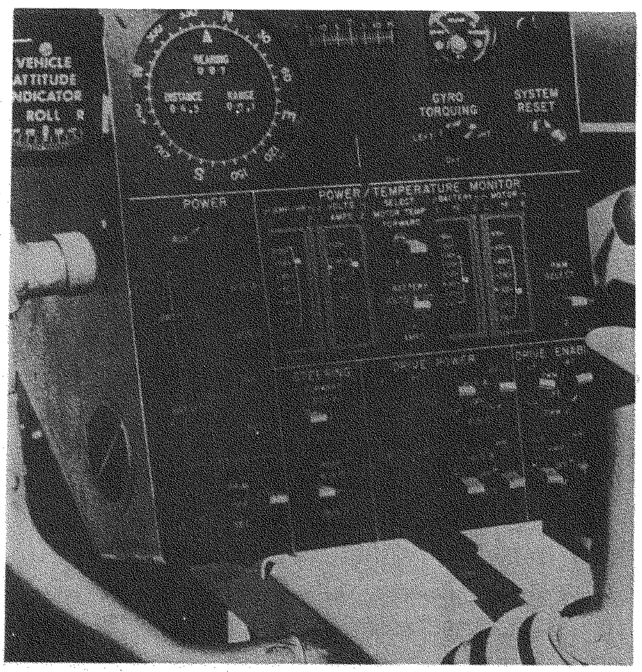


Figure 4.5
The instrument panel of the lunar rover. (NASA photo).

The horizontal strip instrument in the center indicates the steering angle of the wheels and is in line with the steering control handle (extreme right) which, located in the center, is a side-arm controller available to the right hand of one astronaut or the left hand of the other. The speedometer in the upper right is a circular instrument with an arc needle. The power and temperature gauges in the center are all vertical strips.

Human factors experts have four sources of information and they always try to utilize *all* of them when working on a problem.

1. The accumulated knowledge in the technical literature.
2. The advice of people experienced in using such devices.
3. Observing and testing the use of prototypes or final models in experimental or field settings.
4. Their own wisdom based on ingenuity and experience.

They face a dilemma when they and/or their data are at odds with the advice of experienced users. While it seems silly to design a flying machine without consulting experienced test pilots, their advice is not always correct. A good illustration was the Mercury astronauts wanting a center joy stick instead of the side-arm controller. In that case the human factors people had to prove to the astronauts that the side-arm controller was better and that they would come to like it. Now consider the following anecdote about the instruments to be included in the Lunar Excursion Module (LEM). Who do think was right?

> Grumman had proposed an ...[artificial horizon instrument], assuming that the astronauts would want it. Arnold Whitaker recalled, "The first thing NASA did was to say that there's no operational requirement for it--take it out. So we took it out. Then the astronauts came along and said, 'That's ridiculous. We must have it.' So we put it [back] in. By this time, we're late. Dr. Shea had a program review and said, 'take it out. I'll accept

> the responsibility for it.' The astronauts found out about it and said, 'We won't fly a vehicle until you put it in.' And NASA put it in, this time with a kit [for easy removal later] (Brooks, et al, 1979, pp. 148-149)."

The rocket engine used in the LEM's descent kicked up so much dust that the moon's horizon was obscured just prior to landing. Having an artificial horizon instrument was a necessity. The astronauts were right.

Early in this chapter I brought up, once again, the issue of functional fixedness which is an enduring problem for designers. I will now end the chapter with an illustration of just the opposite; a design solution in the Apollo program that was functionally simple and effective but innovative because it was counter-intuitive to the way things are normally done in vehicles in this culture.

The problem arose in the design of the seating arrangement for the two LEM pilots. When a vehicle operator is seated before a vertical surface, the person's feet and knees protrude out in front requiring the torso, head and eyes, to be back away from the wall by about two-thirds of a meter. If the operator's viewing window is in the wall, there is usually no problem because vehicles generally travel laterally, not vertically. The view out ahead is relatively unrestricted when the operator's head is a short distance back from the windshield (for instance, as it is in an automobile).

However, the LEM is landed, for all practical purposes, straight down. To give the pilots the best possible view in the direction they are going, they should be able to have their heads right up against the window. The only practical way of doing that would be to have them fly the LEM while standing up. At first blush, the idea of pilots flying around standing up in a cockpit seems almost ludicrous--it just isn't the way things are done. An indication of this in your own experience is that, a few moments ago when you read the first sentence in the previous paragraph referring to the "seating arrangement for the LEM pilots", it probably sounded appropriate to you.

The position finally selected for the LEM pilots was standing, and in their context it made good sense. While in orbit around the moon they would experience no gravity, and standing would be comfortable. Standing in the space craft while it is on the moon's surface would be easy because the gravity is only one-sixth of that on earth. The deceleration rate on approaching the moon's surface was never great enough to make standing difficult, and the final 100 foot descent was done at a very gentle two-feet per second. The standing position proved to be an elegant solution. It was simple and worked perfectly. The pilots were equipped with simple restraint harnesses that would have kept them from tumbling around in case of a hard landing.

We have seen that it is sometimes hard to break the mental sets that cause us to want to do things new to our experience in much the same way as we have done similar things before. When dealing with space, where the novelty is often greater, it is even harder to break those mental sets. However, the positioning of the pilots in the LEM is an illustration of a creative human factors solution which was not at first obvious.

On July 24th, 1969, the final sprint in the space race between the U.S. and the U.S.S.R. came to an end as astronauts Neil Armstrong and Edwin (Buzz) Aldrin of Apollo 11 stepped from their LEM, *Eagle,* onto the surface of the moon. While their colleague, Michael Collins, orbited the moon in the command module Columbia, they spent 2.5 hours collecting 50 lbs of rocks and dust, and set out some experiments that were left to function automatically. Then they rocketed up to rejoin Columbia, and returned safely to earth. President Kennedy's 1961 challenge, to put men on the moon and return them safely to earth within the decade, had been met with months to spare.

Apollo 12 landed two more men on the moon. Apollo 13 suffered the explosion of an oxygen tank in the service module. The crew rode out the flight around the moon and back to earth after crawling into their LEM. It was nip and tuck all the way, but with much ingenuity and only modest suffering they were eventually able to reenter the command module in earth orbit and then returned safely to earth. Apollos, 14, 15, 16, and 17 each put a pair of astronauts on the moon. All returned safely. Apollo 15 took the first rover to the moon and the Apollo 17 crew drove their moon rover 22 miles. No longer was the U.S. second in space.

Chapter Five

Skylab

Skylab was the United States' first space station (see Figures 5.1 and 5.2).

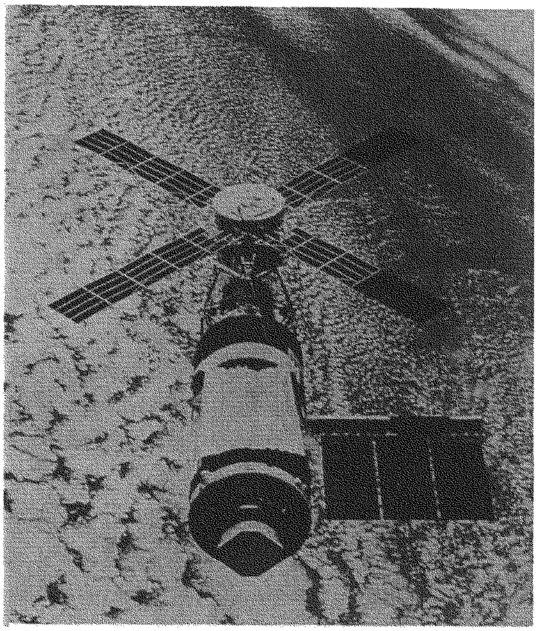


Figure 5.1
Skylab in orbit. (NASA photo).

It was launched on May 14, 1973 and was designed to travel at an altitude of 270 statute miles above the earth (235 nautical miles—see Box 5.1) in orbits that carried it 50 degrees north and south of the equator. As such it flew over 80% of the developed land and 90% of the human population (Belew, 1977).

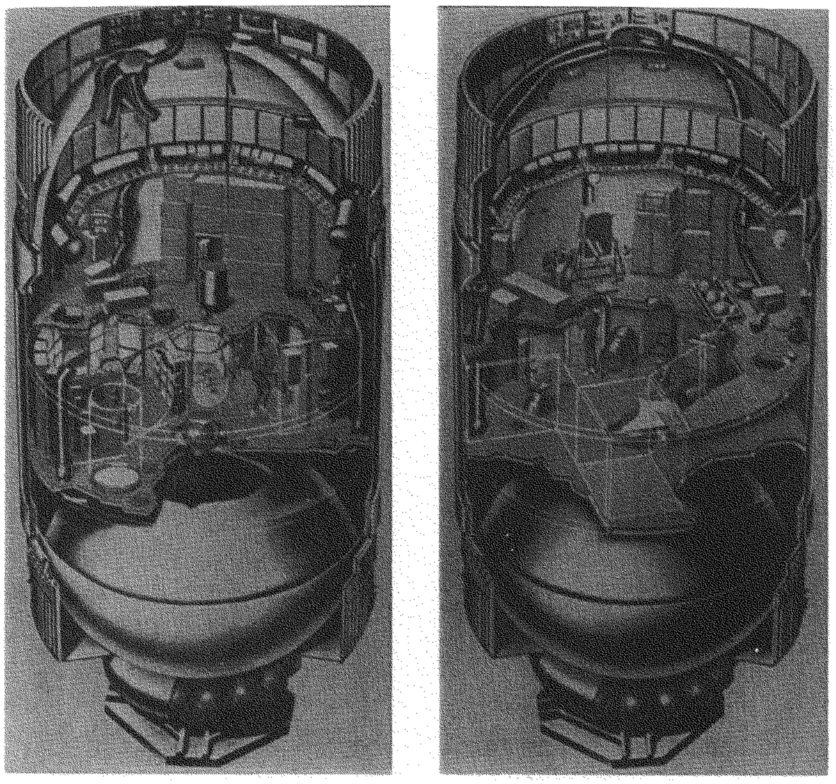


Figure 5.2
Two cutaway views of the Skylab working and living areas. (NASA drawings).

Skylab was launched atop a two-stage Saturn V rocket. This was the 14th and final flight of that great rocket. In all, 15 Saturn Vs were built. Two flew on unmanned test flights, eleven carried Apollo crews to the moon, and the fifteenth is in mothballs. The space station was placed into orbit without a crew on board. The first crew to occupy Skylab rode up nine days later in an Apollo command and service module aboard a Saturn IB, a much smaller rocket than the Saturn V. The first task of this first crew was to dock their Apollo module to the space station.

Box 5.1

Statute vs Nautical Miles

The *miles* that we are all accustomed to seeing on road signs and maps are statute miles. They are based on the U.S. Customary Unit of length which is the yard, with a foot being equal to one third of a yard. A statute, or land mile, is equal to **5,280** feet. However, the nautical mile is based on the length of one minute of arc of a great circle on the earth, given in meters. When expressed in feet, the length of a nautical mile is about **6,076** feet.

The nautical mile is used in navigation because distances can then be related to solar time since the earth rotates on its axis 15 degrees per hour (360 degrees/24 hours). When speeds refer to statute miles they are expressed in miles per hour (MPH). However, when speeds refer to nautical miles they are expressed in knots (K).

Skylab was a big space station--about the size of an average three bedroom house, and on earth it weighed nearly 100 tons. It was built from modified Apollo equipment, and the largest segment of the three-part structure was an empty liquid hydrogen fuel tank from the third (upper or smallest) stage of a Saturn V rocket. This was converted into a spacecraft with two stories, one a laboratory and the other the living quarters (McAleer, 1987). This is what is shown in Figure 5.2. Connected to one end of the tank was an airlock module with a hatch through which crew members could exit the space station wearing pressurized space suits. Connected to the airlock module was another module called a docking adapter, and it was to the end of this that the crew would dock their Apollo module with its service module attached to the back of it. Thus when the space station was manned, it consisted of five modules all connected in a line.

When the Skylab modules were first mounted atop the rocket for launch, a solar observatory was connected to the docking adapter at the top of the stack. Then the whole stack was covered with protective panels that formed a nose cone to protect the modules while passing through the earth's atmosphere. Once deployed in space, the streamlined nose cone was jettisoned. Then the solar observatory was rotated 90 degrees so that it was located on one side of the docking adapter, thus making it possible for the Apollo module to connect with the end of the docking adapter. After this was done large wing-like solar panels were deployed to generate electricity (see Figure 5.3).

The development of the Skylab was a great opportunity for designers. Heretofore, spacecraft were tiny capsules consisting of little more than cockpits. With the development of much larger space laboratories, crew members would be able to be erect and move about much the way one would in a building on earth. Of course, in earth orbit where centrifugal force almost completely counteracts the effects of gravity, one cannot walk as we can on earth. When astronauts move about, they refer to it as *translating*. They simply push off and drift to wherever they are going and then must grab on to something to stop. Actually in low earth orbit there is a small effect from gravity (about .065g), and technically it is referred to as a micro-g environment. For all practical purposes, from a human standpoint, this is not noticeable. Thus the environment is popularly referred to as zero-g.

Many fascinating human factors questions suddenly had to be faced such as; now that there is room for a toilet, how do you design one for zero-g where nothing *falls down*? Or, will crew members sit *down* at a table to eat? Or, will they lie *down* to sleep? Space limitations will only allow me to address one major issue in detail in this chapter, although I will briefly discuss several others.

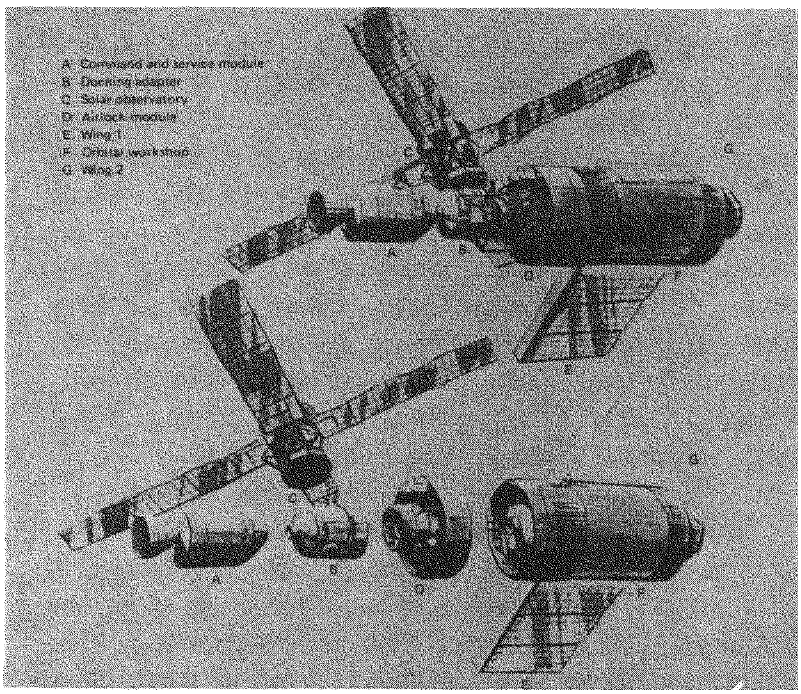


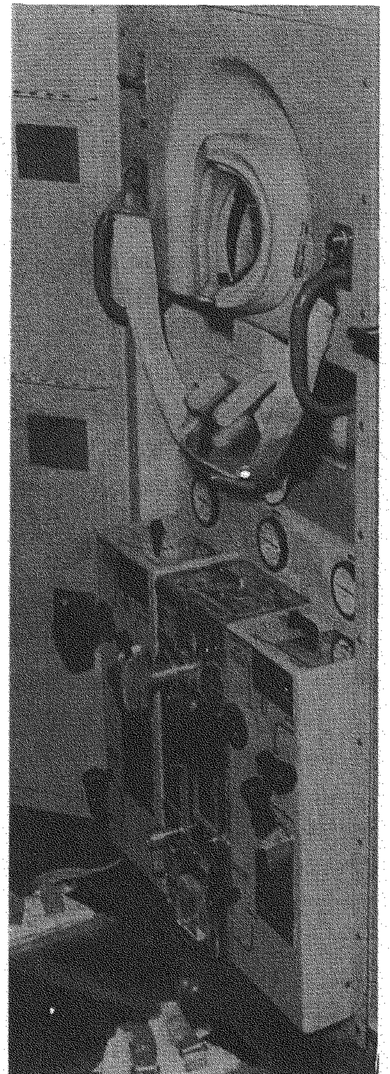
Figure 5.3
The various components of Skylab (NASA drawing).

The primary issue that I will address here is that of restraint. That is, how can weightless crew members be held still and steady, such as at work stations, so that useful work can be accomplished? However, it would be unfair to pose such fascinating questions as those with which I opened the previous paragraph and then not answer them. Therefore I will first respond to them and then go on to address in somewhat more detail the topic of astronaut restraint in Skylab.

Toilet design remains a difficult problem to this day. The crew of Spacelab (Spacelab will be dealt with in the next chapter) use the toilet in the shuttle which differs from the Skylab toilet. However, the basic principle for moving waste material away from the body that is employed in both is airflow. Air, drawn in from beneath the toilet seat, carries the waste to some storage point. In the case of the Skylab toilet, solid waste was separated from liquid waste (see Figure 5.4) and carried to a plastic container that could be sealed, labeled, and then frozen so that the contents could be analyzed later on earth to gain medical and physiological information.

The toilets on the shuttle orbiters freeze-dry the solid waste in a stainless steel sphere, and the liquid is stored in a separate tank from which it is vented overboard into space. What is really interesting from a human factors point of view is where the toilets are located. On earth, toilets are located on the floor and waste falls into them. In space it is not physically necessary to have toilets on the floor. In fact, on Skylab the toilet was on the wall (see Figure 5.4 on page 64). Crew members simply heisted themselves up using the hand holds provided and then fastened the (toilet) seat belt and sat there on the wall facing down at the floor. Getting used to living in space where down, up, floor, ceiling, and wall, all lose their normal meanings probably is a process similar to adapting to a culture quite different from one's own.

However, the toilet on the wall idea doesn't seem to have caught-on because the toilets in the shuttle orbiters are on the floors, and the plans for the toilet in the new space station *Freedom* call for it to be on what will be perceived as the floor.



The waste management unit in June 1971. Having the toilet mounted in the middle of the wall posed no problem in zero gravity. Between the toilet and the lap belt is the holder for the urine receiver. Urine would be collected in the three drawers at the bottom. The foot restraints on the floor proved of little use.

Figure 5.4
The Skylab toilet. The photo is reprinted from Compton and Benson, (1983). Their accompanying caption is quoted.

In fact, because some astronauts have experienced momentary episodes of disorientation when translating from one part of a space vehicle to another, NASA now plans to have cues for a local vertical designed into all spacecraft. This might involve such techniques as having the floor areas darker than the ceiling areas.

Now to the question of sitting to eat. Counter-intuitive as it may seem, sitting while weightless is not particularly comfortable. On earth we sit because it is much less strenuous than standing. The heart does not have to pump blood against gravity as much, we are supported on a large area across our buttocks and thighs, and with our legs hanging down like counterbalancing pendulums our upper torsos are very stable and require less muscle activity to balance. The force of gravity pulls our bodies down and into conformity with the shape of the chair. However, in space there is no gravity against which to have to pump blood, and no balancing is necessary because without gravity one can't tip over. To bend into the sitting position requires the contracting of abdominal muscles to get the 90 degree bend at the waist, and contracting leg muscles to get the bend at the knees. This requires constant effort. The easiest way to sit in space is to use a seat belt that pulls one into conformity with the seat and back of a chair. In orbit it is most comfortable to eat while erect (see below).

Before discussing sleeping, it is necessary to describe what an erect body in a relaxed position would look like in space. Without other forces acting upon it a human body takes on roughly the position it assumes when floating in water, with the arms somewhat raised out in front. This is referred to as the *neutral body position* and will be discussed at greater length in the next chapter (You may want to look ahead to Figure 6.6).

During weightless sleep, a person assumes the neutral body position. Astronauts on board Skylab were oriented with their feet toward the floor, although one crewman, who didn't like the flow of air up his nose, slept with his head toward the floor. Crew members on the shuttle orbiters usually encase themselves in a lightweight mummy type sleeping bag. For one thing, this restrains the arms from rising, which when seen by awake crew members, looks very "spooky".

We evolved in the 1-g environment on the earth. The combination of gravity pulling us down and the friction between our feet and the ground created a very stable platform for accomplishing many behaviors. On earth, a quarterback can throw a football 50 yards or more. If an unrestrained astronaut attempted the same feat, the ball would go one way and his or her body would go the other (Newton's second law of motion--for every action there is an equal and opposite reaction). On earth, a plumber puts a wrench on a pipe, takes a good wide stance, and with a lot of force turns the pipe. However, an unrestrained space plumber would simply rotate around the stationary pipe. In fact, an unrestrained astronaut will soon begin to drift away from a work site in the air currents from the ventilation system. Clearly, astronauts must have ways of being restrained if they are to conduct muscular work.

Since we are accustomed to being restrained by our feet and thus having both of our hands free to manipulate things, it would seem that restraining the feet would be a good way to begin. In fact, that is just where designers and engineers started. And since simplicity in design is usually best, it would seem that cloth foot loops, strategically located, ought to do the job just fine. Simply translate over to a work site, grab on so as to stop, slip your feet into the straps, and go to work. Here is an illustration of a good common-sense solution that is obvious. However, it is exactly because one can not trust either common sense or the obvious, that we need a field such as human factors. Please observe Figure 5.5 (next page). The photo on the left shows the Skylab waste management compartment (NASA jargon for the bathroom). Notice the foot restraints which were carefully placed on the floor to be used by the crew. Now observe the same area, in the photo on the right, in which Jack Lousma is shaving, and notice how he is restraining himself, with the foot loops lying unused beneath him. Something is wrong here. Devices were designed and supplied to be used and they are not being used. Who do you think is wrong, the user or the designer?

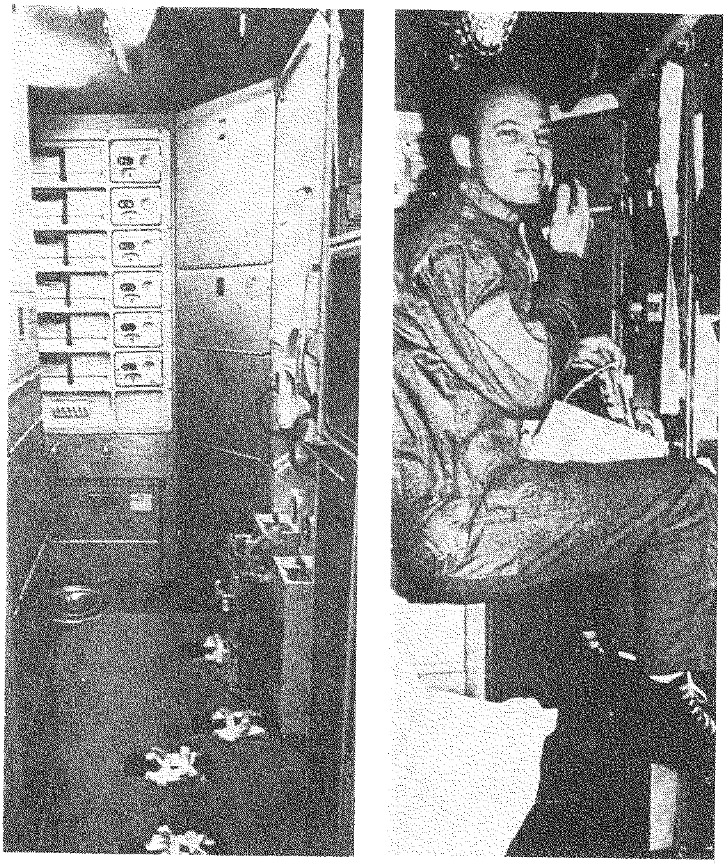


Figure 5.5
Two views of the Skylab waste management compartment. In the view on the left, the compartment is empty and the foot restraints are clearly visible. In the view on the right, astronaut Jack Lousma is shaving and using an innovative (and more satisfying) method of restraint (NASA photos).

You already have some of the information you need to solve this conundrum. Part of the trick here is in having the correct psychological set to perceive the relevancy of the information to the solution of this design problem. Creating that frame of mind is part of what goes into training someone to work in human factors.

As shown in Figure 5.5, (previous page) astronaut Jack Lousma did not use his foot restraints while shaving, and in the quoted caption in Figure 5.4, Compton and Benson state (in reference to the foot restraints in front of the toilet), "The foot restraints on the floor proved of little use" (1983, p. 153). The question then arises, were there any foot restraints which were used effectively? The answer is that there were. Figure 5.6 shows a view of Skylab, looking down on the bottom of the two-story main structure. Notice that the floors were made of triangular metal grids.

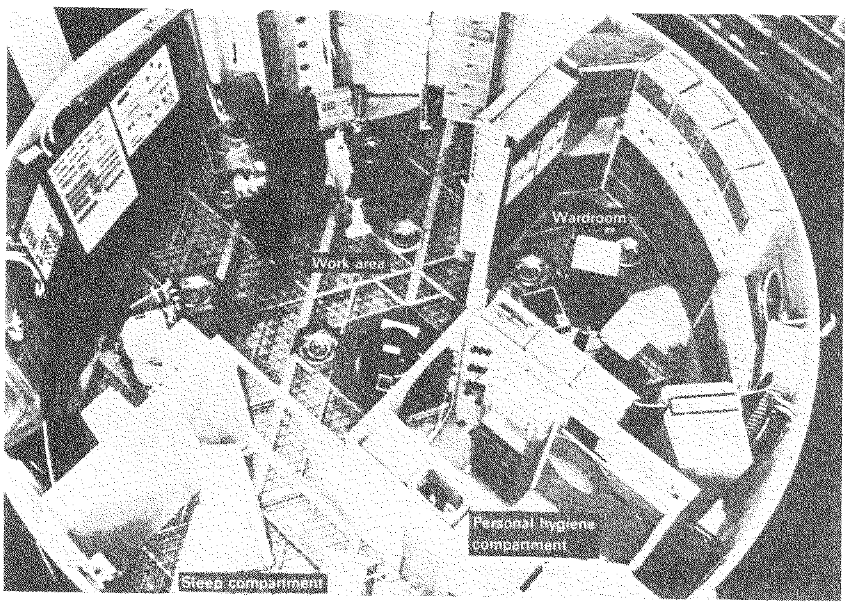


Figure 5.6
The lower deck of the Skylab trainer with the compartments labeled.

The astronauts wore cloth lace-up shoes similar to high-top tennis shoes. To the bottom of the shoe was attached a triangular cleat which was mounted on a short pedestal. The cleat was slightly smaller than the triangles in the floor. By inserting the cleat through a floor triangle and giving a twist of his foot, a crewman could lock himself into position wherever he chose. See Figures 5.7 and 5.8.

Figure 5.7
Skylab shoes showing the mechanism on the sole used to lock the shoe in place on the triangular metal grid floors. (Author's photo from the archives of the National Air and Space Museum).

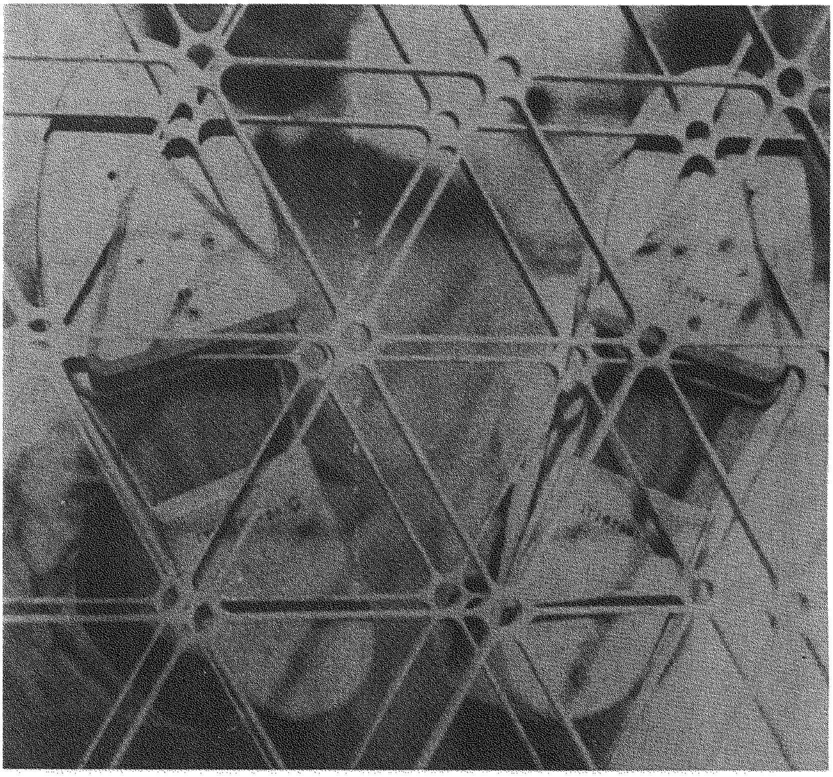


Figure 5.8
Skylab restraint shoe seen from the underside while engaged with triangular floor grids. (NASA photo).

A variety of types of restraint were tried out in Skylab and most of them proved unsatisfactory (Cooper, Jr., 1976). The astronauts find weightlessness to be a delightful experience. Encumbrances such as harnesses around the waist or pelvis with which to attach oneself to anchoring points seriously detracted from the pleasure of the three dimensional freedom the space crews enjoyed. Most such devices, no matter how ingenious the design, were, in the end, discarded.

Jack Lousma flew on the 59-day second manned period of Skylab, and he has also flown as commander of a flight of the shuttle Columbia, on an 8 day mission in 1982 (STS-3). Astronaut Lousma has experienced a wide variety of experimental restraint systems in both Skylab and the shuttle and he has told me that by far the best of the lot were the triangular foot restraints used on Skylab.

In the next chapter I will discuss the space laboratory that succeeded Skylab. It is called ***Spacelab***, and it is carried in the cargo bay of the space shuttle. The new space laboratory was needed because Skylab, which was originally only designed for three on-board missions, was allowed to fall from orbit. The third, and last, manned Skylab mission, which lasted 84 days, ended with the crew's splashdown on February 8th, 1974. A little more than five years after it was abandoned, Skylab re-entered the atmosphere, broke up, and returned to earth as a fiery meteor in the early morning darkness of July 11th, 1979 near Perth, Australia. "Spectacular visual effects were reported and many residents heard sonic booms and whirring noises as the chunks passed overhead.... Officials waited anxiously for news of injury or property damage, but none came." (Compton and Benson, 1983, p. 371).

By this time you have probably come up with some ideas of your own for restraint systems--ideas such as magnets or Velcro on the soles of shoes. In the next chapter I will discuss why those, for instance, can not be used, why Spacelab has a solid floor, and some of the other reasons why restraint remains a difficult design problem.

Chapter Six

Spacelab

Spacelab is a cylindrical laboratory module that is carried into space in the cargo bay of Shuttle orbiters. Figure 6.1 is a line drawing of the exterior of the Spacelab module.

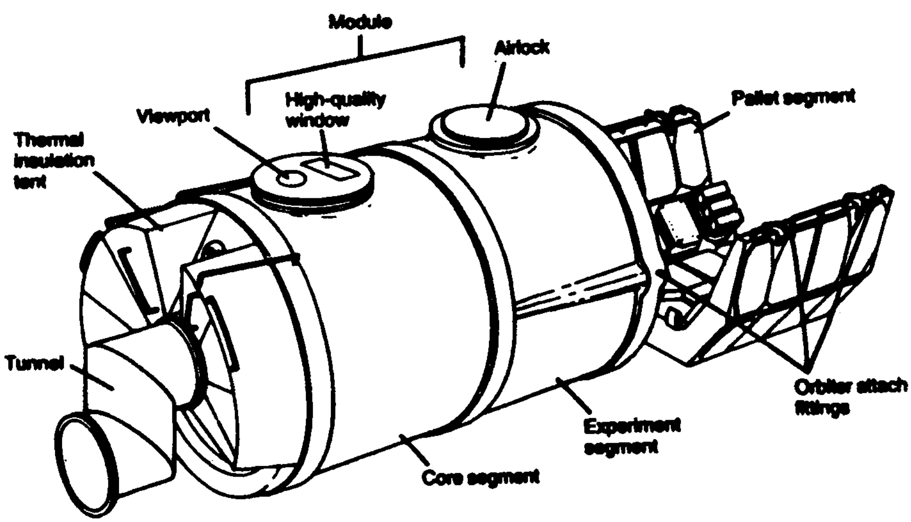


Figure 6.1
The Spacelab module (NASA drawing).

Spacelab was designed and constructed by the European Space Agency (ESA) as a joint space research venture with the United States in which NASA would provide the orbiters, launch and recovery facilities, and the management and communication services. During launch the spacelab module is mounted inside the cargo bay of the orbiter with the cargo bay doors closed. The crew rides aloft in the cabin of the orbiter along with the orbiter crew. Once in orbit, the cargo bay doors are opened thus exposing the Spacelab module, in nearly zero-g, to the very high order vacuum of low earth orbit. Figure 6.2 shows how the module is carried in the orbiters while in space.

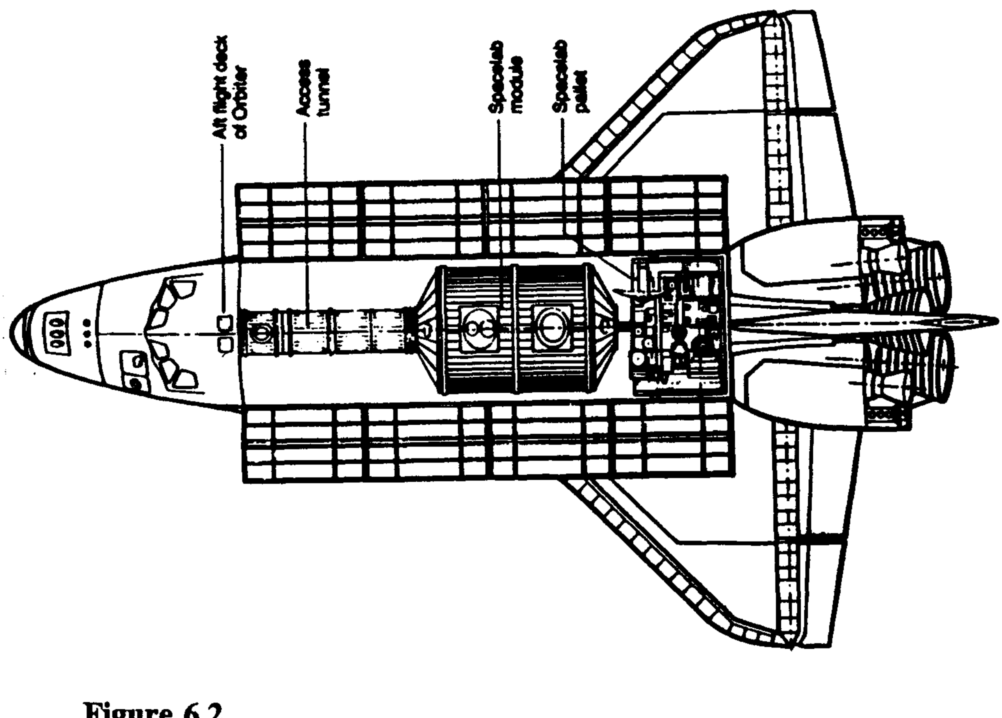


Figure 6.2
Spacelab depicted in the cargo bay of a Shuttle orbiter. Notice that it is located far back in the cargo bay to maintain the orbiter's center of gravity within its longitudinal limits. The tunnel that allows entry from the cabin of the orbiter must then be much longer than the one depicted in Figure 6.1. (NASA drawing).

After the Shuttle and Spacelab are established in orbit with the cargo bay doors open, the Spacelab's environmental system is remotely checked. The orbiter and Spacelab environments are essentially the same--shirtsleeve environments and sea level cabin pressures of 14.7 pounds per square inch (psi). When all checks prove satisfactory, the Spacelab crew enters the tunnel through the air lock located on the orbiter's mid-deck. The tunnel is about three feet wide which is sufficiently roomy, and by pushing off from the air lock, the crew members *translate* through the tunnel and into the Spacelab module.

The Spacelab module is made up of segments which are 4 meters in diameter and 2.7 meters long (13 ft X approx. 9 ft). Until now, all of the flights of the Spacelab module have used two segments enclosed by an end cone on each end, for an overall length of 7m (23ft). Inside, the module has a floor area on each side of which are rows of standard floor-to-ceiling experiment racks which are 48 cm wide (19 in). Beneath the floor is all the plumbing and apparatus for the life-support system and other utilities. Overhead are storage bins, a window, and an airlock to allow small experiment packages to be placed outside and recovered. Figure 6.3 diagrams the module in cross-section.

The first two flights of Spacelab were very successful and demonstrated the usefulness of the module as a space laboratory for short-term studies (the first-generation shuttle orbiters were only designed to be in orbit for up to ten days).

However, when I refer to the first two flights of Spacelab I am referring to what NASA calls Spacelab 1 and Spacelab 3. Spacelab 2 was a flight conducted using only experiments carried on the external pallet (See Figure 6.1) and experiments located in the cabin of the orbiter--the Spacelab module was not carried on that flight. When I use the term Spacelab in this chapter I am referring to the module and thus the second flight of Spacelab is, Spacelab 3.

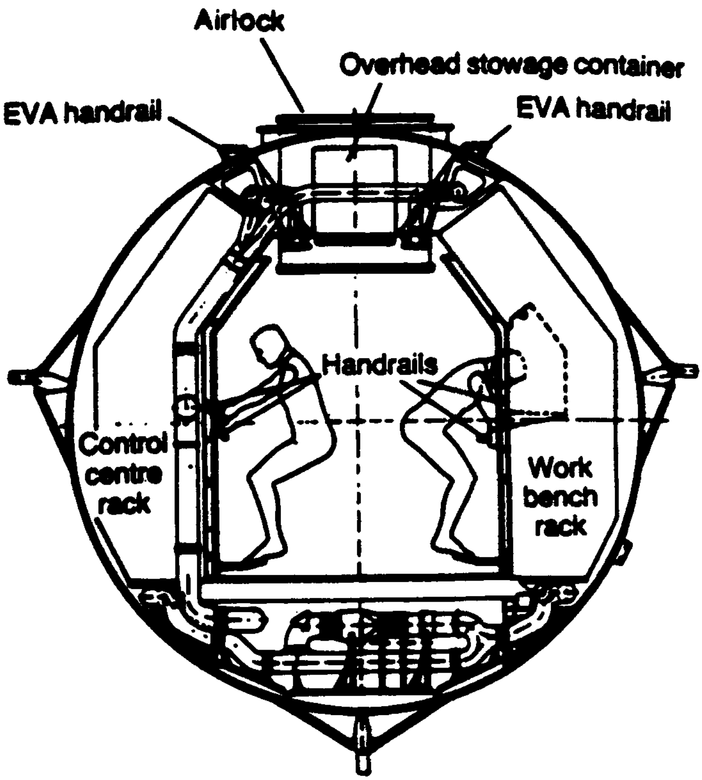


Figure 6.3.
Crew working positions in Spacelab. (NASA Drawing).

In discussing some human factors aspects of Spacelab, I will again discuss crew member restraint, and I will describe a human factors study of restraint system use conducted utilizing video tapes of crew members at work. However, first I have to keep the promise I made at the end of the last chapter, to discuss some of the foot restraints that seem, at first blush, such simple and obvious solutions to the problem. What about Velcro patches on the soles of the footwear and their counterpart Velcro patches on the floor? The problem with the strong Velcro, which is what would be needed, that we use on earth for such things as jacket closures is that it gives off a toxic gas when it burns and thus NASA considers it too dangerous for use in the confines of a space vehicle. A softer and safer type of Velcro is used in space for low effort tasks such as holding pencils in place.

What about using magnets on the footwear soles and steel floors? First of all, steel floors are very heavy and weight becomes a critical factor when it has to be lifted vertically from the earth by a rocket engine. But there are other problems. The spacecraft has many sensitive instruments that could be affected by the magnets. Also, since magnetic fields surround the magnets, they would produce an effect at some distance, so that astronauts would be pulled toward steel objects. It would be very disconcerting to be moving from one location to another and suddenly have one's shoes "lock on to" something made of steel.

Why not use open grid floors as was done on Skylab? That seems to have provided an excellent foot restraint system. The answer is one that will seem strange. Spacecraft are inherently noisy vehicles. They are noisy, to a large extent, because of the noise made by air circulating through ducts and the fans and motors that move the air. Air circulation on earth is greatly simplified by gravity. As air becomes warmer it expands and becomes lighter and rises in the form of convection currents, to be replaced immediately by cooler air. But in zero-g convection currents do not occur. On earth you can have a radio which has air vents at the top and bottom of its case. As the electronics heat up the air, it rises and cool air automatically flows in from the bottom. However, in orbit that same radio would simply get hotter and hotter until it melted itself! In space, if you want air to move, you must move it mechanically, and that makes noise. In an effort to keep down the noise level ESA and NASA engineers wanted to have a solid floor in the Spacelab so that the noisy ductwork, fans, and motors could be isolated by acoustic insulation. As an illustration of this problem, the noise level averages about 72 db in the shuttle orbiters. Compare that with the following typical noise levels: A living room--45 dB; light traffic at 50 feet--55 dB; A freight train at 50 feet--75 dB (Bell, Fisher, Baum, & Greene, 1990). The work of the human factors specialist on earth is truly fascinating, but in space it is even more so.

There were two primary restraint systems used in Spacelabs 1 and 3. Those were cloth foot loops located on the floor, and hand holds located on the walls and ceiling. However, the crew members were quite ingenious in devising their own foot restraints by wedging their feet in-between pieces of apparatus or in small slot-like openings or behind structural supports. This of course suggests that the formal restraints provided by the designers were not satisfactory. Figure 6.4 on the next page shows the relative positions of the foot loops in Spacelabs 1 and 3.

The foot loops are arranged in one of two positions: a) side-by-side, or b) staggered. For example: The pair of foot loops in front of instrument rack 10 in Spacelab 1 are side-by-side, whereas those in front of rack number 7 (also Spacelab 1) are staggered. Clearly, a larger number of foot loops were available in Spacelab 3.

In the previous chapter we saw that cloth foot loops were not used very much by the Skylab astronauts even though the designers obviously expected them to be utilized. Now a new spacecraft has been developed and its designers have put in the very same kind of foot restraints that astronauts would not use in Skylab! If designers are to be convinced that a different restraint device is needed, it will be necessary to provide data which show just how much they are (or are not) used, and to try to find an explanation for why they are not used. It would also help designers if the research could lead to the development of some principles that would specify the nature of satisfactory foot restraints. My students and I conducted just such a study at

Claremont McKenna College's, Aerospace Psychology Laboratory. By reviewing that project and its results, you will get a sense of how at least one kind of human factors research works.

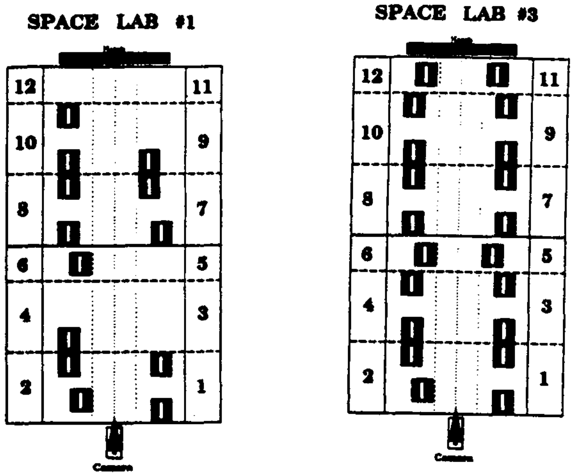


Figure 6.4
Placement of the foot restraints on the floors of Spacelab 1 and Spacelab 3. The numbered squares represent single instrumentation racks and the numbered rectangles represent double racks. The cloth foot loops are represented by the white dashes on the black backgrounds. (Drawing by Jamie Isaac from 2 NASA drawings).

When Spacelabs 1 and 3 flew, a video camera was mounted inside at the end of the module opposite the hatch that opened into the tunnel. The camera looked back at the tunnel opening and was used to photograph the activities taking place. The primary purpose for the camera was to allow NASA ground personnel, and the scientists whose experiments were on board, to see what was going on inside the module. The camera was also taken down occasionally and used to photograph experiments, such as the growing of crystals, taking place in the experiment racks.

Rockwell International, the company that built the shuttle orbiters, had approximately 50 hours of videotape that had been taken on board the two Spacelab flights. Of those 50 hours of tape, about 10 hours showed people, and those segments were made available to my students and me for study. Both flights were just about equally represented on the tapes and there were segments from all stages of each flight. The tapes were in color, had sound, and were of quite good quality.

Ideally, we would have had videotapes of every minute the module had people in it. Then we could simply have made a random selection of one- or two-hundred one-minute epochs and have been able to conduct good studies of each flight and done comparisons between them as well as across the duration of each flight. That was not possible with the tapes we had because the entire time could not be randomly sampled which was a serious drawback to good experimental design. Nevertheless, we did have many hours of activity recorded, and some useful information almost certainly could be derived from a careful study of the tapes.

We set out to do that by first watching the tapes several times through. Simple as this may sound, careful observation is one of the hallmarks of a human factors professional. This work was tedious but important because several behaviors related to restraint became obvious enough to us so that we could operationally define them. One such behavior was using either one or two foot loops. Another was holding on with either one or both hands. Yet another was translating from one location to another. Finally, being out of control or struggling was, sometimes humorously, obvious.

For us, an operational definition was one which allowed us to specify exactly what had to happen to enable a judge to determine that a specific behavior was taking place. For example, translation was defined as "the time spent moving from one location to another beginning the moment restraint is relinquished until the moment restraint is re-established and the crew member is in a position to do work". The real test of whether or not such a definition is adequate is the amount of agreement that occurs between different judges viewing the same video tapes. The statistic we used to determine the amount of agreement is called Cronbach's ALPHA and can vary from 1.0, which would indicate perfect correspondence among all of the judges, to 0.0, which would be no correspondence among any of them. For our four behaviors, ALPHAs were: Translation = .94, Hand Hold = .88, Foot Restraint = .87,and Struggle = .87. These numbers represent very high degrees of agreement and verify that our operational definitions were effective in specifying precisely what the four different judges, who independently timed each of the behaviors using a stop watch, was to be observing.

Each judge independently watched each tape segment four times. On each occasion the judges timed one of the four behaviors for a specified crew member. The average percent of the time spent emitting each of the behaviors was as follows: Translating = 9.4%, Hand Hold = 32.2%, Foot Restraint = 35.3%, and Struggle = 3.7%. This accounts for about 81% of the time. The remaining time was spent in behaving in ways that fell outside the operational definitions of the four behaviors (e.g., simply drifting).

We were able to divide our data into three groups, those representing the first third of each flight, the middle third, and the last third. These data were then plotted on graphs with percent of time spent exhibiting the behavior on the vertical axis and portions of flight (1st, 2nd, or 3rd) on the horizontal axis. From left to right on each graph, the lines for Struggle, and Hand Hold sloped downward, the line for Foot Restraint sloped upward, and the line for Translating was essentially level. This suggests that, as crew members accumulated more experience, they learned to use the foot restraints more and had to use hand holds less. They were also learning how to exist in zero-g with less struggling. The amount of time spent translating from one place to another in the small cabin remained about the same in each third of the flights.

You now know the essentials of the design of our human factors study, and you have some of the data. What can be concluded from this information? First of all imagine yourself in a situation on earth where your work data were comparable to those of the astronauts cited above. For instance, imagine yourself in a chemistry or a biology laboratory trying to work with only one hand while holding on with the other for nearly a third of the time. How much good work do you think you would get done in a normal lab period? To make this scenario a little more specific, let's assume the lab period is three hours long. Here would be your work data:

Holding on with one hand = 58 minutes, (32.2%).

Walking between work stations = 17 minutes, (9.4%).

Being out of control = 6.5 minutes, (3.7%).

Let's begin by imagining something pretty ridiculous. Imagine that your laboratory floor is covered with soap suds and is very slippery--so slippery that during your three-hour lab you spend a total of six and one-half minutes in the process of slipping, sliding, and sprawling in all sorts of crazy positions because of your loss of traction (we'll pretend that you always fall without being injured). For nearly an hour out of the three hours you would only have been able to work with one hand while holding on with the other. You could imagine spending a few minutes during this time stepping over to look at a gauge or dial on an instrument located off to one side and perhaps stepping over to another part of the room to get something. But can you imagine spending 17 minutes in motion?

On earth we would not tolerate such a situation because someone out of control would be injured by gravitational forces. In space only the inefficiency matters and thus we are more likely to accept it as part of the circumstances. However, our little earth bound scenario gives us the perspective that makes this stand out in bold relief as poor human factors design.

After completing this study we went on to consider more specifically, what was happening with the other foot when one foot was in a foot loop. We needed to know why, when two foot loops were available, crew members so frequently used only one of them. This required us to view selected segments of the videotapes once again. This time we selected out those segments which showed a crew member using only one foot and then we determined what was being done with the other foot. It turned out that when we measured the use of two foot loops vs one for periods of up to one minute and periods longer than a minute we found that the single foot loop was often used for the shorter periods but when the person needed restraint for more than a minute, two foot loops were more frequently employed. In fact, in Spacelab 3 during 87% of restraint episodes lasting longer than a minute, two foot loops were used.

Some foot loops were mounted side by side, and some were staggered--side by side, but one loop somewhat in front of the other. The latter is an excellent arrangement because it provides not only lateral stability (side to side) but longitudinal stability (front to back) as well. Spacelab 3 not only had more foot loops than Spacelab 1, but it had more of the staggered type as well. As one might expect, foot loops, both singly and dual, were employed much more frequently in Spacelab 3 than in 1. We can summarize this by saying that we found that when foot restraints were more available they were used more and when there were a greater number of the seemingly more effective staggered variety, they, in turn, were used more.

We found that when only one foot loop was used the other foot swung free if the crew member was stabilizing himself with one hand. But often the second foot was used to push backwards against some structure forcing the crew member's foot further into the one foot loop being used. Apparently this was an attempt to be held down more securely. Another use for the free foot was to wedge it into a space between two structures, or into an opening or behind or under a brace or support. Sometimes only one or, in some cases, both feet were used to improvise an ad hoc foot restraint using various parts of the surrounding apparatus.

By this time we had clear evidence that the foot loop was not an adequate foot restraint device for zero-g environments. What we now needed to do was explain why astronauts were so reluctant to use them and establish some principles that could serve as guidelines for the design of an adequate foot restraint.

Anthropometry is a discipline which is related to human factors through the discipline of physical anthropology. It explores the range of behaviors and their limitations that are a function of the way the human body is articulated. When our research team members looked at the anthropometric diagrams that showed the changes in human posturing that take place in zero-g we quickly understood what was wrong with the foot loop. Figure 6.5 on the following page shows a relaxed and erect person in one-g and again in zero-g.

The position that an erect body assumes in zero-g is essentially the same one it assumes when floating in salt water. This is called the *neutral body position* and is caused by the natural tension among muscles, tendons, and joints. Figure 6.6 on the page after the next gives the specific anthropometric data for the orientations of body parts in this posture.

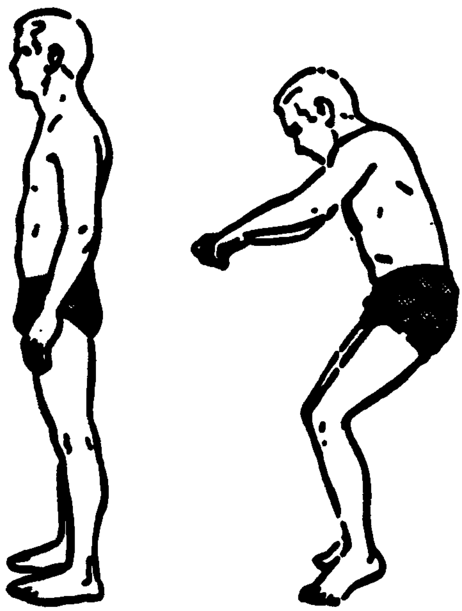


Figure 6.5
The posture of a relaxed erect person on earth (left) and in zero-g (right). (Drawing by Naomi Matsuo from a NASA drawing).

In Figure 6.6, notice that the angle between the shin bone and the sole of the foot is 111°, not the 90° into which they are forced when standing in one-g. Thus to keep one's foot in a cloth foot loop it is necessary to contract the muscles (primarily the tibialis anterior) overlying the shin to raise the foot 21° and then hold that contraction. Astronauts have told us that this is an uncomfortable thing to do. [To experience a close approximation of this, be seated, cross your right leg over your left and rest the middle of your right lower leg on top of the left thigh, and relax.

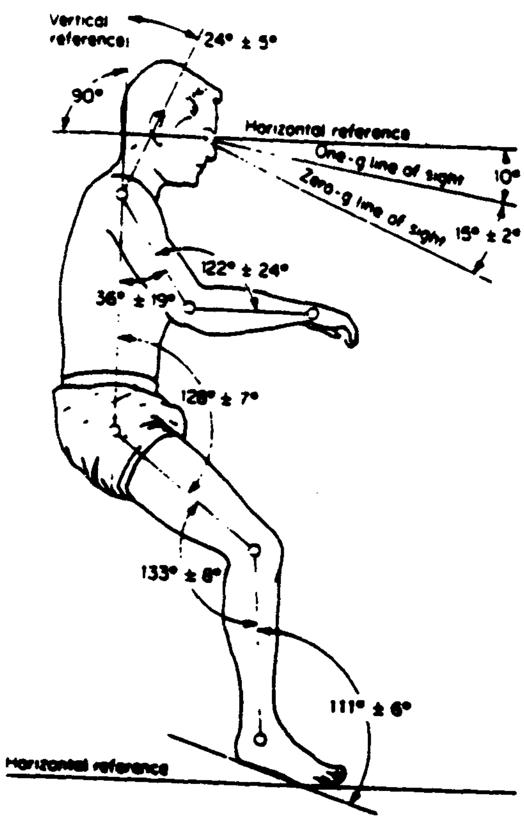


Figure 6.6
The anthropometric data for the orientations of body parts in the neutral body position. (Drawing by Naomi Matsuo from a NASA drawing).

Your right foot will form approximately the 111° angle with the leg that it does in the neutral body position. Now pull it back up so that your ankle and foot form a right angle and hold this position. In less than a minute it becomes uncomfortable even though the leg is essentially horizontal and the foot is not being lifted against gravity.]

A common behavior that we observed was for a crew member to place one foot in a foot loop and then push the back part of the heel of the other foot rearward against some part of the spacecraft structure, forcing himself farther forward, and thus more tightly, into the single foot loop. Clearly, the combination of the body's orientation in the neutral body position and the pliability of the soft foot loops make them an unacceptable foot restraint system, especially for the extended use one might expect on a space station. Our analysis suggests the following principles for an adequate foot restraint for an erect crew member.

1. Provide stability in all three axes.
2. Allow a close approximation to the neutral body position when the user is relaxed.
3. Provide gripping friction beneath (not above) the foot.
4. Orient the user so that eyes and arms are correct distances from work surfaces.
5. Allow the user some choice of the distance the restraint centers are apart and fore-and-aft.
6. Be very reliable once engaged.
7. Be simple and easy to engage and disengage.

Please take a moment and look back at Figure 6.3. Notice that in this early drawing of the work station configuration of the spacelab crew members, the artist drew the astronauts as if they were restrained by a system that allowed them to closely approximate the neutral body position. Note too that this arrangement oriented their heads and arms properly before the work areas. Unfortunately, however, this is not how the crew was restrained in actual practice.

In this simple human factors study we qualitatively identified four major types of spacelab astronaut behavior. However, the importance of these behaviors follows from our then having quantified them. Being out of control nearly 4% of the time is clearly too much. Working with one hand while stabilizing with the other for nearly a third of the time represents a design flaw. Utilizing the foot restraint system provided for *only* one-third of the time suggests what that flaw may be. Spending nearly 10% of the time moving back and forth between the experimental racks represents poor use of crew members whose time is worth more than $17,000 per hour (estimated in 1987 dollars), and suggests that control functions should be centralized. Finally, having demonstrated that the cloth foot loop is an inadequate restraint for zero-g, we were able to specify for designers seven factors which characterize an adequate foot restraint system.

The end of the foot restraint story has yet to be written. Perhaps there will be a return to a grid floor such as the one in Skylab that will be placed over the solid floor of Spacelab. On a recent flight of Spacelab a small section of a new type of restraining floor panel was tested. This paneling was dimpled with hemispheric depressions which served as sockets into which a ball (actually half a ball) attached to the sole of a crew member's shoe could be inserted. The results of the tests of this new panel have not yet been reported.

Chapter Seven

The Space Shuttle

With the successful completion of the Apollo program the next big question was, "where do we go from here?" Once again, to be better able to understand why decisions were made, it helps to look back and try to get a sense of the times. In an address entitled, *A Spacefaring People*, delivered at a conference on the history of space activity, John Noble Wilford stated:

> *The first Apollo landing was, in one sense, a triumph that failed, not because the achievement was anything short of magnificent but because of misdirected expectations and a general misinterpretation of its real meaning. The public was encouraged to view it only as the grand climax of the space program, a geopolitical horse race and extraterrestrial entertainment--not as a dramatic means to the greater end of developing a far-ranging spacefaring capability* [italics in the original] (quoted in Roland, 1985).

In his 1989 history of the Apollo program, William Compton wrote the following.

> A decade and a half after Eugene Cernan left the last human footprint on the moon, the value and the wisdom of the Apollo project can still be debated. As an engineering accomplishment it is unparalleled in history. As a scientific project it enabled researchers on earth to study documented specimens from another body in the solar system, perhaps the only such specimens that will be available in this century. As an exercise in the management of an unprecedentedly large and complex effort it stands alone in human experience.
>
> Yet all of these achievements can be read two ways. Magnificent as they were, the launch vehicles that carried men to the moon turned out to be too expensive for other missions. The choice of lunar-orbit rendezvous as the mission mode--largely dictated by the end-of-the-decade challenge--produced two spacecraft ideally adapted to their function but without sufficient margin for growth to advance the exploration of the moon as far as scientists wanted (1989, pp. 269-270).

In earlier chapters I referred to the Saturn 5 rocket in glowing terms. It was a marvelous machine that stood 363 ft tall with all the majesty of a skyscraper. It consisted of thousands upon thousands of beautifully machined parts, each carefully inspected, tested and assembled, and reinspected. It was powerful and reliable. But it was also terribly expensive. And when it was used, it could only be used once. The state of rocket engine science at that time permitted the development of engines that could perform as did those on the Saturn 5--but only for one flight.

As Americans chafed at the cost of space flight there also didn't seem to be much reason to keep sending men back to the moon just to keep bringing back rocks. But that was about all that could really be done with the Apollo system. Compton, in his Apollo history, clarifies for us why the country's attention was shifting to other things now that the space race was over.

> Americans had plenty to occupy their attention in 1969--civil rights, the plight of the poor, an increasingly unpopular war in southeast Asia, rising federal deficits, and growing concern for the preservation of a liveable environment--and plenty of advocates for every cause clamoring for action (Compton, 1989, p.270).

That was the social context in which NASA had to decide, and persuade congress and the administration to fund whatever it was that we ought to do next in space.

After lengthy and heated debate the decision was made to proceed with both manned and unmanned exploration of space. Unmanned exploration would continue in the tradition of spacecraft such as the series of *Voyager* craft that remotely surveyed many of the planets in the solar system. These were the products of NASA's Jet Propulsion Laboratory, in Pasadena, CA, which would continue its work.

To get people back in space, NASA would build a space station that would remain in earth orbit as had Skylab. This space station could then serve as a center for space science research with active laboratories, and also, as a departure point for trips to other planets such as Mars, or to the moon where eventually a permanent base would be established. In the meantime, there were satellites waiting to be launched for purposes of communication, navigation, weather prediction, and for a variety of military purposes. This launch capability, together with the ability to launch material with which to build the space station and carry crews back and forth, would require a reusable vehicle rated for carrying people.

The design settled upon was what we now call the space shuttle. It represented a number of compromises, and as such will always have its detractors. For instance, since the shuttle would become NASA's primary launch vehicle, the expensive Saturn boosters were dropped from the inventory. Because the shuttle would be less powerful than the Saturn, and because it would have to carry up the very heavy space glider that would return at the end of each launch, the payload that the unit could lift was much less than the Saturn had been capable of. Also, because what the shuttle carried up had to fit into the orbiter's cargo bay, the volume that could be lofted was quite limited. Never again, for instance, would we be able to put up something as big and heavy as Skylab had been, unless it could be taken up in pieces and assembled in space.

On January 5th, 1972 President Nixon announced the plan to go ahead with the Shuttle program. It took more than nine years of intense technological advancement before the shuttle Columbia lifted from the earth early on the morning of April 12th, 1981. After a "smooth as silk" landing some 54 hours later, test pilot John Young, a veteran of both Gemini and Apollo exclaimed "This is the world's greatest flying machine, I'll tell you that" (quoted in McAleer, 1987, p.74).

What the shuttle promised was an inexpensive, reusable, reliable, safe, utility vehicle. It could not only carry satellites up to low earth orbit (some 200 miles) from which they could be easily directed to other orbits with a modest sized rocket motor, but it could retrieve satellites that were brought down to low earth orbit, and bring them back to earth. Until the space station is built, the shuttle can itself serve as a kind of short-term space station to carry out scientific research. It was to facilitate that kind of work that the spacelab discussed in chapter 6 was built. A series of these shuttles would be built and become what would be called the Space Transportation System--hence the designation of shuttle flights as STS followed by some number.

In many ways the shuttle turned out to be everything it promised to be. It is a splendid machine. But it has turned out to be more expensive to operate than intended, and it has required more ground maintenance and attention than was expected. Thus, shuttles fly less frequently than originally planned. With the destruction of the shuttle Challenger and the loss of its crew on January 28th, 1986, in a mishap resulting from a leak in the casing of a strap-on solid propellant rocket, the aura of confidence that had developed after 24 consecutive trips to space, has been diminished.

Box 7.1

The Space Shuttle Orbiters

1.	ENTERPRISE	Only a test vehicle, 1977.[1]
2.	COLUMBIA	First flew April 12, 1981.
3.	CHALLENGER	First flew April 4, 1983[2]
4.	DISCOVERY	First flew August 30, 1984.
5.	ATLANTIS	First flew October 3, 1985.
6.	ENDEAVOUR	First flew May 7, 1992.[3]

[1]Glide tested but never orbited. Now belongs to the National Air and Space Museum.
[2]Destroyed on its 10th flight, Jan. 28, 1986.
[3]Built to replace Challenger.

Just what is a shuttle? A shuttle consists of four elements: an orbiter, about the size of a twin-engined jet liner; a huge fuel tank to carry the liquid oxygen and hydrogen that are used as propellants for the orbiter's three main engines; and a pair of strap on solid propellant booster rockets.

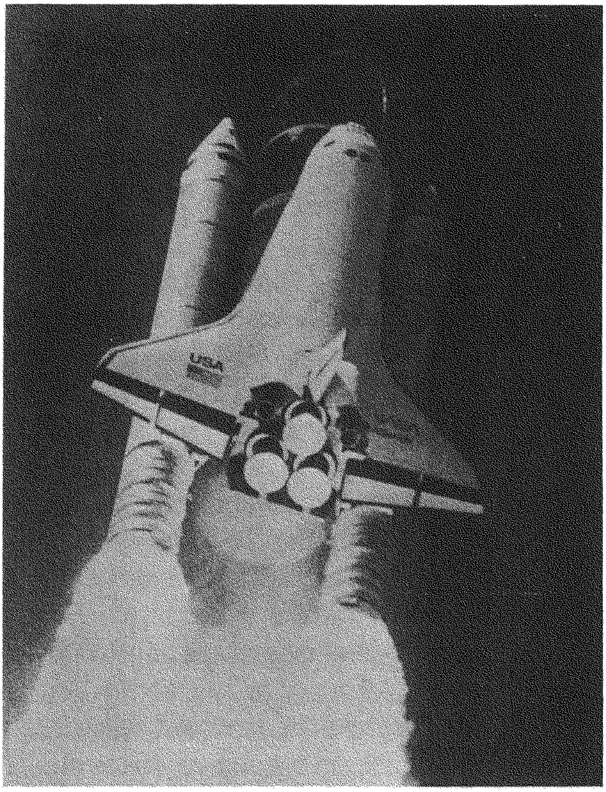


Figure 7.1
The orbiter *Atlantis* during launch. The three main engines on the rear of the orbiter are glowing. On either side of the top main engine are the two engines (dark circles) that will be used for orbital maneuvering. They are fed from tanks inside the orbiter.

The orbiter is attached to the external propellant tank and gets its oxidizer and fuel (hydrogen) through large connecting pipes. The strap on boosters are also connected, one on each side, to the giant external propellant tank. The orbiter has three main rocket engines which draw propellants from the big tank. Together, the two solid propellant, and three liquid propellant engines give the shuttle a takeoff thrust of nearly six and one-half million pounds or about 83% of the thrust of a Saturn 5 rocket.

A shuttle is different from earlier space craft in the following significant ways.

It is almost entirely reusable.
It is both a space craft and an aircraft.
It can carry payloads up and bring payloads down.
It is much larger and has more electrical power, thus:
It has a kitchen with an oven, a toilet, sleeping, and hygiene areas; it can support scientific experiments.
It can carry a laboratory in its cargo bay and thus be a short duration space station.
It has a sea level atmosphere in the cabin (14.7 psi, 79% N, 21% O_2).
It is protected against the heat of reentry by an ingenious system of reusable insulation and tiles that shed heat by radiation and convection. Earlier space craft used ablative heat shields that shed heat by wearing away.
It has engines which can be throttled back to control the forces to which crews and payloads are subjected.

I will begin discussing human factors in the design of the shuttle by addressing what may be the fundamental issue common to all vehicles--how do you steer the thing? By the time the shuttle was being designed the side-arm controller had proven itself in service as the controller of choice in space. However, the shuttle presented a problem, for while it was a space craft, it was also an aircraft. And the pilots who fly aircraft are universally accustomed to having rudder pedals with which to control yaw rather than rotating the hand grip of the controller as is done in space flight.

When something is practiced so frequently that the activity seems to have become "second nature", it is said to be ***overlearned.*** To have pilots fly what will be perceived as an airplane (i.e., an orbiter during landing) using a hand controller to control all three axes would require not only teaching the pilot to use the controller, but teaching the pilot to suppress the earlier, overlearned behavior of pressing rudder pedals. This can be done, of course, but whenever an old response has to be unlearned (suppressed) in order to learn a new one it takes more time and effort. There is also another more insidious problem to be considered. During moments of high anxiety people tend to revert to doing things the way they were first learned--especially if they were overlearned. Therefore in dealing with high performance machinery requiring quick reactions, sometimes during intense stress, there is an advantage to having standardized ways of doing things.

The solution for the orbiters was to keep the controller and use it as it had been used when the orbiter is a space craft. The controller was however moved from the side to between the pilot's legs. Then when the shuttle performs as an aircraft and the controller is operating the wing surfaces instead of reaction control thrusters, it will activate only pitch and roll. Yaw will be controlled by rudder pedals. This has proved to be a good solution.

The issue of training is a very important human factors consideration in preparing people to operate complex machines. Space flight is no exception, as exemplified in the following quotation.

> The shuttle ships do so much that even the men and women who fly them are hard-pressed to

> learn the complexities in their area of responsibility. Joe H. Engle, commander of the second test flight of *Columbia*, summed it up for the novelist James Michener during an interview.
>
> "Look at this pile of manuals we have to know by heart," he told the author. "Hydraulics, propulsion, communications, digital processing, life-support systems, environmental control, orbital maneuvering, reaction controls, navigation guidance, mechanical functioning, big-arm manipulation, reentry data, glide control." Getting to know the world's most complex machine does not come easily (McAleer, 1987, p. 72).

An important innovation in training procedures has been the development of simulations. Simulation itself is nothing new. In the theater a rehearsal is a simulation, and sports practices are simulations that train for real games. Dress rehearsals prior to opening nights are *high fidelity* simulations of the real thing. An even higher fidelity simulation in the theater is to have a benefit performance before the opening night so that the cast will experience the effect of a large audience before being rated by the critics.

With the development of modern computers, simulation of the operation of complex machinery has been elevated to a high station. The learning principle upon which simulators work is called *transfer of training*. There are two types of transfer of training, positive and negative. When participating in an activity improves performance on a target task, the transfer of training is positive--if performance on the target task is diminished, the transfer is negative. Fidelity in simulation is important because, as a general rule, the more the simulation is exactly like the real situation, the better the positive transfer of training will be. To give you an idea of how effective modern airliner simulators have become, consider the fact that an airline pilot can be trained to fly an airliner in a simulator and then go on line duty with only one or two hours of flying in the actual aircraft! We must not loose sight of the fact, however, that when human beings are involved, there is more going on than just moving levers and responding to instruments. An anecdote from the history of cockpit human factors research will make this clear.

The General Dynamics Company had developed a new supersonic jet fighter (the F-16) for the U.S. Air Force. The design of the cockpit of this fighter, perhaps more than any other before it, was heavily influenced by human factors considerations. After the fighter, with its innovative new cockpit, became operational, the Air Force wanted to quantify just how much this new airplane would reduce combat stress on pilots. Combat was simulated by taking highly trained fighter pilots and randomly assigning them to fly either an F-16 or the older fighter that it was replacing. Then F-16s were randomly paired with an older fighter and the two planes went up and did dog fighting in simulated combat in which gun sight computers determined who won. After the simulated combat, each pilot gave a urine sample which was tested for the presence of chemicals indicating the amount of stress that had been experienced.

To the astonishment of the engineers and designers, the F-16 pilots showed significantly higher stress levels than did the other pilots! How could this be? Human factors experts interviewed the pilots to see if they could find a clue as to what had produced these results and they quickly discovered the problem. The pilots who flew the older plane said, in effect, "this was a no lose situation. You fly the old obsolete plane and lose and no one will blame you. What's more, if you win, you're a hero because you beat the new plane with your old machine--you must be terrific." It was just the opposite for the F-16 pilots who found this to be a no win situation. "You fly the F-16 and win and everyone will say that you should have so its no big deal. But if you lose to the guy flying the obsolete old tub you'll be the laughing stock of the squadron."

The things that are most difficult to simulate are related to human emotions such as the anxiety one feels by being up in the air in bad weather when low on fuel, or the loneliness of being 200,000 mile away from earth on your way to the moon. Nevertheless, modern high fidelity aircraft simulators are almost astonishing in the accuracy with which they duplicate the events and sensations a pilot will experience in the real aircraft--even down to hearing and feeling the tiny thump of rolling over expansion joints in the concrete during simulated taxiing.

It is important that I not leave the reader with a sense that operating a simulator is usually an emotionless exercise in lever moving and dial twisting until the actions become routine. For the airline pilot, just as for the fighter pilots mentioned earlier, there is a lot of pride at stake in doing a job well. In addition, a commercial pilot who fails his simulator check ride can have his job in jeopardy. The simulators also can do things that are just downright scary even if they aren't real, and herein lies some of their greatest value.

With simulators things can be practiced that would be impossible or too dangerous in a real plane. For instance, one can simulate having a fire in a baggage compartment, having a tire blow out during landing on a wet runway in a cross wind, have a landing gear not come down, or have an engine fail while accelerating and have to abort a takeoff. Suppose, for example, that a pilot practicing engine failure during takeoff is a bit slow in initiating the abort procedure. Imagine what it must be like in a machine that feels like a real airplane, to have the engines screaming in reverse thrust, to be stomping on the brakes and see the end of the runway coming up and knowing you can't stop. Many a pilot leaves the simulator soaked in anxiety produced sweat, having eaten a large portion of humble pie. But the nice thing about crashing in the simulator is that the instructor simply repositions you back at the beginning of the runway and you keep doing it until you get it right.

Simulators of air and space craft come in three basic types: procedures trainers, fixed base, and moving base. Procedures trainers are cockpit mock-ups. They have instruments and levers and circuit breakers and all of the things one would find in a cockpit. But usually nothing works. They are all there and in the correct places so the student can learn what is there and where it is located. In their simplest form they can be cardboard setups with the parts and instruments simply printed on the cardboard. They are useful for learning routines such as how to start an engine. You learn a lot just by looking at the gauge that would be read or reaching over to the button that would be pressed in a real cockpit. Procedures trainers are valuable because they produce good positive transfer and they are inexpensive.

Fixed base simulators are procedures trainers in which everything really works. They are driven by computers and one could go through a complete trip to the moon and back or fly practice approaches and landings at a major airport. When the cockpit interior is the same as the actual space craft or airplane, and when all the sounds and instrument movements are accurate, these are very realistic trainers. Fixed base trainers can also present visual scenes in motion as they would be seen from the windshield of an aircraft or the window of a space craft. For the space craft these would primarily be celestial scenes similar to what one would see in a planetarium show. In an aircraft simulator the scene is usually a night scene of the sky in that location and the airport lights. Cities are portrayed by the lighting patterns that characterize them at night. Daylight scenes are just now beginning to be introduced as computers begin to get fast and powerful enough to depict these scenes changing as they would in real time. Even scenes that are highly simplified can be valuable. The night time scenes, which are much easier to program and display, are very realistic.

Moving based simulators add one thing that fixed base units can't provide, and that is the actual experience of movement. Moving base simulators typically sit atop a group of hydraulic actuators that can cause the simulator to tilt fore and aft, and side to side. They also allow it to move forward and backward, sideways, and up and down. The latter motions can be combined with the tilt motions to experience any motion in all three axes. When a pilot in a fixed base simulator turns the control wheel to the left, the artificial horizon instrument tilts accordingly and the compass begins to rotate indicating that the plane is turning. This is very realistic and new trainees sometimes get dizzy and even nauseated. In a moving base simulator all of the same things happen, and in addition, the simulator actually tips left--the whole cockpit. Thus the semicircular canals in the inner ear of the pilot are stimulated. A moving base simulator pitches down and forward if the brakes are applied and lurches sideways if the craft is skidding. The primary thing of interest here that simulators can not simulate is weightlessness. Other than that, they can duplicate flight situations with great fidelity.

NASA has made excellent use of all three types of simulators in training astronauts. A typical flight in a space shuttle will involve the crew (and its back-up crew) in about two years of training. NASA has simulators, not only of the orbiter cockpits, but of the mid-deck area including the air-lock which is used when exiting the shuttle in space. NASA also has simulators of the Spacelab, which I discussed in Chapter Six, which is carried in the orbiter's cargo bay. For extra vehicular activity simulation, a huge water tank is used. The astronauts, in their space suits, are weighted so that they are just buoyant, and this is the one situation in which weightlessness can be simulated on earth. Water tank simulations have turned out to match very well what takes place in space. The drag produced by the viscosity of water seems to matter little because astronauts never move very quickly and the cumbersomeness of the inflated suit in space pretty well matches the retarded motions in the water.

NASA also has a modified Gulfstream G-II corporate jet plane in which the pilot's side (left) has a shuttle commander's seat, instruments, and controls (McClellan, 1985). The copilot's side, where the instructor rides, has normal Gulfstream controls. A computer conditions the inputs from the orbiter side so that the Gulfstream responds the way an orbiter would. When the instructor moves controls on his side, the aircraft operates as a normal Gulfstream. This has proven to be an excellent trainer for teaching the shuttle commanders to land their orbiters. Keep in mind that it is often the case that the very first time a shuttle commander lands his orbiter, is the very first time he has landed *any* orbiter! There simply is no practical way to practice in the real thing. The high quality of all of the landings that have taken place so far is a testament to the effectiveness of simulators in preparing pilots to operate their machines effectively the first time they do it for real.

I will conclude this discussion of simulation by briefly describing what may have been NASA's most outrageous (but effective) simulator. In an effort to simulate landing on the moon, which has one sixth the gravity of earth, a spindly legged lunar lander simulator was built using the thrust from a turbojet engine mounted with the exhaust directed earthward to support five-sixths of the craft's weight. On the periphery were small rocket thrusters for attitude and directional control (see Figure 7.2 on the following page).

> It was a skittish and somewhat unstable vehicle; on two occasions in 1968 pilots had to eject from it. Nonetheless, it was the only device that could accurately simulate the last few hundred feet of the lunar landing approach and commanders of lunar landing missions and their backups were required to perform as many landings in the LLTV [Lunar Landing Training Vehicle] as time permitted (Compton, 1989, p. 140).

Human factors, as a discipline, has played a significant role in the development of simulation which has become such an important part of training and safety in aviation and space flight.

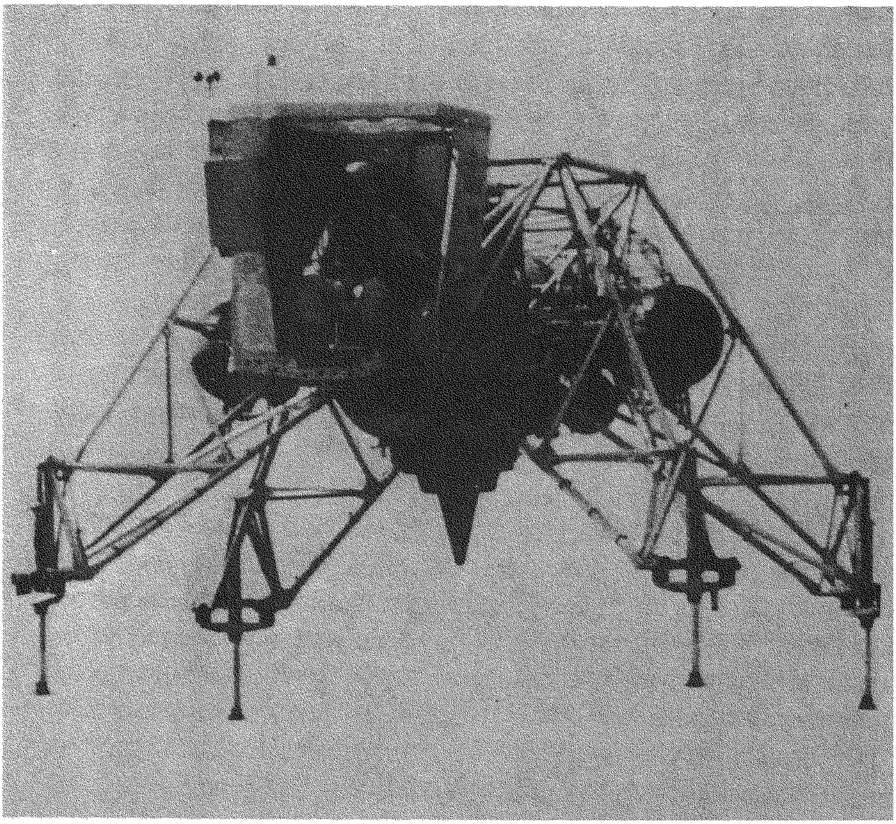


Figure 7.2
Astronaut Pete Conrad practices in the lunar landing simulator.

Shuttle crews spend many more hours in their orbiter simulators than they ever do in their orbiters.

The space shuttle is clearly the most complex of all prior spacecraft and is probably the most complex vehicle ever built. The more complex a machine is to operate, the more opportunities there are for human error to occur. Organizing the management of an operator's workload is an important human factors concern, and in the case of the shuttle NASA has elevated this type of effort to a fine art. While it is true that simulators in some settings are almost exclusively training devices, NASA has used its high fidelity shuttle simulators to excellent advantage as human factors research tools. With such simulators, human factors experts can study crew performance *before* a flight takes place and determine the best placement for instruments and controls, the proper sequencing of procedures and information flow, and the best mix of crew action vs automation.

The *checklist* has been one of the most useful inventions in the history of the operation of machines by humans. A checklist is the equivalent, in words, of a flow chart of the sequence of actions that must take place for a specified event to occur. Here, for instance, is an item from the shuttle commander's check list for T minus five minutes (five minutes before liftoff) at which time the crew starts the auxiliary power units which control hydraulic pressure.

> HYD MAIN PUMP PRESS 1--NORM. Check the HYDRAULIC PRESSURE 1 indicator--it should be HI green [note the use of color coding] (Joels & Kennedy, 1988, p. 1.22).

NASA's shuttle pre-launch flow charts and checklists are prepared with meticulous attention to every detail and then are tested in the simulators until they work smoothly, without error, and without causing undue fatigue.

Human factors researchers have only recently begun to study the characteristics of *prospective remembering*, which is remembering to do something in the future, (Wichman & Oyasato, 1983). An illustration of prospective memory is remembering to lower the landing gear before landing. Many aircraft accidents can be attributed to failures of prospective memory. NASA has managed prospective remembering for shuttle flights well by carefully integrating the activities of the commander and the pilot (analogous to captain and first officer in the airlines) and, because of the greater complexity, they have included the controllers in this process. Even when things are done automatically, it becomes someone's task to check to make sure that the action took place. For example, one minute and fifty-seven seconds before liftoff the external vents on the hydrogen fuel tanks for the main engines automatically close. This causes pressure to build up inside the tank as the liquid hydrogen begins to warm. This is necessary to provide the proper tank pressure for flight. A ground controller watches for this to have taken place and calls the crew to let them know so that, busy as they are, they don't also have that to monitor. The crew then acknowledges so that everyone is sure the information has been transmitted.

Because a shuttle crew trains together for about two years for a flight they get to know exactly what each other is going to do. Along the way, in simulation after simulation, human factors experts help the crew work out procedures and relationships. By the time of their flight they are a highly integrated system. This is very different from the way things work at an airline. There, a pilot meets his or her copilot and flight engineer an hour or two before flight time. Prior training has to have been good enough so that these strangers will be able to operate as an integrated team in the cockpit.

All major airlines have recently begun bringing their crews in for special training called, Cockpit Resource Management (CRM). This management aspect of human factors was developed after investigations showed that many airline accidents could have been prevented if all members of a crew had a special awareness of the importance of always assuring that the critical aspects of any task are managed by someone, and that anyone with important information communicates it to the crew member who needs it. Examples of such accidents are a circling DC-8 that ran out of fuel while all the cockpit crew was occupied with a balky landing gear, or a Lockheed L-1011 that crashed in a swamp when the crew, distracted with a faulty warning light, didn't notice that the autopilot had disconnected.

As you can see, not all shuttle human factors issues deal with the interface between the machine and crew members. Some issues have to do with training, some with management, and some even with interpersonal relationships, both among crew members, and between flight crews and ground crews.

In a crowded shuttle, occasional opportunities for privacy are important and must be included in the planning of procedures, in much the same way that rest times would be incorporated, so as to optimize crew performance. When mixing crew members from different cultures, as is often done for, instance, when the Spacelab is flown in the shuttle, it is necessary to plan for cross-cultural differences that could have powerful motivational effects on the crew.

A fascinating cross-cultural issue has already arisen on one of the shuttle missions. On a 1958 flight of Discovery, Sultan Salman Abdelazize Al-Saud of Saudi Arabia served as a mission specialist to witness the launch of an ARABSAT 1-B communications satellite. Because the sultan was a Moslem, it was necessary for him to face toward Mecca and pray at certain times of the day. However, in low earth orbit the sun rises and sets every 45 minutes, making a solar day only 90 minutes long. The solution to the problem of when to pray was to use Houston time as the reference time for the space crew. Thus, when it was prayer time in Houston, it was prayer time onboard the shuttle. The next problem involved the direction to face while praying: which way was east? Because there is no east in space, the problem was solved when religious authorities decided that facing toward the earth was the appropriate behavior. These were sensible and relatively easy decisions to make. What is most important, from a human factors point of view, is that it was recognized that such decisions had to be made, and the important religious needs of a crew member were anticipated and designed into the procedures protocol before the flight took place.

I will conclude this brief journey through the history of the space program and aerospace human factors, by returning to the question originally raised by engineers when the proposal was first made that they design space craft to carry humans--"is it worth the trouble, complexity, and cost?"

As a final testament to the human spirit and the value of having humans in space I submit the following photograph of three astronauts. When a mechanical grappling device failed to connect to a disabled satellite, they contrived to secure the 4.5 ton vehicle with their gloved hands and attached it to a mechanical capture bar.

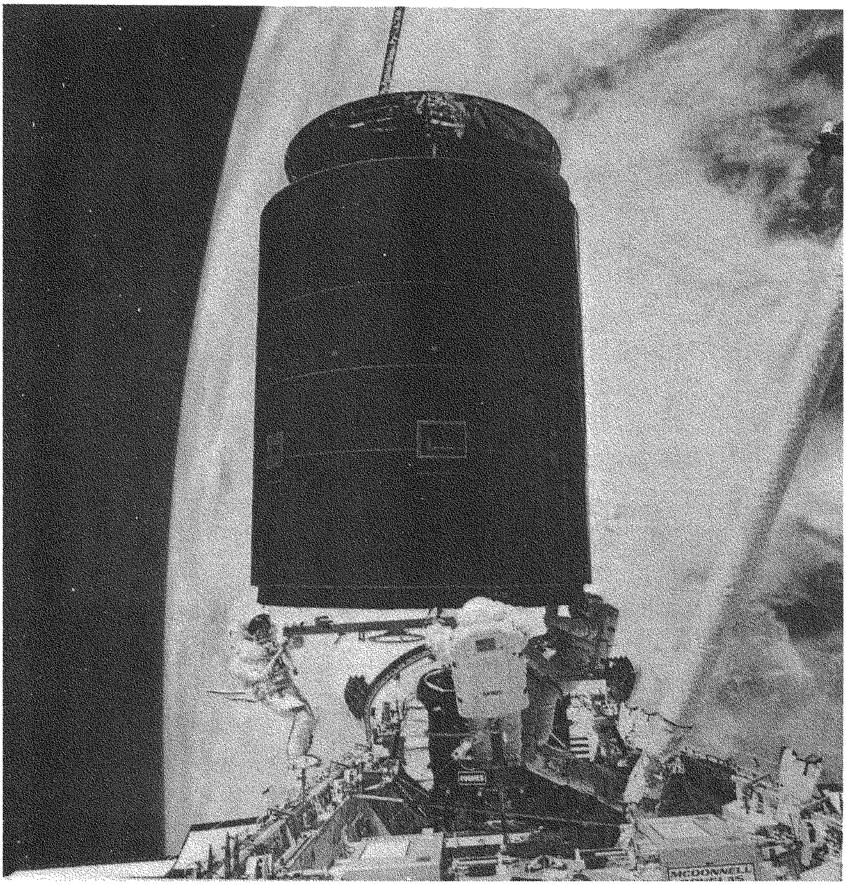


Figure 7.3
Three astronauts on the first flight of Endevour save an Intelsat 6/F3 spacecraft at an altitude of 200 nautical miles. (NASA photo).

Astronaut-physicist Franklin Chang-Diaz, in a crew press conference prior to his third shuttle flight aboard STS-46, pointed out that more than half of the experiments that had been flown on shuttle flights by the summer of 1992 had not worked as planned in space. But, because astronauts were on board to adjust or modify the experiments, most were made functional and their value to science saved. Dr. Chang-Diaz also pointed out that several hundred million dollars' worth of scientific and communication satellites had been repaired or salvaged by shuttle crews. He concluded these remarks by saying that, space science now has become so sophisticated that the shuttle orbiters are serving as laboratories in which scientist-astronauts are conducting important basic research that could not otherwise be done.

Chapter Eight

The Future of Human Factors in Space

I concluded the previous chapter by suggesting that there was sufficient utility in having some spacecraft with people aboard, to justify the added expense that is necessarily involved in building such vehicles. However, I don't believe that the argument for putting people in space hinges on the correctness of the utility assumption. Indeed, if it is correct, it may be nothing more than frosting on the cake. This monograph is being published in 1992, the year in which we celebrate the five-hundredth anniversary of the voyage of Christopher Columbus to the *new world.* The argument over whether it is worth the cost to have a *manned space program* still remains a lively debate among space scientists, especially as each new year's budget is being considered in the U.S. Congress. So the utility argument has not yet been set to rest.

But when past writers of science fiction dreamed and wrote of space exploration, they did not write only of automated spacecraft and robots. They dreamed and wrote about human space explorers, and in doing so, may have expressed a human motive that has its roots deep in our animal nature. Surely the evidence shows that, wherever it was on earth that humans began, we have spread out to cover most of the planet. And we did so long before one could attribute this to crowding on the earth. Imagine an anthropologist from another planet who comes to earth and studies

Homo sapiens. Surely this extra terrestrial scholar would characterize us as a species with a strong curiosity and an intense drive to explore. Perhaps this need to explore was best put in the elegantly simple reply of the great British mountaineer, George Leigh Mallory, when he was asked why he wanted to climb Mt. Everest and he replied, "Because it is there".

The point is that, in spite of the strong arguments to the contrary, we indeed *do* have a program that puts people into space, and I find it hard to believe that it will not continue--the evidence from the past is just too compelling. It seems reasonable then to end this exploration of the application of human factors in the spacecraft that have been built, by thinking a bit about the space craft that are yet to be built. However, before looking ahead, I think it will be useful to briefly look back at the two big fatal accidents that have occurred in NASA's history. When fatal accidents occur, something is almost always wrong in terms of human factors.

I may have given the impression that the ranks of those designing and building spacecraft were replete with human factors professionals, actively participating, doing research, and giving advice. While it is true that human factors professionals have been involved in the space program, one has to remember that this is a new profession, and it is only slowly coming into full acceptance. Human factors professionals should not only be found on the design and production teams, but they should also be active members of the policy making and management groups, because, as I have shown, policy and management decisions often affect safety, either directly or obliquely through procedures established for the use of machinery.

Much of what I have written about the human factors issues in the space program actually were dealt with by astronauts, engineers, managers, and policy makers, whose experience had made them sensitive to such issues. In addition, I do not want to suggest that the two accidents would not have occurred if there had been more human factors personnel involved. I simply have no evidence regarding such a notion.

However, I do want to show how a mind-set can occur in a context of repeated success, and the confidence this breeds, which allows persons from a variety of disciplines to ignore serious design and procedural flaws which, under the right set of circumstances, can produce a tragic occurrence. What is sometimes maddening about this phenomenon is that the flaws are so difficult to recognize before hand and, in retrospect, are so obvious. Astronaut, Michael Collins, described it well in the following recollection of the first of the two accidents, which occurred on January 27, 1967 during practice for, what was to be the inaugural Apollo launch with a crew aboard.

> Don finally hung up and said very quietly, "Fire in the spacecraft." ...All I could think of was, My God, such an obvious thing and we hadn't considered it. We worried about engines that wouldn't start or wouldn't stop; we worried about leaks; we even worried about how a flame front might propagate in weightlessness and how cabin pressure might be reduced to stop a fire in space. But right here on the ground, when we should have been most alert, we put three guys inside an untried spacecraft, strapped them into couches, locked two cumbersome hatches behind them, and left them no way of escaping a fire. Oh yes, if the booster caught fire, down below, there were elaborate, if impractical, plans for escaping the holocaust by sliding down a wire, but a fire inside the spacecraft itself simply couldn't happen. Yet it had happened and why not? After all, the 100 percent oxygen environment we used in space was at least at a reduced pressure of five pounds per square inch, but on the launch pad the pressure was slightly above atmospheric, or nearly 16 psi. Light a cigarette in

> pure oxygen at 16 psi and you will get the surprise of your life as you watch it turn to ash in about two seconds. With all those oxygen molecules packed in there at that pressure, any material considered "combustible" would instead be almost explosive. And combustible materials--books, clothing, supplies--there were plenty, also plenty of ignition sources. There was supposed to be none of the latter, but let's face it, the inside of a Block I spacecraft was a forest of wires, a jungle which had been invaded over and over again by workmen changing, and snipping, and adding, and splicing, until the whole thing was simply one big potential short circuit (Collins, 1974, pp. 270-271).

Prior to the Apollo fire, which killed Virgil (Gus) Grissom, Edward White, and Roger Chaffee, there had been no deaths in spacecraft in the U.S. space program. Astronauts had been killed in airplane accidents, but those were unrelated to the design of spacecraft or the operation of the program. Chaffee was a rookie astronaut but Grissom and White were national heroes, and their deaths by fire while trapped in a spacecraft stunned the nation, and brought the Apollo program to an abrupt halt. Investigations were held and many changes were instituted over the 19-month period before the first Apollo flew on October 11, 1968.

Most of what is necessary to know about this accident is mentioned in the above quotation. I will add a clarification for the over-pressure in the module and then discuss just one of the many human factors errors that were ultimately corrected.

When humans, breathing air (78% nitrogen and 21% oxygen), go from sea level pressure to a lower pressure, they run the risk that some of the nitrogen which has become dissolved in their blood will come out of solution and form bubbles. Medically this is known as dysbarism. It is the same phenomenon that occurs with carbon dioxide when a champagne bottle (the contents of which are under pressure) is opened. When the bubbles in the blood get to joints in the limbs they collect and produce excruciating pain known commonly as ***the bends***. Serious cases of the bends are totally incapacitating and severe cases are fatal--thus the disorder must be protected against.

The typical protective procedure is to breath pure oxygen at normal pressure for about three hours before depressurization, to purge all nitrogen from the blood. This was what was being done in the practice for the Apollo launch when the fire occurred. In that case, however, the pressure inside the module was increased by about 2 psi so that if there were any leakage it would be from oxygen leaking out of the module and not from nitrogen leaking in.

I want to consider with you a single human factors consequence of this simple two pound over-pressure. To get out of the command module one had to remove three successive hatches, only the inner two of which were sealed on the day of the fire. The innermost hatch was the hatch in the pressure vessel. After unlatching, it had to be pulled inward to remove it. Thus, in space, the 5 psi over-pressure on the inside forced the hatch more tightly against its seal. If the hatch is a square 24 inches on a side, then the total surface area is 576 square inches. With an interior pressure 2 psi greater than that on the outside (16.7 vs 14.7) the total force pushing the hatch outward is 1,152 lbs. Obviously no one lying on his back on a couch in a cumbersome space suit could reach over his head and pull in a hatch that required more than half a ton of force. Nevertheless, before they lost consciousness the crew had frantically tried to dislodge the hatch. Once the fire started in the sealed spacecraft the pressure inside rose rapidly until it reached 29 psi, at which time the pressure vessel burst open. Just before the spacecraft ruptured, the force required to open the hatch was more than four tons. No one on the outside could get in. No one on the inside could get out. The crew died of asphyxiation and inhaling toxic combustion products.

This is about as startling an example of bad human factors design as one can ever expect to see, and it is only one of a number of faulty designs and procedures that had to be corrected after the fire. Needless to say, a single, outward opening hatch, with an emergency quick-release system was developed before the first manned flight of Apollo.

The second accident was the loss of the shuttle *Challenger* on the morning of January 28, 1986. Since the Apollo fire, the U.S. had sent 27 men out to orbit the moon and landed a dozen on it. No more lives had been lost. Then came the shuttle program. One after another, there had been 24 successful flights. No longer did one have to be a test pilot with the "right stuff" to go into space. A U.S. Senator and an Arab prince had already flown on shuttles, and on this day a school teacher would go aloft to broadcast science lessons from space. Millions of adults and school children, in the U.S. and in countries around the world, who had come to take space flight for granted, watched with renewed enthusiasm as their TV sets showed the always dramatic liftoff from the Kennedy Space Center. Seventy-three seconds later they stared in disbelief and shock at what has come to be referred to as the explosion of the Challenger. The 1.5 billion dollar spacecraft that had flown successfully nine times before was gone--and with it the seven wonderful members of its crew. Once again the dark cloud of grief and mourning engulfed the nation, and this time most of the world. And once again boards of inquiry were formed to determine what went wrong.

There was a design flaw. But it was not one that would likely have been caught by a human factors expert. The solid propellant rockets were made in sections that were then stacked on top of one another and joined together. The flaw had to do with the design of the joints between the sections. The joints were designed not to leak hot gases that built up great pressure inside the casing sections. A rubber-like gasket was used to help seal the joint against leaks. This gasket is called an O-ring because it is a ring that is circular in cross section.

However, this design flaw, by itself, would not have brought down the shuttle. Had the rubber-like material been soft and pliant, it probably would have done the job as it had, at least adequately, on the 24 preceding flights. But this particularly cold Florida day was much colder than it had ever been for a previous shuttle launch. Icicles hung on many parts of the shuttle and its gantry. The O-ring must have been brittle and non-pliant. Fifteen engineers from the company that made the solid propellant boosters had recommended against the launch when it was so cold. However, the word never got to those who made the final launch decision. In fact, for several years, concerns about the seals had been voiced at different levels, but again, the word never got to NASA's top managers. Here we see a human factors failure that is related to the design of procedures and decision making policies as opposed to the design of equipment.

Shortly after liftoff, hot exhaust gases on the right solid propellant booster breached a joint seal and spurted out the side against the large external propellant tank. The hole got larger and became a small sideways thrusting rocket. Eventually the strut that connects the lower end of the booster to the external propellant tank failed. The base of the booster swung outward causing the tip to swing inward and puncture the oxygen tank in the top section of the big tank. The whole structure became very unstable and things began to break. When the hydrogen tank failed, a massive fire began and the bottom end of the hydrogen tank blew off giving a huge sudden increase in thrust to the vehicle. The Challenger separated from the rest of the structure which held it in a position that kept its wings from producing lift. The explosion did not destroy the Challenger with its force. Now, however, freed from the large external propellant tank, the Challenger suddenly became an airplane going just under 2,000 mph and its wings produced too much lifting force which caused the vehicle to break up into pieces just as it was put together--the wings, the engine compartment, the cargo bay, the crew compartment, and the nose cone. The crew compartment fell some 8 miles and struck the water at a terminal velocity estimated at somewhat more than 200 mph. The entire crew, almost certainly unconscious from lack of oxygen in the damaged and decompressed compartment, was killed instantly.

Investigations took place. The problem with the seals was clarified and fixed. The serious communication and decision making problems were discovered and significant organizational and procedural restructuring of NASA took place. Many other improvements, some of which had been called for earlier by astronauts, were finally implemented. Nose wheel steering was added, carbon brakes were added as well as new hydraulic systems, and a crew escape system. The escape system allows crew members to bail out of a gliding orbiter between 5,000 and 20,000 ft altitude at about 200 mph. A 21 ft telescoping pole extends beside the main entry hatch. A crew member attaches a ring to the pole and slides out away from the wings and tail and then opens a parachute for descent.

I have highlighted two different types of human factors concerns for you. One was the Apollo escape hatch problem--a classic illustration of the person-machine interface. The other was the launch decision problem for the Challenger--an illustration of a newer and less well known aspect of human factors involving policies and procedures. This is consonant with a conceptual model of human factors proposed by Edwards, which he called the SHEL model (1972). He said that system designers have three resources at their disposal:

S oftware--rules, regulations, laws, customs, habits, orders;
H ardware--buildings, equipment, vehicles, apparatus;
E nvironment--the context in which the resources interact;
L iveware--human beings or other animals.

Elsewhere, Edwards has pointed out that, while the classic ergonomic interface was between Liveware-Hardware, recent experience has shown the importance of the Liveware-Software interface (1988).

> In order to achieve safe and effective operations, the interface between S and L requires very careful engineering. The software must not be in conflict with human characteristics; it is futile to formulate rules with which conformity cannot be attained and unwise to formulate them such that undue difficulty is generated. During the investigation of violations of a particular type, it is profitable to enquire whether the rules, rather than the violators, are basically at fault (1988, p. 13).

After a hiatus of 32 months following the Challenger accident, the redesigned shuttles are now flying again using their redesigned procedures, and it is time to look to the future and think about human factors in the spacecraft that are yet to come.

I will begin by listing, what I see as the six next most likely space ventures involving human occupants.

1. **Space station *Freedom*.** A low earth orbit station now in the advanced design and early building stages. In his State of the Union Message of January 5, 1984, President Reagan directed NASA to develop a permanently manned space station and to do so within a decade. NASA has named this structure ***Freedom.*** It will be an international enterprise in which Japan and the European Space Agency (ESA) will each contribute a laboratory module, and Canada will provide the mechanical arms, as they did for the shuttle orbiters. The U.S. will provide a habitat, another laboratory, and the mini-modules, called nodes, that connect the various modules together and which also provide emergency sanctuaries. The U.S. will also provide the solar panels to generate 56 kw of power for the early version of the station, the radiators to cool it, and the scaffold-like superstructure on which to mount all of the elements (please see Figure 8.1).

The advantages of the station are that it can be built with current technology and by being in low earth orbit it is protected by the Van Allen radiation belts. These are two concentric donut shaped areas around the middle of the earth, the inner consisting of protons and the outer electrons.

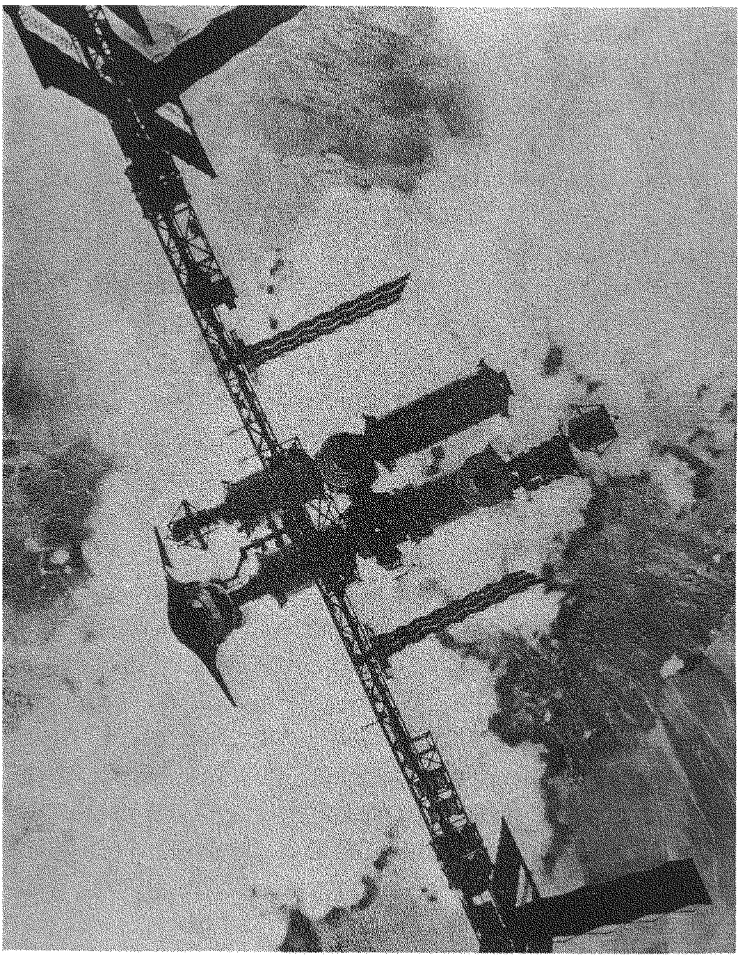


Figure 8.1.
An artist's rendering of the most likely first configuration of the space station *Freedom* as of July, 1992 (viewed from above looking down at the earth). (NASA illustration).

Cosmic rays are trapped in these belts. Periodically, changes in the solar wind (the stream of radiation from the sun) cause some of the trapped particles to "rain" into the earth's polar regions. When they strike the upper atmosphere they produce the northern lights or aurora borealis in the northern hemisphere and the aurora Australis in the southern hemisphere (Damon, 1990). The station can be reached by the shuttle, and will serve as a basic research facility in which to learn how to live and work in weightlessness. It has two serious disadvantages. one is that its orbital decay rate from friction with molecules at the top of the atmosphere is quite large and it will have to be speeded up periodically. The other is that half of each revolution is spent in the darkness of the earth's shadow, during which time the solar panels do not generate electricity.

2. **The National Aerospace Plane (NASP).** The prototype research version of this plane is referred to as the X-30. This would be a *single-stage-to-orbit* vehicle, which means that there are no rocket stages that are jettisoned or strap-on boosters that fall away. Everything that goes up together, comes back together. The plane will take off from a runway using wings for lift and turbojet engines for thrust, just like a modern airliner. It will accelerate to Mach 3 or 4 (3 or 4 times the speed of sound), and then transition to ram jet engines which will accelerate it to Mach 5 or 6, after which it will switch to scramjet (supersonic combustion ram jet) engines to speeds above Mach 12. The NASP will fly to the outer edges of the atmosphere using liquid hydrogen and atmospheric oxygen as propellants. Then it will go into orbit using liquid hydrogen/liquid oxygen rocket engines. An airliner version of this plane, which could fly between any two points on earth in less than two hours, is often referred to as the *Orient Express*. Much new technology must be developed before this vehicle and its engines can be built.

3. **The Delta Clipper.** This is a single-stage-to-orbit, re-useable, cargo and passenger carrying rocket. A 1/3 scale model, proof of concept vehicle is now being built by the McDonnell

Douglas Space Systems Company, and is scheduled to fly at White Sands, New Mexico, in the spring of 1993. This vehicle will take off vertically and go to orbit, from which it could launch satellites or service the space station *Freedom.* It will reenter the atmosphere on its side, and then land vertically by backing down using the thrust of its engines. It is planned as an adjunct to the shuttle orbiters, that would be less expensive to operate and have shorter turn-around times between flights. Because it uses present technology it could serve in the interim until the NASP can be built. Its primary disadvantage is its small payload.

4. **A Space Station at L4 or L5.** Imagine a circle which represents the moon's orbit around the earth. Picture it as a clock face with the earth at the center and the moon at the three o'clock position. Now imagine a point on the circle at the one o'clock position. Lines between the moon, earth, and this point form an equilateral triangle. There is another such point at the five o'clock position on the circle. These are known as libration points or Lagrangian points, after the French mathematician Joseph Lagrange who determined them theoretically. The point out in front of the moon in its orbit is L4, while the one following the moon is L5. A space station placed at either of these two points will remain there with no expenditure of energy as a result of the interaction between the gravitational fields of the earth and moon. It would always be in sunlight and be an excellent way-station for trips to the moon or from which to launch spaceships to other planets such as Mars. However, we will probably establish a small moon base before building this station.

5. **A Moon Base.** The moon is an excellent place for nonterrestrial work. It has only 1/6 the gravity of the earth and no atmosphere so one can go to it and leave it with low expenditures of energy. Its soil, called regolith, is rich in oxygen and many minerals important to industry such as iron, aluminum, titanium, calcium, and silicon (Bova, 1987). Structures that would be very flimsy on earth are plenty strong in the moon's weak gravity. But that gravity, weak though it may be, makes life much easier for

earth creatures because one can walk, and things do fall down, and they also stay put when set down. One could spend much more time on the moon without suffering the serious deconditioning one would in the weightlessness of an orbiting space station. The moon's drawbacks are its lack of water, and the fact that its surface is a very hostile radiation environment. Surely we will go back to the moon within two or three decades.

6. **A Mars Base.** This will represent a great step in human adventuring. Reasons for going to Mars are that it is another planet like the earth, with gravity, an atmosphere, weather, and very importantly, vast amounts of water. Mars is the nearest planet to earth and not closer to the sun as is Venus, which is too hot to visit, nor very far away such as Uranus which is very cold. The primary problem in going to Mars is that it is still very far away. For instance, using present technology and the advantageous relative positions of Mars and Earth in 1998 and 2001, the mission time would be 2 years and 8 months--9 months on the outbound transfer orbit, 16 months on Mars, and about 7 months to return (Damon, 1990). Before this kind of trip can be undertaken, much better spacecraft electric power systems are needed and much more needs to be known about space physiology. A space station will be an important laboratory for learning the latter.

The most significant difference between the early space flights and those to come in the near future is their duration, e.g. 90 days on the space station, much longer periods on the moon, and periods measured in years on early Mars trips. The next most important difference is that the crews will almost certainly be multinational because of the need to share the enormous costs involved. The space station *Freedom* leads the way in this new trend.

In complex groups on extended missions in the future, inter-group and intra-group procedures and policies will assume much greater significance than was the case in the past. The spacecraft needed can be built. Human factors can make them "user friendly". But human factors must better understand group processes to be able to guide the design of successful future space projects from a systems point of view. This point of view will conceive of the three system resources--spacecraft, crew members, procedures--as interacting in an environment that is physical, social, and political.

Index of Key Human Factors Related Terms

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